GEOLOŠKI ANALI BALKANSKOGA POLUOSTRVA
Volume 86 (1), July 2025, 171-191
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https://doi.org/10.2298/GABP240827003R
Original scientific paper
Оригинални научни рад

Characterization of hydrogeological units and hydrodynamics of a section of the aquifer system in the city of Cartago, Costa Rica

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Abstract. The study focuses on the hydrogeological characterization of the aquifer system in the central sector of Cartago, Costa Rica. This area was selected due to its significant urbanization and agricultural activities, both of which heavily depend on groundwater resources. The conceptual hydrogeological model was developed using well records, field hydrogeological observations along rivers and material extraction pits, macroscopic sample collection for thin-section analysis, spring and well inventories, and piezometric level analysis. A series of hydrogeological profiles were modeled to visualize the subsurface configuration of hydrogeological units and their relationships with existing geological materials. In areas with sufficient well density and adequate geographic distribution, the groundwater flow dynamics within the hydrogeological units were also analyzed. The results revealed that the aquifer system consists of a variety of materials, predominantly alluvial and laharic deposits, which function as aquifer hydrogeological units. These materials contain interspersed clay lenses, fine sands, and coarse sands, which collectively influence the formation of saturated zones, aquitards, and aquicludes. Additionally, these characteristics determine the degree of confinement of the aquifer units. In some sectors, this confinement results in water upwelling, creating artesian conditions. Flow directions were predominantly oriented from north to south, following the surface gradient, although variations in flow direction highlighted the complexity and interconnectivity of the units. For the first time, the hydrogeological model of the Cartago aquifer system was defined. It comprises the Taras, La Chinchilla, Cartago, El Bosque, Tejar, and Dulce Nombre hydrogeological units. Each of these units corresponds to a specific portion of the study area within the central sector of Cartago, which lies atop the Cartago aquifer system.

Key words:
Costa Rica, tropical hydrogeology, alluvial materials, laharicmaterials, volcanic aquifers.

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Апстракт. У раду се приказаују хидрогеолошке карактеристике издани у централном сектору града Cartago (Костарика). Ова област је изабрана због значајне урбанизације и пољопривредних активности, које у великој мери зависе од подземних вода. Концептуални хидрогеолошки модел је развијен коришћењем података из бушотина, хидрогеолошких осматрања на терену дуж река и раскопа материјала, прикупљања макроскопских узорака за анализу петрографских препарата, инвентара извора и бушотина, као и анализе пијезометријских нивоа. Моделована је серија хидрогеолошких профила како би се визуализовала подземна конфигурација хидрогеолошких јединица и њихови односи са постојећим геолошким јединицама. У областима са довољном густином бушотина и одговарајућом географском дистрибуцијом, анализирана је и хидродинамика тока подземних вода унутар хидрогеолошких јединица. Резултати су показали да је систем издани састављен од различитих седимената, претежно алувијалних и лахарских наслага, које функционишу као хидрогеолошке јединице у колектору. Ови материјали садрже сочива глине, ситних и крупних пескова, који заједно утичу на формирање засићених зона, изолатора и водонепропусних јединица. Поред тога, ове карактеристике одређују степен збијености колектора који у неким секторима, узрокује избијање воде на површину, стварајући артешке услове. Смер тока је углавном оријентисан од севера ка југу, пратећи нагиб терена, иако су варијације у смеру тока истакле комплексност и међусобну повезаност јединица. Први пут је дефинисан хидрогеолошки модел система колектора Cartago. Систем обухвата хидрогеолошке јединице Taras, La Chinchilla, Cartago, El Bosque, Tejar и Dulce Nombre. Свака од ових јединица одговара одређеном делу истраживане области у централном сектору Cartago, који се налази изнад колекторског система Cartago.

Према GPS мерењима, раседна зона Fethiye-Burdur представља јужну границу егејске екстензионе области. Егејски регион се карактерише уједначеним кретањем према југозападу брзином од 30 mm/god. у односу на Евроазијску плочу. Теренска осматрања и модели раседних површи недавних земљотреса, унутар и око области језера Burdur, одражавају нормално и лево-бочно косо раседање имајући у виду СИ екстензију раседне зоне. Према предложеном кинематском моделу, различита сеизмотектонска понашања раседне зоне Fethiye-Burdur потичу од ригидног утицаја Yeşilova перидотитског масива навлаке Lycian, а која се дешавају на југозападу језера Burdur. Кинематске интеракције, између углавном СИ вергентних паралелних раседних сегмената Fethiye-Burdur раседне зоне, резултирају различитим сеизмотектонским карактеристикама. Сходно томе, добијен је нови кинематски модел за језеро Burdur и његову околину.

Кључне речи:
Костарика,
тропска хидрогеологија,
алувијалне наслаге,
лахарске наслаге,
вулкански колектори.

Introduction

In Central America there is an enormous dependence on groundwater, coming from sources such as wells and springs (Losilla et al., 2001). With the increase in population, climatic phenomena and contamination of aquifers, the availability of water resources can worsen (UNESCU, 2020), causing greater exploitation of new water sources and social problems in the region. In Costa Rica, the water resource is not well distributed and is threatened by the absence of territorial planning, deforestation, changes in water use, the deterioration of watersheds, the lack of planning and pollution (Hernández & Fernández, 2020).

In the central area of Costa Rica, where the Central Valley is located, four main cities of Costa Rica are located, San José, Heredia and Alajuela, in the Western Central Valley and Cartago in the Eastern Central Valley, which are separated by the hills of Ochomogo and the Cerros de la Carpintera (Vargas et al., 2020). The central area of the city of Cartago and its surroundings has two main sources of water supply, one derived from the Orosi reservoir and the other from springs. The wells that are distributed in different sectors are used to reinforce the water supply and are an important alternative for water supply, especially at times when there is greater urbanization, characterized by the construction of condominiums.

To the north of the city of Cartago is the largest area of horticultural production in Costa Rica, however, there are also important agricultural areas around the city that can be a potential source of contamination by agrochemicals (Álvarez et al., 2021).

Despite being an important urban area, there are few hydrogeological investigations carried out in the central area of Cartago, as is the case of Ramírez & Zúñiga (2014) and Castanedo (2015). Some other important works around the area are Ramírez (2006), Ramírez (2007), Quintanilla et al. (2008) Arellano et al. (2012), Zúñiga & Ramírez (2015), Obando (2017), Jiménez (2018), however, none of them concentrates on the central part of the city of Cartago, so it is necessary to carry out a first characterization of this area, which can serve as an input for the generation of a conceptual hydrogeological model which is the basis of future research.

Study area

Costa Rica is in Central America, situated between Nicaragua to the north and Panama to the south (Fig. 1). The eastern coast is bordered by the Caribbean Sea and the western coast by the Pacific Ocean. The country has a surface of 51.179,92 km^2 and is divided into seven governing provinces. The city of Cartago is in the Western Central Valley, in the central region of the Republic of Costa Rica, in Central America (Fig. 2). The total study area covers 25.9 km^2. The study area corresponds to the central sector of the city of Cartago, Costa Rica, geographically located between the coordinates 506540–511640 m east and 1088350 m – 1093400 m north of the Transverse Mercator Cylindrical Conformal Projection system for Costa Rica.

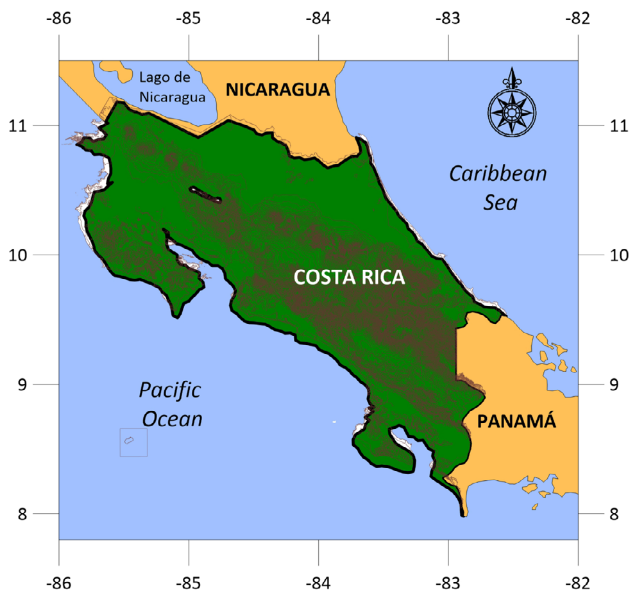

Fig. 1. *Location of Costa Rica in Central America.*

The studied area is situated 24 km southeast of San José, capital of Costa Rica, has a tropical humid montane climate, with average temperatures ranging from 12 to 20 °C, at an altitude of 1435 m above sea level on the slopes of the Irazú Volcano, the highest in the country. Agriculture and livestock farming are the main economic activities.

