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Brackish Aquifers and Caprock Characterization, Key Tools for Sustainable Projects in the Hydrocarbon Industry.

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- Artículo Técnico [X]
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Abstract
There are various concerns about changes that our planet may face in the coming decades associated with various phenomena such as climate change, among others. Changes such as the reduction in groundwater recharge rates, the reduction of freshwater resources due to overextraction and saline intrusion are some of them, whose may affect the quality of groundwater resources may have in the medium and long-term.

The hydrocarbon industry has taken measures to mitigate the impacts of its operation by undertake into important sustainability strategies. An example of these are the projects that aim to reduce the water and emissions footprint. The water footprint reduction is one of the most important actions that must be carried out actually by all industrial sectors, since water sources can be strongly affected by climate change. The hydrocarbon sector is one of the greatest commitments to sustainable projects and actions to reduce the water footprint is one focused.

Different tools are becoming important bases for the development of sustainable projects. In the case of the water footprint, a fundamental tool for the transition, replacement or increase of water resources is in the knowledge of Brackish Water. This type of water had not been previously characterized and this research allows us to approach this source of water as an interesting tool in the face of future challenges.

In the case of the study area, the brackish water comes from underground sources, that is, aquifers that for some reason provide this type of water. This is a fundamental step in hydrogeological knowledge since from the formations with Brackish Water we have the formations Saline and Brine Water, prospective reservoirs for future greenhouse gas (GHG) sequestration projects. It is for this reason that the second focus tool of this research is the cap rock, a fundamental part of the oil system and that governs, acts and protects each of the reservoirs that we have in the study area.

The conventional hydrocarbon reserves development and the future unconventional resources production will require both tools "Brackish aquifers and Cap rock", due to the inclusion of diverse strategies associated with Water Source, Water Disposition, GHG sequestration, and Drinking Water Protection, among others.

Keywords Brackish Water, Brackish Aquifers, Cap Rock.

Introduction
In recent decades, greater awareness has been generated of the use of natural resources required in industrial processes. Water has been one of the main focuses of optimization, and indicators such as the Water Footprint and Water Neutrality have been relevant. The hydrocarbon industry is no stranger to these changes, and on the contrary, it is an industry that makes significant efforts to optimize the use of its resources.

The Water Footprint and Water Neutrality indicators applied to the hydrocarbon industry seek to reduce to the minimum possible, the requirement of freshwater in the exploration and development of its reserves and resources. Likewise, essential tools are implemented in parallel such as protecting and preserving surface and underground freshwater sources.

Water neutrality also known as Fresh Water Neutral means that, for every gallon of fresh water we use, we offset or replenish that gallon through aquatic environmental conservation projects or treatment technologies that return beneficial fresh water to the environment (Southwestern company, 2022).

The idea of the water-neutral concept is to stimulate individuals and corporations that undertake water consuming or polluting activities to make their activity 'water neutral' by reducing water consumption and pollution and by compensating for the negative impacts of remaining water consumption and pollution through investing in projects that promote the sustainable and equitable use of water within the environment and community that is affected. Water consumption and pollution can be reduced for example by investing in water saving technology, water conservation measures and wastewater treatment. Compensation for negative impacts can be done for example by investing in improved watershed management or by supporting poor communities that do not have access to clean water to set up and maintain their own water supply system. The water-neutral concept was conceived by Pancho Ndebele at the 2002 Johannesburg World Summit for Sustainable Development (Hoekstra, 2008).

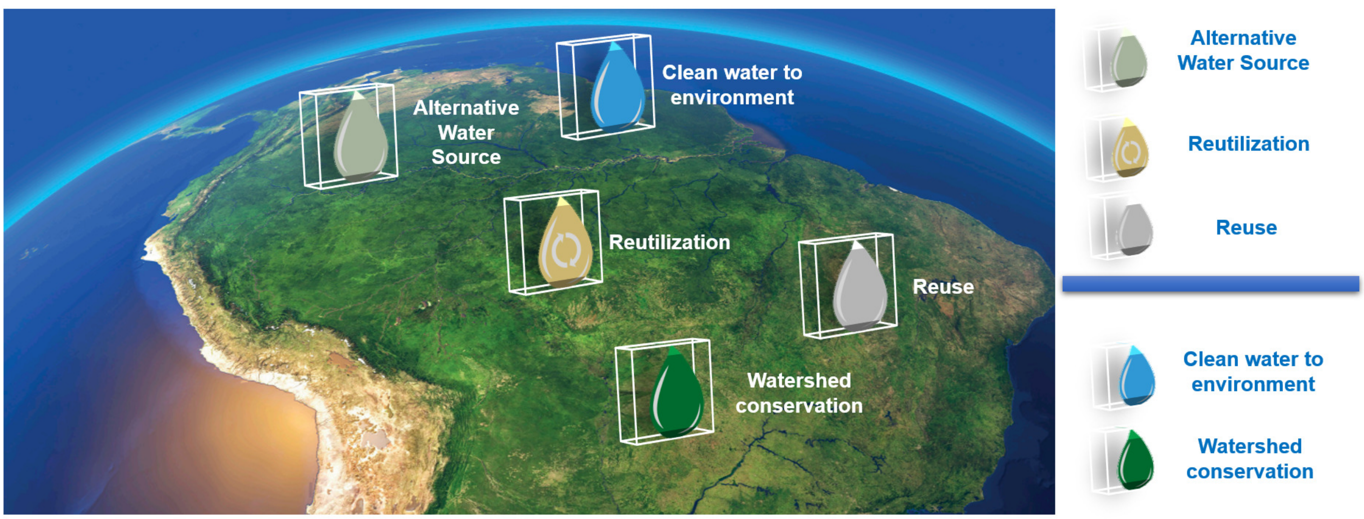

Figure 1. Fresh Water Neutral Tools. Modified from World Meteorological Organization (WMO, 2022).

According to the conditions of each operational area, there are different pillars to favor the Water Neutrality scenario. The alternative of undrinkable water sources is one of the most interesting pillars since it allows a significant reduction in the use of fresh water. This study focuses on finding undrinkable water to reduce the blue water footprint in developing conventional and unconventional hydrocarbon resources.

