Artículos

Hydrogeological potential in soft formations and hard rocks: A case study in the Cauca River Canyon, Antioquia, Colombia

Potencial hidrogeológico en formaciones blandas y rocas duras: Un estudio de caso en el cañón del río Cauca, Antioquia, Colombia

Palacio, Paola Andrea; Díaz, Rodrigo Alonso; Vela, María Alejandra; Ossa, Juliana

Paola Andrea Palacio
Universidad de Antioquia, Colombia
Rodrigo Alonso Díaz
Universidad de Antioquia, Colombia
María Alejandra Vela
Universidad de Antioquia, Colombia
Juliana Ossa
Universidad de Antioquia, Colombia

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Abstract: From the end of 2020 until July 2021, the first phase of a study that evaluated the hydrogeological potential in tropical dry forest (TDF) areas took place in the bosque seco tropical (BS-T), which was associated with the Cauca River Canyon in the jurisdiction of Corantioquia. Based on the litho-structural evaluation of the area, hypotheses were established by which conditions of greater or lesser aquifer potential were assigned according to the different types of geological materials present. The first step to confirm these hypotheses was an inventory of groundwater points. The results indicated the existence of more than 1172 points, including springs, hand-dug wells, galleries and wells.
Relating the occurrence of these water points with the lithological units, approximately 560 points in Quaternary deposits and rocks of the Amagá Formation and the Urrao Member of the Penderisco Formation were found; 146 were located in volcano-sedimentary deposits of the Combia Formation, and more than 466 were associated with hard rocks. It is thus concluded that in the study area, the igneous and metamorphic rocks, intensely affected by tectonic effects, have gained permeability conditions, which was evidenced by field observations, which confer aquifer conditions. This finding provides new research perspectives toward fractured environments and presents groundwater as a main and alternative source to meet the needs of the population, in addition to playing a fundamental role in terms of the ecosystem sustainability of the tropical dry forest.

Keywords: hydrogeology in Antioquia, groundwater, inventory of groundwater points, hydrogeological potential, tropical dry forest.

Resumen: Desde finales del año 2020 hasta julio de 2021 tuvo lugar la primera fase de un estudio que evaluó el potencial hidrogeológico en zonas de bosque seco tropical -Bs-T- asociadas al cañón del río Cauca en jurisdicción de Corantioquia. Con base en la evaluación lito-estructural de la zona, se establecieron hipótesis mediante las cuales se asignaron condiciones de mayor o menor potencial acuífero, según los distintos tipos de materiales geológicos presentes. El primer paso para confrontar estas hipótesis con la realidad fue el inventario de puntos de agua subterránea; los resultados, al año 2021, señalan la existencia de más de 1172 puntos, entre ellos: manantiales, aljibes, galerías y pozos.

Relacionando la ocurrencia de estos puntos de agua con las unidades litológicas, se encontraron cerca de 560 puntos en depósitos del Cuaternario, y en rocas de la Formación Amagá y el Miembro Urrao de la Formación Penderisco; 146 se ubican en depósitos vulcano-sedimentarios de la Formación Combia y más de 466 se asocian con rocas duras. Se concluye así, que en la zona de estudio las rocas ígneas y metamórficas, intensamente afectadas por efectos tectónicos, han ganado condiciones de permeabilidad, la cual fue evidenciada mediante observaciones en campo, que les confieren la condición de acuíferos. Este hallazgo brinda nuevas perspectivas de investigación hacia medios fracturados y presenta el agua subterránea como una fuente principal y alternativa para satisfacer las necesidades de la población, además de cobrar un rol fundamental en términos de la sostenibilidad ecosistémica del bosque seco tropical.

Palabras clave: hidrogeología en Antioquia, aguas subterráneas, inventario de puntos de agua subterránea, potencial hidrogeológico, bosque seco tropical.

1. Introduction

Based on the porosity and permeability conditions of the geological units present in the study area, the following categories were classified: aquifer, aquitard or aquifuge, and they were assigned a hydrogeological potential: very high, high, medium, low or null. The areas obtained for each category were subsequently refined from the results of the inventory of water points, with which the information that fed all the elements of the conceptual hydrogeological model was gathered, laying the foundations that allowed the involvement of communities in the construction of knowledge and preparation for the subsequent definition and application of management measures.

In the regions associated with the Cauca River Canyon, in the department of Antioquia, groundwater has an important role as a main or secondary source of supply in the demands of consumption, economic and recreational activities, and their satisfaction. With the objective of deepening their knowledge and having the tools to protect the tropical dry forest ecosystem in the jurisdiction of Corantioquia, at the end of 2020, an exploration was launched into the hydrogeological potential of geological formations located in the area of direct and indirect influence of the tropical dry forest (bosque seco tropical or BS-T) associated with the Cauca River Canyon.

During the first months of development of the project, the collection of available secondary information was carried out, which could serve the initial purposes of groundwater exploration. The starting point was the recognition and determination of the area of influence, followed by the development of a sociodemographic evaluation that would allow the first approach to the fieldwork.

The geological conditions, determined both by the type of rocks and by the tecto-structural affectation on them, provided guidelines to identify and characterize the different types of hydrogeological units. For this, an assembly of the geological cartography at a scale of 1:100 000 and 1:400 000 of the Servicio Geológico Colombiano (SGC) was verified in the field.