According to the weather station of the Costa Rica Institute of Technology, the annual rainfall over a 20-year period was 1399 mm. The driest average month was March, with a value of 20.8 mm, and the wettest average month was October, with a value of 228.4 mm. The annual mean temperature is 18.34 °C,

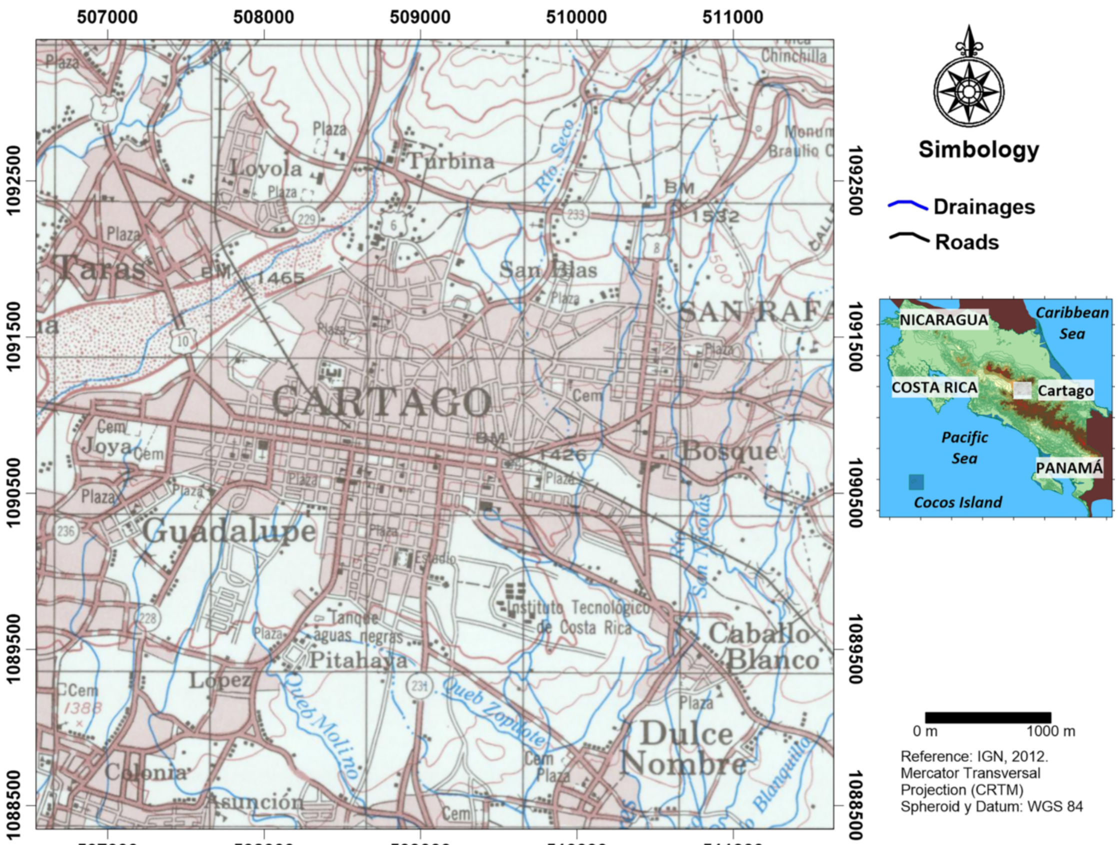

Fig. 2. *Location of the central area of the city of Cartago and its surroundings.*

and the annual relative humidity reaches 89.4% for the period between 1997 and 2016.

Several significant studies have been conducted in the study area, providing valuable input for understanding this work. Basic geological information primarily relied on the study by Krushensky (1972), at a 1:50,000 scale, which serves as the main source of regional information and has been the foundation for most geological studies in the area. Additional sources of geological information included the works of Montero & Kruse (2006), Insuma (2013), Sojo (2018), and Vega (2018).

The primary source of hydrogeological information for this study was obtained from the National Service for Groundwater, Irrigation, and Drainage (SENARA) well archive. Other hydrogeological sources in the study area included the works of Obando (2017), Jiménez (2018), and Montes (2020). All these sources provided a basic hydrogeological context for the surroundings of the city of Cartago.

Materials and methods

To determine the geological characteristics on which the hydrogeological units were based, a series of studies of the area were compiled, including those by Krushensky (1972), Quintanilla et al. (2008), Zúñiga & Ramírez (2015) and Sojo (2017). Based on geological studies, all the information was digitized, and a map of geological units was created using MapInfo software.

After completing this stage, field surveys were conducted with the aid of topographic maps and aerial photographs to locate outcrops of lithological materials and collect macroscopic samples for basic description. Lithological reconnaissance sites included not only road cuts along farm paths but also various locations along the Reventado, Taras, and Toyogres rivers. The vector cartographic base (contour lines and drainage) and the aerial photographs used were obtained from the Istarú Map of the National Geographic Institute

(IGN) (2012). At each site, the thicknesses of lithological units were measured to relate them to well lithology data.

Records from registered wells in the archive of the SENARA were analyzed, allowing for hydrogeological profiles to be constructed in different areas of the study zone. The SENARA well archive provided the hydraulic characteristics of the hydrogeological units in wells where such data were available. The information from the well records was digitized in Microsoft Excel and later imported into MapInfo for the construction of hydrogeological profiles.

For the construction of hydrogeological profiles, the topographic contours from the Istarú map were used to create a Digital Elevation Model (DEM) in Golden Software Surfer. Profile lines were then drawn from the DEM for each identified sector within the study area. For each profile line, the depths of lithological materials and piezometric levels were added in Golden Software Grapher.

Results and discussion

Regional geological context

The lithological description of the materials comprising the study area is based on Krushensky (1972). This can be observed in Figure 3.

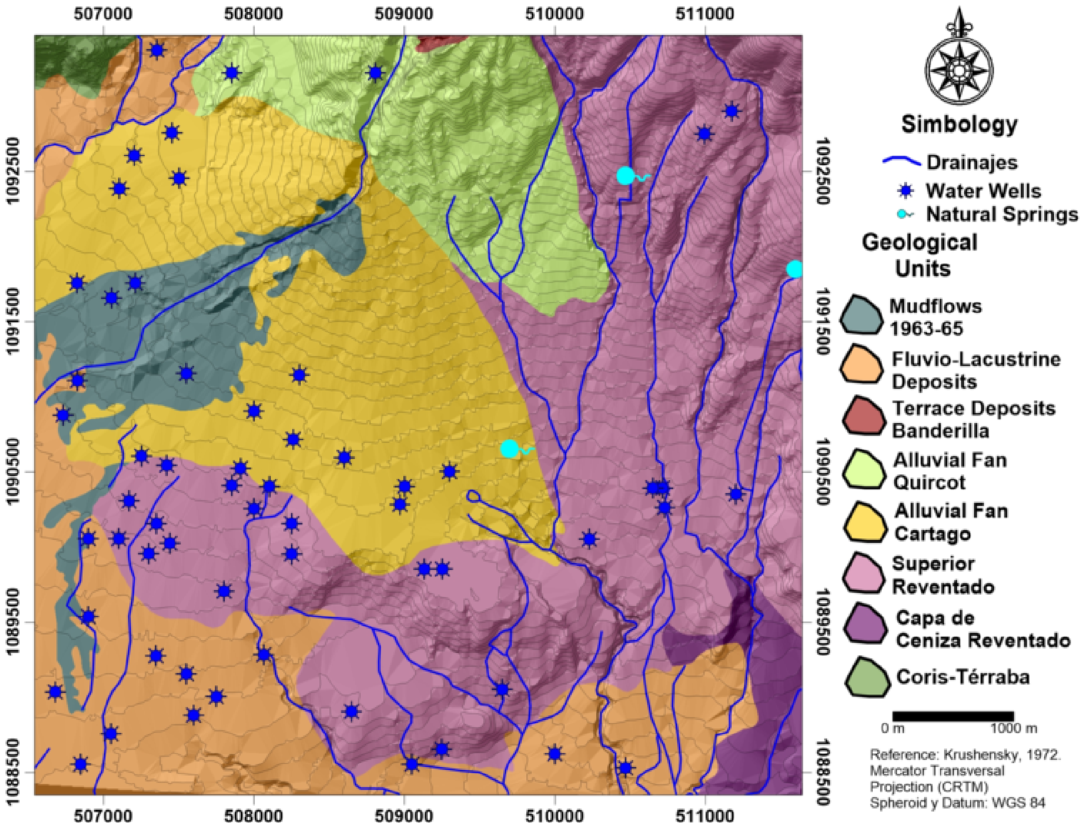

Fig. 3. *Map of geological units and location of wells and springs in the study area. Source: Krushensky (1972) and Senara.*

Térraba-Coris

Siltstone and shale of the Térraba Formation crop out in the western corner of the mapped area. Unweathered outcrops of the Térraba Formation are rare, and weathered outcrops can easily be mistaken for those of the Coris Formation. The Térraba Formation appears as a dark-greenish-gray siltstone that weathers light olive-gray and light gray or white.

The Coris Formation is formed of sandstone and mudstone and is generally poorly exposed in the mapped area. It consists of light-yellowish-gray to dark-reddish-orange fine- to medium-grained argillaceous sandstone.

Capa de Ceniza Reventado

The Capa de Ceniza Reventado member is a distinct, yet thin layer composed entirely of ash. This unit is heavily weathered, consisting of fine ash that is characteristically dark orange-brown to reddish-brown.

Superior Reventado

The Superior Reventado member comprises at least four regionally extensive major lava flows and numerous smaller, localized flows. The Superior Reventado member is composed primarily of interbedded lava flows, up to 30 meters thick, and lahar deposits ranging from 2 to 8 meters in thickness. Ash deposits vary significantly in thickness depending on proximity to the summit vent. Lahars in the upper member are soft, easily eroded, and typically unstable in stream cuts. Rock fragments are abundant, ranging in size from sand grains to blocks up to 5 meters across. These fragments vary from angular, relatively fresh, hard rock to rounded or subrounded clay-rich remnants of the original material, distinguishable from the matrix only by differences in color and texture.

Alluvial Deposits

The Quircot fan comprises weathered debris derived from the Reventado Formation. Coarsest materials, including porphyritic basaltic andesite boulders and blocks up to 4 meters in diameter, dominate the fan’s head. Sorting and bedding are poorly developed. Individual deposits resemble modern mudflows, consisting of chaotic mixtures of fragments of varying size and roundness.

The Cartago Fan, located on the southern margin of the Quircot fan, extends beneath the city of Cartago. Bedding within the Cartago fan is sporadic and crudely developed, with minimal sorting, apart from a general southward decrease in coarse debris.

Both the Cartago and Quircot fans are compositionally like the lahars of the Reventado formation but contain significantly less clay. Comparative analysis with the mudflows from the 1963–1965 eruptions strongly suggests that both fans originated from similar mudflow deposition processes.

Terrace deposits

Distinguishing the deposits of the Quircot fan from those of the Banderilla terrace is challenging, as both units are primarily composed of mudflow deposits derived from the Reventado formation. However, the uppermost terrace deposits exhibit well-bedded, moderately well-sorted pebbly sandstone, fine gravel, and sand. The surface of the terrace is soil-covered and scattered with large boulders, resembling the surfaces of recent lahar terraces and the Quircot fan.

