Estimating the role of mountain block recharge for hydraulically connected alluvial aquifers, in the Cauca Valley Colombia

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***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 200-500mm/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, when using the water balance. 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 ƌO18 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, nontheless, 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-component; Mountain hydrology, groundwater recharge, Mountain block recharge, water balance, stable isotopes, hydrochemistry

I. INTRODUCTION

The Cauca Valley in Colombia major economic activity is the sugar cane production, giving the benefitial climate conditions of the region the crops could produce record yields. The only limitation is water availability, to overcome this, groundwater is exploited it during the dry seasons. Since the pumping rates are increasing, together with the expasion of sugar cane production, it is important to understand the amount of renewable water resources available for a sustaible development growth.

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).

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.

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). 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.

II. STUDY AREA

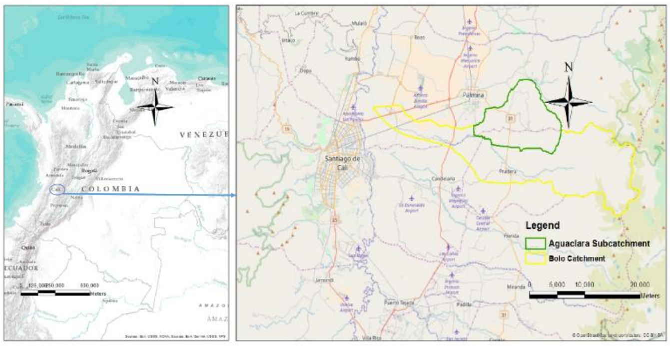

Figure 1 Study area

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 km2. 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 km2, 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. Within the valley, one of the most important catchment is the Bolo catchment, highlighted in Figure 1 by the yellow line, and one of the sub-basins of the Bolo catchment is the selected study area of Aguaclara represented in Figure 1 by the green.

Located between the western part of the Central Cordillera, and the Cauca Valley, with a total area of 112, 69 km2, and elevations between 1000 and 1850 m.a.s.l. the Aguaclara 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.

III. METHODOLOGY

Given that the main objective of the study is to estimate 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 has an experimental area in the northeastern part of the basin that has been instrumented and monitorized by Cenicaña, as presented by Figure 2. According to the discharge measurement stations, the instrumented area was divided in 5 sub-basins. 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).

For the estimation of the amount of water available for MBR, two approaches were used, first a water balance was applied to the recorded data of climatology and discharge, and finally hydrochemistry and stable isotopes were used to establish hydraulic connectivity between the elevated locations and the aquifers in the valley.

A. *Water balance*

Based on the principle of conservation. 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 leaving the catchment will be the water available for MBR. According to the authors, using an estimation of actual ET, and a measured stream runoff (RO), the calculation of MBR can be given by:

$$MBR = P - ET - RO \qquad (1)$$

Where (P) is precipitation, ET refers to evapotranspiration and RO is the surface runoff. The time step selected for the water balance was monthly, established mainly by the availability of evapotranspiration data.

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. The calculation of each of these parameters is explained next.

1) *Precipitation*

Orographic features have an important effect on precipitation patterns. Considering that the available precipitation consists on

