Boletín Geológico

Boletín Geológico, 49(2), 45-63, 2022

https://doi.org/10.32685/0120-1425/bol.geol.49.2.2022.627

Received: October 31, 2021

Revision received: August 15, 2022

Accepted: August 23, 2022

Published online: December 28, 2022

Research article

Potential and prospects for hydrogeological exploration according to lithostructural criteria in Antioquia department, Colombia

Potencial y perspectivas de exploración hidrogeológica según criterios litoestructurales en Antioquia, Colombia

Teresita **Betancur**[1], Cristina **Martínez**[1]

1. School of Engineering, Universidad de Antioquia, Medellín, Colombia.

Corresponding author: Teresita Betancur, teresita.betancur@udea.edu.co

Abstract

In the department of Antioquia, in addition to the geological units with primary porosity, the tecto-structural characteristics of the hard rocks confer permeability properties to the metamorphic and igneous units that allow the flow and storage of groundwater. This work aims to synthesize useful information to identify potential areas to conduct new hydrogeological explorations in Antioquia.

The official geological map at 1:100 000 scale, adjusted to the geological map of Antioquia 1:400 000 scale, provided the basic input to separate the different types of rock and their structural affectations to identify permeability characteristics that were scored ranging from very low and very high. The concept of determining hydrogeological potential based on geological criteria is centered on the idea that the nature and distribution of aquifers and aquitards in a geological system are controlled by the lithology, stratigraphy, and structures of the deposits and geological formations.

The results of this study showed that the Medellin Dunite, slope deposits, Guineales Formation, Tertiary alluvial, Cerrito Formation, Sincelejo Group, Corpa Formation, terraces and recent alluviums, and Mesa Formation have very high aquifer potential (23.4% of the departmental area); 5% of the surface of the department has rocks with high aquifer potential; 35% has rocks with moderate aquifer potential; and the remaining 37% of the department has a lower aquifer potential.

Based on these findings, in terms of the groundwater potential in Antioquia, the area includes geological units with porosity and primary and secondary permeability. Thus, groundwater exploration in this department is urgently needed to provide hydrogeological knowledge to assist in the search for complementary sources of water supply for the population.

Keywords: groundwater, secondary permeability, hydrogeology in Antioquia.

Citation: Betancur, T., & Martínez, C. (2022). Potential and prospects for hydrogeological exploration according to lithostructural criteria in Antioquia department, Colombia. *Boletín Geológico, 49*(2), 45-63. https://doi.org/10.32685/0120-1425/bol.geol.49.2.2022.627

Resumen

En el departamento de Antioquia, además de las unidades geológicas con porosidad primaria, la afectación tectoestructural presente en las rocas duras confiere a unidades metamórficas e ígneas propiedades de permeabilidad que permiten el flujo y almacenamiento de aguas subterráneas. Este trabajo tiene como objetivo sintetizar información útil para la identificación de potenciales zonas para la realización de nueva exploración hidrogeológica en Antioquia.

El ensamble de la cartografía geológica oficial, escala 1:100 000, ajustado al mapa geológico de Antioquia 1:400 000, suministró el insumo base para separar los distintos tipos de roca y la afectación estructural que sobre ellos se ha registrado, para así imprimirles características de permeabilidad que se calificaron con rangos entre muy bajo y muy alto. La determinación del potencial hidrogeológico, a partir de criterios geológicos, parte de la idea según la cual la naturaleza y distribución de acuíferos y acuitardos en un sistema geológico están controlados por la litología, estratigrafía y estructuras de los depósitos y las formaciones geológicas.

Como resultados, se encontró que la Dunita de Medellín, los depósitos de vertiente, la Formación Guineales, los aluviales del Terciario, la Formación Cerrito, el Grupo Sincelejo, la Formación Corpa, las terrazas y aluviones recientes, y la Formación Mesa tienen potencialidad acuífera muy alta (23,4 % del área departamental); el 5 % de la superficie del departamento tendría rocas con potencial acuífero alto, y el 35 %, medio; en el 37 % restante el potencial sería menor.

A partir de estos hallazgos se concluye que el potencial de aguas subterráneas en Antioquia abarca unidades geológicas con porosidad y permeabilidad primaria y secundaria; en este sentido, la exploración de aguas subterráneas en el departamento es una tarea urgente en pro del conocimiento hidrogeológico y la búsqueda de fuentes complementarias de abastecimiento para la población.

Palabras clave: aguas subterráneas, permeabilidad secundaria, hidrogeología en Antioquia.

1. Introduction

Aquifers are geological formations that allow the storage and circulation of water under conditions that meet the quality and quantity, from an economic perspective, to satisfy human needs (Betancur et al., 2020). However, the domain of the *hydrogeology* discipline transcends the field of aquifer formations and focuses on the water-rock relationship under geological (Verma et al., 2016; Hoque et al., 2017), hydrological, and ecosystem considerations (Brkió, 2019), including the interaction of groundwater with surface and marine waters, and considering recharge, transit, and discharge zones (De Vries and Simmers, 2002; Harlow and Hagedorn, 2018; Mussa et al., 2020).

A hydrogeological unit is a geological formation, part of a geological formation, or a group of geological formations with similar hydraulic properties. Among their characteristics, conductivity is the one that determines the importance degree of an aquifer, and then, references can be established to determine the potential of a unit as more or less productive. It should be clear that the conditioning of the economic viability of extracting water from a geological formation is mediated by the need or demand of the resource; thus, in terms of hydraulic conditions, no net limits can be established to qualify a formation as an aquifer or not. Classical hydrogeology recognizes the aquifer characteristics of formations with conductivities up to the order of 10^{-4} m/day; thus, those that exceed 1 m/day are more favorable (Custodio and Llamas, 1996).

Determining hydrogeological potential based on geological criteria is based on the classical concept that the nature and distribution of aquifers and aquitards in a geological system are controlled by the lithology, stratigraphy, and structures of the deposits and geological formations. Lithology is the physical structure of these formations, including the mineral composition, the size, and the packing of the grains, the sediments, and the rocks that constitute the geological system, as well as the dynamic effects printed on them by tectonics. Stratigraphy describes the geometry and age relationships between various units. The structural characteristics, such as foliation, fractures, folds, and faults, are the conditions of the geological system produced by deformation on the rocks. In unconsolidated deposits, lithology and stratigraphy are the most important controls. Thus, knowledge of lithology, stratigraphy, and structures directly affects the understanding of aquifer and aquitard distributions (Freeze and Cherry, 1979).

Deposits and detrital sedimentary rocks, as well as volcaniclastic formations, are associated with their original porosity characteristics and, with them, permeability variables that are translated into hydraulic conductivity (Ren and Santamarina, 2018). Limestone formations usually develop karst structures (Kalhor et al., 2019). At the same time, crystalline intrusive and metamorphic rocks are naturally moderate with very low permeability, given their compact texture; consequently, their aquifer potential is considered limited compared to that of porous formations (Briški et al., 2020).

Studies on aquifers in fractured environments have increased given the extent of hard rocks in the global geological context and the growing dependence on the water that circulates through them (Fiume et al., 2020). Hard rocks constitute the basement of all continents (Lachassange et al., 2021) and are particularly exposed on the surface of the great shields of Africa, India, North America, South America, Australia, and Europe.

Regarding the hydraulic conductivity (Qian et al., 2019) and the presence of fractures and cleats presented by several authors, notably (Srinivasa Rao et al., 2000), the differentiation and analysis of factors such as density, suitability, roughness (Scesi and Gattinoni 2007), and openness make it possible to define the aquifer conditions. Lachassange et al. (2021) show that dyke-type structures can also lead to the occurrence of routes for the movement of fluids such as water. The development of shear zones, a satellite effect common to faulting processes, represents another source of permeability qualities in hard rocks (Henriksen and Braathen, 2006).

On the surface, rocks are exposed to intense weathering processes, which affect their storage capacity and hydraulic conductivity. Lachassagne et al. (2021) suggest that hard rock aquifers develop mainly within the first 100 m below the soil surface on profiles that comprise an unconsolidated layer, generally of low permeability, followed by a layer on which a layer network of fractures that generate permeability has developed. Given this concept, the role of weathering is fundamental for the formation of aquifers in fractured environments.

Anand and Paine (2002) and Dewandel et al. (2006) showed that fractured aquifers, mainly in igneous and metamorphic rocks, are subject to weathering, especially chemical weathering, which leads to variable porosity and hydraulic conductivity. Based on hydraulic tests, according to the volumes of injected water, these authors estimated conductivities above 10^{-5} m/day. Rukavicková et al. (2021) studied the hydraulic conductivity of eight different granitoids in the Bohemian massif in the Czech Republic and found that in comparison to the other granitoids, the coarse-grained granitoids have microcracks with greater length and opening, connectivity, and hydraulic conductivity. In addition, they noted that for different types of granitoid rocks, the appearance of the fractures and the hydraulic conductivity of the rock matrix were similar.

The use of spatial modeling tools to determine the possible conditions that favor the presence of groundwater in hard rocks has been applied in several regions where there is a need for alternative sources of groundwater. Arnous (2016) combined geospatial analysis methods to define the possible presence of water in rock masses in Egypt, and Anbarasu et al. (2020) used spatial analysis tools to delimit areas of aquifer interest in India. In both cases, satellite image interpretation methods were used to determine the thickness of weathering profiles and lineament density.

Hydrogeological data in Colombia covers less than 15% of the national territory, although the data do identify more than 75% of the territory has favorable natural characteristics for developing aquifers (Vargas et al., 2013; Ideam, 2019). However, access to high-quality water continues to be a condition experienced in many regions, including more than 40% of the population in rural areas, and in many urban centers (DNP, 2021). This same scenario occurs in the department of Antioquia.

The regional context of the geology of Antioquia, including the geodynamic situation associated with its location in a zone of tectonic plate interaction, leads to the need to consider that, in addition to the geological units with primary porosity, the tecto-structural effect present in the hard rocks confers metamorphic and igneous formation permeability properties that allow the flow and storage of groundwater.

This study aims to synthesize, from the geological maps of the Servicio Geológico Colombiano (SGC) –scale 1: 100 000– and other official sources, useful information to identify potential aquifers for future hydrogeological exploration in Antioquia.

2. Geological framework

The department of Antioquia, located in the northern corner of Colombia, is a territory in which physiographic conditions are marked by a great variety of reliefs, from the coast in the Gulf of Urabá, the paramos of the Western and Central cordilleras, the depressions in the Valleys of Cauca and Magdalena, and the foothills of the coastal zone at the entrance to the Atlantic (Figure 1). The topographic conditions, the influence of the intertropical convergence zone, and the impact of air currents from the Pacific, Caribbean, and Amazonia determine its complex climatic conditions and variable humidity regimes (Arias et al., 2021).

