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GROUNDWATER MODEL OF A FRACTURED ROCK SYSTEM AS A TOOL FOR GROUNDWATER MANAGEMENT: THE ESTIBANÁ SUB-CATCHMENT, AZUERO PENINSULA, PANAMA

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ABSTRACT

Panama has abundant water resources; the annual average precipitation is 2,924 mm/year. However, lack of understanding of this resource has led to poor management decisions and as a consequence, parts of the country suffer from water scarcity in dryer than average years. Groundwater is of particular interest to us since rural communities in Panama mostly depend on this resource to supply their needs, especially within the Central Pacific Region of the country, where the dry season can extend up to seven (7) months during El Niño years. Therefore, researching alternative water sources such as groundwater is crucial for securing water availability for current and future generations. The objective of this project is to study the groundwater of a small catchment within the Central Pacific Region, the Estibaná sub-catchment, located in the District of Macaracas, Province of Los Santos. In the initial stage of the project, we performed geological and geophysical explorations and collected groundwater quantity and quality data as a first step for building a robust numerical groundwater model of the study area. This paper presents a summary of our findings in the form of a preliminary hydrogeological conceptual model. Once the numerical model is built we will be able to simulate different management and climate change scenarios that would help water managers make more informed decisions.

Keywords: Panama, Volcanic aquifer, Groundwater models, Fractured rocks

1 INTRODUCTION

Historically, groundwater research has been focused on homogenous porous media aquifers. Nevertheless, 50% of earth's land surface is covered by hard rocks (igneous and metamorphic rocks, karst formations and consolidates sedimentary units) which are heterogeneous and form fractured rock aquifers (Singhal and Gupta, 2010). Advances have been made especially in the past few decades, in understanding how groundwater flows through fractured rocks. However, most of the research has been geared towards site characterization for the purposes of nuclear waste disposal and remediation of contaminated sites(Cook, 2003; Singhal and Gupta, 2010). Attention to the study of fractured rock hydrogeology at regional scales for the purposes of water supply development is very recent. This has been increasingly important for developing countries in Latin America, Asia and Africa (Singhal and Gupta, 2010) since the majority of the rural communities are on hard rock aquifers.

Most of the world's rural population relies on groundwater to supply their needs and Panama is no exception. Despites receiving an annual average precipitation of 2,924 mm/year, there are areas in Panama that suffer from water scarcity, especially the Central Pacific Region, where the dry season can extend up to seven months (ANAM, 2013). The Central Pacific Region, located in south-central Panama, is a mostly rural area where people rely on groundwater for agricultural and domestic needs. It is mostly conformed by hard rocks where groundwater development is more challenging. Our poor understanding of the hydrogeology of the region has prevented local professional and authorities from making informed decisions about the best places to drill. Also, poor placement of wells and unregulated pumping has caused existing wells to go dry during periods of drought. Climate change, deforestation and soil degradation have the potential of reducing groundwater recharge thus reducing its availability (Panwar and Chakrapani, 2013). In addition, population growth and increasing agricultural activities will increase its demand. Therefore, characterization and modeling of fractured rock hydrogeology in this area of the country is crucial to securing groundwater availability for present and future generations.

During the last few years, there has been some advancement in the understanding of the groundwater behavior in this area of the country. Preliminary studies done by Castrellon Romero (2016, 2018) based on very limited geological and stream gauge data suggest that groundwater flow follows topography closely and rivers act like sinks for groundwater.

To continue deepening our understanding on groundwater resources of the Central Pacific Region we decided to focus on a small catchment, the Estibaná sub-catchment, located in the District of Macaracas, Province of Los Santos. In this initial stage of the project we performed geological and geophysical explorations and collected hydrologic data (precipitation and streamflow measurements) and water quality data to build a robust hydrogeological conceptual-numerical model of the study area. This paper presents a summary of our findings in the form of a preliminary hydrogeological conceptual model. Once the numerical model is built we will be able to simulate different management and climate change scenarios that would help water managers make more informed decisions.

2 STUDY AREA DESCRIPTION

The Estibaná sub-catchment has an area of 296 km^2 and it is part of the La Villa Watershed, which is in the central part of the Azuero Peninsula in south-central Panama (Figure 1). According to Köppen climate classification this area of the country experiences tropical savannah climate (Dirección de Hidrometeorología de ETESA, 2007). Within the study area there are two meteorological stations and two streamflow gauges operated by the Department of Hydrometeorology of ETESA (Figure 1). One met station (128-004) is inactive but has historical precipitation records from 1955 to 2014 and the other met station (128-017) is currently active and has been in operation since 2014 measuring different climatologic parameters such as temperature, wind speed, humidity, solar radiation and precipitation. Similarly, one streamflow gauge is inactive (128-02-01) but has historical daily streamflow records from 1961 to 1998 and the other station is currently active (128-02-02) and has been recording hourly streamflow levels since 2015. Five additional rain gauges were installed within the study area in August and September 2018 to get a better representation of the rainfall distribution within the study area (Figure 1).

