Assessment of groundwater flow dynamics and water quality in the alluvial fan of Fuego and Acatenango volcanoes, Guatemala

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Abstract

One of the biggest El Niño events ever registered occurred in 2015. In Guatemala, the rainfall values were reduced by 50% in four months of the wet season. This situation caused severe drought conditions in the Pacific basin. The water scarcity situation was managed by the formation of water users boards which successfully promoted dialogue between population and large users of water, the sustainable management of resources and the implementation of surface water monitoring systems. In this scarcity scenario, groundwater has been found to be an alternative for water supply. In countries subject to extreme climatic events such as Guatemala, integrated water resources management becomes an essential tool. To achieve water exploitation sustainability, the understanding of groundwater systems with a scientific basis is required. This thesis aims to generate a regional understanding of groundwater resources dynamics in the geological formation of Fuego and Acatenango volcano alluvial fan, which allows the development of strategies for the appropriate management and protection of groundwater. A field campaign for geophysical surveying and hydrogeochemistry sampling on wells, boreholes and springs were carried out. Interpretation of field data considering geographical, geological, climatic and hydrologic information of the area lead to: (1) the definition of a lithostratigraphic model; (2) the definition and characterization of the main hydrogeological units; (3) the identification of the preferential recharge areas and the calculation of the recharge; (4) the development of a conceptual model of the functioning of the groundwater systems; (5) the characterization of groundwater quality and the main geochemical and anthropogenic processes that determine it; and, (6) the planning of future groundwater monitoring and management measures. It is a pioneer study in Guatemala, with the valuable support of the ICC, which allow the establishment of new groundwater research goals in Guatemala at both local and regional scale.

Keywords: Groundwater, Geophysics, Hydrogeochemistry, Conceptual model, Guatemala

1. Introduction

Guatemala is a country located in Central America bordered by Mexico (north and west), Belize (northeast), Honduras (east) and El Salvador (southeast). It has a coastline of about 400 km with the Atlantic (Caribbean Sea) and the Pacific Ocean (south). The country has a wide volcanic arc with 37 volcanoes related to the subduction of the Cocos plate beneath the Caribbean plate, and three of them are still very active – Pacaya, Fuego and Santiaguito. Present and prehistoric volcanism in this region has significantly impacted both the regional landscape and the people of Guatemala. The Fuego Volcano, 44 km away from the capital Guatemala City, is one of Central America's most active volcanoes and last erupted on June 2018 causing a large number of fatalities and affecting more than 1.7 million people according to estimates by the Guatemalan authorities. Due to its geological, geomorphological and climatic characteristics, extensive agricultural production has developed during the last decades in the Guatemalan Pacific Coast. Cotton, banana, plantain, tobacco, sugarcane, palm oil and rubber, amongst others, have sequenced over time. This crop succession has been caused by three principal factors: market prices fluctuations, plagues and diseases and water scarcity events. In order to mitigate these crop risks, the Guatemalan Sugarcane Industries Association (ASAZGUA) invests a part of its resources for the optimisation and sustainability of sugarcane crop and sugar production. One of their main goals is to prevent new trigger events that would suppose a crisis in the sector, and oblige to change to a different agricultural production system. In this framework 2010, the Institute for Climate Change Research (ICC) was created to address adaptation and mitigation strategies for climate change impacts. Those strategies are to be conceived regionally, integrating local communities, environment and production systems. To achieve this goal, the ICC established five action lines: (1) Research on climate and hydrology; (2) Integrated watershed management; (3) Hazard risk management; (4) Productive systems sustainability; and, (5) Capacities development and dissemination. In a few years, ICC has become a key regional actor, coordinating work with local private companies, public institutions, local communities and international projects. The ICC research programme on climate and hydrology aims to generate information and analysis of meteorological and hydrological resources. These inputs lead to the development of scientifically based strategies that increase the life quality of communities, the sustainability of the agricultural production systems and the conservation of ecosystems and biodiversity. The research on groundwater resources is nowadays a primary matter for the ICC as this resilient water resource is crucial to guarantee water supply for the population, agriculture and to mitigate climate change impacts. A groundwater monitoring programme was set up in 2015 which includes the regular measurement of groundwater level in domestic shallow dug wells. El Niño phenomenon strongly affects the rainfall and temperature patterns along the western coast of America. In Guatemala, El Niño event produces a decrease of rainfall and an increase of temperature, leading to drought events. One of the three strongest El Niño events ever registered, which lasted 14 months, took place during the period 2014-2016, being called El Niño Godzilla [1]. This event reduced by 12% the rainfall during the rainy season (May to October) on the Pacific coast of Guatemala during the years 2015-2016 compared to average rainfall in the period 2007-2014 [2]. In 2016, during the wet season first four months (May to August) the rainfall accumulated was 50% lower than the average but the two last months were rainier than the average. As a result, discharge of main streams and springs was reduced by 50% in the last months of the dry season[3]. El Niño Godzilla event triggered a conflict for water availability that was enhanced by the unplanned and improvised water management practices that are common in the area. The irrigation demand peaks in the dry season, which generated a conflict due to water scarcity known as "Guatemalan Water

