Estimating the role of mountain block recharge for hydraulically connected alluvial aquifers

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Resumo

O Vale do Cauca na Colômbia é cercado por dois limites impermeáveis. No entanto, estudos recentes descobriram que as montanhas podem contribuir significativamente para a recarga do sistema aquífero no vale, estimada em cerca de 200-500 mm/ano. Este estudo localizado numa área elevada da Cordilheira Central, na sub-bacia de Aguaclara, tem como objetivo estimar a contribuição potencial para a recarga do sistema aquífero do fluxo regional em que a água circula através dos basaltos da Cordilheira Central do vale. O balanço hídrico sugeriu um valor máximo de 25 mm/ano para a recarga do sistema, sob condições favoráveis à recarga do conjunto de montanhas. A hidroquímica e os isótopos estáveis sugerem que existe de facto relação entre as áreas mais elevadas e a água no sistema aquífero, apresentando a amostra mais empobrecida um valor de $\delta^{18}O$ de 12.1‰ semelhante aos valores determinados nas áreas mais elevadas. Os resultados desta pesquisa mostraram que o basalto da Cordilheira Central parece ter um papel importante no armazenamento de água durante a estação mais húmida, com uma recarga estimada em cerca de 32% da precipitação anual. No entanto, a água é armazenada por tempos de residência curtos e usada para a evapotranspiração e o excesso deixa a bacia como escoamento superficial contribuindo para recarregar o sistema aquífero no Vale após percolação nos depósitos aluviais.

Palavras-chave: Hidrologia de montanha, recarga de águas subterrâneas, recarga de blocos de montanhas, balanço hídrico, hidroquímica, isótopos estáveis.

Abstract

The Cauca Valley in Colombia is surrounded by two impermeable boundaries. However, recent studies have found that the mountains can significantly contribute to the aquifer recharge in the valley, estimated between 200-500 mm/year. This study, focused in a high elevated area of the Central Cordillera, in the Aguaclara sub-basin, to estimate the potential contribution to the valley aquifer through regional flow system traveling in the basalts of the Central Cordillera. The water balance suggested a maximum potential of 25 mm/year to the system recharge, under favorable conditions to the mountain block recharge. Hydrochemistry and stable isotopes suggested that there is in fact connectivity between the higher elevation areas with the water in the aquifers, founding the most depleted sample of $\delta^{18}O$ of 12.1‰, similar to the values of the most elevated areas. The results of this research showed that the basalt of the Central Cordillera seem to play an important role to store water from the wet seasons, with an estimated recharge of about 32% of the yearly precipitation. Nonetheless, the water is stored for short residence periods and then it is used for evapotranspiration and the excess leaves the catchment as surface runoff to recharge the aquifers in the Valley after percolating in the alluvial deposits.

Keywords: Mountain hydrology, groundwater recharge, Mountain block recharge, water balance, hydrochemistry, stable isotope

Table of Contents

List of Figures

List of Tables

List of Acronyms

MBR	Mountain block recharge
NGTs	Noble gas temperatures

List of Symbols

Enter your text	Enter your text (without dot at the end)

List of Software

Baseflow SWAT	Baseflow separation tool from SWAT model
BFI	Baseflow separation tool from Stockholm university
Chemdiagnosis5	Water chemistry analysis
PHREEQC	Inverse geochemical tool

Chapter 1

Introduction

This chapter provides a general overview to the region where this study was carried out in Colombia, and explains the relevance of the objectives established for this research, as well as the description of each of these objectives, and hypothesis of how this work could contribute to the water management tasks in the study area.

1.1 Background

Groundwater use has been a solution for the increasing demand of freshwater resources around the world. However, its extensive use is a concern for the water agencies aiming to implement measures so that the water resources are used in a sustainable way, to avoid fast development of an area at the expense of the environment and freshwater resources. Since 2015 awareness of sustainable development has increased as it is one of the main objectives of the United Nations (UN), hence, it is important to understand what this terms means. The UN website defines it as "*development that meets the needs of the present without compromising the ability of future generations to meet their own need" (United Nations).* From a water resources perspective it could be interpreted as using the available water that is part of our lifetime cycle, amount of precipitation that falls within our life cycle and the contribution to recharge of it to groundwater, and not the use of fossil groundwater.

The amount of fresh water available in groundwater is 30 times larger than the amount within rivers and lakes worldwide, it can also be found almost everywhere with good quality conditions. These characteristics make it play an important role in both the environment and economy (IGRAC). At the same time groundwater is vulnerable to overexploitation and its inappropriate use can be reflected in reductions of surface water as stream flow and lake levels, land subsidence, salt water intrusion and changes in the water quality (U.S. Geological Survey 1999). Hence groundwater recharge quantification is a basic prerequisite for a proper resource management (Lerner et al. 1990).

(Lerner et al. 1990) defined groundwater recharge as "the downward flow of water reaching the water table forming an addition to the groundwater reservoir". When considering natural recharge, the described flow may come from either precipitation percolating through the soil and reaching the water table, or from losing streams, rivers, lakes, and wetlands. As water is constantly coming into the system, it leaves it as discharge to surface water and as evapotranspiration (U.S. Geological Survey 1999). Thus it becomes necessary to estimate the real change in storage of the groundwater reservoir to have a good estimation of the amount of water available to abstract that is in fact renewable.

Different methodologies have been developed for the estimation of the groundwater recharge, including direct measurements (groundwater heads, lysimeters and seepage meters), water balances, tracers (environmental and natural), Darcian methods (measurements and modelling) and base flow discharge analysis. Groundwater analyses are often done by integrating two or more methods, either in the estimation of recharge of for the validation of results. This is a normal process since there is not a fixed methodology due to the uniqueness of each system.

(Scanlon et al. 2002) explained how by using as many methodologies as possible it is possible to reduce the uncertainties associated to individual methods, hence the error can be constrained and the reliability of the results improved. The uniqueness of each groundwater systems requires a particular analysis that adjusts to the conditions of the study area. Groundwater modelling has the capability of integrating different methods according to the available data, and because of this, it has become a standard tool for hydrogeologists to evaluate recharge, discharge and obtain a sustainable yield for the aquifers (Zhou and Li 2011).

(Manning 2011) and (Zhou and Li 2011) explained how all groundwater models are a simplification of the real hydrogeological systems with many geological simplifications that are often needed due to the data scarcity, but also simplified physical boundaries. Boundary conditions of the model deal with the surroundings of the study area, making them a highly vulnerable aspect (O. Lehn et al.).

One common assumption for aquifers adjacent to mountains is that the boundary between the mountain front and alluvial basin can be considered as a closed boundary, with only important transfer if the rock is highly permeable (Lerner et al. 1990). Another traditional approach to estimate the mountain block recharge (MBR) is to assume that all of it comes as flow in the streams from the rivers entering a catchment, infiltrating to the aquifer by the riverbed. However, it has been concluded that the particular conditions of mountainous catchments (orography, soils thickness, temperature elevation lapse, potentially higher albedo) usually lead to a higher amount of water coming in than the water leaving the system as discharge and evapotranspiration (Wilson and Guan 2004). This could imply that the difference between the water entering the system and the amount leaving the catchments as surface water or loss in evapotranspiration, is percolating to the bedrock and moving through it, potentially reaching aquifer located in the lower areas.

Recent studies that have focused on the groundwater recharge coming from the mountain block, found that it can be more relevant than previously considered (Ajami et al. 2011; Doyle et al. 2015; Manning 2011)(Doyle 2013; Earman; Flint et al. 2002; Gleeson and Manning 2008; Guan 2005; Kao et al. 2012; Manning and Solomon 2005; Wilson and Guan 2004). In most of these studies as well as in the present research MBR refers to subsurface inflow to an aquifer from the adjacent mountains. Manning has explained why the study of the mountain research has gained importance in recent years: "While potentially important, MBR remains poorly understood, primarily due to the complexity of mountain-block hydrologic systems coupled with scant subsurface hydraulic data from mountain blocks and mountain front zones" (Manning 2011). The described conditions explain why a more conscious approach should be taken when estimating the mountain block recharge, contrary to the assumption of the mountain being a physical barrier, since it could represent an unaccounted and constant source of water. Not all modellers make the assumption and try to include MBR in the models, but it is usually introduced in the calibration stage, and used to obtain a match between observed values and the results of the simulation (Kao et al. 2012).

1.2 Problem definition

Mountain block recharge is still a poorly understood process and direct evidence of its existence is rare (Wilson and Guan 2004). Nevertheless, its relevance has increased over the past 25 years since studies in different locations have found that it could account for over 20% of the recharge to an aquifer (Manning 2011). Mountain block recharge could be an underestimated parameter in most of the groundwater models that assume that the bedrock is an impermeable boundary (Guan 2005). With this assumption or even including the MBR as a calibration parameter, it is possible to force a good match between observed hydraulic heads and modelled ones giving the impression of an accurate model (Kao et al. 2012). However, it has been found that the inclusion of the MBR data can improve the calibration process of the models inducing more constraints to the ranges used for different parameters of the models (Doyle et al. 2015).

On the other hand, even when mountain block recharge has been included, high overestimations have been introduced into the models (Gleeson and Manning 2008; Manning and Solomon 2005) due to the complexity of mountainous regions and consequent complicated hydrology (Wilson and Guan 2004) and the difficulty in validating the magnitude and even the direction of flow moving through the fractures (Gleeson and Manning 2008). Advances in technology and computing power can help to integrate multiple recharge estimation methods to obtain reliable calculations of MBR. However, as with most groundwater parameters MBR will be specific to each hydrogeological system and the results should not be extrapolated to other systems. (Doyle et al. 2015) found that apparently similar systems in Oregon, US and British Columbia, Canada showed the contribution to MBR from the precipitation differed from 8% to 70%. This demonstrates how challenging it might be to include the recharge from mountain systems to adjacent aquifers.

Understanding the contribution from the mountain block recharge to a system is one of the main challenges for water management in order to estimate a safe yield for aquifers. Safe yield is included in the water budget approach use by water management and refers to a use under the condition that natural groundwater recharge is higher than withdrawals (U.S. Geological Survey 1999). Another important particularity of the mountain block is that it is highly vulnerable to climate change, due to the reduced capacity of water storage (Wilson and Guan 2004). This might not be true where, as in Colombia, natural ecosystems present at high elevation have an important function in regulating the water cycle thanks to the vegetation characteristics.

Colombia is one of the richest countries regarding water resources (FAO 2003). However, the country is sensitive to climate change and currently, some areas are under stress because of anthropogenic activities such as mining (both legal and illegal), deforestation, and unplanned development and cattle raising. Another factor is the natural distribution of precipitation, controlled by atmosphere front conditions, distance to the ocean, solar radiation, topographic conditions, and vegetation (Guzman et al, 2014). In recent years more attention has been given to the proper management of water resources. Programs like “Water Funds” (Fondos de Agua) are helping to protect watersheds to guarantee future water resources. These programs are being carried out in the main regions of the country, in Bogota, Medellin and the Cauca Valley (Sostenibilidad Semana 2014).

For the Cauca Valley sugar cane production represents 38% of the GDP, and its productivity has been recognized internationally (Casa Editorial El País Cali). The geographical location of the region gives certain advantages that allow production throughout the year. The absence of seasonal changes in temperature benefit the yield of crops, yet precipitation has a seasonal behaviour that could decrease the crop yield. To ensure an optimal amount of water for the crops both surface water and groundwater are used for irrigation. It is estimated that 94% of the extracted groundwater goes to irrigation in the region, and 2 % is dedicated to supply over one million of inhabitants (CVC 2014).

Given the relevance of groundwater for the economic development of the region, a proper management of water resources needs to be carried out. Water resources are controlled by the regional agency that has worked with Deltares and IHE to assess the characteristics of the aquifer and establish operation policies for a sustainable use of the resource, obtaining both conceptual and numerical models of the regional aquifer that are useful for assessing the impacts of extraction and climate change. Studies as the one by (Cespedes 2017) are helping to understand the interactions of surface water and the aquifers in the Cauca Valley. However, given the lack of information the aquifer boundary conditions of the numerical model ignore deep flow coming from the bedrock, considering that the water coming from the mountains enters the system as surface flow and subsequently recharges the alluvial aquifer through river infiltration. In the interpretation of the system it was assumed that even if there is presence of regional flow through the bedrock that reaches the aquifer as MBR, the amount of water coming is not significant in comparison to the direct recharge from rain and rivers. Estimating the potential of MBR conditions of the study area could be crucial given that the valley is surrounding by the Western Cordillera on the West and by the Central Cordillera on the west side.

1.3 Research objectives

The general objective of this research is to assess the potential occurrence and relevance of recharge from the mountain block to the Cauca alluvial aquifer, as well as to establish an estimate of the amount of recharge that occurs from this source. The following specific objectives need to be addressed in order to achieve the main objective:

- Based on long-term rainfall and runoff data evaluate the occurrence of a missing component in sub-catchment water balance that could account for MBR.
- Use the baseflow separation to estimate the potential of recharge.
- To establish hydraulic connectivity of the mountain block to the adjacent aquifers.
- To produce a conceptual model of the hydrology of the catchment.

1.4 Hypothesis

Previous studies in the Cauca valley have shown that higher elevation areas tend to have larger recharge values (Cespedes 2017; Deltares 2016), however, it has been considered that there are no underground fluxes coming from the mountains. Recent studies have found that mountainous areas could significantly contribute to the recharge of adjacent aquifers through regional flows moving in the so far assumed impermeable rocks as those found in the Central Cordillera. The hypothesis is therefore that the hydrological processes in the mountainous region that are yet to be understand, are contributing to the groundwater recharge in the adjacent Cauca valley alluvial aquifer, moving through fractures and faults in the bedrock.

Chapter 2

Study area

This chapter provides the location context of the area, and establishes the connection between the study area and the region where it is located. An overview of the genereal characteristics that could affect the hydrogeological study carried was also done.

2.1 Introduction

The general location of the study area is presented in Figure 1. The study area is a tributary of the Cauca River which has a longitudinal extension of 1350 km, with a drainage area of about 63300 km^2. The Cauca River is the second largest river in Colombia, crossing through six different states of the country before joining the largest Magdalena River. The study area is located in the Cauca Valley state, with an area of 3470 km^2, and an average elevation of 1000 m.a.s.l. The valley is located between the Western Cordillera and the Central Cordillera of the Andes mountains. The elevations of the mountainous area contributing to the Cauca River go up to 4100 m.a.s.l. The big difference in area between the catchment and the valley itself explains the importance of the contributions from the mountains around the Cauca Valley. The main tributaries to the Cauca River are Ovejas, Timba, Palo, Amaime, Riofrio, Tulúa, Bulalagrande and Guachal rivers.

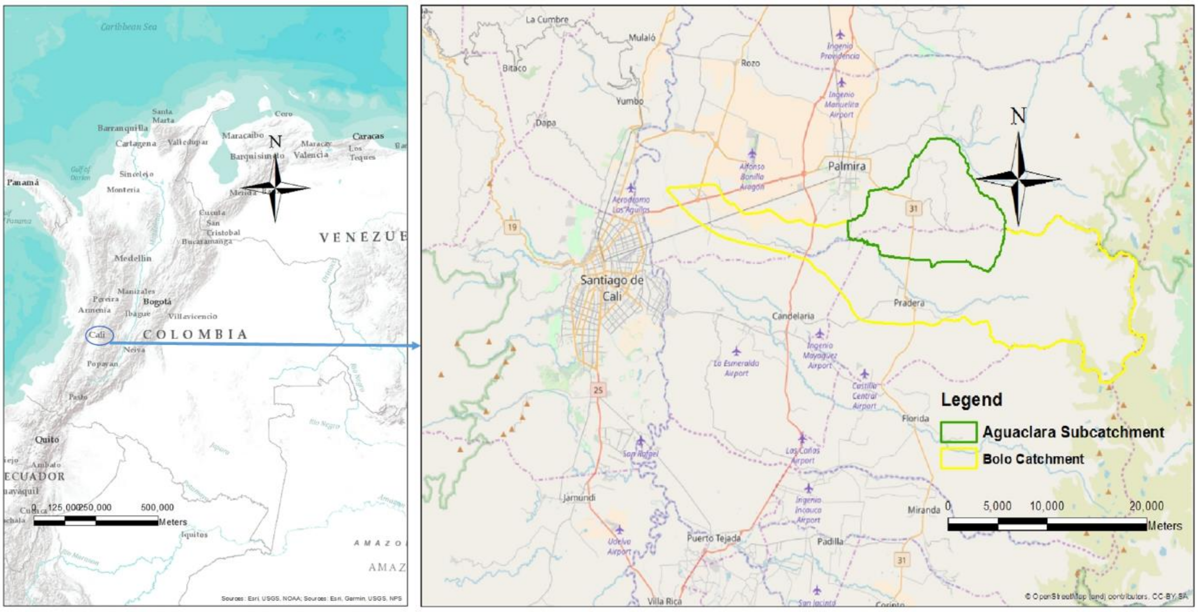

Figure 1 Study area location

Guachal major contributors are Fraile and Bolo rivers. The catchment for the Bolo River is marked in Figure 1 by the yellow line, it has an area of 410 km^2, including a large range of topography going up to 4100 m.a.s.l., through this large and variated area different elevation zones can be found, which produce diverse ecosystems on themselves Cespedes (2017). Interaction of surface water and groundwater for the Bolo catchment was studied by Cespedes (2017) as part of the project Eviden4Policy. Information and results from that research has been an important contribution to the current research.

Within the Bolo Catchment the second largest tributary is formed in the study area of this project; in the sub-catchment Aguaclara, highlighted in green in Figure 1. Located between the western part of the Central Cordillera, and the Cauca Valley, with a total area of 112, 69 km^2, and elevations between 1000 and 1850 m.a.s.l. As shown by Figure 2, the catchment has a dense drainage network, mainly in the higher areas. The multiple streams from the elevated areas create the rivers of major order. In the study area the main rivers are Aguaclara River and Vilela River.

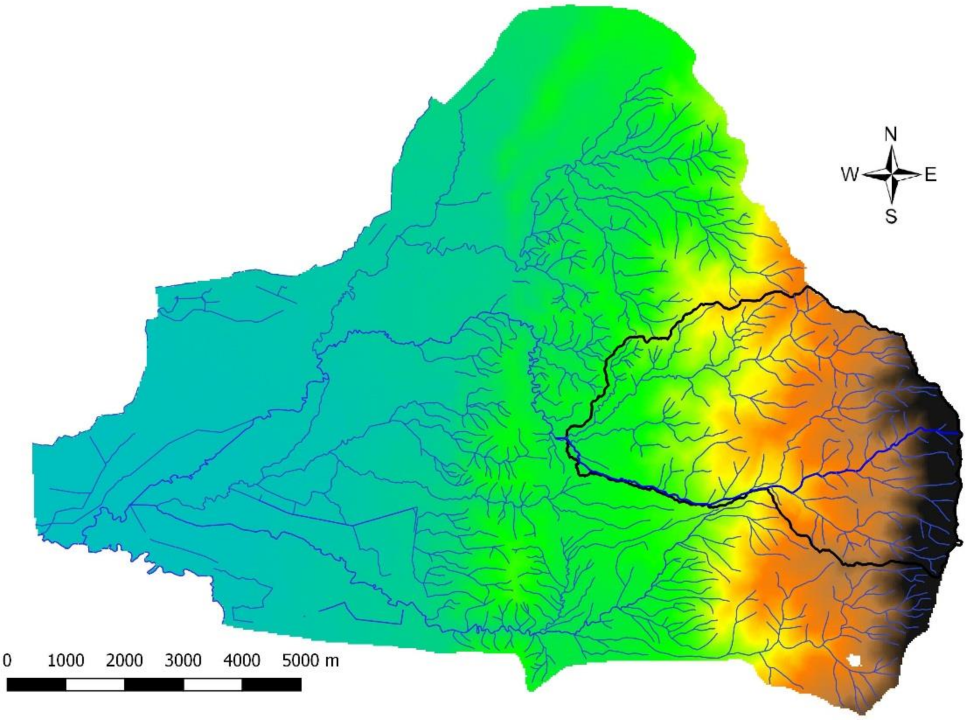

Figure 2 Hill shade and stream network Aguaclara

In the higher parts of Aguaclara catchment, highlighted in Figure 2 by the black line, Cenicaña has installed a dense monitoring network to evaluate the impacts of land use change on the overall water availability. Founded in 1977, the Colombian Sugar Cane Investigation Centre (Cenicaña), is a non-profit private corporation. Supported mainly by the sugar mills, the goal of the centre is to contribute the development, competitiveness and sustainability of the sugar cane agroindustry in Colombia Cenicañá (2014). Given the relevance of water for the agroindustry, one of the focus of the institution has been the availability of water, collecting important information over the last 3 years in the area.

The monitoring network occupies 21 km^2, representing 18.56% of the total area sub-catchment as shown in Figure 2. The streams within this area originate from 1200 to 2800 m.a.s.l. while the entire sub-catchments is between 1050 to 3100 m.a.s.l. According to the division established by the Territorial Management Plan, the study area includes all the orographic classes, from plains to high slope areas with high torrentiality and intermittent discharges being an important characteristic (Plan de Ordenamiento Territorial / 2000). The existing instrumentation is an ongoing project started in 2012, which has been complemented over time. However, this means that the data is limited for a short period.

2.2 Climate

In Aguaclara, and in general for Colombia, the climate conditions will be determined by its elevation and proximity to mountains. It is predominately a temperate area, with warmer conditions in the lowest part of the catchment that follows the dry adiabatic temperature lapse rate of 0.6 °C reduction per increase of 100 m elevation. Regarding precipitation, it has a spatial distribution, as a result of topography, being direct relationship with elevation. As for temporal distribution, the behaviour is bi-modal, consisting of two dry periods and two wet periods. The first dry season is usually between December and February, followed by a rainy season starting in March and finishing in May. Then the second dry season starts in June and finishes in September, followed again by a rainy season from October to December Deltares (2016).Figure 3, presents the pluviometric calendar of the region. However, the precipitation is affected by the ENSO phenomenon, which influences the precipitation patterns, creating longer periods of either season.

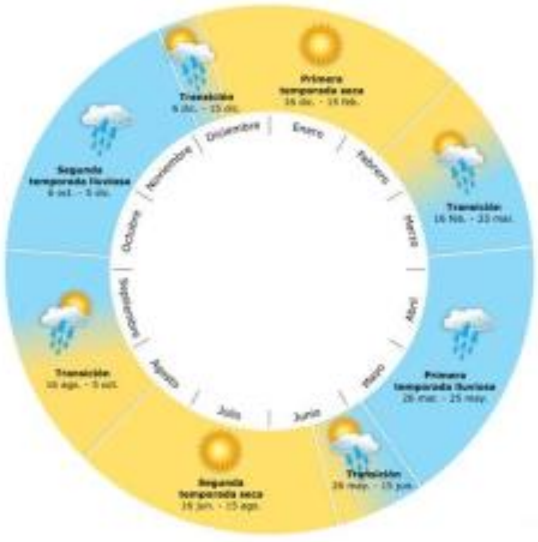

Figure 3 Annual pluviometric calendar. Source: Cenicaña, 2010

2.3 Geology

The Aguaclara catchment is located in the western part of the Central Cordillera. The Central Cordillera is the oldest cordillera, and is formed by pre-cambric and Palaeozoic sediments and rocks Deltares (2016). In the higher parts of the catchment igneous rock are found, mainly composed by quartz diorites. These igneous rocks have suffered strong weathering and erosion, with the eroded material transported down and deposited as sands (built up of quartz and many other minerals) in the alluvial fans Cespedes (2017). Figure 4 presents the main formations found in Aguaclara. The main faults crossing the system are the Guabas-Pradera fault on the west side, and to the west the Potrerillos fault. The former is described as the western boundary of the igneous rock and the sediments of the Neogene, the latter has been defined as an as a structure of several kilometres, in the mountain front of the Central Cordillera, separating the alluvial fans. Both these faults as well as others located in the surroundings of the catchments, are oriented North-South, and are considered relatively active, playing an important role in the formation of the geomorphology of the area Rodríguez Cuenca et al. (2005).

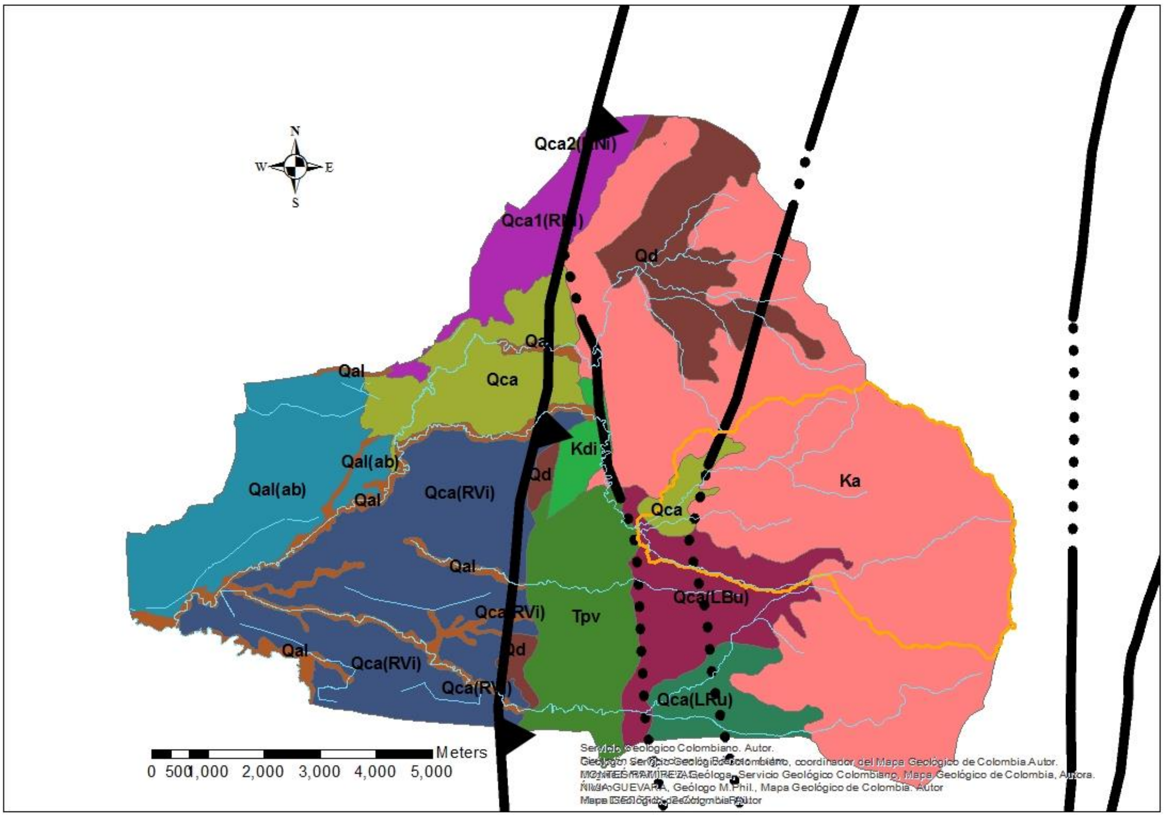

Figure 4 Geological Map of the Aguaclara catchment. Main streams presented in blue lines and instrumented area highlighted by orange line. Created with information from Colombian Geological Service (SGC)

Ka- Amaime formation: The highest part of Aguaclara the main formation is composed of massive tolitic basalts. Meaning an igneous rock, which will have a significant content of pyroxene, reflected in high content of SiO_2. Basalts, are characterized by the lack of primary permeability. If present, their aquifer properties depend on secondary fracturing either due to release jointing or connected with faulting. Plateau basalts, are characterized by thickness of the basaltic lava and the lack of primary permeability.

Amaime Formation outcrops in the occidental part of the central Cordillera. The eastern limit of this formation is the main fault system Cauca-Almaguer, on the other side of the fault formation Bulalagrande formation is located.

Tpv -Vilela Formation: Originated in the Pliocene, it is a sequence of poorly consolidated interstratified conglomerates, distinguished for being oligomitic with pebbles from the basalts in the Amaime formation.

In the plane part of the Piedmont of the Central Cordillera, multiple alluvial and colluvium fans are located. The sediments of these areas are mainly fine and heterogeneous in the source of material, with an abundant content of volcanic ashes, mixed with the alluvial sediments.

Qca – Alluvial fans: Complex systems found in the Piedmont. The main sediments found in these systems are gravels and sandy gravels with thin layers of sand. Materials are usually in thin layers and sporadic lens. Internal stratification is not clear for the alluvial fans, but a tendency of decreasing grain size towards the surface has been found.

Qal – Alluvial deposits: Mainly formed by heterogeneous clastic material, where the grain size is controlled by temporal base, alluvial plain development and distance to Piedmont, usually, steeper terrain will contain larger size of clasts, while finer material is deposit in the lower parts where transport capacity decreases (Echeverria, 2009). Deposits are also divided in three units, the most superficial unit is mainly formed by gravel and sand layers with intercalation of silts and clays. Below this unit, a unit conformed by clays, with some lens of sand and fine gravels.

Qd- Debris: Formed by thick clastic deposits of stratified gravels, sandy gravels and sands with local silt units (Cespedes, 2017).

