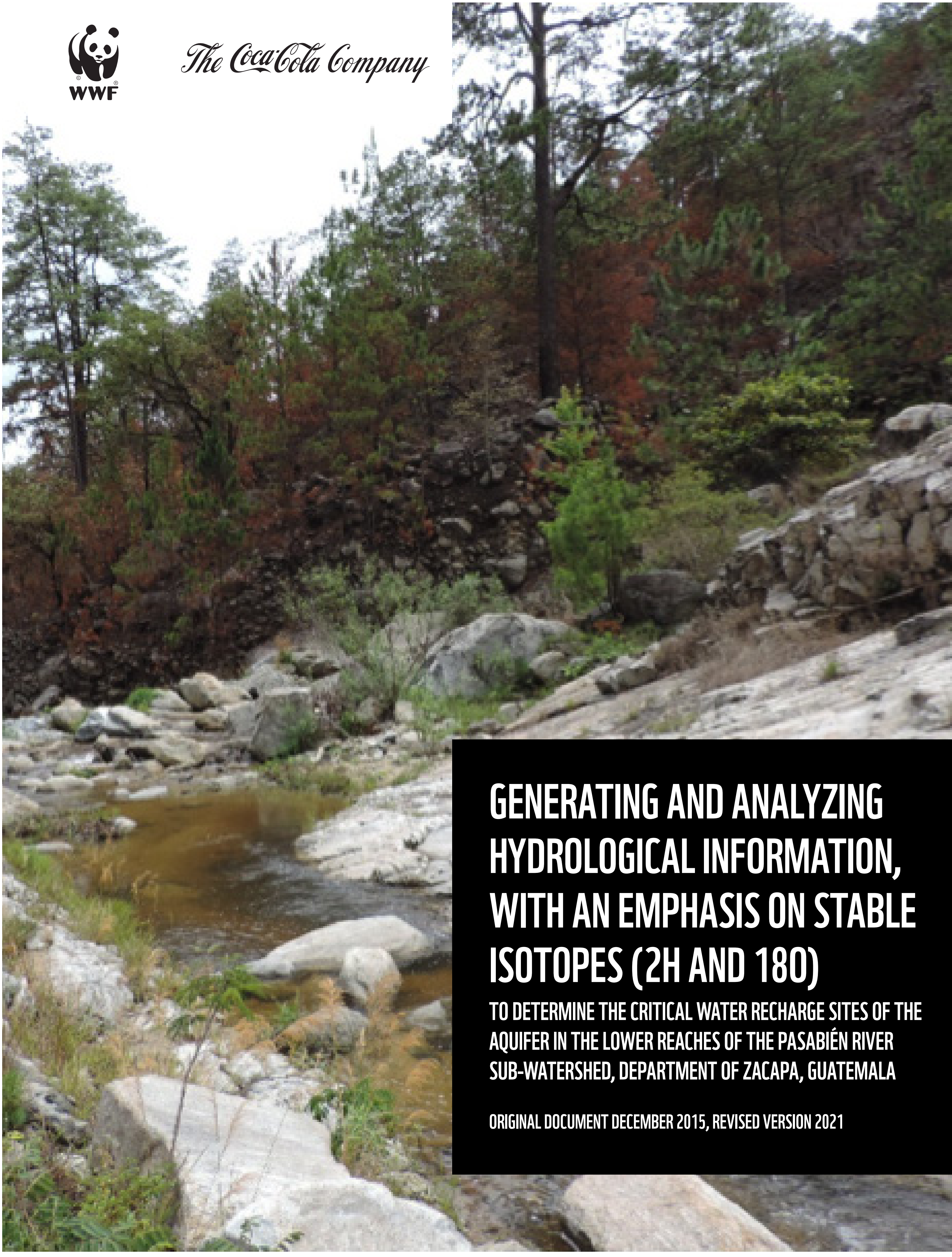
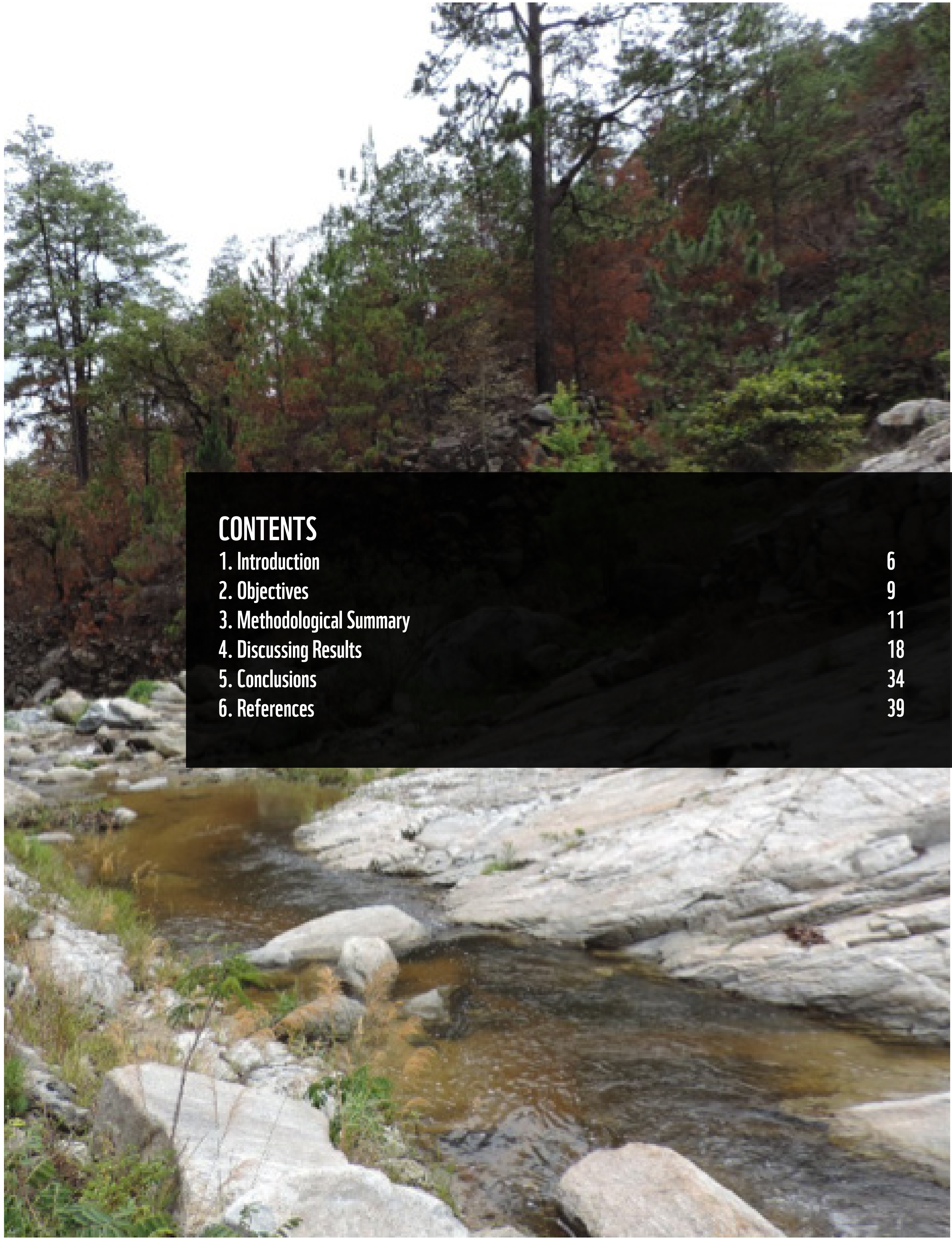


GENERATING AND ANALYZING HYDROLOGICAL INFORMATION, WITH AN EMPHASIS ON STABLE ISOTOPES (2H AND 18O)

TO DETERMINE THE CRITICAL WATER RECHARGE SITES OF THE AQUIFER IN THE LOWER REACHES OF THE PASABIÉN RIVER SUB-WATERSHED, DEPARTMENT OF ZACAPA, GUATEMALA

ORIGINAL DOCUMENT DECEMBER 2015, REVISED VERSION 2021



CONTENTS

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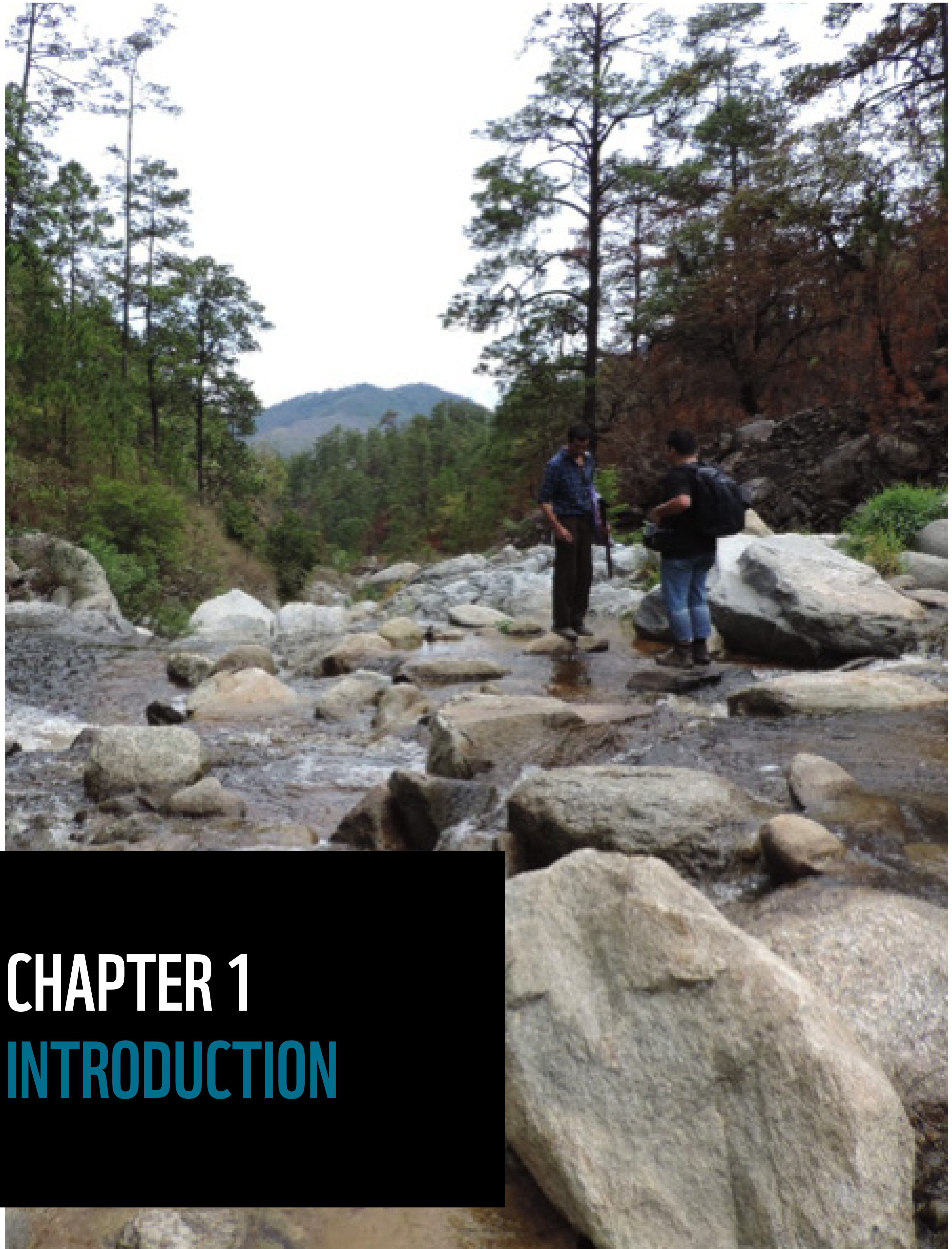


CHAPTER 1
INTRODUCTION

This report integrates field data and a preliminary analysis of the research titled "Generating and Analyzing Hydrological Information, with an Emphasis on Stable Isotopes (2H And 18O), to Determine the Critical Water Recharge Sites of the Aquifer in the Lower Reaches of the Pasabién River Sub-Watershed, Department of Zacapa, Guatemala."