Fluviolacustrine Deposits

Consist of fine sand and silt to the west of the Río Reventado. It consists of flat-lying, generally well-bedded fine- to medium-grained quartz sand, silt, and clay. These deposits are primarily derived from the erosion of the Coris and Térraba Formations.

Mudflows Deposits

The debris in these mudflows generally mirrors that found in the Quircot and Cartago fans. The deposits are poorly sorted, with a range of sizes from clay to boulders as large as 4 meters on each side. All coarse lithic clasts in the deposits are hard and relatively unaltered, while deeply weathered materials have been ground into sand and clay during the downstream movement of the mudflows.

Groundwater quality

Of the 70 wells used as the basis for this study, only two have recorded data on water chemical quality. Due to the limited information, it is not possible to establish a chemical characterization of the groundwater. The results are presented in Table 1.

The groundwater quality from wells IS-335 and IS-93 exhibits notable differences in their chemical characteristics, which could impact their suitability for various uses.

Table. 1. *Chemical characteristics of the water from wells IS335 and IS-93.*

	IS-335	IS-93
pH (u.t)	6.02	6.77
Turbidity (u.c)	< 5	0.74
Color (u.c)	< 5	< 0.1
Electrical Conductivity (μS/cm)	324	235
Total Solids (ppm)	312	244
Disolved Solids (ppm)	312	244
Suspended Solid (ppm)	< 1	244
Partial Alkalinity (ppm)	< 1	<1
Total Alkalinity (ppm)	88.2	145
Total Hardness (CaCO3) (ppm)	145	181
Carbonate Hardness (ppm)	88.2	145
Non-Carbonate Hardness (ppm)	57	36
Calcium (Ca2+) (ppm)	33.2	43.9
Magnesium (Mg2+)(ppm)	15	17.2
Chlorides (Cl−)(ppm)	15.2	5.4
Sulfates (So4−) (ppm)	58.3	1.2
Silicie (SiO2) (ppm)	60.3	68.8
Ammonium (Nh4+) (ppm)	0.81	< 0.01
Iron (Fe) (ppm)	0.037	0.05

The pH of both wells is slightly acidic, with IS-335 having a pH of 6.02 and IS-93 at 6.77, which is typical for many groundwater sources. Both wells exhibit low turbidity and color, indicating that the water is relatively clear, with IS-93 showing lower turbidity (0.74 NTU) and color (<0,1) compared to IS-335 (<5 NTU). The total solids concentration is higher in IS-335 (312 ppm) than in IS-93 (244 ppm), which suggests a greater mineral content in IS-335, contributing to its higher total and carbonate hardness (145 ppm and 88.2 ppm, respectively) compared to IS-93 (181 ppm and 145 ppm, respectively).

Notably, IS-335 has a significantly higher non-carbonate hardness (57 ppm) than IS-93 (36 ppm), indicating higher concentrations of minerals like calcium and magnesium in a non-carbonate form. IS-93 has higher calcium (43.9 ppm) and slightly higher magnesium (17.2 ppm) levels compared to IS-335 (33.2 ppm and 15 ppm, respectively).

The chloride concentration is notably higher in IS-335 (15.2 ppm) compared to IS-93 (5.4 ppm), which may suggest saline influence or contamination in IS-335, while sulfate levels are also significantly higher in IS-335 (58.3 ppm) compared to IS-93 (1.2 ppm), pointing to greater exposure to sulfate-rich sources.

Both wells show elevated silica levels (IS-335: 60.3 ppm, IS-93: 68.8 ppm), which is common in groundwater but could influence corrosion in water systems. Ammonium concentrations are higher in IS-335 (0.81 ppm) than in IS-93, which has negligible levels (<0.01 ppm), potentially indicating organic contamination in IS-335. Iron concentrations are low in both wells, suggesting minimal issues with iron contamination.

Overall, while both wells provide groundwater of generally good quality, IS-335 is higher mineral content, including elevated sulfates, chlorides, and ammonium, could affect its suitability for certain uses, requiring further monitoring for potential impacts on water quality. In contrast, IS-93 appears to provide softer, cleaner water, making it more suitable for direct consumption and other sensitive uses.

Hydrogeology characterization

Northwest sector

This area is dominated by the dynamics of the Taras rivers as the main drainage, the Arriaz River, where the spring of the same name emerges, and the Norberta stream, where the Padre Méndez Spring is located, upstream of the study area, both springs are captured by the Cartago Municipality (Fig. 4).

The lithological materials found in this sector correspond mostly to laharic deposits, which present a silt-clay or silt-sand matrix, with floating grains of various sizes, between centimeters to decimeters in some cases up to metric and most of them sub-angular.

Sometimes alluvium layers are recognizable, such as in the Taras River. These sequences are very characteristic of this part of the study area and are also present in the Toyogres River, at the other end of the study area.

These lithological materials present an evident relationship with the surface drainages, which determines the hydrodynamics of groundwater in this sector. This hydrogeological relationship is based on the deposition sequences of alluvium, lahars and mud flows and the formation of confined aquifer systems, aquicludes and aquitards.

Fig. 4. *Left: Laharic deposits overlying a thin layer of alluvium in the Taras River. Right: Lava materials outcropping in the Norberta Creek waterfall, where the Padre Méndez Spring is located. Laharic deposits overlie these lava flows.*

Between the Arriaz and Taras Rivers, the hydrogeological units shown in the IS-73 well correspond to lahar materials which are found overlying a layer of lava that in turn overlies an alluvial deposit. In well IS-509, the stratigraphic sequence of the materials indicates the same layers except for the alluvium, although it could be inferred that this is located at a greater depth.

Towards the south and southwest sector of the Taras River, wells IS-92, IS-460, IS-153 and IS-335, show a greater thickness of the lahar materials which also increase their clay content as one advances in the direction of the Reventado River and which is evident in the wells IS-422, IS-14 and IS-15 which are further south.

In all the wells the lithological descriptions very varied, however, it is considered that the aquifer in these wells is in various lithological materials which present a high degree of hydraulic connection. In the IS-73 well it is found in the alluvium, in the IS-509 it is found in the lavas and in the wells to the south and southwest of the Taras River (IS- 460, IS-335, IS-153, IS- 14 and IS-15) is found in lahars. In this way and as is evident, the formation of the aquifer in this sector is due to the saturated thickness of the materials and not to a specific lithology.

The average thickness of the aquifer in the northwest sector is between 30 m in the northern part and varies between 20 and 12 m towards the south and southwest. This aquifer is confined with pressure heads ranging from 7 m north of the Taras River and between 5 m and 13 m south of the Taras River. In some cases, the aquifer behaves freely as well IS-153. Further to the south, the thickness of the aquifer varies between approximately 6 and 12 m with pressure heads of 12 m.

The variations in the thickness of the aquifer in the northwest sector and the pressure heads that indicate its degree of confinement may be due to the different sequences of materials and the degree of saturation they have; the aquicludes are probably related to important clay fractions in the lahars and that are not entirely evident in the lithological description of the well. It is likely that the Arriaz Spring that is located to the north, outside the study area, originates from the confinement of this aquifer.

In this sector, the lahar materials do not present homogeneity in their composition and act as aquicludes as well as aquitards; this is the situation observed in the IS-153 well, which is free and could show semi-confinement behavior of this aquifer in some sectors.

The hydrogeological profiles described are presented below (Figs. 5, 6 and 7).

In this same sector, towards the south, the aquifer manifests itself in the alluvium layer (Fig. 8), which, unlike the previous ones, is more related to the hydrodynamics of the Reventado River. At this point the thickness of the aquifer varies from 6 m to 12 m in a southwest direction, with variations in the pressure head between 11 and 12 m of water column.

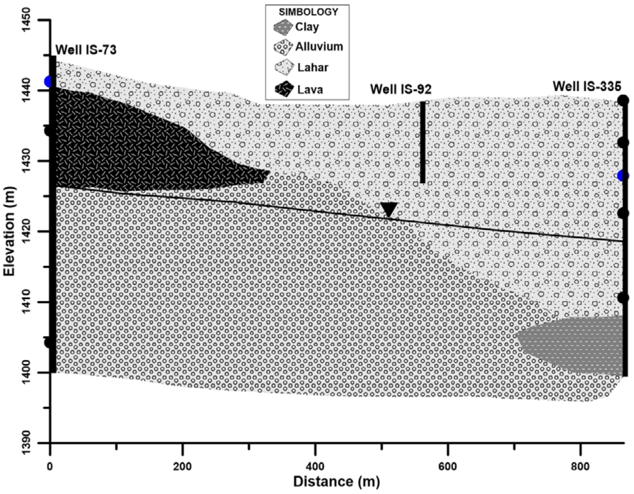

Fig. 5. *Hydrogeological profile IS-73 - IS-92 - IS-335. The aquifer originates from the saturation of the alluvium as well as the lahar and the aquicludes are related to variations in the composition of the lahar, probably due to clay fractions.*

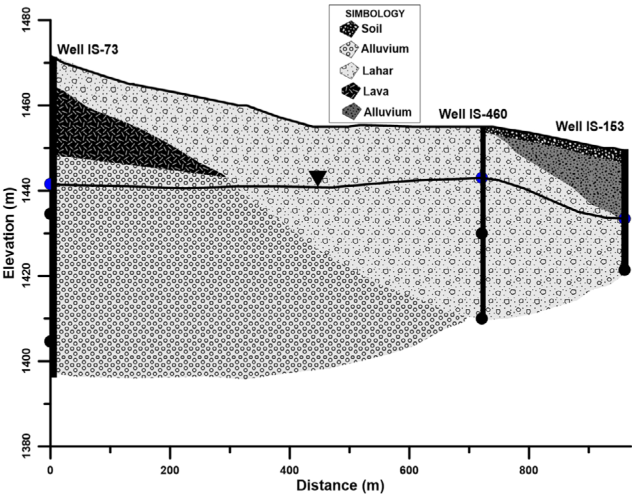

Fig. 6. *Hydrogeological profile IS-73 – IS-460 – IS-153. The aquifer appears between the alluvium and the lahar. The aquicludes that generate confinement originate from variations in the composition of the lahar. In the IS-153 well, the aquifer is free, probably due to the alluvial layer that overlies it.*