The study of aquifers cannot ignore a fundamental variable of the geological system "the caprock", since it allows the generation of compartments within the reservoirs to generate a natural separation of them and avoid the mixing of these fluids. Caprocks are fundamental in this type of hydrocarbon systems where different types of resources are found, from oil and gas in source rock, as well as hydrocarbons in storage rock, saline water, brackish water and fresh water.

The procedure included a rigorous geological analysis, dynamic testing of study wells. For example, logs analysis, sample acquisition, hydraulic parameters, and hydrochemical/isotopic characterization, among other characteristics.

Innovation has also been incorporated during the development of these studies. New tools and procedures have been implemented for the first time to characterize these groundwater bodies, including spectroscopy logs, flow induction tests using nitrogen, and formation integrity tools for caprock characterization among the most important.

Application.

Groundwater is a fundamental part of the hydrogeological cycle in the intramountainous regions of Colombia as, it plays a crucial role in sectors such as agriculture. Specifically, in the sedimentary basin of the Middle Magdalena Valley (MMV) a thick column is composed of water bearing porous formations. However, it has not been adequately characterized, although, from the analysis of electrical logs, vertical changes in its quality have been observed (Ramos and Sáchica, 2013).

Site description. This study is developed for the Middle Magdalena Valley basin, which recently celebrated 100 years of commercial hydrocarbon production. Despite their extensive time in operation, the main assets have a recovery factor that indicates that there is still a long way to go. Likewise, in its extensive drilling, the potential of its source rock resources has been evaluated through several studies in existing wells.

The first commercial hydrocarbon field in Colombia was Infantas, discovered in 1918 in the Middle Magdalena Valley basin. In the following decades, other fields were discovered, among the most important La Cira, Casabe, Provincia, Bonanza, Llanito, Gala, Galán, Lisama, Tesoro, Nutria, Tisquirama, San Roque, Payoa, Las Monas, Cocorná and Velasquez. The original oil in place associated with this basin exceeds 6 billion of original oil in place, which leads us to think about the high potential of the source rock associated with these hydrocarbons.

This sedimentary basin is geomorphologically located along the central portion of the valley crossed by the Magdalena River, between the Eastern and Central Cordilleras of the Colombian Andes, covering an area of 32,000 km2. It includes part of the departments of Boyacá, Santander, Cundinamarca and Antioquia, among others.

The geological growth of the Central and Eastern Mountain ranges gives rise to the opening where the basin of the Middle Magdalena Valley was deposited. Thus, the evolution of this basin begins at the same time as the uplift of these two mountain ranges (Mesozoic) (Sarmiento-Rojas, 2001).

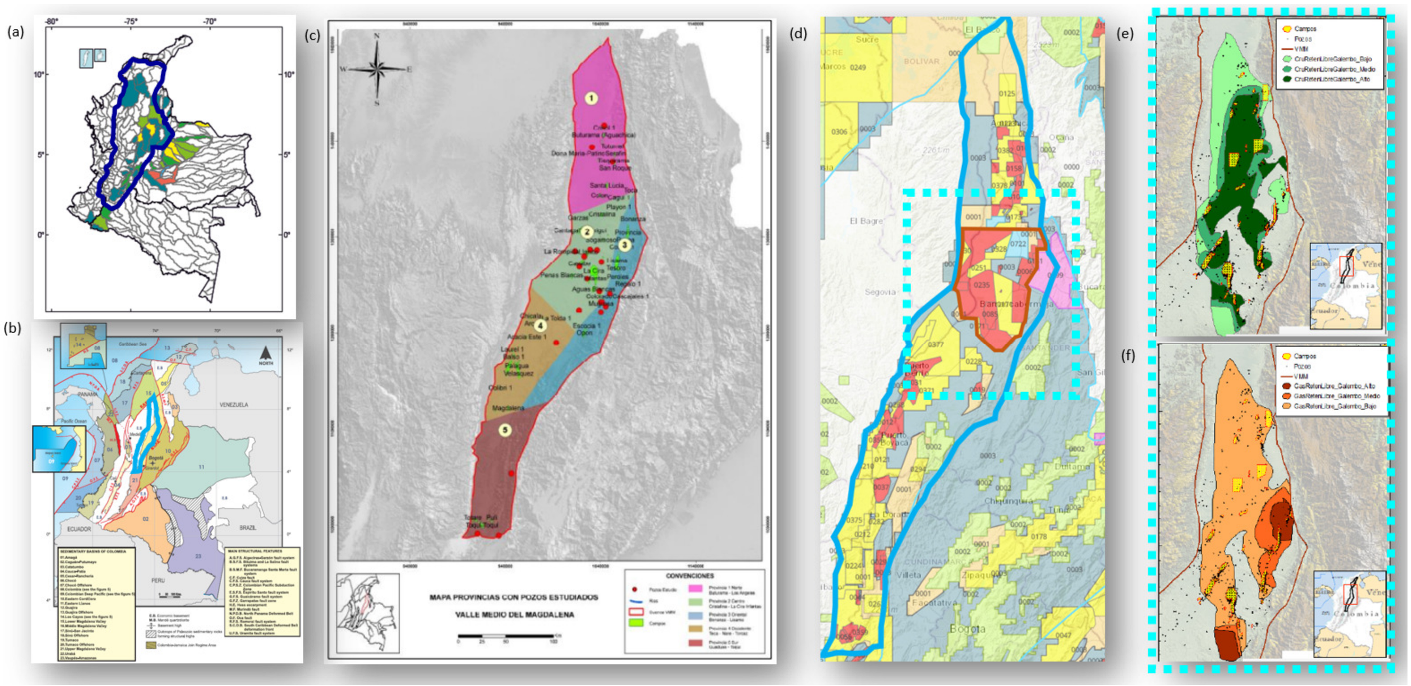

Figure 2. Magdalena Cauca hydrographic Basin and Middle Magdalena Valley Sedimentary Basin. Estudio Nacional del Agua and Agencia Nacional de Hidrocarburos.

The most important hydrocarbon-producing formations are part of the Paleocene. The Lisama, Esmeraldas, La Paz, Mugrosa and Colorado Formations are the main sources of the more than 6 Billion oil discovered in the Basin's history. These formations rest on deposited Members of Cretaceous origin, whose formation characterized as source rock has been called La Luna.

