# Ecohydrology of paramos in Colombia:
## Vulnerability to climate change and land use

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## Vulnerability to climate change and land use

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# Abstract

High mountain ecosystems provide many environmental goods and services, particularly hydrological services. Besides the anthropic hazards to these ecosystems, climate change is expected to generate a decrease in runoff in Andean region, including paramos. However, there are not enough information about the hydrological functioning of paramo ecosystems and their vulnerability, to make decisions. This work aims to assess the vulnerability and ecohydrological resilience of Colombian paramo ecosystems to climate change, considering the land uses they have. To do this, we study three paramos: Belmira and Romerales in central and Chingaza in eastern Andes cordillera, we measured several hydro-climatic, vegetation and soil variables during at least two years, and we calibrate the WaSim hydrological model for specific basins in these ecosystems. We used the hydrological model to project the hydrological responses of studied basins with the expected climate changes in Colombian high mountain, in the medium term. Results show that eco-hydrological vulnerability to climate change of paramo of Chingaza is very low and Belmira has a low vulnerability; while the projected changes in Romerales are critical, indicating a very high vulnerability to climate change. The most altered paramos by anthropic activities evidence the loss of some of their hydrological characteristics, which make them more vulnerable to climate change, however, after these ecosystems have been impacted by changes in land use, it is possible to recover most of the properties and hydrological functioning of a natural ecosystem through a conservation or restoration program.

**Key words:** climate change, ecohydrology, paramo ecosystems, tropical high mountain, vulnerability to climate change

# Content

# Figures list

**Page**

# Tables list

**Page**

# Introduction

Paramos are ecosystems distributed like islands in the highest parts of tropical Andes, in areas too cold for the development of forests (Hofstede et al. 2003). This ecosystems are recognized by their physical-biotic characteristics that make them permanent source of water; but also by their capacity to store atmospheric carbon trough accumulation of organic matter in the soils and vegetation (Hofstede et al. 2003). On the other hand, their localization and distribution in small patches, the anthropic pressure reducing their areas, and the invasion of plant species from neighborhood ecosystems (Morales et al. 2007), suggest that these ecosystems are very vulnerable; however, the magnitude of risks and vulnerability of these ecosystems to climate and land use changes, is still unknown (IDEAM 2011).

Vulnerability is a central concept to ecosystems research, especially everything related to climate change (Füssel 2005). IPCC describes vulnerability as the propensity or predisposition to be adversely affected". Thus, vulnerability encompasses a variety of concepts and elements including sensitivity or susceptibility to harm and lack of capacity to cope and adapt" (IPCC 2013). In the incorporated terms by IPCC_AR5 (2014), it is found a mixture of biophysical characteristics of the ecosystems and the goods and the environmental services, with social economic elements and infrastructure, among others, being these previous the ones which have been considered in most of the vulnerability studies developed so far (Cárdenas & Tobón 2016). The term adaptability refers to changes in behavior and characteristics of a system that enhance their capacity of face external tensions (Brooks 2003), or the process of adjustment to actual or expected climate and its effects (IPCC 2013).

The main threats to paramo ecosystems are of two kinds: one of global and regional character, related to changes in climate, and the second threat comes from human activity, specifically, land use changes, as crop establishment, introduction of cattle and mining, which are affecting these ecosystems, due to the increase of the agricultural frontier; a trend which is observed in most of the Andean highlands (Hofstede et al. 2003). Although there is uncertainties on how climate change will affect paramo ecosystems, some studies show that the effect may be evident not only in reductions in their area, but also in changes in their hydrological regime (Castaño 2002, cited by Hofstede et al. 2003).

According to IPCC (2001), climate is the result of interaction of components of global climatic system: atmosphere, oceans, terrestrial surface, cryosphere and biosphere, inside which is considered the human activity. However, many of the relationships between these components are not fully understood and most recently we face a new uncertainty, which is climate change.