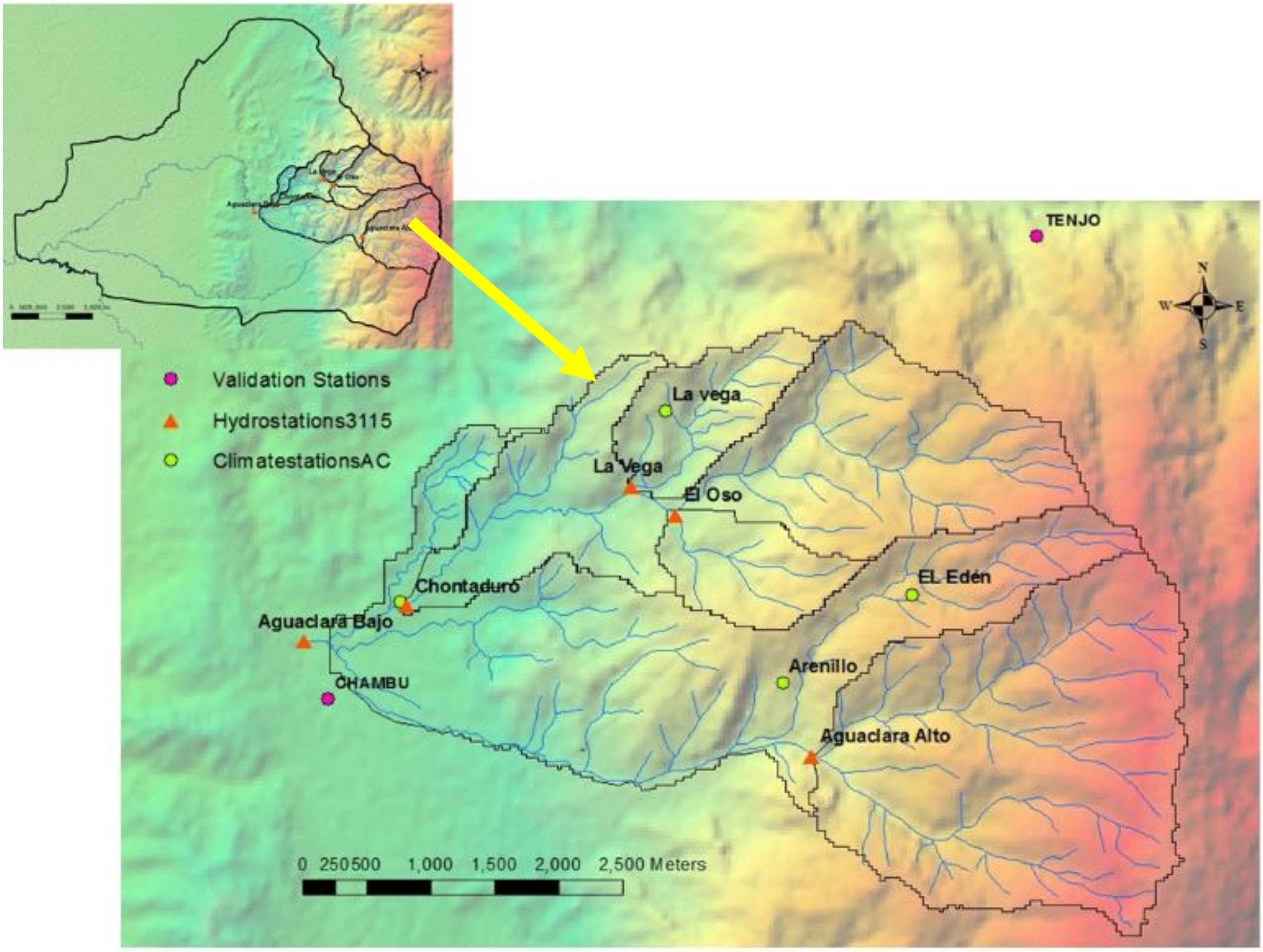

Figure 2 Instrumented area

point measurements for each of the climate station presented in Figure 2, but knowing that many hydrological characteristics and especially rainfall have spatial variability (Dingman 2 002), 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:

$$p(z) = a + bz \qquad (2)$$

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.

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.

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. The main data used in this research was the USGS Simplified Surface Energy Balance (SSEBop) version 4.

The remote sensing method has a resolution of 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.
To validate the use of the selected method, it was compared to the results of ET from the measured data by the climate stations, couple to the land use map of the area, this data was only available for the period between May and December of 2015. 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.

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, presented in Figure 2 by the red triangles. From the stage level, the mean daily streamflow is calculated and the reported values were used in this research. 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.

B. Baseflow separation

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 C14 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 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.

C. Hydrochemistry and stable isotopes

During fieldwork executed between April and May 2018, 36 water samples collection, and on field measurement of water parameters were done to assess the existance of hydraulic connectivity between the high elevated areas and the aquifers of the valley. 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).
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 CO2 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.
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, O18 and deuterium H2, 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.