These Paleocene formations, which are known as the formations of the petroleum cycle, also have Saline to Brine Water, resources that have not been quantified but that have been used in part for water disposal projects due to their interesting properties as a storage rock. On these are the formations of Neogene age mainly composed of the Real Group which rests on an inorganic clay unit known as the Cira Shale.

Some of these formations or units present in the Real Group can transmit large volumes of water (transmissivity >1 square meters per day), which can be considered aquifers. An aquifer is "a stratum or geological formation that allows water circulation through its pores or cracks, thus making possible for mankind to take advantage of it in economically appreciable quantities to meet his needs" (Custodio and Llamas, 1983).

In this Real Group, the freshwater resources appear in its upper part, which also extend to the Quaternary formations, which, due to their accessible depth, are part of the drinking water resource that is used in the area, as well as the top of the Group. In the middle and deepest part of this Group of formations or units, there is a transition zone of aquifers whose water resources go from freshwater to brackish water and end with saline water, in compartments delimited by different cap rock, essential part of this studio.

In resume, the stratigraphic column allusive to the porous formations in the MMV under study from base to top is composed of Paleogene formations, which have been characterized due to the fact that many of these are part of the petroleum cycle. Neogene units with interesting transition zones. Lastly, Quaternary formations are also used for their freshwater content and complete the stratigraphic column of investigation (Figure 3).

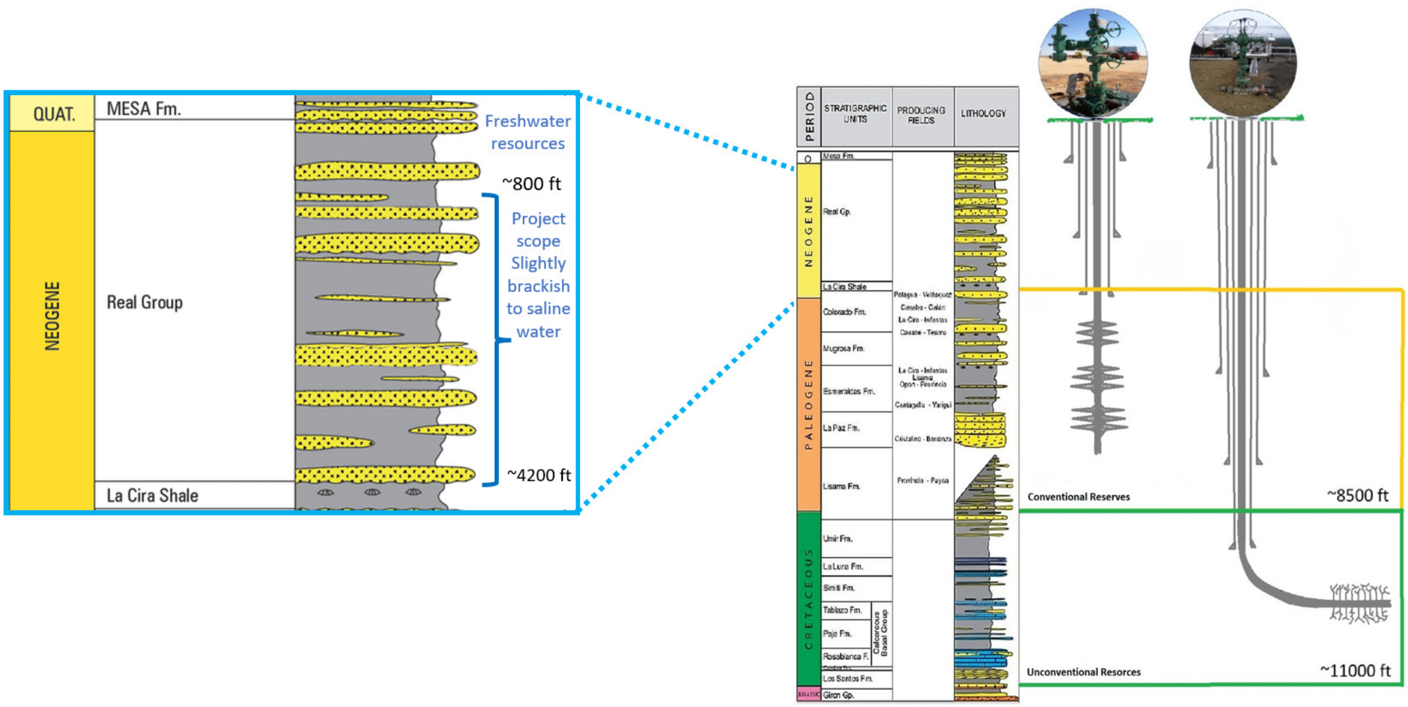

Figure 3. Stratigraphic column of the Middle Magdalena Valley. Authors - Modified from Vargas, 2012.

Figure 3 shows a large number of formations or units represented in gray. These units are mineralogically recognized as clayey, and some of these can be considered as "caprock" (for example the top of the Colorado formation recognized as the La Cira Shale unit), however, there are not many studies that make a deep analysis. Figure 2 presents an interesting discretization achieved from the progress of this study together with previous information. The Chontorales and Enrejado units present different clay layers interspersed with sandy deposits. Due to the difference between the fluids that these formations store, an analysis of their behavior as Caprock was included.

Methodology. A complete characterization of groundwater sources and its interaction with the petroleum system was conducted in 2018 aiming to plan sustainable operations in the area of interest. To accomplish this objective, it was proposed to increase the geological and hydrogeological knowledge combining multidisciplinary teams and implementing new technologies to better characterize geological, petrophysical, mineralogical and hydraulic properties of the formations of interest leveraging an important pillar to fulfill water footprint reduction goals in all exploration and production activities close to the study area.

The study involved two study wells (further referred as study well #1 and study well #2) to gather information from geological formations that had not analyzed in the past by using techniques that allow the identification of hydraulic and mechanical properties.