Climate change can be identified by changes in the mean and/or the variability of climate properties, which persists for extended periods, typically decades or longer. Climate change may be due to natural internal processes, external forcing, or to persistent anthropogenic changes in the composition of the atmosphere or in land use (Agard & Schipper 2014). At global level, this changes in climate might lead to long term and potentially extensive changes in the hydrological cycle, with significant impacts on society and environment (Davies & Simonovic 2005). At ecosystem level, like paramos, the changes occur at more detailed space-time scales, through extreme events that are repeated, even though chaotically (Buytaert et al. 2010).

Evidences of climate change in Colombia indicate that average temperatures are rising at a rate of 0.13 ° C per decade, while total annual rainfall has decrease at some altitudes and increase in others (Ruiz 2010). Meanwhile, extreme precipitation events associated with downpours are increasing in most of the country (Ruiz 2012) and the number of days with temperatures equal or below to 0°C above 2500 masl are declining (Pabón 2012). According to Ruiz (2012), the more likely climate change scenario in Colombia, is a sustained increase in the average temperature throughout the territory, with more significant increases in most of the Caribbean and Andean regions.

In the highlands of Colombia, the rising temperatures associated with climate change have been related with the anthropic pressure for productive activities on undisturbed natural ecosystems of high eco-hydrological value, but greatly fragil (Morales et al. 2007). In general, it’s expected that these changes in land use will generate destruction of natural vegetation, soil erosion and affect soil properties, such as decrease in moisture retention capacity and quality of surface and percolation water, the increase in the weathering of organic matter and losses of nutrients (Morales et al. 2007).

Paramos are very important within Andean region, since they provide the water and hydropower generation for most of the population located in the Colombian Andes, as well in urban or rural areas. Until now few studies, if any, have focused on the evaluation of vulnerability to climate change, of specific ecosystems like paramos, based on biophysical criteria; therefore, this study aims to evaluate a number of biophysical factors that affect the vulnerability of ecosystems, specifically on the paramos in Colombia, and determine how these ecosystems respond to stress and disturbances, in terms of their eco-hydrological functioning, water yield and regulation. Such determination does not imply deny the close and complex relationship between natural and social systems (Folke et al. 2002), but this work focus on the characterization of the main biophysical variables affecting the paramo ecosystems, influencing their vulnerability and the services they provide, as a mechanism to generate solid bases to support the future decisions related to the conservation and management of these ecosystems.

Accordingly, we conducted a comprehensive study of biophysical variables in three paramos in Colombia, with different climatic and environmental conditions (Table I-1), to understand the eco-hydrological functioning and to assess the eco-hydrological effects caused by changes in land use, separately from those of climate change, considering a wide range of biophysical factors.

Table I-6-1. Climatic and environmental conditions of studied paramos

| | Belmira | Chingaza [c] | Romerales [d] |
|---|---|---|---|
| Altitude (m) | 2500 – 3250 [a] | 2500 – 3400 | 2800 - 4200 |
| Avg. T (°C) | 8 [a] | 6 | 6 |
| Avg. P (mm) | 1850 [a] | 3500 | 1200 |
| Land cover | Frailejones and grasses, with patches of high stubbles [b] | Grasslands in the drier slopes, while in the wet predominate chusque and frailejones. The species that form cushions are typical in swamps or in places with high soil moisture | In the higher parts there are sandbanks and wetlands. The middle slope is dominated by grasslands and frailejones, in some parts with bushes. In the lower part there are stubbles and logged forests |
| Soils | Derived from igneous and metamorphic rocks, and granitic plutonic, partially covered by weathered volcanic ashes. Entissols and Inceptisols and few patches of Andisols [e] | Developed from Glacier movements (Lahars), shales and sandstones, with high SOM, without volcanic ashes. Main soils classes are: Entisols, Inceptisols and Histosols [f] | Developed from moderately to weathered volcanic materials, with pyroclastic and basaltic material and abundant ashes deposited throughout the time. Main soils classes are Andisols, Inceptisols and few Histosols [e] |

Sources: (a) Vélez et al. (1990), (b) Corantioquia (1999), (c) CAR (2001), (d) Salento (2000), (e) IGAC (1995), (f) Vargas y Pedraza (2003)