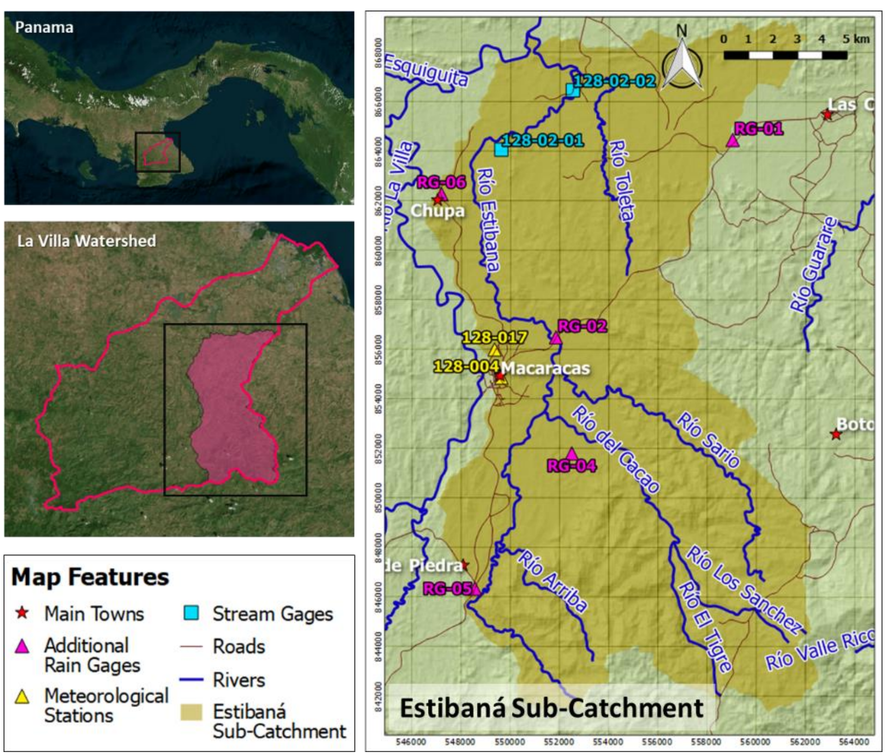

Figure 1. Study area location within La Villa watershed in south central Panama.

Average flows and rainfall for the Estibaná sub-catchment, calculated from ETESA's historical records are 5.65 m^3/s and 1573 mm/year, respectively. In this area, a large part of the territory has been deforested to make pastures for intensive livestock and agricultural activities, mainly rice, corn and sugar cane crops (Castillo M. and Patiño M., 2014). Although farmers still rely on rainfall for their seasonal crops, many farmers have groundwater fed irrigation systems to water their crops year-round. Nevertheless, there is no accurate data to estimate the amount of groundwater being pumped for irrigation, and water that is pumped for domestic purposes is negligible compared to other quantities in the regional water budget for the La Villa groundwater basin (Castrellon Romero, 2018).

3 METHODS

In order to characterize the study area, several data collection and fieldwork campaigns have been carried out. Geological and geophysical explorations have been conducted to identify the main geological formations within the study area, as well as the main structures (faults and fractures) that could have an impact on groundwater flow. In addition, groundwater level and groundwater quality have been monitored to identify overall groundwater flow patterns within the study area.

3.1 Geological Exploration

During the geological exploration, outcrops were identified and rock samples were collected along different routes within the study area (Figure 2). Each rock sample taken from the field was georeferenced and identified with a code made out of letters and numbers that indicate the type of material collected, the zone from which it was taken and the quantity/number of sample. In total, 56 routes were traveled and 496 outcrops were identified. This field exploration complemented the existing geology and shed light to new elements to be considered when describing the regional and local geological features of the study area.