2.4 Geomorphology

From the geomorphological point of view, it follows the patterns that were also visible in Figure 2 with Gravitational-Fluvial Mountain in the eastern areas at the Cordillera shown in Figure 5. Between the piedmont and the mountain an area of Colluvium Alluvial deposits coming from the mountains is located, area where the Debris is deposit. At the edge of the mountains the Colluvium-Alluvial Piedmont is located, as the slope decreases the quaternary deposits change to finish mainly in alluvial piedmont in the most eastern area. In this part of the catchment antique and recent fans are located.

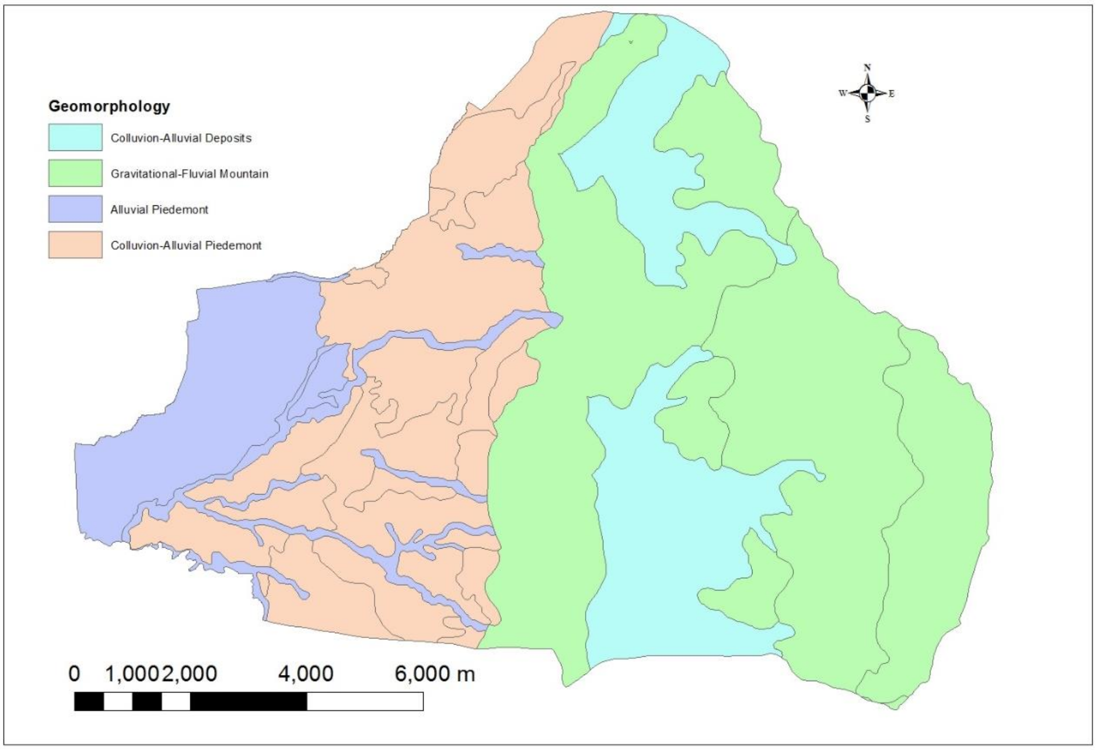

Figure 5 Geomorphology

2.5 Land use

As presented in Figure 6 most of the Aguaclara catchment is covered by herbaceous and shrub crops. In the most western and lower areas, sugar cane is the most common crop. At higher elevation fruits, vegetable and coffee crops are present. Recently reforestation processes has been implemented along the Cauca Valley to protect the catchment, areas previously used for cattle are being replace by natural forest. This could be observed in the higher elevated areas covered by both forest and dense scrub. Not large urbanization areas are present, however, over the last years an increase in recreational constructions has occurred.

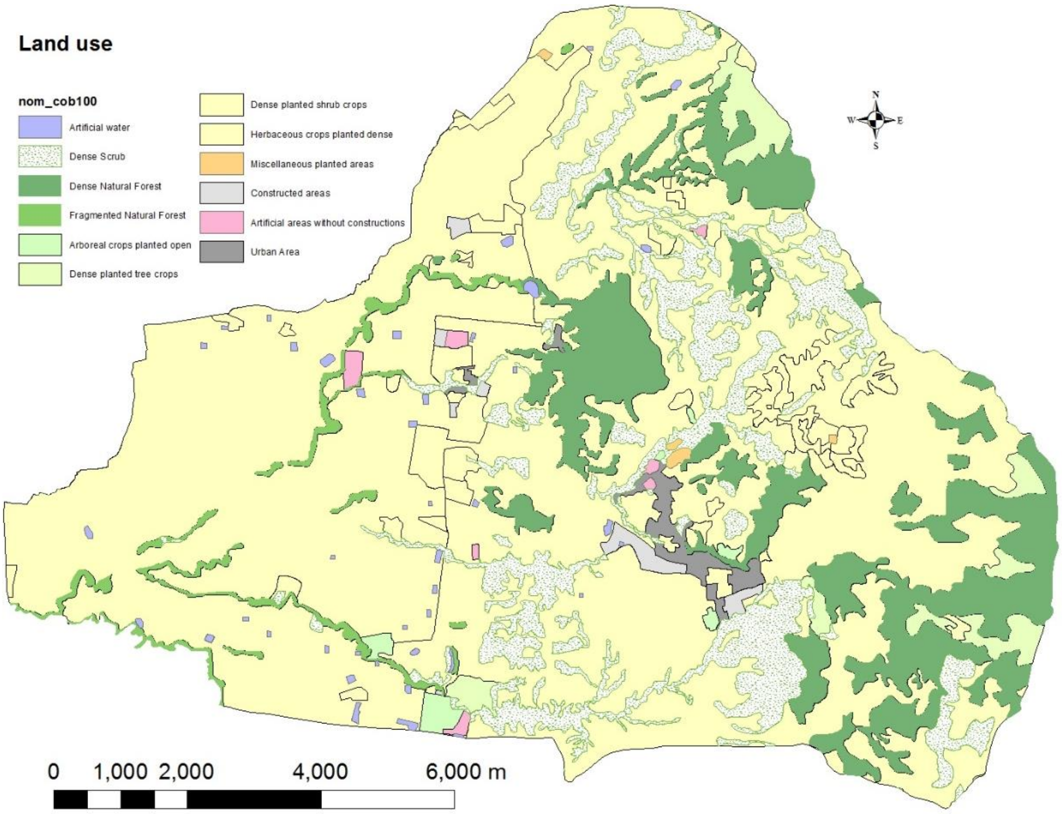

Figure 6 Land use

Chapter 3

Literature review

This chapter provides the technical information necessary to understand the procedure and results from this research and the criteria to establish the methodology taken.

3.1 Hydrogeological assessment

Groundwater recharge is an extensively study field of hydrogeology, given the relevance it has for the sustainable use of water resources. Multiple parameters have an impact in the recharge of an aquifer, as the geology, geomorphology, climatology, hydrology, land use of the areas above the aquifer and hydraulically connected areas Scanlon et al. (2002). The estimation of recharge may also be calculated for different time scales, depending on the study objective. Reliability of the assessed recharge is strongly connected to the availability of data in the study area and time. However, data is not always available and availability differs between locations, depending on resources invested for hydrogeological studies, interest of local, national and international institutions, and the relevance of groundwater for the study area and policies of water managers. This is why multiple approaches to the recharge estimation have been developed as water budget, baseflow studies, natural and artificial tracers, numerical modelling, Darcian techniques, water table fluctuation method, Chloride balance. But each of the methods has its own assumptions to conceptualize nature that sometimes might be an oversimplification leading to large uncertainties in the recharge estimation. These methods have been reviewed by (Hogan et al. 2004; Lerner et al. 1990; Scanlon et al. 2002). Authors concur to suggest an integration of multiple methods, when possible, to increase the accuracy of the results.

3.2 Mountain block recharge

In his PhD thesis (Earman 2004) reflected on how the contribution to the adjacent basin aquifers from the mountains was recognized as important in the United States by 1898. However, hydrogeologists chose to set the mountain blocks as impermeable boundaries and assumed that all the infiltrated water coming from the mountain will enter the downslope basins as flow in the streams until it reaches the alluvial material that has enough permeability to allow the flow go to the aquifers. This flow was called Mountain Front Recharge (MFR), and it is a concept that is still used. (Wilson and Guan 2004) defined the location of the mountain front could be between the point where soil type and vegetation changes at the area between mountain and Piedmont and the plinth angle where Piedmont meets the edge of the basin floor, this area is where most of the faults are present and they will play an important role for the MBR.

There are two possible definitions of the mountain front recharge. First, it can be considered as the flow coming from the mountains that enters the catchment as surface runoff, this flow could come from local flow paths discharging just the mountain front zone as shown in Figure 7 (Ajami et al. 2011; Earman 2004); or it can be considered as all the water coming from the mountains that reach the adjacent aquifers, through the streams and by regional flow paths coming in from the fractured bedrock, that is defined as mountain block recharge(Doyle et al. 2015; Gilbert and Maxwell 2017; Manning and Solomon 2005; Wilson and Guan 2004).

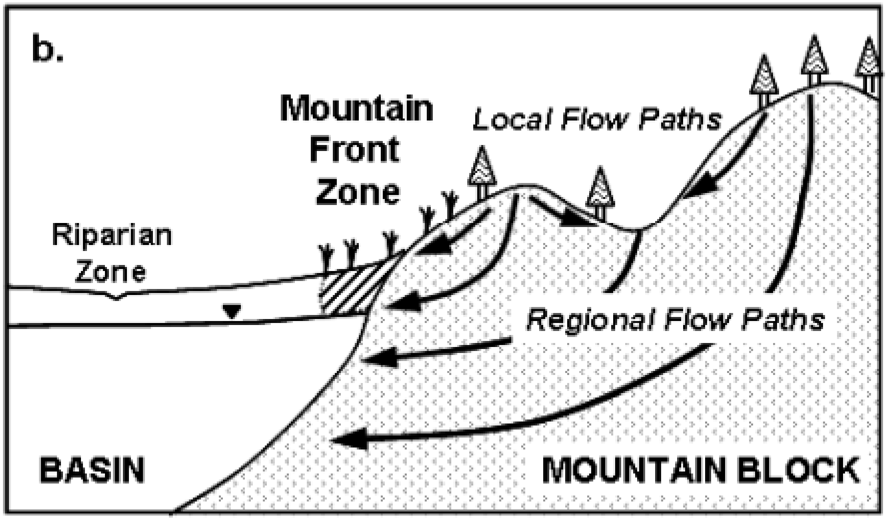

Figure 7 Cross section to show hydrological processes of MBR and MFR. Taken from (Wilson and Guan 2004)

By 1963 J.H. Feth published a study where a model with the traditional assumption for the MFR together with the chemical characteristics and hydraulic heads could not reach a result, meaning that there was water coming from the mountain through the fractured rocks that he called “hidden recharge” (Earman 2004). In the late 1990s and beginning of the 2000s, more authors became aware of the possibility of significant amounts of water being recharged through these hidden paths connecting the base rock of the mountain to the aquifer. Over the last 20 years more studies have focussed on this topic (Ajami et al. 2011; Doyle et al. 2015; Manning 2011)(Doyle 2013; Earman; Flint et al. 2002; Gleeson and Manning 2008; Guan 2005; Kao et al. 2012; Manning and Solomon 2005; Wilson and Guan 2004).

Guan and Earman dedicated their PhD research to study the interactions between mountain areas and the basins located in the lower parts. Earman concluded that for semi-arid areas located in western region of USA, the precipitation condition of the mountains compensates for the low recharge potential of the lower elevation areas. He also explains the relevance of springs to explain the water coming from the MBR, explaining that springs in the lower areas discharged water coming from high elevations and were later re-infiltrated. Highlighting that regional flow through the bedrock is evident during dry periods, when without significant precipitation contribution and minor snow availability, some perineal channels are found. Additional proof is found during construction works of tunnels and operation of constructed tunnels that present flux coming through the supposedly –impermeable mountain block. (Earman 2004; Guan 2005) concluded that for the described regions MBR needs to be considered, due to its great relevance. Earman suggested that is possible to delineate recharge zones by implementing remote sensing, including information of geology, vegetation, evapotranspiration, and topography.

In his research, Guan (2005) established several conditions that will affect the interactions between soil and the bedrock. According to him slope steepness, soils and bedrock characteristics, vegetation cover, and the particularities of mountain hydrology need to be considered before assuming an impermeable boundary. Guan tried to consider both the soil layer overlaying (including dynamic of hillslope processes) a hard rock and the deep percolation to the mountain (both flux passing to the aquifer and interflow). He explains how the fractures in a bedrock make the impermeable bedrock assumption a misconception of the systems since with high amounts of precipitation water will percolate.

By using numerical modelling Guan (2005) evaluated multiple scenarios to assess the main parameters controlling the mountain hydrology. When using steady-state simulation the effects were not captured. But when using transient simulations the simulations captured how the steepness and precipitation have significant effects on runoff generation, as expected. The author explained that even if the bedrock permeability is one of the main variables for the MBR, having a reliable permeability that represents the bedrock in a large area is one of the biggest challenges for the estimation of MBR. The author suggested that intensive field fracture characterization coupled with numerical modelling may provide good information.

3.3 Methods for the estimation of MBR

Similar to all the groundwater recharge studies, different authors have taken different approaches and methodologies to study the mountain block contribution to their study area, according to the characteristics defined in section 3.1 of this document. A brief resume of the publications that had been essential for the present research is presented.

In their publication (Wilson and Guan 2004), explained how mountain hydrology had not been fully understood. The authors described that so far it had been focused on the stream response to precipitation, not acknowledging other particular characteristics of the mountains that change the water balance. Special conditions as thin soils that can store less water for later transpiration, lower temperatures, reduced evapotranspiration, and possible larger albedo face from snow. For them, it is required a different approach for the proper assessment. They referenced the paper “Assessing the hydrological significance or the world’s mountains,” (Viviroli et al. 2003), where the authors conclude that the contributing mountain area to a catchment has 4 times more impact than the area of the basin floor, to explain the relevance that mountain hydrology should have.

Two approaches for studying MFR are described: 1) Basin centred, where the mountain front is a boundary condition for the aquifers of the basin (Darcy’s Law along the mountain front and calibration of Groundwater models), in this approach the hydrology of the mountains is not considered. 2) Mountain-centred correlation between the precipitation in the mountain area and the MFR are established, using geochemistry and isotopes, local empirical equations, regression method, subtraction of ET to precipitation. An individual analysis of each of these methods is done explaining the limitations and assumptions of each of the methods.

Wilson and Guan (2004) explained that usually only one approach is taken, either assuming an impermeable boundary in the bedrock focused on the complex hydrology of the mountain, or in the other case understanding the processes in the bedrock without understanding in detail the hydrology of the mountain. In their research the authors ran numerical simulations to assess the relevance of the flow in the bedrock, finding that bedrock with high bulk permeability, probably controlled by fractures, could lead to significant amounts of water percolating to it. However, it is possible for the water to leave the system through fractures and faults, either to streams or to the surface as springs. Finally, the authors suggested a more integrated high-resolution mountain centered approach in which complex hydrology of the mountains, together with detailed groundwater interactions allow to evaluate the system response to climate variability, vegetation change, and human interaction.

(Gleeson and Manning 2008; Manning 2011; Manning and Solomon 2005) used Noble gas recharge temperatures (NGTs), groundwater ages (natural tracers H^3/) $He^3$and heat transport modelling for the characterization of the groundwater circulation to assess flow regimes and be able to determine if some of the estimated MBR were actually feasible for the Salt lake Valley. The collection of data was intensively done in more than 50 wells and through periods over a year in the valley and data was not collected in the mountainous part because heterogeneities in the mountain block will be integrated into the flow pathways, which means that the water carries an integrated signal. Another reason for using data from the valley was that wells are located there. The noble gas concentration allowed the researchers to estimate a location where the water was recharged and to attach an elevation to it. This was possible by establishing the temperature of the water table at different elevation locations, assuming a small difference to the surface temperature, due to temperature elevation lapse. Later a model was constructed assuming a mountain block permeability with uniform behaviour in the entire depth. As a result of their study, the authors found a significant component of the MBR to the aquifer recharge, although the results differed by more than 50% when compared to previous studies in the region, and reduced the established range for MBR by 70%.

In 2008 (Gleeson and Manning 2008) used numerical simulation in 3D to demonstrate the influence of relief characteristics in the fluxes coming from the mountains, especially to define the parameters controlling the regional flow systems. Most of the models used a 2-dimensional approach as a usual simplification. However, the authors found a new component that had been ignored by 2D simulations, there is another flux perpendicular to the traditional simulated regional flow, and this perpendicular flow needs to be addressed, given that it might have similar values to the regional flow. Both regional, and perpendicular flow are highly sensitive to by the topographical and geological conditions, authors found that under similar conditions more topographical roughness will produce higher regional and perpendicular fluxes. Another important finding from the study is that perineal flow could be an important indicator of regional flow occurrence. They concluded that precipitation, hydraulic conductivity and water table elevation will control the distribution of flow going to local, regional or perpendicular systems. According to their findings, regional and perpendicular flow will increase with a lower water table elevation.

Similar to the study carried out in 2005, in 2011 Andrew Manning used noble gas recharge temperatures together with radiocarbon ages to study eastern Española Basin, located in USA. The use of radio activated carbon was to evaluate possible changes in the mountain block recharge within thousands of years. In this region, the Mountain front recharge accounted for 82% of the aquifer recharge, of which some calculation assessed a range from 42% to 70% to the fraction coming from the MBR. The authors found that in fact, MBR contribution was between 20% and 50%.

(Kao et al. 2012) explained how most of the methods used for the assessment of MBR, usually require high resolution and reliable data. The authors explained how MBR studies, including the ones carried by Manning, had a limitation because they require highly detail information of soil and hydrological properties, which make them expensive and applicable only at a small scale. For this reason, they suggested an approach by applying the standards methods of base flow and rainfall infiltration, together with Geographical Information Systems, to calculate the amount of recharge in a sub-tropical basin, located in Taiwan, finding similar values for the MBR to previous studies with more complex methods as ^{18}O and ^{14} C isotopes. Indicating that if done properly simplified methods could provide a good estimation for the mountain block recharge.

(Chen and Lee 2003; Kao et al. 2012) were able to obtain similar results of the MBR in the largest basin in Taiwan, by using an analysis of the baseflow to evaluate the recharge, to the results obtained by the more expensive method of C^{14} and tritium dating techniques. The method used was based on the estimation of a stable baseflow and the use of a simple groundwater budget developed by (Cherkauer and Ansari 2005). This balance considers the groundwater influx (GW_{in}) and efflux (GW_{out}) between watershed and adjacent aquifers, the infiltration to the system I, the baseflow contribution to the streams Q_{bf}, the evapotranspiration ET, pumped water NP, and the changes in water storage $\Delta S/t$ as presented in Equation 1

Equation 1 Groundwater budget equation

$$I + GW_{in} = Q_{bf} + GW_{out} + ET + NP + \Delta S/t$$

To evaluate the recharge of the groundwater, the authors consider $GW_{in} = GW_{out} = Np = S/t = 0$ reducing the equation to

$$Recharge = Net\ recharge\ (I - ET) = Q_{bf}$$

(Lee et al. 2006) estimated that the groundwater recharge for the entire area of Taiwan, includes 31% of recharge from mountainous area, by coupling the water balance, the baseflow record and the stable base flow analysis. Calculating the baseflow index from the daily record, and multiplying by the long term mean difference between ET and precipitation, the groundwater recharge was estimated. For their methodology, the authors, assumed that the stored volume of water is negligible and the baseflow will represent the lower bound to groundwater recharge within the catchment. For a better estimation of the baseflow through the year, (Chen and Lee 2003) developed the stable-baseflow-analysis presented by Figure 8.

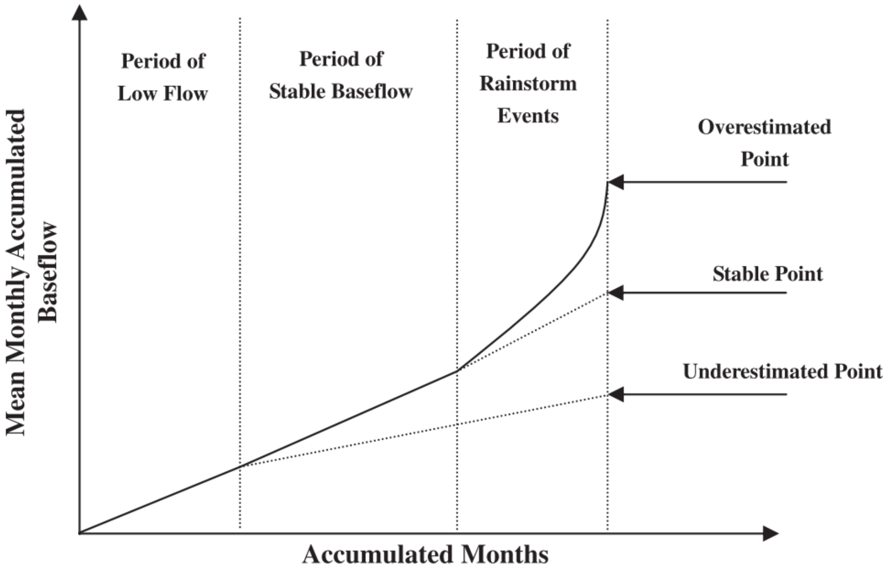

Figure 8 The diagram of the stable-base-flow analysis.(Chen and Lee 2003)

Similar to (Manning and Solomon 2005; Wilson and Guan 2004), Ajami et al. (2011) highlighted the relevance of the contribution from the mountains to the recharge of aquifers in arid and semi-arid regions. However, at the same time they recognize the difficulty that estimating the amount of water has, given the complex hydrological process in mountainous catchments, and the high sensitivity to difficult to estimate parameters like the bedrock permeability and capacity of storage. The authors provide a summary of different approaches to calculate the MBR, given the main assumptions of them, and potential challenges involving their use. The study is carried in a mountainous catchment located on an Island in Santa Catalina, USA where the bedrock is composed of highly fractured granite and gneiss. Their approach was to focus on the interaction between precipitation, stream flow and catchment storage dynamics. By inverting the water balance they developed storage-discharge relationships to quantify the MBR rates, based on the changes of baseflow. The results were validated by using Isotopes to validate connectivity of the bedrock, MBR seasonality, and contributions of the fractured bedrock to streamflow during dry periods. For their methodology, the assumptions taken were low ET rates during dry periods and perineal flow condition at the gauge.

Continuing with the study carried by Doyle in her MSc thesis, (Doyle et al. 2015) used tritium and noble gas data and results to calibrate regional groundwater model in a humid region in US. The calculated contribution of MBR corresponded to 8% of the precipitation in the mountains, which accounted for 45% of the recharge of the aquifer. By using a sensitivity analysis to different parameters it was proved how the flow models can easily match observed data, but by adding the natural tracer information different model parameters can be constrained. This approach is known as unconventional calibration targets and includes age and travel times of groundwater, solute distribution and temperature. At the same time it is clear that traditional groundwater model, without including MBR could appear accurate when only hydraulic heads are analysed, but the calibrated hydrogeological parameters may not be representative of the real conditions of a study area.

(Doyle et al. 2015) explained how when no data is available for the hydraulic characteristics of the mountain block, it is acceptable to use an equivalent porous media instead of trying to simulate the fractures network. For the calibration including the NGTs data, the authors found that is better to use the noble gas recharge elevation (H), rather than the concentration given that the dependence of the concentration with H is weaker than the dependence of temperature (T) with H. The obtained results indicated that there was a clear contribution of the higher areas to the aquifer recharge. The only perforated well in the mountainous part of the study area was found to have water characteristic that proved the regional flow in the system, reflected in the presence of water recharged in higher elevation areas.

In the analysis, the authors found that the calculated recharge elevation was sensitive to the permeability of the fractured bedrock and to the distributions of recharge. In general water head is less sensitive to changes model parameters, than the groundwater age, elevation recharge and temperature. The sensitivity was more obvious in deep wells where is more likely to have a larger contribution to the MBR.

(Gilbert and Maxwell 2017) studied the contribution of the mountain block recharge to the groundwater system in the valley area of the San Joaquin Basin in California, US. The terrain covered included relatively moist, snow dominated and semiarid systems. This region exploits groundwater to improve the agricultural activities of the region that represent an important income, but the exploitation is so extensive that it may not be sustainable. For their studies the authors integrated hydrogeological models with detailed hydrological studies in the basin, to assess the interactions of watershed impacts to short scale and space changes that are expected to happen due to development of the region. Initially, it was thought that the groundwater contribution from the incoming precipitation to the system was negligible due to the discharge and mainly high evapotranspiration processes. However, the authors considered that the mountains were hydraulically connected to systems through the fractures.

Chapter 4

Methodology

This chapter describes the followed methodology to achieve each of the objectives established for the research. The explanation of the assumptions taken is provided for the reader to understand the considerations of them and why they were established.

Given that the main objective of the study is to develop a conceptual model of the recharge process from the mountain block, as well as establishing an estimate of the amount of recharge that occurs from this source, a mountain centred approach was followed (Manning 2011; Wilson and Guan 2004). As data availability is crucial for the groundwater recharge studies, Aguaclara basin is an experimental basin that has been extensively instrumented by Cenicaña. The recorded data was used and integrated into the calculation to assess the variations in time, that had been found relevant for the MBR estimations (Ajami et al. 2011; Gilbert and Maxwell 2017; Wilson and Guan 2004).

4.1 Data collection

MBR moves through regional flow in the bedrocks, this means that the process time scale is most likely larger than one year, and possible reaching hundreds of years. Therefore long term data is highly valuable for its study, as mentioned earlier Cenicaña has installed a monitoring network operating since 2014 and it has been improved over the last four years. The hydrological information used for the current investigation has been obtained from the monitoring network is presented in Figure 9, and formed by; five streamflow gauges represented in the map as yellow triangles; five climate stations displayed as red stars in the map; nine rain gauges symbolized as blue dots in the map.

Additionally to the hydrological information obtained from the monitoring network, water samples were taken to analyse the hydrochemistry and use stable isotopes as natural tracers to understand the water processes and interactions with the subsurface in the study area. Given that the movement of water in the bedrock would be through fractures created due the stresses during the entire existence of the rock, the pathways will not follow a clear direction. Because of it the sampling point area was extended outside the instrumented area, and even out of the Aguaclara sub-basin, all sampling points are presented in Figure 33.

During fieldwork, in situ parameters such as temperature, pH, and electrical conductivity (EC), alkalinity and silicate content were measured at spring, well and river locations in the field. EC routing was performed to identify possible groundwater contributions to river flow. To measure alkalinity Hanna Freshwater Alkalinity Colorimeter – Checker® HC HI775 was used on the field and for silica content Hanna High Range Silica Colorimeter – Checker® HC HI770 was used.

The sampling process for the springs, was done trying to reach the most upstream point as possible. Given that springs could support the existence of MBR (Ajami et al. 2011; Guan 2005; Wilson and Guan 2004), and the elevated number of springs in the Aguaclara sub-basin, an assessment of spring occurrence was performed on site validating their existence and if they were ephemeral flows or perennial, the assessment consisted mainly in the information provided by the inhabitants of the area.

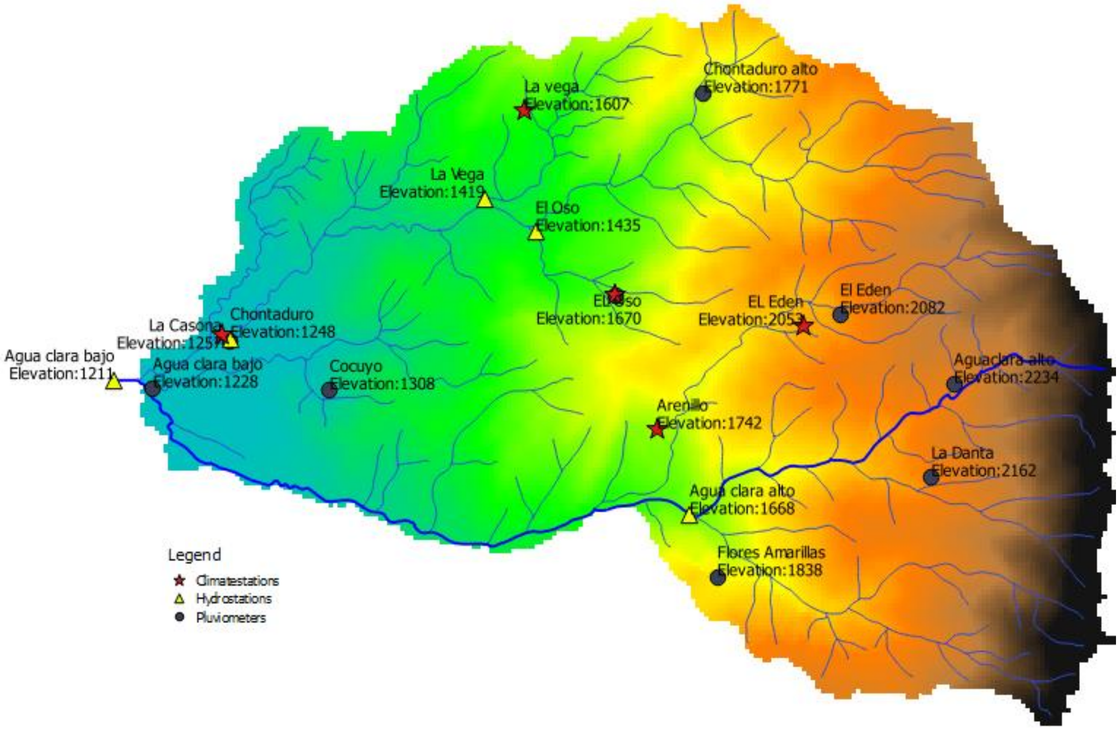

Figure 9 Monitoring network Aguaclara.