This work meets the general objective of this research, "Assess the eco-hydrological vulnerability and resilience of paramo ecosystems in Colombia to climate change, considering the different land uses they have", aimed at answering the research questions proposed: i) what is the vulnerability of paramo ecosystems in Colombia to climate change and what is their resilience to such changes, based on different land uses and management?, ii) what are the most vulnerable eco-hydrological functions or processes of paramos to anthropic disturbances and stress factors related to climate change?, iii) what are the control variables in the assessment of eco-hydrological vulnerability of paramos to climate change, with different conditions of land use in Colombia?

Accordingly, this thesis is composed by six chapters: chapters one to five are self-contents, i.e., each of them develops specific topics related to research questions, with methodologies, results, conclusions and bibliographic references. The first chapter explores the concept of vulnerability to climate change and proposes the conceptual model and biophysical variables to consider when evaluating the vulnerability of paramo in Colombia to climate change, as it was developed in this research. The second focuses on the horizontal precipitation measured in the study sites, their spatial and temporal distribution and its contribution to total water inputs to the ecosystems. The third chapter presents some important physiological characteristics of frailejones (*Espeletia spp*.), which are the tallest and more conspicuous plant species in the Colombian paramos. This specific research was developed in order to quantify the water outputs, due to transpiration of vegetation, in the water balance of studied ecosystems. The fourth chapter discusses the vulnerability of paramo soils, to changes in rainfall patterns, as one of the most likely effects in the country, according to the regional climate change projections. The fifth chapter analyzes the hydro-climatic variables measured in the three paramos during two years, comparing the current environmental and hydrological conditions in the three ecosystems and their eco-hydrological functioning. We also used climatic projections made for the high mountain in Colombia, based on multi-member Atmospheric and Atmosphere-Ocean Coupled General Circulation Models, to project the hydrological responses of paramos in future climate change scenarios (IPCC_AR5 2014), using a hydrological modelling approach. Finally, the sixth chapter summarizes the central part of this study, which is, the analyzes and discussion of main findings of the reserach, to answer the scientific questions regarding the eco-hydrological vulnerability of paramo ecosystems in Colombia, under land use and climate change scenarios.

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# 1. Assessing the biophysical vulnerability of ecosystem services to climate change: a conceptual and methodological approach[1]

## Abstract

The vulnerability to climate change has been considered and assessed from different perspectives, and depending on the objective of the study or the author, there are a number of definitions and approaches, without consensus about the best indicators to assess it. In recent decades, most of the studies related to climate change, have focused on the determination of the impacts of climate change and the assessment of vulnerability of a population to hazards, which is the socio-economic vulnerability. This paper discusses the importance of evaluating the intrinsic vulnerability of ecosystems and the services they provide, based on biophysical aspects, as the fundamental basis to assess the vulnerability of the populations that depend on these ecosystem services. Therefore, we propose a conceptual model and a methodology for assessing the biophysical vulnerability of a given ecosystem, to climate change. We also present, as an example, a case of study, where we define the variables or indicators to be considered to assess the intrinsic vulnerability of ecosystems, in this case, the hydrological vulnerability of tropical high mountain ecosystems to climate change.

Keywords: biophysical variables, climate change; paramo, tropical ecosystems, vulnerability

## 1.1 Introduction

The concept of vulnerability is widely used and mostly applied to vulnerability of population to hazards (Füssel 2010). Currently it is closely related to climate change studies, since scientists, international organisms and state institutions have tried to determine the vulnerability of their territories and populations, with the aim of create adaptability actions and policies before the possible transformations or negative changes

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take place, especially with the global climate change (Arribas et al. 2012; Beniston et al. 2011).

Nevertheless, there is no clarity about the concept of vulnerability, nor about the terms associated and the methods to assess it. Although most of the authors refer to the definitions given by the IPPC (IPCC_AR5 2014; IPCC 2001; IPCC 2002), these are so general that it may be widely interpreted or developed. As a result, there are many conceptual differences and different approaches to face the problem and several vulnerability indicators used, but none of them have been widely accepted (Brook 2003; Füssel 2005; Füssel 2010; Klein 2004).