Based on the porosity and permeability conditions of the geological units present in the study area, the following categories were classified: aquifer, aquitard or aquifuge, and they were assigned a hydrogeological

potential: very high, high, medium, low or null. The areas obtained for each category were subsequently refined from the results of the inventory of water points, with which the information that fed all the elements of the conceptual hydrogeological model was gathered, laying the foundations that allowed the involvement of communities in the construction of knowledge and preparation for the subsequent definition and application of management measures.

2. Reference framework

The study area was delimited, considering the hydrographic subzones of the Cauca River basin which is a part of the BS-T ecosystem under the jurisdiction of the Regional Autonomous Corporation of the Center of Antioquia (Corantioquia). It has an area of approximately 10 662 km2 and runs through the municipalities associated with the Cauca River basin from Caramanta to Valdivia, with elevations ranging between 171 and 3609 meters above sea level (masl).

This ecosystem corresponds to a forest biome that develops at low altitudes from 0 to 1000 masl in intertropical areas with temperatures above 24 °C and annual rainfall between 700 and 2000 mm (IAVH, 1998). It is characterized by climate variability of one or two periods of very marked drought per year (rainfall less than 100 mm) of at least 5 to 6 months (Bullock et al., cited in Pizano and García, 2014). In the BS-T, the evapotranspiration process consumes most of the water, so the recharge and rate of change in the phreatic levels play an important role in the sustainability of vegetation because it becomes the only alternative to be used by plants in the processes of nutrient absorption and transpiration (Le Maitre et al., 1999).

In Colombia, this biome exists in at least six biogeographic regions: the Patía River Valley, the southern Cauca Valley, the Cauca River Valley, the upper and middle Magdalena River Valley, the departments of Santander and Norte de Santander and in the region of the Caribbean coast and Orinoquía (Figure 1). In the study of the tropical dry forest (TDF) ecosystem conducted by the Alexander von Humboldt Institute for Biological Resources Research (Pizano and García, 2014) and based on studies available since 1997 (IAVH, 1998; IAVH; 1997;Cabrera and Galindo, 2006), a loss close to 92% of the 9 million hectares covered by this ecosystem is evidenced in the map presented by Etter et al. (2008). In addition, it is mentioned that those territories that have been deforested and were BS-Ts currently present desertification scenarios; consequently, they are no longer productive for the development of agriculture or livestock, that is, they are unsustainable (Benítez et al., 2014). The state of this ecosystem in Colombia urgently needs measures to conserve the remnants that survive.

The Cauca River Basin is one of the most populated regions in Antioquia. Anthropic pressure on the territory has affected the natural balance of the ecosystem to the point that there is a scarcity of water for humans and other life forms in the region, including the BS-T, characteristic of the low-lying areas in the vicinity of the Cauca River Canyon. Thus, a project was proposed to deepen knowledge of the hydrogeological systems in the region, the opportunities offered by groundwater as the main or secondary sources of water and its relationship and impact on the sustainability of the BS-T ecosystem.

In the Earth's crust, the nature of various geological units allows some features to conserve intergranular porosity or primary porosity, while others do not. However, porosity can be acquired thanks to subsequent events, such as dynamic effects or by the action of weathering, which results in secondary porosity.

Considering that a hydrogeological unit is a geological formation, part of it has similar hydraulic characteristics, which are related to the capacity to store water (porosity) and the possibility of flow between the pores (permeability or coefficient of hydraulic conductivity). Hydrogeological units are classified as aquifers, aquitards, aquicludes or aquifuges. An aquifer can store and transmit enough water in acceptable quantity conditions, and its extraction can be economically viable; an aquitard stores and transmits water very slowly, so its exploitation demands more energy than the previous one; an aquiclude stores but does not allow the transit of water between the pores;