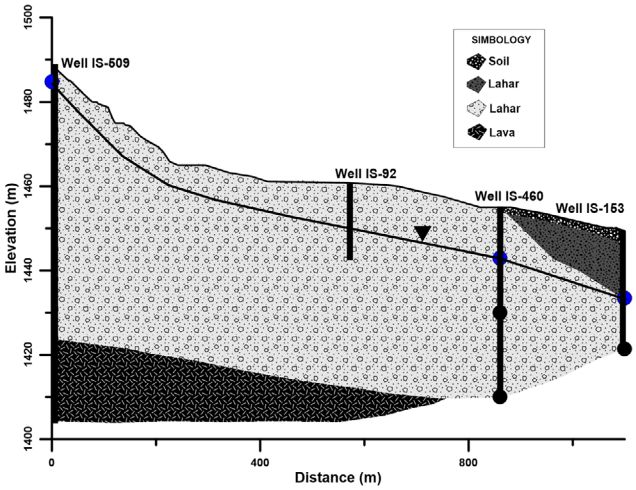

Fig. 7. *Hydrogeological profile IS-509 – IS-92 – IS-460 – IS-153. In this profile the aquifer again manifests itself in the lahar layer. In IS-509 well, it is not indicated where the aquifer may be, so it could also be associated with a saturation of the lava layer and the lahar that originates the aquifer.*

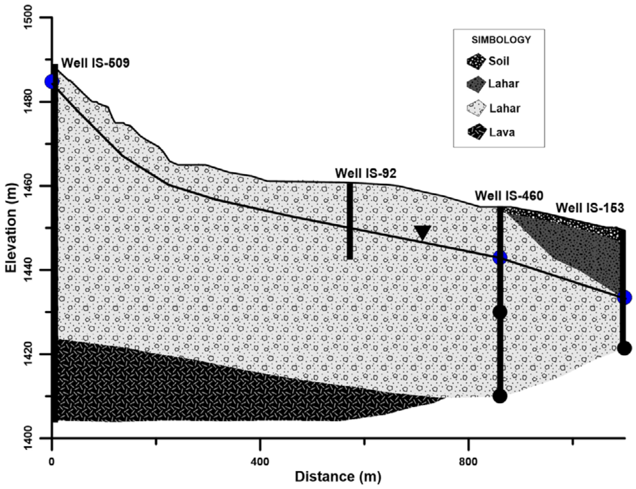

Fig. 8. *Hydrogeological profile IS-422 – IS-14 – IS-15. The degree of confinement that appears in this part of the sector is greater than in the other wells, possibly due to a greater amount of clay material present.*

The pressure heads in this part are greater due to the layers of clay that overlie the lahars as well as the variations in the clay content in the lahars and that are characteristic of the Reventado River.

Regarding the flow of groundwater in this part of the Cartago aquifer system, it can be said that it indicates a flow direction from the northeast to the west and to the south (Fig. 9).

In Table 2 the basic characteristics of the hydrogeological units of the northwest sector corresponding to the Cartago Aquifer System are shown. The nomenclature used is in accordance with the methodology proposed by the ASTM (2004).

In the northeast sector, the location of one of the most important springs for the Municipality of Cartago stands out, known as Arriaz, located on the east bank of the river of the same name.This spring indicates that it is probably an outcrop of the Cartago aquifer system in the northwest sector. To the north there is likely to be thicker layer that appears in the IS-73 well and that overlies the alluvium.

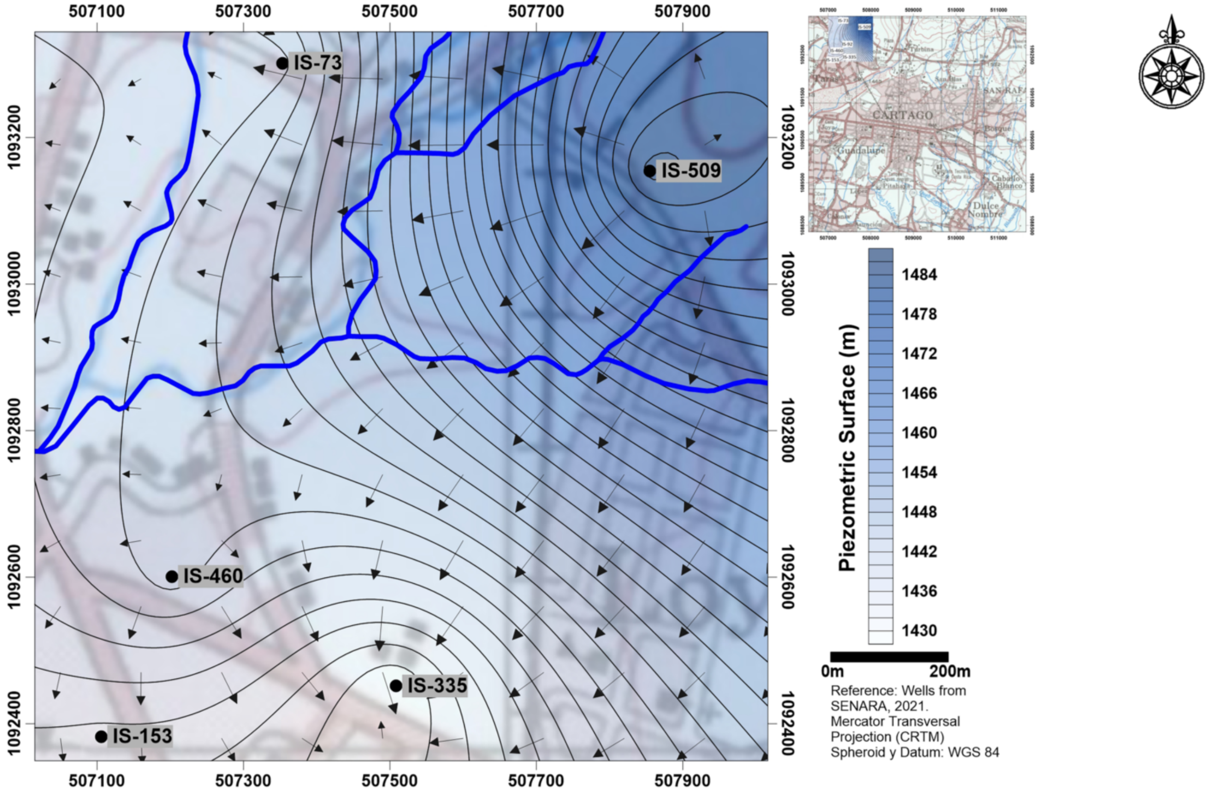

Fig. 9. *Piezometric surface obtained from the modeling of piezometric well levels.*

Finally, just to the east, where the Cerros de la Carpinterabegins, it is possible that one of the borders of the Cartago aquifer system can be found, since in this sector the lava materials present a strong clay formation and there are no drainages or springs registered.

Table 2. *Characteristics of the hydrogeological units of the northwest sector of the Cartago Aquifer System.*

Hydrogeological characteristics	Taras hydrogeological units
Lithology	Alluviums and Lahars
Piezometric level depth (m)	16,52
Classification	Confined
Hydraulic gradient	0,021
Thickness (m)	15,38
Pressurehead (m)	8,08
Transmissibility (m^2/d)	No data

Northeast sector

In this area the La Chinchilla and San Nicolás Rivers are found as the main drainages and its border is the Toyogres River (Fig. 10), to the west.

The materials found in this area correspond to sequences of clays, lahars and lavas, these materials are described lithologically in the IS-386 well. Superficially, in the Toyogres River, lahars are recognized on surfaces overlain by layers of clay.

Fig. 10. *Toyogres River channel to the west of the northeastern area. Note the lahars on the left side of the photo.*

In the northeast sector, only two wells with lithological records are registered. In depth it can be said that the hydrogeological units of this sector correspond to clayey materials in the upper part, overlying layers of lahars, which in turn are on top of lava materials. This sequence is observable in well IS-386, in well IS-419 only the lahars are noticeable (Fig. 11).

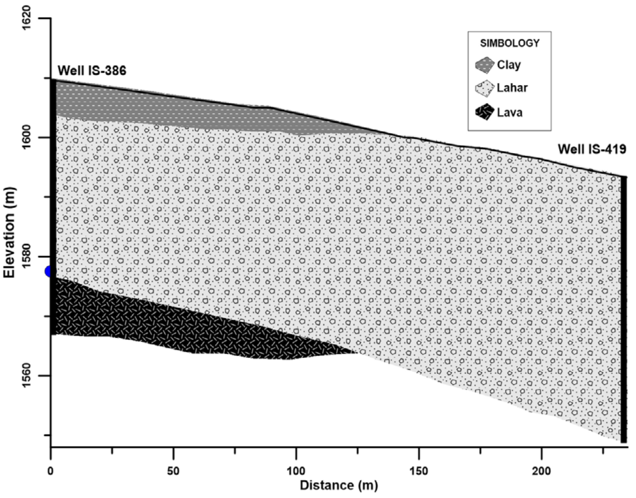

Fig. 11. *Hydrogeological profile IS-386 – IS-419. In this sector, lahar materials do not present hydrogeological conditions for the development of aquifers.*

In this sector, the piezometric level of the aquifer system only appears in well IS-386 since the log from well IS-419 indicates that the well is dry. Considering the lithological record, it can be noted that the aquifer system in this sector corresponds to lava, like what was observed in the IS-509 well in the northwest sector. The materials in this sector do not present saturation. The springs closest to the study area are at a minimum distance of approximately 700 m. These springs are the San Blas Spring and the El Rodeo Spring captured by the municipality of Cartago.

In Table 3 the basic characteristics of the hydrogeological units of the northeastern sector corresponding to the Cartago Aquifer System are shown. The nomenclature used is in accordance with the methodology proposed by the ASTM (2004).