IV. Results and Discussion

A. Water Balance calculations

The year 2015 was the year with the most completed data set for discharge measurements at the outlet of the monitored area, and for climate parameters. So initially the water balance was carried for the entire area, and after the evaluation for the period between January 2015 and December 20117 was done.

1) Precipitation

Precipitation spatial distribution was done according to the methodology described earlier. Orographic effects result in more precipitation at the higher elevations in the instrumented area, than those located the lower parts of the Aguaclara sub-catchment where the alluvial deposits are located, 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. The validation of the spatial distribution obtained was done with two external stations from the regional authority, displayed in Fig 2 by the pink dots, obtaining a Pearson coefficient of 0.944 between the measured values at the stations and the estimated from the hypsometric method.

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.

2) Evapotranspiration

Temporal comparison of the two remote sense models, showed similar patterns through the evaluated period, but also showing usually higher of actual evapotranspiration for the ETensemble V1.1, as presented in Fig 3. Although graphically the difference is evident, t-test was carried finding a significant difference between the models. 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.

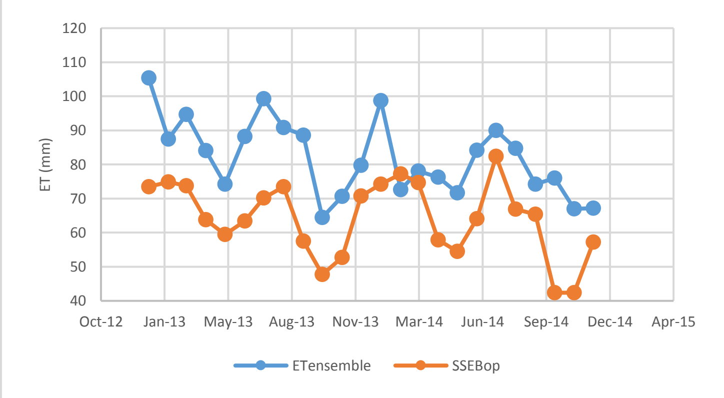

Figure 3 Remote sense models comparison

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, as presented by Fig 4. Although for the very dry months the differences between the two methods seemed to increase per each of the sub-basins in the monitored area, when the entire catchment was considered, the differences between the two methods decreased, with a total difference of 10 mm between May 2015 and December 2015. This result suggest that the use of the SSEBop model provides reasonable estimations of the actual evapotranspiration, and a more conservative estimation than the higher resolution model Etensemble.

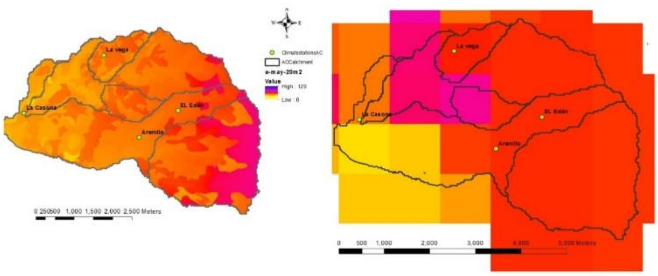

Figure 4 May ET comparison between measured data coupled with land use (left) and SSEBop (right)

3) Streamflow

As indicated in 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 Fig 2.

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 in 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

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%.

4) Water balance

With the spatial distribution of precipitation and evapotranspiration, the water balance was done by substrating the ET to the rainfall, the result obtained was then multiply it by the area, and finally the measured discharge for the month was extracted for the balance. 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.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.
The results 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 2, and the graphical representation including the period to period variation and the cumulative amount of MBR for the year 2015 are displayed Fig 5.

Table 2 Water balance results 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%

The approach for the calculation of the MBR was to take assumptions for the missing data which 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.
Note how in Fig 5, 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.