Crisis" between extensive agriculture water users and smaller farmers and communities [4]. In 2015, the major water consumers kept the usual intake rates from the rivers without considering the drought situation. Due to the severe drought, lack of water supply started in February for several downstream communities, industries and impacting the dependent ecosystems (mangroves). A national water law is not yet approved for Guatemala. In the last decades, more than 23 water law proposals have been rejected by the Congress for different reasons, including the interests of major water consumers or Mayan communities cosmovision of water management. The lack of a water law also meant that the public institutions could not address adequately the Water Crisis management and the different stakeholders in each catchment had to join together to negotiate a fair water distribution between communities, agriculture demand and ecosystems needs. Stakeholders' boards, management and monitoring systems were created that year and have successfully overcome the main problems proving to be a transitory solution until a national water law is approved, and public institutions have enough capacity to lead these processes. On the other hand, agricultural major water consumers who had to reduce the intake from rivers started planning groundwater development, along with measures to increase irrigation efficiency. Although this lead to a solution to the water scarcity problem, this solution can be considered short-term for several reasons. First, there is a lack of knowledge on groundwater resources dynamics, quantity and status so, by the moment, the well development planning has been "blind", or in the best of cases guided by consultants or perforation companies advise. Moreover, there is a lack of knowledge on the surface-groundwater interaction. In the 6-month dry season, the river baseflow mainly comes from groundwater. Hence, if groundwater is being overexploited and aquifer levels decrease, the investment that is being made at this moment for groundwater development might dry up the rivers again, leading to a similar crisis that in 2015. To summarize, groundwater development has come to be a fast solution to water scarcity issues for Guatemalan Pacific coast major water consumers. However, the deficient management caused by lack of information might lead to water scarcity problems in the mid-term. In order to perform proper groundwater management, it is essential to know in detail the hydrogeological systems and to coordinate the water use between the different users. In this context, this research aims to generate a regional understanding of groundwater systems which allows the development of strategies for the appropriate management and protection of groundwater. This includes pioneer research in this study area regarding recharge areas identification, hydrogeological units definition and hydrogeochemical description, the development of the groundwater system conceptual model and water balance first estimation.

2. Study Area

The study area is the Fuego volcano and Acatenango alluvial fan, also named after the main rivers in the area: Coyolate, Achiguate and Acomé (Fig. 1). It is a physiographical unit with an extension of 2,185 km2, and it is one of the most productive areas of Guatemala, where 91% of the land use is agriculture or cattle. The Guatemalan Pacific coastal plain is an extensive sedimentary wedge located between the Middle American Trench and the Volcanic Arc. Due to Cocos plate subduction processes, the Guatemalan Pacific coastal plain geology is a forearc basin formation, with a synclinal shape where the axis corresponds with the ocean shore [5]. Offshore deep well profiles which are closer to the coast present 200-meter deep Pleistocene