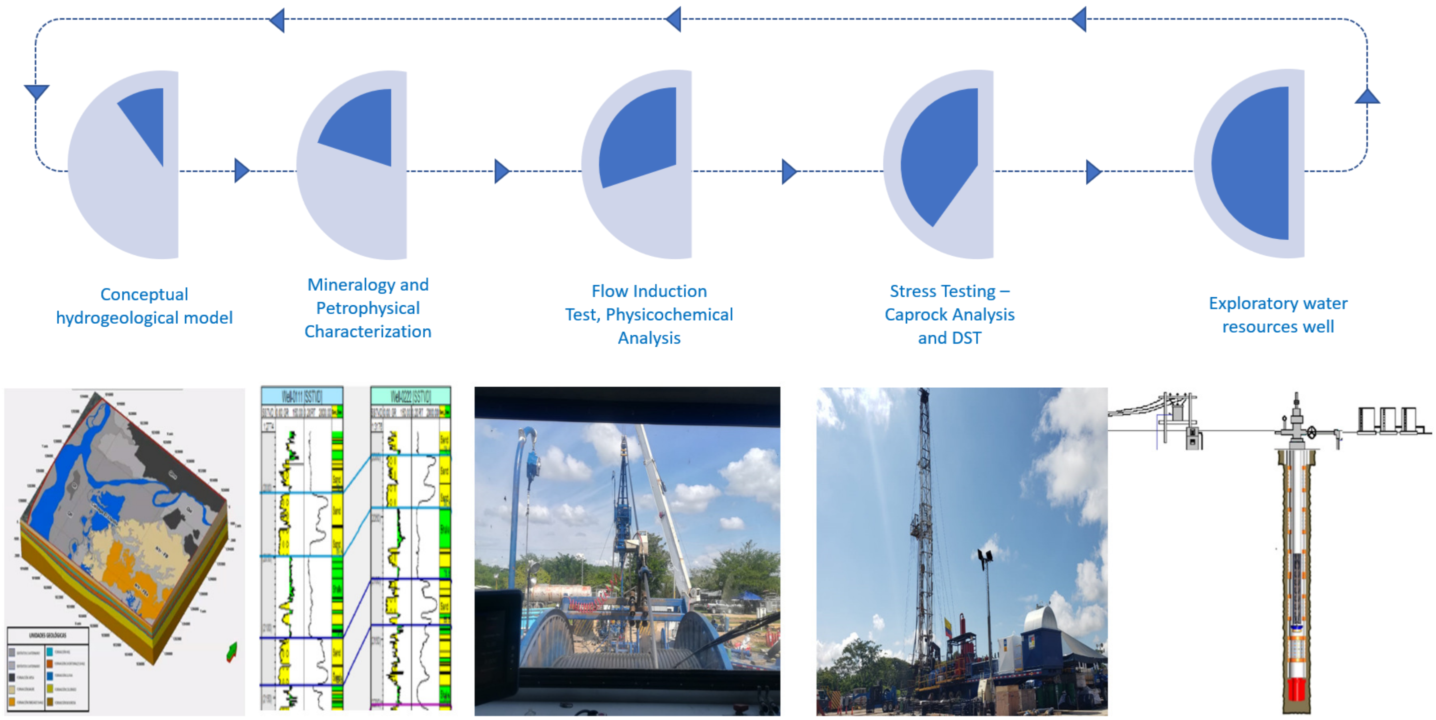

Figure 4. Methodology implemented.

Results. The Real Group, with a thickness of 4,054 meters measured in its type section, is one of the most extensive and perforated stratigraphic structures in the basin under study. According to Wheeler (in Pilsbry and Olsson, 1935) the "Real Series" of fluvial origin is composed of sandstone bluish-grey, coarse-grained hard, with intercalations of laminated dark grey shale, sequence followed by a massive conglomerate with gravel of brown and black chert. Towards the base, shales grey with red spots interbedded with massive cross-bedded sandstones and massive conglomerates accumulated unconformably over the Colorado Formation in a net contact.

In the study area, surface and subsurface works have allowed to conclude that the Real Group occurs with the same succession of strata although its thickness may vary between 850 to 950 meters which is substantially thinner than such reported in the type section at the Opón river. Nonetheless, it is clear that all of the 5 stratigraphic formations can be differentiated owing to their distinctive mineral content, sedimentary structures and fossil fragments

Although the Real Group has been extensively drilled, not much information has been obtained from the electrical logs, especially in its intermediate and deeper formations. Key information has been obtained punctually in some newer wells by incorporating not only classical electrical logs such as gamma ray, spontaneous potential, resistivity, and neutron-density but special logs such as spectroscopy and acoustic logs. Well log`s analyses have revealed that spontaneous potential is affected by changes in salinity of the formation waters as depth increases (freshwater in Bagre, slightly brackish in Hiel and brackish in Lluvia). The gamma ray log happens to be affected by the presence of radioactive minerals, such as potassium feldspars, making it not a good indicator of clay content by itself. Similarly, resistivity, like spontaneous potential records, shows a higher correlation to fluid changes than lithological changes and therefore, a thorough petrophysical interpretation for these formations was carried out by analyzing all technologies integrally

The clay content or volume of shale (VSh) was estimated mainly from the combination of open hole logs such as gamma ray, spontaneous potential, resistivity, and neutron-density but incorporating descriptive information from mud logging or formation evaluation logs (FEL). The spectroscopy or mineralogical nuclear log, acquired in study well 1, allowed to identify the minerals present in the formations of the Real Group, discriminating type and quantity of clays (Figure 3). Likewise, matrix density calculations, key element to estimate matrix porosities and permeabilities, was obtained from this special log combined with the x-ray diffraction (XRD) analyses performed in outcrop samples (Figure 5).

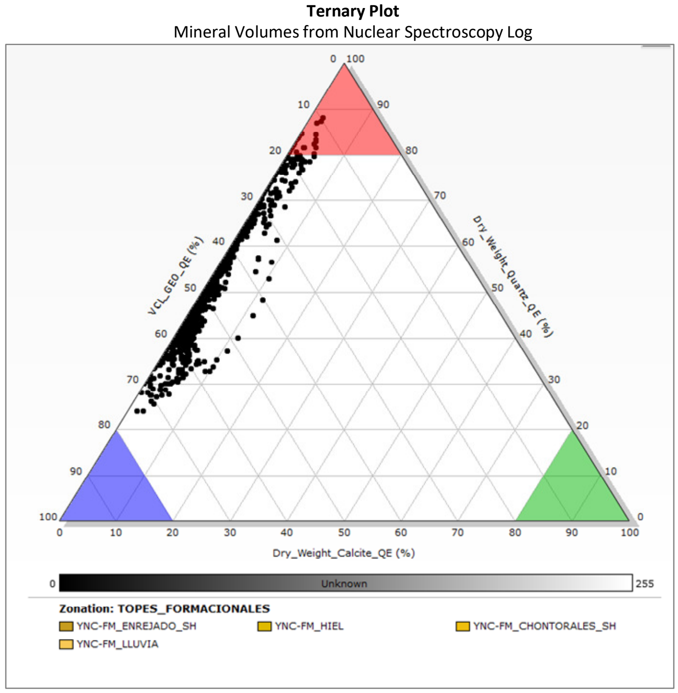

Figure 5. Minerals present in the formations of the Real Group.