The mosaic of covers and types of soil, together with the dense network of currents, move the runoff flows that conver-

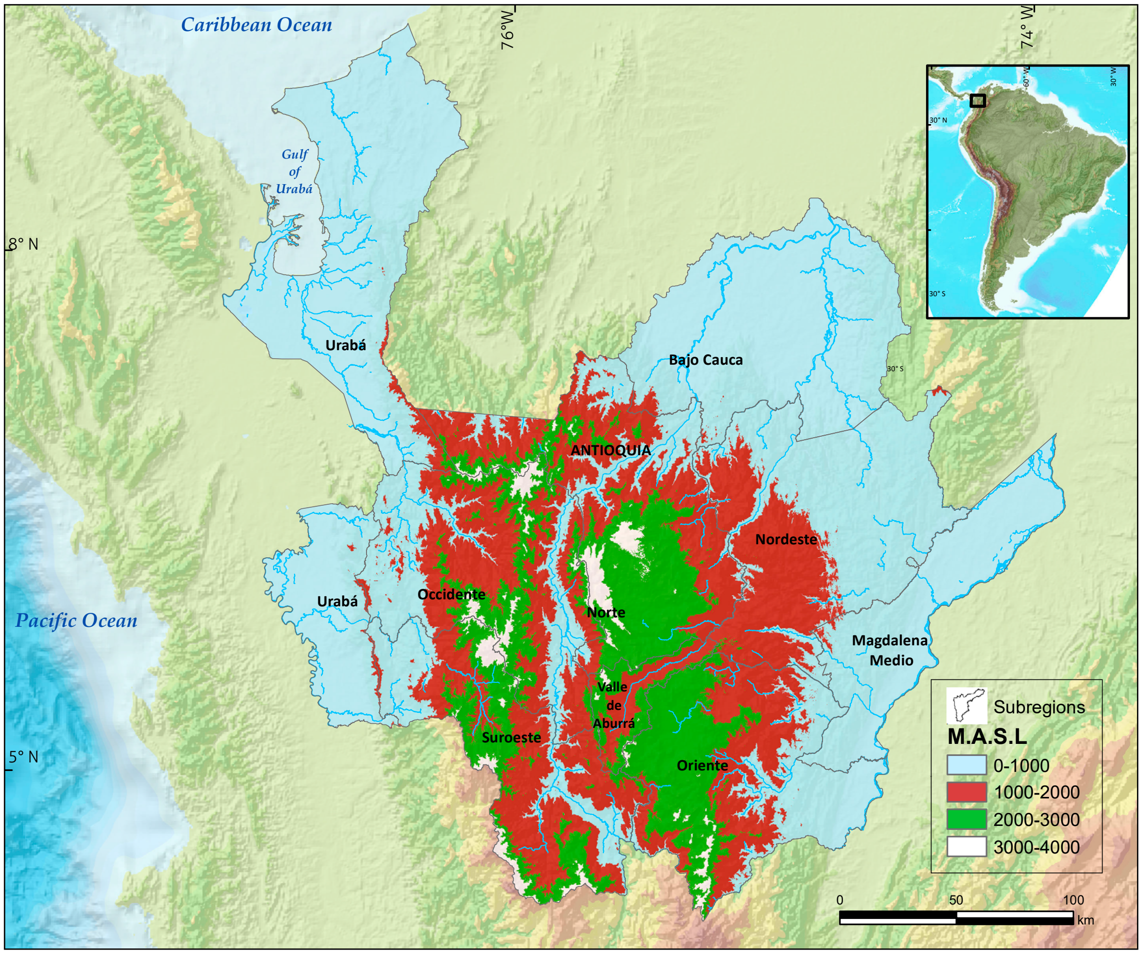

Figure 1. Study area
Source: Official DTM.

ge in the different hydrographic subzones (Vargas et al., 2013), and all the tributaries finally reach the Caribbean Sea.

The average annual precipitation in Antioquia is 2920 mm/year (Poveda, 2007), varying spatially between 1500 mm and 4000 mm/year (Mejía, 2008). The areas with lower rainfall are in the valley of the Cauca River, to the west of the department. The greatest rainfall amount occurs at the boundaries of the department of Chocó, at the southwestern end, in the vicinity of El Carmen de Bolívar, followed by the lower Cauca of Antioquia and the southeastern part in the Central Cordillera. The distribution of rainfall during the year is bimodal in most of the department; however, to the north, in the lower Cauca and the Gulf of Urabá, the regime is monomodal with a single dry season from December to March and a rainy season the remainder of the year. On average, evapotranspiration is 1170 mm/year (Poveda, 2007).

At the interannual time scale (several years, less than a decade), the climate of most of Earth is controlled by the El Niño Southern Oscillation (ENSO) phenomenon, which occurs because of the interaction between the circulation of winds and sea temperatures over the tropical Pacific. In Colombia, specifically in Antioquia, during El Niño, there is a drastic decrease in rainfall and river flows. During La Niña, the opposite processes occur, and there are storms, river floods, and other flooding events (Poveda et al., 2010).

For Antioquia, these characteristics evoke the image of a territory full of water: humidity in the atmosphere, rainfall over the entire geographical area, and drainage circulating in intricate channels on the surface. However, it should be noted that this territory experiences other complex events that occur naturally and through human action, such as deforestation and illegal mining, and climate change with a change in hydrological systems. In addition, groundwater, whose occurrence will also depend on geological conditions, is also important.

In the department of Antioquia, there are metamorphic, igneous, and sedimentary rock units, whose ages have been assigned from the Proterozoic to the Recent (González, 2001).

The rocks of the Precambrian and Paleozoic periods were affected by several plutonic bodies until the Cretaceous period, a time in which, in addition to magmatic activity, the accumulation of sediments and products of oceanic volcanism to the west of the Central Cordillera occurred. These rocks were attached, by tectonic effects, to the continent in the Mesozoic period (González, 2001).

As observed on the different versions of the geological map of Antioquia (González et al., 1996; González, 2001), the Cauca River basin, the lower Cauca, and the Urabá region are characterized by the presence of sedimentary rocks originating during the Paleogene-Neogene period.

González (2001) and Restrepo and Toussaint (2020), among others, noted that the uplift of the mountain ranges extended until the Pliocene, a period during which the action of erosive processes gave rise to the formation of alluvial and lacustrine deposits, marine areas and watersheds; this activity continues today.

As implicit in the previous text, the structural impact on the rock units that frame the geology of Antioquia has determined the presence of faults and associated with them, fractures, joints, and shear zones that have modified the original structural patterns conferring to these hard formations secondary permeability conditions that favor the presence and flow of groundwater, from recharge to transit to discharge.

Colombia has been divided into 16 hydrogeological provinces, considering the sedimentary basins and tectonic units that correspond to unique geological events whose physical limits are marked by regional megafractures documented in the geological studies of the country, especially those that describe the subdivision of land (Vargas et al., 2013). In the territory of Antioquia, the provinces Sinú, San Jacinto, Urabá, Valle Medio del Magdalena, and Valle Bajo del Magdalena are present.

The hydrogeological knowledge of Antioquia is limited to 7 aquifer systems that represent approximately 12% of the departmental territory (Ideam, 2019). However, the use of groundwater exceeds the boundaries of these systems and transcends the field of sedimentary rocks with primary porosity. In addition, access to drinking water in mainly rural areas, and in some several urban centers is low and reaches, on average, 28% of the population (Gobernación de Antioquia, 2018), a circumstance that forces people to seek alternative water supply sources to improve their standard of living.

Ecosystem considerations are beyond the scope of this work, but it is necessary to note that surface water-groundwater interactions largely determine ecosystem functionality. This is one more argument in favor of increasing knowledge of the lithostructural conditions that can determine the dynamics of groundwater.

3. Materials and methods

Considering the purposes of this study, the geological-structural evaluation focused on determining the porosity and permeability conditions that are relevant to promoting the storage and flow of groundwater, in terms of defining aquifer potential to identify relevant structural features for the subsequent delimitation of potential recharge zones. The characteristics of the deposits and clastic sedimentary rocks were considered, and

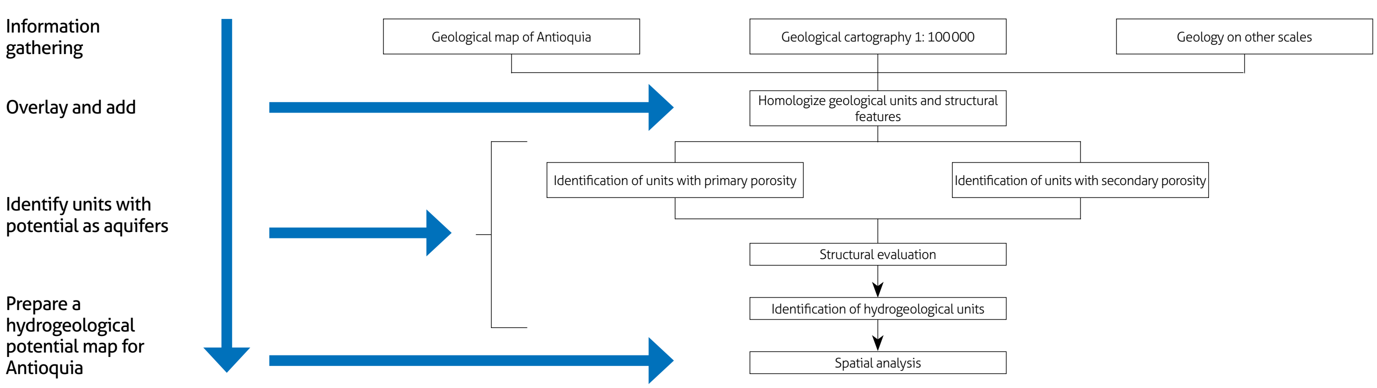

Figure 2. Methodological scheme

similarly, the conditions of the hydrogeological unit were determined for the hard rocks that have or have not been structurally affected and weathered. The approach for analyzing the information is illustrated in Figure 2.

The synthesis of Antioquia geological information was based on the review of the official geological map generated by the Servicio Geológico Colombiano (SGC) and on some field verification campaigns (Betancur and Martínez, 2021). A map at a scale of 1: 100 000 was used by González (2001), González et al. (1996); Kassem et al. (1979); Calle and González (1980, 1982); Bermúdez et al. (2012); Dávila et al. (2018a); Dávila et al. (2018b); Feininger (1970); Fonseca et al. (2011); Fonseca et al. (2012); Geotec (2003); Gómez et al. (2008); Gómez et al. (2009); Gómez et al. (2011); González (1992); Londoño and González (2002); González et al. (2015a); González et al. (2015b); González et al. (2015c); González et al. (2015d); González et al. (2015e); González (1980); Hall et al. (1970); Agustín Codazzi Geographical Institute (IGAC) and Geosciences, Mining and Chemical Research Institute (Ingeominas) (2005); Mejía et al. (1983 a and b); Rodríguez et al. (2013); Rodríguez et al. (2010); Rodríguez and Ulloa (1994); Rodríguez et al. (2005); Zapata et al. (2013); Zapata and Cossio (2001).

From this map, units were assembled, grouped, and confirmed, considering the interpretation and nomenclature recorded in the geological maps of Antioquia at a scale 1:400 000 (González, 2001) or in the most recent map product at 1:100 000. For the Bajo Cauca, details of the 1:25 000 map were included (Corantioquia and Universidad de Antioquia, 2014), and for the Aburrá Valley, the geological map at scale 1:10 000 was included (Metropolitan Area of the Aburrá Valley [AMVA], and Microzonation Consortium, 2007).

Clastic sedimentary rocks and deposits are geological units with primary porosity, while the presence of fractures, joints, shear, dissolution voids, and even weathering confer secondary porosity to the solid medium. No porosity characteristics are applied to an unaltered rock without structural affectation.