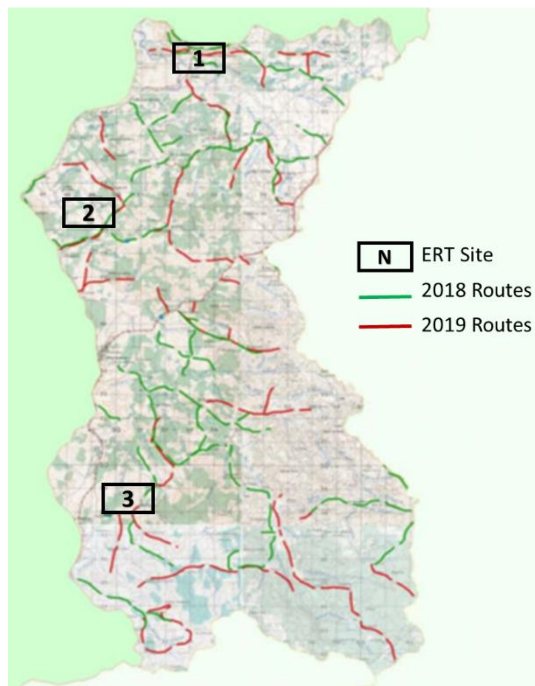

Figure 2. Geological exploration routes and geophysical exploration (ERT) sites.

3.2 Geophysical Exploration

For the geophysical exploration in the study area, we performed ERTs at three (3) different sites within the study area (Figure 2). Electrical resistivity tomography (ERT) is a low-cost non-invasive 2D geophysical tool with a wide range of applications, including the identification of geological discontinuities or faults (see e.g. Caputo et al., 2007; Fazzito et al., 2009, Suski et al., 2010; Díaz et al., 2014; Mojica et al., 2017). At each site, several parallel tomographies were taken. The development of this work involved the use of a Syscal R1 switch-48 resistivity meter (Iris Instruments), with two multi-cable-systems with 24 stainless steel electrodes each and an external 12 V battery for operation. Prior to geophysical survey, acquisition and geometric parameters were set: maximum value for standard deviation of the v/i ratio or standard deviation of the apparent resistivity (1% with v measured voltage and i the intensity of the transmitted current); (b) minimum and maximum number of stacks for measurement (3 and 6 for this study); (c) the time cycle (500 ms); and (d) rho mode for acquisition parameters. Regarding the geometrical parameters, we used a Wenner - Schlumberger array, that corresponds to a new hybrid electrode configuration between the Wenner - α and the Schlumberger arrays (Pazdirek and Blaha, 1996); the number of electrode (48) and the spacing between them (5 m obtaining in each test a total length of 235 m). The Wenner - Schlumberger array is characterized by a slightly better coverage compared to other electrode arrays that are also common, such as the dipole - dipole and the Wenner - α already mentioned before (Alfouzan, 2008; Loke, 2004) and likewise, this new hybrid array has a depth of investigation superior to those already mentioned in this section. Apparent electrical resistivity data for each given profile were converted to a true resistivity distribution with Res2Dinv by Geotomo (Loke and Barker, 1996) which is based on the regularized least-squares optimization inversion technique. For each profile, we used a dataset or pseudo-section starting model and the smooth-constrained or L2 norm method (deGrooth-Hedlin and Constable, 1990) as a constraint of inversion technique.

3.3 Groundwater Quantity and Quality Monitoring

Groundwater level measurements have been taken manually in 16 monitoring wells within and near the boundaries of the study area since May 2015 (Figure 3). The frequency of the measurements is monthly, but from August 2016 to April 2018, no measurements were conducted. The monitoring wells in this area are inactive production wells approximately 30 meters in depth that were initially drilled to supply drinking water to the nearby communities (Castrellon Romero, 2018). In addition to groundwater level monitoring, water samples for chemical tests were collected from seven of these wells in March 2019 using the micro-purge method. These data were used to generate a Piper Diagram in order to identify the dominant water types within the study area.

4 RESULTS AND DISCUSSION

4.1 Geology

The predominant rocks of the Estibaná river sub-catchment are the vulcano-clastic rocks of the Pesé Formation (Paleogeno-Oligocene) and the volcanic rocks of the Playa Venado Formation (Upper Cretaceous). Other types of rocks are also observed, such as the limestones of the Changuinola-Ocú Formation to the north of the catchment within the distension area, and large weathered intrusive bodies of granodioritic composition near the headwaters of the Estibaná river.

The upper part of the Estibaná river sub-catchment is composed of basalts and fine-grained andesites, which are present in the beds of the Cacao and Arriba rivers, as well as in the upper part of the Estibaná river. The basalts and andesites extend throughout almost all of the southeast of the sub-basin (Figure 3) and show heavy fracturing, especially in the Rio Arriba area, which suggests the existence of regional faults crossing this region.

The middle part of the catchment, known as the Macaracas Valley, is composed mainly of pyroclastic material (lapilli tuffs) of the Pesé Formation. According to drilling cores, this formation is at least 300 meters deep within the valley. Longitudinally, the Pesé Formation extends from the foothills of the upper part of the sub-catchment to the middle and lower parts of it. In a very small area within the Macaracas Valley it is believed that there is a small layer of sandstone, created by erosion processes (Figure 3).This layer is associated with the Santiago Formation (Neogene-Miocene).