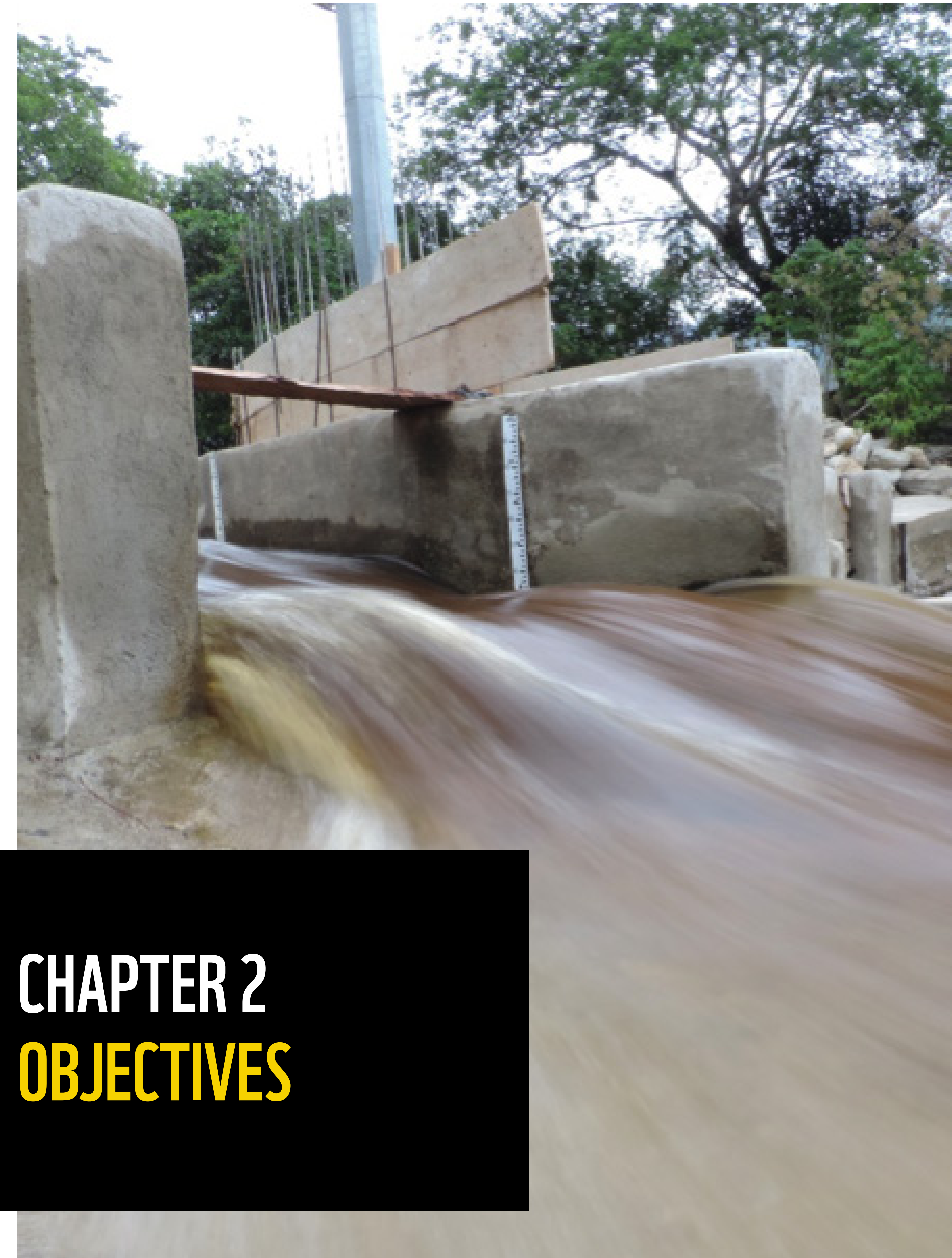
The main objective of the study is to analyze water stable isotopes, since this method has proven to be very useful to define the origin, distribution, and availability of water resources.

Isotopes are the atomic nuclei of elements with the same number of protons but different number of neutrons. Isotopes, therefore, belong to the same chemical element, but have a different atomic weight, since this results from the sum of protons and neutrons in the nucleus. The water molecule is composed of hydrogen and oxygen. Hydrogen is the simplest element in nature. Normal hydrogen atoms contain a proton and an electron, but when the hydrogen atom has a neutron accompanying the proton, it is called Deuterium and it is expressed by the symbol 2H. Chemically, the isotopes have the same characteristics, but they differ physically because their weight is higher.

Many natural processes result in an unequal distribution of heavy and light isotopes, and this distribution can provide information about isotopic transformations. The process by which lighter isotopes form chemical bonds, which require less energy to break, is called fractionation. Isotopic variation can be used to tag and trace elements that move in complex biogeochemical cycles, such as the water cycle.

Rainfall in Guatemala comes from the evaporation of seawater. With the isotope method, water can be traced because the concentration of these heavy isotopes decreases progressively as they move away from the sea or rise into the mountains as water vapor. Isotope concentrations can be determined in rain, rivers, and groundwater or aquifers. The stable isotopes in water are 2H or Deuterium and 18O, whose concentrations can be used to determine the location of water-recharge zones.

Field implementation followed a specific protocol to gather biophysical variables relating to temporary and spatial distribution of water resources in the sub-watershed. In order to define the critical water recharge and regulation sites, the following main approaches were established: a) validating novel water research methods to plan water resources, climate-change risk management, and conservation schemes; b) generating scientific information on which to base strategies that ensure water supply for the population, the economic sector, and ecosystems, and c) developing a pilot experience that can be replicated in other strategic sub-watersheds, both in the Sierra de las Minas Biosphere Reserve and in Central America.



CHAPTER 2 OBJECTIVES

General Objective

To determine the water-recharge sites for the aquifer in the lower reaches of the Pasabién sub-watershed.

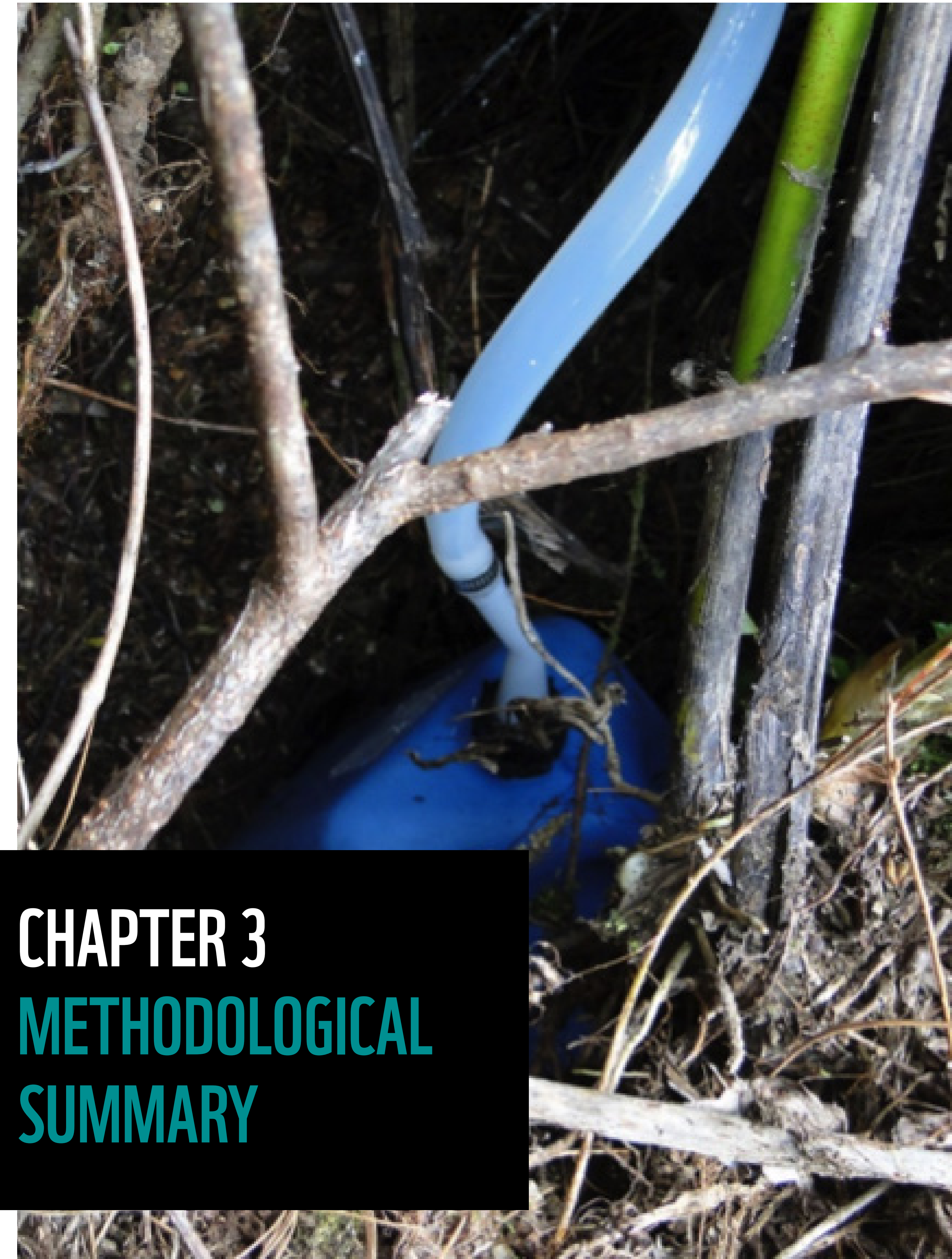
Specific Objectives

• To collect rainwater, surface runoff, and groundwater samples.

• To establish 2H and 18O stable isotope ratios in sampled water.

• To monitor and analyze complementary biophysical information, especially water-quality, climate, hydrological and hydrogeological information.

• To develop a conceptual model that explains the origin, distribution, and availability of water resources in the Pasabién sub-watershed.



CHAPTER 3
METHODOLOGICAL SUMMARY

Geography of the Study Area

The Pasabién sub-watershed is located 125 kilometers (km) northeast of Guatemala City, in the departments of Zacapa (97%) and Alta Verapaz.

It spans 10,084 hectares (ha); 9,358 ha (92.8%) in the municipality of Río Hondo, and 443.73 ha in the municipality of Pasabién, (04.4%) in the department of Zacapa, and 282 ha (02.8%) in the municipality of Panzós, in the department of Alta Verapaz. The lowest reach of the sub-watershed is 180 meters above sea level (m asl), at the point where it joins the Motagua River. The highest reach is almost 3,000 meters above sea level (m asl), in the Sierra de las Minas. The middle and upper reaches of the Pasabién sub-watershed overlap with the core zone and the buffer zone of the Sierra de las Minas Biosphere Reserve (RBSM) (Figure 1).

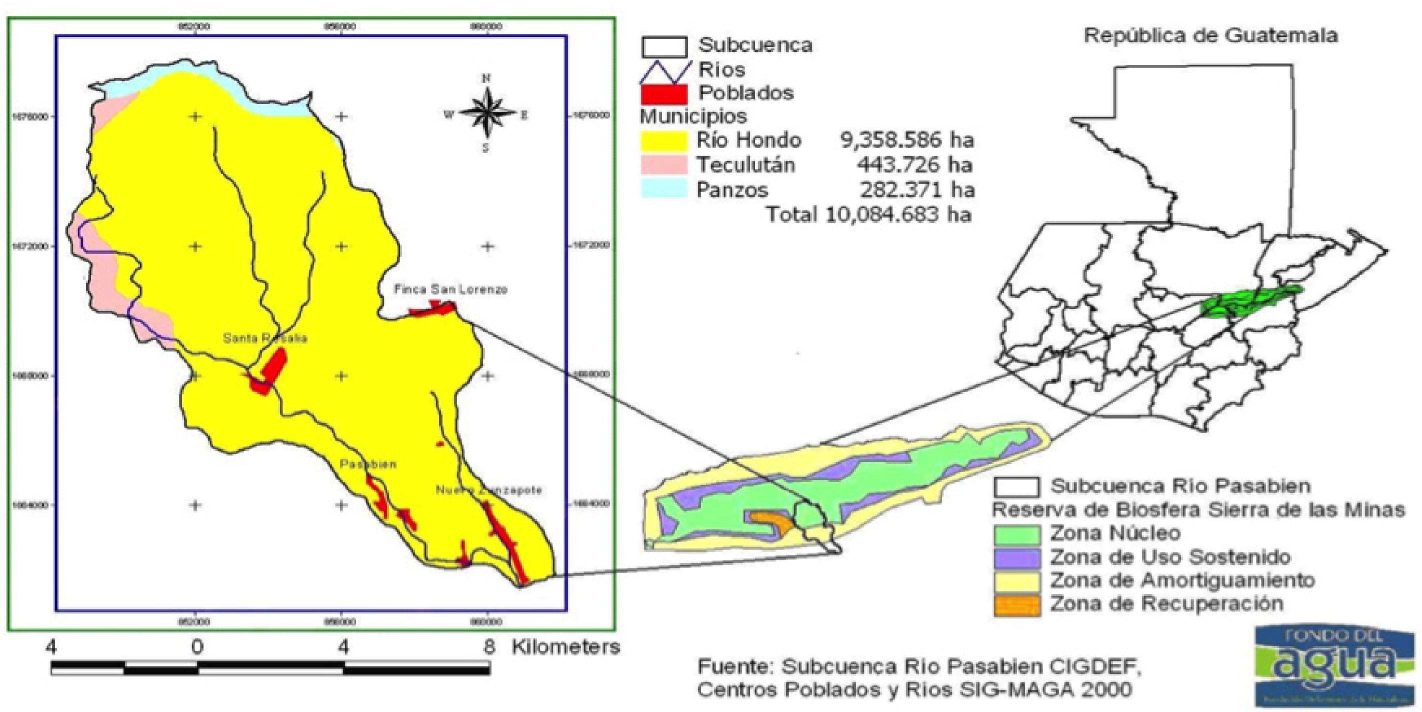


Figure 1: Overall Location of the Pasabién Sub-Watershed

Monitoring Isotopes 2H and 18O

Secondary biophysical data were gathered for this work, emphasizing geological, climate, and hydrological information to provide context and demarcate the study area and to establish the 2015 sampling period, with the aim of analyzing stable isotopes (2H and 18O) and obtain complementary data on water quality.