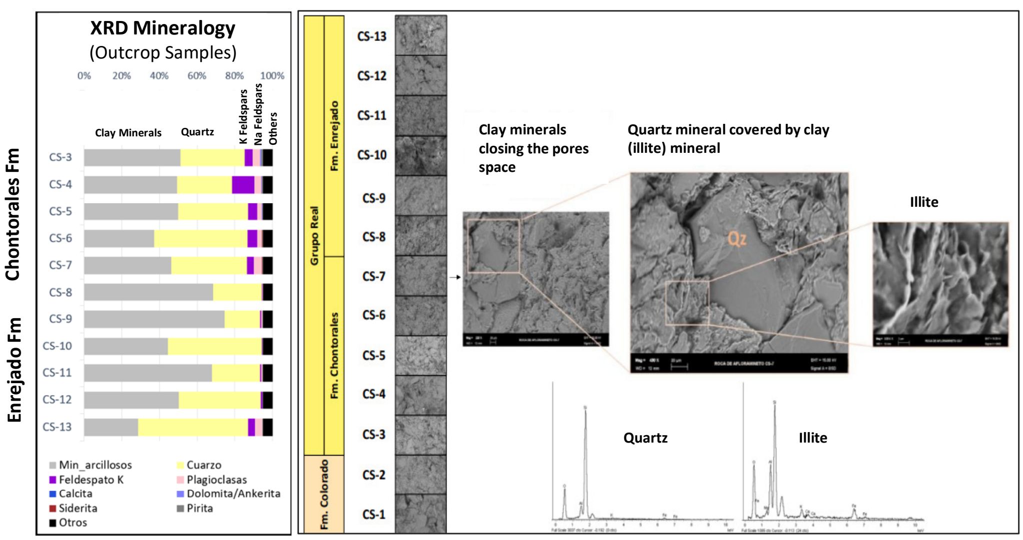

Figure 6. Scanning electron microscope (SEM – EDX) pictures taken in outcrop samples corresponding to Enrejado and Chontorales formations.

From the clay analysis it is deduced that the predominant mineral is kaolinite, followed by illite, with smaller amounts of montmorillonite and chlorite. Reactive clays are mainly identified in the intervals that act as seals or aquitards. On the other hand, the sandstones that work as reservoirs or aquifers stand out for their content of quartz minerals, potassium, and sodium feldspars (plagioclase) and illite as the main clay mineral.

The mineralogical log (Figure 5), in addition to identifying and quantifying minerals, also provides a curve of total organic carbon content (TOC), which makes it possible to identify areas with saturation of hydrocarbons (liquid or gaseous) and/or presence of carbon. In the study well #1, the TOC increase in Hiel is associated with the presence of carbon, but also with traces of hydrocarbon adhering to the casing walls (identified in the cement log). The estimated salinity curve (ASAL) obtained from the nuclear spectroscopy log shows a great consistency with the salinity results from the analysis of water samples (Figure 7).

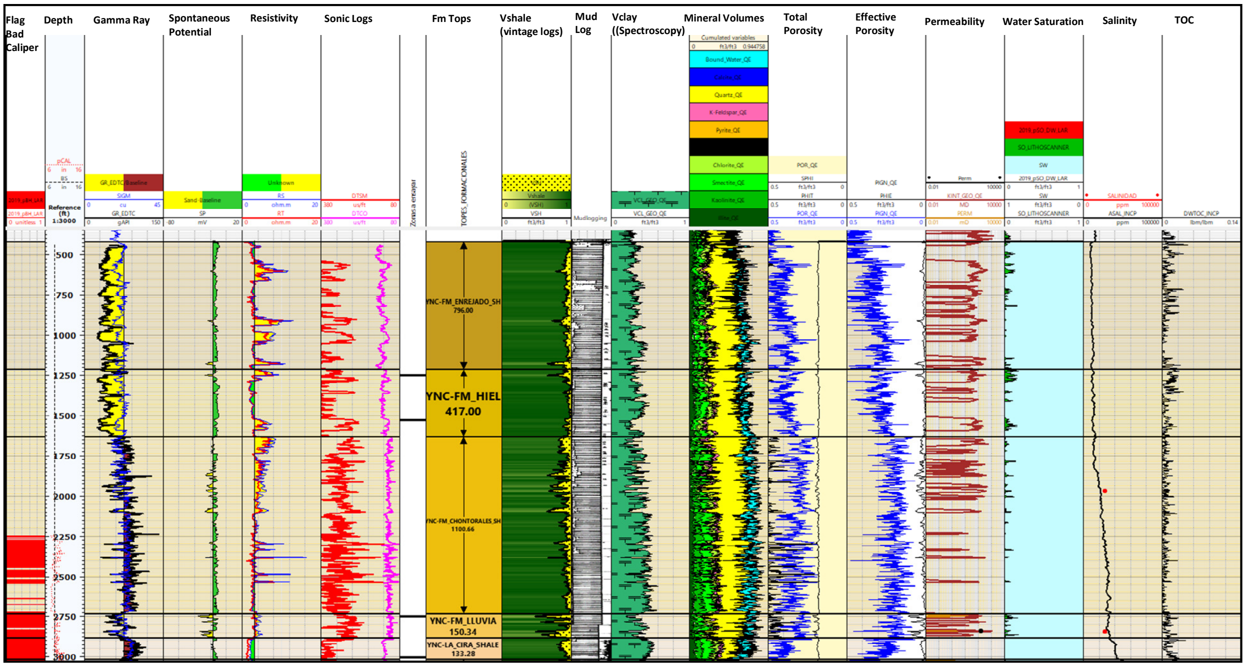

Figure 7. Mineral volumes and rock properties at Enrejado, Hiel, Chontorales and Lluvia formations.