The term vulnerability has traditionally been used in territorial studies, mainly referred to social-economic aspects, infrastructure, community and institutional organization, which combined with the natural hazards of the population territory, represent the risk. Despite the fifth report of the Working Group II (IPCC_AR5 2014) gives a new definition of vulnerability; this concept is still associated to sensibility, susceptibility and capacity of adaptation; but it also includes concepts such as hazard, impact and risk, which formerly were not considered within this kind of evaluations. In incorporated terms in the IPCC_AR5 (2014) are also biophysical characteristics of the ecosystems, goods and environmental services, mixed with social-economic elements and infrastructure, among others, being these last, the more common, in most of the vulnerability studies developed so far. That is to say, the term of vulnerability has been applied to determine the state of risk or the hazard to a population before the effects of the climate change. Nevertheless, the intrinsic vulnerability of these ecosystems, has been partially investigated, in spite of the evidence of the impacts of the climate change on the natural disasters (IPCC_AR5 2014). Particularly, the IPCC AR5 collected and quantified the effects of the climate change on resources such as water (Jimenez et al. 2014), the terrestrial ecosystems (Settele et al.2014), and other ecosystems and natural resources (Oppenheimer et al. 2014), but it does it in terms of impacts and its projections, more than vulnerability per se. Another approach from the biophysical perspective is the evaluation of the vulnerability of species of flora and fauna, according to the index proposed by NatureServe, as an answer of researchers to assess vulnerability, facing the growing requests of information by the decisions makers (Young et al. 2015). This index considers elements of exposition and sensibility of the studied species, based on their characteristics, as a support to understand how the climate change may influence the biodiversity of a particular region (Pacifici et. al 2015).

However, it persists a gap in the identification and characterization of biophysical factors determining the vulnerability to climate change of a given ecosystem and its functioning, differentiating the biophysical from the social-economic vulnerability (Hassan et al. 2005), to the extent that the economy and the human welfare are dependent on the maintenance of the integrity and the resilience of the ecosystems (Gómez-Baggethun & De Groot 2007). In this sense, it is fundamental to know the characteristics and natural traits to ecosystems supporting the functioning and social development, to establish the threshold at which ecosystems support impacts (resilience), before they suffer important and irreversible loss of the goods and services they provide.

From the above, it is clear that conceptual differences exist in the focal points of vulnerability assessment of ecosystems to climate change and on the methodological gaps to evaluate it, despite there is a wide theoretical frame about the topic. In this context, if is intended to assess vulnerability to climate change of a particular ecosystem, it is necessary to set out a specific methodology or an indicator that takes it into consideration, understanding that a climate vulnerability index generally comes from the combination of a number of indicators that represent the vulnerability (IPCC_AR5 2014).

In consequence, this document presents a theoretical approach in which, throughout a serial of biophysical variables, we evaluate the intrinsic vulnerability of ecosystems according to their specific conditions, using a study case in which it is evaluated the vulnerability to climate change of the hydrological functions of the paramos in Colombia, associated to ecosystem services, such as water regulation and water yield (Millennium Ecosystem Assessment 2005).

## 1.2 Methodology

With the aim of assessing the intrinsic vulnerability of the ecosystems, three steps were followed:

- Review of the conceptual frame about vulnerability to climate change and the indicators used in related studies.
- Formulation of a concept for the assessment of vulnerability, focus on the specific biophysical variables of a given ecosystem, and stablishing the differences between the intrinsic vulnerability of the ecosystem (biophysical), from the effects that, impacts

caused by climate change to the ecosystem, may have over the population (socioeconomic).

- Proposal of a methodological route and the biophysical variables to consider in a conceptual model to assess the hydrological vulnerability of ecosystems.