4.2 Water budget

The water budget is a method based on the principle of conservation. This approach is generally use to make a quantitative evaluation of the water resources. According to Sokolov and Chapman (1974) the inflow of water to the catchment will come from precipitation (P) and surface and subsurface inflow to the catchment. The outflow of water will be giving by surface and subsurface outflows as discharge ($Q_{sur}\&Q_{sub}$), evaporation from any water body surface, and transpiration from the vegetation around the area, that will join as evapotranspiration (ET). Water storage (ΔS) could happen whenever the inflows are larger than the outflows. The authors suggest that a discrepancy factor (ɳ) should be included due to the potential measurement errors on each of the parameter of the balance. Assuming that there is not water coming in from another catchment, and no human interventions the general equation is given by Equation 2

Equation 2

$$P - ET - Q_{sur} - Q_{sub} - \Delta S - \eta = 0$$

For this research the method was chosen to provide an indirect evaluation of the MBR in the instrumented area of the Aguaclara sub-catchment. Both annual and multiannual approaches of the water balance are usually used to disregard the changes in water storages, meaning the water that potentially percolates to the bedrock would not be evaluated. To understand better the processes of the catchment, a monthly time step was selected. Later the long term balance was evaluated to check for an unaccounted quantity of water that could be moving through regional flows in the bedrock as MBR to the valley aquifers.

The water balance used in the following calculations is based on the description by Wilson and Guan (2004), for the focused subsurface and component of water moving in the mountainous catchments. Focused subsurface refers to the flow of water moving from the bedrock openings like fractures and faults that reaches the basin aquifer, the subsurface flow Q_{sub} leaving the catchment in Equation 1 is the water available for MBR if it reaches the aquifers on the Valley. According to the authors, using an estimation of actual ET, and a measured stream runoff (RO), the calculation of MBR can be given by Equation 3

Equation 3

$$MBR = P - ET - RO$$

Note that in the previous equation the discrepancy factor is not included, meaning that it will join with the calculated MBR. As mentioned earlier this factor accounts for the errors in the calculation of the other parameters, meaning that there is not yet a generally accepted method with 100% of accuracy to calculate each of the components of the water balance. The explanation of each of the selected parameters included in the balance is given below.

According to Equation 3 the MBR was then calculated for each month, with this approach the range of MBR, is referring to the portion of water from the water yield that does not leave the catchment as surface runoff or loss to ET. As mentioned earlier, the use of this method will join the MBR, changes in storage and the balance discrepancy, which could lead to an overestimation of the MBR. As result validation with other methods were used to evaluate the existence of the MBR Sokolov and Chapman (1974).

4.2.1 Precipitation

Precipitation is the main source of water for the Aguaclara catchment, therefore, for a detailed hydrology, both temporal and spatial distributions were analysed. The time distribution was done from the point measured data through the years 2015 to 2017. The spatial distribution was done by implementing the same data and analysing the changes at different locations during the same times. The level of detail of the hydrological study is proportional to the distribution of the point measurements. Unfortunately, due to operation and maintenance limitations, the rain gauges presented in Figure 9 did not have complete data sets to be included, reason why the analysis was done with the four climate stations installed in the catchment. The spatial analysis is done mainly to create a distribution of precipitation in the study area, however, it is known that this introduces uncertainty to the calculations executed.

Orographic features have an important effect on precipitation patterns. Considering that the available precipitation consists on point measurements, but knowing that many hydrological characteristics and especially rainfall have spatial variability (Dingman 2002), the data was used to create contour maps, producing maps with continuous spatial variation. To include the effect of relief in the precipitation distribution the conventional hypsometric method was selected given the conditions of the catchment and also the availability of data. This method relies on precipitation being a strong function of elevation that could be expressed by a simple linear relation call orographic equation as follows:

Equation 4

$$p(z) = a + bz$$

Using the four data sets for each of the evaluated months, to establish the values for the interception (a) and slope (b), the values were interpolated using the elevation data for the catchment to distribute precipitation along it. The monthly distribution was done for the months presenting a correlation coefficient over 0.7 between rainfall and elevation, the excluded months corresponding mainly to the dry seasons.

Although correlation was stronger on yearly basis, a detailer time-step was chose to have a better estimation of the available water that could go to mountain block recharge. Once the slope and interception for each month was obtained, the elevation lines were converted to points, to be used in the monthly equations. Using GIS, the values were interpolated to be distributed across the catchment area by IDW interpolation, as a result of the interpolation rasters with pixel size of 20x20 meters were created.

4.2.2 Evapotranspiration

The highest output of water in the balance is the evapotranspiration (ET), however, its measurements are usually complex and some authors (e.g. Diagman 2002) considered virtually impossible to measure directly. To add more complexity, the different processes in a mountain region result in larger variations across the catchment, than the plain areas in the Cauca Valley.

Due to the difficulty of its estimation multiple methods have been developed to try to calculate the evapotranspiration. One commonly used method for estimating actual ET is to implement the water balance for its calculation as the missing component, while limitation to a maximum potential of ET for a particular region. Likewise, soil water balance approach could be used in the ET calculation. Models using remote sensed data coupled with weather models are also used to assess the actual evapotranspiration. Point measurements of climate parameters (e.g. wind speed, radiation, humidity, etc.), integrated with local vegetation and land use conditions can also be used to estimate ET. Wilson and Guan (2004) highlighted the relevance of ET estimations to establish water balance accuracy for MBR calculations. They concluded that ET calculation is a challenge in areas with complex terrain and varied vegetation, typical of the mountains. Giving the difficulty of its assessment, and to reduce uncertainty of the estimation of MBR, the remote sense models and point measured data were evaluated in this research.

4.2.2.1 USGS Simplified Surface Energy Balance (SSEBop)

Evapotranspiration could be affected by multiple weather conditions and land use including vegetation of the area. Over the last 20 years, an important reforestation process took place in the Aguaclara catchment, mainly in the higher areas, introducing dense vegetation in some zones, which will increase the relevance of the interception on the evapotranspiration process. It is very likely for the interception to play an important role in the overall water balance. Interception refers to the portion of water that falls over the canopy of vegetation and then is evaporated, it is considered to be a significant fraction of the total evapotranspiration Dingman (2002). The difficulty of it measurement, in an area with multiple species of vegetation has led researcher to opt for an actual measurement model, that includes vegetation and land use parameters.

The remote sensing method used here was the Simplified Surface Energy Balance based model SSEBop version 4 by USGS. The resolution of the model is 1km, and the time step provided is monthly. The SSEB model has shown strong correlations when compared with data from lysimeters, and it includes corrections for the elevation to the evapotranspiration calculation. The initial SSEB model, not including USGS improvement, is suggested to be used with good accuracy for elevations under 2000 m Senay et al. (2011), which is below the mean altitude of the instrumented area in the Aguaclara sub-catchment. According to the developer the selected model includes in its simulations the landscape of the territory.

4.2.2.2 Point measured ET

Data from four installed climate stations in the instrumented area of Aguaclara was used. Three of these stations are fabricated by DAVIS and according to the manual of the installed stations, they have an estimation of the ET described by the seller as reference ET, being the value measured the expected ET for grass. However, this values should be adjusted to the vegetation around the area and the soil characteristics, by multiplying the data by a crop coefficient (DAVIS). According to the specifications, ET values are calculated from hourly averages of weather variables, including wind speed, humidity, solar radiation and temperature. The calculated ET is given by Equation 5

Equation 5

$$ET_o = w * \frac{R_n}{\lambda} + (1 - W) * (e_a - e_d) * F$$

In the equation ET_o is the potential ET in mm, w is the weighting factor that expresses contribution of radiation component, R_n is the mean solar radiation, λ is the latent hear of vaporization, e_a is the water vapour saturation, e_d is the actual water vapour present and F is a wind function. Detailed explanation and description of the factors is available in (DAVIS). According to the specifications, once the reference ET_o has been obtained, is possible to calculate the actual ET by multiplying it by a crop coefficient (K_c) according to the vegetation in the area. This calculation of actual evapotranspiration apparently are not restricted by the availability of water in the soil, which could represent a better estimation for the potential evapotranspiration more than actual ET. Given the conditions in the catchments is very likely that the actual ET is not too far from the potential ET, and according to the specifications, the measurements were considered like actual ET for comparison. After finding a correlation between elevation and ET, a similar correlation distribution analysis to the one done for precipitation was carried out for the measured ET of the stations. Finally the referenced ET was multiplied by the crop coefficient of each of the land use map taken from the “Plan de Ordenamiento Territorial” using the 25m resolution. The used crop coefficients were obtained from the FAO website and literature, specified in Appendix B

Data from SSEBop version 4 model was used in the majority of calculation of the water balance. The selection was related to the availability of data. For the inclusion of the water balance, the average ET was calculated for each of the sub-basins established according to the stream gauges.

Nonetheless, and understanding the relevance of the evapotranspiration in the water balance, a validation of the accuracy was done by comparison to other methods. First a comparison to a different remote sense base model was done. ETensemble V1.1 model with a higher resolution of 250x250 m, developed by the WA+ team, available online. The developer claims that the ETensemble V1.1 combines 7 ET datasets including SSEBop (wateraccounting). However, so far the model is only available for the period starting in January 2003 to December 2014. The ET values for locations within and around the catchment for the years 2013 and 2014 were used to compare the performance against SSEBop v4.0.

4.2.3 Streamflow

The instrumented area of the Aguaclara catchment includes 5 streamflow gauging stations capable of measuring the level of water every 15 minutes were installed. From the stage level, the mean daily streamflow is calculated and the reported values were used in this research.

Similar to ET, when discharge is not available, the water balance is used to estimate it, but for the purpose of this research the discharge measurements are crucial. Unfortunately the most downstream stations, covering larger areas, tend not to have a continuous data set, mainly at the outlet of the study area. Out of the 36 months that the monitoring network has been operating, only 6 months are complete, and another 3 have data for most of the period.

However, the measurements are crucial as an input for the water balance and the understanding of the main processes in the catchment. To provide an estimation for the water balance, the discharge at the outlet was completed for the periods when it was not available. Correlations between other streams and the outlet were evaluated, as were correlations including precipitation data, but the estimations were not accurate, and the results did not show a clear pattern. The estimation of the missing discharge data, was then done trying not to overestimate the discharge of the rivers, and thereby underestimate the importance of MBR occurring in the area.

4.3 Baseflow separation

The baseflow separation is another method to evaluate the mountain block recharge. For its use discharge from the studied catchment is assumed to be formed by a rapid response (runoff) component and a slow flow, called base flow, coming from groundwater. Understanding that during the periods with no rainfall, outputs of water to evapotranspiration and discharge are larger than the water coming from precipitation, the baseflow in those periods is considered to be a change in the storage of the groundwater Gustard and Wesselink (1992).

The estimation of baseflow is used to estimate the recharge occurring in the catchment. Baseflow was assessed by hydrograph separation. Baseflow separation method is based on the interaction of streams and groundwater. A relationship between the physical properties of the watershed and the rate of recharge is established. This method assumes that groundwater recharge is equal to the streamflow baseflow for the watershed. Understanding that the streamflow has two components, one coming from the surface flow, and a second, coming from the discharge of groundwater. Kao et al. (2012) estimated the MBR by the application of this method, comparing it to tritium and C^{14} tracers, in this research it was implemented to validate results of the water balance and understand processes of the catchment.

The principles of the method according to Chen and Lee (2003) are two. First, it requires daily data for the streamflow, and second, a linear interpolation is used to estimate groundwater discharge during the period of surface runoff. As in all the recharge estimation methodologies some assumptions are taken. In this case, the assumptions of the method are that interflow, evapotranspiration in the saturated zone, and other losses in the catchment are negligible, groundwater table is invariable and the aquifer is underlain by impermeable material (Chen and Lee 2003; Kao et al. 2012). The methodology is presented in Figure 10.

The separation between runoff and baseflow is often arbitrary, and usually are based on subjective physical reasoning (Arnold et al. 1995). To facilitate the further progress with the results, as data is collected, two free available software were used during this research to estimate the fraction of baseflow for each of the gauged streams in the instrumented area of Aguaclara. The Baseflow filter Program from the Texas A&M University (SWAT) and the Baseflow Index by University of Oslo, used by the European Drought Centre.

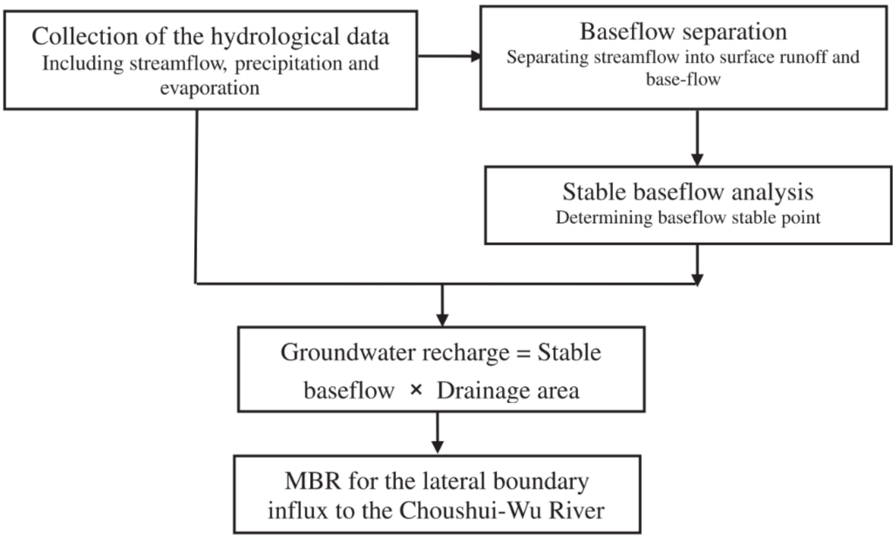

Figure 10 Flowchart for MBR estimation using Baseflow separation. Taken from (Kao et al. 2012)

Analysis of recession curve of baseflow to assess the groundwater-stream interactions. The results obtain from baseflow SWAT is the fraction of streamflow contributed by the baseflow. The software is a digital filter, which according to the signals filters streamflow in high frequency signals for the surface runoff and low frequency signals from the baseflow. The streamflow data is filtered three times, FR1 forward, FR2 backward and FR3 again forward. The process of filtering the streamflow data for separation is giving by

$$q_t = \beta q_{t-1} + \frac{1+\beta}{2} * (Q_t - Q_{t-1})$$

In the equation $q_t$is the quick response surface runoff at time step t, Q_t is the original streamflow, and β is the filter parameter. With this the baseflow b_t can be calculated as

$$b_t = Q_t - q_t$$

Similarly the Baseflow Index (BFI) Visual Basic Application executable in Excel was use to separate the baseflow component from the measured streamflow at the stations (Morawietz). Both of these methods are useful to avoid the subjectivity in the manual separation of the baseflow component in the discharge measurements. Once the contribution of baseflow was obtained, the calculation of recharge was done according to the stable baseflow methods as presented in section 3.3

4.4 Hydrogeological and hydrochemical study

4.4.1 Geological assessment

Geological information used during this research was obtained from Colombian Geological Service (SGC) with a resolution of up to 25 meters. It includes the major geological formations in the study area and the main faults. All information is freely available online at (www2.sgc.gov.co). In the field a validation of land use maps and carbonate minerals occurrence was carried out.

It is well known that permeability of the bedrock is crucial for the mountain block recharge occurrence. However, the proper assessment of the bulk permeability would require an unrealistic number of samples from discrete location to be properly done (Manning and Solomon 2005).

The permeability of the bedrock is controlled by the fractures of the system, but even if some information could be found, the extrapolation of fracture information from 1D to 3D is highly uncertain. Therefore in this research, the assessment of the bedrock permeability was not done, but instead, an estimation of the potential amount of water that could be flowing downwards to the bedrock was done by the implementation of the water budget. This is a common practice according to Wilson and Guan (2004), who explained that even when considering bedrock permeability a percolation rate is assumed.

4.4.2 Hydrochemical study

As the chemical composition of groundwater is related to the different processes that have taken place since recharge has occurred, the hydrochemical data can provide information about the flow paths Larsson (1984). Dissolved ion composition of the groundwater is to a large extent controlled by the interaction it has had with the soil and rocks through which it flowed Earman (2004).

Ions chemistry is important to understand the conditions of groundwater, springs and river base flow, since dissolved ions are controlled by lithology, groundwater flow rate, natural geochemical reactions and human activities Somaratne et al. (2016). For the study area where not carbonate minerals are found, HCO_3 and CO_3 originate from dissolution of silicate minerals present in the formations in the mountain.

During the fieldwork campaign executed during April-May 2018, 36 water samples were taken in order to find hydraulic connections between the most elevated areas in the mountain and the adjacent aquifer in the valley. For the sampling, the wells were purged, either with the well pump when available or with the bailing until field parameters (pH, temperatures, and EC) are stable, and then the samples were collected 25 ml sampling bottles were filled trying to not leave air in the bottle. For the anion analysis samples were filtered using and the containers were rinse when collecting the sample, then anions concentrations were measured at the IHE laboratories by Ion Chromatography System., the measurement was carried by Inductively Coupled Mass Spectrometry (ICP-MS). For the cation analysis samples, the procedure was similar, without the rinsing since the bottles had been pre-acidified using concentrated nitric acid (HNO_3 10%).

During fieldwork the deep wells in the study area were not operating, due to the lack of necessity in the rainy season. In order to establish regional flows the deep wells information is crucial, hence additional information from samples taken by Cespedes (2017) were used as additional three samples from deep wells.

Results from the laboratory, integrated with the field measurements were processed by using the spreadsheet “ChemDiagnostics”, complemented with PHREEQC. The coupling of the software provides the water types, ionic balance, saturation index for CO_2 and Calcite, and the calculated error. Spatial analysis of the results was done to understand the processes that occur at the catchment. Special attention was paid to the samples from deep wells, since those are the ones that can help identify the characteristics of regional flow that is the way the MBR would be moving from the mountain to the adjacent aquifers.

4.4.3 Stable isotope study

The traditional methods applied in this research are useful for estimation of the amount of recharge that might come from the mountain block. However, the assumptions of each of the methods or even not accounted spring occurrence could lead to errors in the estimation, resulting in inexistence recharge added to the groundwater model. The existence of regional flow paths that could potentially reach the aquifer in the area was validated by the use of stable isotopes. Natural tracers including stable isotopes are valuable for the analysis of flow systems in mountainous regions, where usually hydraulic data is limited due to the elevated drilling costs. Moore (2002) defined stable isotopes as a useful method for fractured rocks, as the objective of the research.

Stable isotopes refer to the ratio of O^{18}/O^{16} and H^2/H, these are the most common environmental tracers used in hydrology Leibundgut et al. (2009). As indicated by ratio, the method consists in finding the proportion of the less abundant species. Different physical and chemical processes will change the isotopic abundance ratio. Geological conditions, temperature, and elevation would control these processes. These changes make environmental tracer useful tool to understand the processes the groundwater had been through since it was recharge and even to estimate the conditions in which it was deposited. Usually, seasonal changes can also be identified by the stable isotopes analysis, but if the variations are small, as expected for Colombia, it is feasible to carry a spatial analysis.

The sampling for isotopes was done similar and usually simultaneously to the ions sampling, without the use of special filters, since waters did not show larger turbidity. The analysis was carried at IHE laboratories, with the LGR Liquid Water Isotope Analyser. Each of the samples was analysed three times, per run isotopes are measured 9 times, and the results with deviation higher than 2% are excluded. The reported values are given in comparison with the Vienna Standard Mean Ocean Water, and expressed in parts per thousand as presented by Equation 6

Equation 6

$$ď = (R_{sample} - R_{standard})/R_{standard}\ x\ 1000$$

The approach of this research was to try to do a spatial analysis by collecting samples across the entire catchment for precipitation, streamflow in rivers and springs, and groundwater. In order to prove the hydraulic connection of the hard rock in the mountains with the lower areas samples were collected in wells located in the valley downstream from the Aguaclara catchment. During fieldwork deep wells were not in operation, reason that limited the amount of information about regional flows.

Stable isotopes were used mainly to validate hydraulic connections between the mountain and the adjacent aquifers, but it cannot provide an estimation of the amount of recharge. However, O^{18} and deuterium H^{2}, are useful for determinate the maximum recharge elevation. (Earman 2004; Scanlon et al. 2002). Data collected by the Atomic Energy Agency (IAEA) for the precipitation at different elevations near the study area was used to interpreted and understanding the results of the Isotopes samples.

4.5 Conceptual model

Finally the assessed information was used to explain the main processes occurring in the mountain and the interactions between these and the potential MBR. The model contains the detailed hydrology for each part of the catchment, to understand the interaction between mountain processes and groundwater in the study area. This conceptual model was developed with the hydrogeological information obtained in the study, the geochemistry and the groundwater flow systems found through the investigation. The geological information included in this model comes from literature of the areas around the sub-catchment Aguaclara, including stratigraphy, structural features and hydraulic connections in the system. A graphical representation with a proper description of the research findings are included in this conceptual model.

Chapter 5

Results and discussion

The obtained results of the research are presented and the interpretation of the results is also carried out in the present chapter. The estimation of the mountain block recharge, and hydrological processes in the catchment is also provided in this chapter. Finally, a conceptual model integrating the main results of the research is given.

5.1 Water budget calculations

For establishing a proper water budget analysis, a detailed understanding of the hydrology is important since there is a constant exchange of fluxes in the subsurface and surface that includes shallow and deep groundwater flows. The multiple exchanges will be controlled by topography, geology, soil cover, and vegetation. To apply the water balance equation it is necessary to calculate each of the variables in Equation 2 and Equation 3. The results can be used to estimate the changes in storage for the instrumented mountainous area, and evaluate if they are reflected in the Aguaclara catchment as presented in Figure 11. By calculating the differences between the inputs of water, in this case from precipitation, and the outputs of water as surface runoff and evapotranspiration, it was evaluated if there was an excess of water that could potential be percolating to the bedrock to MBR.

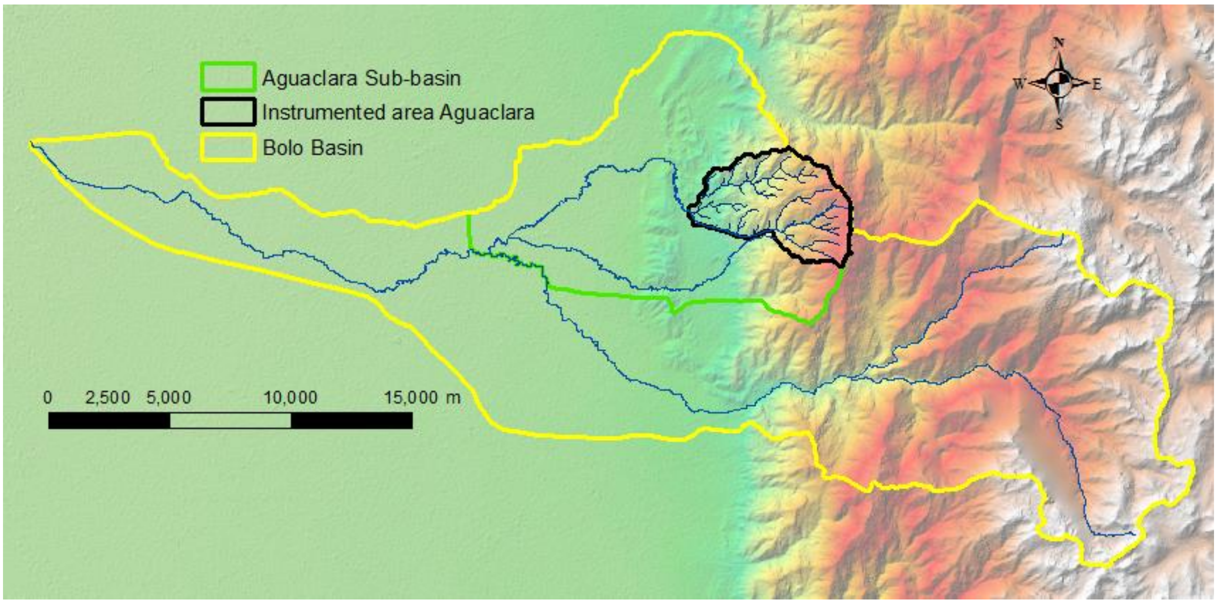

Figure 11 Overview of the area.

5.1.1 Streamflow

The instrumented area of 21 km^2 is formed by small sub basins as discussed earlier, the springs within these sub-catchments are the primary source of streamflow in the area, during the dry months between June and August. According to the methodology, the catchment was divided in sub-catchments according to the distribution of streamflow gauges, which means it was divided in 5 sub-catchments, where the measure of discharge was available. This division allows the analysis of different areas of and even individual calculation to better understand the hydrological conditions. The division is presented in Figure 12.

Streamflow measurements were not fully available for the years the monitoring network has been active, and the data set for Aguaclara Bajo, the most downstream of the catchment that integrates all the other measured streams plus some other tributaries was fully available only for 6 months. Table 1 presents the missing data for the other streams. In order to improve as much as possible the results, the period of record that was considered was adjusted to use the best quality data. Four out of the six months where the Aguaclara Bajo measurements were completed, were for the year 2015. To complete the data sets, and be able to use the data in the water balance for the entire year, estimating the MBR, some approximations were done.

Table 1 Missing discharge measurements

Q Station	Months missing	Count
La Vega	Nov-Dec 16	2
Aguaclara Alto	May-Sep 17	4
El Oso	Jan-Feb 15	2
Chontaduro	Dec-Jul 16/Dec17	9

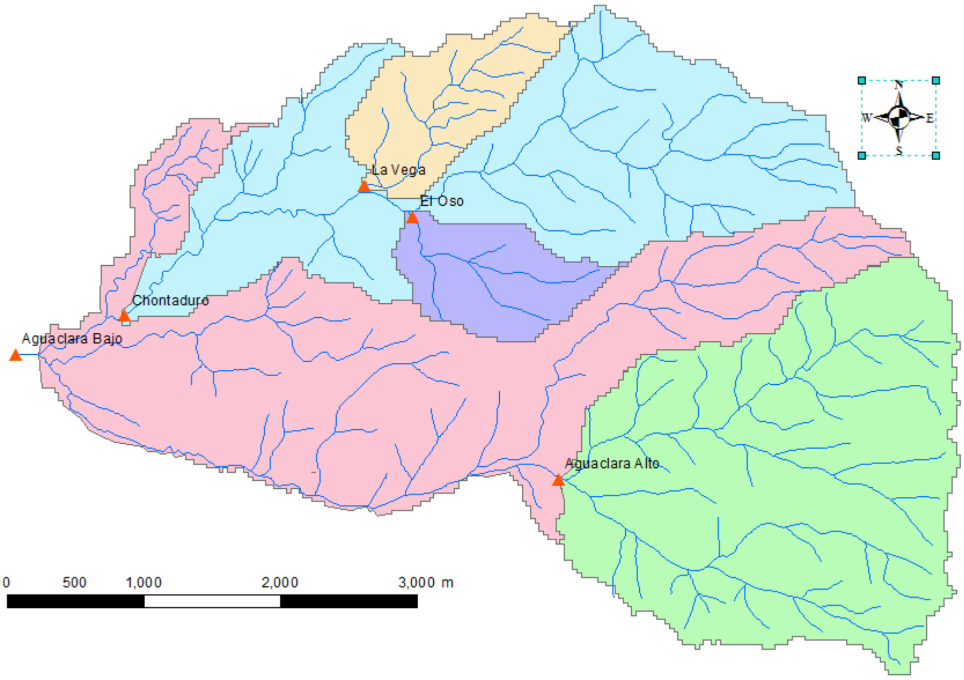

Figure 12 Sub-catchment created for evaluation of study area

For the months of March and October 2015, the measurement were available for 30 and 26 days respectively. As the selected time step for the water balance was month, the average of the daily flow was multiplied by total number of days (31) in the month for those months for the estimation. At the outlet only four months had complete data, hence the other estimation to complete the data was by adding the discharge from the Chontaduro and Aguaclara Alto that are the main streams in the catchment. This estimated was based given that the sum of those months accounted on average 95% of the amount in the registered 4 months of the year, or 90% if March and October are included. But as mentioned there was not a clear pattern, since the two complete measured months of 2017 have an average of 125% larger for the sum of the two streams, when compared to the actual value at the outlet.