La Felice et al. (2014) characterized the fractures of the volcanic rocks on Mount Amiata in Italy, which are characterized by having a matrix that confers very low permeability; however, these rocks contain an aquifer of great importance. The authors deduced that within these rocks, the flow and storage of groundwater occur mainly through fractures, that is, faults and associated fracturing zones. The discontinuities and the intersections of the fractures are zones and potential sites of high permeability that favor the circulation and storage of groundwater. This finding coincides with that described by Norton and Knapp (1997) and Faulkner et al. (2010), who state that in volcanic rocks, the flow of groundwater occurs mainly through discontinuities (fractures, shear zones, and faults).

Nikic et al. (2020) noted that ultramafic rocks generally have very low porosity, so they are classified as almost or completely waterless rocks. However, due to tectonic activity and exogenous processes over geological time, some ultramafic rocks exhibit a certain degree of secondary porosity due to fracturing. Thus, hydraulically interconnected fractures can form fractured aquifers, such as the one found in Gruda, on Mount Zlatibor, in western Serbia. These same authors stated that at a macroscale, the ultramafics of Gruda are rocks without porosity whose hydrogeological importance is not significant; however, at a medium scale (m), secondary porosity takes on some importance, and although it is not significant, this porosity allows some permeability and formation of a fractured aquifer. However, at a microscale (dm, cm), secondary fractures are significant from a hydrogeological perspective.

Cilona et al. (2016) performed a structural analysis on rock outcrops in a sandstone–shale sequence exposed along the Santa Susana Field Laboratory and its surroundings (California), and they studied the joints and faults of multiple scales that cross this area. In their study, they showed that the rock has a high frequency of hydraulically active fractures that consist of a combination of joints and strata divisions that slope 30° toward the northwest. This was determined from observations in vertical boreholes, which provided information on the parallel fractures of the formation but not on the subvertical characteristics. The authors state that the abundance of zones with shear fractures and zones of relatively small faults that cross these lithological units causes the strata of shale and siltstone that have very low primary permeability to exhibit strong vertical hydraulic connectivity.

In 1999, Karro and Lahermo noted that although intact igneous or metamorphic rocks are compact and do not contain groundwater, these rocks are almost always fissured and fractured to a variable degree and that the irregular appearance of fissures and fractures in the crystalline bedrock, their interconnection, and the size of their openings or the abundance of the filling material constitute a complex, heterogeneous, and anisotropic medium for the flow of groundwater. The same authors noted that groundwater is more mobile in the shallowest parts of bedrock and that its movement slows with increasing depth; in addition, the depth limit that would separate these two domains would be approximately 200 m.

The hydraulic conductivity (K) of open fractures and fractured rock zones can be high; however, it varies by orders of magnitude from 10^{-5} m/s to 10^{-12} m/s, depending on the tectonic properties of rock units, type of petrographic rock, and abundance of clayey fracture fillings (Karro and Lahermo, 1999). In the most favorable cases, the hydraulic conductivity of the upper part of fractured bedrock can equal the typical K values of the permeable stratified material ($<10^{-5}$ m/s).

Based on these considerations and the effects of weathering on the different types of rock, a scale was proposed to classify permeability values between the very high and very low ranges (Table 1).

Table 1. Criteria to rank the potential permeability according to structural characteristics

Structures	Permeability
Intense fracturing or dissolution (karstification)	Very high
Units with primary porosity and grain size greater than silt	High
Fractures, more joints and shears in the rock unit	Moderate
Presence of joints with uniform distribution in the geological unit	Low
Local jointing that does not incorporate the entire polygon of the geological unit	Very low
Structurally unaffected rocks	NA

Table 2 proposes a double-entry matrix to rank the hydrogeological potential of a geological unit, considering its conditions of porosity (horizontal reading) and permeability (vertical reading). To test the aquifer condition, hydrogeological exploration work that results in a conceptual hydrogeological model should be carried out, considering these prioritization criteria. For rock units without pores or permeability, the definition of potential does not apply.

Table 2. Possible aquifer potential according to porosity and permeability conditions

Porosity / Permeability	Primary	Secondary by fracturing	Secondary by dissolution	No pores
Very high	Very high	Very high	Very high	Very low
High	Very high	Very high	Very high	Very low
Moderate	High	High	High	Very low
Low	Moderate	Low	Moderate	Very low
Very low	Low	Low	Low	Very low
Nonpermeable	Very low	Very low	Very low	Very low

4. Results

According to the methodological order outlined above, the geological map of Antioquia, the structural conditions, and the definition of aquifer potential according to litho-structural characteristics are described below.

4.1. Homologation of geological units: *Geological map of Antioquia*

During the map assembly process, four specific scenarios occurred:

i) Between one plate and another, continuity and coincidence were recorded in the designation of the geological units. When this occurred, the polygons were merged, and the description and nomenclature were preserved.
ii) Between two neighboring plates, discontinuities were recorded that led to discrepancies in the shape, extension, or characterization of units. In these circumstances, meticulous readings of the reports and, when available, field notebooks were used to compare rock types with the units arranged in the departmental geological map, and the new limits were digitized. Then, the name and description of the unit were assigned according to the geology of the departmental map of Antioquia.
iii) There were gaps in the geological plates at a scale of 1:100 000 (Plate 103 was not available, and Plates 114, 115, and 104 did not overlap). Thus, these gaps were completed based on the geological mapping of 1:400 000 (Geotec, 2003; González et al., 1996).
iv) There were some data with higher resolution scales, and thus, adjustments were applied to the areas of Bajo Cauca, Urabá, and Valle de Aburrá, including some units that had an extent was readable at 1:100 000.

Additionally, the major structural features, such as fault lines or lineaments, were coupled, and other structures were merged.

Considering the importance of knowing the geology in a hydrogeological context, first, we describe the units of hard rocks (metamorphic and igneous) were described, and then we describe the soft units (sedimentary rocks and unconsolidated deposits), also considering their age (Figure 3).

González (2001) presents an extensive description of metamorphism in Antioquia, and the evaluations are summarized here: the metamorphic rocks of the study area are located to the north of the department, on the western side, and on the axial part of the Central Cordillera. Some units have been assigned Precambrian ages, such as the Puente Peláez Mig-

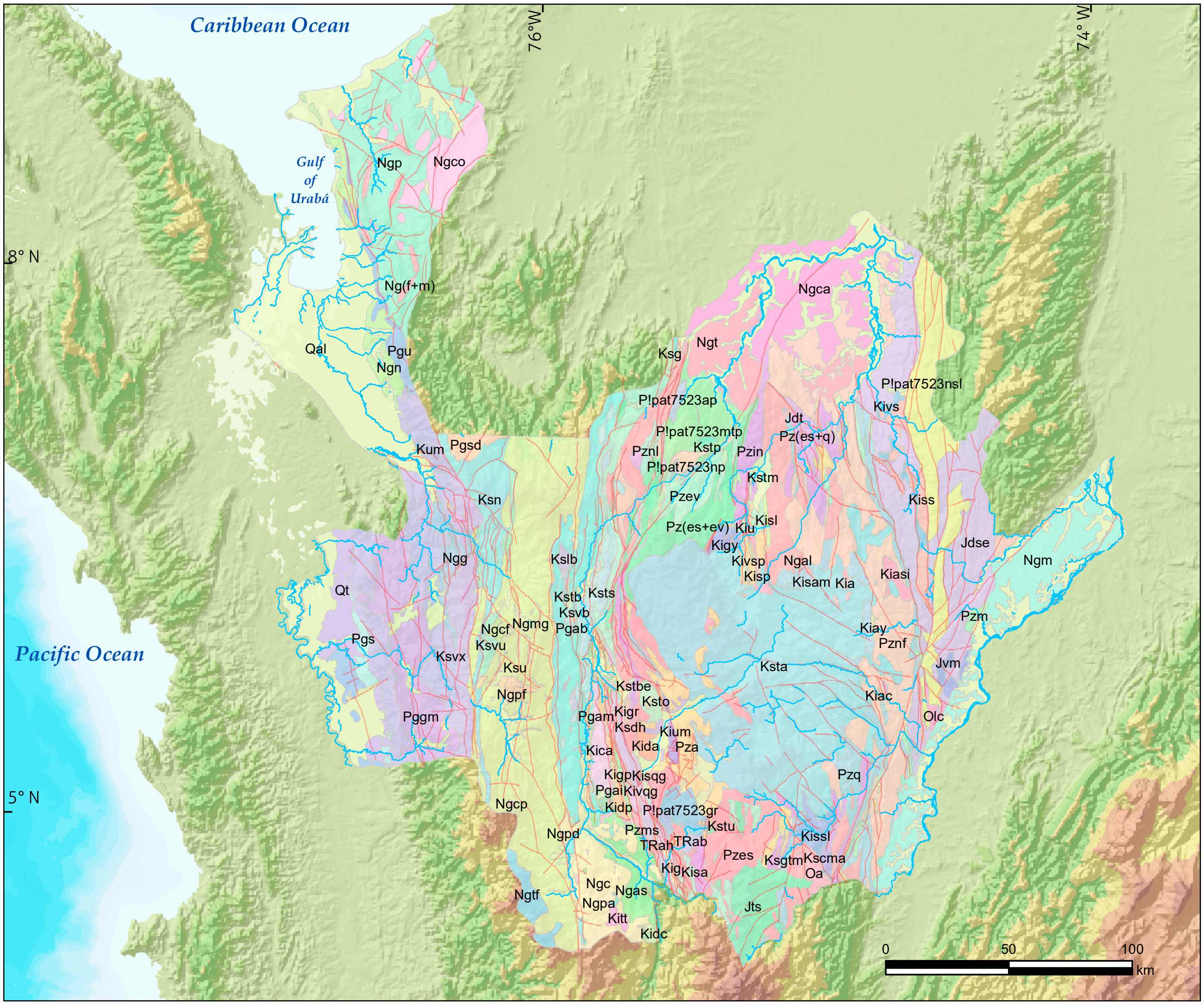

Figure 3. Geological map of Antioquia
Geological legend can be read in González (2001) and referenced geological mapping bibliography.
Source: adapted from González (2001).

matites (TRmPP-PЄgr), the Puquí Complex (PЄmpt), and the San Lucas quartz-feldespatic (PЄnsl). Those of Paleozoic age include the Cajamarca Complex (Pznf, Pznl, Pzes, Pzev, Pzq, and Pzm), the Valdivia Group, part of the Ayurá-Montebello Group, and the Cajamarca Group. During the Triassic and Jurassic periods, some migmatites were formed, including the Medellín Amphibolites (TraM) and gneissic bodies (TRgLC). Metamorphic rocks of Cretaceous age have been identified west of the Quebradagrande Complex, toward the Cauca River, and these rocks constitute a lithodemic unit called the Arquía Complex (Kica). Tectonic activity in the Tertiary period determined the occurrence of very low metamorphism rocks (Pgsd).