Accordingly, and in order to assess the intrinsic vulnerability of ecosystems to climate change, we set the conceptual framework for vulnerability and the associated terms, stablishing the differences between them. Consequently, the different concepts used to define and evaluate vulnerability were considered, mainly those related to climate change and ecosystem vulnerability. From this assessment, a broad concept of vulnerability is proposed, separating the purely socio-economic approach from those based on biophysical aspects. Further it is defined the main parameters or biophysical variables, from which one can determine the intrinsic vulnerability of ecosystems, specifically the hydrological vulnerability of ecosystems to climate change.

Finally, we propose a conceptual model to assess the hydrological vulnerability of ecosystems to climate change, including the control variables or parameters. This model is being applied to evaluate the vulnerability of paramo ecosystems in Colombia, as an approach for validation of the method proposed here.

## 1.3 Results and discussion

### 1.3.1 The concept of vulnerability: several meanings

The vulnerability refers to the possibility of a system to suffer damages due to the exposition to a hazard, which is associated to the reduction of the system capability to preserve its structure and its functioning (Gallopín 2006). For this reason, it is necessary to determine if a certain change of the ecosystem is behavioral or structural, which require to study the system and its functioning under natural conditions and under the effects of certain natural or inducted phenomenon, and its resilience.

The term vulnerability has been traditionally used in hazards and risks studies or in environmental impact studies, where the threat represents the probability that a natural or anthropic disastrous event occurs, during certain period of time, in a determined site; while vulnerability is understood like the susceptibility of a physic environment of a territory or system to the action of hazards (Ingeominas 1998). In other words, the vulnerability is an internal risk factor of the system exposed to the hazard and it corresponds to its intrinsic disposition to be damaged (Paniagua 1995). The risk is the product from the previous two, i.e., the risk represents the consequences of the combination between a certain level of hazard and a level of vulnerability of the threatened system (Ayala-Caicedo, 1993, cited by Mardones and Vidal 2001).

In this sense, it is recognized that vulnerability is intrinsic to the state of the physic environment or to the system, associated to its resilience, and not an assessment of the effects caused by the phenomenon or hazard. While in the first case does not exist an agreement about the variables determining vulnerability, it is widely known that the effects that may cause a disaster vary according to the nature of the phenomenon, specifically its intensity and duration, but also on the specific characteristics of population or exposed systems (Cardona 1993). In this case the risk assessment is in function of:

$$Rt = (E.Rs) = (E.H.V) \qquad 1.$$

Where Rt is the total risk, E represents the elements under specific risk (Rs), H is the hazard level and V the vulnerability (Cardona 1993).

In this context, the fundamental difference between hazard and risk is that the hazard is related to the probability of appearance of a natural or induced event, while the risk is related to the probability of appearance of certain negative consequences or effects from the event, which are related not only to the exposition level of the system, but also to the vulnerability of the system to be affected by the event (Fournier, 1985). For this reason, the concept of vulnerability becomes in a basic element for the evaluation and prevention of risks.

A particular case of hazards and risks, widely known and accepted, is related to the global changes that may affect the stability of human and natural systems. These changes are specifically related to the increasing greenhouse gases that are altering the temperature, precipitation and other climatic variables. Some authors suggest to classify the climate change related hazards on three main categories: i) recurrent and discreet hazards such as storms or extreme droughts; ii) continuous hazards such as increasing of temperature or reduction of the precipitations that may take place during decades (Brooks et al 2005), iii) discreet singular hazards such as changes in climate cycles associated with alterations of the oceanic circulation (Roberts 1998; Cullen et al., 2000, cited by Brooks 2003).

Climate change has a trigger effect on the natural or biophysical environment, whose alterations affect human population. In other words, the human beings are affected by the hazards related to climate change, according to the magnitude and speed of the change, as long as it modifies the conditions or the natural functioning of the ecosystems and the services they provide (IPCC 1997).

Consequently, vulnerability is a function of the impacts caused to the system and its capability of response, which, in turns, depends on the exposition level and its sensibility (Figure 1-1). Nevertheless, the fact that a system vulnerability depends on the exposition is to say that a system not exposed to disturbances must define as a non-vulnerable, which might be an error (Gallopín, 2006).