During December 2015 neither Aguaclara Bajo nor the Chontaduro stations were working. For this reason the estimation of this period has larger uncertainty, however, in order to evaluate the occurrence of MBR, the minimum possible obtained value was chosen, by adding the discharges from Aguaclara alto, El Oso and La Vega. The other alternative could have been to use only a relationship between Aguaclara Alto and Aguaclara Bajo, this would have increased the used value by 17%.

Discharge in each of the stations was used for the water balance, but it is known that a portion of the streamflow moves through the shallow subsurface of the streambed sediments. The magnitude of this subsurface discharge is very difficult to measure, but it existence was proven during the fieldwork in the rainy season, around the El Oso sub-catchment where a significant amount of water was flowing in the higher areas, but going downstream the flow disappear and came up further down or when the streambed was disturbed. As explained by Wilson and Guan (2004) this flow can be significant and it is usually neglected, due to the complexity of its regular measurements to be included in the water balance. However, the installed streamflow gauges include weirs that help overcome this condition, and reduce uncertainty in the calculations of the water balance.

5.1.2 Precipitation

The analysis started with the temporal distribution of precipitation. As described in the initial chapters of this document, a bi-modal distribution of precipitation is the general rule for the area. For the wet season to dry season there is usually a transition phase. These transitions are different according to the shift occurring, with longer transition times, from the wet season to the dry one.

During the time studied some patterns were clear, but as expected ENSO phenomena impacted the main characteristics of the seasons through the years. It is the case for 2015, during the first wet season of the year a clear reduction of rainfall was presented, with a total precipitation of half the regular rainy season among the three years. Giving the availability of data from the streamflow stations, special attention was paid to the year 2015 to estimate the water balance.

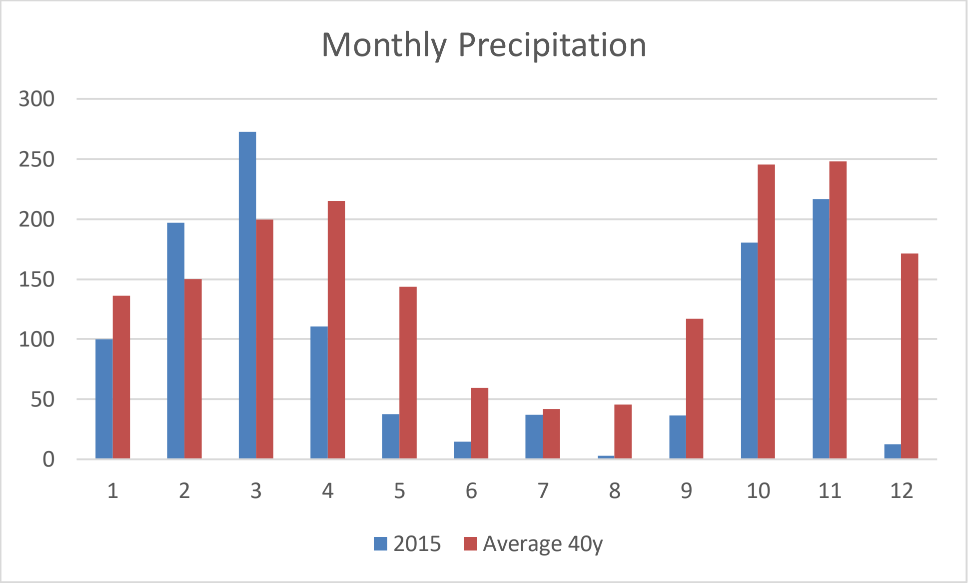

Figure 13 Monthly rainfall average for 2015 and mean rainfall in the area for stations at similar elevations. Note: values measured in 2015 January and February are likely to have an error, according to the analysis.

To complement the time distribution and be able to estimate the catchment precipitation, the spatial distribution was done according to the methodology described earlier. Orographic effects result in more precipitation at the higher elevations in the instrumented area (see Figure 11), than those located the lower parts of the Aguaclara sub-catchment where the alluvial deposits are located. The constructed maps from this method are available in Appendix A, and Figure 14 presents the results for October 2015. Figure 14 shows that the higher elevation areas tend to have higher values of rainfall during the wet seasons, with more than twice the amount of rainfall. Correlation between elevation and precipitation decreases during the dry periods when the precipitation events are produced by smaller scale processes, like the local formation of convective precipitation

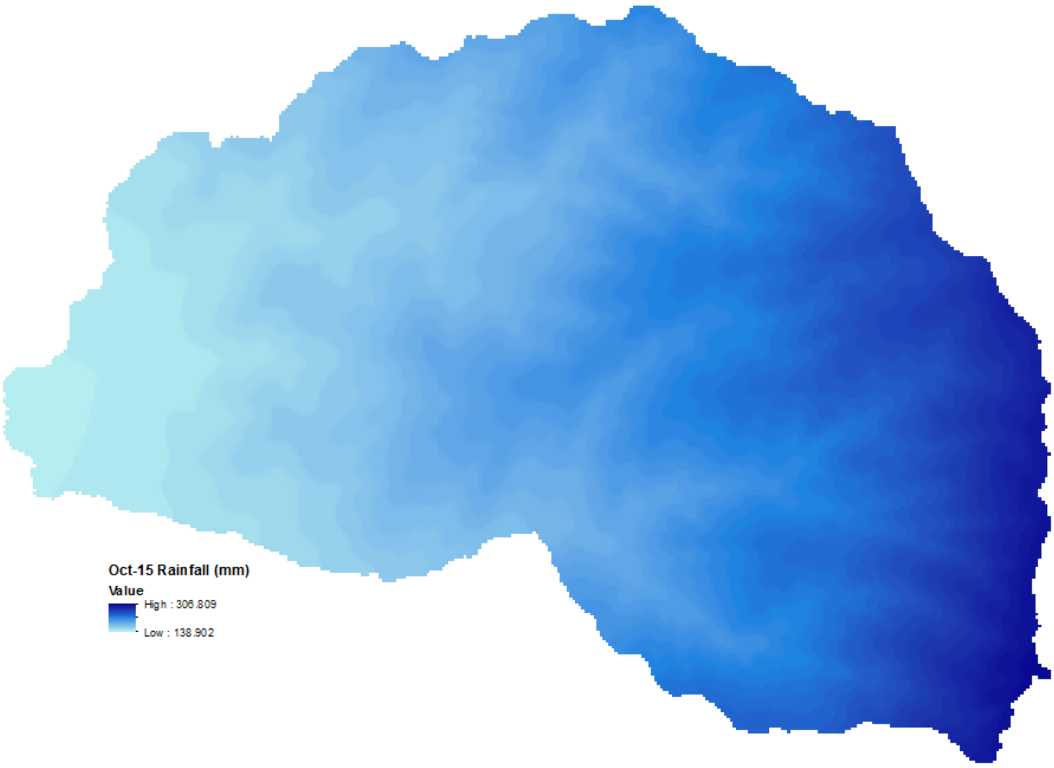

Figure 14 Rainfall distribution for October 2015 at the instrumented area.

To test the methodology used in the precipitation distribution, the values estimated by the hypsometric method at each of the stations were compared with the measured monthly precipitation, Figure 15 shows the comparison between the calculated data from the functions and the actual measurements at the stations used to distribute rainfall. The results showed a clear correlation and the Pearson’s coefficient for the data set is 0.994. The methodology used showed an averaged error of 6% for the predicted values. Since the slope and intersection values of the hypsometric function were obtained from the data set tested, the high correlation was expected. Therefore, additional verifications were carried out for stations not included in the calculation of the hypsometric function.

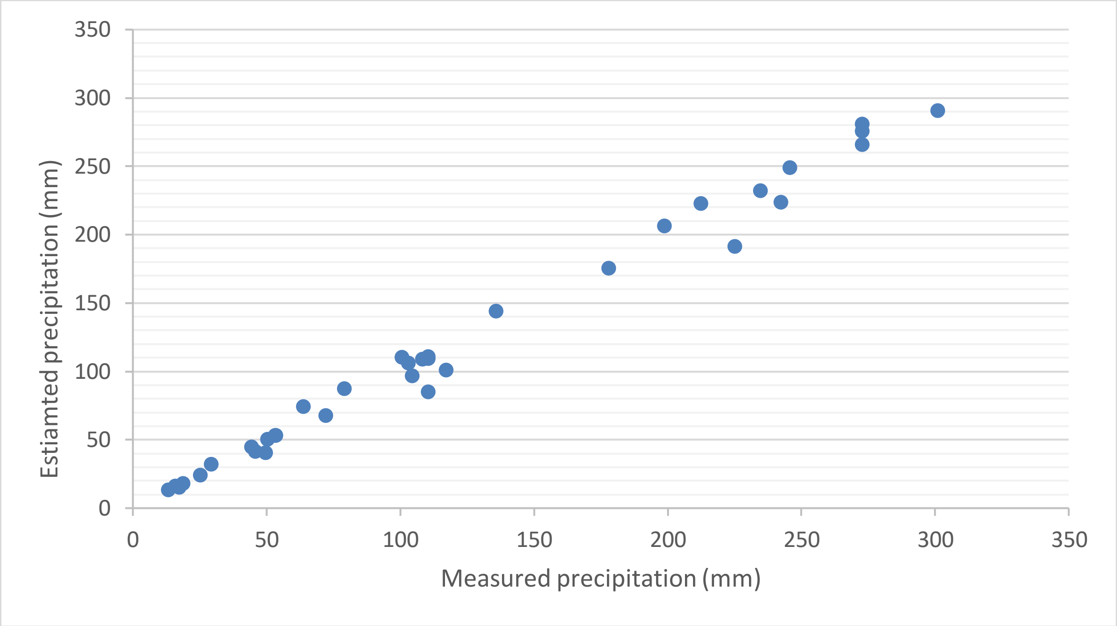

Figure 15 Measured Precipitation values at stations vs estimated values by hypsometric method

Two extra stations from CVC (Tenjo and Chambu) were used to validate the precipitation distribution in the area. The locations of these stations are shown Figure 16. CVC stations measurements were not included in the development of the precipitation maps. The data from the stations was extracted at the location of the station to verify the results of precipitation distribution. The validation was done for the entire period between March 2015 and February 2016, including the months when the correlation was not strong, and the results validate the use of the hypsometric method, with a Pearson's coefficient of 0.944, as presented by Figure 17. There is significantly good correlation of the estimated values by the method used, however, for the month of September 2015, there is a large difference visible as the larger outliners in Figure 17, during this month the CVC station recorded a rainfall more than two times the most elevated station (El Eden) at the instrumented area. Nonetheless, the results of the spatial distribution are positive. Considering the good results of the method, and given that on yearly basis the correlation of precipitation and elevations is higher than on monthly basis, the yearly was calculated according to the yearly function, and using the mean elevation of the catchment.

Uncertainty and errors are usually present in hydrological studies. Additionally, the high relief of the area, together with the shorter measurement periods will increase the uncertainty of the results Dingman (2002). However, the results for the spatial distribution seem to be accurate. Nevertheless, these measurements in the rain gauges are subject to malfunctions, as it was found during the initial data review since some stations presented frequently exact same value of precipitation.

The precipitation records at the instrumented area for the months of January and February of 2015, showed clear errors given that the values for the four stations in the instrumented area had the exact same value. However, for the month of January they seem to have a similar value to the averaged of the area, and to those measured at the Chambu station of CVC. For February the precipitation seems to belong to a more elevated area, since the values are almost twice the average measured, and the CVC stations did not reflect this large increase at that period.

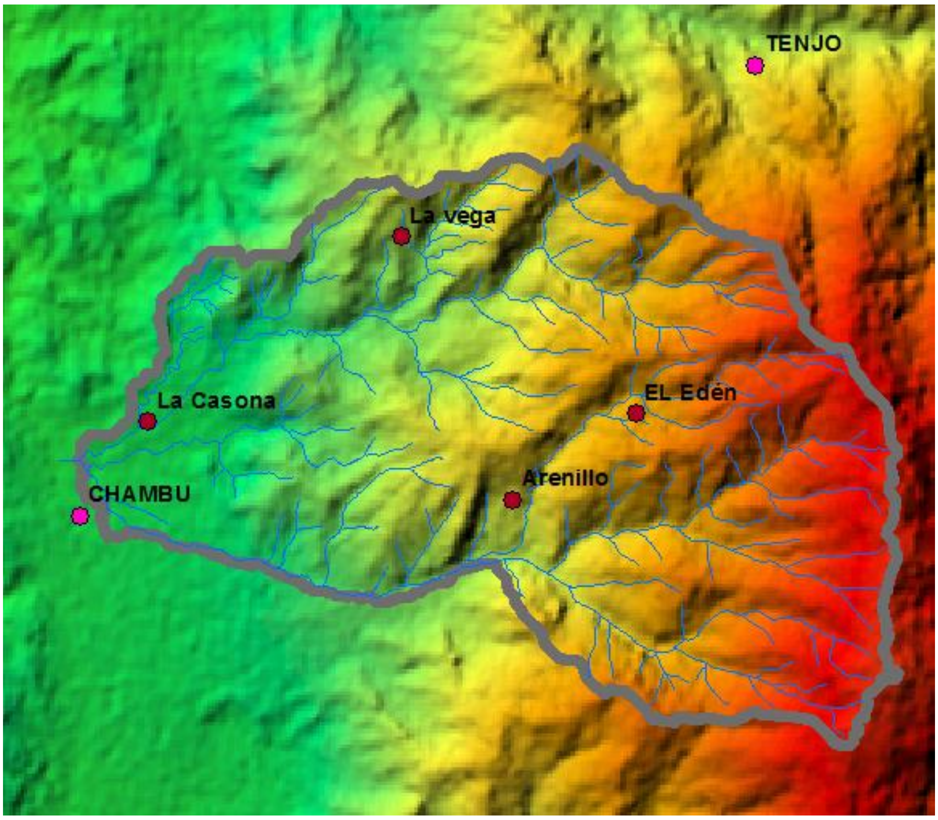

Figure 16 Climate stations for precipitation prediction validation on top of a topographic map. Stations used within instrumented area (red dots) and CVC stations (pink).

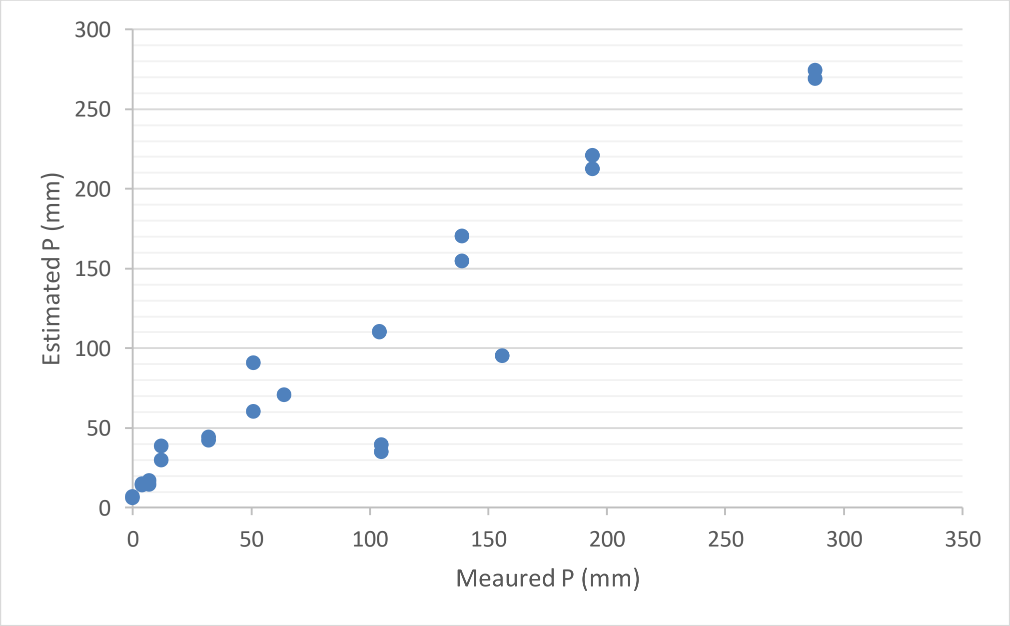

Figure 17 Precipitation distribution functions validation for period March 2015 to February 2016

Up to this point, it has been shown that a good spatial distribution of precipitation in the study area could be assessed by the hypsometric method whenever a correlation between point measured and elevation was possible. However, due to the conditions of precipitation during the dry periods, when rainfall results from local processes, the correlation of those periods was under 0.5, which suggest that under 25% of the precipitation variation could be explained by changes in elevation. It is the case for the months of July and August with correlation coefficients of 0.36 and 0.20 respectively. For December 2015, the correlation was (-0.88), but since it was an extraordinary dry month as presented in Figure 13, and the correlation does not follow the trend of the other months in the year, nor the December behaviour of the years 2016 and 2017, therefore, it was treated as a dry month. After analysing the general water budget, it was decided that in order to estimate the potential relevance of MBR the best way was to establish favourable conditions for its occurrence. Hence, it was determined to use the maximum recorded precipitation in the catchment, even though the standard deviation was 18%, 38% and 35% of the selected value, respectively for July, August, and December.

5.1.3 Evapotranspiration

Figure 18 and Figure 19 show the temporal comparison of the two models, displaying similar patterns through the evaluated period, but also showing usually higher of actual evapotranspiration for the ETensemble V1.1. Although graphically the difference is evident, t-test was carried finding a significant difference between the models. As shown by Table 2 the ETensemble V1.1 measures are statistically higher than the ET calculated from the SSEBop with an average difference for the year 2013 of 21.44% and 17.31% for the second evaluated period, and a total average of 19.29% for the two years.

Table 2 t-test results for ETensemble V1.1 and SSEBop v4.0 comparison Jan 2013-Dec2014

	Variable 1	**Variable 2**
Mean	80.40	64.71
Variance	118.21	113.16
Observations	24	24
Pearson Correlation	0.67	
Hypothesized Mean Difference	0	
df	23	
t Stat	8.82	
P(T<=t) two-tail	7.72E-09	
t Critical two-tail	2.07	

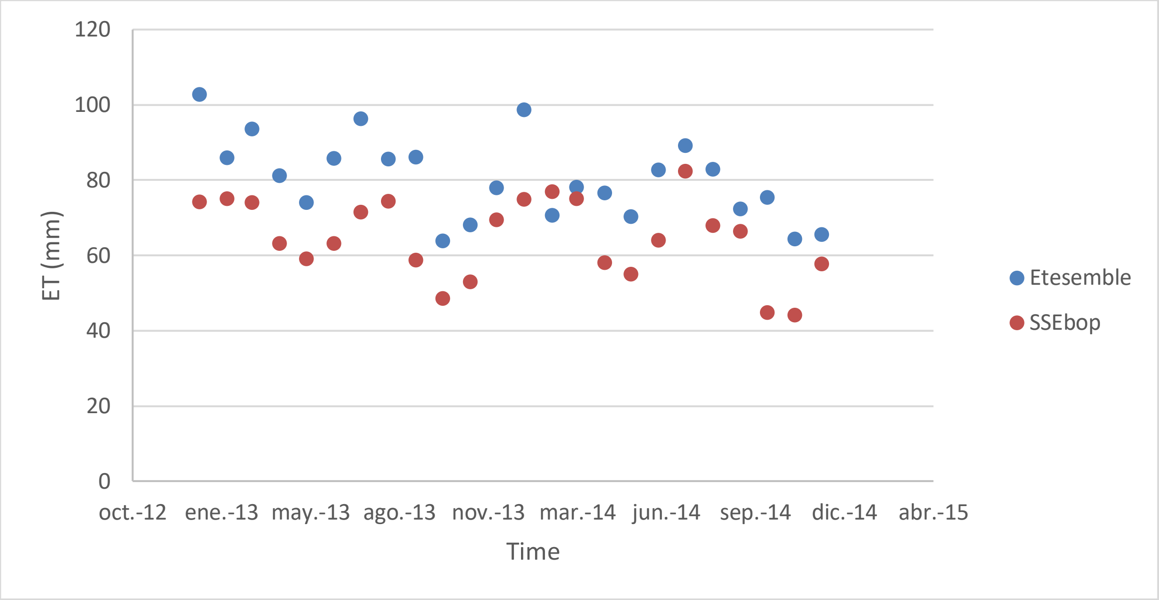

Figure 18 Temporal plots for ETensemble V1.1 and SSEBop v4.0 at study area.

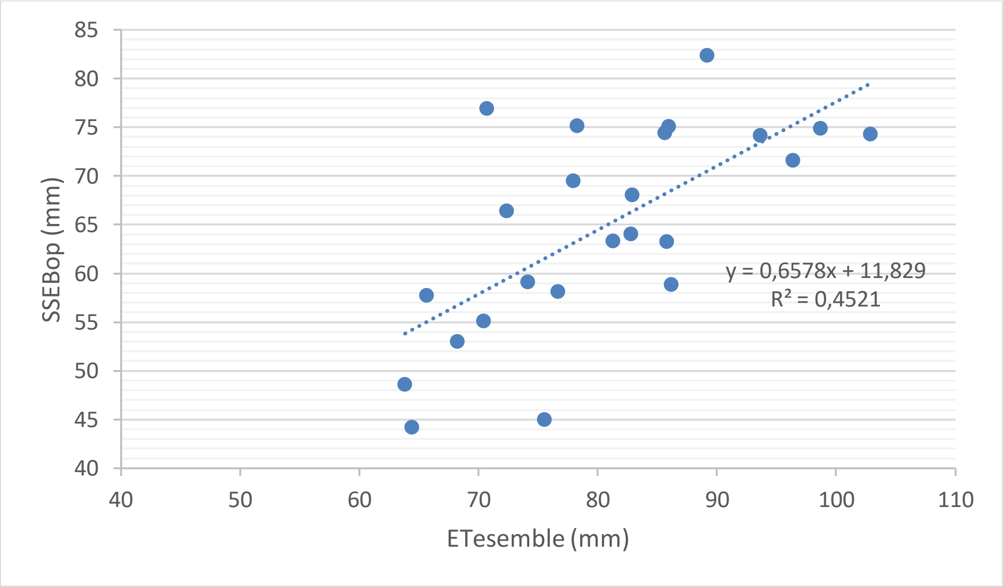

Figure 19 Comparison ETensemble vs SSEBop

Remote sensing data has some advantages and is a helpful available tool, however it is important to understand the uncertainties of the available models. The second validation of the ET calculation was done with the data measured by the monitoring network. In the initial comparison of the data from the model is displayed by Figure 20, neither a good match nor correlation was obtained. As mentioned this calculation was done according to the land use of the area. The stations specifications, suggest this calculation as the actual ET, however given that not a clear assessment of the water available in the soil is established, this could actually refer to the potential evapotranspiration.

The results of the ET calculated at each station after the inclusion of the land use, compared to those obtained at the point of the station from the SSEBop model are presented in Figure 22 In the comparison it is possible to observe that the general patterns over time seem to be similar in both calculations. The

SSEBop model values are usually below the calculated from the measurements. It could be explained by the previous comment that the suggested calculation of actual ET according to specification of the equipment, might be more representative of the potential even when including the crop coefficients.

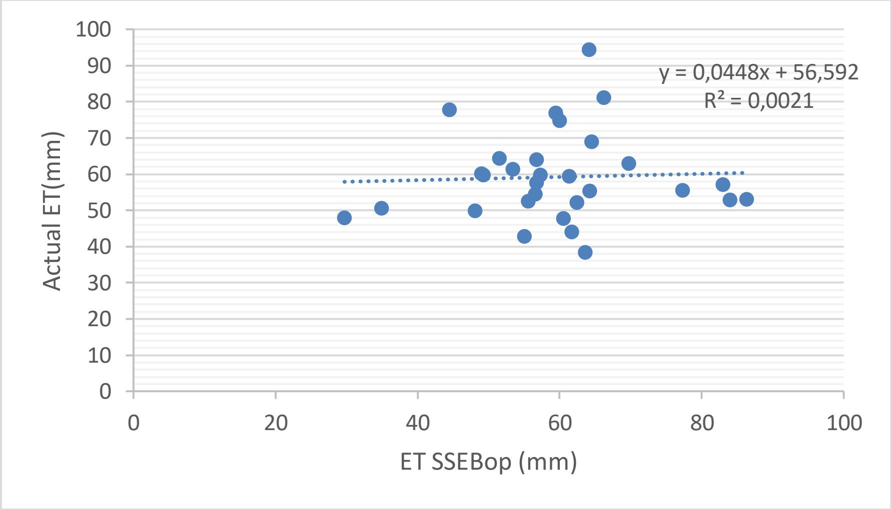

Figure 20 Comparison of ET values for stations between May 2015 and November 2015

However, the previous comparison has to be taken carefully, since the stations are points, in an area with a land use that may not be representative for the larger part of the catchment, making them differ with those from the SSEBop, since the model uses pixel of 1 km. Hence a fair comparison for the ET at each of the sub-basins is presented in Table 3and the graphically presented in Figure 21. Maps per month are available in **¡Error! No se encuentra el origen de la referencia.**.