Most likely, the igneous activity that marks the territory of Antioquia began during the Permian–Triassic event when the intrusion of some granitic *stocks*, such as those of Amagá Stock (Trga) and El Buey Stock (Trab), occurred (González, 2001; Mejía et al., 1983 a and b; Rodríguez et al., 2005). Igneous activity in the Central Cordillera extended until the Triassic with the intrusion of adamellitic *stocks* (Trah) on the western flank of the Central Cordillera and continued, in a more intense way, during the Jurassic with the emplacement of the Segovia batholiths (Jdse) (González et al., 2015e) and Sonsón (Jts) (González, 1980), continuing until the end of the Cretaceous, with two well-defined magmatic cycles, one in the Early Cretaceous and another in the Late Cretaceous, corresponding to the great Antioquia Batholith (Ksta), located in the central part of the department (Gómez et al., 2011; Feininger et al., 1970). These intrusive cycles were manifested on both the eastern and western edges of the Central Cordillera. The basic plutonism affected both the axial part and the flanks of the Central Cordillera during the Lower Cretaceous: they have dioritic to gabbroid compositions; they are distinguished in Yarumal, Pueblito, (Kidp), and Heliconia (Ksdh); in some cases, they are associated with serpentinized ultrabasic rocks (Mejía et al., 1983 a and b).

The marine sedimentation of the Cretaceous was interrupted or followed by periods of intense basic volcanism of the ocean floor, such as that indicated in the Quebradagrande Complex (Kisqg) toward the western flank of the Central Cordillera in Campamento (Calle and González, 1980). The Cañasgordas Group with a basal unit, the Barroso Formation or Barroso Vulcanites (Ksvb), is the oldest lithological unit in the Cordillera Occidental and represents intense basic oceanic volcanism from the end of the Early Cretaceous to the Late Cretaceous (Mejía et al., 1983 a and b). Serpentinized ultramaphite bodies and gabbros associated with volcanic rocks could represent tectonically emplaced fragments of ophiolites during the Late Cretaceous (Ksvu, Kium) (Londoño and González, 2002; González and Salazar, 2002; Geotec, 2003).

On the Cordillera Occidental, syntectonic and post-tectonic plutons emerged, some with batholithic dimensions, such as the Farallones Pluton (Ngtf), which marked the continuation of the magmatic activity initiated in the Cretaceous. Related to the current valley of the Cauca River are subvolcanic intrusions, with predominant andesitic composition and porphyritic structure and ages between the late Miocene and the Pliocene (Ngpa, Ngpd) (Feininger, 1970; Calle and González, 1980).

Volcanic rocks of oceanic affinity are found in both the Central Cordillera and Cordillera Occidental; in the latter, they are normally interspersed with marine sediments. The boundary between the two mountain ranges is accompanied by ultramafics and gabbros in the Romeral fault system. According to their geographical and tectonic positions, the vulcanites of the Quebradagrande Complex (Kivqg) and the Barroso Volcanic Member (Kivb) have been recorded in the study area (Mejía et al., 1983 a and b). Between the Mandé Batholith (Pggm) and the western flank of the Western Cordillera extends a body of volcanic rocks called the Santa Cecilia La Equis Complex (Ksvx) (Geotec, 2003).

On the sediments of the Amagá Formation, in contrast, the flows and pyroclastitcs of the Combia Formation (Ngc) were deposited, after which, a cycle of intense volcanic activity began that occurred until recently (Calle and González, 1980, 1982).

Cretaceous sedimentary rocks are associated with the two mountain ranges that cross the department (Central and Occidental). Some formations are exclusively sedimentary, while others are interspersed with basic volcanic rocks. According to their geographical or tectonic position and age, the following units were defined and described: San Pablo Formation (Kisp)**,** La Soledad Formation (Kils), Abejorral Formation (Kisa), Quebradagrande Group (Kisqg), and Cañasgordas Group (Ksu.). Some of these lithological units are essentially sedimentary, but others show an intimate spatial relationship with basic volcanic rocks in an oceanic environment, both in the Western Cordillera and along tectonic systems in the Central Cordillera (Hall et al., 1970; González., 1980).

In the department, considering the differences in the sedimentological characteristics and accumulated environments of the different sedimentary and epiclastic sequences of the Cenozoic, these have been grouped for their description and characterization in basins according to their geographical location. One of these basins corresponds to the Amagá-La Pintada-Bolombolo basin, which is in the southern-central region of the department and is characterized by an intramontane basin of tectonic origin, where coal banks and mantles appear that are of economic importance and have been exploited for more than 80 years (González, 2001). Sedimentation in this basin during the Cenozoic was controlled by tectonism in the area along the Romeral Fault System. The Late Paleogene-Early Neogene sedimentation of the Cauca River basin is continental and constitutes the Amagá Formation (Ngsa, Pgia, Pgam), characterized by the presence of coal banks and layers (Calle and González, 1980).

Quaternary deposits are mainly alluvial (Qal, Qt) and increase their extent toward the flat areas of the department. Flow and colluvial deposits (Qf), due to their extension, are not always represented on the map, although they may be locally significant.

4.2. Structural conditions

The department of Antioquia is located near the union of the Nazca, Caribbean, and South American plates, which results in complex tectonics marked by subduction and faulting mechanisms. Of the successive deformations to which this territory has been subjected over time, the current tectonic conditions have only been valid in the late Neogene. That is, the Western and Central Cordilleras have acted approximately as a single tectonic block during the last episodes of the Andean orogeny (Restrepo and Toussaint, 2020).

The notion of segments or terrains indicates that northwestern Colombia, as part of the South American plate, was formed by a series of allocatene terranes (mosaic tectonic blocks limited by faults) accreted to an autochthonous block during different geological periods (González, 2001). According to Restrepo and Toussaint (2020), the Cordillera Central consists of the Tahamí terrain and part of the Chibcha terrain; the Western Cordillera is associated with the Calima terrain and part of the Cuna. The two mountain ranges are physiographically and geologically different.

The faults that are currently represented in Antioquia have a perpendicular arrangement: the first system is represented by the Palestina and Mulato faults to the east and Cauca-Romeral to the west with a direction between NNE-SSW and NE-

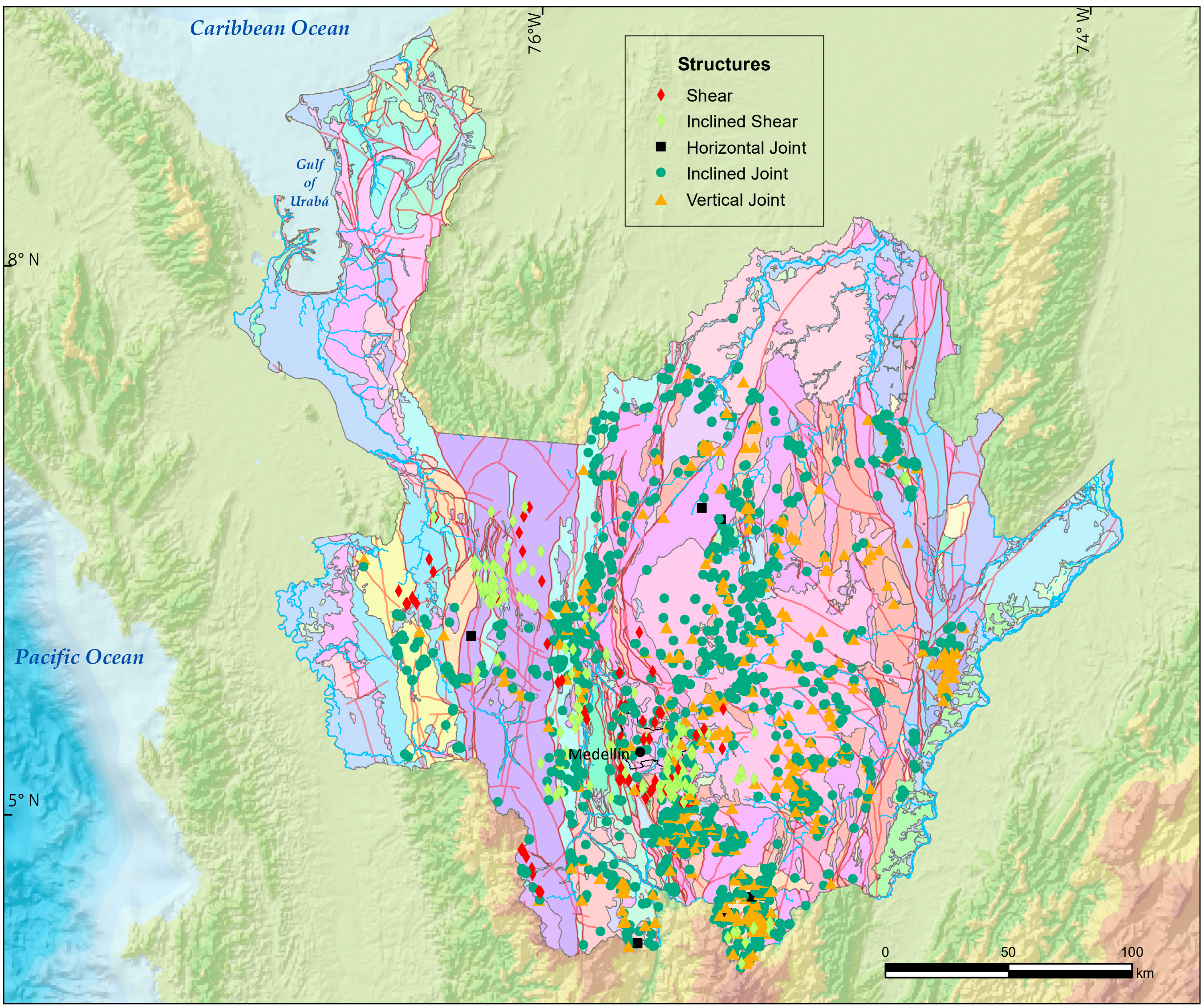

Figure 4. Structural features that determine secondary permeability
Source: Geology from González (2001) and studies carried out by environmental authorities.

SW. The second system has an approximate NW-SE to E-W direction and consists of the Monteloro, Nare, Nus, Caldera, Balseadero, and El Bizcocho faults and the alignments of the San Bartolomé and Arma Rivers (González, 2001). The most notorious fault systems in the Central Cordillera are Palestina, San Jerónimo, Espiritu Santo, and Romeral; those in the Western Cordillera are Sabanalarga, Cauca, Anzá, Peque, Urrao, Cañasgordas, Abriaquí, Tucurá, San Pedro, Murrí, Murindó, and Atrato.

The remnants of this tectonic activity are marked at the lithological level by the occurrence of folds, fractures, joints, and shears that normally modify the initial permeability characteristics of the rocks. Figure 4 shows that the different hard rock units are marked by jointing effects and how the greater relative presence of vertical and inclined attitudes indicates factors that favor infiltration (first) and posterior lateral flow. It should be noted that several of the igneous bodies and some metamorphic bodies derived from them have acidic to intermediate natures, in geochemical terms, and original granular textures, circumstances that at the time of weathering favored the development of profiles (for example, *gruss*) like textures of permeable stratified media.

4.3. Aquifer potential according to litho-structures

Based on the identified permeability conditions, according to the presence and type of structural features and the primary or secondary porosity, the aquifer potential characteristics were identified for each rock unit present in the department of Antioquia (Figure 5 and Table 3.). According to the categories defined here, 23.4% of the departmental area has very high aquifer potential, 5% has high potential, 35% has moderate potential, and 34% has low potential.