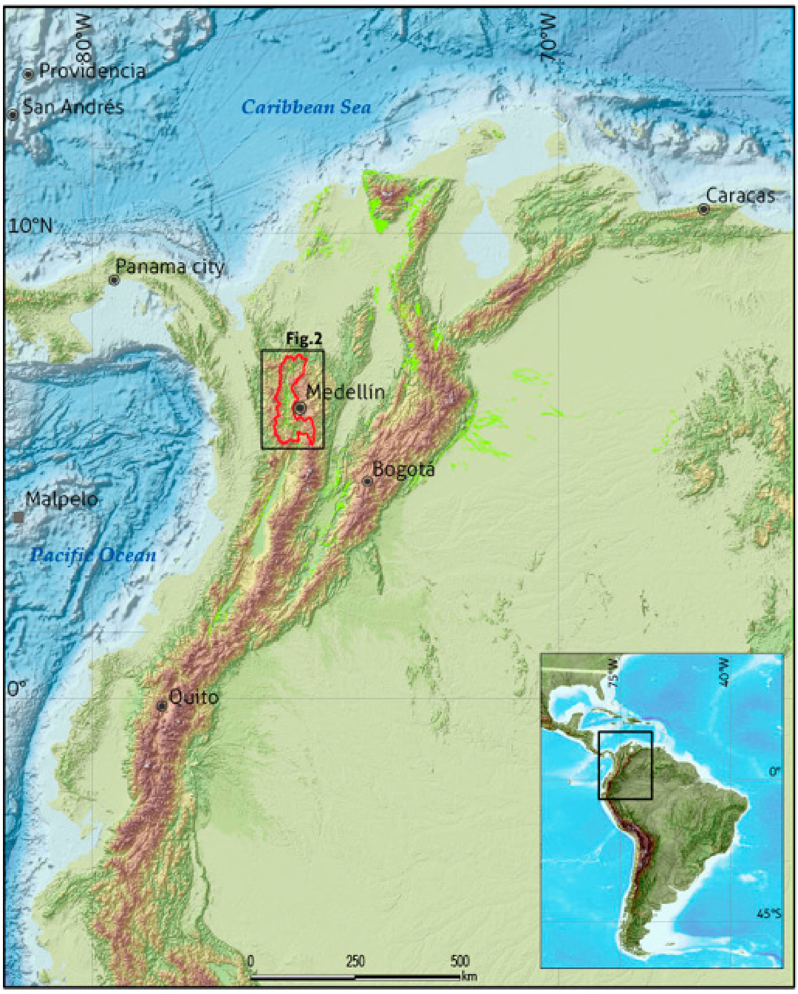

FIGURE 1.
Distribution of the tropical dry forest in Colombia at a scale of 1:100 000
See legend in this kmz file (see in Google Earth). Source: Modified from Instituto de Investigación de Recursos Biológicos Alexander von Humboldt (2014).

and finally, an aquifuge does not store or let groundwater flow (Custodio and Llamas, 1996).

Those materials that make up units with hydrogeological potential, in order of importance, are the following: unconsolidated deposits of gravel and sand, karst formations, conglomerate sedimentary rocks or sandstone with low amounts of finer material, volcanic rock, and other rocks according to origin and evolution. Igneous rocks that have acquired secondary porosity and permeability, especially when their thicknesses are considerable in the case of deposits and sedimentary rocks. In contrast, they are not aquifers: clay and silt deposits, siltstone or claystone sedimentary rocks and igneous or metamorphic rocks without alteration.

Before 2021, several studies were conducted to understand hydrogeological systems in different regions of Antioquia, mostly focusing on hydrogeological units associated with sedimentary rocks and recent deposits. Two of these hydrogeological systems are located within the study area: the first is in the western subregion, with an extension of 103 km2, which includes the municipalities of Santa Fe de Antioquia, San Jerónimo, Sopetrán and Olaya; the second system integrates the municipalities of La Pintada and Valparaíso associated with the Cauca River with an area of 184 km2.

Table 1 shows the studies that were consulted, and Figure 2 shows the location of the hydrogeological systems that present progress in their knowledge.

The study area included approximately 40 geological units with formation ages between the Proterozoic and Cenozoic eras, including 7 metamorphic units, 24 igneous types and 9 sedimentary types.

Figure 3 shows the geological map of the area studied, which corresponds to an adaptation by Betancur Vargas (2021), modified from González (2001), and geological maps at scale 1:100 000 and 1:400 000 (Servicio Geológico Colombiano).

In any hydrogeological exploration project, one of the first activities developed is the inventory of groundwater points. Where a water point is a natural place, civil works allow direct or indirect access to the aquifer. In this sense, the previous definition includes all existing boreholes, whether or not exploited, abandoned or even destroyed, and the sources or springs that in principle should be considered natural spillways of the aquifers (Custodio and Llamas, 1996). The following were the objectives of this study: springs, filtering galleries, hand-dug wells, wells and piezometers.