Table 3 ET comparison for May, October and November 2015 between SSEBop and measurements coupled with land use

	May		**October**		**Nov**	
	ET (mm) Land use	**ET (mm) SSEBop**	**ET (mm) Land use**	**ET (mm) SSEBop**	**ET (mm) Land use**	**ET (mm) SSEBop**
La Vega	49.19	59.81	63.59	38.38	64.17	55.26
El Oso	51.51	64.38	60.50	47.79	61.32	59.33
Chontaduro	48.91	60.12	55.02	42.78	56.51	54.48
Aguaclara Alto	56.74	57.58	29.69	47.84	34.91	50.59
Agua Clara Bajo	48.07	49.93	61.67	44.10	62.35	52.24
Total	51.13	56.10	50.31	44.74	52.57	52.81

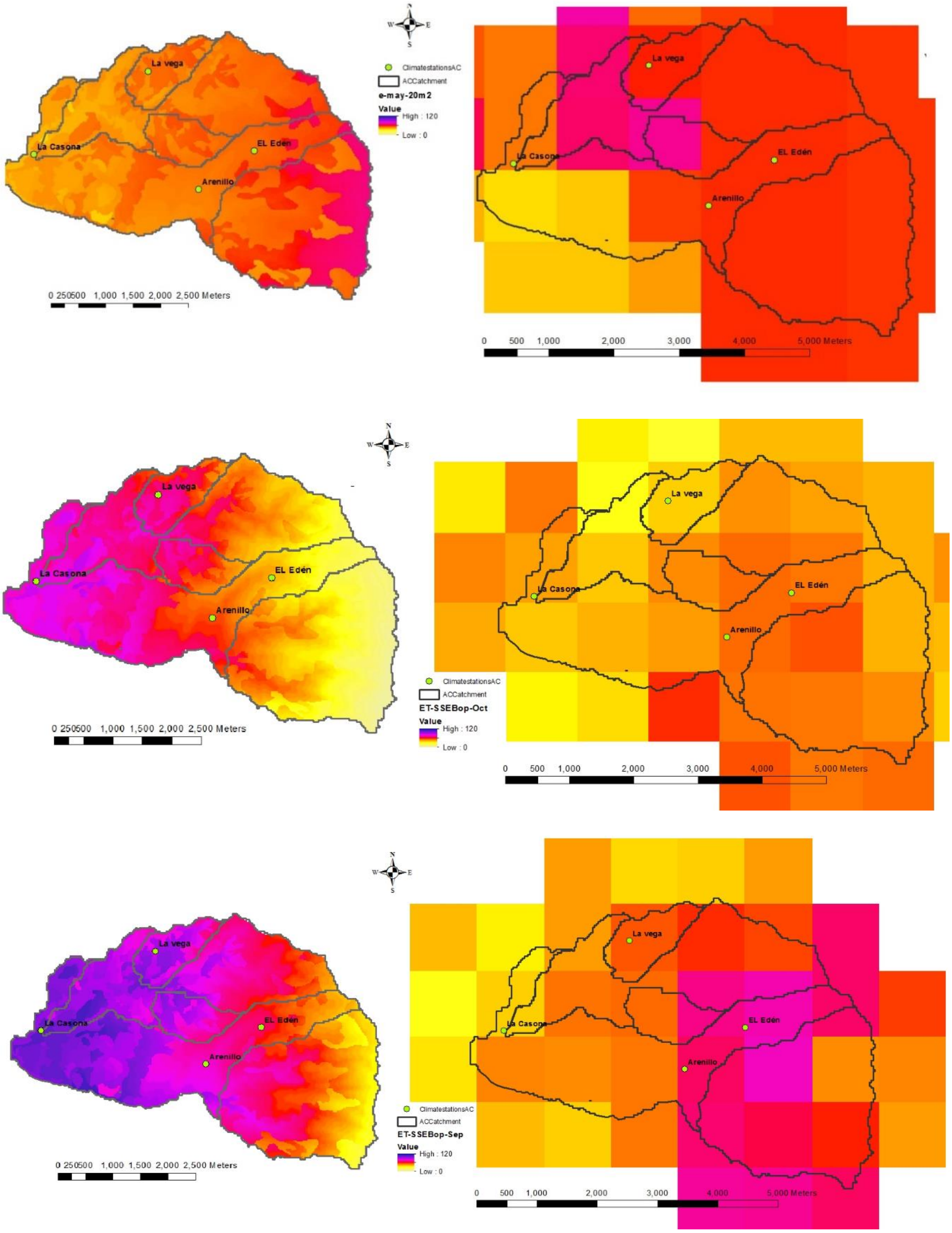

Figure 21 ET maps for May, October and November 2015, ordered from top to bottom .Left according to measurements in the area. Right: SSEBop

The spatial distribution of the calculated ET by the two methods shows differences, mainly in how the SSEBop model seems to calculate higher ET towards the elevated areas, while the measurements indicate the opposite. Generally ET should decrease with elevation (Earman 2004; Guan 2005; Wilson and Guan 2004). However, the difference seems to decrease significantly when the entire catchment is considered. In Table 3 the total ET for the catchment was calculated according to the proportional area of each sub-catchment. For the period evaluated between May and December 2015 (according to available data) the difference between the two methods for the entire catchment is 10 mm less for the SSEBop model. Graphical representation per sub-catchment available in Appendix B

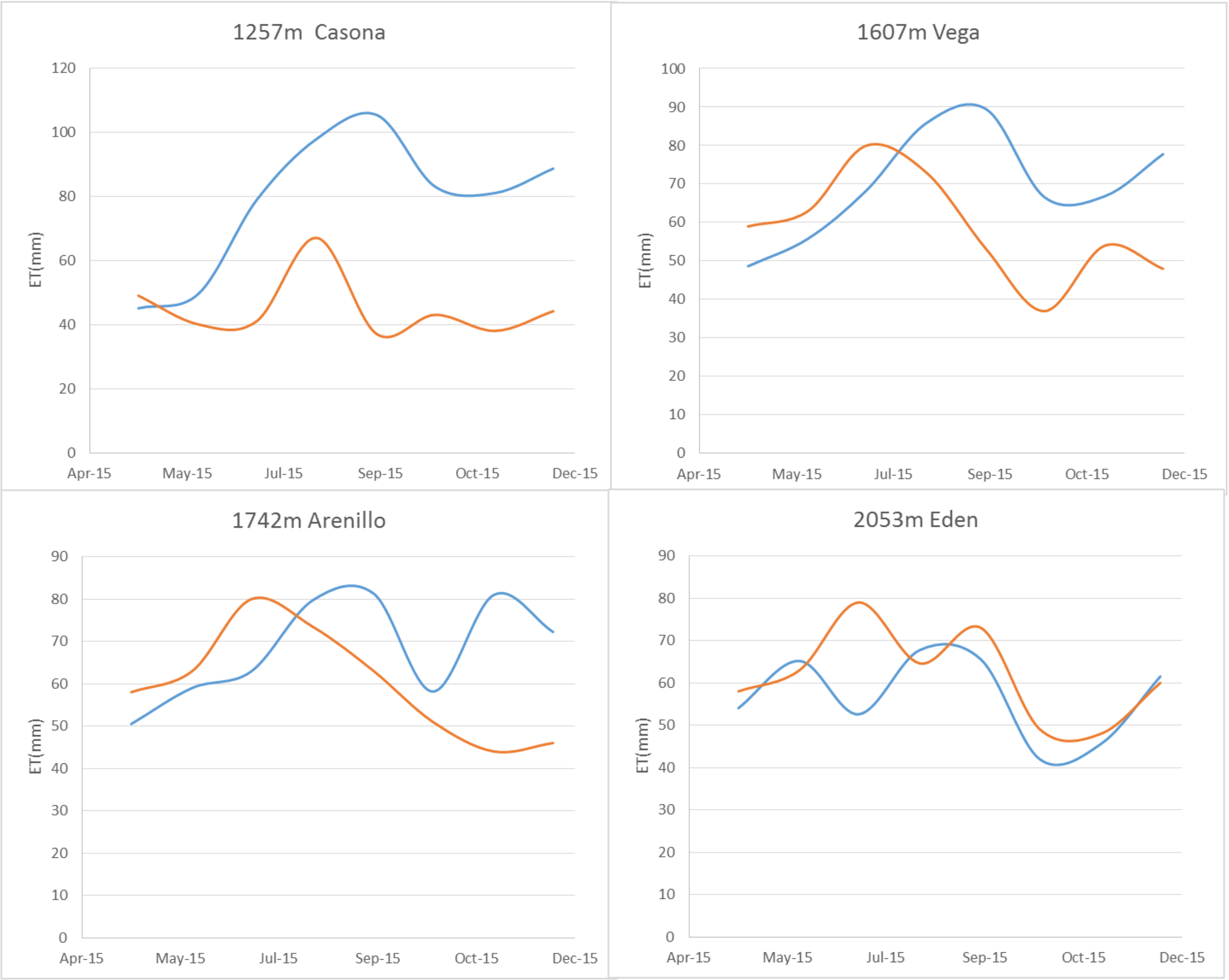

Figure 22 Actual ET by measurement at stations and crop coefficient (blue) and estimated by SSEBop (orange) comparison

5.1.4 Water Balance

The created maps for the monthly spatial distribution of precipitation and evapotranspiration were operated in GIS. The procedure was carried for the two methods of estimating ET, according to the data available, as mentioned earlier the actual ET values are mainly from SSEBop. All created maps area available in **¡Error! No se encuentra el origen de la referencia.**, and Figure 23 presents the results of subtracting ET to P, for one wet period in March 2015 and one dry period in June 2015. The obtained results show the availability of water in mm distributed for each of the sub catchments presented in Figure 12 this was then converted to total volume of water by multiplying the result with the area. From the result of the operation, the discharge of the streamflow gauge or the calculated as described in section 6.1.1 was subtracted.

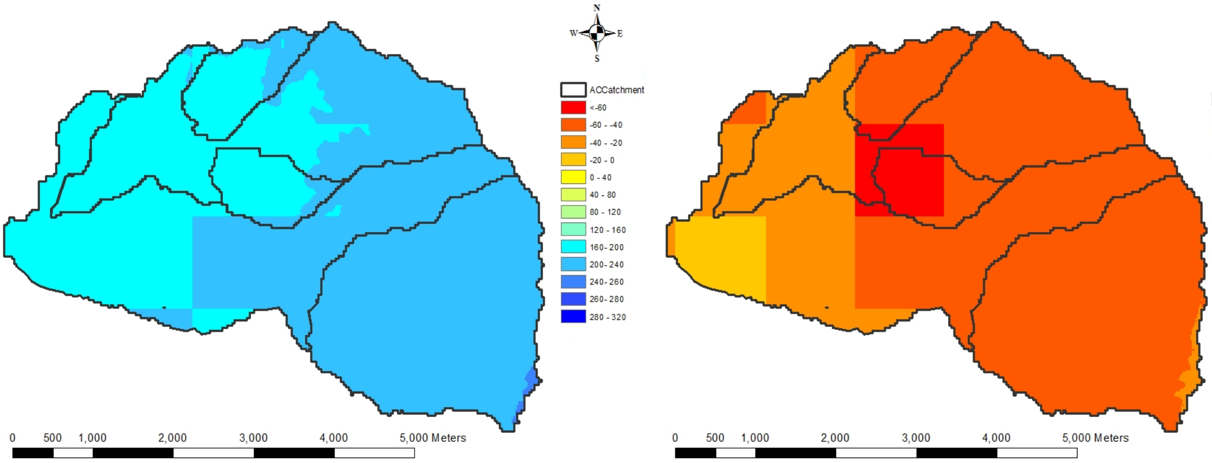

Figure 23 P-ET (mm). March 2015 on the left and June 2015 on the right

According to the availability of the data, the water balance was done for the most complete period which was the year 2015. Table 4 presents the results during one of the months in the wet season, where MBR and changes in storage are taken together and discrepancies in parameter estimations are ignored During the year 2015, only the three months of March, October and November (wet periods with accurate data available) had a positive balance of water that could go to storage and/or MBR recharge. Reaching a total potential of 396.5 mm which would represent up to 29% of the annual precipitation for the catchment.

The previous estimation is an indicator for the wet periods. But during the dry season opposite balance result appears as presented in Table 5.The negative balance implies that there is more water coming out of the catchment than the amount coming from precipitation, indicating that water must be coming out from storage in the subsurface. Water in the subsurface could be portioned between MBR and storage.

Table 4 Water Balance March 2015

Mar-15								
CATCH	AREA	P (mm)	P-ET (mm)	P (m3)	P-ET (m3)	Q(m3)	ΔS+MBR (m³)	ΔS+MBR (% of P)
La Vega	1,154,563	278	197	320,708	227,729	57,792	169,936	53%
El Oso	937,775	281	196	263,629	183,704	88,807	94,898	36%
Chontaduro	5,431,770	282	202	1,529,819	1,096,051	555,403	687,246	45%
Aguaclara Alto	6,312,894	299	223	1,884,996	1,405,373	747,793	657,580	35%
Agua Clara Bajo	7,010,843	278	201	1,948,139	1,410,836	1,678,118	1,035,915	53%
Total Chontaduro				2,114,156	1,507,484	555,403	952,081	45%
Total Aguaclara				5,947,291	4,323,693	1,678,118	2,645,576	44%

Table 5 Water Balance June 2015

Jun-1								
CATCH	AREA	P (mm)	P-ET (mm)	P (m3)	P-ET (m3)	Q(m3)	ΔS+MBR (m³)	ΔS+MBR (% of P)
La Vega	1,154,563	16	- 48	18,318	-55,574	26,072	- 81,646	-446%
El Oso	937,775	16	-60	15,468	-56,582	32,551	- 89,133	-576%
Chontaduro	5,431,770	17	-43	90,123	- 234,633	358,154	- 534,163	-431%
Aguaclara Alto	6,312,894	20	-43	124,816	- 272,896	596,745	- 869,640	-697%
Agua Clara Bajo	7,010,843	16	- 37	111,367	- 256,785	954,899	- 256,784	-109%
Total Chontaduro				123,909	- 346,788	358,154	- 704,942	-569%
Total Aguaclara				360,092	- 876,469	954,899	- 1,831,368	-509%

The results from Table 4 and Table 5 reflect that the storage in the subsurface has an important role in the hydrological processes in the catchment. The interaction between the different months, will take care of removing the storage from the long term calculations of the MBR. For the purpose of the analysis of the potential MBR, multiple analyses were carried out according to the availability of data and in order to understand parameters that could conditioned its estimation, and the general hydrological procedures of the catchment. The results for the entire catchment are presented in Table 6, and the graphical representation including the period to period variation and the cumulative amount of MBR for the year 2015 are displayed Figure 24

Table 6 Results water balance for 2015

2015	
Positive balance from wet season (m3)	10,040,524
Positive balance from wet season (mm)	482
Potential MBR from wet season (%)	35.67%
Total balance for the period (m3)	521,545
Total balance for the period (mm)	25
MBR%	1.9%

During the previous sections the approach for the calculation of the MBR was explained, in which the assumptions taken for the missing data were as favourable as possible for the occurrence of MBR. ET values were used from the SSEBop model which compared to the ETensemble V1.1, showed an average 20% less ET. Precipitation for the dry periods was established as the highest measured value for the entire catchment, and the missing runoff data was completed under a most likely underestimation. Note in that during the wet periods a very significant amount of 35.67% of the year precipitation is most likely stored in the subsurface. However, the results shown that the fraction of water that could potentially go to the MBR on 2015 is not significant, and could be easily part of the discrepancy of the water balance. The final calculated recharge that could go to MBR, at the end of December 2015, under the assumed conditions is 25.92 mm. Given that the calculated recharge at the alluvial deposits within the Aguaclara sub-basin in Figure 11, is between 250 to 511 mm/year Cespedes (2017), the amount could represent up to 10% of the recharge, however, with a standard deviation of 93 mm, along the year, and representing 2% of total precipitation in the catchment under the most favourable conditions it seems that the main contribution to recharge from the mountains enters the valley basins as surface runoff.

A per catchment representation of the balance is presented in Figure 24. Note that the behaviour of four out of five catchments through the year follow the same patterns. Precipitation is also shown in this plot to understand the effects it has on the groundwater of the catchment. In this plot, the yellow line representing Aguaclara Alto, presents a constant negative balance and additionally seems to be the most sensitive area to changes in precipitation, reflected in the earlier and faster changes through the year. El Oso seems to have a different behaviour mainly in second rainy season in October, when in contrast to the other catchments does not increase its recharge and remains decreasing constantly.

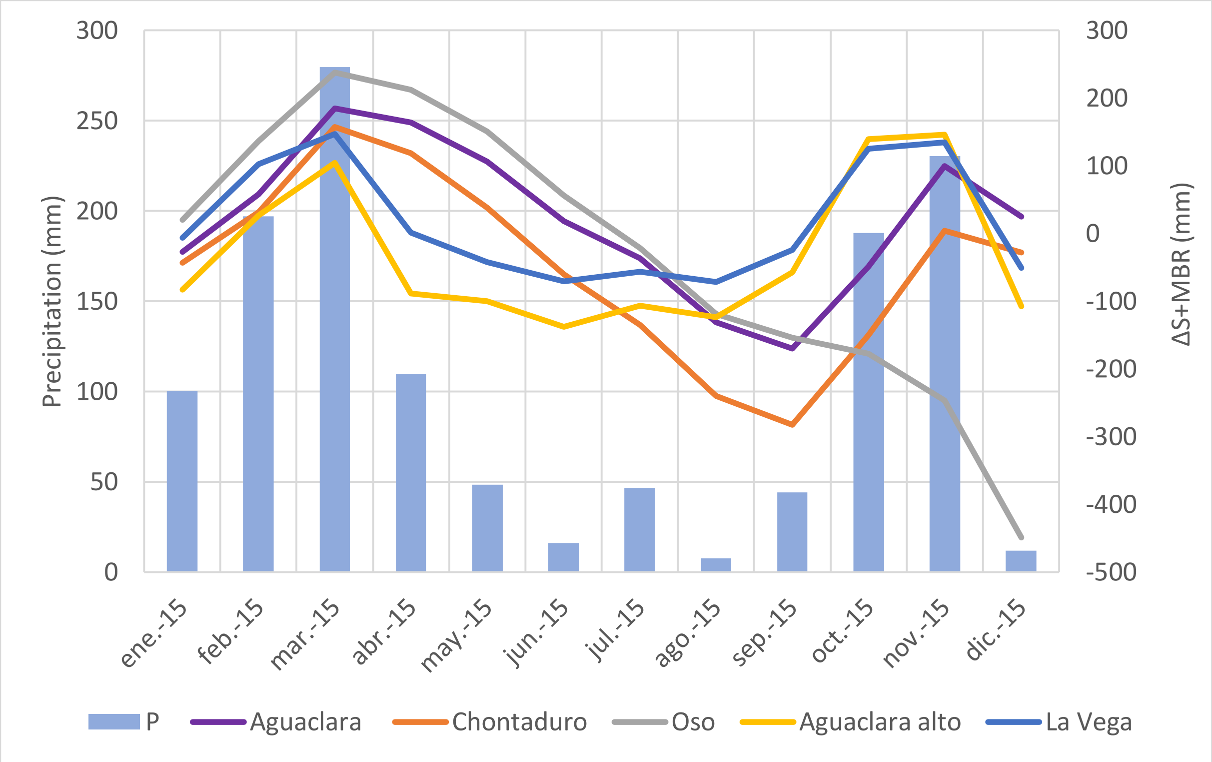

Figure 24 Cumulative Water Balance and average rainfall year 2015

One major observation of this method is that the accuracy depends mainly on the estimation of ET, with all the described difficulties. Therefore, an evaluation of the balance was also done when using the ET calculated according to the measurements and land use as explained earlier. Measurements of ET were only available for the period between May and December of 2015. The results of the monthly ΔS+MBR for the catchment, and the cumulative values are presented in Figure 25.

In Figure 25 it is possible to observe very low variations between the two general results, even when there was not a good correlation between the two values of ET at the stations. In this case the cumulative ΔS+MBR is always negative. From the monthly water balance, it seems that the 1 km resolution for the ET model has a good estimation, having similar result to those obtained from on field measurements. Nevertheless, the data of ET measurements is not that long, hence, firm conclusions cannot be drawn.

The results so far have shown that even under the most propitious conditions the relevance of the MBR seems to be small. Nevertheless, the year 2015 was a very dry period due to El Niño, with less than 62% of average precipitation when compared to the last 40 years, as observed in Figure 13 and this is still considering the probably overestimation of rainfall for the month of February. For this reason, an extended analysis was done according to the availability of data and also the findings described so far, i.e. that the SSEBop ET calculation is probably a good approximation, for the entire catchment, having a similar results to those obtained from the actual measurements available for the year 2015.

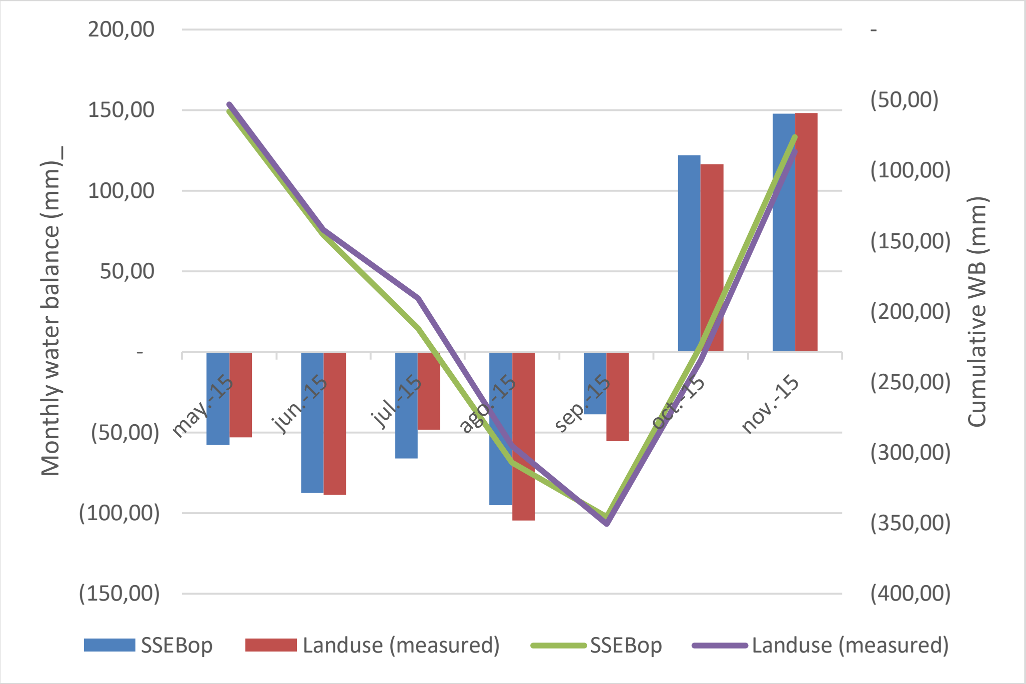

Figure 25 Water balance for the entire instrumented catchment, comparison between measured ET and Modelled ET

For the precipitation, the correlation with elevation was weak for the year 2017. Hence, the used precipitation for the water balance of the years 2016 and 2017, was taken from the measured data at the stations, as presented in Table 7. Regarding the discharge measurements difficulties with the operation of the network have limited the continuous collection of data, but the information for the smaller catchment was significantly more complete than at the outlet station of the Aguaclara. Again since a clear pattern is not follow for the discharge measurements, and also in order to create the most favourable conditions to assess the occurrence of MBR the missing values were assumed 0 for the balance, meaning that the balance for those months will only be the rainfall minus the evapotranspiration. However, even under these conditions the amounts of water that could potentially go to MBR do not seem to be significant as reflected in the Figure 26 and presented in Table 8 result for Chontaduro represents the amount of water at the end of November 2017, due to missing streamflow data. In Figure 26, whenever the line is cut, indicates that discharge data was not available. An important remark is to indicate that the selection of the period to be evaluated could drastically affect the results. This given that if the analysis is done until the end of the wet seasons, the resulting amount could be higher than 100 mm, which would be significant. In this research the periods were taken until December, but always considering the large variations. The water at the end of December 2017 is under the standard deviation, reinforcing the theory that the storage of water in the subsurface has significant relevance for the hydrological processes in the catchments, but the amount available for MBR is not significant.

Table 7 Source of precipitation data for water balance of 2016-2017

Catchment	P data from
La Vega	La Vega station
El Oso	Arenillo station
Aguaclara Alto	El Eden station
Chontaduro	Average 4 stations

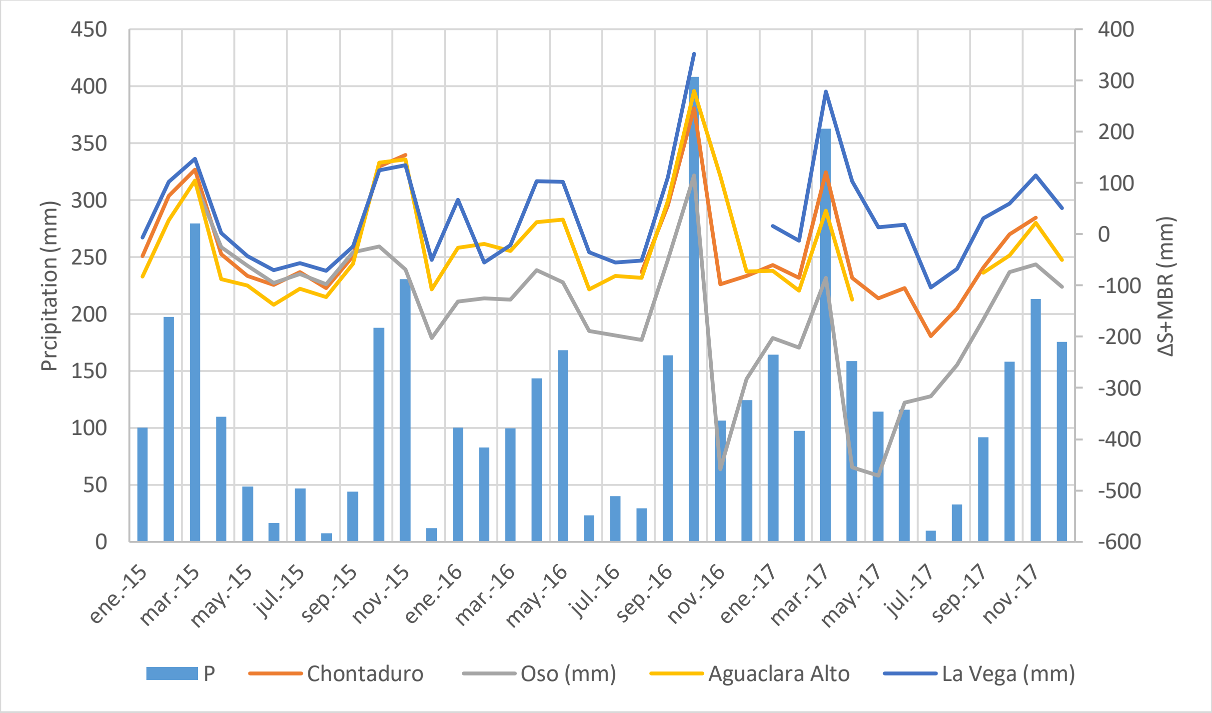

Figure 26 Cumulative Water Balance and average rainfall from Jan 2015 to Dec 2017 per sub-catchments (Non-connected lines indicate periods without discharge data)

Table 8 Water balance results for 2015-2017 (mm)

	Chontaduro	Oso	Aguaclara Alto	La Vega
Jan/15-Dec17	31.66	- 103.01	- 49.93	51.21
Jan/16-Dec17		100.20	57.64	101.80
SD	99.27	145.22	95.89	99.62

5.1.5 Sensitivity analysis

For reducing the uncertainties in the calculations of MBR, considering that the period used to the more detailed analysis was particularly dry, and the challenges of the estimation of ET, a sensitivity analysis was carried to estimates the changes in the MBR when one of the parameters of the water budget is modified. The changes in the dependent y variable from a change in the independent x variable is mathematically given by the partial derivative dy/dx. For the purpose of this research the y variable is the resulting MBR on a yearly basis. The finite approximation of the partial derivative is given by (Lenhart et al. 2002)

$$\frac{dy}{dx} = (y_2 - y_1)/2\Delta x$$

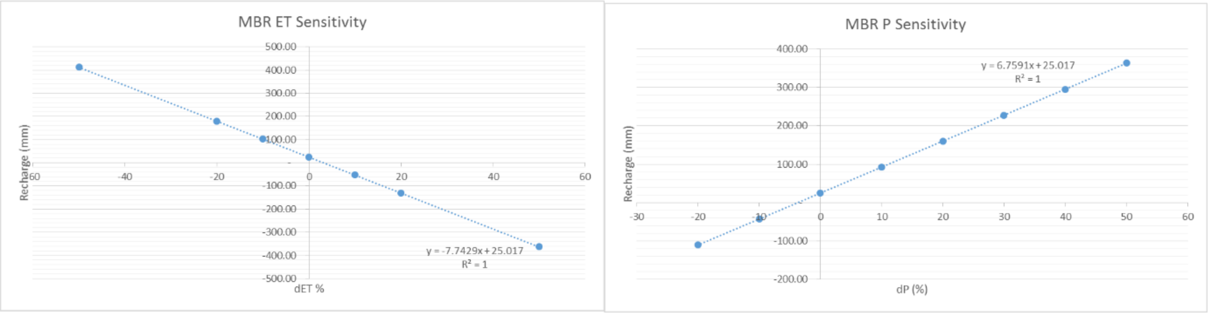

Figure 27 Sensitivity Analysis for the MBR. Left to changes in ET. Right to changes in P

Considering the potential amount of water (in mm) on the y axis and the variation of the main variables ET and Precipitation, Figure 27 was created The change is one of the most important components for the sensitivity. Hence, to evaluate the changes, a function of MBR to changes in ET and precipitation was considered. The results show larger sensitivity to the ET changes as the slope is slightly higher than the slope from precipitation. Another important factor that will reduce the slope of precipitation is the presuamable increase in discharge that is no accounted here. The correlation between discharge and precipitation was establish per month and then compared to obtain dQ/dP, however, no clear relationships were obeserved and large variabilities in the different subcatchments was found. The comparison also showed that the increased of Q during the wet months was significantly higher, than the averaged for the entire year, but again the variations were too large. Even though the dQ/dP did not show a clear pattern between 2015-2017, the averaged for the simulated period was 1.04 between three data sets complete for the 4 sub-catchments.

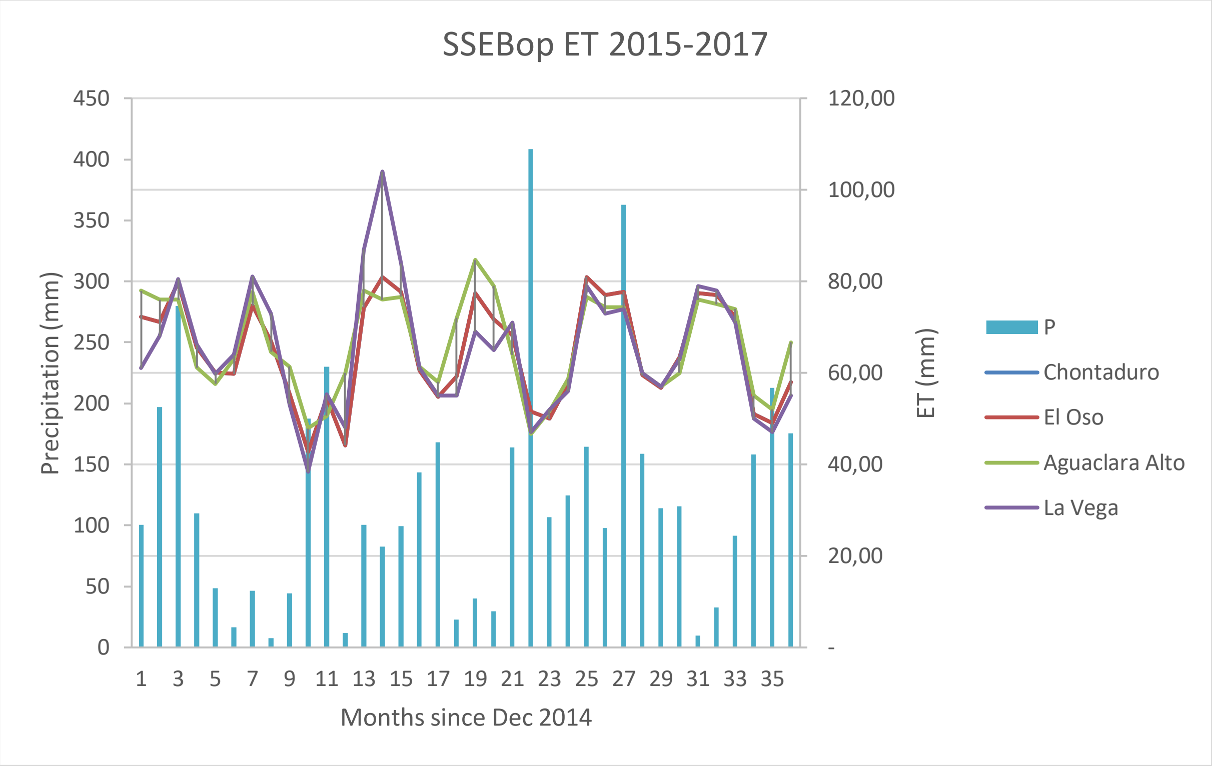

Figure 28 ET variations and P variations during Jan 2015 – Dec2017

The variation of variables was done independently, assuming that a different method for calculating the actual ET was used, as the ETensemble. However, is reasonable to assume that actual ET is a dependent variable of precipitation. By using the data for the years 2016 and 2017 it was evaluated how this change could happen. Figure 28 presents how the variables behave, per catchment for the ET and an average of precipitation. The analysis was done with the point value of precipitation as presented in Table 7. An annual average increase in ET of 3% was found. Results are presented in Table 9. Observe how even with an increase of almost 50% of precipitation for La Vega in 2017, the increase on the ET estimated by SSEBop is only 5%. This could be a result of the important contribution of the subsurface storage that closes the gap between potential and actual ET. Due to the differences found between measurements and the model, which were reduced when analysing the entire catchment, probably the most reliable results would be the ones from Chontaduro as it covers a larger area and the variations of elevation in the area.