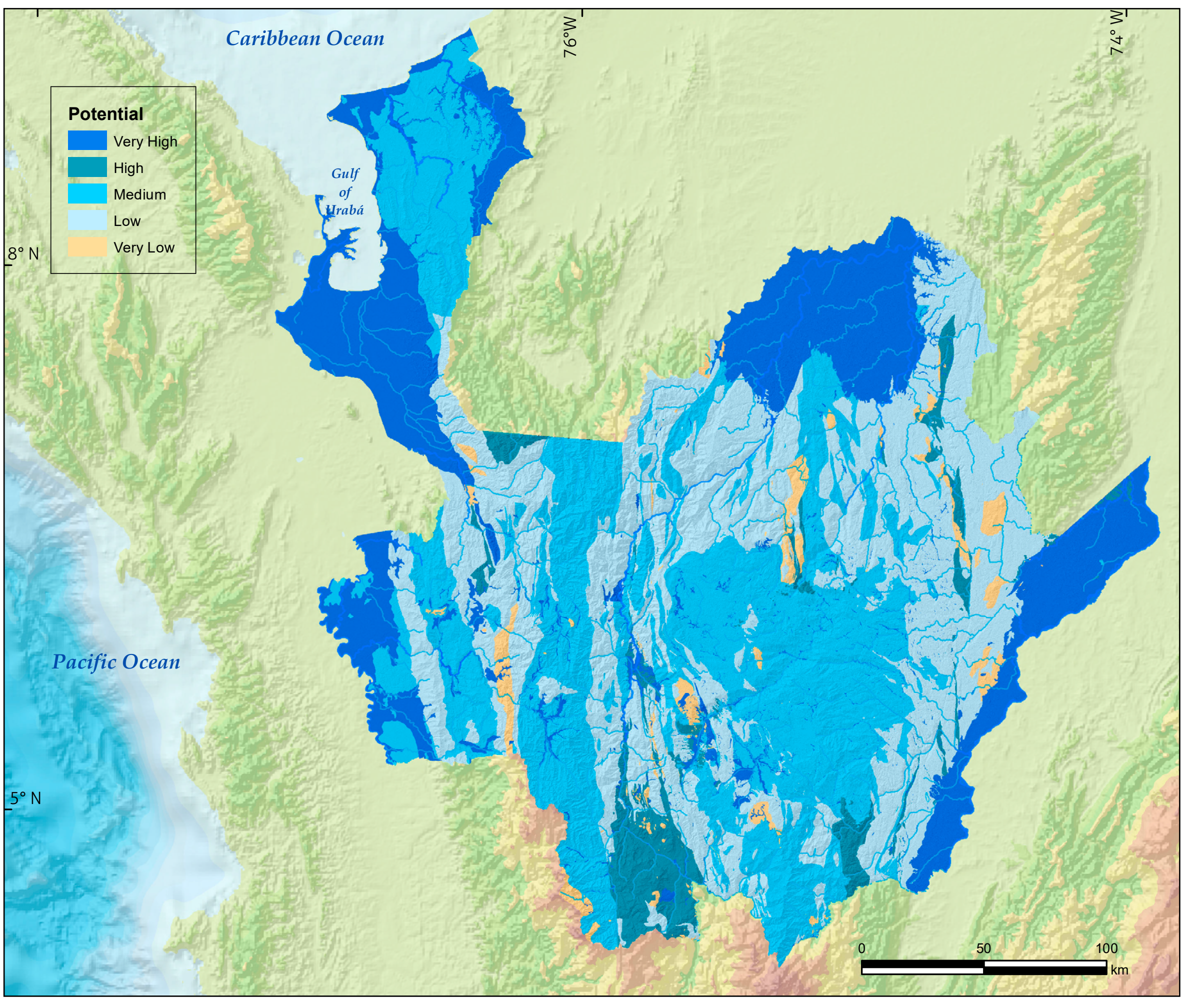

Figure 5. Groundwater potential in Antioquia department

Table 3. Hydrogeological potential by geological unit

		Very high aquifer potential			
Kium	Medellín Dunite	Ngce	Cerrito Formation	Qt	Alluvial terraces
Q2v, Qd, Qfa, Qi	Slope deposits	NgQs	Sincelejo Group	Qal	Recent floods
Ngg	Guineales Formation	Ngco	Corpa Formation (T2)	Ngm	Mesa Formation
Tal	Tertiary alluvium	Qd	Sliding deposits	Q6	Slope deposits
		High aquifer potential			
Oa	Aquitania metasediments	Ngc	Combia Formation – Volcanic Member	Kiss	Eastern Segovia Sedimentites
Pzm	Cajamarca Complex: Marbles	E1E2sc	Cruces Sedimentites	Ksam	Amalfi sediments
Pgai	Amagá Formation - Lower Member	N2Q	Vergel Sedimentites	Kissl	San Luis Sedimentites
Pgam	Amagá Formation - Middle Member	Kils	La Soledad Formation	Kisp	San Pablo Formation
Ngas	Amagá Formation - Upper Member	NFI	Debris flow deposits	N1rl	Real Group
Ngam	Amagá Formation	Qll	Anthropogenic Landfill	PGSD	Conglomerates
		Moderate aquifer potential			
JKgms	Sajonia Mylonitic Gneiss	Ksta	Antioquia Batholith	Kisa	Abejorral Formation
TRmPP PЄgr	Puente Peláez Migmatites El Retiro granulites and migmatites	Ksts	Sabanalarga Batholith	Kslb	Interstratified chert and fine clastic rocks
Pzes	Cajamarca Complex: Quartz-sericitic schists	Pggm	Mandé Batholith	Ksu	Cañasgordas Group Penderisco Formation - Urrao Member
N2qb	Quibdó Formation	Jts	Sonsón Batholith	N1 sv	Beibaviejo Sedimentites
Pgs	Salaquí Formation	Pgu	Uva Formation	Qto	Pyroclastic rocks
Q2fl, Q2 l: MEDIO	Lacustrine and fluviolacustrine deposits	Ng (pv + am) (T1)	Pavo Formations and Arenas Monas		
		Low aquifer potential			
PЄnsl	San Lucas Feldspathic-quartz	Pza	Amphibolites	TRgLC	La Ceja Gneiss
PЄnp, Pєap, PЄmtp	Puquí Complex: Micaceous Gneiss Amphibolites (Pєap) Metatonalite (PЄmtp) and Gneiss (PЄnp)	Pzin	Gneiss Syntectonic Intrusive	Pn	Porphyroblastic Gneiss
Olc	La Cristalina Formation	Kica	Arquia Complex	Pnl	Augen Gneiss
Pzms	Sinifaná Metasediments	Pgnp	Palmitas Gneissic Granite	PzagC	Caldas Garnet amphibolite
Pznf, Pznl	Cajamarca Complex: Feldspar-quartz and aluminum Gneisses	Pnc	Cataclastic Gneiss	TreAB	Baldias Amphibolic Schists
Pzev	Cajamarca Complex: Actinolite-chlorite schists	PzaM	Alto de Minas Amphibolites	TreC	Cajamarca Schists
Pzes + Pzev	Cajamarca Complex: Intercalated schists	Pzei	Amphibolites and Amphibolic schists	PzeC	Caldas Schists
Pzq: LOW	Cajamarca Complex: Quartzites	PraM	Medellín Amphibolites	Pcaa	Amphibolite lens
Pzmc	La Cruz Metasediments	fqd	Quartzodiorite	Pnia	Abejorral Intrusive Gneiss
Trga	Amagá Stock	Kigr	Romeral Gabbro	Kida	Altavista Stock
Trah	La Honda Stock	Kivqg	Quebradagrande Complex - Vulcanites	Kia: LOW	Adamelites
Work	El Buey Stock	Kivb	Barroso Formation- Vulcanites	Ksgtm	Tres Mundos Stock
Jdse	Segovia Batholith	Kivu	Uramita Volcanite	Kscma	Aquitania stock
Kidp	Pueblito Diorite	Kidc	Cambumbia Stock	Ksvx	Santa Cecilia - La Equis Complex
Kigy	Yarumal stock	Kitt	Támesis Stock	Pgab	Buriticá Andesites
Ngpf	Páramo de Frontino Stock	Ksvb	Cañasgordas Group - Barroso Formatiojn	KgSD	San Diego Stock
Ngcf	Cerro Frontino Stock	N1n4n5bb	El Boton Basalt	KcdE	Estancias Stock
Ngvpf	Paramo of Frontino Vulcanites.	Kcdu	Ursula Stock	KcdMl	Medialuna Stock
Ksg	Gabbro	Pnim	Alto de Minas Gneissic Intrusive	J1gn	Norosí Granite
Kigc	Copacabana Gabbro	Kgn	Cataclastic Granite	Ku	Uré Basic Ultrabasic Complex
Pniv	Rio Verde Intrusive Gneiss	Kisqg	QuebradagrandeFormation	Ksn	Penderisco Formation Nutibara Member
Traql	Quebrada Liborina Stock	Pnip	Pantanillo Intrusive Gneiss	Taa	Sandstones and clay stones

No aquifer potential					
Ꞓeam	Migmatites	Jvm	La Malena Volcanic Complex	Kivs	Segovia Vulcanites
Jml	La Iguaná Mylonite	Jdt	La Tina Stock	Ksdh	Heliconia Diorite
JkmbP	Picacho metabasites	Kiu	Ultramafics of Romeral	Kstmi	Quebrada Maní Batholith
Pbsd	Very low degree metamorphicrocks	Kum	Western Cordillera Ultramafics	Ksto: N/A	Ovejas Batholith
Kat	Felsic tonalite	Kstu	La Unión Dome	Ngtf	Farallones Batholith
Ngpd	Porphyritic hypo-abyssal rocks Dacitic porphyries	Ngmg	Morrogacho Stock	Ngpa, Ngpd	Porphyritic hypo-abyssal rocks
E2PADP	Pantanos Porphyry	Nglh	La Horqueta Stock	Ngpa	Porphyritic augitic andesites
N1n4n5mn	Nudillales Monzonite	PRgb	San Isidro Granulites	Ngpa	Porphyritic Andesite
Kcdgm	Mistrato Pluton	Prga	San Isidro Granulites	K5K6-bp	Plutonic units associated with Barroso Formation
Tada	Dacitic porphyries	Kld	Diorite	JuR	Romeral Peridotite
Ksvu	La Horqueta Monzonite	Pca	Medellín Ultrabasic	J1gg	Guamocó Granodiorite
s	Skarn	J1nha	Norean Volcanic Complex	Kisls	El Sireno Lodolites
t	Ultramafics (talc)	K	Serpentinites		

In relation to the geological units that, because of this evaluation, have been called *formations with a very high hydrogeological potential*, it should be noted that to a large extent, they contain the aquifer systems evaluated and tested through hydrogeological exploration efforts. The Medellín Dunite (Kiu) is a pseudokarst formation, and important sinkhole systems have been identified through which the recharge and storage of groundwater is generated and manifested in permanent outcrops in the Santa Elena Plateau and the slopes of the Aburrá Valley; this area would thus constitute the Medellín Dunite aquifer (Universidad de Antioquia and AMVA, 2015, 2017), although notably, for some authors, this formation has the character of a recharge zone (Patiño et al., 2021); the Cerrito Formation (Ngce) and the Sincelejo Group (NgQs) host the aquifers of the lower Cauca (Corantioquia and Universidad de Antioquia, 2014). The Corpa Formation defines the presence of the confined aquifer, with a multilayer nature, of Urabá (Universidad de Antioquia and Corpourabá, 2016). Similarly, several of the aquifer systems identified in Antioquia include alluvial and watershed deposits within their units; this is the case for the middle Magdalena (Gotta Ingeniería and Corantioquia, 2018), western Antioquia (SHI SAS and Corantioquia, 2015), Valle de Aburrá (Ossa et al., 2021), and Valparaíso-La Pintada aquifers in southwestern Antioquia. (SHI SAS and Corantioquia, 2014). Therefore, these units are confirmed to have the characteristics of formations with very high aquifer potential.