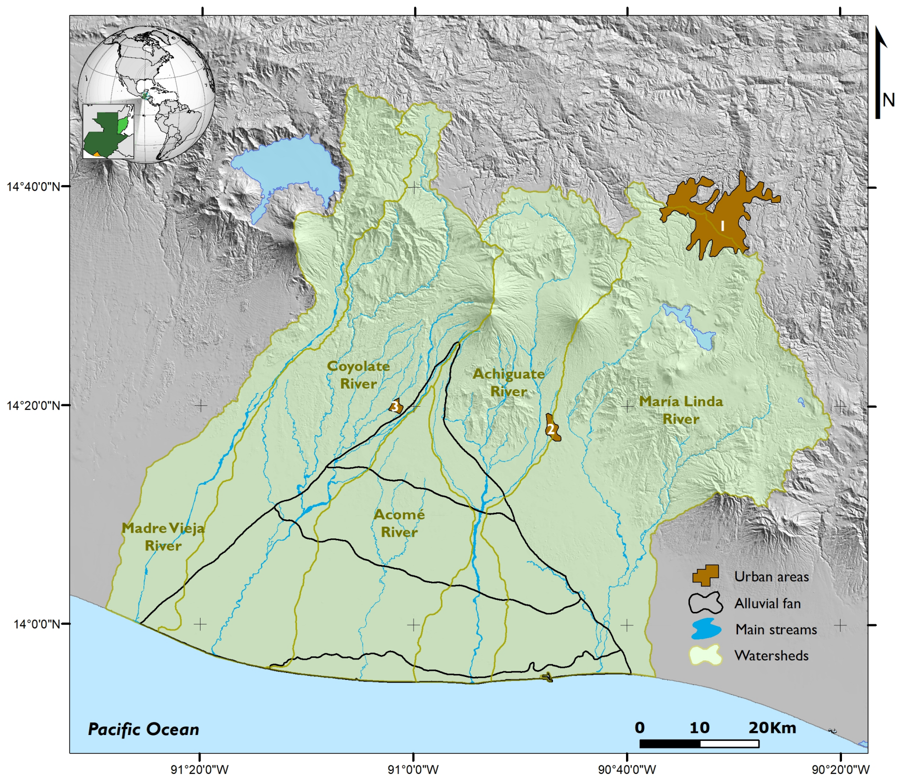

Figure 1: River catchments and main streams in the study area. Urban areas: 1. Guatemala City; 2. Escuintla; 3. Santa Lucía Cotzumalguapa. Please note the volcanoes located in the north-east of the fan vertex.

green mudstone with layers of sandstone, while the well profiles on the Pacific side of the trench present silicic mudstone layers. The Caribbean plate mudstone Pleistocene layers are followed by Pliocene and Miocene green mudstone with sandstone layers before the basic and ultrabasic rock basement (serpentinised peridotite) is reached around 2,100 mbsl [6].

The recent deposits in the coastal plain have their origin associated with the volcanic chain and outcrops in the river beds. Variability in the sediment flow is dependent on volcanic activity and the alternation of dry and rainy seasons, as well as synoptic extreme rainfall events [7]. These geodynamic processes created three extensive alluvial fans in the Pacific basin: Samalá River alluvial fan, Fuego volcano alluvial fan and Los Esclavos Alluvial fan. Due to the nature of these formations (rock blocks in sandy matrix to fine sands and clays), they probably correspond to aquifer formations [8]. The central Fuego volcano alluvial fan has the greatest extension, and it is one of the most agriculturally productive areas in the region due to its natural conditions: nutrient-rich soils, water availability and flat topography, this is the reason why it was selected as target unit for groundwater research. The hydrogeology of the Guatemalan Pacific basin is yet unexplored. Few studies have addressed this topic, most of them decades ago for irrigation purposes. While groundwater units are not well defined, physiographical formations might be an appropriate starting point to address the investigation and understanding of groundwater systems. Since 2015, ICC started monitoring shallow domestic wells in the Pacific basin; the analysis of the collected data indicates that the groundwater flow follows a north-south direction, as piezometry is strongly related to topography in unconfined detritic aquifers.

3. Methodology

Many studies have shown the significant contribution of geophysics to better defining aquifer geometries [9]. These subsurface investigation techniques clarify the geological structure and aquifer geometry [10][11]. Aquifer geometry can be defined at a catchment-scale with using remote imaging techniques to identify the geological formations, outcrops and aquifer possible extension. Afterwards, local scale studies can be performed with geophysical methods, to get finer results [12]. Hydrogeological characterization is usually completed with piezometric and geochemical studies. Hydrodynamic characterization is used to follow the spatial and temporal piezometric behaviour and determine the groundwater flow [13][14]. Groundwater chemistry may trace the water origin and water-rock interactions [15]. Therefore, both the hydrodynamic and geochemical properties are related to lithologic facies and geometric structure. All possible investigation methods and available hydrodynamical and hydrogeochemical data must be integrated in order to clarify the main aquifer units and their functioning [16]. In this study, a conceptual hydrogeological model will be built based on geology, geophysics, water balance and hydrochemistry: 1. Catchment-scale geometry was previously defined based on physiographical units. It was assumed that the aquifer corresponds to an alluvial fan. 2. Aquifer units are defined after carrying out a geophysical survey. Hard data, such as borehole logs, resistivity logs and previous studies available will be used to validate data interpretation and selected interpretative models. 3. Hydrochemical and natural isotope analysis will be used to describe local and regional flow systems. 4. Recharge estimation will be performed by a water balance method, chloride mass balance method and water table fluctuation method. The combined interpretation of the results of these methods will help to develop a conceptual hydrogeological model of the study area.

3.1. Experimental design

As no previous information about the regional hydrogeology of the area was available during the planning of the geophysical campaign, the spatial setup of the measurements was distributed as close as possible to a regular square grid. The idea was to generate north-south and west-east cross sections to assess the geometry of the formations. A total of 34 measurements were made, given the time and resources available. A total of 34 water samples where collected, in springs, dug shallow wells, deep drilled boreholes and rainfall collectors. Aqui podria poner brevemente donde se tomaron las muestras, los parametros de campo y el diseño de los colectores de lluvias. Samples were collected at the beginning of the rainy season, between April 26th and May 17th, 2018.