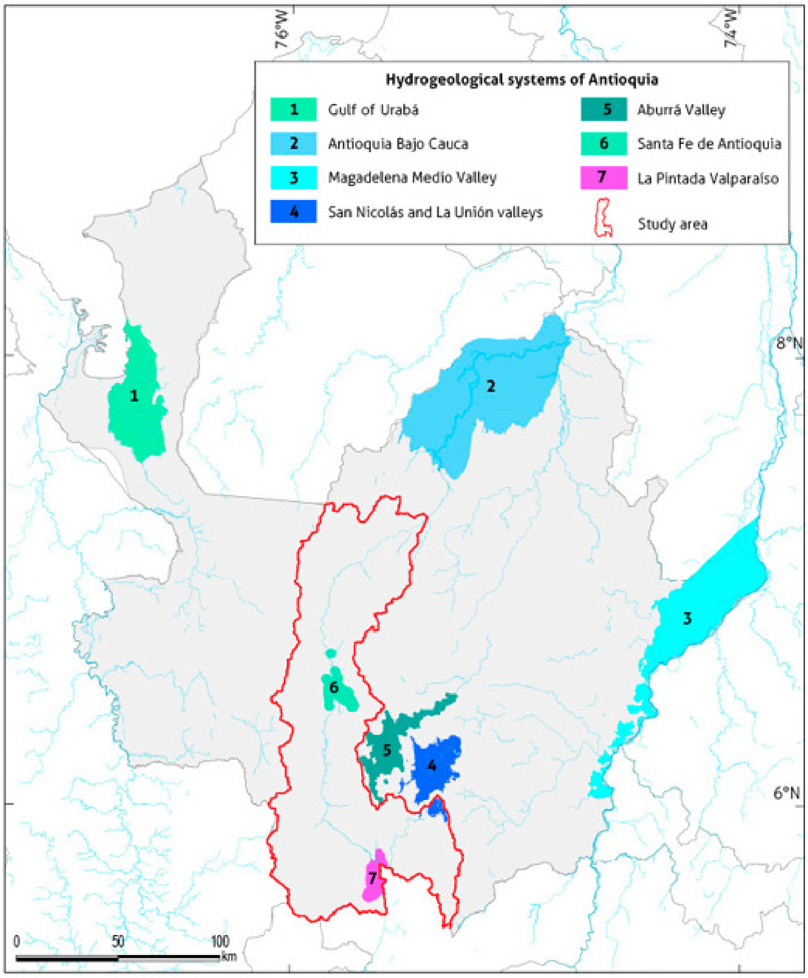

FIGURE 2.
Location of the hydrogeological systems of Antioquia that present progress in their knowledge
See legend in this kmz file (see in Google Earth). Source: Modified from the Public Companies Foundation of Medellín, Government of Antioquia (2018).

TABLE 1.
Hydrogeological studies consulted as secondary information

Aquifer System	Studies consulted	Author
Gulf of Urabá	Plan de manejo ambiental de acuífero sistema hidrogeológico Golfo de Urabá	Universidad de Antioquia and Corpouraba (2016)
	Análisis de calidad y cantidad	Corpourabá (2016)
Magadelena Medio Valley	Estudio regional del agua	Corantioquia and GOTTA Ingeniería (2016)
	Formulación del plan de manejo ambiental del acuífero del Magdalena Medio	Corantioquia and GOTTA Ingeniería (2017)
Aburrá Valley	Plan de manejo ambiental del sistema acuífero de la cuenca del río Aburrá	AMVA and Universidad de Antioquia (2018)
	RedRío, componente aguas subterráneas. Convenio 1050	AMVA and Universidad de Antioquia (2018)
Santa Fe de Antioquia	Estudio regional del agua	Corantioquia and SHI (2016)
	Formulación del plan de manejo ambiental del sistema acuífero del Occidente Antioqueño	Corantioquia and GOTTA Ingeniería (2017)
Antioquia Bajo Cauca	Plan de manejo ambiental del sistema de acuífero del Bajo Cauca antioqueño	Corantioquia and Universidad de Antioquia (2014)
	Estudio regional del agua	Corantioquia and GOTTA Ingeniería (2016)
San Nicolás and La Unión valleys	Investigación de aguas subterráneas región valles de San Nicolás. FASE II	Corantioquia and Universidad Nacional de Colombia (2001)
	POMCA Río Negro	POMCAS Oriente Antioqueño Consortium (2017)
	ICA Aguas subterráneas	Cornare (2016)
La Pintada - Valparaíso	Evaluación hidrogeológica en los municipios de La Pintada y Valparaíso Jurisdicción de la Dirección Territorial Cartama de Corantioquia	Corantioquia and SHI (2014)
	Estudio regional del agua	Corantioquia and Gotta Ingeniería (2016)

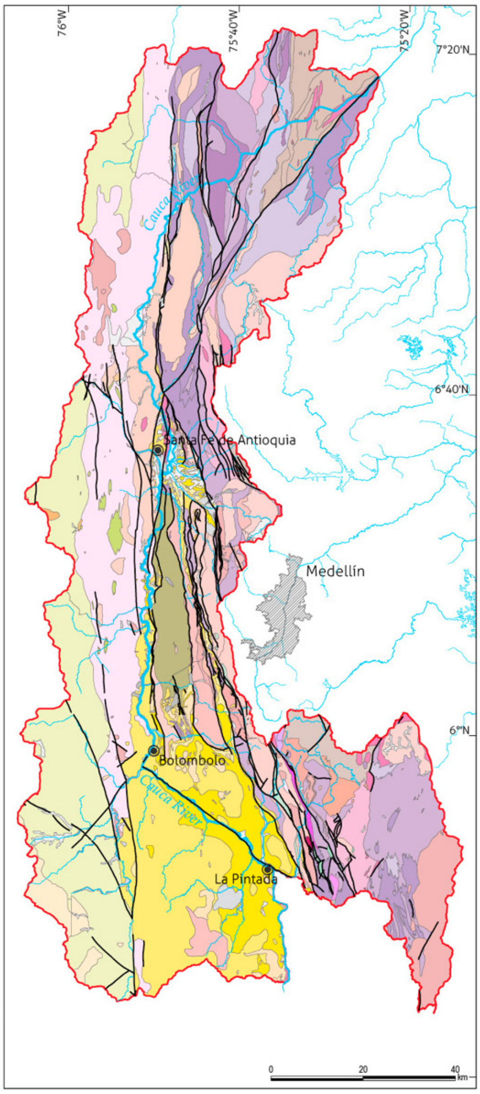

FIGURE 3.
Geological map of the study area
See legend in this kmz file (see in Google Earth). Source: Betancur (2021), modified from González (2001)

3. Methods

In Colombia, the information collected in the inventory of water points is recorded following the parameters defined by the National Single Form of Groundwater (FUNIAS), proposed by the Institute of Hydrology, Meteorology and Environmental Studies (Ideam). This document contains a series of sections of various types, such as administrative location (municipality, village, neighborhood), technical (nature of the work, mode of drilling, diameter, materials, depth, etc.), hydrological (piezometric levels at different times, chemical quality), and uses. This activity can be carried out directly by touring the study area or indirectly by going to people or public and private entities that by their work can indicate the existence of water points and provide the information required for the inventory.