These data help to determine the location of the most probable water-recharge sites for the aquifer located in the lower reach of the Pasabién sub-watershed.
Water sampling was performed in the leeward hydrological region (southern slope of the Sierra de las Minas), locating rainfall, surface runoff and groundwater sampling sites along an altitudinal gradient. Sampling zones were chosen according to the following altitudinal classification:

Portion of the Watershed	Type of Forest or Place and Elevation
Upper reaches of the watershed	Dwarf forest at 2,700 m asl Cloud forest at 2,250 m asl San Lorenzo at 1,750 m asl
Middle reaches of the watershed	Santa Rosalía (900 m asl)
Lower reaches of the watershed	Pasabién town nearly 250 m asl

Table 1: Altitudinal Location of Isotope-Sampling Zones in the Pasabién River Sub-Watershed

The composite samples collected are used to observe representative isotopic concentrations at different sampling times and periods of the year. During the dry season, sampling was performed monthly, and during the rainy season, sampling was generally performed every two weeks. In October (the rainiest month), weekly sampling was performed (see Figure 2).

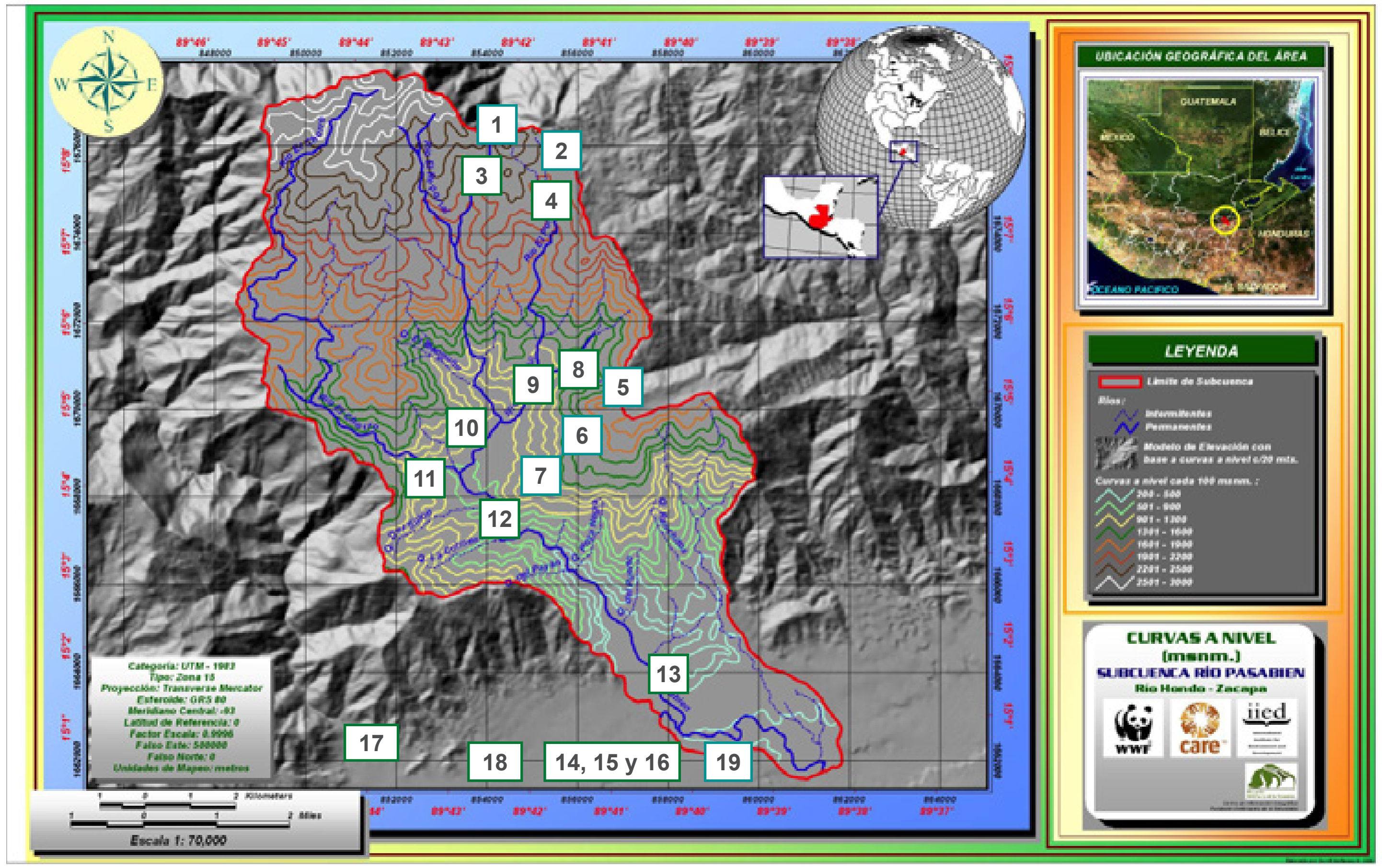


Figure 2: Water-Sampling Site Locations for the Stable Isotope Analysis

Location of the Rainfall, Surface Runoff, and Groundwater Sampling-Site Network in the Pasabién Sub-Watershed

Table 2 and Figure 2 show the location of the sites where field water sampling was performed. They also identify the main characteristics and the nature of the water that was sampled; that is, whether water samples originate from rainwater collectors , surface runoff, springs, or wells. The codes in Table 2 refer to the number of sampling sites per type of water: P (precipitation) stands for rainwater samples, R (river) stands for samples taken from rivers, and W (well) stands for the samples taken from wells.

Table 2: Geographical identification and location and description of the sampling sites to collect water data. Sub-indices I of the rainfall, flow, and well components located in the variable-measurement column indicate that water samples will be collected for their analyses in the isotope laboratory.

No.	Code	Name of Site	Altitude m asl	Measurement of Variables						Location	
				Rain	Rain i	Flow	Flow i	Well	Well i	Latitude	Longitude
1	P1	Dwarf forest	2600							15° 08’ 09”	89° 42’ 08”
2	P2	Cloud forest (El Timbo)	2300							15° 08’ 42”	89° 42’ 08”
3	R1	Río El Inglés upper reaches	2000							15° 08’ 08”	89° 40’ 36”
4	R2	Río El Portón upper reaches	2000							15° 07’ 28”	89° 40’ 16”
5	P4	San Lorenzo	1750							15° 05’ 06”	89° 40’ 10”
6	P5	El Naranjo	1300							15° 05’ 15”	89° 41’ 02”
7	P6	Santa Rosalía	950							15° 05’ 15”	89° 41’ 02”
8	R3	Santa Rosalía, El Inglés	950							15° 05’ 15”	89° 41’ 02”
9	R4	Santa Rosalía, El Portón	950							15° 05’ 09”	89° 41’ 52”
10	R5	Santa Rosalía, El Repollal	950							15° 04’ 40”	89° 42’ 17”
11	R6	Santa Rosalía, La Cascada	950							15° 04’ 05”	89° 42’ 19”
12	R7	Santa Rosalía, La Presa	900							15° 04’ 04”	89° 42’ 18”
13	R8	Balneario Pasabien	300							15° 02’ 25”	89° 42’ 01”
14	W1	Coca Cola plant, well 1	250							15° 00’ 05”	89° 40’ 32”
15	W5	Coca Cola plant, well 3	250							15° 00’ 05”	89° 40’ 32”
16	W6	Coca Cola plant, well 4	250							15° 00’ 05”	89° 40’ 32”
17	R9	Río Teculután, Las Minas station	250							15° 00’ 45”	89° 44’ 08”
18	R10	Río Motagua	180							15° 00’ 50”	89° 57’ 32”

Source: Developed by the author

Water Quality Data and Other Hydro-Chemical Characteristics

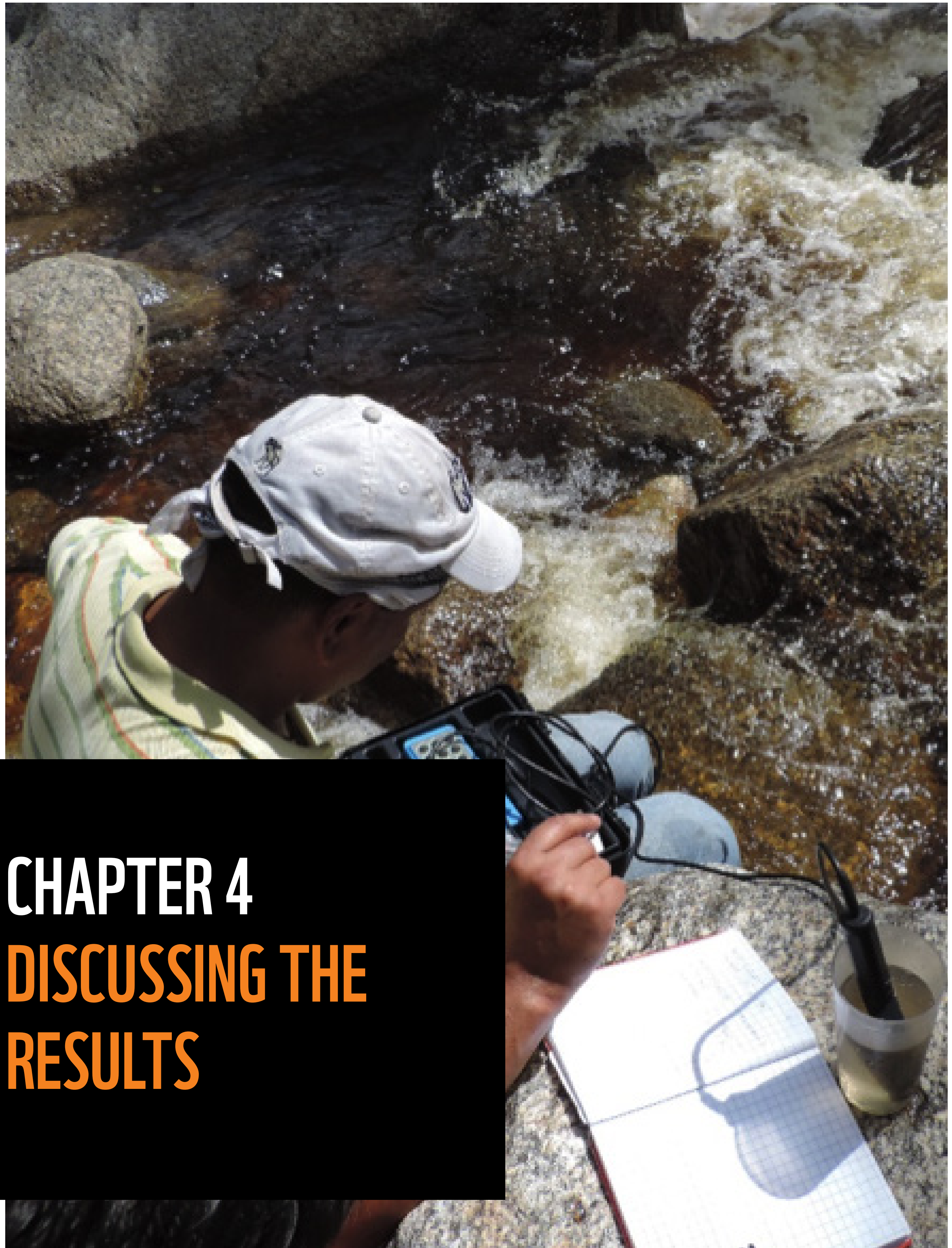
Basic water-quality data were obtained for each one of the samples collected. These data included temperature, dissolved oxygen, electric conductivity, total dissolved solids, and pH. In addition, some of the samples taken from the wells during the rainy season were analyzed to determine hardness and the presence of silica.