The factor common to all the geological units categorized with high hydrogeological aquifer potentials is that their rocks have primary porosity, based on their detrital sedimentary genesis, with the presence of layers of sandy and conglomerate textures. In addition, due to their structural involvement, these formations have developed (added) secondary porosity conditions, whose continuity and flow must be tested by hydrogeological exploration.

The units that have moderate aquifer potential include important bodies of igneous rock, some with a batholith dimension, others of a metamorphic nature, in which the presence of joints and the occurrence of powerful weathering profiles have been recorded.

5. Discussion

Based on the level of knowledge about groundwater in Antioquia, it has an irregular spatial distribution and a limited representation. In the Eje Bananero de Urabá, the aquifer system has been studied continuously since 1994 (Universidad de Antioquia and Corpouraba, 2014). The hydrogeological system of the Aburrá Valley was evaluated for the first time in 2002 (Universidad de Antioquia and Integral, 2002), and then with the Metropolitan Area of the Aburrá Valley (AMVA), it has been monitored since 2010. In the subregions of the lower Cauca (Universidad de Antioquia and Corantioquia, 2014), Magdalena Medio (Gotta Ingeniería and Corantioquia, 2018), the western (SHI SAS and Corantioquia, 2015) and southwestern (SHI SAS and Corantioquia, 2014) subregions have generally complete hydrogeological information; for the eastern part of the department, attempts to evaluate the potential of groundwater have been carried out in the past.

After consulting and verifying in the field the socioeconomic conditions that account for access to and sources of water supply for the population residing in the nine subregions of Antioquia, it was confirmed that access to groundwater resources goes far beyond what is in the official figures. The individual supplies from artisanal wells and that of many human conglomerates in rural areas since birth reveal a reality that has not been recorded in regional and national water assessments. Notably, springs are erroneously recorded as surface water sources in official records.

The results of the litho-structural characterization presented here clearly show that the groundwater potential in Antioquia is manifested through igneous and metamorphic formations that have acquired secondary permeability due to the tectonic effects printed on them by the geodynamics affecting northeastern Colombia in addition to the effect of weathering processes, which have reached depths that can reach several tens of meters. The potential of intermediate to acidic plutonic formations, in which the development of *gruss*-type textures defines permeability conditions close to those of granular sedimentary deposits, is striking. There are also several detrital sedimentary rock units that have not been explored.

The exploration of areas with very high and high hydrogeological potential can be undertaken using conventional techniques of hydrogeological research. The step toward researching and quantifying the volumes in hard rocks should be planned in terms of prioritizing and defining a methodological route that involves geophysical techniques, an evaluation of remote sensing information, hydrological quantification, a structural evaluation, geophysical tests, a hydraulic characterization, and geochemical and isotopic validation, among others.

It is important to highlight the importance of a thorough understanding of the hydrological dynamics in a territory in terms of ecosystem sustainability. In addition, if one considers that the largest reserves of fresh liquid water that exist on the planet are found underground, then any interference with the natural system implies a stress factor that can cause negative impacts.

6. Conclusions

Based on the evaluation of the textural and litho-structural characteristics of the rock units present in Antioquia, it was possible to delimit zones of very high, high, moderate, low, and very low hydrogeological potential. To make this determination, the porosity and permeability characteristics that enable the storage and flow of groundwater were analyzed from the genesis and evolution of the different units.

The geological units that showed a greater hydrogeological aquifer potential correspond to rocks with primary porosity whose genesis covers a wide time scale. However, the presence of moderate aquifer potential in the surface extension that covers 35% of Antioquia and is associated with saprolites derived from hard rocks previously affected by fracturing was significant.

Knowledge of the hydrogeological potential in a region is of crucial importance for identifying groundwater sources, as this knowledge helps in understanding regional hydrological dynamics and identifying factors to guide decision-making in relation to generating interventions that consider environmental sustainability criteria.

7. Acknowledgments

This work compiled data on the hydrogeological characteristics of Antioquia obtained by entities such as the Universidad de Antioquia, Universidad Nacional de Colombia (Medellín), the Servicio Geológico Colombiano (formerly Ingeominas), Corporación de Desarrollo Sostenible de Urabá (Corpouraba), Corporación Autonóma Regional del Centro deAntioquia (Corantioquia), Área Metropolitana del Valle de Aburrá (AMVA), and the Corporación Autónoma Regional de las cuencas de Rionegro y Río Nare (Cornare). These data were able to be synthesized thanks to the sabbatical year commission given by the Universidad de Antioquia to the first author. This effort was supported by GIGA.

References

Anand, R. R., & Paine, M. (2002). Regolith geology of the Yilgarn Craton, Western Australia: Implications for exploration. *Australian Journal of Earth Sciences, 49*(1), 3-162. https://doi.org/10.1046/j.1440-0952.2002.00912.x

Anbarasu, S., Brindha, K., & Elango, L. (2020). Multi-influencing factor method for delineation of groundwater potential zones using remote sensing and GIS techniques in the western part of Perambalur district, southern India. *Earth Science Informatics, 13*, 317-332. https://doi.org/10.1007/s12145-019-00426-8

Área Metropolitana del Valle de Aburrá (AMVA), & Consorcio Microzonificación (Solingral S.A., Integral S.A., Inteinsa, Universidad EAFIT, Universidad Nacional de Colombia, sede Medellín). (2007). *Microzonificación sísmica detallada* *de los municipios de Barbosa, Girardota, Copacabana, Sabaneta, La Estrella, Caldas y Envigado*. https://repositorio.gestiondelriesgo.gov.co/handle/20.500.11762/19862

Arias, P., Ortega, G., Villegas, L., & Martínez, A. (2021). Colombian climatology in CMIP5/CMIP6 models: Persistent biases and improvements. *Revista Facultad de Ingeniería, Universidad de Antioquia*, 100, 75-96.

Arnous, M. O. (2016). Groundwater potentiality mapping of hard-rock terrain in arid regions using geospatial modelling: Example from Wadi Feiran basin, South Sinai, Egypt. *Hydrogeology Journal, 24*, 1375-1392. https://doi.org/10.1007/s10040-016-1417-8

Bermúdez, J. G., Arango, M. I., Rodríguez, G., Zapata, G., & Ramírez, C. (2012). *Cartografía geológica de las planchas 72 Pueblo Nuevo y 82 Montelíbano, departamento de Córdoba. Escala 1:100 000*. Servicio Geológico Colombiano. http://recordcenter.sgc.gov.co/B13/23008010024552/mapa/pdf/2105245521300004.pdf

Betancur, T., & Martínez, C. (2021). Acople de la cartografía geológica disponible para Antioquia a escala 1:100.000, base para la exploración hidrogeológica. In *Memorias XVIII Congreso Colombiano de Geología*. https://sociedadcolombianadegeologia.org/acople-de-la-cartografia-geologica-disponible-para-antioquia-a-escala-1100-000-base-para-la-exploracion-hidrogeologica/

Betancur, T., Duque, C., Martínez, C., García, D., Villegas, P., & Paredes, V. (2020). Delimitación de potenciales zonas de recarga. Caso de estudio: acuífero multicapa del eje bananero del Urabá antioqueño. *Revista Politécnica, 16*(32), 41-55.

Briški, M., Stroj, A., Kosović, I., & Borović, S. (2020). Characterization of aquifers in metamorphic rocks by combined use of electrical resistivity tomography and monitoring of spring hydrodynamics. *Geosciences*, *10*(4), 137. https://doi.org/10.3390/geosciences10040137

Brkió, Z., Kuhata, M., Larva, O., & Gottetein, S. (2019). Groundwater and connected ecosystems: An overview of groundwater body status assessment in Croatia. *Environmental Sciences Europe*, *31*, art. 75.

Calle, B., & González, H. (1980). *Geología y geoquímica de la plancha 166 Jericó. Escala 1:100 000*. Servicio Geológico Colombiano. http://recordcenter.sgc.gov.co/B4/13010010024374/mapa/pdf/0101243741300002.pdf

Calle, B., & González, H. (1982). *Geología y geoquímica de la plancha 186 Riosucio. Escala 1:100 000. Producto. Versión 1982 estandarizada en 2009*. Servicio Geológico Colombiano. http://recordcenter.sgc.gov.co/B4/13010010024379/mapa/pdf/0101243791300002.pdf

Cilona, A., Aydin, A., Likerman, J., Parker, B., & Cherry, J. (2016). Structural and statistical characterization of joints and multi-scale faults in an alternating sandstone and shale turbidite sequence at the Santa Susana Field Laboratory: Implications for their effects on groundwater flow and contaminant transport. *Journal of Structural Geology, 85*, 95-114. https://doi.org/10.1016/j.jsg.2016.02.003

Corporación Autónoma Regional del Centro de Antioquia (Corantioquia), & Universidad de Antioquia (2014). *Plan de manejo ambiental del sistema acuífero del Bajo Cauca antioqueño, segunda etapa*. https://www.corantioquia.gov.co/ciadoc/fauna/GA_CV_964_2013.pdf

Custodio, E., & Llamas, M. R. (1996). *Hidrología subterránea*. Ediciones Omega.