In the first instance, a review of secondary information was carried out to locate previously identified water points, such as records of groundwater concessions by the Environmental Corporation, information from existing FUNIAS, and the Water Resource Information System (Sistema de Información del Recurso Hídrico), Environmental Impact Studies (EIA), Aquifer Environmental Management Plans (PMAA), Watershed Management Plans (POMCA), Water Resources Management Plans (PORH), and a review of the databases provided by the corporation.

The collection and collection of primary information was carried out through field trips by professionals in hydrogeology, supported by a social, communication and relationship component, which was aimed at identifying the key actors, direct users and users of indirect resources of the underground water resource, as well as the organizations or entities that are part of the exercise of socialization and appropriation of the knowledge generated by the project in the territory.

For both primary and secondary information, the coding of the inventory of water points defined by Ideam was implemented, according to the FUNIAS; this structure allows, in a methodical way, the assignment of a unique code to each water point. This represents the possibility of ordering and unifying the registration information of the points from different sources, allowing a database with a common language between entities, which became a management tool for authorities and environmental entities in the administration. of water resources.

Figure 4 shows the methodological scheme that was used for the inventory of groundwater points.

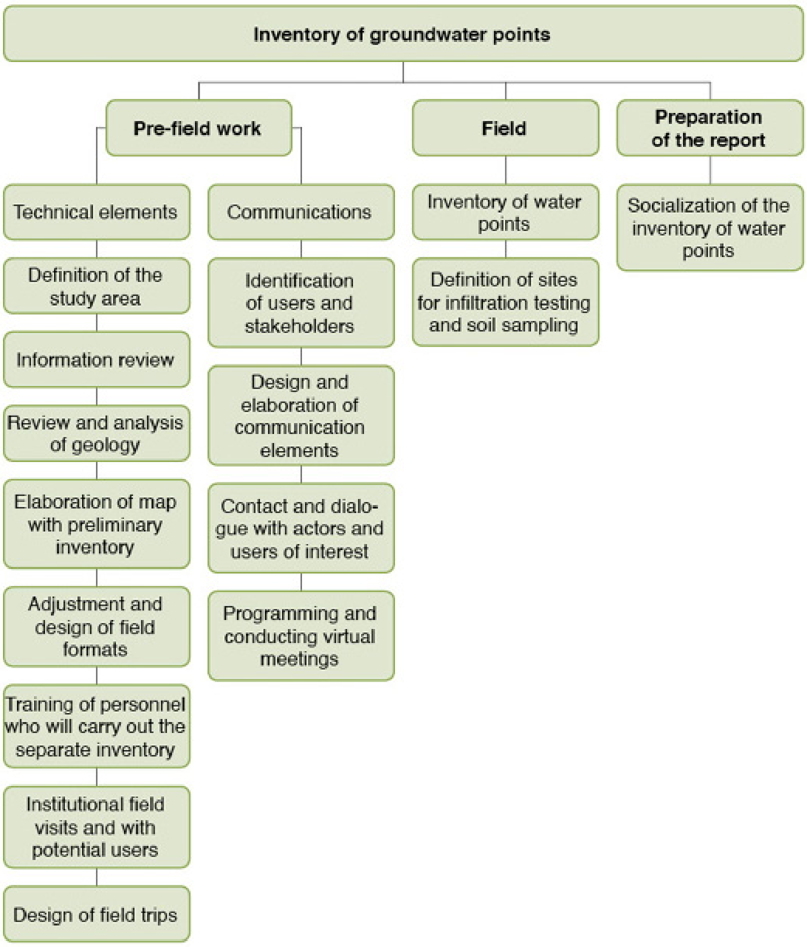

FIGURE 4.
Methodological scheme of the groundwater inventory

For the characterization of the hydrogeological units, a geological-structural evaluation was carried out that focused on determining the relevant porosity and permeability conditions that promoted the storage and flow of groundwater. The deposits and clastic sedimentary rocks, given their primary porosity, were evaluated and verified in the field as potential aquifers. Likewise, the condition of the hydrogeological unit was determined for the hard rocks that have been or have not been affected structurally or by weathering with the help of professionals with experience in hydrogeology.

The fault systems with direct interference in the study area are the San Jerónimo System, the Espiritu Santo Fault and the Romeral System. The large fractures have, in general, a clear morphological expression and present fractured, sheared rocks with alteration and brecciation, while the smaller ones present only some of these characteristics and are preferentially marked by visible alignments in the aerial photographs.

Prior to the inventory and applying the Analytic Hierarchy Process (AHP) methodology based on the work of Saaty (2008), ten professionals in geology and hydrogeology, knowledgeable in the area of study, were consulted about the

TABLE 2.
Rating scale of hydrogeological conditions based on porosity and permeability

Unit type	Qualification of hydrogeological potential
Aquifer	Very high
	High
	Medium
Aquitard	Low
Aquifuge	Null

hydrogeological potential of the geological units in question (see annex 2). For this exercise, different levels of importance were considered, according to the porosity and permeability characteristics of each unit and the categories: aquifer, aquitard or aquifuge. This was done to assign hydrogeological potential based on the qualitative weighting matrix of Table 2. Analytical and hierarchical processes, such as Saaty, with a sufficiently large survey size and expert and independent evaluators, allow assigning weights and guarantee a reasonable reduction of the so-called "decision bias" (Universidad de Antioquia and Corpourabá, 2016).