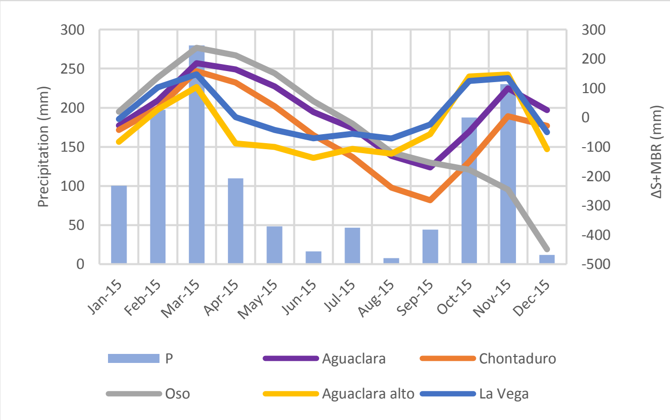

Figure 5 Cumulative Water Balance and average rainfall year 2015

The initial results for 2015, showed that even under the most favorable 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.
For the precipitation distrution of the years 2016 and 2017, data was taken according to Table 3. 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 6

Table 3 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

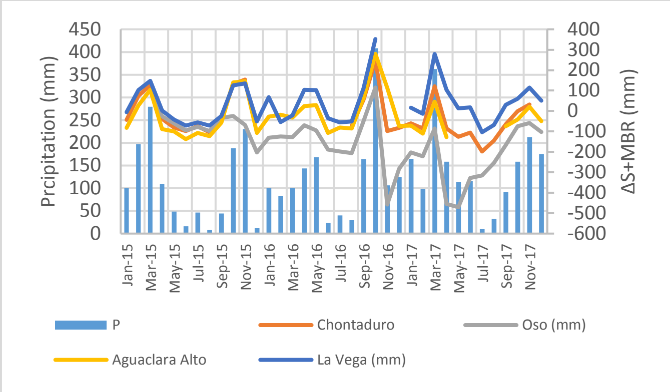

Figure 6 Cumulative Water Balance and average rainfall from Jan 2015 to Dec 2017 per sub-catchments. Non-connected lines indicate periods without discharge data

Table 4 result for Chontaduro represents the amount of water at the end of November 2017, due to missing streamflow data. In Fig 6, 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 4 Water balance results for 2015-2015 (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

B. Baseflow separation

The baseflow separation method confirmed the results of the amount of recharge calculated for the wet periods, and also confimed the particularly large amount of discharge for El Oso catchment, that could be explained by local fluxes between the catchments in the mountainous areas, where this catchment will be a discharge area for fluxes coming from higher elevation areas.
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 of the described 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 5 Results recharge from baseflow

	WB Total area	Baseflow Chontaduro	La Vega	Aguaclara Alto	El Oso
Positive balance from wet season (mm)	482	457	172	689	1448
Recharge from wet season (%)	35.67%	31.55%	12%	47.52%	99.79%

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 electrical conductivity (EC) and HCO3 concentrations of any other measured streams, and even higher than two of the assessed springs.

C. *Hydrochemistry and stable Isotopes*

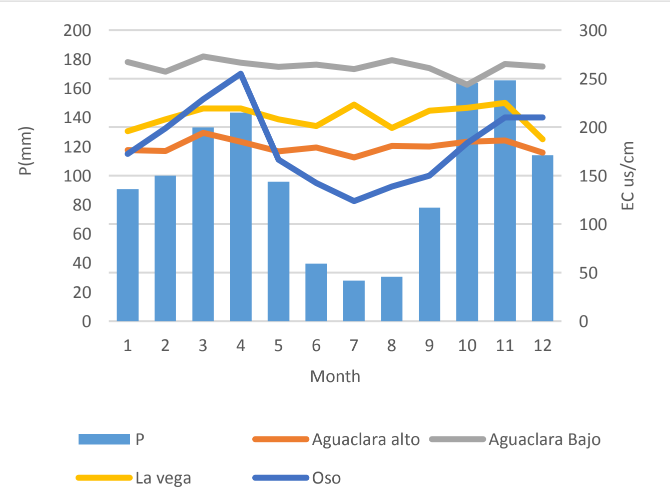

Figure 7 (2014-2018) Averaged EC seasonal variations according to averaged seasonal precipitation (40 years)

The water balance and the baseflow separation methods suggested short residence time for the recharged water, which is stored by the basalts of the mountain. The monthly measurements of EC, validated this theory, since there is not a major increase of mineralization of the water being discharged in the dry seasons. As presented by Fig 7.