In the lower part of the sub-catchment, a zone of distension associated with the Ocú-Parita Fault has been identified. The Ocú-Parita Fault is an inverse regional fault that crosses the Azuero peninsula from West to East and has a steep dip north (Buchs et al., 2011). This zone of distension has several displaced blocks, which supports the concept of being a seismic damping fault zone. In the area adjacent to the fault, the Changuinola-Ocú Formation of the Upper Cretaceous is present. This formation is characterized by limestone rocks and volcanoclastic sediments (tuffs) intercalated with clays and silts.

Within the study area, intrusive bodies outcrops with different degrees of weathering have also been identified. Generally, the intrusive bodies of the central region of Azuero come from the batholith of Loma Montuoso, which is contains felsic magma that produces quartzodiorites and granodiorites. These quartz-dioritic bodies during the weathering generate "continental sands" with high contents of quartz and magnetite.

To the southwest of the sub-catchment we have found outcrops of the Valleriquito Formation (Eocene-Oligocene), whose rocks have high contents of silica and felsic minerals (between 60% and 70% of quartz), which coincides with the description of the Loma Montuoso's batholith. Likewise, outcrops of intrusive bodies of mafic composition and porphyritic texture have been observed, with well-developed hornblende crystals, which are very different from the intrusive bodies generally described in this region. These intrusives, which are identified as hypabyssal or subvolcanic bodies, have been found in three sites within the sub-catchment: In El Guabo, located west of the sub-basin near the La Villa river; in the sector of San Luis, near the Ocú-Parita Fault; and in the upper part of the Cacao River. The hypothesis explaining the formation of this magma is that during the tectonism and the displacement of blocks that occurred in the central part of the Azuero Peninsula, liquid mafic manga rose after the consolidation of El Montuoso and Valleriquito batholiths.

Table 1. Geological formations within the Estibaná sub-catchment.

Formation	Era	Period	Epoch	Rock Type	Age
Santiago	Cenozoic	Neogene	Miocene	Sandstones	5 Ma
Pesé	Cenozoic	Paleogene	Oligocene	Agglomerates and tuffs	23 Ma
Vallerriquito	Cenozoic	Paleogene	Eocene-Oligocene	Intrusive	28.4 Ma
Quema	Cenozoic	Paleogene	Eocene-Oligocene	Hypabyssal	28.4 Ma
Changuinola	Mesozoic	Cretaceous	Late Cretaceous	Limestones and tuffs	65 Ma
Playa Venado	Mesozoic	Cretaceous	Late Cretaceous	Basalts and lavas	65 Ma