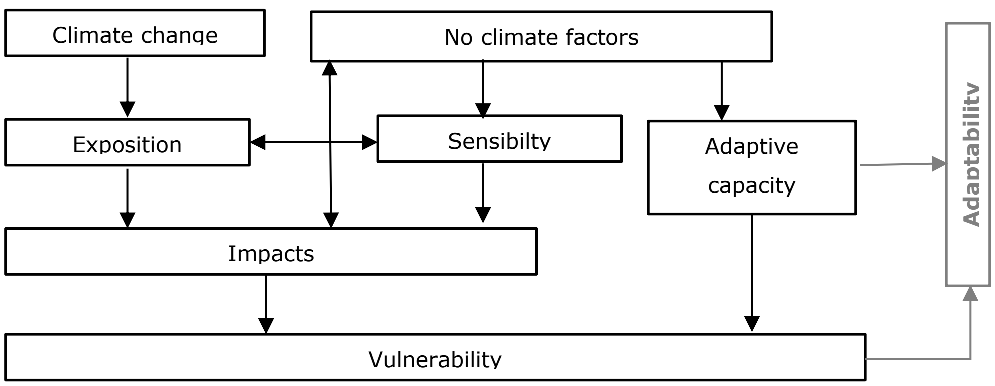


Figure 1-1. Elements defining the vulnerability of a system.
Adapted from Füssel (2010)

According to Brooks (2003), definitions of vulnerability to climate change, tends to fall into two main categories (figure 1-2): one of them considers vulnerability in terms of the potential damage that some event or hazard, related to climate scenarios, may cause to a system. In this case, the analysis are focused to studies of biophysics impact and the identification of adaptation options (Agard & Schipper 2014), and the second, considers vulnerability as an inherent state of a system that exists even before facing any event of hazard (Pelling 2003). According to the definition of IPCC_AR5 (2014), this form of vulnerability refers to the incapacity of dealing with pressures or external changes such as climate change conditions, and they recognize that contextual vulnerability is a characteristic of social and ecological systems, generated by multiple factors and processes (O'Brian et al. 2007).

Besides the diversity of meanings related to the concept of vulnerability, the literature has a variety of associated terms such as resilience, sensibility, stress, exposition, impact, capability of adaptation and capability of response (Füssel & Klein 2006; Füssel 2007; Swanston et al. 2011; Tremblay & Anderson 2008; Venevsky 2006; Brooks 2003; Füssel 2005; Gallopín 2006; IPCC 1997; IPCC 2001). Despite there is a sort of consensus about the definitions of these terms, the acceptance of each vulnerability assessment, like the way it is incorporated, measured or evaluated, is still a subjective issue, and depends on the author and the study type.

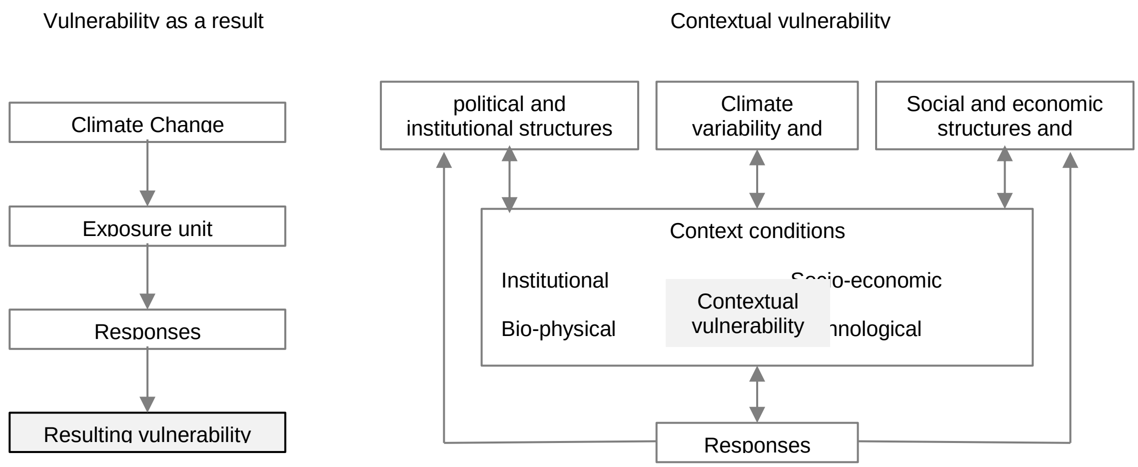


Figure 1-2. Representation of the two interpretations of vulnerability to climate change: (a) vulnerability as a result and (b) the contextual vulnerability.
Adapted from O'Brien, et al (2007).