4. Results and discussion

4.1. Geophysical survey and borelog data

After survey data collection and inversion, three significant phenomena where identified in the study area: (1) a thick coastal aquifer which present signs of saline intrussion; (2) Shallow (thicker than 20 metres) clay layers distributed along the study area, which might form local semiconfined aquifer systems; (3) Resistivity values decrease outside of the alluvial fan formation, which indicates that either the material or the water quality in the previously defined study area is different than that of the surrounding areas. Available borehole logs assessment revealed the following phenomena in the study area: (1) a superficial unit formed by alluvial coarse and mixed material; (2) a deeper unit formed by silt and clay with coarse material interbeddings which might correspond to confined aquifer systems. This clay unit transitions from continental to marine towards the coast, the limit of this formation was defined using the available information. (3) Fractured andesites as underlaying formation in the northern area.

4.2. Lithostratigraphic model

A lithostratigraphic model was compiled taking into consideration all the knowledge generated by VES interpretation and borehole logging analysis (Fig. 2). These results will be used as a base for hydrochemical and isotope water analysis, and will be the basis for future numerical model development.

Holocene alluvial sediments (Qha, QhM): Alluvial deposits are superficially widespread in the study area, forming the main shallow aquifer unit of the alluvial fan. Although the formation is heterogeneous in grain size distribution, two large confining units where located. VES results revealed these formations have resistivities of 10 and 25. Confining units separate the alluvial coarser deposits creating a thin, shallow aquifer in the mid and low part of the alluvial fan and a thick regional semi-confined aquifer underneath.

Holocene marine sediments (Qhm): Beach coarse deposits are formed of unconsolidated coarse sand-sized sediment. They are located close to the littoral area and can achieve thicknesses over 150 metres, becoming the thickest aquifer unit in the coastal zone. Local water extractions have proved this aquifer to be highly productive.

Holocene volcanic debris (QvD): It is considered to be the result of mass colluvial movement processes. The unit is located in the northernmost side of the alluvial fan, formed by volcanic debris. Fieldwork observations describe the unit as a structureless mixture of volcanic dark sand, gravel, cobbles and boulders, with sandy silt to silty clay matrix. Rock fragments present a subangular shape. Formation resistivity range is the highest measured in the study area from 250 to 800Ωm.

Pleistocene alluvial sediments (Qpa): Mainly formed by a thick succession of grey clayey and green silty continental and lacustrine materials leading to formation resistivities around 15Ωm. Fluvial coarser deposits are interbedded in the formation. Although seldom fluvial deposits present clayey matrix, usually these units are a target of borehole drilling companies, which might indicate they form deep confined aquifer units.

Pleistocene marine sediments (Qpm, Qpms): Sand interbedding become less significant while clayey silt and clay layers become thicker in-depth. Marine fossils are found in this formation. Resistivity values range between 10 and 15 Ωm. Formation is significantly more extensive than the overlaying Holocene marine sediments.

Pleistocene transition sediments (Qpi): Deposits of mixed alluvial and marine origin have been mapped in borehole core analysis. A shift in low-end VES results was also measured in this transition zone, reaching resistivity values around 5Ωm.

Tertiary volcanic rocks (Tv): The subduction of Cocos plate started in the Miocene, generating vulcanism processes in the Central American volcanic belt. Fractured andesites have been found in deep borelogs in the northern part of the study area. Close to the study area, there are volcanic outcrops aged from the Tertiary, which are formed by tuffs, lava flow, laharic material and volcanic sediments. This formation is fractured and saturated. End-resistivity values correspond-