Soil Water Balance

Methodological processes were based on the proposal by Schosinsky (2006). Data were taken from the study "Hydrological Evaluation of the Pasabién and Pueblo Viejo Sub-Watersheds (WWF 2007, Avalos and Rosito). Three phases had to be developed to generate a soil water balance and to determine water recharge. Digital cartographic information on geology, soils and vegetation cover was integrated, in order to delimit the mapping units. In addition, rainfall, temperature, and potential evapotranspiration data were generated based on the isoline maps, and then it was integrated.

The field-work phase (undertaken in 2006) consisted of performing infiltration tests (Porchet method) for each mapping unit that had been defined, determining the effective representative depth, and taking soil samples. The infiltration rates were also determined and then the basic infiltration was estimated. With this information, monthly and annual recharge was calculated for each mapping unit defined. The water balance consists of determining the water inputs to the system, such as precipitation, and then subtracting evapotranspiration, surface runoff, vegetation interception, and deep-water recharge.

By integrating the information described above, which is linked to geology, climate, hydrology, hydrochemistry, and water quality, a profile that represents the conceptual hydrogeological model of the sub-watershed was developed. Lastly, the water recharge of each sub-watershed was analyzed, and the behavior of this recharge was analyzed according to the biophysical properties of the micro-watersheds and sub-watersheds.



CHAPTER 4 DISCUSSING THE RESULTS

The biophysical aspects that are key to determining water-recharge processes are the ones pertaining to geology and climate.

The main geological formations in Teculután, in the high reaches of the Pasabién sub-watershed and surrounding sub-watersheds to the west contain granite, gneiss (rocks with little aquifer formation), marble and Quaternary alluvium (loose material consisting of gravel, sand, silt and clay). The geological profile (Figure 3) confirms possible aquifer formation, especially in the marble and alluvium formations.

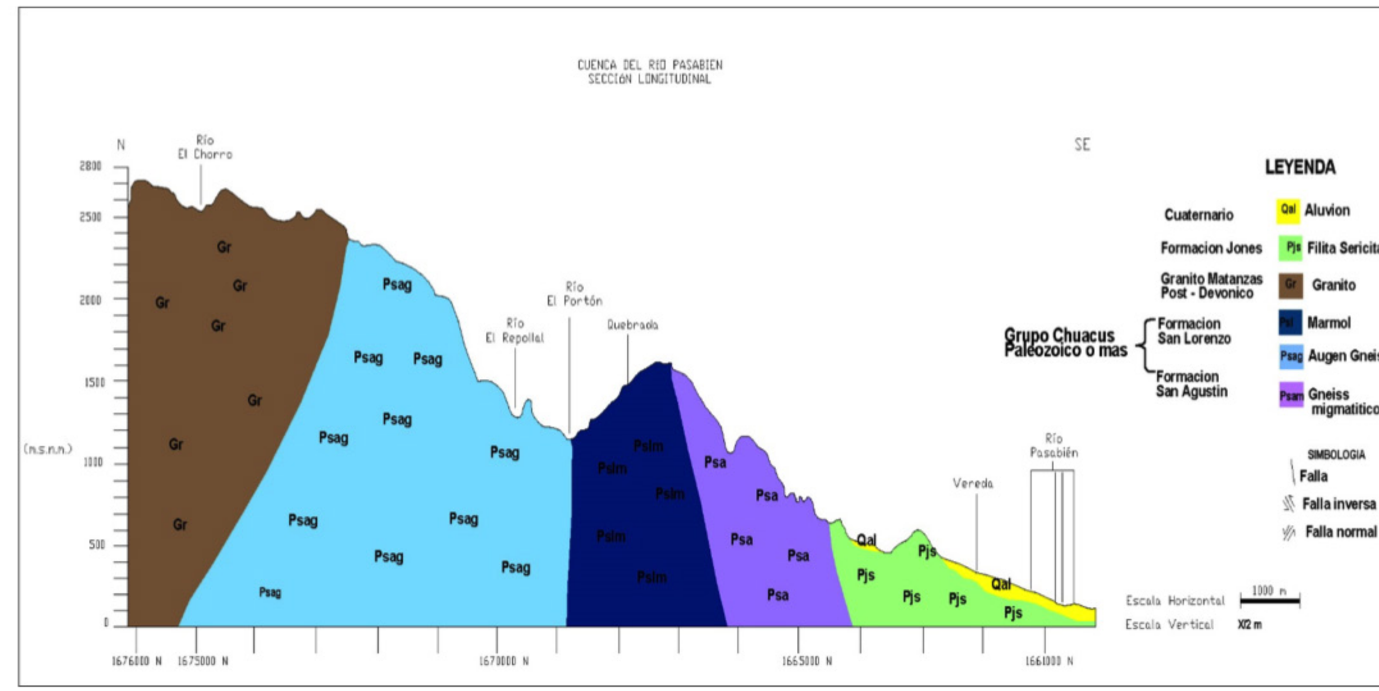


Figure 3: Pasabién Sub-Watershed Geological Profile. Source: Pasabién Sub-Watershed Preliminary Geological Map (CORDILLERA, S. A. 2007).

Figure 4 shows historical precipitations for the 1994-2010 period and their comparison with a very dry year (2009-2010) and a very wet year (2010-2011). There is considerable contrast between the high and low reaches of the sub-watershed, as well as among the historical average and the very dry and the very wet years.

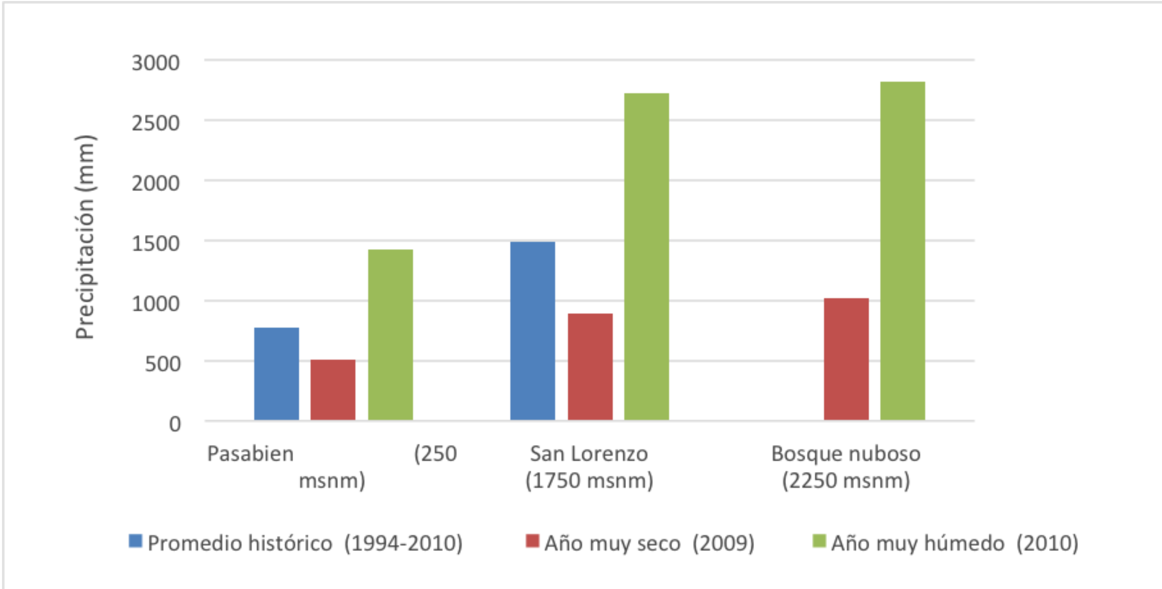


Figure 4: Historical precipitation and Precipitation in a Very Dry Year and a Very Wet Year (2010) of Weather Stations Located in the Pasabién Sub-Watersheds.

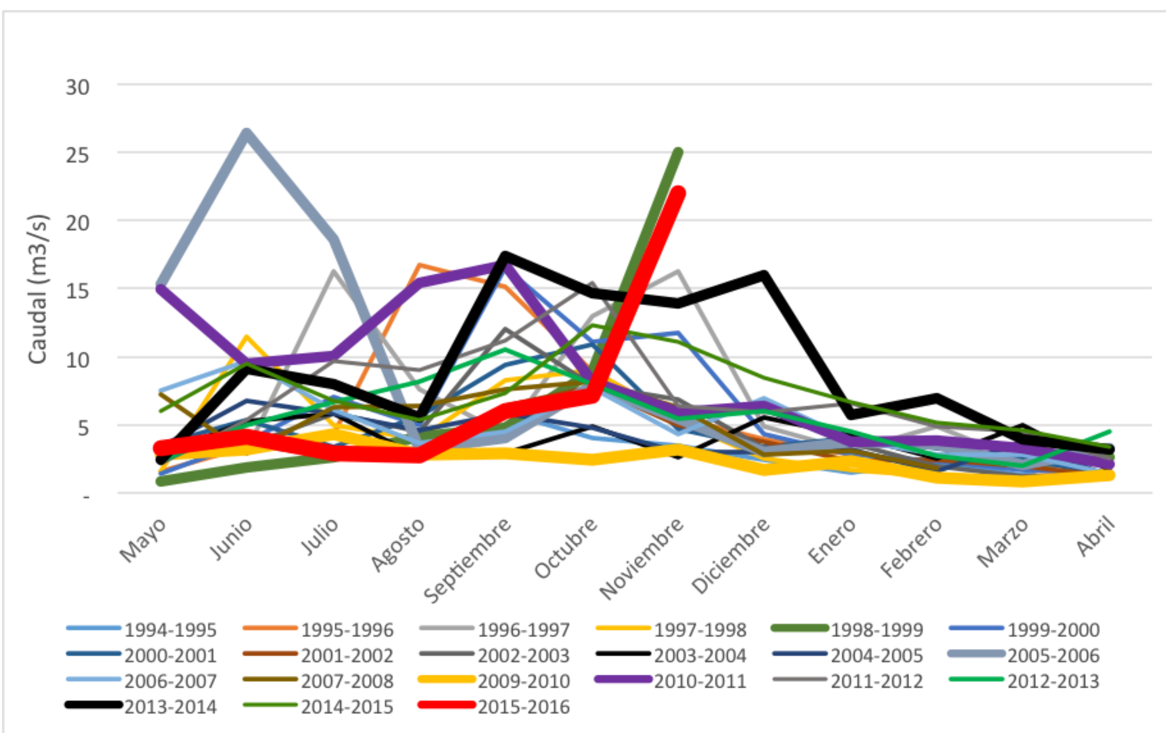


Figure 5: Historical Monthly Flows (1994-2015 Period). The following years are notable: 1998-99, 2009-10 and 2015 as very dry years, and 2005-2006, 2010-2011, 2013-14 as very wet years with record historical months. Data from the Las Minas station in the Teculután sub-watershed. Source: INDE.

Figure 5 shows the historical flow record, which indicates that the driest years occurred in the 1998-1999 periods, 2009-2010, and the first part of 2015. The lowest flows were recorded in July and August 2015, although November is recorded as the month with the highest monthly flow. In contrast, the highest flows were recorded in 1998, 2005-2006, 2010-2011, and 2013-2-14, with extreme precipitation events. The data on groundwater isotopic fingerprints were similar and consistent from the beginning of sampling until November 2015.

Figures 6 and 7 show the graphs for 2H or Deuterium isotopic load distribution of the samples collected in various periods of 2015. Additionally, the categorization of these water samples according to the location, source, and nature of the monitoring sites is shown.

In this regard, it is possible to establish a difference between the water linked to the baseflow, which shows that the aquifer in the middle reach of the sub-watershed is connected to the groundwater in the middle and upper reaches. Figure 8 shows the local meteoric water line; that is, the definition of the isotopic footprint of the water from precipitations and its relationship with the groundwater in the wells at Alimentos y Bebidas del Atlántico, S. A. (ABASA).

Discussing the main results

a) Traceability of water from precipitation

It was possible to establish that the precipitation samples for February and March, which could only be collected (only site with rain) in the high reaches of the sub-watershed (cloud forest) present isotopic loads near zero; that is, it is "heavy" water associated with fog or horizontal precipitations (linked to orographic rainfall), (Figures 6 and 7).

The isotopic load of precipitation samples at the beginning of the rainy season (April, May, and June) are classified as "light"; that is, with values above -60 in 18O (Figures 6 and 7).