Central sector

It is in the western sector of the city of Cartago; it covers practically the entire Western district of the city. In this part of the study area, there are no outcrops that allow corroborating the lithological descriptions of the located wells. It is the area where the most hydrogeological profiles exist and where the complex hydrogeological dynamics of the area are shown due to the sequences of alluvial, laharic, and clayey materials, among others.

Table 3. *Characteristics of the hydrogeological units of the northwest sector of the Cartago Aquifer System.*

Hydrogeological characteristics	La Chinchilla hydrogeological units
Lithology	Lavas
Depth of piezometric level (m)	36
Classification	Confined (probably)
Hydraulic gradient	No data
Thickness (m)	No data
Pressure head (m)	No data
Transmissibility (m^2/d)	No data

Although no surface drainage is observed in this sector, the different sequences of deposition of lithological materials that are described in the well logs indicate that the Reventado River and the Toyogres River have an enormous influence on this part of the system and Cartago aquifer, both to the west and east. Additionally, the appearance of some surface drainage, such as the Molino stream and the Zopilote stream can be observed, which may be related to the outcropping of springs from aquifers confined in this sector. The presence of the La Basílica Spring is evidence of this. Since the entire area is urbanized, it is impossible to find outcrops of materials, and the existing drainage systems are piped, making it difficult to conduct a more in-depth analysis.

The lithological descriptions of the wells IS-405, IS-43, IS-264, IS-27, IS-28 and IS-445 (Fig. 12) indicate the presence at depth of alluvial materials, which in some sectors appear as thick alluvium (gravel) and sands. In some sectors, such as in wells IS-43, IS-27 and IS-28, these alluviums have clay lenses which cause the formation of aquifer layers, as in the case of IS-43, in which three aquifers separated by clay lenses are described. Transversely, the descriptions of wells IS-26, IS-43, IS-19 and IS-23 (Fig. 13) show that the sequence of alluvium and clays is more evident in the same way as in the case of the descriptions of wells IS-264 and IS-22.

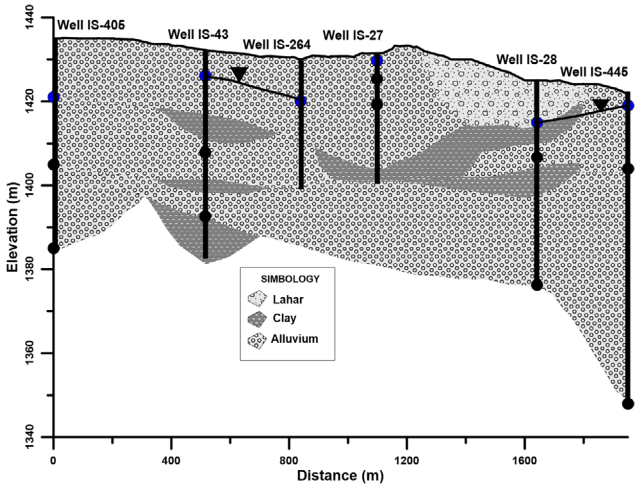

Fig. 12. Hydrogeological profile IS-405 – IS-43 – IS-264 – IS-27 – IS-28 – IS-445. The sequences of alluvium and clay that make up three aquifers in this part of the Cartago aquifer system separated by layers of impermeable clay that act as aquicludes.

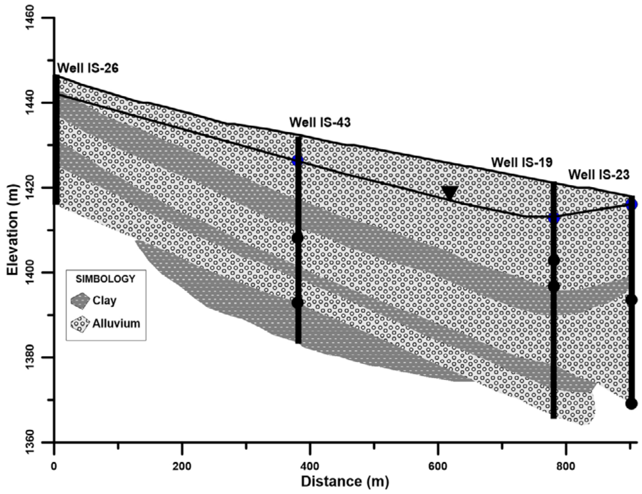

Fig. 13. Hydrogeological profile IS-26 – IS-43 – IS-19 – IS-23. This cross-sectional profile of the central area of Cartago shows the alluvium and clay sequences and the formation of several aquifers.

The aquifer hydrogeological units in this part of the Cartago aquifer system show variable thicknesses, in some cases they are around 20 m as in well IS-405 up to 56 m in well IS-445. It is likely that the granulometric composition of the alluvial deposits generates this variation in thickness, since as described in the records, the lithologies indicate from coarse to fine sands, gravel and sand are also manifested in some parts and sand in others clays, either alone or with gravel. These depositions allow not only the formation of several aquifers but also important variations in thickness. In the shallower aquifer that appears in wells IS-27 and IS-19, the thickness is around 6 m.

The deeper hydrogeological units indicate a variable degree of confinement with pressure heads from 14 m as in well IS-445, to 22 m as in well IS-23. The piezometric surface in this part can be at a depth from almost 2 m to 6 m for these same wells. An important factor in these degrees of confinement is related to the fact that clay lenses are present, which due to their impermeability act as aquicludes and can generate more pressure in the pore space of the alluvial deposits. In the case of shallower aquifer hydrogeological units, a certain confinement occurs with pressure heads from 4 m to 10 m. The piezometric surface of this hydrogeological unit is at depths from 2 m to 8 m.

Further to the southwest, from the east bank of the Reventado River, the descriptions of the wells IS-329, IS-265, IS-18, IS-23, IS-24 and IS-163 (Fig. 14), show the occurrence of alluvium and lahars. In well IS-329, lahars are described throughout the record, while in well IS-18, sequences of alluvium, lahars and clays are shown.

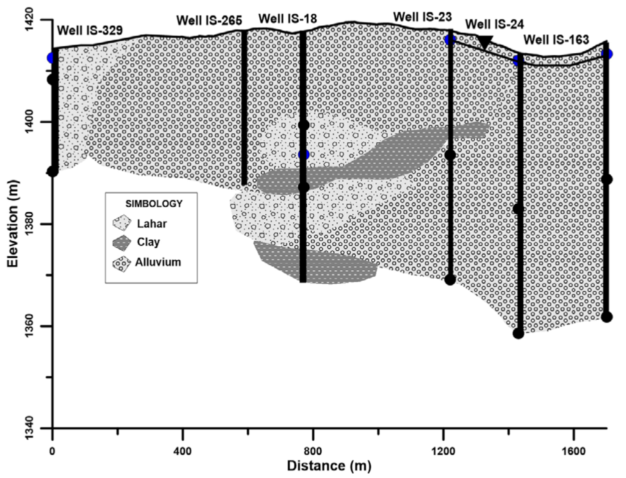

Fig. 14. Hydrogeological profile IS-329 – IS-265 – IS-18 – IS-23 – IS-24 – IS-163. This profile shows the relationship of alluvial materials with lahar materials. Clay lenses are additionally observed

The hydrogeological units here show saturated thicknesses ranging from an average of 25 m in the alluviums such as those shown in wells IS-23, IS-24 and IS-163 and from 6 m to 18 m in the lahars of the wells IS-18 and IS-329. Further to the south the thickness of the alluvial materials decreases, such as the average 11 m in wells IS-321 and IS-495. As described before, in the case of alluvial materials that present sequences of gravel, sand and clay (all in combinations), it is normal for different aquifers to appear in the same well, as in the case of well IS-293 where there is the aquifer with a thickness of 13 m and then further down with a thickness of 7 m. In this case, it is likely that both are separated by layers of sand with clay, which act as aquitards and cause these aquifers to have semi-confined behavior in other places.

In a north-south direction, this arrangement of materials is equally clear. In wells IS-265 and IS-299, the aquifers are found in alluvial materials, which, as well IS-321 and well IS-293, are overlain by layers of clay, while other records show the presence of laharic materials as in well IS-18 and IS-32 (Figs. 15, 16 and 17).

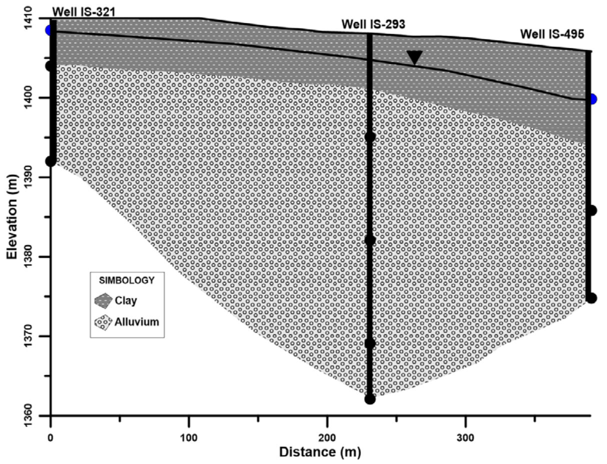

Fig. 15. Hydrogeological profile IS-321 – IS-293 – IS-495. In this profile, the arrangement of a clay layer overlying the alluvium described in the lithological record is notable.

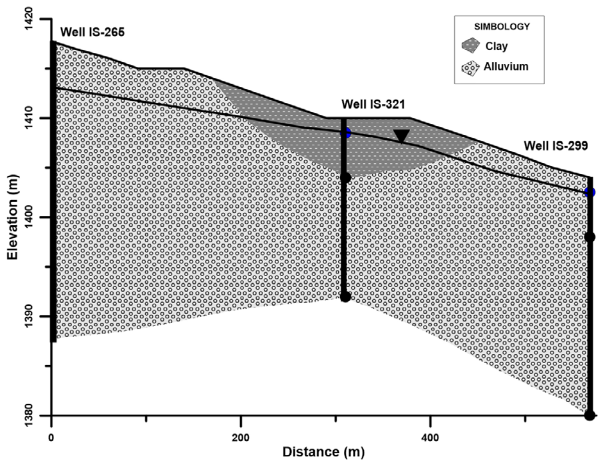

Fig. 16. Hydrogeological profile IS-265 – IS-321 – IS-299. A layer of clay is shown overlying the alluvial materials. This characteristic occurs in many areas of this part of the Cartago aquifer system.