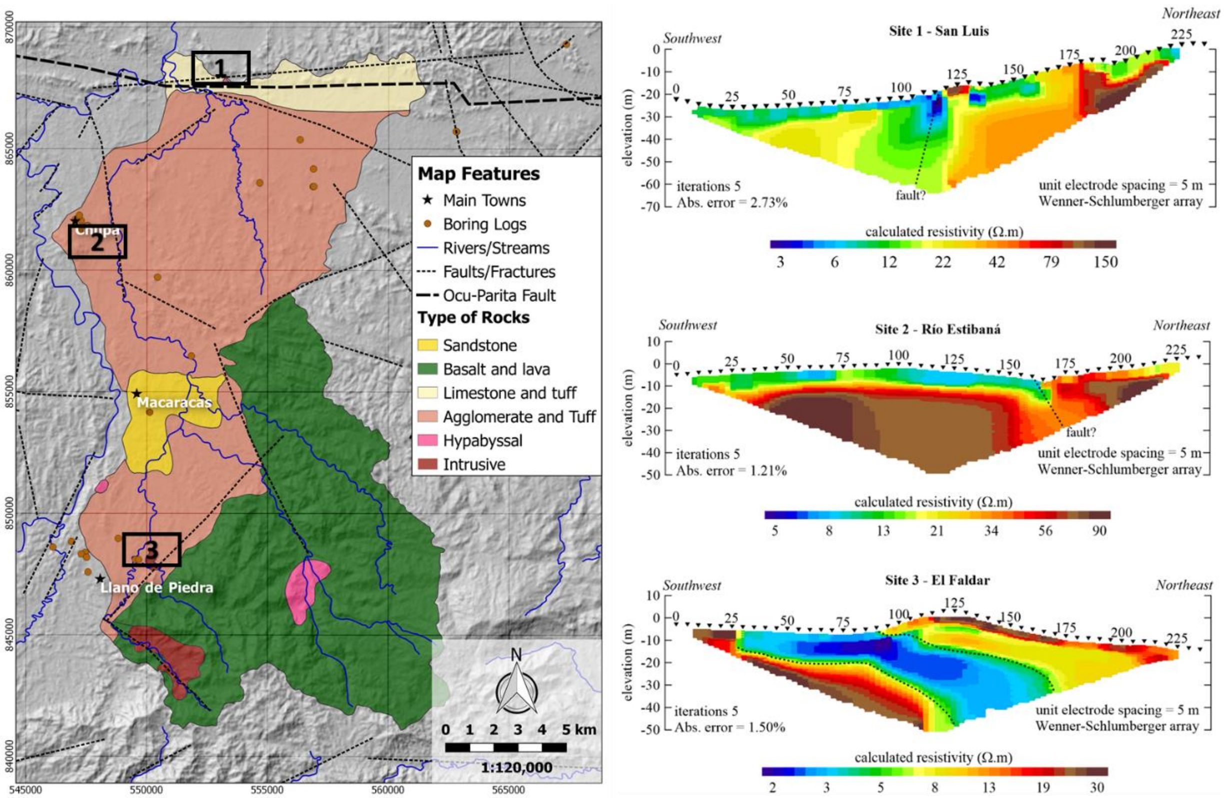

Figure 3. Geology of the Estibaná Sub-Catchment (left) and results from the ERTs (right). Inverted triangles represent electrodes.

4.2 Electrical Resistivity Tomography

The geophysics work focused on the exploration at three (3) different zones or areas of interest using Electrical Resistivity Tomography (ERT). Site 1 (San Luis) corresponds to the Ocú-Parita fault zone. In this tomography we find a low resistivity zone (in blue and light blue) with resistivity values from 3 to 6 Ω.m. The geological interpretation of this is that it could be the limit of the fault zone or a contact zone between the fault's intrusive and the valley's pyroclastic sediments. The northern part of the cross-section shows higher resistivity values (42 to 150 Ω.m) which could be associated with dense intrusive rocks which have been found outcropping near this site. Site 2 (Río Estibaná) shows an area of high electrical resistivity (34 to 90 Ω.m) at a depth between 15 and 20 m, which indicates the presence of intrusive rocks beneath the agglomerates. The low resistivity area between 150 and 175 m at Site 2 suggest the presence of a fault and/or fracture in this area. Site 3 (El Faldar) shows an area of very low electrical resistivity (2 to 5 Ω.m) in direction Southwest – Northeast which is associated with a very humid weathered intrusive.

4.3 Hydrogeological Units

Hydrogeological units, also known as hydro-stratigraphic units, are defined as a set of geological formations that have similar hydraulic characteristics (Anderson et al., 2015). In the Estibaná river sub-catchment there are six (6) different hydrogeological units, which correspond to the different geological formations described in the previous section. These formation/units are Playa Venado (basalts), Quema (fresh intrusives), Valleriquito (weathered intrusives), Pesé (tuffs), Santiago (sandstones), Changuinola-Ocú (limestones). The characteristics of these units are described below (Table 2).

Table 2: Range of hydraulic conductivities of the hydrogeological units from the Estibaná sub-catchment, estimated from literature (Singhal and Gupta, 2010).

Hydrogeological Unit	Type of Rocks	Hydraulic Conductivity [K] (m/s)
Playa Venado	Basalts and lavas	10^{-9} - 10^{-2}
Quema	Porphyritic crystalline rock (hypabyssal)	10^{-13} - 10^{-9}
Valleriquito	Weathered crystalline rock (granodiorites and continental sands)	10^{-9} - 10^{-8}
Pesé	Lapilli tuffs and agglomerates	10^{-9} - 10^{-7}
Santiago	Sandstone	10^{-6} - 10^{-4}
Changuinola-Ocú	Limestone and tuff	10^{-13} - 10^{-2}

In the tropics, it is common to find heterogeneous volcanic formations with highly permeable agglomerates and fractured lavas, intercalated with pyroclastic deposits that, depending on the degree of consolidation, can have a very low permeability (Foster, 1993). In the Estibaná sub-catchment the basalts of the Playa Venado formation are heavily fractured, which suggests that this formation may have a fairly high hydraulic conductivity (K). According to Singhal and Gupta (2010), the hydraulic conductivity for fractured basalt can vary between 10^{-9} to 10^{-2} ms^{-1}. On the other hand, pyroclastic rocks such as tuffs usually have a moderate hydraulic conductivity, in a range of 10^{-9} to 10^{-7} ms^{-1} (Singhal and Gupta, 2010). Depending on their degree of consolidation and weathering, tuffs can have a specific yield (Sy) of 0.10 to 0.20, which makes them a unit with large capacity for water storage (Foster, 1993).