According to the responses obtained, the initial mapping of hydrogeological potential was proposed (Figure 5, upper left: a), which was key for the planning of the field work, aimed at the development of the inventory of water points, one of the most suitable tools for the construction of preliminary knowledge of the hydrogeological conditions of the area. As a result of the matrix, the areas of potential were identified; then, the geology in the field and superposition of the inventoried water points corroborated or corrected the different lithological units of the study area.

4. Results

In the first stage of the project, 1172 water points were identified, distributed in 751 springs, 394 hand-dug wells, 13 piezometers, 12 wells and 2 filter galleries. The initial approach to the hydrogeological potential was corroborated by field reconnaissance work and the superposition of the inventoried water points, making it possible to confirm or redefine the hydrogeological character of the lithological units, which allowed us to complete the categorization exercise of the units from their benefits or limitations and as storage and facilitators of groundwater flow.

The results of the process of evaluating the hydrogeological potential of sites and subsequent additions to the inventory can

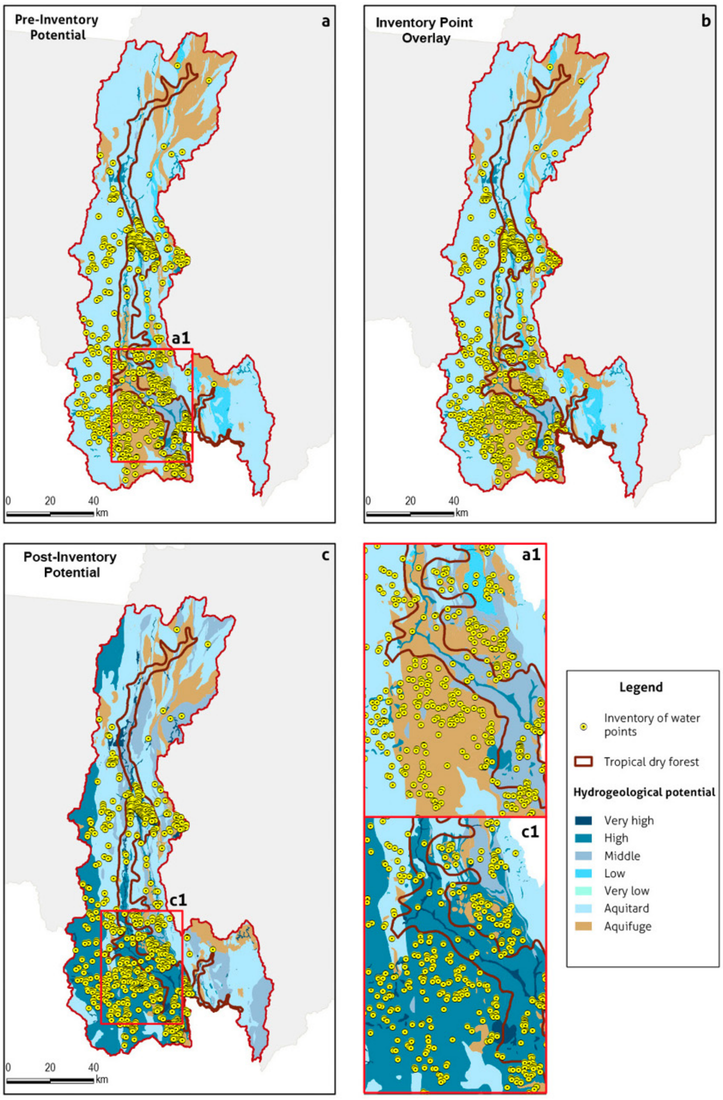

FIGURE 5.

Representation of the superposition of water points and hydrogeological potential adjustment

See legend in this kmz file (see in Google Earth). Source: Adapted from Corantioquia and Universidad de Antioquia (2021).

be visualized in Figure 5.Table 3 shows the results for some of the geological units of interest, according to the type of rock. In Table S1, detailed information regarding the total number of points inventoried is shown.

According to the results of synthesis and geological verification in the field, in the area of direct and indirect influence of the BS-T associated with the Cauca River in Corantioquia, 33% of deposits and sedimentary rocks are soft geological formations and 67% are hard rocks (igneous and metamorphic). Ninety-six percent of the soft rocks have a high or very high hydrogeological potential, and in the case of igneous and metamorphic rocks, which are mostly structurally affected, 24% have a medium hydrogeological potential, and 1.5% have a high hydrogeological potential. This distribution can be visualized in Figure 6.

As a result of this exercise, it was found that the quaternary deposits are the geological units with the highest concentration of water points, with the alluvial deposits and terraces having the greatest amount, a total of 358. The Amagá Formation, Upper Member, Combia Formation and Urrao Member of the Pendersco Formation are geological units that follow in importance, taking into account the number of water points associated with them. In the first unit, 109 water points were recorded, 146 points were identified in the Combia Formation, and 93 were found in the Urrao Member.

The aquifer potential is also evidenced in units such as the quartz-meritic schists of the Cajamarca Complex (62 water points inventoried); the Sabanalarga Batholith (13 points); Buriticá Andesite (21 points); Sheep Tonalite (17 points) and Pueblito Diorite (10 points).