Regarding the thicknesses of the aquifer hydrogeological units in these profiles, they range from 12 m or more in wells IS-321, IS-203 and IS-32 to 18 m in well IS-299. The pressure heads that indicate the degree of confinement of an aquifer system are, as in the previous cases, variable, from 4.5 m in wells IS-321 and IS-299 to 12 m in well IS-32. The depths of the piezometric level are 1.5 in the wells IS-321, IS-299 and IS-32.

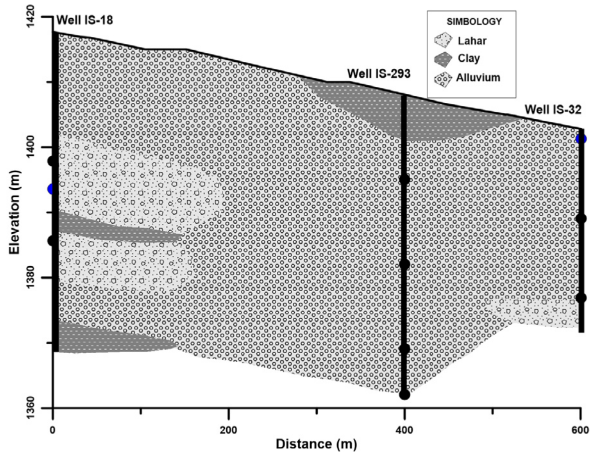

Fig. 17. Hydrogeological profile IS-18 – IS-293 – IS-32. The arrangement of the materials in a north-south direction. In this part of the Cartago aquifer system, saturated thicknesses not only occur in alluvial materials but also in lahar materials.

Despite the considerable number of wells found in this part of the study area, hydraulic data of the aquifers obtained from pumping tests are not available.

In the southernmost part of the central part of the city of Cartago, there is a clear domain of alluvial materials as in all the cases mentioned above and evidenced from lithological records. These materials are overlying the volcanic materials from the Irazú volcano.

In this part of the Cartago aquifer system, the available information only shows the most superficial aquifer hydrogeological units. However, the presence of aquifers found in volcanic deposits is to be expected (Fig. 18).

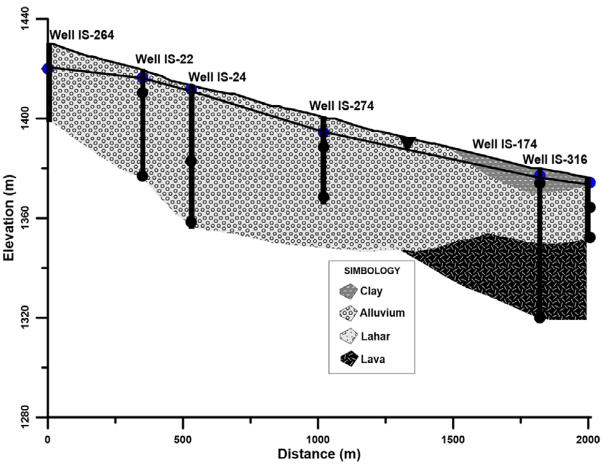

Fig. 18. Hydrogeological profile IS-264 – IS-22 – IS-24 – IS-274 – IS-174 – IS-316. The dominance of alluvial materials and how these overlie the volcanic materials from the activity of the Irazú volcano.

With respect to the piezometric surface derived from the hydraulic head values of the aquifer hydrogeological units, it can be said that these indicate direction of flow from the north to the south (Fig. 19).

Eastern sector

The hydrogeological dynamics of this part of the Cartago aquifer system is strongly influenced by the

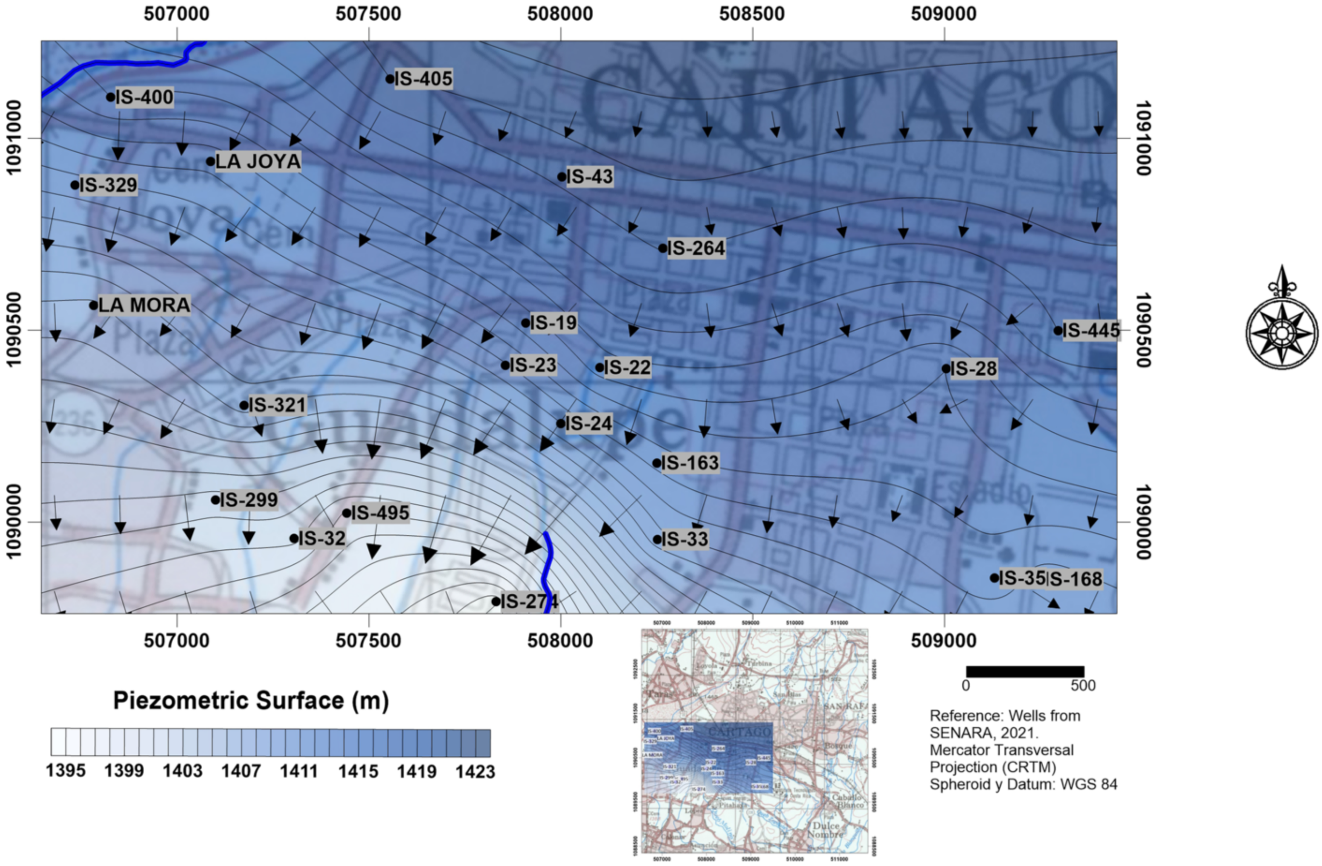

Fig. 19. *Piezometric surface obtained from the modeling of piezometric well levels.*

Table 4 indicates the basic characteristics of the hydrogeological units of the northwest sector corresponding to the Cartago Aquifer System are shown. The nomenclature used is in accordance with the methodology proposed by the ASTM (2004).

Table 4. *Characteristics of the hydrogeological units of the central sector of the Cartago Aquifer System.*

Hydrogeological characteristics	Cartago hydrogeological units
Lithology	Alluvial deposit (gravel and sands)
Depth of piezometric level (m)	3,7
Classification	Confined
Hydraulic gradient	0,0159
Thickness (m)	22,4
Pressure head (m)	13,6
Transmissibility (m^2/d)	20

Toyogres River, which functions as the main river and the Chinchilla and Tatiscú Rivers that act as important drainages that must be considered in the hydrogeological analysis in this part of the area of study.

In this part of the study area, only one spring is recorded, and it is the one corresponding to the Las Brisas Spring, on the Toyogres River. This spring is in an urban area and due to its potential contamination it is not used for human consumption. The dominant materials in this part of the study area correspond to lahars as described in wells IS-268, IS-411 and IS-93 (Fig. 20), especially on the surface and towards the western sector. As you go deeper, the lithological descriptions indicate the presence of tuffs and lavas, which is related to an area of greater influence of volcanic materials.

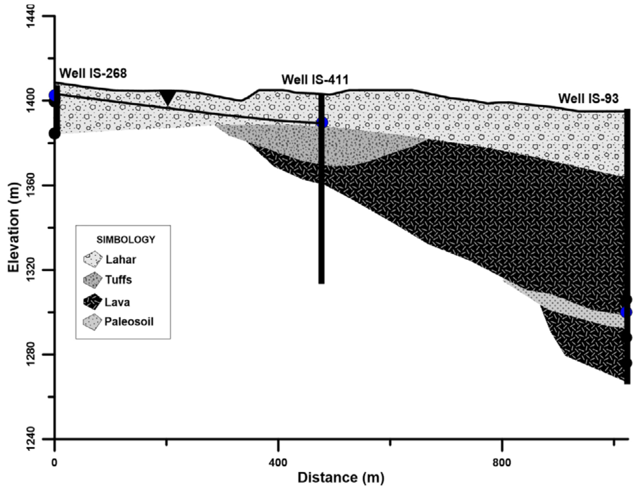

Fig. 20. *Hydrogeological profile IS-268 – IS-411 – IS-93. The appearance of lava materials at depth in well IS-93 near the Toyogres River.*

From the Tatiscú River sector to the southwest, the dominant materials correspond to laharic deposits which are described in well IS-268 as unconsolidated deposits, composed of lavic blocks whose sizes are variable, some of which are metric. These pebbles and fragments are immersed in a sandy clay matrix in a ratio of 20–80%. In some sectors of the Toyogres River and the Barquero River, alluvial materials are visible overlying the lahar deposits.