Table 9 ET and P variations

	dP 2016/2015	dp 2017/2015	dET 2016/2015	dET 2017/2015
La Vega	1.15	1.49	1.08	1.05
Aguaclara Alto	1.15	1.02	1.04	1.04
El Oso	1.26	1.32	0.98	0.91
Chontaduro	1.15	1.31	1.05	1.07

5.2 Baseflow separation

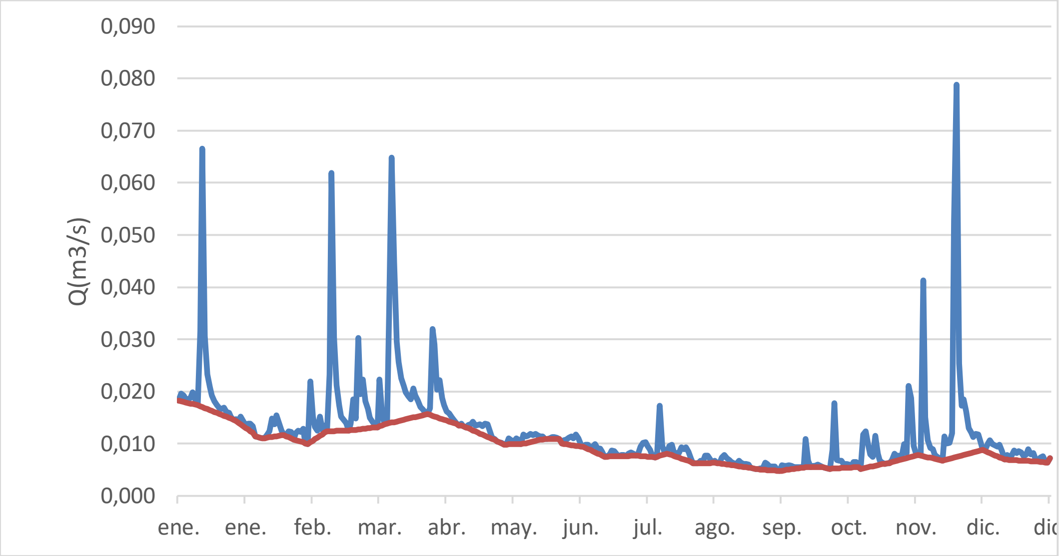

Figure 29 Hydrograph separation for La Vega 2015. Baseflow in orange

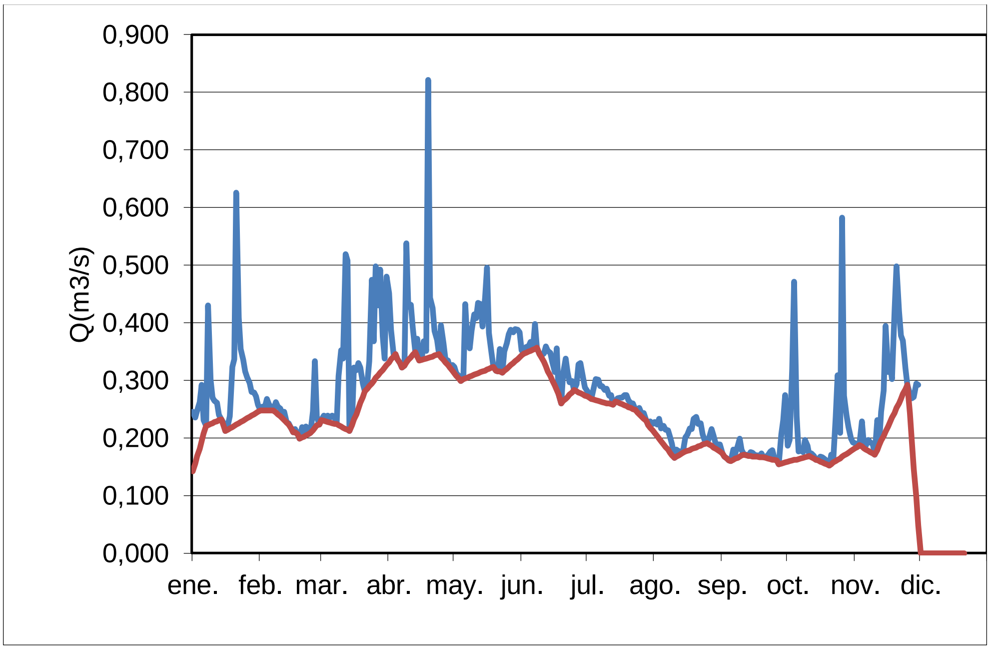

Figure 30 Hydrograph separation for Chontaduro 2017. Baseflow in orange

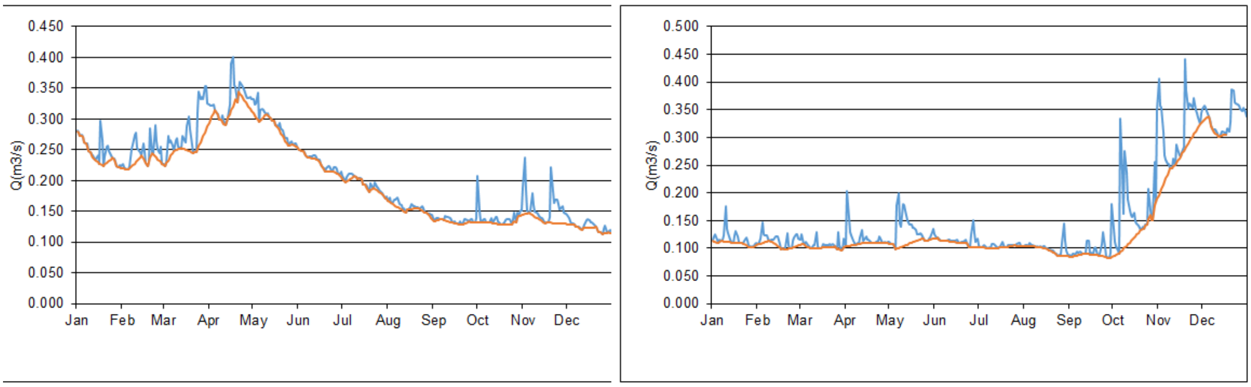

Figure 31 Hydrograph separation for Aguaclara alto 2015 on the left and 2016 on the right. Baseflow in orange

Figure 29 to Figure 31 show the hydrograph separation obtained from the BFI software, for three of the catchments in the study area. Here the relevance of the baseflow in the overall processes of the catchments is clear, mainly during the dry months between May and September. When checked with the baseflow tool from SWAT, both methods result in large contribution of the baseflow to the perennial flows in the study area, with contributions of over 67%. The results also shown a tendency of the baseflow to be more relevant in the higher elevation catchments, like Aguaclara alto and El Oso.

Table 10 Baseflow results

	SWAT			BFI				
Catchment	**Baseflow Fr1**	**Baseflow Fr2**	**Baseflow Fr3**	**BFI 2014**	**BFI 2015**	**BFI 2016**	**BFI 2017**	**BFI Annual**
La Vega	0.81	0.72	0.67	0.654	0.765	0.587	0.732	0.6845
Aguaclara Bajo	0.82	0.74	0.68	0.709	0.701		0.658	0.689
Aguaclara alto	0.92	0.86	0.82	0.895	0.952	0.890	0.897	0.908
Chontaduro	0.84	0.77	0.71		0.752	0.648	0.848	0.749
El Oso					0.812	0.843	0.870	0.842

As suggested by Lee et al. (2006), an integration with the water balance can be done using the Baseflow index of the Catchment. The BFI for the Aguaclara Bajo does not show large differences for the years 2014 and 2015, which are the more complete data sets, and the result is also similar to the FR3 obtained from the SWAT model.

Following the described methods, the baseflow analysis was used to estimate the groundwater recharge to the systems. First the stable method of (Chen and Lee 2003) was used for each of the stations that counted with at least data representing one month of the year of the average, for the recorded when available Figure 32 presents the calculation of the method.

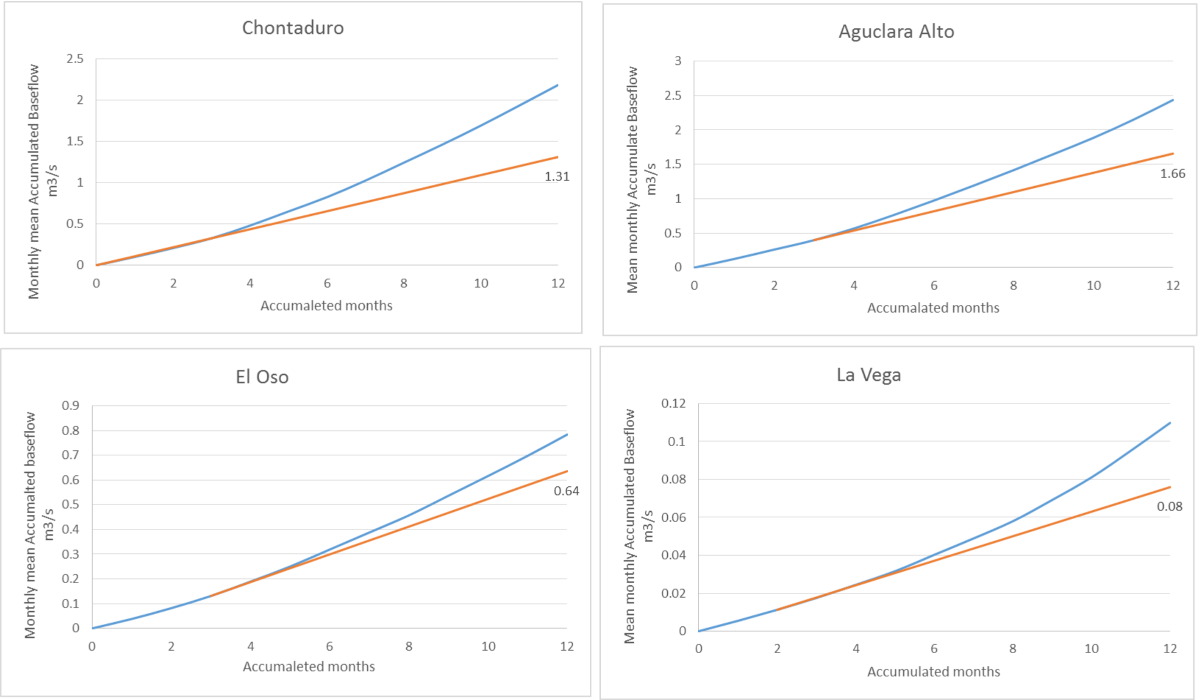

Figure 32 Baseflow analysis for stations at Aguaclara. Orange line is the estimated stable streamflow line. Blue line is the cumulative baseflow.

The stable baseflow was then converted to yearly volumetric units, and by using the drainage area of each of the catchments it is presented as mm of precipitation going to recharge. Results for each of the sub-catchments are highly variable, as observed in Table 11 and for “El Oso” the amount even exceeds the precipitation. This could be due to the sub-catchments division created from the HEC-GeoHMS tool to define the area of each sub-catchment, an increase of 24% of the area needs to be done to achieve the balance, which is still unrealistic. The result could then be explained from subsurface water contribution moving through local flow systems from the other catchments located in higher areas. The result is consistent with the findings of the water balance, where El Oso catchment showed a constant decrease during the year 2015. SWAT tool presented error when trying to calculate the baseflow contribution, it could be due to the found excess.

Nevertheless, some patterns remain clear, such as the larger contribution in the higher elevation areas like El Oso and Aguaclara alto. For the catchment of Chontaduro, that represents 36% of the total monitored area, the results of recharge are similar to those found by the water balance with a recharge of 32%. For the purpose of this research is considered that the Chontaduro calculation is representative of the study area for subsurface recharge, since it is comparable with the recharge calculated during the wet seasons, but the amount of baseflow coming out of the catchments exceeds the calculated recharge by this method, as presented in Table 11. In this comparison it was also found that the over 100% estimation of recharge for catchment El Oso is explained given that the discharge of the catchment exceeds the amount of water available from precipitation, even before subtracting the amount of water that will go to evapotranspiration. One possible explanation for this is contribution of water from other sub-basins moving through local flow systems in the subsurface, this theory is supported by higher EC and HCO_3 concentrations of any other measured streams, and even higher than two of the assessed springs.

Table 11 Calculated recharge by stable baseflow analysis

CATCH	AREA (m2)	Stable-Baseflow (m^3)	Recharge (mm)	R (%)
La Vega	1,154,563	199,592	173	12%
El Oso	937,775	1,670,327	1,781	123%
Chontaduro	7,524,108	3,444,478	458	32%
Aguaclara Alto	6,312,893	4,353,338	690	48%

Table 12 Comparison of volumes for stable baseflow and actual baseflow

	AREA (m2)	Stable Baseflow	Vol actual Baseflow
La Vega	1,154,562	199,592	289,367
El Oso	1,153,464	1,670,327	2,057,305
Chontaduro	7,524,108	3,444,478	5,739,283
Aguaclara Alto	6,312,894	4,353,337	6,396,878

5.3 Water Chemistry

Distribution of the samples is shown in Figure 33 and the description of each sample is available in Annex 1

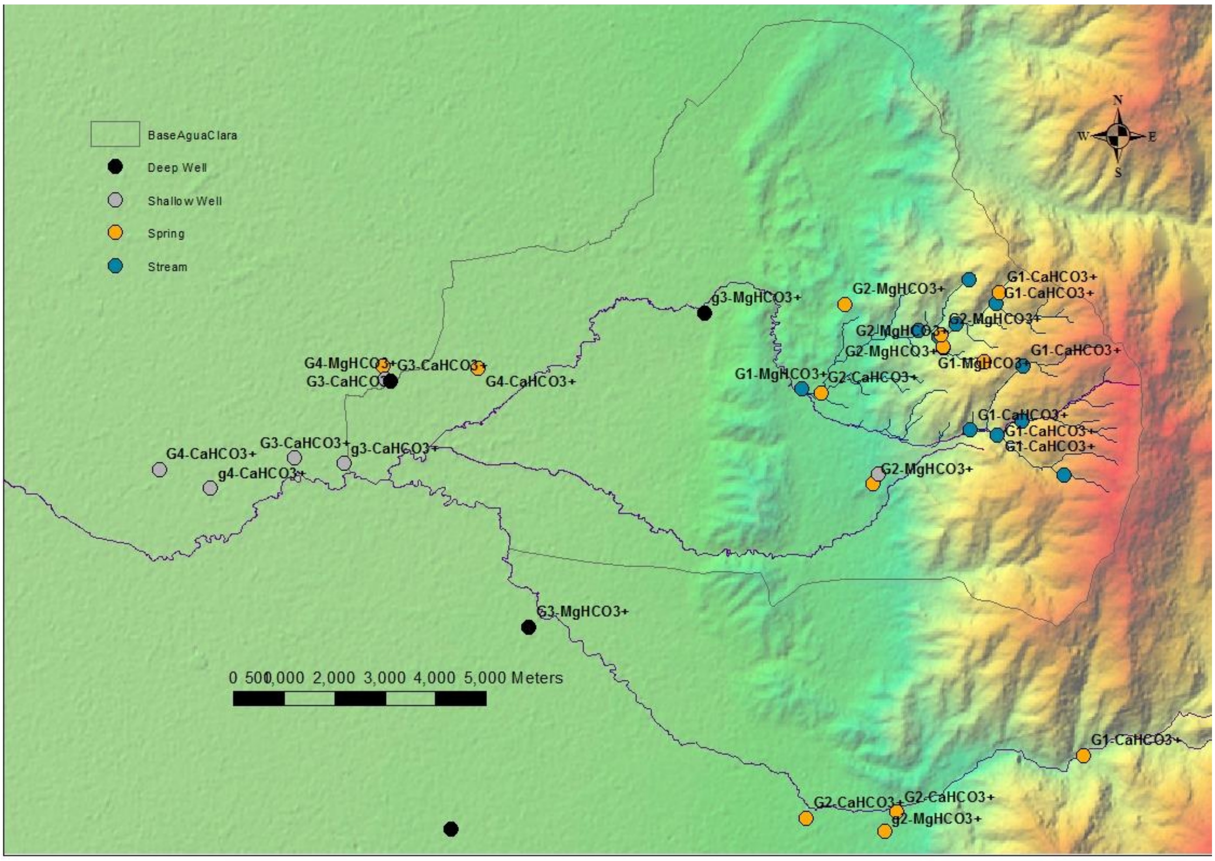

Figure 33 Collected samples with water types

The chemistry analysis was carried out by implementing ChemDiagnostics 5 complemented with PHREEQC. The calculated absolute error for the ionic balance of the samples was less than 10% for the 78% of the samples, and 8 samples resulted in larger errors; histogram of the error is available in the Appendix D. For the samples within the 10% error presented only two water types divided in $MgHCO_3$ and $CaHCO_3$, as presented in Figure 33. The water types found are according with the most abundant cations being $Ca^{2+}$and Mg^{2+}, and the anions being HCO_3. The major ions Na, Cl^- and SO_4 are present in lower concentrations along the studied area. The dominance of calcium and magnesium in the cations, is consistent to the characteristics expected from a basaltic area, since the content of sodium or potassium content is usually under 5% Best (2002) .

As described on Chapter 4.4, EC was measured during fieldwork. Electrical conductivity is an indicator of dissolve ions in the groundwater that in the Aguaclara catchment will be related to the time that the water has been in contact with minerals of the soil or rocks that is moving through. Figure 34 presents a distribution of the EC over different elevations. EC increases as elevation decreases and water has been in contact with the soil and bedrock. Note that the variations of the shallow wells, as well as the average of the conductivity is higher than those for the deep wells. In this plot is also clear that the water moving in the springs, increases the EC in the lower areas, as it has been in contact for longer periods with the subsurface. During the monitoring campaigns in the instrumented area, the EC has been measured in the last years. However, the observed increased in contribution from groundwater to the streams observed in the water budget was not clear in the collected data so far.

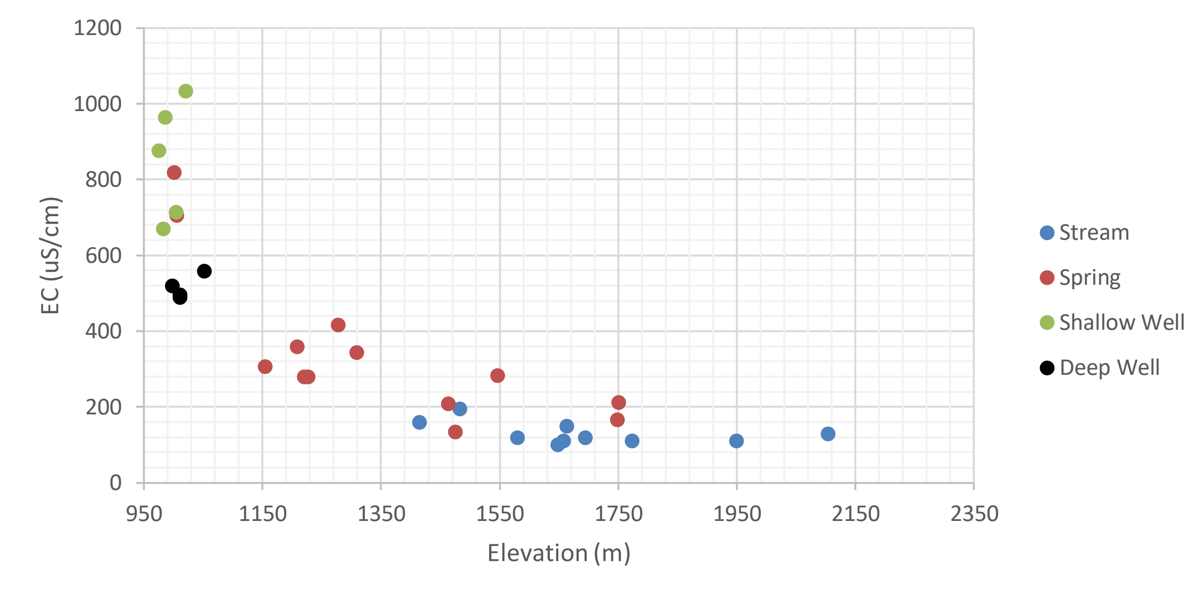

Figure 34 EC distribution of the collected samples.

Given the proven relevance of the baseflow to the discharges of the catchment, mainly during the months of June, July and August comes from the groundwater, higher EC values were expected. Figure 35 presents the seasonal variations of EC at the station illustrated in Figure 12. Results indicate that the discharged water during the dry periods has not been in contact with the subsurface for long periods of time, as the changes between the dry and the wet season are not significant. Even if during the dry season the contribution of baseflow is almost the total streamflow, the stability of the EC during the dry season suggests that baseflow is not significantly enriched in dissolved ions, because of the suggested short residence times. In the water balance, La Vega seem to react fast to the seasonal changes in precipitation, but for the El Oso stream, the EC presents larger variations.

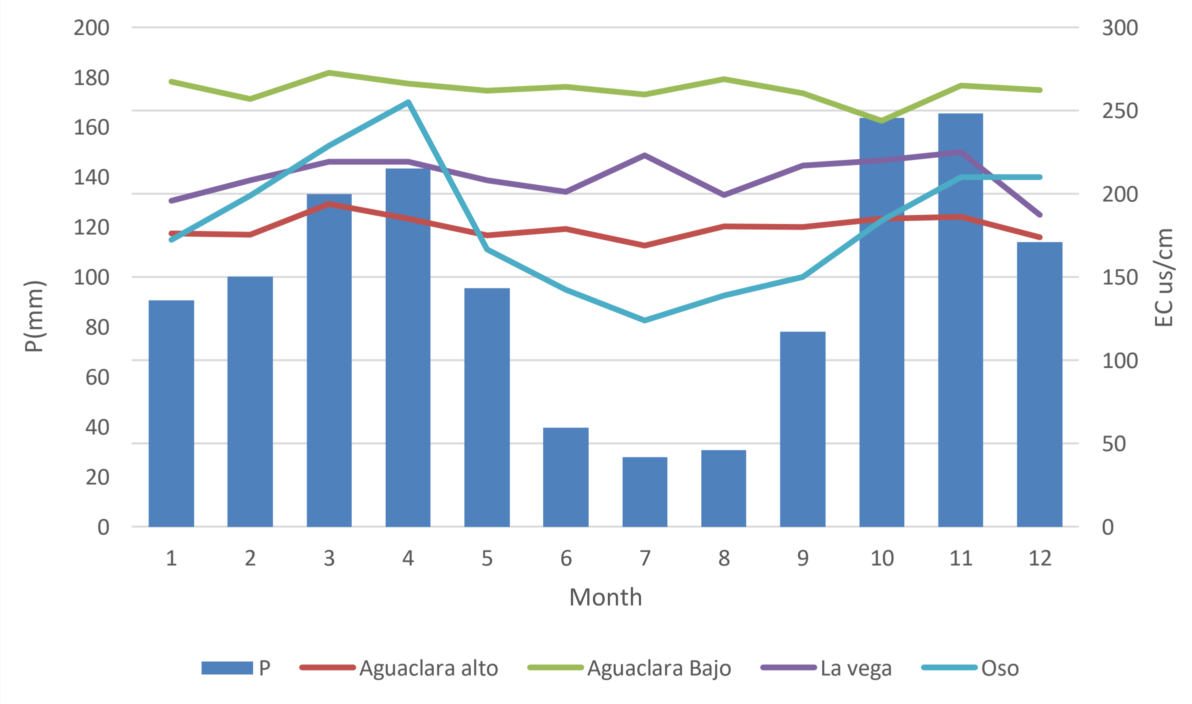

Figure 35 (2014-2018) Averaged EC seasonal variations according to averaged seasonal precipitation (40 years).

Figure 36 shows how the water in longer contact with the subsurface has higher concentration of the major ions resulting in higher EC. Initially it could be expected for deep wells to present higher concentrations of ions, since they are more likely to have longer residence times, but according to the analysed samples, both the lowest springs and the shallow wells tend to have higher concentrations. Appelo and Postma (2005) explained that the concentration of dissolved solids in rocks with the characteristics of the basalt found in the elevated part of the Aguaclara catchment does not depend on the residence times as much as it could do in other rock types, given the higher content of soluble mineral in these rocks, making the dissolution rates faster.

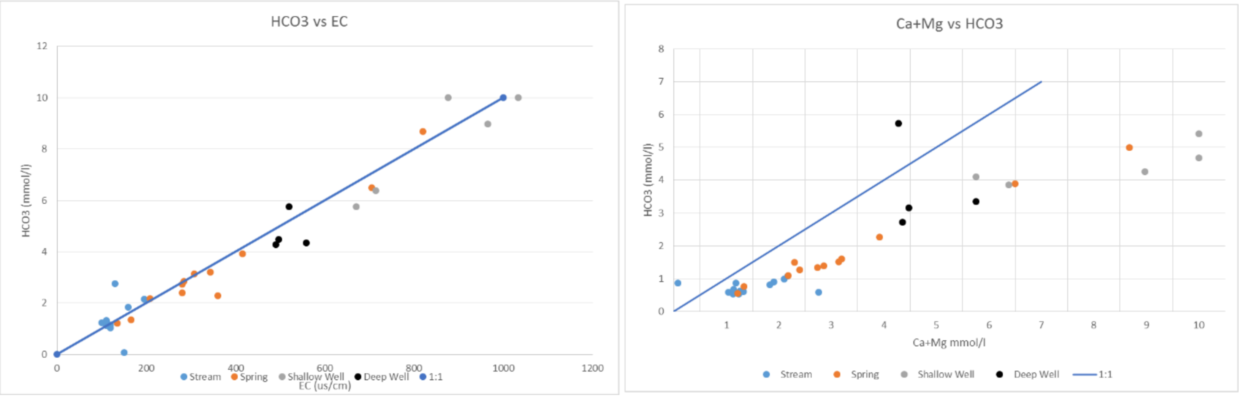

Figure 36 Major dissolve ions in sampled points

Bicarbonate in the water usually indicates interaction with CO_2 in the soil, or interaction with silicate mineral that could happen in the bedrock. Figure 37 presents the content of HCO_3 to the different samples in comparison to their elevation. Long residence times of groundwater are expected to result in higher concentration of bicarbonates. However, in the collected samples the shallow wells have higher concentration of bicarbonate, this could be due to larger availability of dissolved CO_2.

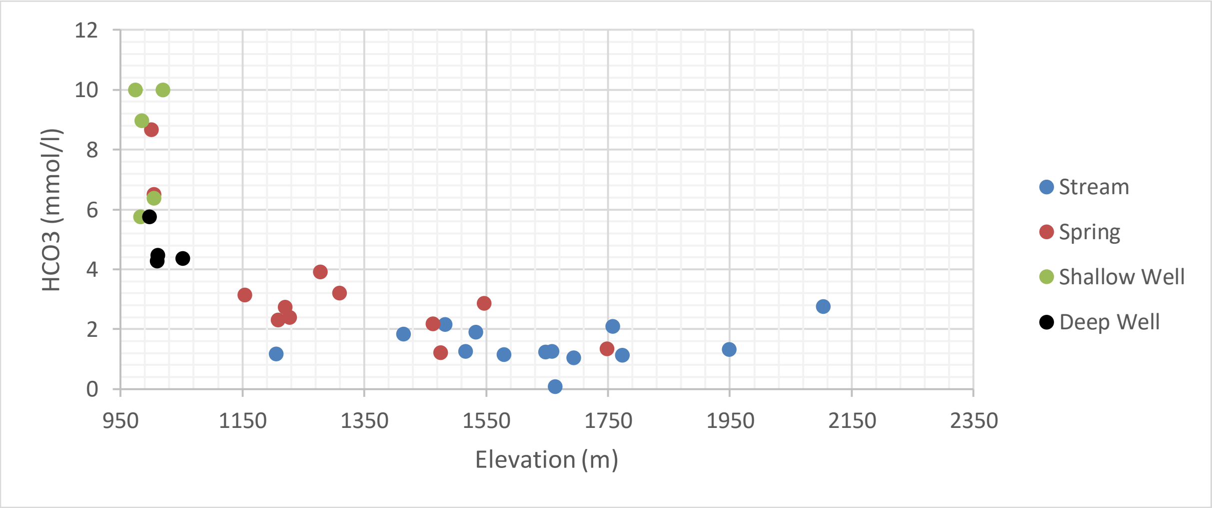

Figure 37 HCO3 distribution at different elevations

Chloride concentrations are used as natural tracers Appelo and Postma (2005) for the estimation of groundwater, during his research in the Bolo Catchment Cespedes (2017), found that moving east towards the higher elevations in the Aguaclara catchment the concentrations of Cl decrease. Similar results were found in this research, with concentrations below the detection limit of chloride (2mg/l) for most of the samples in the mountainous area, and increasing concentrations near the alluvial deposits in the valley. However, 3 out of the 4 sampled deep wells, showed lower concentration of Cl, different to the shallow wells and springs located in those areas. The difference between the concentrations of chloride could due to recharge of water from the high elevation areas either through regional flow systems, or water moving through the streamflow that is then infiltrated in the alluvial cones.