***Petrophysical Analysis*.** For the study well 1, the gamma ray, sigma, mineral volumes, water volume, porosity and permeability logs were used to identify and adjust the stratigraphic tops that had previously been identified in other nearby wells. Around the study well, several others have been drilled and there, the gamma ray (GR), spontaneous potential (SP) and resistivity (Rt) logs were present. Formation evaluation logs (FEL) and volumes of clay (VSh) were also used as reinforcement, where available.

From the analysis of the south-north cross-section it was possible to observe the thickness of the Chontorales and Lluvia, this remains constant while the Hiel shows slight variations in thickness laterally. On the other hand, from the northeast-southwest cross-section an increase in the thickness of the Lluvia and Chontorales could be observed to the west, as the units deepen in this part of the basin.

The porosity was obtained from neutron-density logs, and sonic as a second alternative, incorporating the analysis of the spectroscopy logs where available. Of these formations to date, there are no results of laboratory analysis in wells, for the calibration of the porosity curves and/or permeability. There are porosity and permeability laboratory measurements, obtained in outcrop samples, so they are useful as a reference or guide. Greater variability and dispersion are observed in the Hiel unit, this is due to the formation be divided into two subzones: Upper Hiel with higher sand content and another more clayey zone, the Lower Hiel with isolated fluvial channels and separated by floodplains.

Lluvia in general, stands out as a more homogeneous vertical and spatially variable stratigraphic section. The total porosity appears in a wide range (10-30%) with an average of 25% for the entire thickness of the formation (gross). Regarding the estimation of the permeability, the following is the one calculated from the spectroscopy log. This has matrix grain density corrections and is more accurate than those estimated by other methods based on basic logs (Figure 5).

Water saturation was initially estimated by applying the Archie model with m and n equal to 2 and a equal to 1, with a formation water salinity of 10,000 ppm NaCl (Mohamad A. M., and Hamada, G. H., 2017). It is important to mention that in this case and knowing the presence of aquifers, the objective of the calculation focuses more on the estimation of the salinity of the formation water and its variations in the vertical. From the salinity analysis with the nuclear spectroscopy tool, an equivalent salinity of 18,000 ppm was obtained for Lluvia, 25,000 ppm for the sandstone intervals of Chontorales, and 17,000 ppm for Hiel. However, a more robust petrophysical model is being developed at Quanti Elan (Techlog). This new model will integrate the results of laboratory analyzes recently obtained in rock and fluid samples, but also the results of dynamic tests.

For the cut-off definition, crossplots VSh-Porosity and permeability-porosity (PHIT) were constructed. It is observed that the porosities increase as the VSh decreases. This graph allows estimating the clay cut-off value (35%) for the definition of net pay, demonstrating this form of porosities equal to or greater than 15% (PHIT) for the intervals with the best rock quality.

On the other hand, porosity versus permeability plots reflects that with a porosity cut-off of 15%, the permeability of the interval would be equal to or greater than 10 mD (quality rocks medium to high). Finally, it is mentioned that water saturation cut-offs were not applied. Additional, sensitivities were performed with permeability cut-offs (1mD, 10mD, 100mD).

The execution of hydraulic testing was included in the stratigraphic flow units where previously no information had been acquired (i.e., Hiel formation). Finally, the implementation of mechanical analysis in the so-called cap rock in order to demonstrate its sealing capacity.

From base to top and according to the petrophysical interpretations 27 hydrogeological units can be recognized in the Real Group in the area of interest: Lluvia (1 aquifer and 1 aquitard), Chontorales (4 aquitards and 3 aquifers), Hiel (1 aquifer), Enrejado (5 aquitards and 4 aquifers), Bagre (4 aquitard and 4 aquifers)

***Hydraulic Analysis and Water Quality*.** In general, the aquifers of the Bagre, Hiel, and Lluvia formations are continuous regionally extensive, with a specific capacity generally between 2 and 5 l/s/m. The aquifer of Bagre is generally of the free type and the others, due to the intercalations with clayey levels, are of semi-confined and confined type.

At the end of 2020, the intervention of study well 1 was carried out, where it was proposed to execute a flow induction with two objectives: to bring water to the surface to carry out the physicochemical analyses and to obtain the hydraulic characteristics of the units Hiel and Lluvia of Neogene age. Before taking samples, a spectroscopy log was run with the aim of detailing the mineralogy of these formations, since this is an important factor that influences the quality of the water contained within them.

Due to the depth of the formations under study (2100 feet for Hiel and 2800 feet for Lluvia), and the presence of aquitards or cap rock on them, it can be considered that the percolation from the shallow aquifers is very low or null, therefore that the composition can be mainly affected by the dilution of said minerals during a considerable residence time.

The flow induction was carried out individually for each unit of interest and to complement the study. A surface sampling campaign was carried out in water source wells near the study area, producers of the Bagre, Mesa, the Quaternary Sands and the Colorado and Mugrosa Formations of the Paleogene. Through the physicochemical analysis, it was possible to show that the formations mentioned (Bagre, Mesa and Quaternary Sands) contain freshwater (water with a content of less than 2000 mg/L of total dissolved solids), and even its elements do not present a high risk for human consumption and for irrigation activities as established by the legal government terms.

On the other hand, a high concentration of elements detected with the spectroscopy log was found in the deepest formations (Hiel and Lluvia). In the case of the Hiel and Lluvia formations, three samples were taken during flow induction, one at the beginning, one during and one at the end.

It is noteworthy that in all these elements or compounds, their value is above the permissible value recommended in the regulation (risk index of the water quality for human consumption) in the Hiel and Lluvia formations (between 0 and 5 points out of 100). Some of elements have greater economic and indirect consequences on human health, according to the same regulations as in the case of Calcium, Aluminum, Zinc, Manganese, Molybdenum, and total Alkalinity. Iron was not considered since it could be generated by corrosive phenomena in the study well 1. The results of physicochemical analysis are possible to compare between Hiel and Lluvia formations versus community source freshwater wells that currently exist in the area.