During the months of February, March and April, the surface waters sampled in the rivers located in the middle and lower reaches of the Pasabién sub-watershed show high influence –or isotopic concentration– of water from the cloud forest and "heavy" precipitation; that is, fog or horizontal precipitation, typical of the upper reaches of the sub-watershed or cloud forest at that time of the year.

It is important to note that rainwater collected in the upper reaches of the sub-watershed is quite evident in the lower reaches of the sub-watershed. This indicates that rainwater was able to be traced from its origin as rainfall to its manifestations as surface water currents and aquifers in the middle and lower reaches of the sub-watershed.

b) The isotopic loads of the water from the aquifer in the lower reaches of the sub-watershed, especially from the ABASA wells, have been highly consistent and constant throughout the whole sampling process (January to November 2015). There is a similarity between the isotopic loads of the water from the ABASA wells and the September and October 2014 rainfall in the middle reaches of the sub-watershed. Furthermore, this same correlation is evident between the water from the wells and the water in the middle reaches of the Pasabién sub-watershed during the 2015 rainy season.

In regard to hydrogeological aspects, the existence of permeable geological structures in the middle reaches of the sub-watershed and the geological fractures and faults has been defined, specifically between San Lorenzo (1,750 m asl) and Santa Rosalía (900 m asl). The geology of meta-sedimentary rocks (marble and others) are rare exceptions in this region, with a predominance of plutonic, metamorphic (often crystalline) and mafic formations; that is, with little formation of deep aquifers. These data are consistent with the hydrogeological information on the sub-watershed.

c) The isotopic load of the minimum flow is the same as that of the aquifer mantle in the lower reaches of the sub-watershed. This is evidence that there is active communication between groundwater and surface water in the middle and lower reaches of the Pasabién and Teculután sub-watersheds (Figures 8 and 9).

This suggests that, in addition to being the site where water is captured from the aquifer in the lower reaches of this sub-watershed (ABASA wells), the middle reaches of the Pasabién sub-watershed, at least, are essential if high water quality is to be maintained.

d) According to Table 3, water sample values from the ABASA wells show the presence of silica and relatively high hardness values. This suggests that there are high residence times in sites with geological marble material and related rocks.

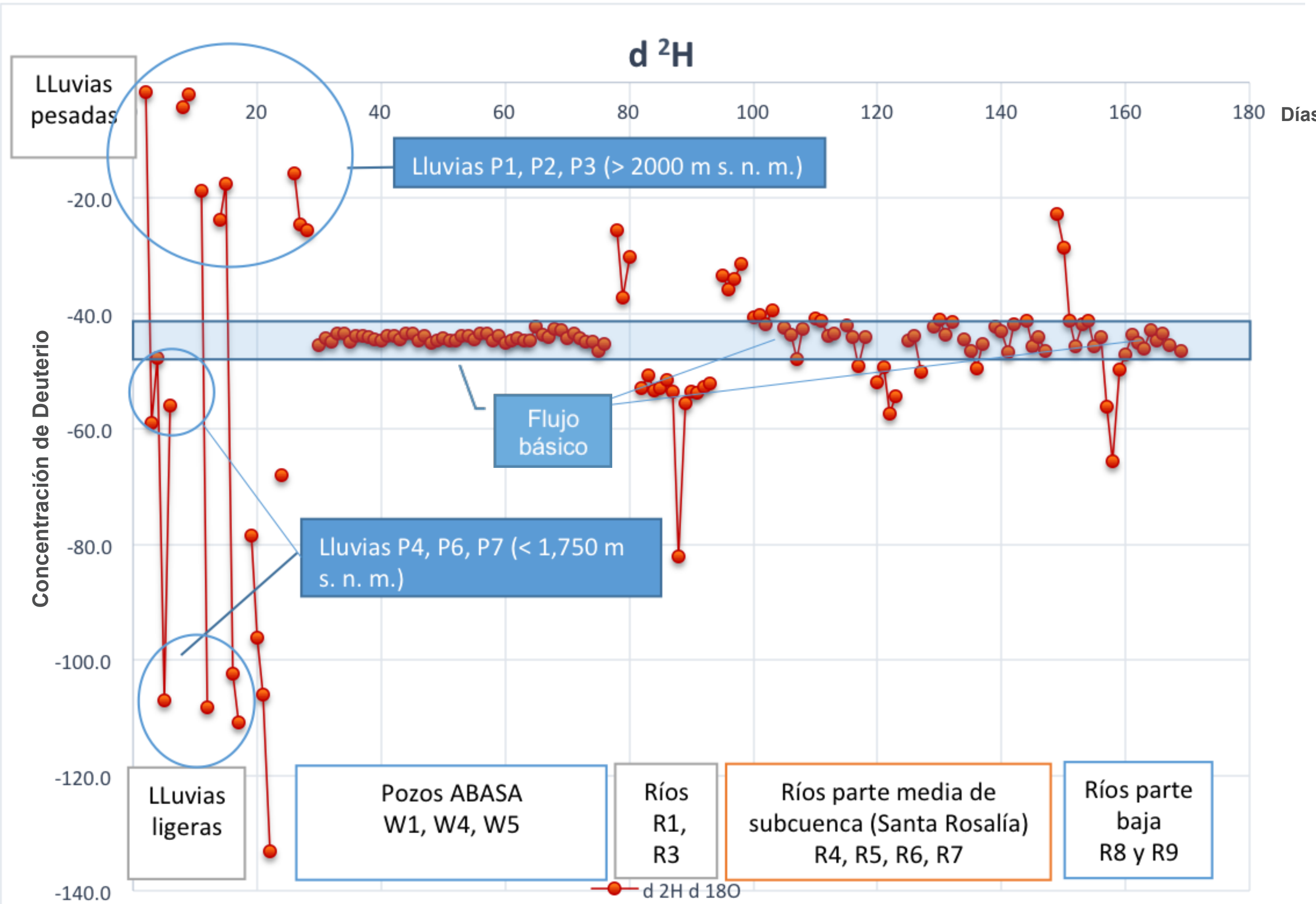


Figure 6: Deuterium (2H isotope) concentration, according to the sample sites and the definition of basic flow concentration or water connected to the main aquifer (emphasis on the first 2015 quarter).

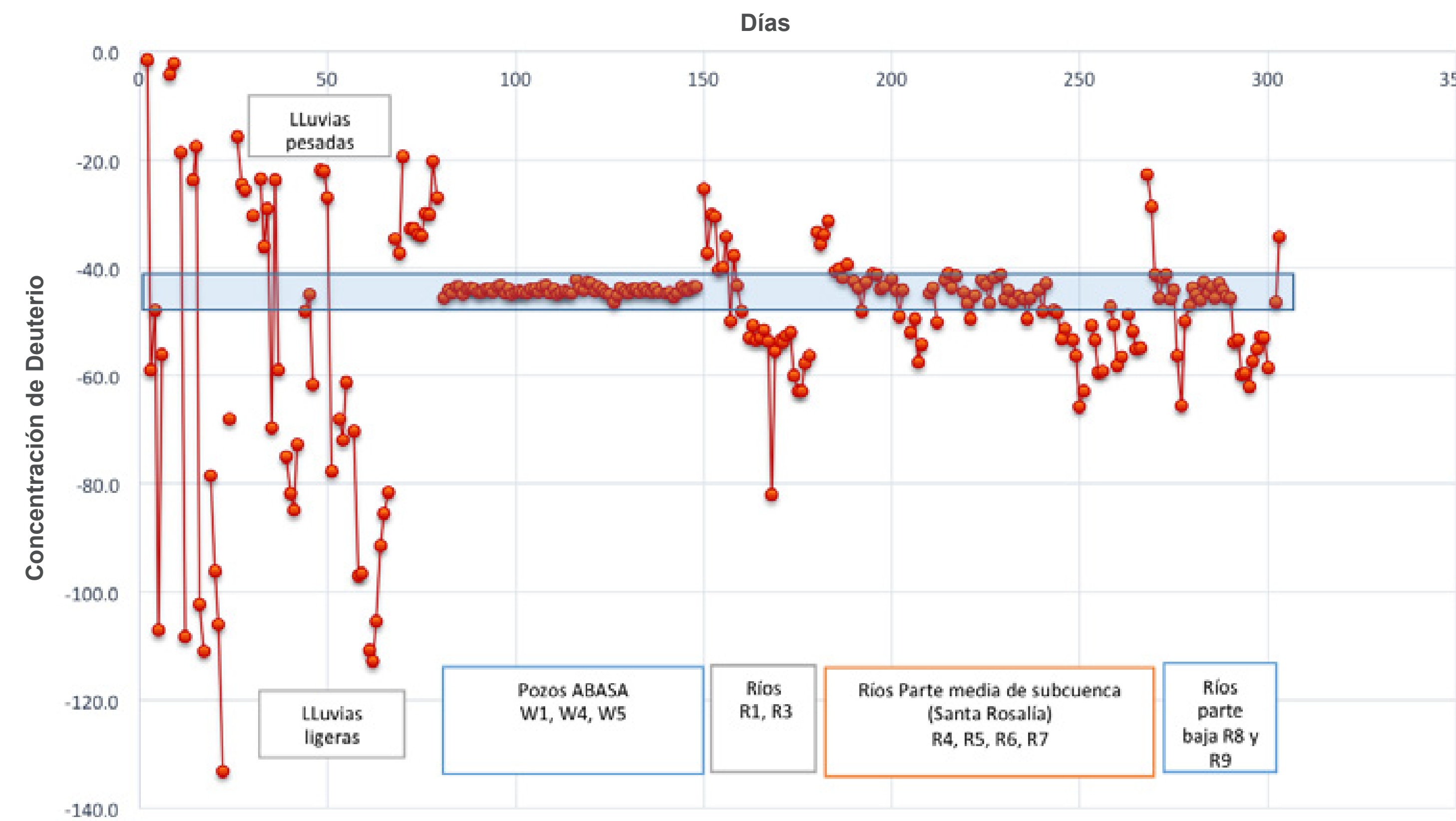


Figure 7: Deuterium (2H isotope) concentration, according to the sample sites and the definition of basic flow concentration or water connected to the main aquifer (October 2014-November 2015 period).

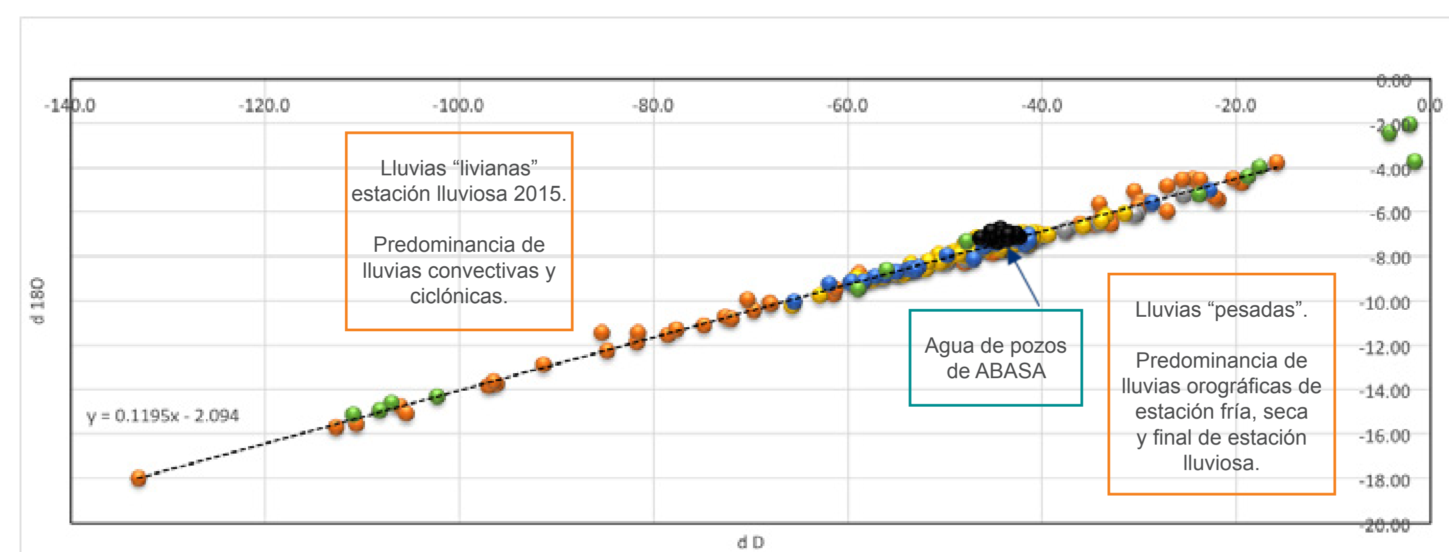


Figure 8: Meteoric water line of the Pasabién sub-watershed and relationship with isotopic concentrations of well water.