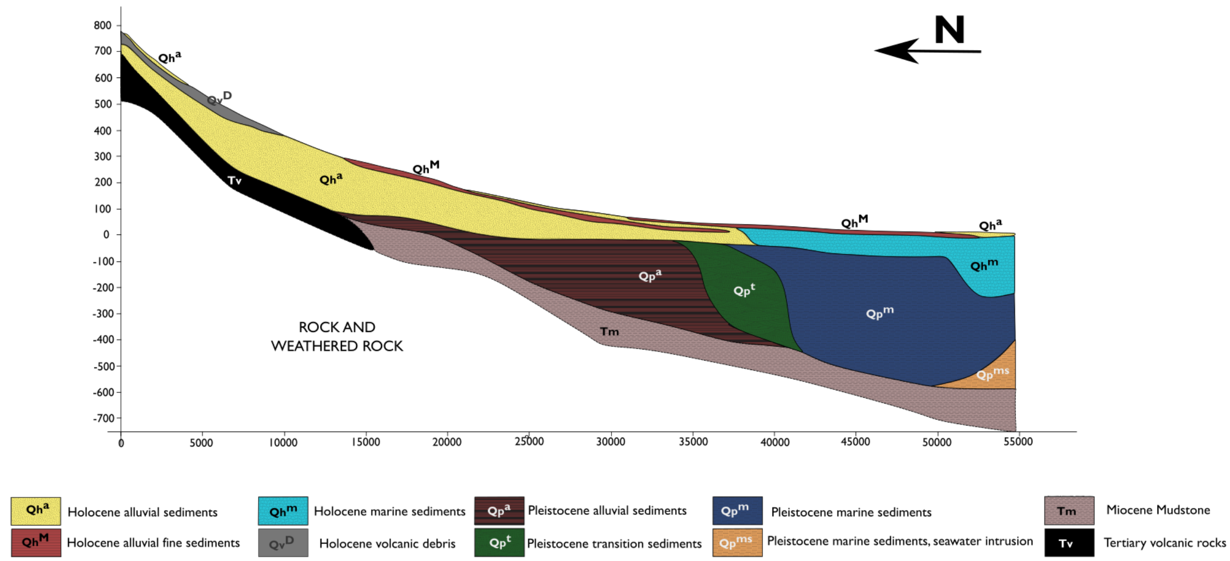

Figure 2: Alluvial fan lithostratigraphic model central cross-section. Qh= Holocene; Qp= Pleistocene; T= Tertiary; a= alluvial; M= mud; m= marine; D= debris; t= transition; v= volcanic; s= salinized; Maximum investigation depth was 800 meters, please note that lower boundary of Tertiary formations are delimited with a dashed line as depth of these formations is unknown.

ing to this unit are higher than the southern values, reaching end-resistivities between 15 and 25 Ωm.

Miocene mudstone (Tm): The deepest layer measured is most probably a massive mudstone Miocene formation. Low sedimentation velocity environments in the period when Cocos plate started subduction processes leading to vulcanism in the area. Similar deep Miocene mudstone formations have been identified in Chiapas, México [17]. The resistivity of mudstone can be as low as 1Ωm, matching the low-end resistivity of VES results. Miocene and Pleistocene mudstone layers were found in the DSDP near to the study area [6].

The combination of resistivity cross section and the lithostratigraphic model was performed to identify formation resistivity values for the identified lithological units. Archie's Law equations were used to calculate the pore water resistivity in different locations from electrical conductivity values measured during fieldwork. Water sampling location and well screens depth were used to identify the formation resistivity interpreted from the VES. Archie's law was used to define the formation factor, and the material corresponding to the calculated values according to standard values. Formation factors values in the area range from 1 to 7. The higher values correspond to basalt rock volcanic deposits which have coarse materials and low mineralized waters. Holocene alluvial sediments formation factor ranges from 1 to 4, as the unit would be composed of fine to coarse sand deposits with some local clay formations. Pleistocene continental deposits and coastal alluvial Holocene sediments would have a formation factor between 1 and 3, being composed with clay and fine sand fractions. Finally, the marine Pleistocene and Holocene formations have formation factors lower than 2, which indicates they are mainly formed by clay materials. However, significant deposits of coarse sands have been identified in borehole logs in the marine Holocene formation. The porosity of the rock is an essential parameter for aquifer numerical modelling. In the study area, formation factors decrease seaward. The porosity results are an example which should be corrected with analysis of drilling geological samples as effective porosity is the input for the model. These values would be required to refine the accuracy of this results. The geometry of the lithostratigraphic model was used to generate the solids part of a numerical model using Groundwater Modeling System (GMS) software. This can be the basis for further groundwater numerical model development, in near future research projects.

4.3. Hydrogeochemistry

Analysis of major ions was carried out at IHE-Delft laboratories. Major (Na, K, Ca, Mg) and other minor and trace elements (Mn, Fe, Ni, Cu, Zn, Sr and Pb) were measured using an Inductively Coupled Plasma Mass Spectrometry (ICP-MS). Anions (Cl, NO3, SO4) were determined using Ion Chromatography (IC). Bicarbonate (HCO3) was measured using a HACH titration kit in the field. Results accuracy was checked using the ion balance error. While all the samples presented an error lower than 10%, a 65% of the samples had an error below 5Field parameters reveal a general increase in groundwater temperature towards the coast. Superficial values range from 24 to 30°C, reaching 34°C for deeper wells due to the geothermal gradient. A spring collected at the highest sampling elevation has the lowest temperature of all sampling points but the spring with the second highest outcrop elevation has a water temperature more elevated than a nearby well, which can be explained because the spring was not accessible and had to be measured several meters downstream. Hence, the temperature measurement of that spring could be inaccurate. Electrical conductivity values increase towards the coast due to water mineralization. In coastal samples, shallow wells present higher conductivity values, which might be induced by the combination of three processes – irrigation recirculation, evaporation and seawater mixing processes. Water groups were formed based on hierarchical cluster analysis (HCA). Ward's method with squared Euclidean distance was used to group water types. Seventeen variables were used for the multivariate analysis: pH, EC, Na, K, Mg, Ca, Cl, HCO3, SO4, NO3, Na/Cl, SO4/Cl, δ18O, DO, Fe, Mn and Sr. Cluster analysis results suggest four groups of groundwater. Water type 1 corresponds to water with low residence times, which hydrochemistry can be used to describe low mineralized waters on recharge areas. Along the groundwater flow path towards the south, it gradually gains bicarbonate and cations, mainly sodium and magnesium. Water type 1 is formed by generally poorly mineralized oligohaline water sampled in springs and shallow wells in the northern half of the study area. This group contains the only monitored drilled well in the proximal part of the alluvial fan. Water type 2 corresponds with most of the deep pumping wells, used for irrigation purposes. Denitrification processes have already occurred. Despite high residence time in the aquifer system, main water type is still oligohaline. Water type 3 is formed by four wells located 2.5 and 8.5 km inland. Three of the wells are shallow, but one is a deep well screened between 73 and 218 meters below the surface. Although sampling points are shallow meridional wells high mineralization can be associated with elevated residence times. This group can possibly be related upward flows related to the groundwater system discharge area. Water type 4 is formed by only two samples from shallow wells, which are the closest to the coastline (1,161 and 469 m). This water type presents the highest ion concentration and highest