In general, the hydraulic properties of crystalline/intrusive rocks depend on their degree of weathering and fracturing (Singhal and Gupta, 2010). Within the study area there are two different intrusive rock formations: Quema and Valleriquito. These formations have been preliminarily classified as separate hydrogeological units, since they show different degrees of weathering and fracturing. The Quema Unit/Formation contains mildly weathered fresh porphyritic intrusive rocks, while the Valleriquito Unit/Formation is heavily weather. Although a weathered rock is more porous than a fresh rock, the porosity is not directly proportional to the permeability of the rock. Therefore, although knowing the degree of weathering of the rocks helps in the hydrogeological characterization of the rocks, on-site tests must be carried out to determine their hydraulic properties.

The Changuinola-Ocú Formation has been described as a set of pelagic and hemipelagic limestones that were sedimented together with pyroclastic material on the shallow ocean floor (Buchs et al., 2011, Kolarsky et al., 1995). If the limestones are compact, their hydraulic conductivity is very poor (10^{-13} to 10^{-12} ms^{-1}). However, this formation is associated to a fault area where the limestones can be fractured and depending on the size and type of the fractures, the hydraulic conductivity can be up to 10^{-2} ms^{-1} (Singhal and Gupta, 2010).

The extension and thickness of the sandstones from the Santiago Formation are still unknown. It is suspected that it is not a very deep layer, since it is believed to be a hanging valley originated by erosion processes. Also, the degree of consolidation of these sandstones is unknown and therefore it is difficult to estimate their hydraulic conductivity. In general, the older the rock, the lower its porosity and its hydraulic conductivity, since they are more compact and the degree of cementation is greater. Some Tertiary sandstones have turned out to be very productive aquifers, such as the Dakota Formation in the United States and the Nubian Formation in North Africa (Singhal and Gupta, 2010).

4.4 Hydrodynamics

During 2018, groundwater levels in the study area were the lowest at the end of the dry season (May – July) and the highest after the wettest months (November – December). In general, groundwater levels peaked two to three months after the precipitation peaked (Figure 4A), a behavior that is common for wells in the greater La Villa groundwater basin (Castrellon Romero, 2018, 2016). Piezometric levels in tropical areas tend to be generally shallow and follow topography closely (Foster, 1993). In the Estibaná sub-catchment, Depth to water in most of the observation wells did not exceed 10 meters (Figure 4A). The only exceptions being PM-24 and PM-65 located in the highlands to the southeast of the sub-catchment (Figure 4B). Groundwater levels follow topography closely with higher groundwater elevations occurring in the highlands to the southeast of the study area (Figure 4C). Nevertheless, in environments dominated by volcanic rocks and consolidated sediments, faults and fractures are also important factors that control groundwater flow since they can behave as conduits or barriers that facilitate or impede the flow of water, respectively (Singhal and Gupta, 2010). Therefore, in order to understand the distribution of groundwater elevation in the study area, the effect of faults and fractures must be taken into consideration.