Dávila, C., Gil, C., Ibáñez, R., López, C., Orozco, L., Patiño, A., Pinilla, A., Quiñones, C., Román, J., Ramos, K., & Savanier, D. (2018a). *Anexo J. Mapa geológico de la plancha 92 Tierradentro. Escala 1:100 000*. Servicio Geológico Colombiano. https://recordcenter.sgc.gov.co/B23/678_19MemExPl92Tierradentro/Mapa/Pdf/AnexoJ_MapaGeolPl92.pdf

Dávila, C., Gil, C., Ibáñez, R., López, C., Pinilla, A. Quiñones C., Ramos, K., & Román J. (2018b). *Anexo J. Mapa geológico de la plancha 91 Belencito. Escala 1:100 000*. Servicio Geológico Colombiano. Bogotá. https://recordcenter.sgc.gov.co/B23/677_19MemExPl91Belencito/Mapa/Pdf/AnexoJMapaGeolPl91.pdf

De Vries, J. J., & Simmers, I. (2002). Groundwater recharge: An overview of processes and challenges. *Hydrogeology Journal, 10*, 5-17. https://doi.org/10.1007/s10040-001-0171-7

Departamento Nacional de Planeación (DNP). (2021). Agua limpia y saneamiento. In *Objetivos de Desarrollo Sostenible*. https://ods.dnp.gov.co/es/objetivos/agua-limpia-y-saneamiento

Dewandel, B., Lachassagne, P., Wyns, R., Marechal, J. C., & Krishnamurthy, N. S. (2006). A generalized 3-D geologicaland hydrogeological conceptual model of granite aquifers controlled by singleor multiphase weathering. *Journal of Hydrology, 330*(1-2), 260-284. https://doi.org/10.1016/j.jhydrol.2006.03.026

Faulkner, D. R., Jackson, C. A. L., Lunn, R. J., Schlische, R. W., Shipton, Z. K., Wibberly, C. A. J., & Withjack, M. D. (2010). A review of recent developments concerning the structure, mechanics and fluid flow properties of fault zones. *Jour-*

nal of Structural Geology, 32(11), 1557-1575. https://doi.org/10.1016/j.jsg.2010.06.009

Feininger, T., Barrero, D., Castro, N., Ramírez, O., Lozano, H., & Vesga, J. (1970). *Mapa geológico de Colombia, oriente de Antioquia. Cuadrángulo I-9 y parte de los cuadrángulos H-9, H-10, I-10, J-9 y J-10. Plancha 117 Amalfi, plancha 132 Yolombó, plancha 148 San Carlos, plancha 168 Argelia (Aquitania), plancha 188 La Dorada. Escala 1:100 000. Producto. Versión año 1970 estandarizada en 2010*. Servicio Geológico Colombiano. Bogotá. http://recordcenter.sgc.gov.co/B4/13010010024246/mapa/pdf/0101242461300010.pdf

Fiume, B., João Fernandes, A., Bolognini Barbosa, M., Hirata, R., & Bertolo, R. (2020). Integrated application of geophysical loggings and fracture survey on rock exposures for identifying transmissive fractures in crystalline aquifer: Case study in the city of São Paulo. *Brazilian Journal of Geology, 50*(1), 1-17. https://doi.org/10.1590/2317-4889202020190034

Fonseca, H. A., Fuquen, J. A., Mesa, L. D., Talero, C. A., Pérez, O. G., Porras, J. J., Gavidia, O. A., Pacheco, S. M., Pérez, J. F., Amaya, E., García, Y., & Enrique, F. (2011). *Cartografía geológica de la plancha 133 Puerto Berrío. Escala 1:100 000. Contrato 041/2010*. Servicio Geológico Colombiano. http://recordcenter.sgc.gov.co/B13/23008010024508/mapa/pdf/2105245081300001.pdf

Fonseca, H. A., Fuquen, J. A., Mesa, L. D., Talero, C. A., Pérez, O. G., Porras, J. J., Gavidia, O. A., Pacheco, S. M., Amaya, E., García, Y., & Enrique, F. (2012). *Cartografía geológica de la plancha 108 Puerto Wilches. Escala 1:100 000. Contrato n.° 041/2010*. Servicio Geológico Colombiano. http://recordcenter.sgc.gov.co/B13/23008010024507/mapa/pdf/2105245071300001.pdf

Freeze, R. A., & Cherry, J. A. (1979). *Groundwater*. Prentice Hall.

Geotec Ltda. (2003). *Geología de los cinturones Sinú – San Jacinto – Planchas 50 Puerto Escondido, 51 Lorica, 59 Mulatos, 60 Canalete, 61 Montería, 69 Necoclí, 70 San Pedro de Urabá, 71 Planeta Rica, 79 Turbo, 80 Tierralta. Escala 1:100 000*. Servicio Geológico Colombiano. Bogotá. http://recordcenter.sgc.gov.co/B4/13010010020013/mapa/pdf/0101200131300008.pdf

Gobernación de Antioquia. (2018). *Anuario estadístico de Antioquia*. http://www.antioquiadatos.gov.co/index.php/anuario-estadistico-2018

Gómez, J. F., Albarracín, H., Sepúlveda, J., Sepúlveda L., Rodríguez, G., Salazar, G., Zapata, G., & Nivia, A. (2011). *Mapa geológico de la plancha 131 Santa Rosa de Osos. Escala 1:100 000*. Servicio Geológico Colombiano. Bogotá. http://recordcenter.sgc.gov.co/B13/23008010024403/mapa/pdf/2105244031300001.pdf

Gómez, L. A., Fuquen, J. A., Quintero, C., Patiño, A., Beltrán, A., López, C., Lancheros, J. A., Renzoni, G., & Manrique, M. (2009). *Cartografía geológica y muestreo geoquímico escala 1:100 000 de la plancha 149 – Puerto Nare (Puerto Serviez). Contrato 398 de 2007. Producto. Versión 2009*. Servicio Geológico Colombiano. Bogotá. http://recordcenter.sgc.gov.co/B12/23008010024352/mapa/pdf/2105243521300002.pdf

Gómez, L. A., Patiño, A., Renzoni, G., Beltrán, A., Quintero, C., & Manrique, M. (2008). *Cartografía geológica y muestreo geoquímico escala 1:100.000 de la plancha 119 – Barrancabermeja Valle Medio del Magdalena. Contrato 398. Producto*. Servicio Geológico Colombiano. http://recordcenter.sgc.gov.co/B12/23008010024350/mapa/pdf/2105243501300002.pdf

González, H. (1980). *Geología de la plancha 167 Sonsón y Plancha 187 Salamina. Escala 1:100 000. Versión 1980. Versión digital 2009*. Servicio Geológico Colombiano. Servicio Geológico Colombiano. Bogotá. http://recordcenter.sgc.gov.co/B18/23008010028501/mapa/pdf/2105285011300005.pdf

González, H. (1992). *Mapa geológico de Colombia, plancha 106 Liberia. Escala 1:100 000. Producto. Versión 1992 estandarizado en 2009*. Servicio Geológico Colombiano. http://recordcenter.sgc.gov.co/B4/13010010024236/mapa/pdf/0101242361300002.pdf

González, H. (2001). *Mapa geológico del departamento de Antioquia. Escala 1:400000*. Ingeominas. https://miig.sgc.gov.co/Paginas/Resultados.aspx?k=130100101040020038000000000

González, H., & Salazar, G. (2002). *Geología de la Plancha 145 Urrao. Escala 1:100 000*. Servicio Geológico Colombiano. http://recordcenter.sgc.gov.co/B4/13010010024480/mapa/pdf/0101244801300004.pdf

González, H., Cossio, U., Maya, M., Vásquez, E., & Holguín, M. (1996). *Mapa geológico del departamento de Antioquia. Escala 1:400 000. Mapa. Versión 1996*. Ingeominas. https://recordcenter.sgc.gov.co/B4/13010040020038/mapa/pdf/0101200381300002.pdf

González, H., Maya, M., Cardona, O. D., Arias, E., N., Castañeda, D. M., Ruiz, C. F., Montero, J. E., Camacho, J. A., Palacio, A. F., Gómez, J. P., Vélez, W., & Álzate, G. A. (2015b). *Mapa geológico de la plancha 94 El Bagre. Escala 1:100 000*. Servicio Geológico Colombiano. http://recordcenter.sgc.gov.co/B18/23008010028502/mapa/pdf/2105285021300007.pdf

González, H., Maya, M., García J., Gómez, J. P., Palacio A. F., Ruiz, C. F., Camacho, J., Montero, J. E., Grimaldo, J., & Álzate, G. A. (2015a). *Mapa geológico de la plancha 84 Los Canelos. Escala 1:100 000*. Servicio Geológico Colombiano. http://recordcenter.sgc.gov.co/B18/23008010028501/mapa/pdf/2105285011300005.pdf

González, H., Maya, M., García, J., Gómez, J. P., Palacio, A. F., Ruiz, C. F., Montero, J. E., Camacho, J., Grimaldo, J., Vélez, W., & Álzate, G. A. (2015c). *Mapa geológico de la plancha 95 Buenavista. Escala 1:100 000*. Servicio Geológico Colombiano. http://recordcenter.sgc.gov.co/B18/23008010028503/mapa/pdf/2105285031300005.pdf

González, H., Maya, M., Tabares, L. F., Montoya, A., Palacio, A. F., Sánchez, C., Barajas, A., & Vélez, W. (2015e). *Elaboración de la cartografía geológica de un conjunto de planchas. Escala 1:100 000, ubicadas en cuatro bloques del territorio nacional, identificados por el Servicio Geológico Colombiano. Plancha 118 San Francisco. Versión 2015*. Servicio Geológico Colombiano. http://recordcenter.sgc.gov.co/B19/23008010028505/mapa/pdf/2105285051300007.pdf

González, H., Maya, M., Tabares, L., Montoya, A., Arias, E. N., Osorio, J. H., Pérez, O., Buriticá, L. F., Vélez, W., & Álzate, G. A. (2015d). *Mapa geológico de la plancha 107 Cerro Azul. Escala 1:100 000*. Servicio Geológico Colombiano. http://recordcenter.sgc.gov.co/B19/23008010028504/mapa/pdf/2105285041300005.pdf

Gotta Ingeniería S. A. S., & Corporación Autónoma Regional del Centro de Antioquia (Corantioquia). (2018). *Formulación del plan de manejo ambiental del Sistema Acuífero del Magdalena Medio Antioqueño*. https://www.corantioquia.gov.co/ciadoc/AGUA/AIRNR_110_CNT1706_46_2017_00FASE%20APRESTAMIENTO.pdf

Hall, R., Álvarez, J., Rico, H., & Vásquez, H. (1970). *Mapa geológico de Colombia. Cuadrángulo H-7 Ituango: plancha 104 Ituango - plancha 115 Toledo. Cuadrángulo H-8 Yarumal: plancha 105 Valdivia - plancha 116 Yarumal. Escala 1:100 000. Producto. Versión 1970 y 1975 estandarizado y digitalizado en 2010*. Servicio Geológico Colombiano. http://recordcenter.sgc.gov.co/B4/13010010024235/mapa/pdf/0101242351300002.pdf

Harlow, J., & Hagedorn, B. (2018). SWB modeling of groundwater recharge on Catalina Island, California, during a Period of Severe Drought. *Water, 11*(1), art. 58. https://doi.org/10.3390/w11010058

Henriksen, H., & Braathen, A. (2006). Effects of fracture lineaments and in-situ rock stresses on groundwater flow in hard rocks: A case study from Sunnfjord, western Norway. *Hydrogeology Journal*, 14, 444-461. https://doi.org/10.1007/s10040-005-0444-7

Hoque, M., Burgess, W. G., & Ahmed, K. M. (2017). Integration of aquifer geology, groundwater flow and arsenic distribution in deltaic aquifers - A unifying concept. *Hydrological Processes, 31*(11), 2095-2109. https://doi.org/10.1002/hyp.11181

Instituto de Hidrología, Meteorología y Estudios Ambientales (Ideam). (2019). *Estudio nacional del agua, 2018*. http://documentacion.ideam.gov.co/openbiblio/bvirtual/023858/ENA_2018.pdf

Instituto Geográfico Agustín Codazzi (IGAC) e Instituto de Investigaciones en Geociencias, Minería y Química (Ingeominas). (2005). *Investigación Integral del Andén Pacífico Colombiano - Cartografía Geología, Geomorfología, Suelos y Amenazas de las planchas 58, 59, 68, 69, 79, 79BIS, 89, 89BIS, 90, 100, 101, 102, 112, 112BIS, 113, 127, 128, 143, 144, 163, 164, 165, 183, 184, 185, 202, 203, 204, 221, 222, 240, 241, 259, 260, 278, 279, 298, 299, 318, 319, 320, 339, 340, 341, 361, 361BIS, 362, 363, 383, 384, 385, 386, 407, 408, 409, 427, 427BIS, 428, 447 y 447BIS. Escala 1:100 000*. Servicio Geológico Colombiano. http://recordcenter.sgc.gov.co/B4/13010010024479/mapa/pdf/0101244791300009.pdf

Kalhor, K., Ghasemizadeh, R., Rajic, L., & Alshawabkeh, A. (2019). Assessment of groundwater quality and remediation in karst aquifers: A review. *Groundwater for Sustainable Development*, *8*, 104-121. https://doi.org/10.1016/j.gsd.2018.10.004

Karro, E., & Lahermo, P. (1999). Occurrence and chemical characteristics of groundwater in Precambrian bedrock in Finland. *Geological Survey of Finland*, 27, 85-96.