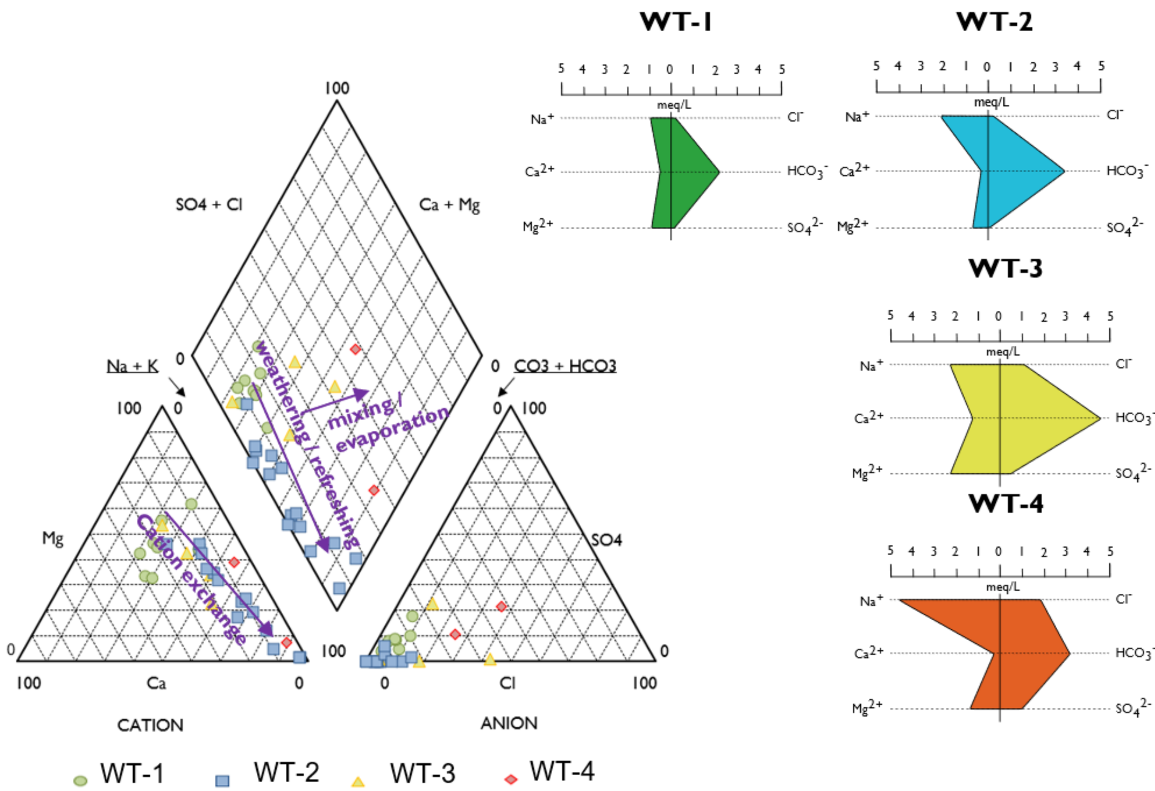

Figure 3: Piper plot of groundwater samples labelled as water groups and Stiff diagrams with mean values for each water group (values in meq/L).

electrical conductivity. However, it is still considered freshwater; further analysis will indicate that evaporation processes might occur instead of seawater mixing processes.