The low content of chloride found in most of the water samples, could be a limitation for the chemical analysis and understanding. But thanks to the composition of the basaltic rocks, it is possible to use silica for some applications as it acts as a quasi-conservative substance similar to Cl− Leibundgut et al. (2009) . According to Stumm and Wollast (1990) weathering of silicate mineral from earth crust contribute to almost 45% the total dissolved load of the world rivers.

Interaction of water with silicates is mostly reflected in an increase on pH, cations and silica. Weathering of silica plays a relevant role in the global CO2 sinking Appelo and Postma (2005). Further studies have included, and since the concentrations of chloride in the catchment were under the detection limit for most of the samples Si was used to develop the understanding of some of the main processes in the catchment

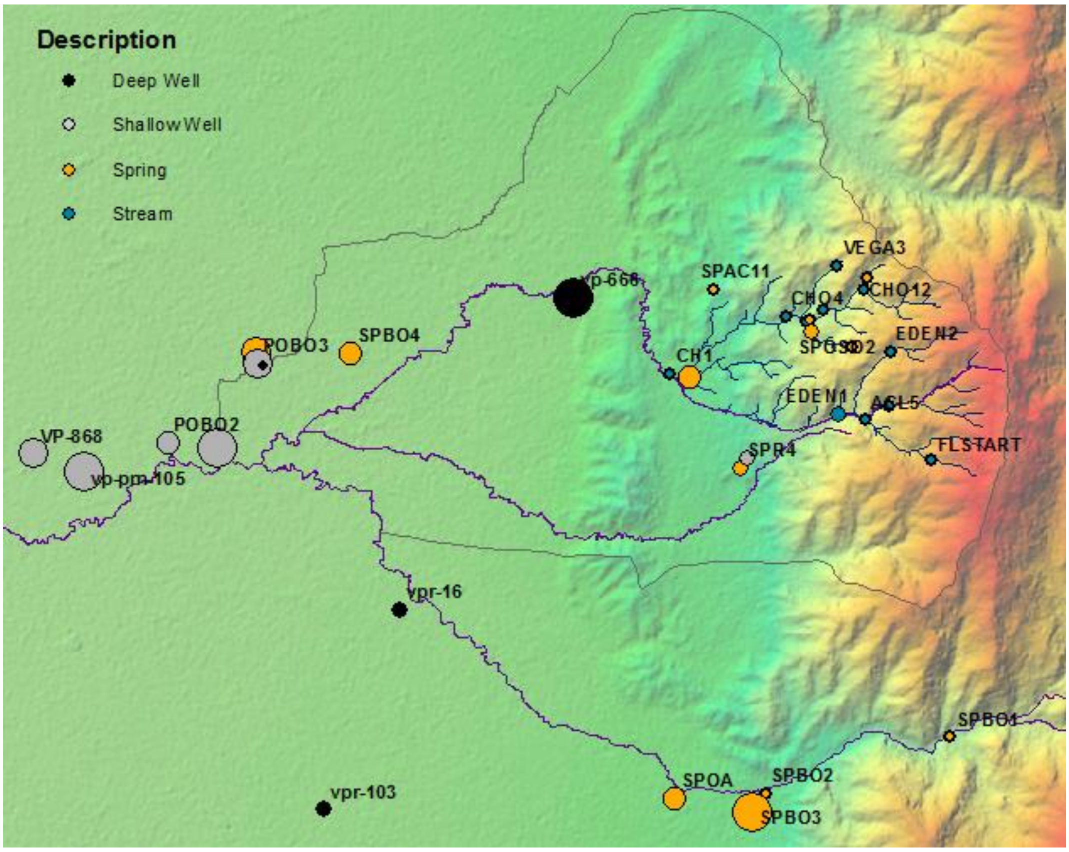

Figure 38 Cl concentrations of the samples. Size increases proportional to concentration. Smaller size

out of range of detection.

Chloride concentrations provide major characteristics of the water types found during fieldwork. Following Stuyfzand (1989) classification, water types obtained from ChemDiagnostics suggest that all the water is between Oligohaline and fresh, as a result of the low concentrations of Cl, most of them under detection limit. This also determines the class of the samples, being positive for all the samples, which indicate freshening taking place. Alkalinity divides the samples between streams, springs and wells, increasing in that order, according to the interactions with the subsurface.

As described earlier the geological conditions found in Aguaclara are strongly related to basalt. The tholeiitic basalt formations is created under rapid cooling of lava with a magnesium rich crystallization, resulting on olivine and pyroxene silicate mineral as found in the Amaime formation. These processes also affect the stability of the silicate minerals, resulting in more unstable when facing degradation conditions, Amaime formation has high content of active degradation minerals, usual in volcanic rocks as shown in Figure 39 Igneous and metamorphic rocks, have primary silicate minerals like pyroxenes and mica Appelo and Postma (2005) found around the Central Cordillera and the study area..

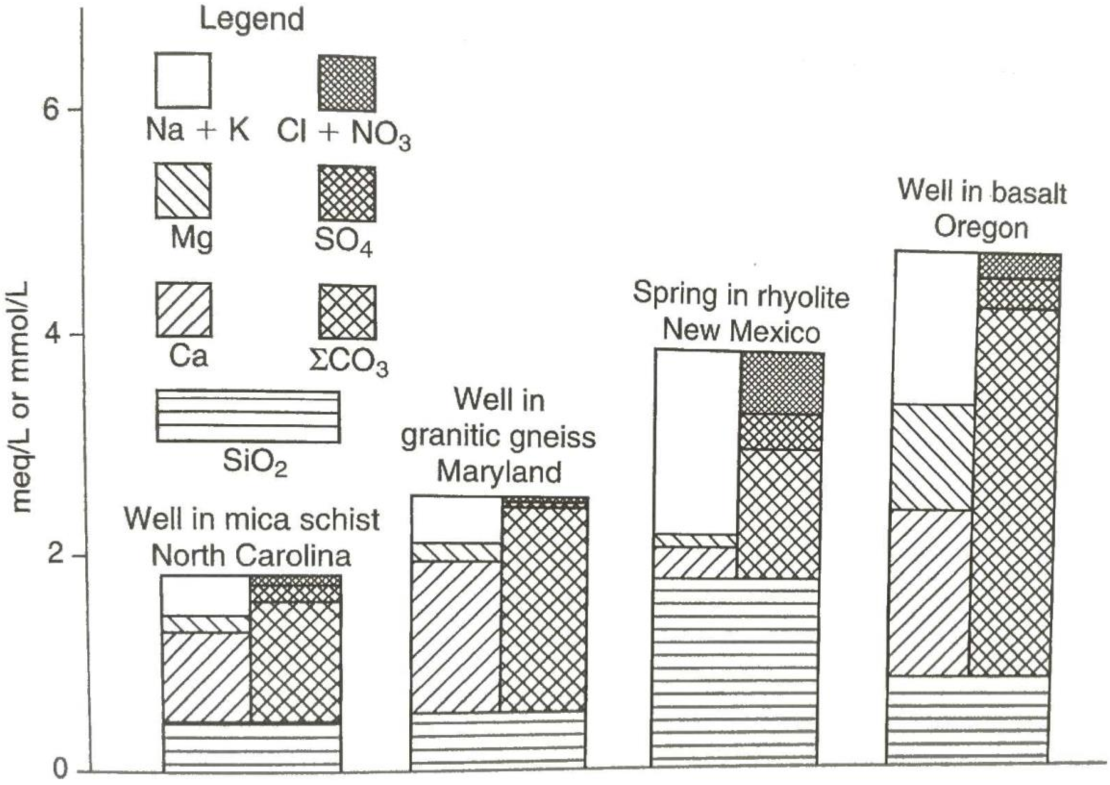

Figure 39 Examples of groundwater compositions in igneous and metamorphic rock. Dissolved silica mmol/L and charged ions in meq/L. Taken from (Appelo and Postma 2005).

Silica concentrations could also prove the existence of regional flow paths coming from the mountains, given the geological conditions at the higher parts of the catchment. When in contact with water, the silicate minerals in the rock will be released, during the weathering process of the rock. Hence, the source of silica in the water will come from the interaction water-rock (Pradeep et al. 2016). Finding differences between the concentrations of silica could indicate that some flows content water that had been in contact with the bedrock for longer times

To analyse the concentration of silica around the catchment Figure 40 presents the silica concentration together with the CO_2 pressure of the samples collected. Note that the two samples with larger content of silica are the two springs located furthest to the west in the lower part of the catchment SPBO4 and SPBO5, at the alluvial deposits (see location at Figure 4). The larger concentration of Si indicates a higher residence time, since the weathering process of silicate is slow. The combination of a lower CO_2 pressure indicates that recharge has happened in an area of lower biological activity in the soil, linked to lower temperatures at higher altitudes, and most of the subsequent weathering occurred in a closed system.

Note that the higher concentration of CO_2 in the shallow wells, above the PCO_2 of -1.5 expected for the soil and groundwater, are linked to higher biological activity, linked to higher temperature and possibly agricultural practices that are quite intensive in this area. A higher CO_2 content will allow a stronger weathering of silicate minerals and consequently higher concentrations of ions, as presented for Ca^{2+} in Figure 42. In this plot it is possible to identify some contribution of groundwater to the four streams with lower PCO_2, even during the rainy season when samples were collected.

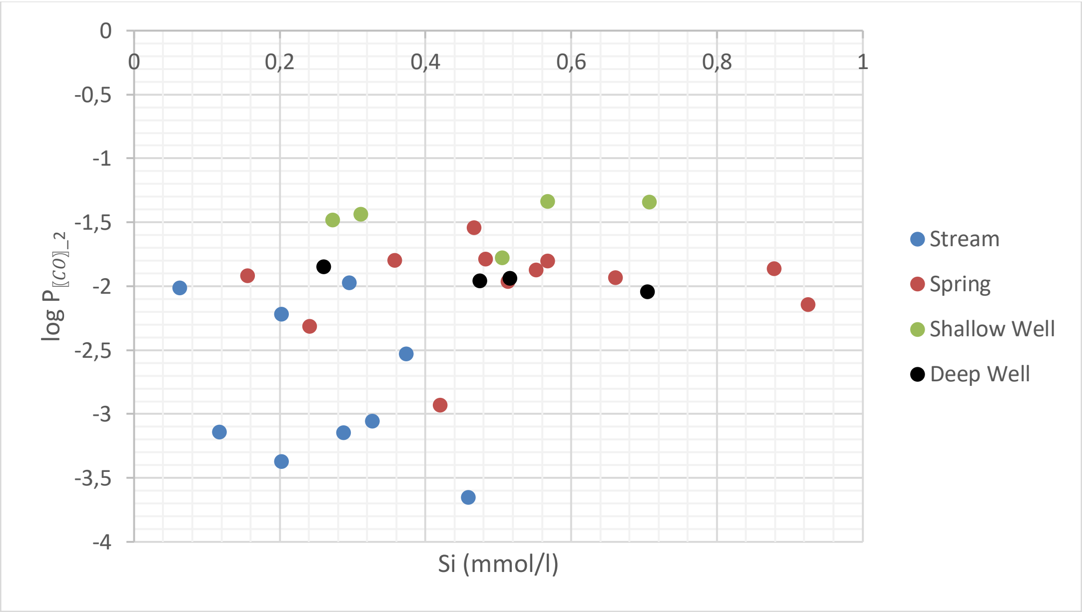

Figure 40 Log (PressureCO_2) vs Si (mmol/l)

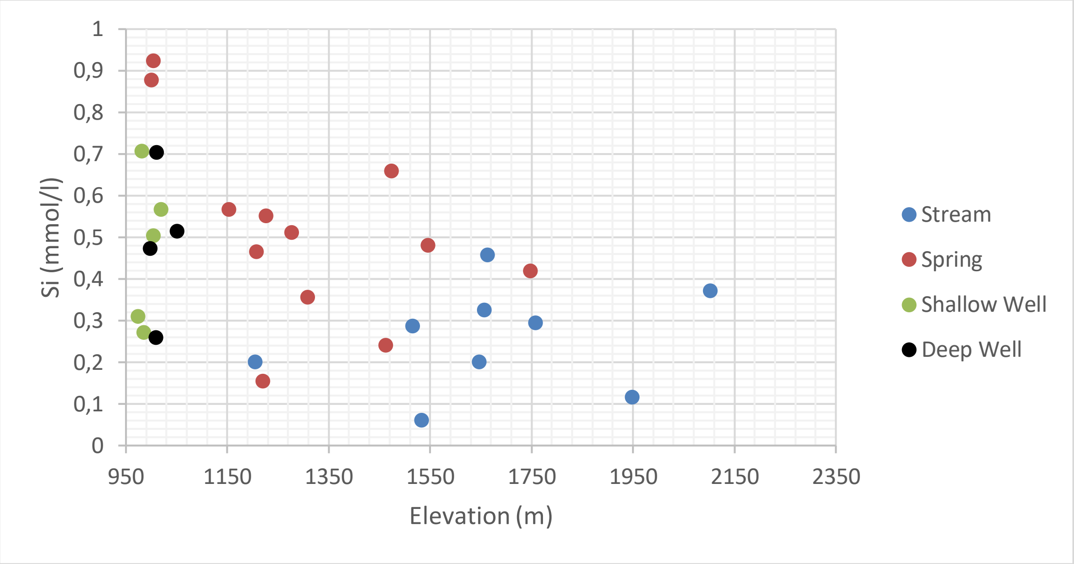

Figure 41 Si distribution along elevations

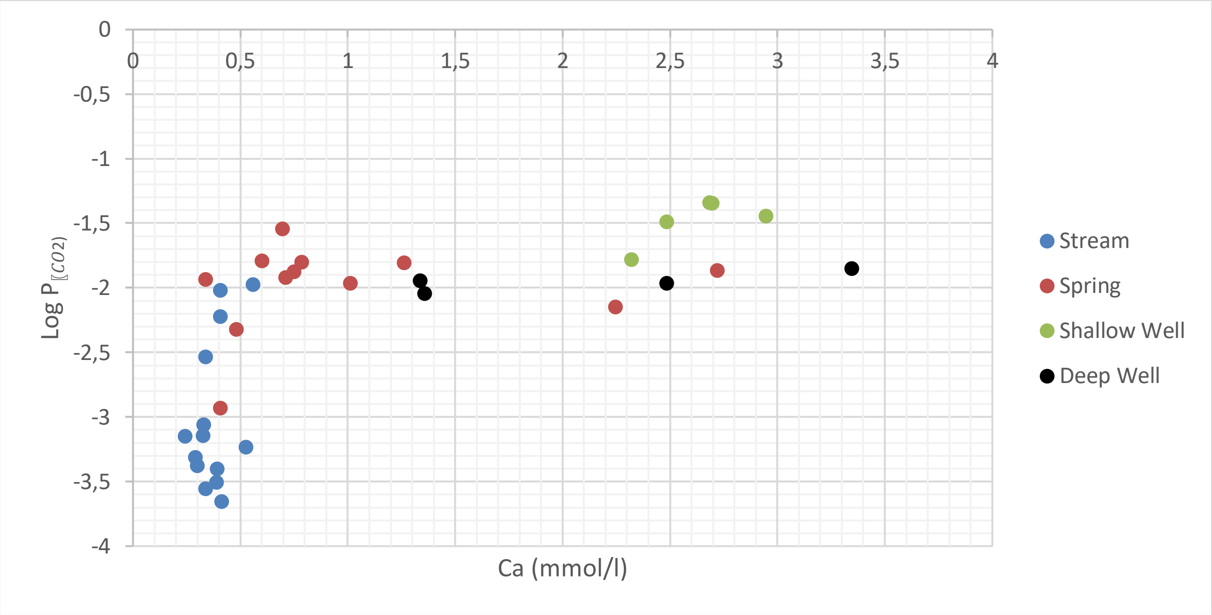

Figure 42 Plot of logPCO$_2$ vs Ca^{2+}

5.4 Stable Isotopes

As mentioned earlier, stable isotopes in freshwater will have a different ratios between hydrogen and oxygen isotopes, where the ratios are controlled mainly by different physical, chemical and biological processes. Temperature produces a fluctuation of the isotopic composition of the rain Appelo and Postma (2005). Even if temperatures in Colombia do not have seasonal changes, the concentration of both analysed stable isotopes presented seasonal variations in the year 2003 to 2004, as shown in both Figure 43 and Figure 44 the seasonality reflects larger variations in concentration of the Isotopes that follows from the precipitation cycle than the differences found with increase of elevation.

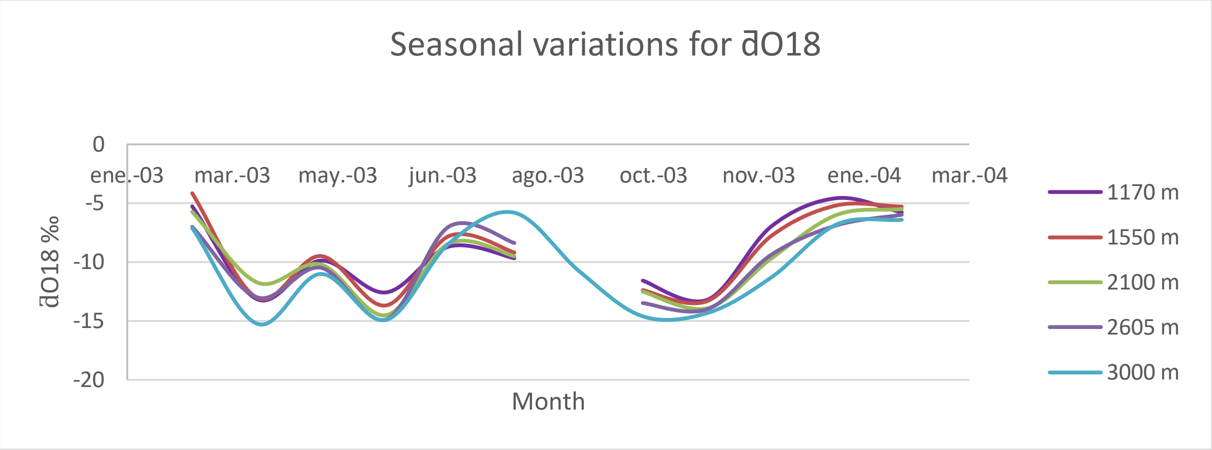

Figure 43 Seasonal fluctuation of ƋO18 for different elevations around the study area. Data from (IAEA) for 2003-2004

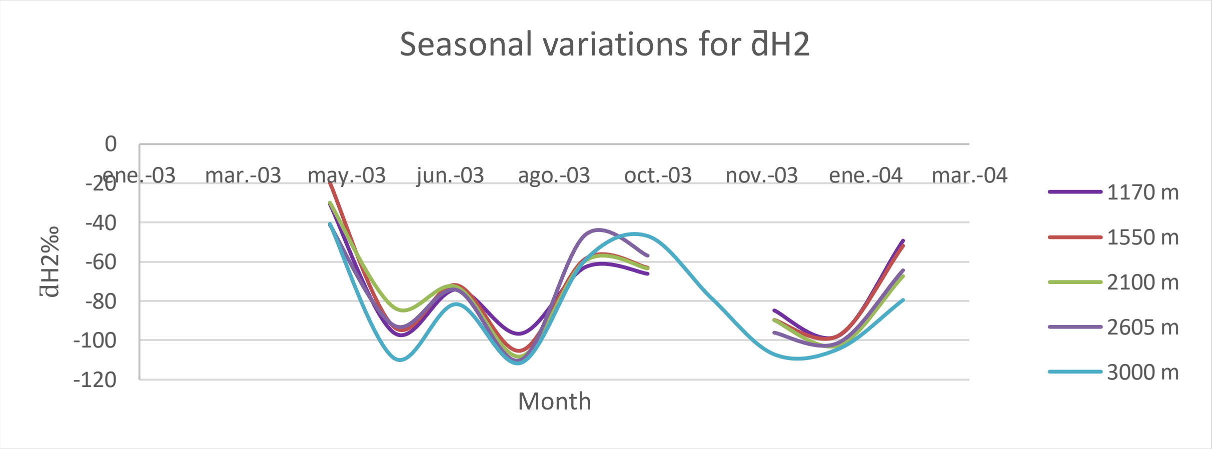

Figure 44 Seasonal fluctuation of ƋH2 for different elevations around the study area. Data from (IAEA) for 2003-2004

The ratio of depletion of samples collected in streams, springs, shallow wells and deep wells are presented in Figure 45, O^{18} concentrations of the deep wells located in the most western areas shown a similar ratio to the ones found in the high elevations in the mountains. However, the range for the entire set of samples are between -12.01‰ and -8.97‰, that is within the range of any of the elevations along the year. Even with this clarification the most depleted sample was the one found in the deep well VP-103 (189 m) in the south west area of Figure 45, and considering that the samples in deep wells still represent a mix of the waters in the well, it is highly likely that this water comes from higher elevations, where more depleted O^{18} is found. This theory could be also validate for the analysis of deuterium, since the well VP-648 (85m), also turns out to be the third most depleted sample found for this isotope, similar to the results obtained in the higher areas of the catchment. Having such a limited amount of samples in deep wells limits the severity of the conclusion, since there is still one deep well (with unregistered depth) which isotopes are similar to the ones found in the shallow wells and springs of the lower areas.

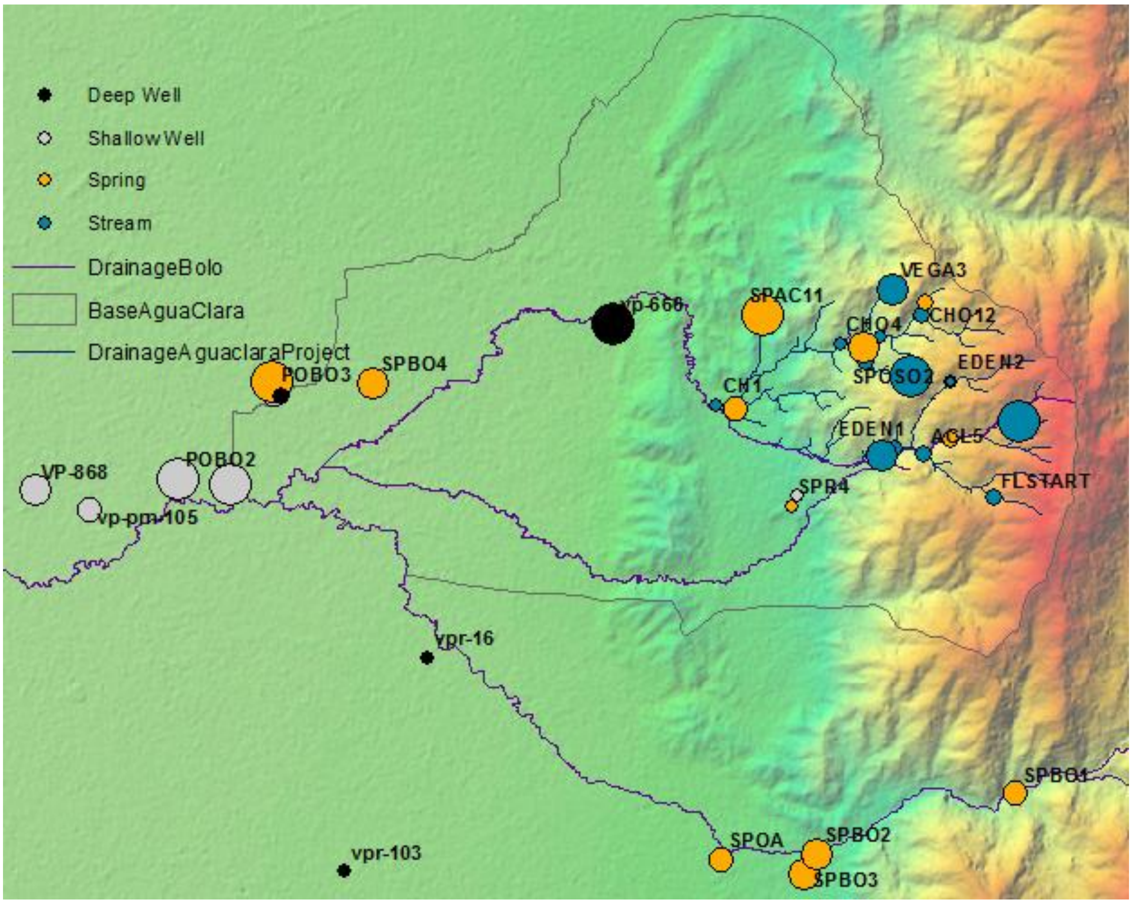

Figure 45 đO18 distribution of collected samples. Smaller means more deplete

Stable isotopes as well as chloride could be use as conservative tracers to analyse flow path. Figure 46 presents the comparison of both stable isotopes with chloride. Note that multiple samples present the same concentration for Cl, this is because their concentrations were actually under the detection limit. It is apparent that the deep wells share more characteristics with the streams in the high elevation areas, than with the shallow wells or springs around the areas where they are located. The results of the stable isotopes themselves shown also similar characteristics to the behaviour of the isotopes in the catchment so far. Figure 47 shows the relationship between ɗH^2 and ɗO^{18} for the different type of samples, the slope for the deep well is similar to the slope for the streams samples taken in the high elevation areas. According to Leibundgut et al. (2009) precipitation is depleted due to temperature and moisture depletion as increasingly as elevation increases. However, the same authors suggest a couple of years of data collection for a proper estimation of groundwater recharge altitudes and for this study only samples from one rainy season were collected.

Isotopes results relate the water from the deep wells to water from the streams located at high elevation areas. The similarities found, could suggest the existence of regional flow connecting the mountains to the aquifers in the valley. A different theory is that water from the mountains could travel fast through the streamflow and then percolates to the subsurface in the valley. However, not a significant number of deep wells data was available and the results could also be explained according to the seasonal variation of isotopes depletion, since the maximum depletion found is still within the range of the rainy season when the samples were collected.

It is possible however, that the water is traveling fast as runoff, and then infiltrates to the deeper aquifers once it reaches the alluvial deposits in the valley. This since according to the water balance there does not seem to be a significant amount of water that could be coming from the mountains.

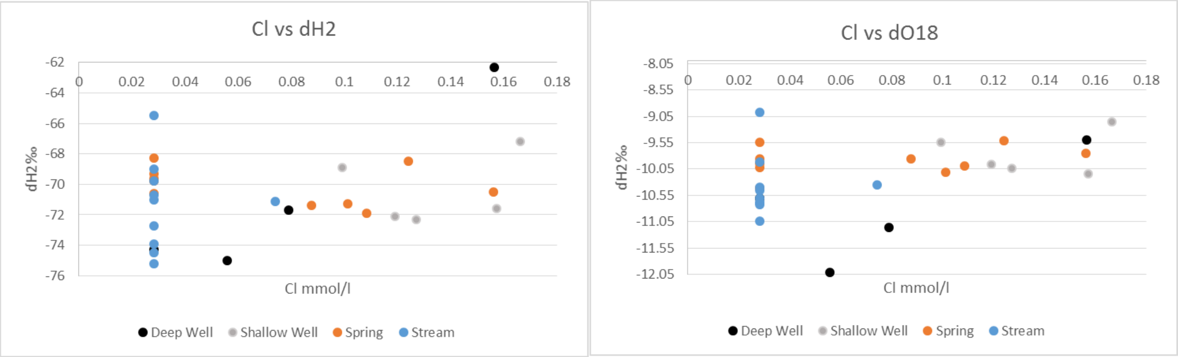

Figure 46 Conservative tracers for collected samples

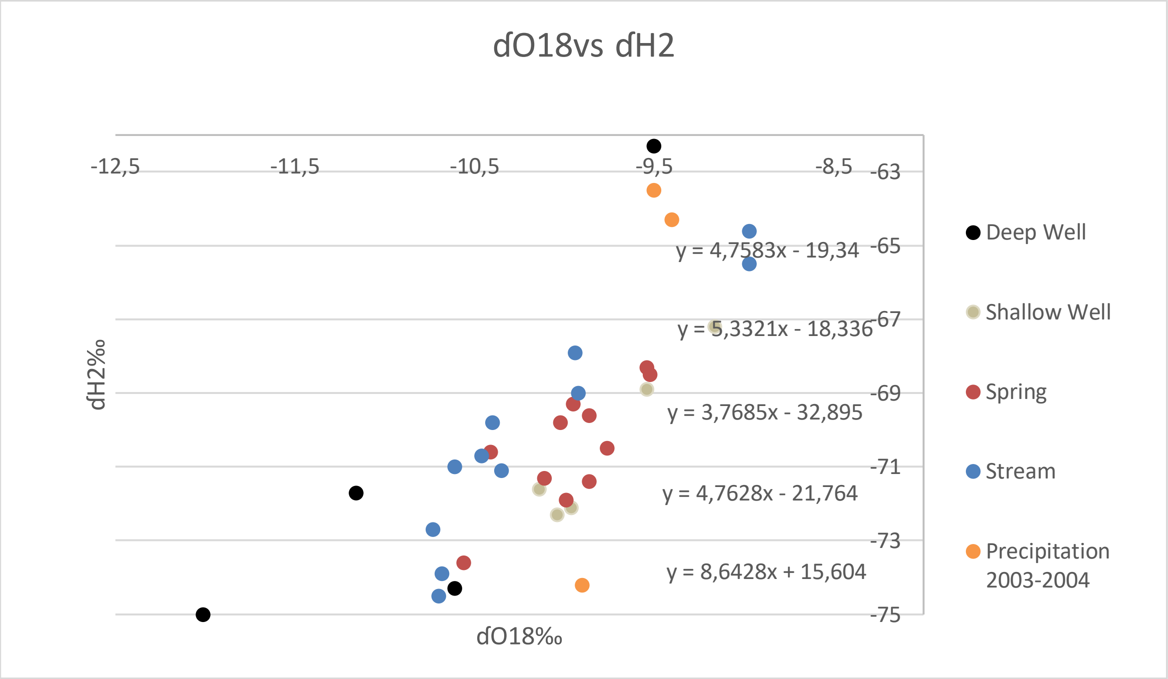

Figure 47 Stable Isotopes

Chapter 6

Conceptual Model

This chapter integrates all the obtained results, in two conceptual models that could explain the hydrogeological conditions of the Aguaclara sub-basin, as well as the found interactions between the mountain and the alluvial aquifers in the Cauca Valley.