Towards the San Nicolás River, the materials that make up the hydrogeological units and that are described in the wells IS-411, IS-281 and IS-235 correspond to lahars composed of stones of cm to dm sizes, even some metric, wrapped in a clay matrix with variable percentages of sand. These lahars are found to be overlying lava materials as the description deepens, as in the case of the IS-411 well, where the lahars overlie the tuffs and lavas, while in the IS-93 well only the lavas are described.

With respect to the information on the hydraulic properties of the aquifer hydrogeological units in this part of the Cartago aquifer system, it can be said that these have thicknesses between 15 m in the IS-268 well in the eastern sector, near the Tatiscú River at 20 m in the IS-235 well towards the Chinchilla River, these saturated thicknesses correspond to the laharic materials which are described in the well logs as units where sands and gravels are included in a clay matrix. Variations in this composition imply the formation of aquifer layers, as in the case of IS-235, which records three aquifer zones. The pressure heads of these aquifer hydrogeological units corresponding to the lahars indicate that these aquifers are confined; these pressure heads vary from 3 m in the IS-268 well to about 20 m in the IS-235 well. The depths of the piezometric charges range from 3 to 6 m to more than 13 m.

In the case of well IS-93, it is observed that there is an aquifer hydrogeological unit corresponding to lava materials. The thickness of these hydrogeological units, are around 12 m. The hydraulic loading depth of this unit is more than 90 m. This aquifer appears confined, with a pressure head of about 12 m.

Table 5 shows the basic characteristics of the hydrogeological units of the northwest sector corresponding to the Cartago Aquifer System are shown. The nomenclature used is in accordance with the methodology proposed by the ASTM (2004).

Table 5. *Characteristics of the hydrogeological units of the central sector of the Cartago Aquifer System.*

Hydrogeological characteristics	El Bosque hydrogeological units
Lithology	Lahardic deposits
Depth of piezometric level (m)	7,5
Classification	Confined
Hydraulic gradient	0,2744
Thickness (m)	17,5
Pressure head (m)	12,4
Transmissibility (m^2/d)	11,9

Southwest sector

As in the case of the central sector, with which it borders to the north, there are no surface drainages in which outcrops of the lithological materials described in the wells can be observed. To the south it borders the Agua Caliente River. The dominant materials in this part of the Cartago aquifer system and that are recognizable in the bed of the Reventado River, correspond to laharic materials.

From the northwest, in a southeast direction, the materials described correspond mainly to lahars and clays, such as those described in the IS-221 well (Fig. 21), which vary towards the alluvium and clay sequences, as was the case of the central sector, and ending with the descriptions of lavas in depth further

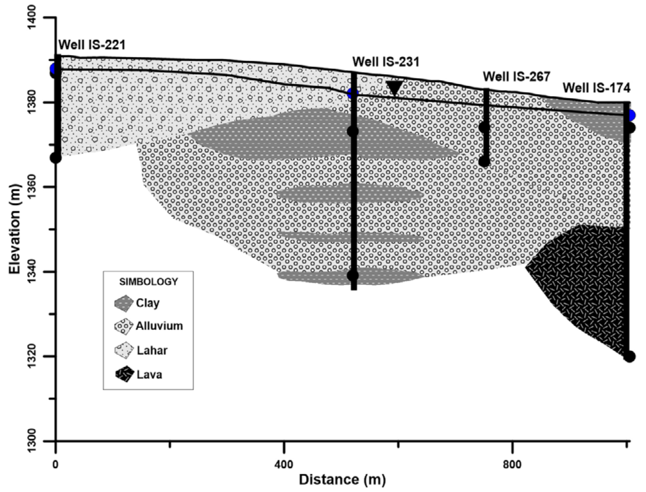

Fig. 21. Hydrogeological profile IS-221 – IS-231 – IS-267 – IS-174. Note the presence of lava materials towards the southeast, on the left side of the profile.

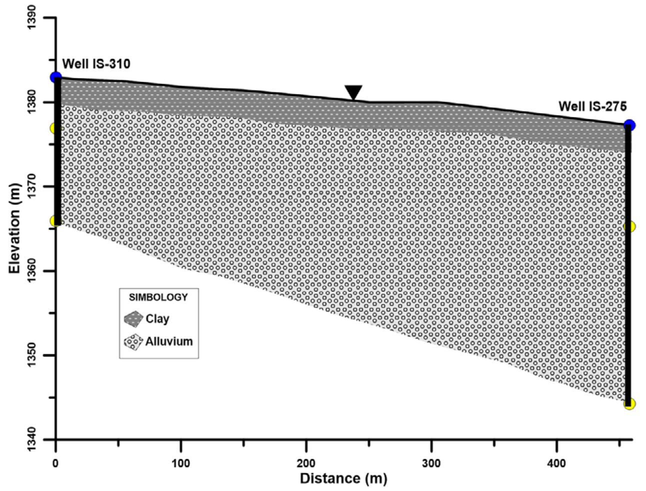

Fig. 22. Hydrogeological profile IS-310 – IS-275. In both wells the piezometric levels are artesian. This upwelling may be due to the significant pressure exerted by the clays and clay sections in the alluvium.

to the southeast, which again allows us to infer that the alluvial and laharic deposits rest on the volcanic materials of Irazú. It is expected that, towards the Reventado River, the presence of lahars will be described in the wells. During the field trip through the study area the presence of these lahars was observed. The descriptions indicate the presence of layers of clay, sand and alluvium as in the case of those described in well IS-231, well IS-267 and well IS-316. These descriptions of alluvial materials are also evidenced to the north of these wells, in the descriptions of wells IS-274 and IS-154. Already at depth, the descriptions indicate the presence of lava materials at depth as indicated in well IS- 174. Towards the southwest, the materials described show layers of clay overlying alluvial materials such as those written in wells IS-310 and IS-275 (Fig. 22).

With respect to the hydraulic properties of the hydrogeological units in this part of the Cartago aquifer system, the thicknesses of the aquifers range from approximately 20 m, as described in wells IS-274 and IS-221, to 8 m as well IS-267. Some other thicknesses values are around 10 to 14 m as in wells IS-154, IS-316 and IS-310. There is a thickness of 54 m shown in the IS-174 well. However, in this case the aquifer hydrogeological units are not only in alluvial materials, but also in lava. The depths of the piezometric surfaces in this part of the Cartago aquifer system indicate levels that range from 2 m, as well IS-316, to a maximum of 8 m, as in well IS-267, however, some descriptions indicate the presence of artesian levels as is the case of wells IS-310 and IS-275.

In this way the pressure heads in these hydrogeological units vary from heads of 10 m as in wells IS-154 and IS-316 to 3 m or even less, as in wells IS-221 and IS-174. In some cases, they are so high that, as mentioned, they imply the formation of artesian aquifers, such as in wells IS-310 and IS-275. Regarding the number of wells in this part of the study area, hydraulic data of the aquifers obtained from pumping tests are not available. With respect to the piezometric surface derived from the hydraulic head values of the aquifer hydrogeological units (Fig. 23), it can be said that these indicate direction of flow from the north to the south.

In Table 6 the basic characteristics of the hydrogeological units of the northwest sector corresponding to the Cartago Aquifer System are shown. The nomenclature used is in accordance with the methodology proposed by the ASTM (2004).

***Table 6.** Characteristics of the hydrogeological units of the central sector of the Cartago Aquifer System.*

Hydrogeological characteristics	Tejar hydrogeological units
Lithology	Alluvial deposits
Depth of piezometric level (m)	4
Classification	Confined
Hydraulic gradient	0,0218
Thickness (m)	21
Pressure head (m)	8
Transmissibility (m^2/d)	No data

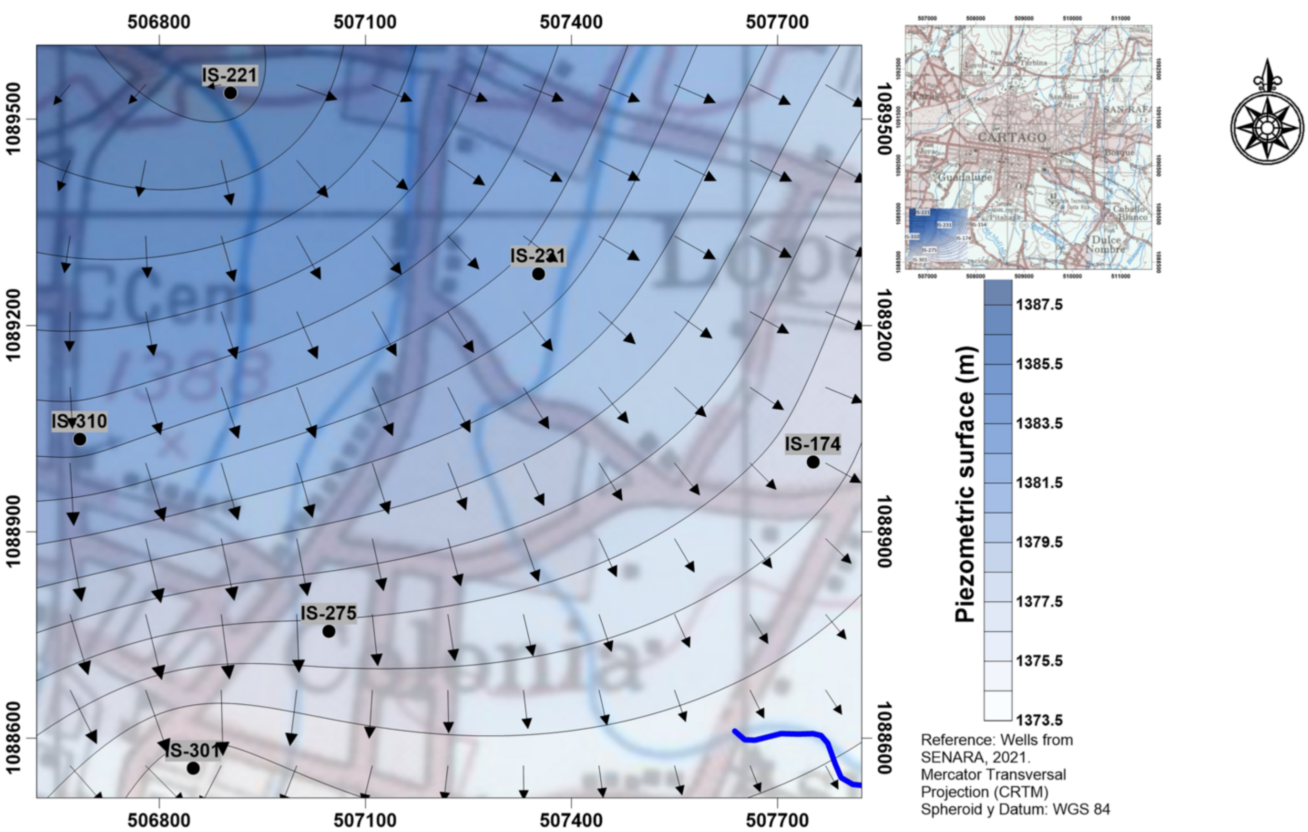

Fig. 23. *Piezometric surface obtained from the modeling of piezometric well levels.*

South sector

Towards the east, the Toyogres River is the main current, while the Molino and Zopilote streams act as secondary currents.