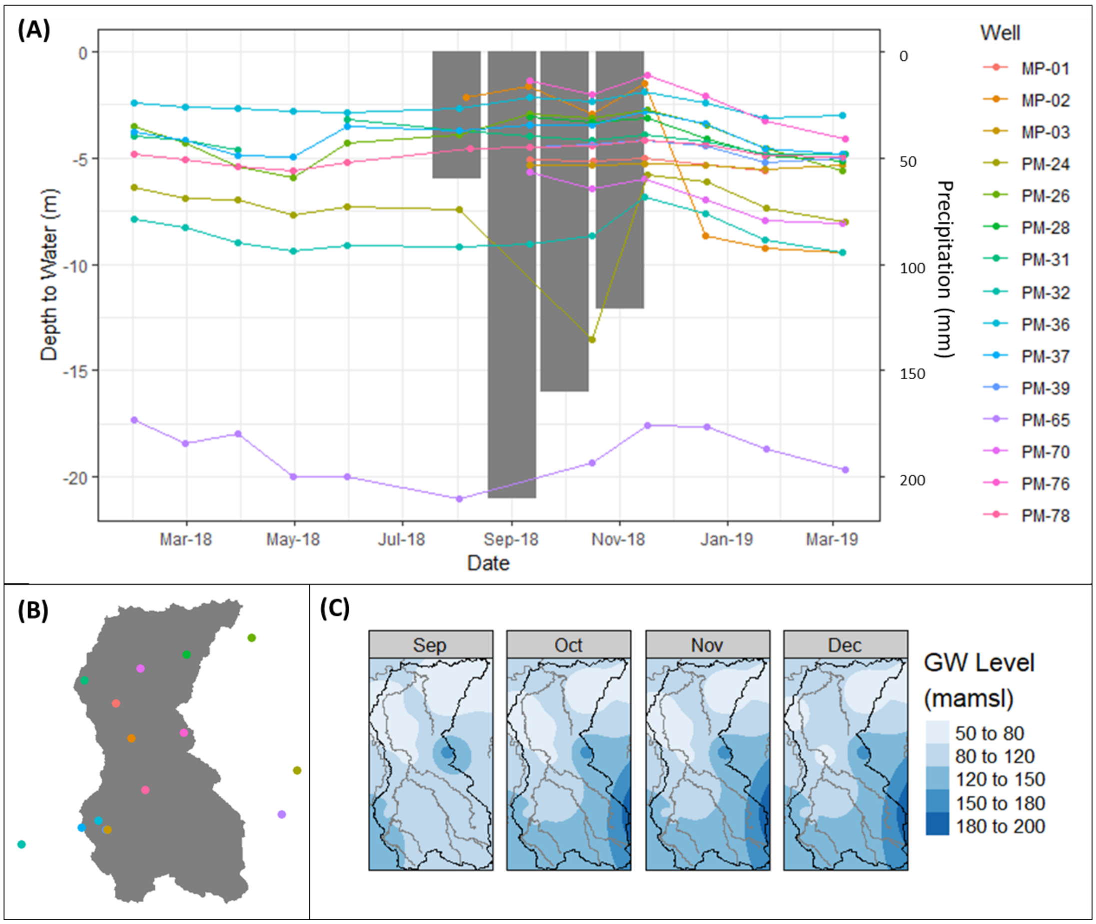

Figure 4. (A) Depth to groundwater in 2018 measured in the project's monitoring wells (lines) and precipitation recorded at rain gauge RG-02 (bars). (B) Location of the project's monitoring wells within the study area. (C) Interpolated groundwater elevation in the study area for 2018.

4.5 Hydrochemistry

In the Central Pacific Region of Panama, the predominant cations found in groundwater are Calcium and Magnesium and the predominant anions are Bicarbonate and Carbonate, indicating null cation exchange which suggests young water with low residence time (Souifer, 2010). Chemical analyses performed in seven water samples from wells within the catchment demonstrate that the water type for 4 out of 7 samples is Calcium-Bicarbonate (Figure 5), which again demonstrates the low residence time of water that was infiltrated not so long ago. This is consistent with the fact that groundwater in the tropics recharges every year during months of intense rainfall (Jasechko and Taylor, 2015).

In the study area we also found two samples with Sodium-Bicarbonate type water (PM-78 and MP-01), suggesting possible points of discharge for groundwater. This could be associated with the proximity of these wells to rivers which have been documented to be local discharge areas for groundwater in this type of systems (Castrellon Romero, 2018). Water sample from PM-39 is Sodium-Chloride type, which is not a surprise since this well had to be disconnected from the distribution network because the salinity levels exceeded the maximum allowed for domestic uses. Sodium-Chloride water types are very common in coastal areas due to saline intrusion. However, PM-39 is 37 km away from seashore. Geologic features such as a calcite of halite formation could be impacting the hydrogeochemistry of this well, nevertheless, the presence of these rocks in the vicinity of this well has not been documented yet.