Process 1. Recharge Precipitation water entering the upper part of the system is very diluted, with EC values below 200μS/cm. Atmospheric carbon dioxide dissolution during rainfall process results in relatively low pH water entering the system. Furthermore, when entering the soil zone, additional carbon dioxide can be dissolved in water, increasing its reaction capacity [18]. Process 2. Increasing residence time: mineral weathering and cation exchange With increased aquifer residence time, weathering processes of a basalt aquifer matrix result in a cation composition evolution to a predominant sodium character. This evolution is attributed to the following geochemical processes: 1. Calcite precipitation/ mineral equilibria. 2. Cation exchange processes. 3. Sodium increase from volcanic glass hydrolysis and dissolution reactions. In the study area, the hydrochemical evolution from a Ca/Mg to a Na composition between water types 1 and 2 is evident, as can be seen in Piper and Stiff plots (Fig. 3). Overall in this process, a decrease in calcium and magnesium concentrations occur while sodium concentrations increase. Besides, pH values increase from 6.5 to 8.5. Apparently, mineral dissolution or mixing processes are essential processes responsible for hydrochemistry natural evolution in the study area. Process 3. Discharge Water type 3 shows high mineralized water near the surface. The highest bicarbonate concentration of this group indicates a high residence time in the aquifer. This might be the result of a natural upward flow when the aquifer water encounters seawater wedge. Hence, the area where water type 3 is found might be considered as deep aquifer discharge areas. It must be considered that intensive irrigation in the coastal area might be a trigger to upward artificial flow, resulting in evolved groundwater hydrochemical facies in the surface. Process 4: Evaporation / Mixing Very shallow groundwater levels can be found close to the coast, where the discharge area has been defined. That fact can result in evaporation processes, which enrich waters in ionic content. Moreover, intensive agricultural activities with such a shallow phreatic level might lead to groundwater pollution with fertilizers and pesticides. Chlorine values in water groups 3 and 4 are higher possibly to evaporation processes. Sulphate values and the Pollution Index, are higher in water type 4, probably related to agricultural activities or perhaps to seawater intrusion.

4.4. Isotope analysis

When rainfall isotope results are analysed spatially, there seems to be a relationship between the distance to the coast and δ18O. This relation is linear when the isotope content is compared to the altitude of the sampling point. As previously stated by other studies in the area [19], isotopic depletion occurs inland and is profoundly influenced by altitude. When groundwater and rainfall isotopic signatures are compared, it seems that the source of the groundwater should be in higher areas. However, due to the limited data availability, this assumption might not be accurate.

4.5. Recharge estimation

WetSpass distributed recharge calculation reveals that from the yearly amount of rainfall (3,684 hm3/ year) in the studied area, 51% is evapotranspired, 23.7% is transformed into runoff, and 26.7% becomes recharge. Wetspass calculations usually present an error of a small percentage. In this case, an average error of -1.7% resulted from the model computation, which is the reason why the percentages do not sum 100%. An integrated approach for recharge estimation using chlorine mass balance and Water Table Fluctuation method were performed. However data scarcity regarding continuous depth to groundwater and chorine concentration lead to "fuzzy" results. So far, distributed water balance results are to be considered as the best approach (Fig. 4).

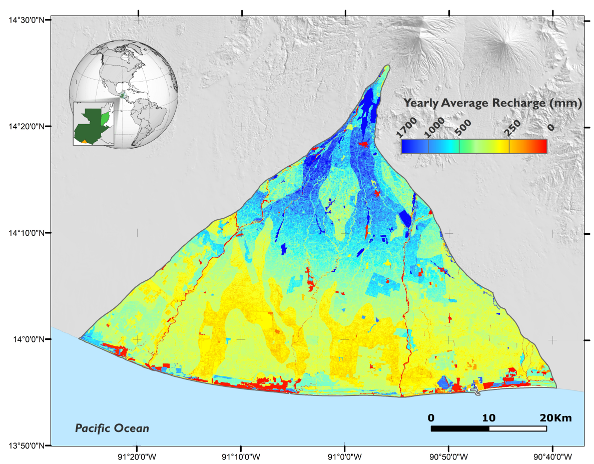

Figure 4: Piper plot of groundwater samples labelled as water groups and Stiff diagrams with mean values for each water group (values in meq/L).

5. Conclusions

This thesis aims to generate a regional understanding of groundwater systems of the Fuego volcano alluvial fan in Guatemala Pacific basin. In a context of global change, this knowledge is essential for appropriate management and protection of groundwater resources.

Detailed field campaigns were conducted for geophysical surveying and hydrogeochemistry sampling. Field data was integrated with geographical, geological, climatic and hydrological information of the area. This is the very first hydrogeological and geochemical study of groundwater resources with a regional scope in this region and an important part of the results may be considered pioneer in the study area: the development of a lithostratigraphic model describing subsurface formations; the development of a hydrostratigraphic 3D model; an hydrochemical characterization of the groundwater which reveals the hydrogeochemical processes that define groundwater quality in the area; the identification of main recharge areas and the quantification of groundwater recharge using a spatially distributed water balance model and two different groundwater recharge estimation methods (WTF and chloride mass balance); the definition of discharge areas; the identification of groundwater flow directions and areas with risk of saline intrusion.