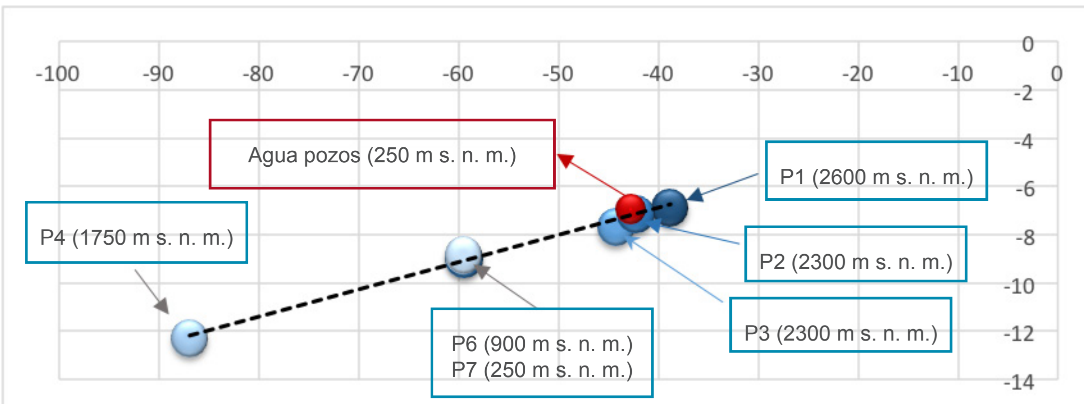


Figure 9: Relationship between arithmetic averages of the main rainfall and well-sampling sites.

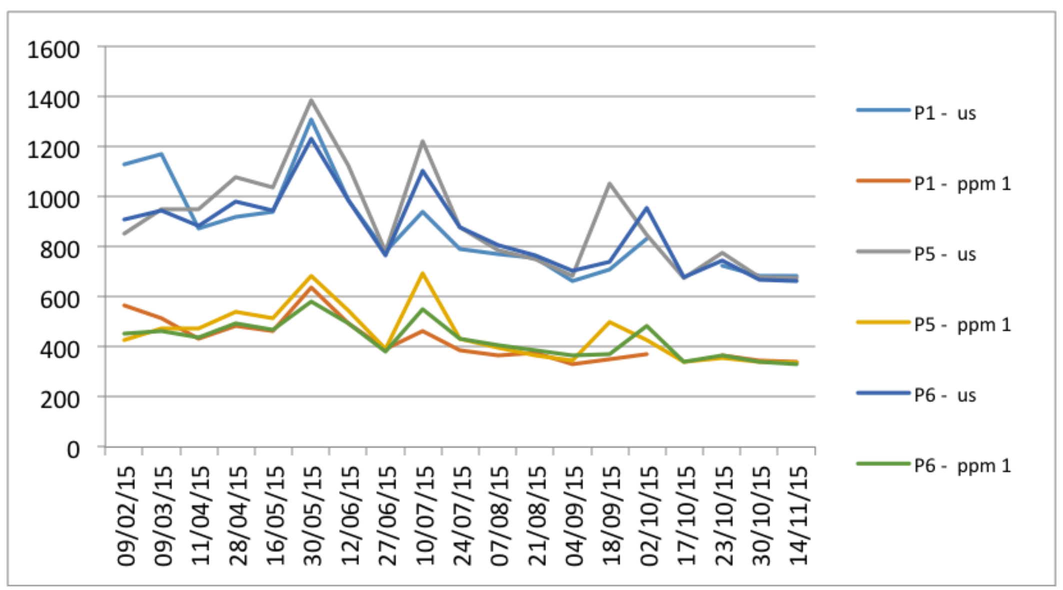


Figure 10: Electrical conductivity (µS/cm) and dissolved-solid data from the ABASA wells (February-November 2015 period).

Dissolved Oxygen in ppm and % for Water Samples from the ABASA Wells						
	Well					
	P1		P5		P6	
Date	ppm*	%	ppm	%	ppm	%
09/02/2015	3.5	58.1	3.3	52.0	3.3	54.0
28/04/2015	3.5	62.3	3.4	53.8	3.8	61.0
16/05/2015	3.9	64.4	3.8	58.4	4.6	72.6
30/05/2015	6.0	99.3	4.6	73.6	4.0	69.0
13/06/2015	3.6	63.6	3.4	54.0	3.6	63.6
27/06/2015	9.9	175.0	5.8	98.9	6.2	103.3
10/07/2015	4.9	81.1	4.1	65.1	3.3	53.7
24/07/2015	4.0	64.8	3.8	61.7	4.4	69.0
07/08/2015	4.1	66.1	3.9	62.4	4.0	64.6
21/08/2015	4.0	68.2	3.8	62.0	4.0	76.6
04/09/2015	5.4	81.3	8.5	107.4	7.5	88.3
18/09/2015	2.8	46.2	3.6	54.1	3.1	58.0
02/10/2015	5.2	86.5	4.4	69.1	3.5	55.0
17/10/2015			4.6	79.7	4.5	73.3
23/10/2015	4.2	66.7	4.3	67.5	4.2	67.5
30/10/2015	4.8	89.9	4.1	68.5	4.1	67.3
14/11/2015	7.1	112.9	7.0	111.1	7.4	110.4

***ppm = parts per million**

Table 3: Dissolved Oxygen Data from the ABASA Wells (February to November 2015 Period).

Hardness of the Water in the ABASA Wells		Silica		
Date	Hardness ppm*	Date	# well	Silica pp*
03/11/2015	320	10/11/2015	5	73
04/11/2015	300	11/11/2015	6	74
05/11/2015	296			
06/11/2015	270			
07/11/2015	249			
08/11/2015	270			
09/11/2015	271			
10/11/2015	270			
11/11/2015	257			
12/11/2015	268			
13/11/2015	255			
14/11/2015	244			

***ppm = parts per million**

Table 4: Dissolved Oxygen Data from the ABASA Wells (February to November 2015 Period).

Water Balance

An analysis of the water balances in the Pasabién sub-watershed was performed to determine the origin, distribution and availability of surface-water and groundwater resources in the sub-watershed, with an emphasis on analyzing its relationship to water supply.

In order to define the hydrological-analysis units, five main ecosystems were identified. Their demarcations by elevations are shown in the description below. Based on this, information from the rainfall gauges in these units was collected (Figure 12).

Ecosystem	Meters Above Sea Level (m asl)
Dwarf forest	Above 2,650
Cloud Forest	Between 2,000 and 2,650
San Lorenzo, Santa Rosalía	Between 900 and 2,000
Middle-Lower sub-watershed reaches	Between 900 and 300
Lower sub-watershed reaches	Lower than 300 (this region has very low slopes)

Table 5: Ecosystems in the Pasabién River Sub-Watershed, Defined as Hydrological Analysis Units

Rainfall-distribution patterns with very low and very high precipitation levels generated significant changes in water recharge. Based on this information, it can be stated that 2015 was a year with a very dry rainy season, with rainfall and water recharge well below the historical average (Figure 11).

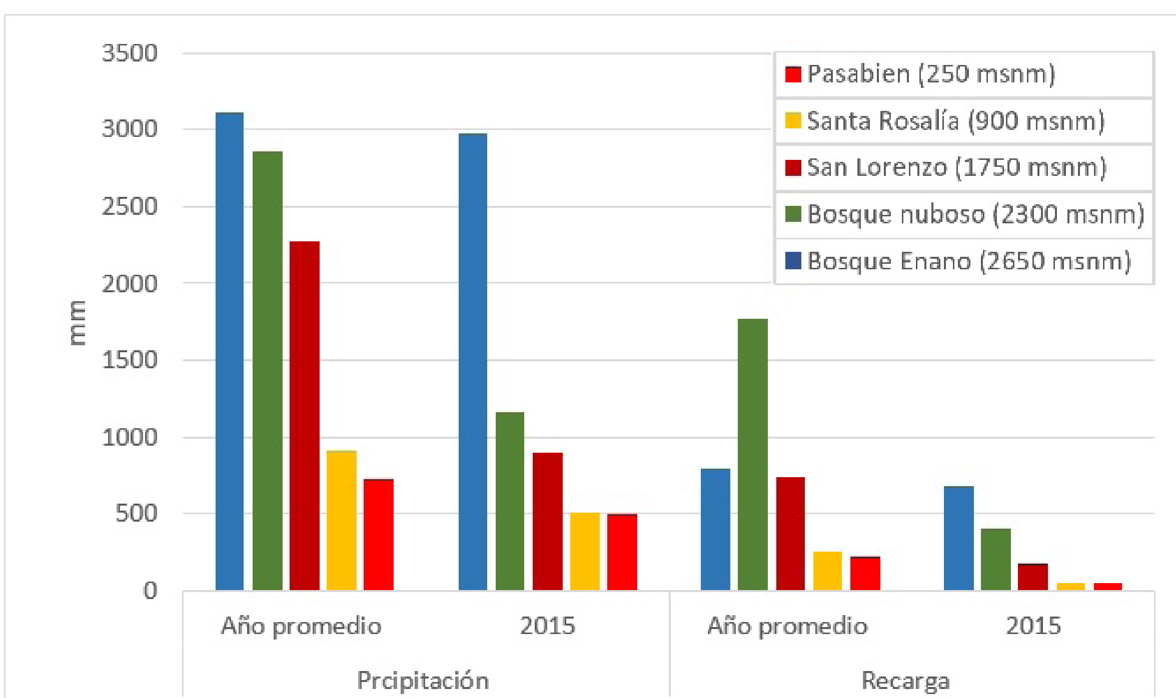


Figure 11: Comparison between precipitation and recharge in historical average years and the year 2015 (very

Figures 13 and 14 show the distribution of historical water recharge and the recharge throughout 2015, respectively. It is important to define this in order to have better elements to analyze temporal distribution of rainfall with greater influence on the water recharge process and aquifer supply.

To establish the historical average year, the month with the highest water recharge is September, followed by October. Cloud forests are the ecosystem with the highest recharge. For the very dry year of 2015, the ecosystem with the highest recharge was the dwarf forest, during the month of November. The dwarf forest is the only ecosystem that does not contrast with the historical average of its water-recharge layers (thickness).