TABLE 3.
Evaluation of the hydrogeological potential in geological units of interest

Type	Unity	Subunit	Structures	Porosity	Preliminary potential to the inventory	Inventory points	Post-inventory potential
Metamorphic rocks	Intrusive Neysics Synthectonics (Pzin)	Intrusive neis of Abejorral	Dynamic effects of variable intensity, marked by fracturing.	Secondary	Low	4	Medium
Plutonic igneous rocks	Stock of Amagá		It is a solid rock, granular to porphyritic, with medium to coarse grain. The texture is granular hypidiomorphic.	NA	Very Low	25	Low
	Combia training	Combia Formation - Volcanic Member	The fine pyroclastic levels of ash tuffs occupy topographically elevated areas. They present jointing.	Primary and secondary	Low	241	High
Sedimentary rocks		Combia Formation - Sedimentary Member	The sedimentary layers are jointed with a horizontal, vertical or inclined attitude.	Primary	High		High
Deposits	Quaternary deposits	Alluvial deposits		Primary	High	363	Very high

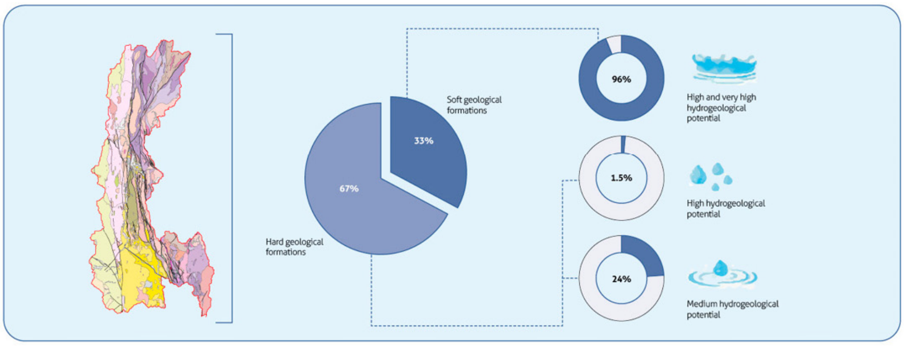

FIGURE 6.
Synthesis of the hydrogeological potential in the study area

5. Discussion

Of the 1172 groundwater points, 947 were identified in the collection of secondary information; although they represent a vast volume in the study area, it is necessary to complete missing data, such as water uses, volumes captured, properties; hydraulics, and subsoil records, with the objective that the information is useful to the inventory. The data obtained in the field work supplemented the primary information of the water point registry, added to the collection of secondary information and promoted dialog with the experts, providing the basis for an approximation to the hydrogeological potential of the study area.

From what was found in the field work, it was possible to corroborate the importance of deepening the study of groundwater and hydrogeological systems in the subregions that made up the study area, considering each area's sociodemographic, economic and ecosystem characteristics, which affect the dynamics of the BS-T.

6. Conclusions

The inventory of water points is a fundamental tool in the classification and redefinition of hydrogeological units; from it, primary information is obtained that allows feeding most of the components of the conceptual hydrogeological model. The fieldwork of the inventory corroborates the importance of building knowledge from the implementation of participation, education and communication strategies that are supported in the dialog of knowledge and in the construction of citizen science.

The 1172 water points documented in the BS-T associated with the Cauca River Basin in Antioquia confirms the hydrogeological potential that exists in the region.

In Antioquia, the hydrogeological potential of igneous and metamorphic rocks that have acquired porosity and secondary permeability after being subjected to intense tectonic effects over time is significant, because 24% have a medium hydrogeological potential and 1.5% a high potential. In terms of groundwater availability, this is relevant data, since hard geological formations occupy a 67% study area.

This information serves as a reference point to deepen the knowledge of fractured environments and highlights the possibility of having alternative and complementary sources of water to satisfy human needs. In addition, it plays a fundamental role in terms of the sustainability of the tropical dry forest ecosystem.

7. Acknowledgments

We thank Corantioquia for financing exploration of the hydrogeological potential in the Cauca River Canyon in its the jurisdiction, making it was possible to carry out this research.

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We also appreciate those people who opened their doors to allow us to collect data about their use of groundwater and shared their perceptions and knowledge with us.

8. Supplementary data

Supplementary data for this article can be found online at https://doi.org/10.32685/0120-1425/bol.geol.49.1.2022.620

Available data

Table S1. Synthesis of information from the inventory of 1172 groundwater points in the study area

Data in kmz files

Figure 1. Distribution of the tropical dry forest in Colombia at a scale of 1:100 000

Figure 2. Location of the hydrogeological systems of Antioquia that present progress in their knowledge

Figure 3. Geological map of the study area

Figure 5. Representation of the superposition of water points and hydrogeological potential adjustment

References

AMVA & Universidad de Antioquia. (2018). Plan de Manejo Ambiental del Sistema Acuífero de la Cuenca del Río Aburrá.

AMVA & Universidad de Antioquia. (2018). Red Río, componente aguas subterráneas Convenio 1050.