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.

Chloride can be used as a conservative tracer, to understand the processes of the catchment. In this research chloride and stable isotopes were analysed as natural tracers, and the results indicate that the water in the deep wells has more similarities with water in the streams from the high elevated areas, than to the shallow wells and springs around them. This could suggest the existence of regional flow connecting the aquifers in the valley to the mountains.

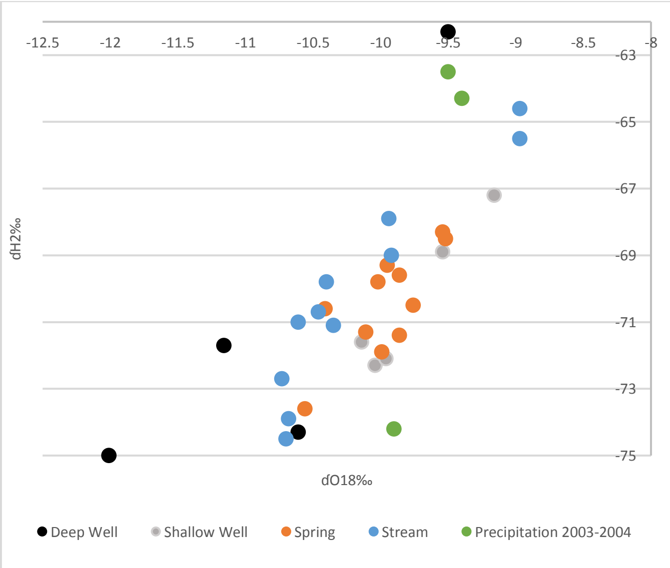

Figure 8 Stable Isotopes

The seasonal variations of the stable isotopes could explain most of the depletion found in deep wells, however, the most depleted sample in a deep well, has depletion values under the ones from it elevation, and considering that the sample is a mix of waters, it does suggest that the water was in fact recharged at a high elevation area. However, due to the wet conditions during the fieldwork, the amount of samples from deep wells was very limited and to reach a relevant conclusion the findings required to be validated by a larger number of samples.

D. Conceptual model

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.

According to the conditions found, it is possible to describe the main hydrogeological processes happening in the catchment as presented as follows: 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.

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.

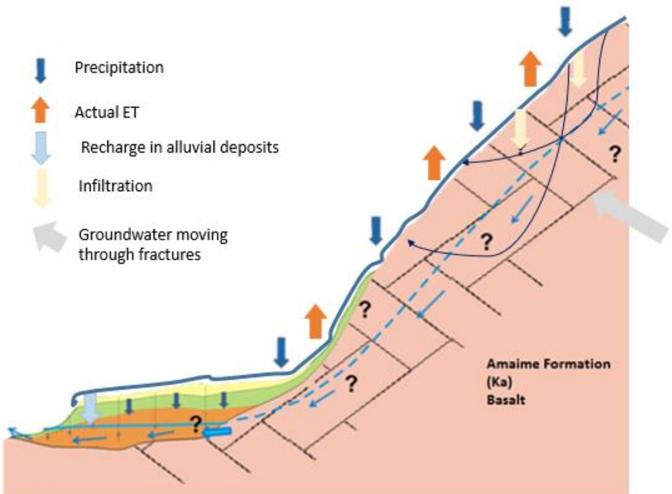

Figure 9 Conceptual model main process in the study area considering MBR (dashed blue lines). Adapted from Doyle (2013)

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. 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. 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 1, 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 does the larger part of the mountainous catchment behave, to evaluate if the contribution to aquifers in the valley could be significant considering the large extension of the Central Cordillera.

V. CONCLUSIONS

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. 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.

• 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.

• 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.

• 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.

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