The lithostratigraphic model defines a shallow semiconfined Holocene aquifer system formed by alluvial heterogeneous-sized materials. This formation reaches a maximum thickness of 150 metres, forming the bigger aquifer system in the study area. Besides, underlying Pleistocene continental and marine clay formations interbedded with coarse material layers most probably form a deeper confined aquifer system. Fractured Tertiary volcanic rocks have been identified in the northern part of the study area, which could form a locally water productive unit. The deepest identified formation has not been crossed by any of the bore logs drilled in the area. However, low end-resistivities indicate that a Miocene or Pleistocene mudstone formation, which has been identified onshore in Deep Sea Drilling Projects, is the most plausible underlying formation.

The hydrogeochemistry analysis identifies that groundwater undergoes basalt rock weathering since the recharge areas. Cation exchange becomes a significant process in areas where clay-rich formations become more abundant. Human influence in groundwater chemistry was not significant in most of the samples. Nevertheless, in the coastal area sulphate and nitrate concentrations tend to be higher than in the rest of the study area. Severe groundwater intrusion has not been detected in the study area. Still, geophysical and hydrochemical results indicate that the coastal area is vulnerable and a potential risk of saline intrusion exists and needs protective management measures.

Recharge processes are mainly defined by topography and precipitation volumes, due to high rainfall variability in the study area. Soil type has been found to have also a strong influence. Areas with higher rainfall present predominance of sandy soils; areas with lower rainfall present predominance of clayey soils. Action must be taken, so recharge processes do not decrease in the northern part of the study area.

The limitations of the present thesis methodologies and results have been thoroughly discussed in the document. Limitations include the study area delimitation criteria, limitations to assess temporal variations in the system, or the lack of regular piezometric level measurements, amongst others. The recommendations proposed in the last paragraphs of this conclusions set the basis to overcome these limitations and strengthen results.

Eventhough thesis results have a general regional scale, the findings lead to some immediate recommendations. The data collected during this thesis do not show a high impact due to severe saltwater intrusion or human-induced pollution. However, the results evidence that Fuego alluvial fan aquifer systems are vulnerable to saline intrusion and pollution. Scenarios where pressure on water resources is increased will lead to higher susceptibility to experience these negative impacts on groundwater systems. Therefore, investment in groundwater research is highly recommended as groundwater is a resilient water resource and prevention actions are cost-efficient when compared to extremely costly remediation measures. It is highly recommended that the current increase in groundwater resources exploitation should be accompanied by the generation of information for the proper monitoring of aquifer properties. This monitoring would allow the anticipation of groundwater quantity and quality problems and the application of minimization measures, which are much more cost-effective than remediation measures.

Deep irrigation boreholes pump sodium-rich water. On the long term, this can lead to soil salinization, which is a known issue in some sectors of the study area. Henceforth, irrigation with these waters should be reduced, and combined with shallow aquifer or river water. In any case, this phenomenon must be further studied to assess the impacts of this practice.

From the actual state-of-the-art and the results of this thesis, the proposed future research guidelines are the following. There is a fundamental assumption that has been taken in this thesis. The alluvial fan was selected as a hydrogeological study area and was studied as a closed groundwater system. However, it is probable that water flow occurs across this physiographical unit boundaries, as the alluvial fan adjacent units can be hydrogeological formations. A possible initial project to overcome this assumption is to generate detailed geological maps of the Guatemalan Pacific basin. In addition, studies similar to this thesis could be replicated in adjacent areas where an aquifer formation would be expected. Furthermore,the extension of the piezometric levels monitoring network outside of the study area can be a primary indicator to assess groundwater flows.

While the present thesis was performed at a reconnaissance scale, indicators of inceptive seawater intrusion processes were found. A detailed study of the saline intrusion status in the coastal area would be recommendable. Electrical Resistivity Tomography would be a useful method to assess saline intrusion in detail. Besides, further groundwater quality analysis of drilled and shallow wells during different seasons should be performed.

The study area is an agricultural region. As such, pollution of shallow groundwater bodies is a risk. Studies addressing the effects of agricultural and population activities in the groundwater is advisable, mainly because the groundwater is the primary water source for the dispersed population in the rural areas. Furthermore, an assessment of the groundwater use and pollution in the households, followed by a dissemination campaign is suggested. During fieldwork several domestic wells were found to be dug next to the kitchen, clothes washing facilities or even in some cases next to latrines. This work could begin in local schools with children, which are always fast learners.

Aquifer parameters of specific yield and hydraulic conductivity for each of the defined units must be estimated. With the defined hydrogeological units, aquifer numerical modelling could be performed. Numerical modelling can be used for the assessment of the impacts of human activities in groundwater, and the outcome of the possible solutions. Furthermore, future scenarios could be used to predict climate change impacts in groundwater bodies.

Once these requirements have been accomplished, given the global change context of the area and the active human component in water systems, a management tool like Water Evaluation and Planning System (WEAP) would be the ultimate decision support system in the area, based on the most innovative tools and methods.

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