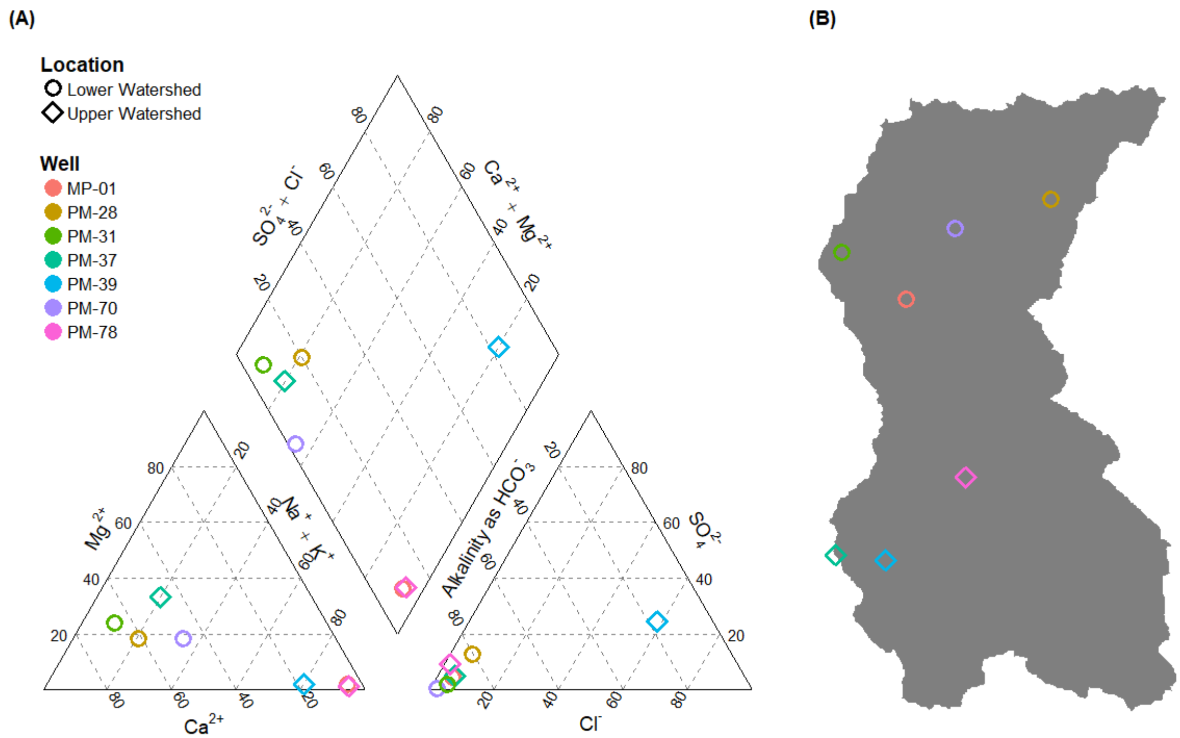

Figure 5. (A) Piper Diagram depicting the dominant groundwater types from selected wells within the study area. (B) Location of wells used for the groundwater sampling campaign carried out in March 2019.

5 SUMMARY AND CONCLUSION

In the Estibaná river sub-catchment there are six (6) different geological formations: Playa Venado (Basalt), Quema (Hypabyssal), Valleriquito (Granodiorite), Pesé (Tuff), Santiago (Sandstone), Changuinola-Ocú (Limestone). These formations have been preliminarily classified as different hydrogeological units since it is suspected that they have a different hydrogeological behavior. The basalts of the Playa Venado Formation show heavy fracturing, which is why they are believed to have a high hydraulic conductivity. The lapilli tuffs of the Pesé Formation are rather compact, so they are expected to have a low hydraulic conductivity, however the tuffs usually have a high specific yield, which favors groundwater storage. It is suspected that the Quema and Valleriquito Formations have different degrees of weathering and fracturing, so they have been classified as separate hydrogeological units, however, their specific properties cannot be estimated without first conducting field tests. The hydraulic conductivities of the sandstones and limestones of the Santiago and Ocú formations depend on their degree of cementation and fracturing. In the case of the Ocú Formation, it is possible that it has a higher hydraulic conductivity because it is in a fault zone, however, the Santiago Formation is difficult to estimate, as not enough tests have been carried out. It is important to note that the entire sub-basin in the process of development and consolidation. It continues to be affected by the tectonic processes that ultimately contribute to a differential fracturing of the geological units. This has led to the development of fractured zones, where several directions of fractures and faults converge. Also, in these sites or zones, high levels of weathering, infiltration and flow from the surface occur.

The groundwater flow patterns seem to follow topography very closely. Nevertheless, ERT results show that certain geological structures such as weathered intrusive rocks and regional faults can influence groundwater flows. The piezometric or phreatic levels are generally shallow and take two to three months to respond to changes in precipitation. Further, the hydrochemistry shows that the water is mostly Calcium-Bicarbonate suggesting young water recharged from recent rainfall events. However, samples close to the rivers are Sodium-Bicarbonate suggesting that these are local groundwater discharge areas.

Two key steps towards building a numerical groundwater model of the study area are: (a) to define the geometry of the aquifers; and (b) identify their hydraulic properties. As the geometry of different aquifers is determined by the geometry of their constituent geological formations, these need to be further investigated. To determine aquifers' hydraulic properties, field tests such as slug tests and pumping tests are needed. Further, geophysical explorations and field test would be required to better understand how topography and faults affect groundwater flow. Nevertheless, these tests can only offer insights into local groundwater flow. Only the development of a numerical groundwater flow model will help us understand how the presence of faults affect groundwater flow at a regional scale. Therefore, further research will include the use of MODFLOW-2005 and the Conduit Flow Process (CFP) package to simulate groundwater flow through faults within the study area. Once it is calibrated, the model could be used as a decision making tool, as it can simulate the effect of different climate change and management scenarios in the water balance of the Estibaná sub-catchment.

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