To conclude, the quantification of the risk index of the quality of water for human consumption was carried out, according to the parameters and ranges established in the regulations. According to the calculations and the recommended ranges, not including the non-acquired parameters, the risk index associated with the quality of the water according to the results of the samples from study well 1 generates a high-risk rating (between 35.1 and 80 points out of 100) for both formations (Hiel and Lluvia). Even if turbidity is included, the Lluvia would reach the range of unviable for sanitation (more than 80 points out of 100), and the Hiel would be very close to this upper limit (78 points).

Regarding productivity, an original pressure of 1280 psi was found in Lluvia formation with a pressure drop of 27%, which produced an equivalent of 4272 barrels of water per day (bwpd). Applying Jacob's method, the transmissibility of 1.43 square meters per day was calculated, a conductivity of 0.07 meters per day for the flow period and a transmissivity between 0.8 and 1.04 square meters per day and a conductivity between 0.04 and 0.053 meters per day calculated for the restoration period.

In Hiel an original pressure of 832 psi was found with a pressure drop of 27%, which produced an equivalent of 4,387 barrels of water per day. Applying Jacob's method, the transmissibility of 2.6 square meters per day was calculated, a conductivity of 0.07 meters per day for the flow period and a transmissivity between 3 and 2.3 square meters per day and a conductivity between 0.07 and 0.06 meters per day calculated for the restoration period. The results of this test are considered 80% reliable due to the time and method used.

With the previous results, it is highlighted that the aquifers under study have the capacity to transmit water, so they could be a source for future industrial operations. Of course, tests must continue to reduce uncertainty. In addition, the extension of these sandy bodies allows to show that there are important resources of undrinkable water in the study sector of the basin.

Caprock analysis. The last part of the methodology included the mechanical analysis of the caprock (Study Well 2) and the analysis of radio distribution pore throat tests performed on 13 rock samples taken from outcrops of the Colorado Formation (2 samples) and the Real Group (11 samples). The work carried out included mineralogical analyzes using the diffraction techniques of X-rays (DRX) and scanning electron microscopy (SEM). In turn they were made analysis of capillary pressures by injection of mercury, analyzes that constitute the most relevant data to observe the distribution of pore throat radio in the samples and their respective association with the sealing capacity of the Formations analysed.

In general, the results obtained show that according to the capillaries and pore throat radio identified in the rocks of the top of the Colorado Formation and the Chontorales and Enrejado Formations of the Real Group, the domain of the pore throat radio is associated mainly to micropores and nanopores, which suggest low permeabilities in the analyzed samples. This was confirmed with electron microscopy analysis where rocks with a plugged appearance were observed, with quartz and clay mineralogy, with grain sizes mostly fine (silts and clays) (Gomez and Sandoval, 2021).

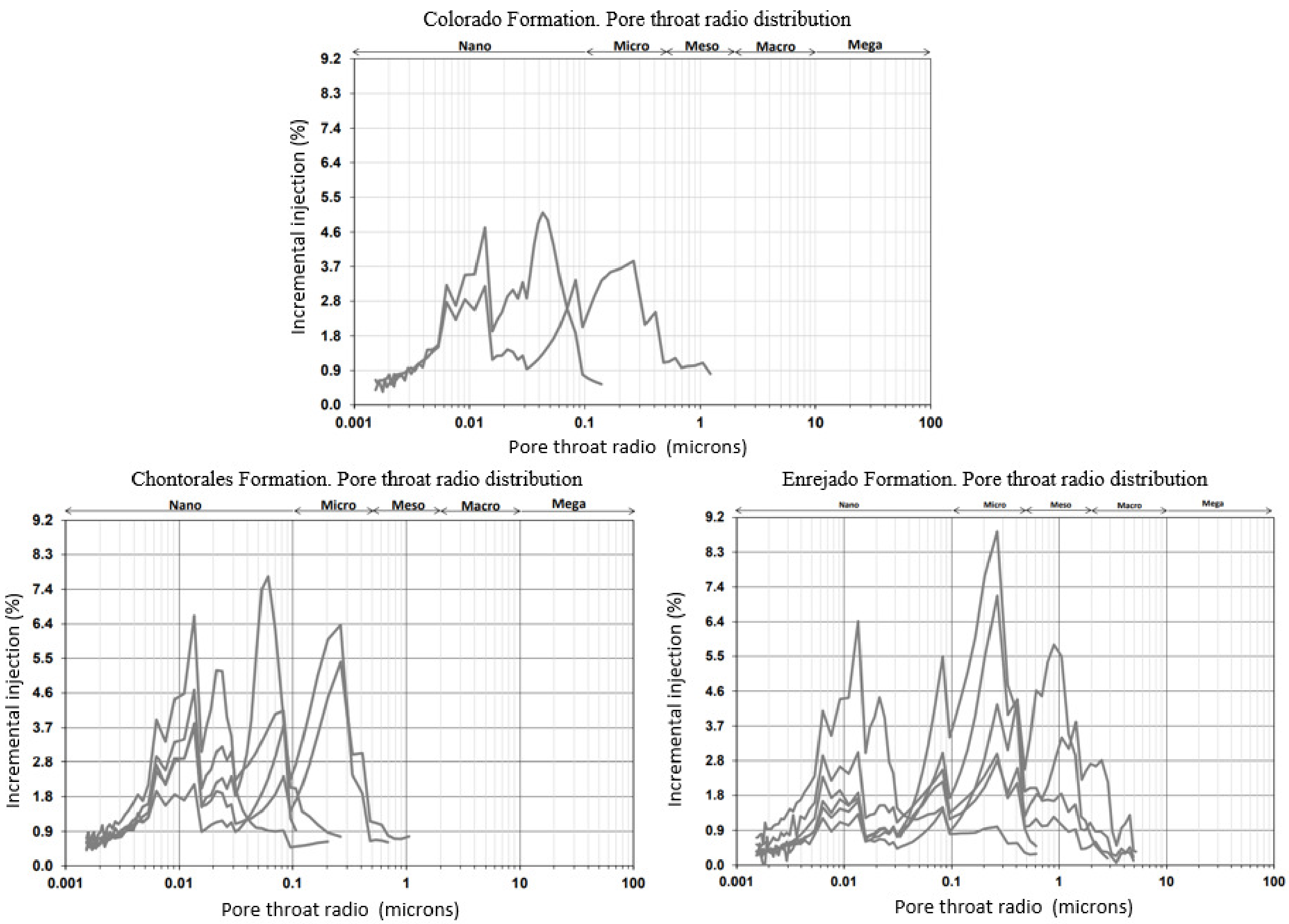

Figure 8. Pore throat radio distribution clay formations.