Kassem, B. T., Álvarez, A. J., & Arango C. J. (1979). *Mapa geológico del departamento de Antioquia. Escala 1:500 000. Mapa. Versión 1979*. Ingeominas. https://recordcenter.sgc.gov.co/B4/13010040020038/mapa/pdf/0101200381300003.pdf

La Felice, S., Montanari, D., Battaglia, S., Bertini, G., & Gianelli, G. (2014). Fracture permeability and water–rock interaction in a shallow volcanic groundwater reservoir and the concern of its interaction with the deep geothermal reservoir of Mt. Amiata, Italy. *Journal of Volcanology and Geothermal Research*, *284*, 95-105. https://doi.org/10.1016/j.jvolgeores.2014.07.017

Lachassagne, P., Dewandel, B., & Wyns, R. (2021). Review: Hydrogeology of weathered crystalline/hard-rock aquifers—guidelines for the operational survey, and management of their groundwater resources. *Hydrogeology Journal*, 29, 2561-2594. https://doi.org/10.1007/s10040-021-02339-7

Londoño, A. C., & González, H. (2002). *Geología de la plancha 129 Cañasgordas. Escala 1:100 000*. Servicio Geológico Colombiano. http://recordcenter.sgc.gov.co/B4/13010010024480/mapa/pdf/0101244801300002.pdf

Mejía, M., Álvarez, E., González, H., & Grosse, E. (1983). *Geología de la plancha 130. Santa Fe de Antioquia. Escala 1:100 000*. Servicio Geológico Colombiano. http://recordcenter.sgc.gov.co/B4/13010010001950/mapa/pdf/0101019501300002.pdf

Mejía, M., Álvarez, E., González, H., & Grosse, E. (1983). Geología de la plancha 146. Medellín occidental. Escala 1:100 000. Servicio Geológico Colombiano. Bogotá. https://recordcenter.sgc.gov.co/B4/13010010001950/mapa/pdf/0101019501300006.pdf

Mejía, O. (2006). *Algunos elementos sobre el recurso hídrico en la jurisdicción de Corantioquia*. Corantioquia. https://www.corantioquia.gov.co/ciadoc/AGUA/AIRNR_AGUA_473CD_2005_V1.pdf

Mussa, K. R., Mjemah, I. C., & Machunda, R. L. (2020). Open-source software application for hydrogeological delineation of potential groundwater recharge zones in the Singida semi-arid, fractured aquifer, Central Tanzania. *Hydrology*, *7*(2), art. 28. https://doi.org/10.3390/hydrology7020028

Nikić, Z., Pušić, M., Papić, P., & Marić, N. (2020). Hydrodynamic model of hydrogeologic fracture system in Gruda ultramafic rocks, western Serbia. *Journal of Hydrology*, *580*, 124268. https://doi.org/10.1016/j.jhydrol.2019.124268

Norton, D., & Knapp, K. (1997). Transport phenomena in hydrothermal systems: The nature of porosity. *American Journal of Science, 277*(8), 913-936. https://doi.org/10.2475/ajs.277.8.913

Ossa, J., Campillo, A. K., Omar, C., & Betancur, T. (2021). Representación espacial de zonas de recarga del agua subterránea a partir de mapas isotópicos de precipitación. Caso de estudio: Valle de Aburrá, Colombia. *Boletín Geológico y Minero de España, 132*(1-2), 65-75. https://doi.org/10.21701/bolgeomin.132.1-2.007

Patiño-Rojas, S. M., Jaramillo, M., Espinosa-Espinosa, C. A., & Arias-López, M. F. (2021). Preferential groundwater flow directions in a pseudokarst system in Colombia, South America. *Journal of South American Earth Sciences*, *112*, Part. 1. https://doi.org/10.1016/j.jsames.2021.103572

Poveda, G. (2007). El clima de Antioquia. In M. Hermelin (ed.) *Geografía de Antioquia*: *Geografía histórica, física, humana y económica*. Universidad EAFIT. https://repository.eafit.edu.co/handle/10784/17431?show=full

Poveda, G., Álvarez, D. M., & Rueda, O. A. (2010). Hydro-climatic variability over the Andes of Colombia associated with ENSO: A review of climatic processes and their impact on one of the Earth's most important biodiversity hotspots. *Climate Dynamics,* 36, 2233-2249. https://doi.org/10.1007/s00382-010-0931-y

Qian, X., Wang, Y., Zhang, Y., Senebouttalath, V., Zhang, A., & He, H. (2019). Petrogenesis of Permian–Triassic felsic igneous rocks along the Truong Son zone in northern Laos and their Paleotethyan assembly. *Lithos, 328-329*, 101-114. https://doi.org/10.1016/j.lithos.2019.01.006

Ren, X. W., & Santamarina, J. C. (2018). The hydraulic conductivity of sediments: A pore size perspective. *Engineering Geology*, *233*, 48-54. https://doi.org/10.1016/j.enggeo.2017.11.022

Restrepo, J. J., & Toussaint, J. F. (2020). Tectonostratigraphic terranes in Colombia: An update. First part: Continental terranes. In J. Gómez, & D. Mateus-Zabala (eds.), *The geology of Colombia*. *Volume 1. Proterozoic – Paleozoic* (pp. 37-63). Servicio Geológico Colombiano. https://doi.org/10.32685/pub.esp.35.2019.03

Rodríguez, E. E., & Ulloa, C. Rodríguez, G., Zapata, G., Gómez, J. F. (2013). E. (1994). *Geología de la plancha 169 Puerto Boyacá. Escala 1:100 000*. Servicio Geológico Colombiano. http://recordcenter.sgc.gov.co/B4/13010010012149/mapa/pdf/0101121491300002.pdf

Rodríguez, G., Sierra, M. I., Zapata, G., Correa, T., Peláez, J., & Nivia, Á. (2010). *Geología de las planchas 58 Sapzurro (Capurganá), 68 Acandí y 79 Bis Unguía (Cerro Tagarí). Escala 1:100 000*. Servicio Geológico Colombiano. http://recordcenter.sgc.gov.co/B12/23008010024303/mapa/pdf/2105243031300025.pdf

Rodríguez, G., Zapata, G., & Gómez, J. F. (2013). *Geología de la plancha 114 Dabeiba. Escala 1:100 000*. Servicio Geológico Colombiano. http://recordcenter.sgc.gov.co/B14/23008010024725/mapa/pdf/2105247251300001.pdf

Rodríguez, G., Zapata, G., González, H., & Cossio, U. (2005). *Geología de la plancha 147, Medellín Oriental.*

Departamento de Antioquia. Escala 1:100 000. Servicio Geológico Colombiano. http://recordcenter.sgc.gov.co/B12/23008010002745/mapa/pdf/2105027451300002.pdf

Rukavičková, L., Holeček, J., Holečková, P., Najser, J., Gvoždík, L., & Pačes, T. (2021). Comparison of hydraulic conductivity of rock matrix and fractured blocks of granitic rocks. *International Journal of Rock Mechanics and Mining Sciences*, *144*, 104743. https://doi.org/10.1016/j.ijrmms.2021.104743

Scesi, L., & Gattinoni, P. (2007). Roughness control on hydraulic conductivity in fractured rocks. *Hydrogeology Journal, 15*(2), 201-211. https://doi.org/10.1007/s10040-006-0076-6

SHI S. A. S., & Corporación Autónoma Regional del Centro de Antioquia (Corantioquia). (2015). *Diagnóstico para la formulación del plan de manejo ambiental del Sistema Acuífero del Occidente Antioqueño en la Territorial Hevéxicos de Corantioquia - Contrato 14-09-241*. https://www.corantioquia.gov.co/ciadoc/AGUA/AIRNR_CN_1608_77_2016_PMAA_OCCIDENTE_APRESTAMIENTO.pdf

SHI S. A. S., & Corporación Autónoma Regional del Centro de Antioquia (Corantioquia). (2014). *Evaluación hidrogeológica en los municipios de La Pintada y Valparaíso jurisdicción de la Dirección Territorial Cartama de Corantioquia*. https://www.corantioquia.gov.co/ciadoc/AGUA/GA_CN_9909_2013.pdf

Srinivasa Rao, Y., Reddy, T. V. K., & Nayudu, P. T. (2000). Groundwater targeting in a hard-rock terrain using fracture-pattern modeling, Niva River basin, Andra Pradesh, India. *Hydrogeology Journal, 8*, 494-502. https://doi.org/10.1007/s100400000090

Universidad de Antioquia, & Área Metropolitana del Valle de Aburrá (AMVA). *Plan de manejo ambiental de acuíferos del Valle de Aburrá*. https://www.metropol.gov.co/ambiental/recurso-hidrico/Paginas/PMAA.aspx

Universidad de Antioquia, & Corporación para el Desarrollo Sostenible del Urabá (Corpourabá). (2016). *Plan de manejo ambiental de acuífero Sistema Hidrogeológico Golfo de Urabá*. http://repositorio.corpouraba.gov.co:8082/xmlui/handle/123456789/87

Universidad de Antioquia, & Corporación para el Desarrollo Sostenible del Urabá (Corpourabá). (2014). *Convenio Interadministrativo de Cooperación 136 de 2013 Universidad de Antioquia-Corporación para el Desarrollo Sostenible del Urabá*.

Universidad de Antioquia, & Integral. (2002). *Estudio de zonas de recarga y acuíferos del Valle de Aburrá*. https://www.corantioquia.gov.co/ciadoc/agua/airnr_cn_2420_2000.pdf

Vargas, O., Campillo, A., García, M., & Rodríguez, O. (2013). *Las aguas subterráneas en Colombia, una visión integral*. Instituto de Hidrología, Meteorología y Estudios Ambientales (Ideam).

Verma, O., Khosla, A., Goin, F. J., & Kaur J. (2016). Historical biogeography of the Late Cretaceous vertebrates of India: Comparison of geophysical and paleontological data. *New Mexico Museum of Natural History and Science Bulletin, 71*, 317-330.

Zapata, G., & Cossio, U. (2001). *Mapa fotogeológico con control de campo de la plancha 93 Cáceres. Escala 1:100 000*. Servicio Geológico Colombiano. Bogotá. http://recordcenter.sgc.gov.co/B4/13010010002309/mapa/pdf/0101023091300002.pdf

Zapata, G., Bermúdez, J. G., Rodríguez, G., & Arango, M.I. (2013). *Cartografía geológica de la plancha 83 Nechí - Departamento de Antioquia. Escala 1:100 000*. Servicio Geológico Colombiano. http://recordcenter.sgc.gov.co/B14/23008010024595/mapa/pdf/2105245951300001.pdf