During the fieldwork phase of this research different information was gathered as well as an understanding of the research area and the main conditions happening in the Aguaclara sub-catchment and the alluvial aquifers in the lower part of the valley. This field information has been synthesized in this chapter by implementing a conceptual model. Based on the available field data, plus knowledge in similar sites to the study area, is possible to obtain a conceptual model that reflect the main processes of the study system Anderson et al. (2015).

The main purpose of a conceptual model is try to simplify multiple and complex natural conditions, to analyse a system and understand which information needs to be investigated further. In order to represent the connection between the mountain block and the alluvial aquifers, a conceptual model was constructed applying the parsimony principle, creating a render of the mountain system behaviour and hydrological conditions around Aguaclara and the Cauca Valley. The construction of this particular model integrates geology, hydrology and hydrochemistry, all used in order to establish the potential flow systems between the mountain block and the aquifer.

As described earlier one of the goals of this research is to validate one of the boundary conditions included in the already constructed numerical model, that provide qualitative results about the interactions of surface and groundwater, as well as impacts of abstractions in the Cauca Valley.`

The Basalt bedrock of the Amaime formation is most likely a groundwater boundary as it has been interpreted in the constructed models so far. The rainfall occurring in the mountains is crucial for the processes in the mountains, and excess of waster is transfer to the Valley as runoff in the streams entering the catchments and also infiltrating to the aquifers through the river sediments in plain areas. It has been found that the bedrock could potentially work as an aquifer storing water excess during the wet periods that is released later in the dry season. In this case, the aquifer is dominated by the fractures. Fractured rocks acquire porosity and permeability as result of the stress that creates the rupture of the bedrocks, the referred stress conditions are result of all the geologic history of the rocks.

The fractures generally have widths under 1 mm, nevertheless, the increase of groundwater discharge to the widths of the fracture is exponential to the power of three, meaning that small increases of the fractures will have large impacts in the permeability of the aquifer Davis and DeWiest (1970). This could lead to good aquifer conditions in some igneous rock. But the basalts of Aguaclara might not be so affected by the weathering process, since when the water is moving through the soil it acquires considerable amounts of silica, meaning that water requires long residence times in order to dissolve the silica in the bedrock. Beside this, the silica rich rocks have insoluble residues that could block the created fractures by clogging them once the weathering happens Davis and DeWiest (1970).

According to the conditions found, it is possible to describe the main hydrogeological processes happening in the catchment as presented in Figure 48. Precipitation patterns in the study area are highly related to the elevation during the wet season, with a difference of over 100% within a distance of 7 km. Initially, water from precipitation will be intercepted by the vegetation, mainly the forest in the more elevated areas. Intercepted water will contribute to the overall evapotranspiration of the area. The water that does not go to evapotranspiration, will either infiltrate to the subsurface or will move on the surface as direct runoff. Storage of water in the subsurface seems to result in an actual evapotranspiration close to the potential, as changes in ET were not as proportional to the changes of precipitation. Infiltration excess and saturation excess are the main processes with which the surface runoff will be produced, though infiltration excess could be rare in the most vegetated areas.

Water infiltrating to the soil could also move laterally in the unsaturated zone as interflow, it will then re-emerge on the surface as direct runoff or move in the subsurface until it reaches a spring or stream to be discharged to Fulton et al. (2005). According to the findings of this research the subsurface, including the bedrock, will play an important role to store water during the wet periods, and during the dry periods, this water will be discharged. The process of recharge and discharge in the Aguaclara catchment will be driven mainly from local flow systems, as it could be the case of El Oso sub-basin, where the discharge of water was higher than the water coming from precipitation. The general graphical representation is shown in Figure 49.

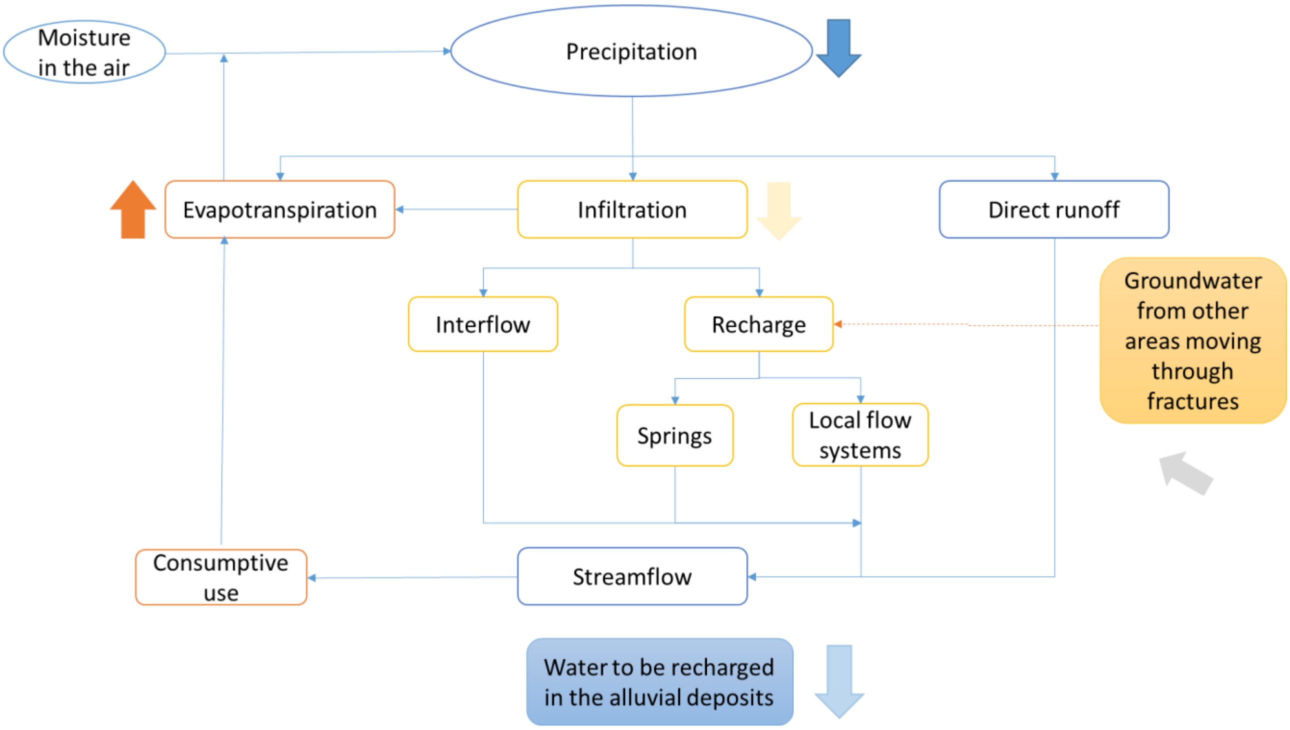

Figure 48 Hydrogeological processes

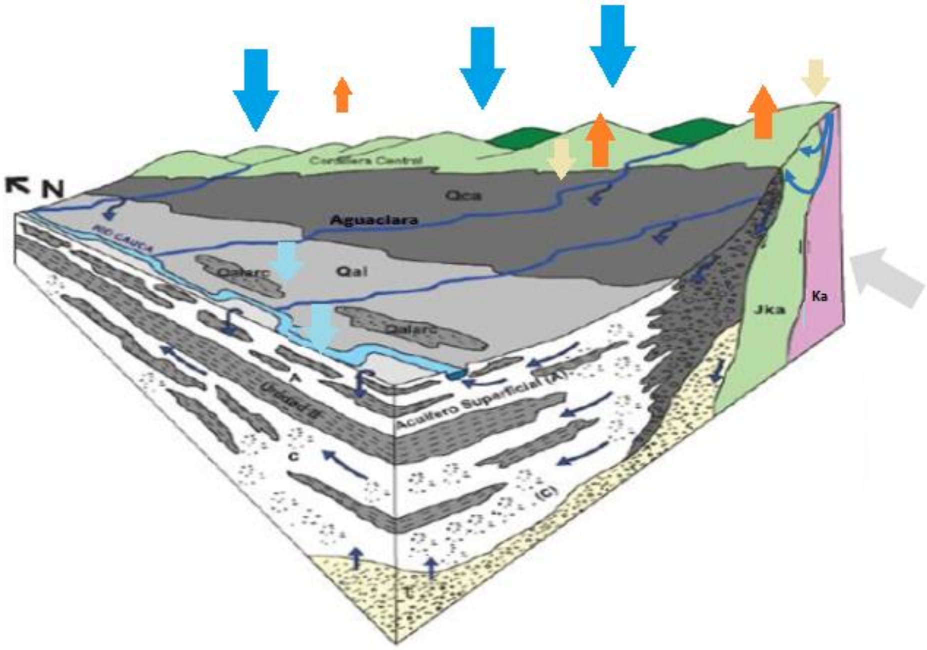

Figure 49 Conceptual model main process in the study area, without considering MBR. Adapted from (*Sànchez et al., 2016)*

Given the uncertainties of the methods used in this research, and the results from the stable isotopes, that suggest a hydraulic connection between the higher elevated areas in the mountains, and the aquifers in the valley, a conceptual model and an interpretation on how MBR could occur was done. Figure 50 represents the main processes and components of the model, following the symbols of Figure 48. Gilbert and Maxwell (2017) calculated the contribution of the mountain block by simulating a flux according to Darcy from the mountain to the aquifers, establishing that the heads in the mountains will follow the topography. This approach could be considered, since storage of water in the bedrock was found in the present research, and also by Cespedes (2016) who established that the water level in the elevated areas of the Bolo Catchment follows the topography. The main limitation of this approach is the estimation of the hydraulic conductivity, determinate this value could be very expensive by field tests, and still, the interpolation of calculated k has large uncertainties. Literature values could be chosen for the simulation, but given that the hydraulic conductivity is the result of secondary porosity it is a specific parameter.

The results of the water balance carried out in the mountainous area, show large differences in storage, up to 443 mm, which will be reflected in the water level (represented by the yellow line in Figure 50). These variations will highly impact the values of the calculated MBR (dash blue arrows in the model). In his research in the entire Bolo catchment presented in Figure 11, Cespedes (2016) found that the Aguaclara catchment river changed the characteristics of the Bolo River. As it has been identified in this research, the streams in Aguaclara have groundwater characteristics. But the difference between the Bolo River and the Aguaclara River implied that larger study area needs to be covered, to identify how the larger part of the mountainous catchment behaves, to evaluate if the contribution to aquifers in the valley could be significant considering the large extension of the Central Cordillera.

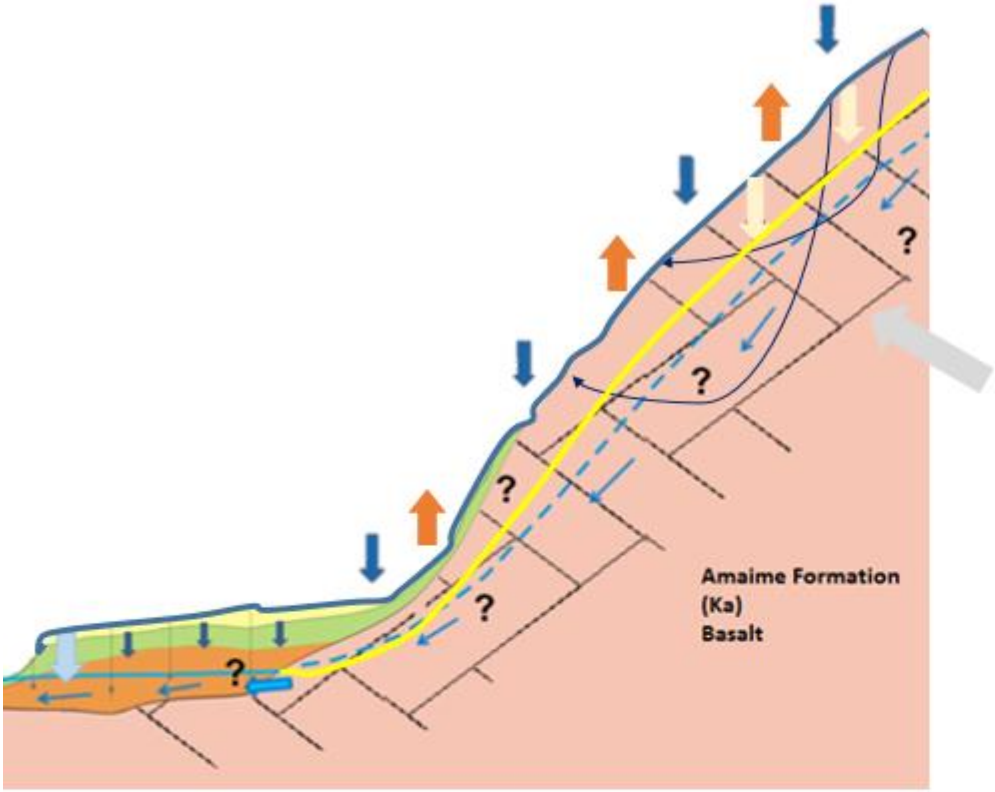

Figure 50 Conceptual model main process in the study area considering MBR (dashed blue lines). Adapted from Doyle (2013)

Chapter 7

Conclusions and recomendations

This chapter finalises this work, summarising conclusions and pointing out aspects to be developed in future work to understand the potential of the MBR for the aquifers in tha Cauca Valley.

Recent studies in mountainous areas around the world have found that MBR could be significant to the recharge of adjacent aquifers. The goal of this research was to estimate the role of the mountain block recharge to the connected alluvial aquifers in the Cauca Valley by taken an instrumented area in the Aguaclara sub-basin.

- For the estimation of the role of the mountain block recharge from the Central Cordillera to the hydraulically connected alluvial aquifers in the Cauca Valley, the water budget method was used to evaluate the availability of water in the mountainous area that could potentially percolate to the bedrock and move along the secondary permeability to reach the aquifers. Even providing the most favourable conditions for the MBR, the calculated amount seems to be under 2% of the precipitation for the year 2015. However, large availability of water during the wet seasons and constant flow of water during the dry periods, is an indicator that even if the water is not going to the aquifers, the storage of water in the bedrock plays a crucial role on the hydrological processes in the catchment.
- Gilbert and Maxwell (2017) evaluated the contribution of the MBR at the San Joaquin river basin, considering that the water table in the mountain region followed the topography. In his research during the wet season, Cespedes (2017) found similar conditions occurring in the Bolo catchment, however, variations in storage larger than 400 mm, could represent larger variations of the water head than those observed by Gilbert and Maxwell (2017).
- The recharge of groundwater in the mountainous area is discharge mainly through local flow paths in the mountainous area, and will reach the aquifers in the valley moving in the streams or even through the streambeds of the rivers.
- For the calculations in the water balance, evapotranspiration is a crucial parameter, but at the same time its assessment has large uncertainties. In this research the actual evapotranspiration calculated by the SSEBop v4 developed by USGS and available online was the mainly value used, given that data is available from the year 2003 to the present year. The calculations were compared to the ones estimated from the values measured at the catchment, including the crop coefficient according to the land use in the area. Overall results for each of the sub-catchments are similar to those obtained from SSEBop. Additionally, ETensemble V1.1 was compared from other period to evaluate the performance of the model, finding that for the period of 2013-2014, the actual ET calculated by SSEBop are significantly lower than those obtained from ETensemble V1.1.
- Even though the sensibility analysis of the water balance showed that an increase of precipitation would lead to increase in the water available for MBR for the calculation of 2015. The estimation or the years 2016 and 2017, with increased precipitation when compared to 2015, did not show significant increase of water available to MBR. The variations of ET from the SSEBop model were less than 8%, even for areas with an increased precipitation of almost 50%. It is believe that increase of precipitation has larger impact on the increase of discharge that the ones estimated, longer periods should be evaluated to understand the interaction between discharge and precipitation.
- The calculation of MBR by the standard method of stable baseflow does not seem to be applicable in the study area, since the values larger than those obtained from the water balance. It could be considered a good estimation for the recharge to the subsurface, but the calculation implies, the recharged water is then discharged as baseflow in the catchment and is not able to go to MBR.
- So far measured EC changes in the streams during the dry season also indicate rather short time of residence of the groundwater in the rock.

- There seems to be discrepancy between the results obtained from the water balance, which indicates that the available water to MBR is very less, and could actually be part of the discrepancy of the balance, and the results from the stable isotopes, as they suggest a connection between the water stored at the deeper parts of the aquifer and the water from the high elevated areas. The depleted isotopes found in deep wells could be due to seasonal changes, but the similarities were usually with the streams in the higher areas, rather than with the shallow wells or springs nearby. However, the amount of sampling points in deep wells is not considered significant to reach a conclusion.
- The results of this investigation suggest that the mountain block is not a significant unaccounted source of freshwater to be consider for water management purposes.
- In his research Cespedes (2017) highlighted that the confluence between the Bolo river and Aguaclara, was a shifting point, where the Bolo river became a discharging area, while previous to that point the river recharged the aquifer. The findings in the present research explain that the mountainous area of the Aguaclara sub-basin has significant amounts of water moving through the subsurface, but mostly discharged by local flow systems as surface runoff.

According to the results of this work, it is suggested for further research about MBR in the Cauca Valley to:

- The already installed 9 rain gauges distributed in the catchment will improve the precipitation maps and reflect in a more accurate distribution of precipitation. This could be important for estimating the spatial distribution mainly in the higher elevated areas.
- Spatial isotopes variations, that could potentially reflect differences according to the elevation that the water had been deposited, are less than the temporal variations for the year 2003-2004, and given that samples did not show variations outside the range of any of the registered elevations along the year, is not possible to make solid conclusions. The collection more samples is suggested to have data that could be significant to reach final conclusions.
- Samples available only during the wet season limited the understanding of the long term processes happening in the catchment and the interactions of the mountains with the aquifers in the valley. Sampling for major ions and isotopes is suggested during the dry seasons to improve the understanding of the processes in the catchment.
- The amount of samples collected from deep wells is still small, reason why the conclusions about them are not solid. The regional flows are easier to understand by having deeper samples, even though the samples result to be a mixing of different waters in the wells.
- The lack of information about the bedrock permeability is one limitation to estimate the potential recharge along the bedrock slopes in the Aguaclara catchment. The use of more sophisticated environmental tracers to further assess the recharge contribution could be carried, although the preliminary results from this research suggest low availability of water to MBR.
- As mentioned in this document, bedrock permeability will strongly impact the mountain block recharge, sampling cores of the Amaime formation to have an estimation of the permeability value could be done. However, even with this estimation it is necessary to be cautious, given that permeability of volcanic rock is determined by secondary permeability, and extrapolating a small sample calculated could lead to misinterpretation of groundwater flows through the mountain rock.

Annex 1

Validation of Random Number

Hydro-chemistry

Random Number

Samples used for hydrochemistry are presented next.

Name of sample	EC	pH	Temp.	Na	K	Mg	Ca	NH4	Cl	HCO3	SO4	NO3	Si	W-type	PI	pH	mu	pct_err	si CO2(g)	si Calcite
CHO9	105	8	19.2	0.11	0.01	0.37	0.24	2.33	0.03	1.26	0.02	0.01	0.29	G1-MgHCO3+	0.8	8	0.002	0.01	- 3.15	- 0.57
OSO1	195.3	8.3	18.7	0.14	0.01	0.55	0.52	3.45	0.03	2.16	0.03	0.01		G2-MgHCO3+	1	8.3	0.003	0.83	- 3.23	0.24
CHO4	159.8	8.5	18.5	0.12	0.01	0.43	0.39	2.83	0.03	1.83	0.02	0.01		G1-MgHCO3+	1.2	8.5	0.003	-4.60	- 3.51	0.24
CH1	120	7	10	0.14	0.01	0.46	0.40	2.48	0.03	1.18	0.03	0.03	0.20	G1-MgHCO3+	0	7	0.002	18.68	- 2.22	- 1.52
OSOALTO	195	7	10	0.13	0.00	0.43	0.56	3.55	0.03	2.10	0.01	0.01	0.30	G2-CaHCO3+	0	7	0.003	-0.97	- 1.97	- 1.14
OSOBAJO		7	10	0.12	0.01	0.50	0.40	3.07	0.03	1.90	0.03	0.02	0.06	G1-MgHCO3+	0	7	0.003	-1.53	- 2.02	- 1.33
EDEN2	110	8	16.2	0.08	0.00	0.27	0.32	2.17	0.03	1.32	0.01	0.02	0.12	G1-CaHCO3+	0.8	8	0.002	-4.10	- 3.14	- 0.47
ACLA6	110	8.1	15.6	0.09	-	0.23	0.29	1.79	0.03	1.13	0.01	0.01		G1-CaHCO3+	0.9	8.1	0.002	-1.93	- 3.31	- 0.49
ACL5	100	8.2	16.4	0.10	-	0.24	0.30	2.12	0.03	1.24	0.01	0.01	0.20	G1-CaHCO3+	1	8.2	0.002	-5.33	- 3.37	- 0.33
FLOAM3	120	8.3	15.8	0.11	0.00	0.25	0.34	1.82	0.03	1.04	0.03	0.02		G1-CaHCO3+	1	8.3	0.002	6.00	- 3.55	- 0.26
EDEN1	120	8.2	18.1	0.11	0.00	0.29	0.39	2.03	0.07	1.14	0.01	0.01		G1-CaHCO3+	1	8.2	0.002	8.87	- 3.40	- 0.23
CHO12	110	7.9	16.8	0.10	0.00	0.27	0.33	2.33	0.03	1.26	0.01	0.01	0.33	G1-CaHCO3+	0.7	7.9	0.002	0.03	- 3.06	- 0.57
VEGA3	150	7.3	17.8	0.11	0.01	0.45	0.41	1.58	0.03	0.08	0.03	0.01	0.46	G*-MgMIX+	0.2	7.3	0.002	83.61	- 3.65	- 2.25
FLSTART	130	7.7	14.1	0.11	0.00	0.24	0.34	3.92	0.03	2.76	0.03	0.03	0.37	G2-CaHCO3+	0.6	7.7	0.003	-38.96	- 2.53	- 0.48
OSOALTOSP	213	8.1	10	0.09	0.01	0.63	0.43	1.23	0.03		0.03	0.02		G*-MgSO4+	0.9	8.1	0.002	91.00		
SPOSO2	284	7	19.9	0.17	0.00	0.78	0.60	5.03	0.08	2.86	0.03	0.03	0.48	G2-MgHCO3+	0	7	0.004	-1.25	- 1.79	- 0.86
SPR4	344	7	10	0.19	0.01	0.81	0.78	5.52	0.08	3.20	0.07	0.03	0.36	G2-MgHCO3+	0	7	0.005	-0.70	- 1.80	- 0.85
SPBO3	360	6.68	23.9	0.24	0.01	0.79	0.69	4.98	0.16	2.30	0.17	0.16	0.47	g2-MgHCO3+	1.1	6.68	0.005	4.62	- 1.54	- 1.16
SPBO1	135	6.73	10	0.15	0.01	0.21	0.34	2.74	0.03	1.22	0.11	0.01	0.66	G1-CaHCO3+	0.2	6.73	0.002	-8.31	- 1.93	- 1.85
SPBO2	280	7.02	21.7	0.27	0.02	0.52	0.75	4.70	0.03	2.40	0.16	0.00	0.55	G2-CaHCO3+	0.1	7.02	0.004	1.65	- 1.88	- 0.79
SPBO5	706	7.72	26.1	0.66	0.01	1.65	2.25	12.39	0.12	6.50	0.27	0.00	0.92	G3-CaHCO3+	1.1	7.72	0.011	8.77	- 2.15	0.77
SPBO4	820	7.54	23.5	0.95	0.02	2.28	2.72	15.74	0.09	8.68	0.13	0.00	0.88	G4-CaHCO3+	0.4	7.54	0.014	10.15	- 1.86	0.74
SPCHO12	208	7.4	18	0.39	0.00	0.60	0.48	3.97	0.03	2.18	0.03	0.02	0.24	G2-MgHCO3+	0.3	7.4	0.003	5.55	- 2.32	- 0.68

SPAC11	416	7.31	21.8	0.18	0.00	1.25	1.01	7.03	0.03	3.92	0.10	0.03	0.51	G2-MgHCO3+	0.2	7.31	0.007	6.35	- 1.96	- 0.20
SPAC10	280	7.13	23.4	0.21	0.00	0.63	0.71	4.61	0.10	2.74	0.04	0.02	0.16	G2-CaHCO3+	0.1	7.13	0.004	- 0.77	- 1.92	- 0.62
SPCHO10	166	7.8	17.2	0.12	0.00	0.36	0.40	2.71	0.03	1.34	0.01	0.03	0.42	G1-CaHCO3+	0.6	7.8	0.002	7.85	- 2.93	- 0.56
SPOA	307	7.07	22.8	0.22	0.03	0.26	1.26	5.79	0.11	3.14	0.20	0.01	0.57	G2-CaHCO3+	0.3	7.07	0.005	- 5.36	- 1.81	- 0.40
Shallow well	802	7	10	0.18	0.00	0.59	0.60	1.56	0.06		0.06	0.07		G*-CaSO4+	0	7	0.003	83.13		
POBO3	1034	7.1	27	1.80	0.02	2.74	2.68	18.40	0.13	10.00	0.46	0.02	0.57	G4-MgHCO3+	1.1	7.1	0.016	7.15	- 1.34	0.38
POBO2	670	6.78	10	0.82	0.01	1.41	2.69	11.71	0.10	5.76	0.19	0.02	0.71	G3-CaHCO3+	0.5	6.78	0.011	18.73	- 1.34	- 0.36
vp-pm-105	876	7.2	26.1	1.00	0.02	1.74	2.94	16.44	0.16	10.00	0.27	0.01	0.31	g4-CaHCO3+	0.7	7.2	0.015	- 1.61	- 1.44	0.52
POBOLO1	715	7.26	10	0.61	0.01	1.53	2.32	11.83	0.17	6.38	0.26	0.04	0.51	g3-CaHCO3+	0.9	7.26	0.011	8.20	- 1.78	0.09
VP-868	965	7.2	26.2	2.95	0.01	1.78	2.48	16.97	0.12	8.98	0.37	0.00	0.27	G4-CaHCO3+	1	7.2	0.014	8.08	- 1.49	0.41
VP-648	520	7.4	10	1.06	0.03	0.87	2.48	11.19	0.03	5.76	0.49	0.00	0.47	G3-CaHCO3+	1.3	7.4	0.011	7.36	- 1.96	0.22
vpr-103	490	7.22	23.2	1.11	0.03	2.38	3.34	11.67	0.06	4.28	0.21	-	0.26	G3-CaHCO3+	0.4	7.22	0.014	47.02	- 1.85	0.21
vp-666	558	7.35	25.3	0.42	0.01	1.38	1.33	8.80	0.16	4.36	0.05	0.58	0.52	g3-MgHCO3+	1.8	7.35	0.008	6.31	- 1.94	0.04
vpr-16	497	7.45	23.6	0.66	0.05	1.80	1.36	9.28	0.08	4.48	0.15	-	0.70	G3-MgHCO3+	0.4	7.45	0.009	18.96	- 2.04	0.12

Chemistry samples. Stream samples represented by blue, springs are yellow, shallow wells are light grey and deep wells are dark grey.

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