The dominant lithological materials in this part of the Cartago aquifer system are mainly exposed in the bed of the Toyogres River. These materials correspond to sequences of alluvial materials and lahars. In the case of the Toyogres River, from the ground surface to about 4 m below, the alluvial materials show important differences which are probably not well described in lithological descriptions. These differences correspond to the sizes of the stones, which vary from coarse sands to gravel, the stones can range from cm to dm sizes, the matrix is sandy, and in some sectors a certain degree of clay is recognizable. With respect to the lithological descriptions, in this part of the study area there is an important change in the surface lithology, probably related to the fault system (Fig. 24). Lithological materials correspond to lahars, which overlie sequences of tuffs and clays which in turn overlie lavas and breccia. These materials are well described in the lithological log of well IS-416. The descriptions indicate the presence of alluvium and clay, which give rise to aquifers hydrogeological units (Fig. 25).

In this part of the Cartago aquifer system, the aquifer hydrogeological units show variations in their thickness, in wells IS-336 and IS-279, the thicknesses are around 14 m, while in IS-44, there is an increase of 10 m, reaching 24 m thick. The depth of the piezometric surface in this part of the study area is variable, the minimum values range from 5 m as is the case of well IS-336 to almost 10 m in well IS-44. In the case of the pressure heads that can be determined in this part of the Cartago aquifer system, the minimums are 1 and 2 m in the IS-279 and IS-44 wells, up to maximums that reach 18 m as in the IS-336.

In Table 7 the basic characteristics of the hydrogeological units of the northwest sector corresponding to the Cartago Aquifer System are shown. The nomenclature used is in accordance with the methodology proposed by the ASTM (2004).

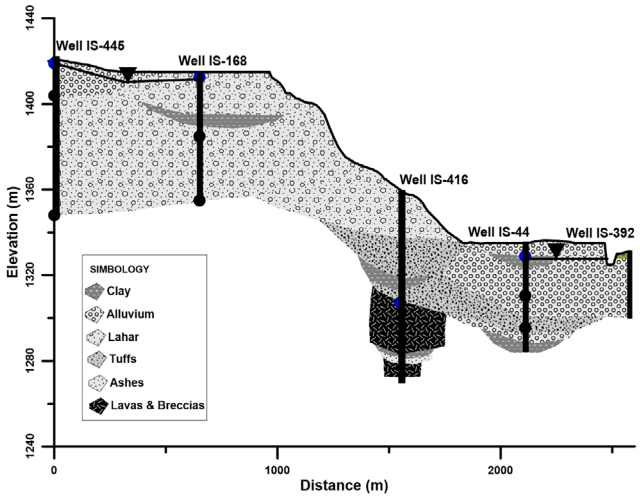

Fig. 24. Hydrogeological profile IS-445 – IS-168 – IS-416 – IS-44 – IS-392. The ttopographic change probably caused by the faulting and which implies the manifestation of lahars in the northern part and alluvial materials to the south.

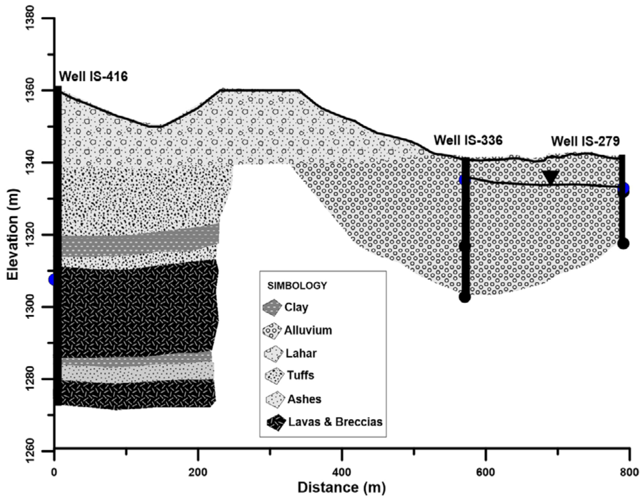

Fig. 25. Hydrogeological profile IS-416 – IS-336 – IS-279.

Table 7. Characteristics of the hydrogeological units of the central sector of the Cartago Aquifer System.

Hydrogeological characteristics	Tejar hydrogeological units
Lithology	Alluvial deposits
Depth of piezometric level (m)	7,78
Classification	Confined
Hydraulic gradient	0,01
Thickness (m)	17,3
Pressure head (m)	7,28
Transmissibility (m^2/d)	No data

Conclusions

The Cartago aquifer system is in a complex area of alluvial and laharic deposits, which present sandy and clayey intercalations. These sequences of materials imply the formation of diverse hydrogeological units which act as aquifers and in others as aquitards and aquicludes. Below these deposits, volcanic units derived from the activity of the Irazú volcano are recognized and are mainly related to lava units and breccias. Based on the analysis of well records, field work and quantitative modeling of hydrogeological information, the following aquifer hydrogeological units were established: Taras, La Chinchilla, Cartago, El Bosque, Tejar and Dulce Nombre.

The degree of confinement, that is, the ratio of the hydrogeological units with respect to their piezometric head indicates that the hydrogeological units mentioned above are confined. This degree of confinement is variable and depends on the clay and sand contents of the alluvial and laharic materials. The hydrogeological units Taras, La Chinchilla, Cartago, El Bosque and Dulce Nombre present variable pressure loads in their confinement, some of them, as in the case of the Tejar hydrogeological unit, imply the appearance of artesian levels, which is related to the confining aquicludes made up of fine materials.

The drainage systems of the Reventado and Toyogres Rivers constitute the main elements in the hydrodynamics of the Cartago aquifer system, due to the different contributions of materials that they make. It is likely that there is an underground contribution through a hydraulic connection effluent from the aquifer system to these drains at certain points.

Despite the existence of a certain group of wells with information, it is necessary to indicate that this work requires greater detail especially with new information, such as more drilling, lithological descriptions accompanied by a better petrographic and mineralogical analysis, inventory of levels of wells and springs, installation of piezometers and monitoring and research wells, among others. One of the biggest drawbacks in this work involved the almost non-existent record of pumping tests, which makes it difficult to characterize the hydraulic properties of the aquifer hydrogeological units.

Numerical modeling of the aquifer system is complex due to the absence of hydrogeological information. It is required to have data on grid length, extraction flow, vertical and horizontal hydraulic conductivity, transmissivity, storage coefficient, static levels, among others.

It is recommended that some well inventory strategies are established in the study area. As is known, in different areas of the country there are unregistered wells which need to be accounted for within the hydrogeological analysis. This can only be done through an action plan that involves private companies and organizations.

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Резиме

Интерпретација хидрогеолошких јединица и хидродинамичких услова дела изданског система у граду Cartago, Костарика

У Централној Америци постоји огромна зависност од коришћења подземних вода из извора и бунара. Са порастом становништва, климатским променама и контаминацијом водоносних слојева, доступност водних ресурса може се погоршати, изазивајући већу експлоатацију нових изворишта и социјалне проблеме у региону. У Костарики, водни ресурси нису равномерно распоређени и угрожени су одсуством просторног планирања, крчењем шума, променама у коришћењу водних ресурса и загађењем.

Централно подручје града Cartago и његова околина имају два главна извора водоснабдевања, један потиче из резервоара Orosi, а други из природних извора. Бунари који су распоређени у различитим секторима служе за појачање водоснабдевања и важна су алтернатива за водоснабдевање, посебно у временима веће урбанизације коју карактерише изградња етаж-

них станова. Аквиферски систем Cartago лежи у сложеном подручју алувијалних и лахаричних наслага, које представљају песковите и глиновите интеркалације. Наизменично смењивање ових седимената условило је формирање различитих хидрогеолошких јединица које се понашају као хидрогеолошки колектори и изолатори. Испод ових наслага утврђене су магматске и вулканокластичне стене које воде порекло од активности вулкана Irazú и углавном се односе на изливе лаве и брече. На основу анализе евиденције бушотина, теренског рада и квантитативног моделирања хидрогеолошких података, установљене су следеће изданске хидрогеолошке јединице: Taras, La Chinchilla, Cartago, El Bosque, Tejar и Dulce Nombre. Дренажни системи река Reventado и Toyogres представљају главне елементе у хидродинамичком систему Cartago, због различите литолошке грађе. Вероватно је да постоји подземна хидраулична веза из колекторског система у ове дренаже у одређеним тачкама. И поред постојања одређених података из групе бунара, потребно је указати да су за даља истраживања неопходни додатни подаци из више бушотина, литолошки описи прачени бољом петрографском и минералошком анализом, инвентарисање нивоа бунара и извора, постављање пијезометара и контролно-истраживачких бунара, између осталог.

Manuscript received August 27, 2024
Revised manuscript accepted February 05, 2025