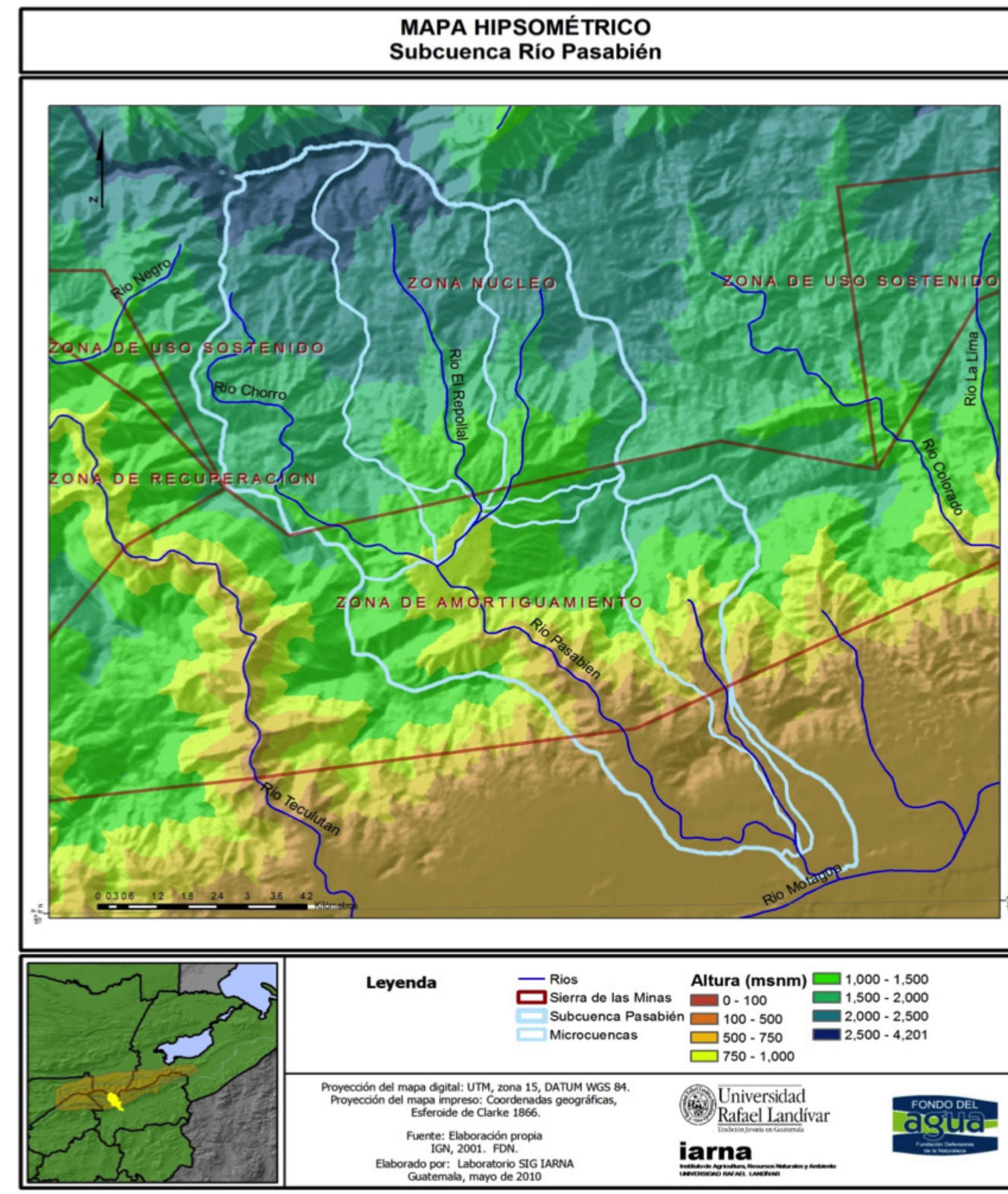


Figure 12: Representative Ecosystems for Analysis

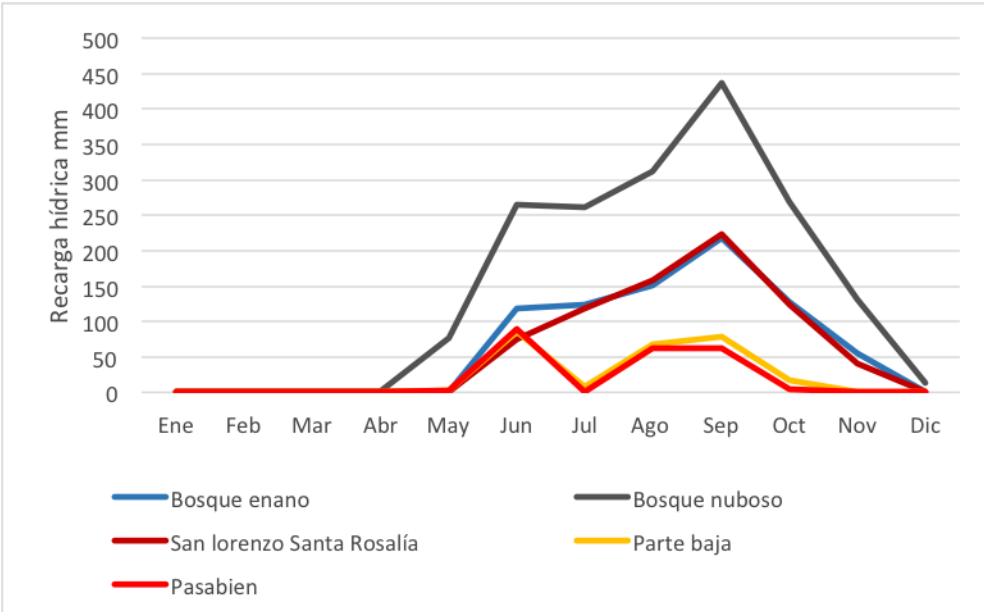


Figure 13: Monthly Water-Recharge Distribution in a Historical Average Year in the Pasabién Sub-Watershed

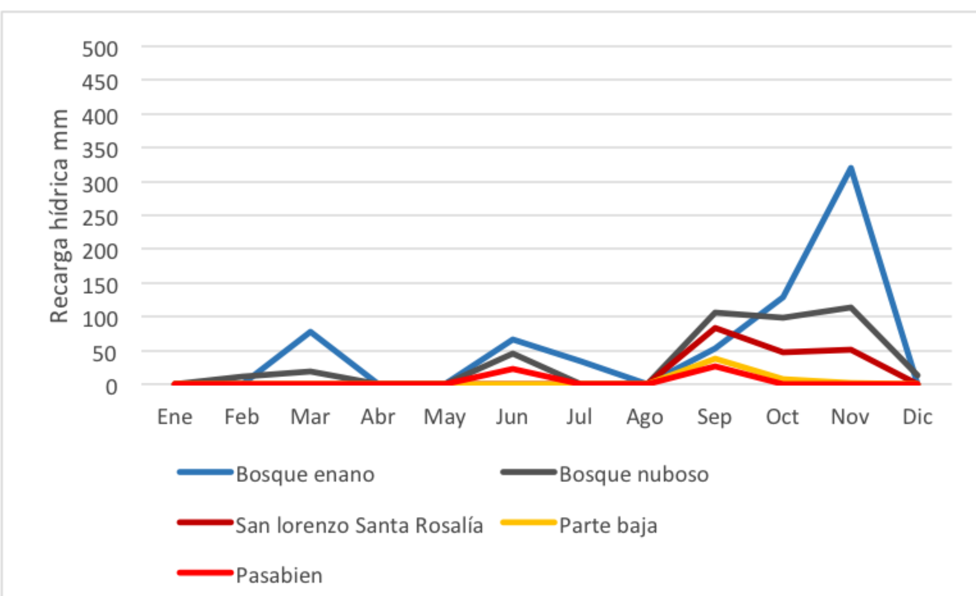


Figure 14: Monthly Water-Recharge Distribution in 2015 in the Pasabién Sub-Watershed

Figure 15 shows the monthly average flow distribution at the gauging point in Santa Rosalía called "La Presa", which is located near the dam with the same name, at 900 m asl. At this site, there are flows that are much lower than expected, with maximum flows of almost 1,300 liters per second (l/s). The accumulated volume during the rainy season is almost 16 million cubic meters (m3). When comparing this value with the estimated water recharge for the ecological regions (Table 6) corresponding to the middle and upper reaches of the sub-watershed, it is evident that there are significant values of deep-water recharge (approximately 10 million m3). This confirms that the middle reaches of the sub-watershed can contribute groundwater to the lower reaches.

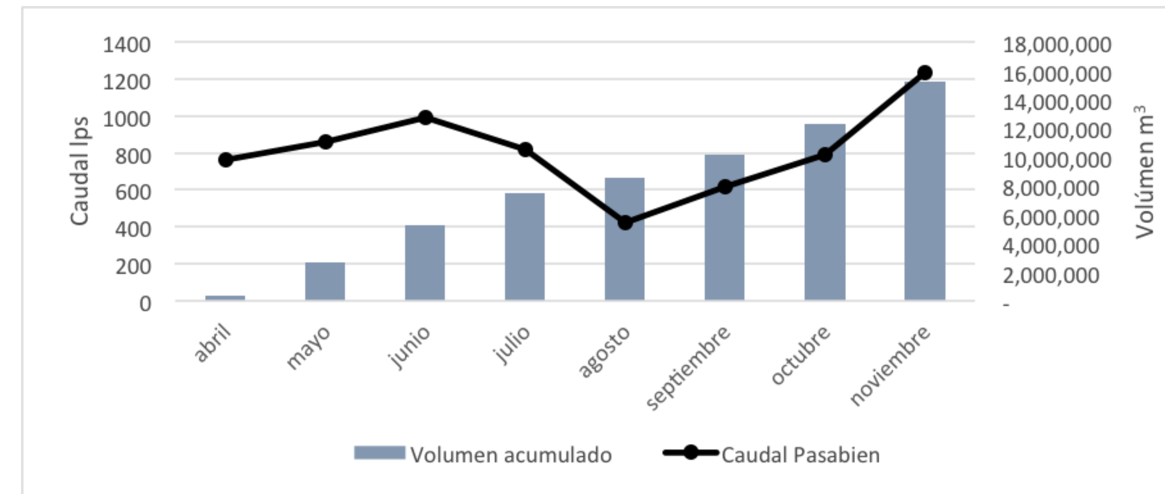


Figure 15: Monthly Average Flow and Accumulated Flow at the Santa Rosalía ("La Presa") Gauging Site, Pasabién Sub-Watershed.

Ecosystem	2015		Precipitation (m^3)	Recharge (m^3)	Surface Flow (m^3)
	Precipitation (mm)	Recharge (mm)			
Dwarf forest	2,971	678	43,078,050	9,837,151	
Cloud forest	1,162	406	34,267,200	11,982,747	
San Lorenzo Santa Rosalía	902	181	17,581,200	3,535,198	
Lower reaches	512	47	12,292,800	1,135,727	
Pasabién	494	49	6,175,000	615,949	
TOTAL			**113,394,250**	**27,106,772**	**Not established**
High and middle reaches of the watershed			**94,926,450**	**25,355,097**	**15,257,525**

Table 6: Precipitation and Layer (mm) and Volume (m3) Recharge in the Various Ecological Regions of the Pasabién Sub-Watershed

Conceptual Model

Integrating the geological, climate, and hydro-chemical information allows the development of a conceptual model for the hydrogeological processes and the origin of the water in the ABASA wells (Figures 16 and 17). The data on stable isotopes, water quality, and soil water balance in a dry year clearly indicate that the water in the aquifer located in the lower reaches of the Pasabién sub-watershed originates from the rain falling in the middle and high reaches of the Pasabién sub-watershed, at 1,750 and 3,000 m asl, during the rainy season.

Figure 17 illustrates the importance of the hydrostatic gradient to maintain the water quality in the ABASA wells. That is, that water recharge occurring in the middle reaches of the Pasabién and Teculután sub-watersheds is accountable for the quantitative supply and the water quality in the aquifers located in the lower reaches of the sub-watersheds that drain from the Sierra de las Minas, especially in those sites where there are marble outcrops.

With these analyses, a conceptual profile of the hydrogeology and the origin of the wells located in the lower reaches of the Pasabién sub-watershed was developed. It is most probable that there is an underground supply from the high-recharge San Lorenzo and Santa Rosalía regions, where there are marble and limestone formations, to the lower reaches of the sub-watershed.

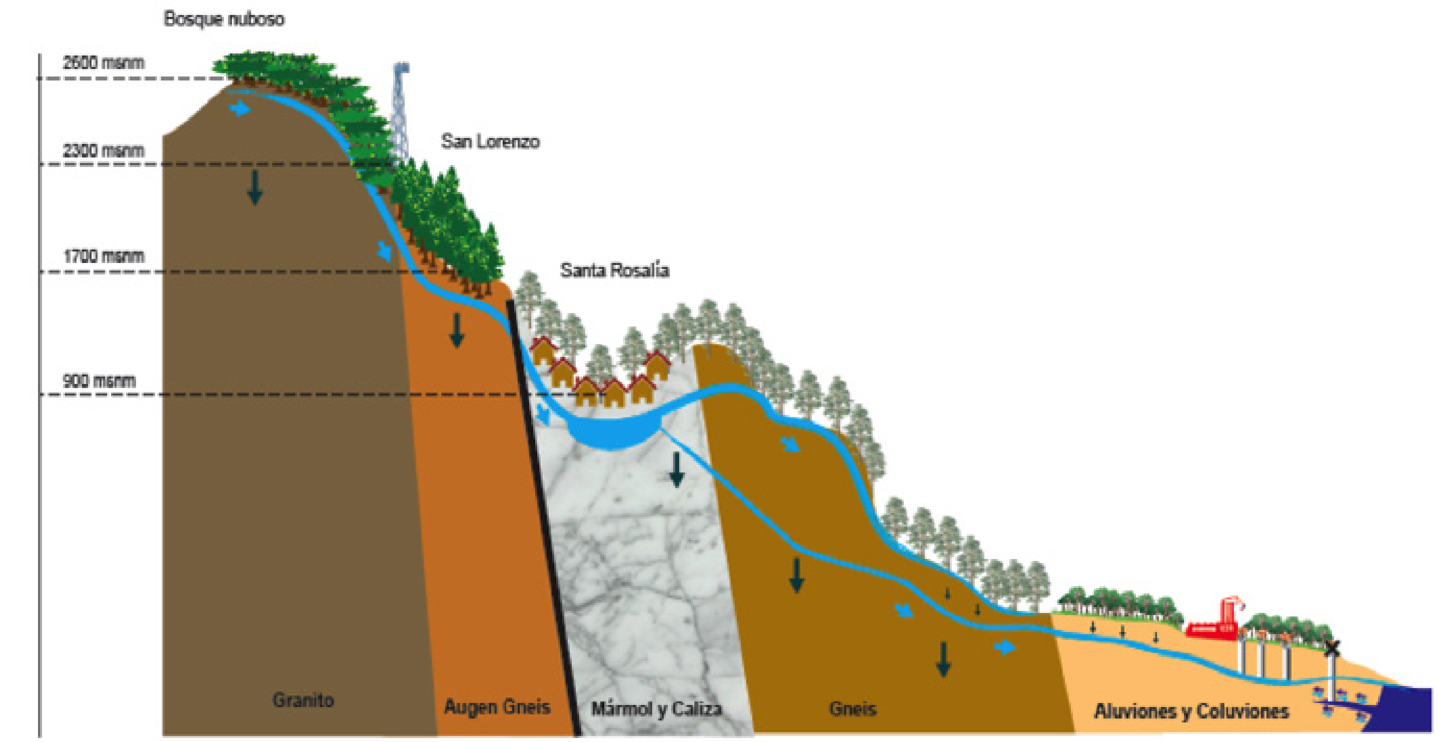


Figure 16: Conceptual model profile of the hydrogeology and the origins of the water in wells located in the lower reaches of the Pasabién sub-watershed.