This study allowed us to conclude that pore throat radio estimated from capillary pressures by mercury injection, for outcrop samples representative of the aquitard intervals of the top of the Colorado Formation and the Chontorales and Enrejado, present an average value of throat radio of pore of 0.2 µm, and vary between 0.015 µm and 0.95 µm, considering for the estimate accumulated volumes of mercury of 35%, 40% and 50%. These dominant pore throat radio values correspond mostly to samples of low flow capacity with predominance of nanopores (< 0.1 µm) and micropores (>0.1> 0.5 µm).

The mineralogical nature identified in the outcrop samples of the Colorado Formation and the Chontorales and Enrejado Formations do not present significant content of carbonate-type minerals, which reduces the risk of fragility of the rocks in these aquitard intervals. Likewise, was recognize quartz rocks with high content of clay minerals (29% - 74%). The mineralogical analyzes carried out using DRX and SEM-EDX show a mineralogical composition mainly dominated by Smectite-type clays and Kaolinite, and are generally described as rocks with quartz-clay mineralogy. On the other hand, the micrographs made in the SEM-EDX analyses allow us to observe a plugged appearance of the pores by clay material (predominance of smectite), which is typical in rocks with low permeabilities.

The lower units (La Cira Shale inorganic), as well as intermediate units (Chontorales Shale inorganic), were included for a mechanical test in this study. In the lower sealing units, a fracture gradient greater than 1.03 Psi/ft was determined with a variable slope for more than 120 minutes without stabilizing (slope > 0), which demonstrates the plasticity of the rock and its ability to absorb hard energy to break. Likewise, the injectivity decreased during the test with a fall-off test at the end where rock recovery was not achieved.

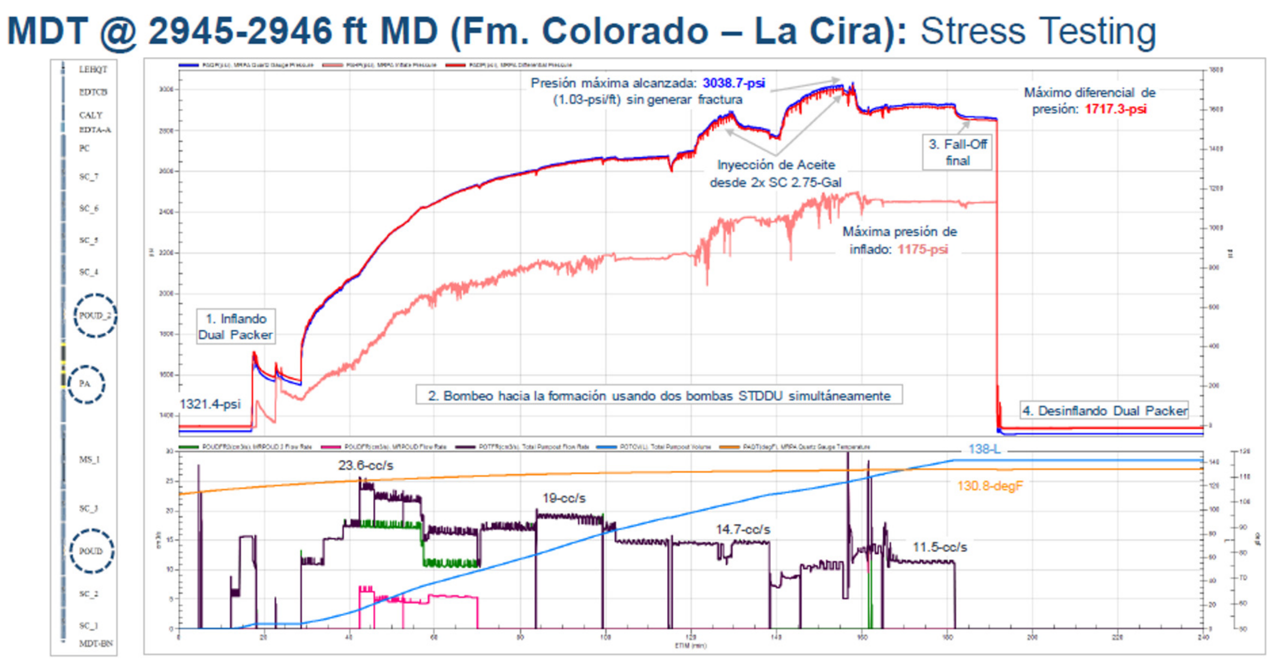

Figure 9. Stress Testing Colorado unit caprock.

Discussion

Water management is becoming highly relevant for energy transition and environmental sustainability (i.e.: related to carbon capture in brine aquifers, hydrogen generation), social impact (i.e: with the preservation of fresh water sources), but also in the development of oil and gas projects (i.e: with the utilization of brine and saline aquifers for waterflooding or fracking). Communities, environmental institutions, industry and financial institutions are all concerned-about this natural and valuable resource. According to the Petroleum Resources Management System (PRMS, 2018), "when a (oil and gas) project is commercial, this implies that the essential social, environmental and economic conditions are met" and based on this, the appropriate water management is key to increasing commercial possibilities.
Ecopetrol has found a way to obtain social and environmental licenses for PPII projects with an "aquifer portfolio", which could also serve to facilitate sustainable oil and gas development and guarantee the energy transition.

Conclusions

The oil systems are in equilibrium with the aquifer systems in the same Basin, as evidenced in the Middle Magdalena Valley region, and must be understood in the most appropriate way to generate their protection and use.There is no doubt that there are tools to increase the value of hydrocarbon assets and the sustainability component implemented.

Hydrocarbon systems that include unconventional resources and conventional reservoirs should not be viewed separately, on the contrary, synergy activities should be sought so that best practices are implemented throughout the system.

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