Betancur-Vargas, T. (2021). Potencial & perspectivas de exploración hidrogeológica en Antioquia según criterios litoestructurales [Memory]. XVIII Congreso Colombiano de Geología, 2021. https://sociedadcolombianadegeologia.org/potencial-y-perspectivas-de-exploracion-hidrogeologica-en-antioquia-segun-criterios-litoestructurales/

Betancur-Vargas, T., Martínez-Uribe, C., García-Aristizábal, E. F., & Escobar-Martínez, J. F. (2017). Identification and characterization of regional water flows contributing to the recharge of an unconfined aquifer. Revista Facultad de Ingeniería, (85), 70-85. https://doi.org/10.17533/udea.redin.n85a07

Bullock, S. H., Mooney, H. A., & Medina, E. (eds). (1995). Seasonally Dry Tropical Forests. Cambridge University Press. https://doi.org/10.1017/CBO9780511753398

Cabrera-Montenegro, E., & Galindo-García, G. A. (2006). Aproximación metodológica para la delimitación de los ecosistemas de enclaves secos. Caso piloto: Cañones del río Dagua & del río Tuluá. Instituto de Investigación de Recursos Biológicos Alexander von Humboldt.

Consorcio POMCAS Oriente Antioqueño. (2017). POMCA Río Negro.

Corantioquia & Gotta Ingeniería. (2016). Estudio regional del Agua (Bajo Cauca Antioqueño).

Corantioquia & Gotta Ingeniería. (2016). Estudio regional del Agua (La Pintada - Valparaíso).

Corantioquia & Gotta Ingeniería. (2016). Estudio regional del Agua (Valle Medio del Magdalena).

Corantioquia & Gotta Ingeniería. (2017). Formulación del Plan de Manejo Ambiental del Acuífero del Magdalena Medio.

Corantioquia & Gotta Ingeniería. (2017). Formulación del Plan de Manejo Ambiental del Sistema Acuífero del Occidente Antioqueño.

Corantioquia & Servicios Hidrogeológicos Integrales. (2014). Evaluación Hidrogeológica en los Municipios de La Pintada & Valparaíso Jurisdicción de la Dirección Territorial Cartama de Corantioquia.

Corantioquia & Servicios Hidrogeológicos Integrales. (2016). Estudio Regional del Agua (Santa Fe de Antioquia).

Corantioquia & Universidad de Antioquia. (2014). Plan de Manejo Ambiental del Sistema de Acuífero del Bajo Cauca Antioqueño.

Corantioquia & Universidad de Antioquia. (2021). Aunar esfuerzos para la exploración del potencial hidrogeológico en zonas de bosque seco en el cañón del río Cauca en la jurisdicción de Corantioquia, Medellín.

Corantioquia & Universidad Nacional de Colombia. (2001). Investigación de Aguas Subterráneas Región Valles de San Nicolás, Fase II.

Cornare. (2016). ICA Aguas Subterráneas de los Valles de San Nicolás & La Unión.

Corpourabá. (2016). Análisis de calidad & cantidad del recurso hídrico del Golfo de Urabá.

Custodio, E., & Llamas, M. R. (1996). Hidrología subterránea, (vol. 2.). Ediciones Omega S. A.

Etter, A. C., McAlpine, C., & Possingham, H. (2008). A historical analysis of the spatial and temporal drivers of landscape change in Colombia since 1500. Annals of the American Association of Geographers, 98(1), 2-23. https://www.jstor.org/stable/25515096

Fundación Empresas Públicas de Medellín & Gobernación de Antioquia. (2018). Antioquia, un territorio para proteger. Fundación EPM.

González, H. (2001). Mapa geológico del departamento de Antioquia. Memoria explicativa. Ingeominas. https://miig.sgc.gov.co/Paginas/Resultados.aspx?k=BusquedaPredefinida=DGBMapGeolDepart

Instituto de Investigación de Recursos Biológicos Alexander von Humboldt. (1998). El Bosque Seco Tropical (Bs-T) en Colombia. https://media.utp.edu.co/ciebreg/archivos/bosque-seco-tropical/el-bosque-seco-tropical-en-colombia.pdf

Instituto de Investigación de Recursos Biológicos Alexander von Humboldt. (1997). Informe Nacional Sobre el Estado de la Biodiversidad. PNUMA, Ministerio de Medio Ambiente, Bogotá, Colombia.

Instituto de Investigación de Recursos Biológicos Alexander von Humboldt. (2014). Mapa actual real de bosque seco tropical en Colombia a escala 1:100 000. http://www.humboldt.org.co/images/documentos/pdf/investigacion/mxd-bst.jpg

Le Maitre, D. C., Scott, D. F., & Colvin, C. (1999). Review of information on interactions between vegetation and groundwater. https://researchspace.csir.co.za/dspace/handle/10204/524

Pizano, C., & García, H. (eds.) (2014). El bosque seco tropical en Colombia. Instituto de Investigación de Recursos Biológicos Alexander von Humbold. thttp://repository.humboldt.org.co/handle/20.500.11761/9333

Saaty, T. L. (2008). Decision making with the analytic hierarchy process. International Journal of Services Sciences, 1(1), 83. https://doi.org/10.1504/IJSSCI.2008.017590

Universidad de Antioquia & Corpouraba. (2016). Plan de Manejo Ambiental de Acuífero Sistema Hidrogeológico Golfo de Urabá. Convenio de cooperación número 21302406-005-2015. Informe final. http://repositorio.corpouraba.gov.co:8082/xmlui/handle/123456789/87