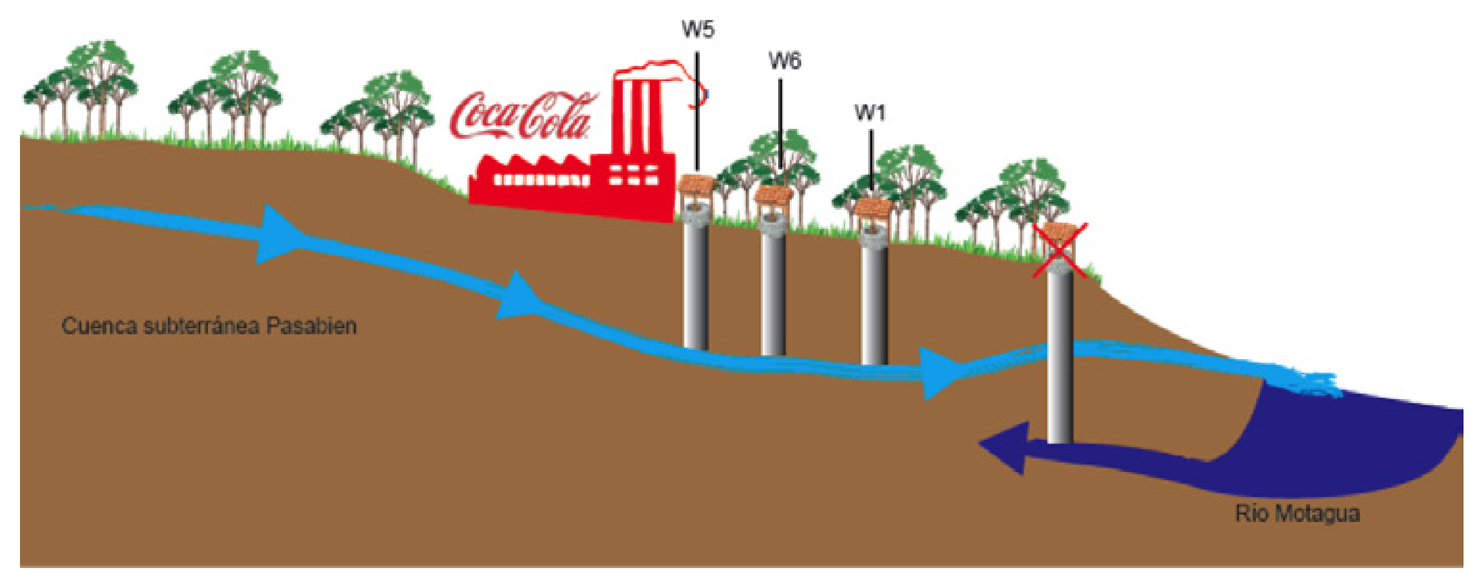
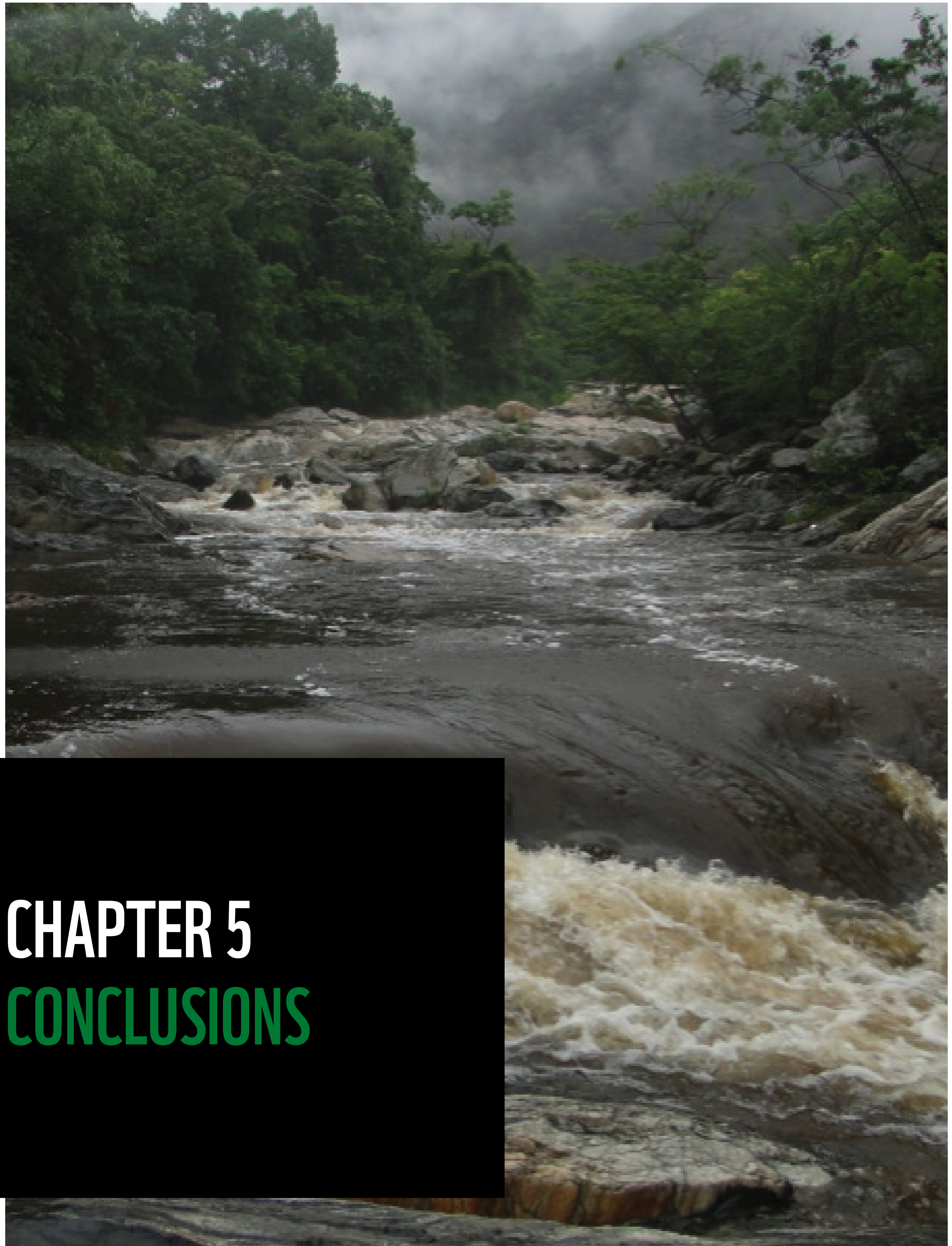


Figure 17: Hydrogeological conceptual model of the lower reaches of the Pasabién sub-watershed (according to isotope and water quality sampling in the February-November 2015 period).



CHAPTER 5
CONCLUSIONS

Through the contextual geological information, it was possible to establish that nearly 90% of the study area has limited capacity to form significant deep aquifers, due to the prevalence of plutonic or metamorphic rocks with low permeability, such as granite, gneiss, and augen gneiss.

However, there are two strata suitable for deep water recharge and subsequent aquifer formation due to the highly fractured and permeable characteristics of the geological material composing them. These strata are the Quaternary alluvium and marble outcrops. These strata are located throughout the lower reaches (towns of Pasabién and Teculután) and the middle reaches (towns of Santa Rosalía and San Lorenzo).

It was possible to distinguish a hydrogeological region that extends beyond the Pasabién sub-watershed, comprising parts of the Teculután and Río Hondo sub-watersheds. It contains very high geological fracturing and the presence of a strip of marble outcrops.

Through the historical climate information, it was possible to define a high inter-annual variability in precipitation along the altitudinal gradient, from the lower to the upper reaches of the Pasabién sub-watershed. In addition, a highly contrasting altitudinal gradient related to annual rainfall averages was found, which is a characteristic of the leeward zones in the lower reaches (250 m asl), with an average rainfall of 750 mm and in the cloud forest (from 2,200 to 3,000 m asl) with about 3,000 mm.

The above, complemented with the historical hydrological information (1994-2015 period) of the Teculután river (Las Minas gauging station), allowed defining the 2015 sampling year as a climatically and hydrologically dry year.

The previously-mentioned data have proven to be biophysical attributes that have significantly contributed to contextualize, analyze, and determine the meteorological origin of the groundwater in the ABASA wells.

Following is a description of the findings stemming from an intensive sampling of rainwater and surface runoff (high, middle, and low reaches), and groundwater (lower reaches 250 m asl) and determining isotopic loads in the water, specifically ^{2}H (Deuterium) and ^{18}O:

a) The three types of precipitations affecting the study area are: orographic rainfall (heavy rains), which are prevalent in the cold and dry season; that is, from November to May; convectional rainfall (light and mixed rains), which are typical of the rainy season (passage of the intertropical convergence zone), from May to November, and cyclonic rainfall (light), occurring also during the rainy season (October).

b) Connection between the base flow (groundwater) from the middle reaches of the sub-watershed (surface runoff) and groundwater from the ABASA wells (lower reaches).

c) A high isotopic relationship was established, by means of arithmetic averages (Figure 9), between the rainfall of the cloud forest (2,300 m asl) and the dwarf forest (2,600 m asl) with the groundwater from the ABASA wells. This establishes the meteorological origin of the water from the ABASA wells and the corresponding aquifer.

d) Evidence of the isotopic charge values in the water from the ABASA wells. This shows that water transfer takes more than one year from the time of the precipitation in the upper reaches of the sub-watershed. In addition, the water recharge from rainfall in the lower reaches (Motagua River valley) and from the inflow of water from the same river is proportionally low.

Water sampling and the water-quality study have yielded the following findings:

a) The water from the ABASA wells is high-quality water, according to dissolved oxygen values. This confirms the findings discussed above: low contamination from the Motagua River watercourse (which evidently contains highly-contaminated and non-potable water). However, villagers and farmers have reported contaminated wells near ABASA's facilities, generally located near highly-populated sites or near the Motagua River.

b) It was established that the hardness values of the water from ABASA's wells are relatively high (index greater than 200). In addition, silica was detected (greater than 70 ppm). This suggests high water residence times in sites with limestone or marble rocks. The water contact with these materials may occur at considerable depths in the Motagua valley or in the middle reaches of the Pasabién sub-watershed. There is marble formation between the towns of Santa Rosalía and San Lorenzo.

The findings from the soil water balances performed in the different ecological regions of the Pasabién sub-watershed are as follows:

a) The ecosystem with the greatest contribution from water recharge sheets in a historical average year is the cloud forest (between 2,000 and 2,600 m asl), with an estimated 1,765 mm.

b) Even in dry years (such as 2015) there are significant water recharge values, such as in the dwarf forest (above 2,650 m asl), especially in November 2015. This ecosystem was the only one of those evaluated that did not significantly change the total amount of annual rainfall layers during the rainy season.

c) According to the hydrogeological characteristics, the ecological region with the highest probability of presenting high values of deep-water recharge is located in the middle reaches, particularly in the region of sedimentary, marble, and limestone rocks. This region is known for its rocks with high infiltration values and a considerable number of faults and fractures. This was confirmed when soil water balances were performed. For 2015 (a very dry year), a deep recharge of 10 million cubic meters per year was estimated. This is an important feature to promote a high degree of water residence times and an annual water-flow regulation through formation of hanging and free aquifers, which release groundwater very slowly. An important feature is that it increases the likelihood of relatively stable groundwater and surface water flows during the dry season. In addition, a hydrostatic pressure gradient is established to prevent well contamination in the lower stretches of the Pasabién sub-watershed, especially the ABASA company's wells.

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