According to IPCC (2001) the sensibility refers to the grade in which a system is affected, whether it is an adverse or benefic way, by climate. Gallopín (2006) states that sensibility is an inherent property of the system, different from its capability of response, therefore, it is an attribute of the system that exists previous to the perturbation and independent from the exposition. The resilience was originally formulated as the system ability to maintain its structure and behavior patterns in presence of external factors, generally stressful (Hollin 1973). In other words, the resilience is the capability that a social, economic or environmental system has to absorb the perturbations, responding and reorganizing while it is subjected to a change, maintaining the same functions, structure, identity and feedbacks (Walker et al. 2004; Agard & Schipper 2014).

In the vulnerability assessment should be clarify also the origin of the hazard that generates the perturbations or alterations to the system, specifically when is referred to stress or to perturbation: The stress is a continuous pressure that slowly increases within the range of the variable and frequently it is generated inside the system. The perturbations are the highest peaks in the pressure beyond the normal range of vulnerability of the system, which usually are external to the system (Gallopín 2006).

In turn, exposition referred to the nature and degree in which a system experiments environmental or social-political stress, considering the magnitude, frequency, duration and the spatial extent of the hazard (Burton et al. 1993), meaning that is considered in this work, despite of the most recent definition given by IPCC_AR5 (2014), indicating that exposition refers to anything, or specific conditions that may be negatively affected. In the same way, the adaptation is defined by IPCC (2014) as the process of accommodation to the current or expected climate and its effects. In accordance to the work group II, in human systems the adaptation has the target of mitigate or avoid the damage or take advantage of its possible benefits, whereas in some natural systems human intervention may help to adjust them to the expected climate and its effects (IPCC_AR5 2014). It is clear that this is a process that requires time, therefore, a high adaptive capability only reduces the vulnerability of the system to hazards that may occur in the future or to hazards with slow changes during relatively long periods, so the system may adapt itself (Brooks 2003).

Indeed, there are many variables for vulnerability assessment, including the consideration of natural or biophysical and anthropic factors (social-economic, institutional, politics, infrastructure, and others), that change according to the reach, the goals, the available information, the study scale, the author, etc. However, it makes no sense to talk about vulnerability and adaptation capability of a system without specifying the risk to which is vulnerable or to which must adapt to, since it is possible that a system has the adaption capability to some hazards, but not to others. Therefore, several authors have concluded that the term “vulnerability” must be used only regarding to specific situation in particular, i.e., vulnerability must be assessed facing a hazard or a range of determined hazards, and making the distinction between the current and the future vulnerability (Brooks 2003; Füssel 2005).

### 1.3.2 Biophysical and social-economic vulnerability: a relevant differentiation

Several authors agree that control factors of vulnerability may be separated in social-economic and biophysical, and these, in turn, in factors related to internal or external factors of the system. As it has been indicated, despite the complete work of IPCC, collecting and presenting evidences of global climate change, its causes and projections (IPCC 2013), as well as the impacts generated over different biophysical elements due of these changes (Jiménez et al. 2014; Oppenheimer et al. 2014), these are not assessment of vulnerability of the systems, according to definitions given by the IPCC, since they are made in term of impacts and projections, whereas vulnerability is evaluated from a social-economic predominant perspective after the sensibility component is included.

Hence, the use of indicators of social-economic origin conduces to a study of the impact of the phenomenon, instead of a vulnerability assessment of ecosystems, which does not allow to take decisions to reduce the risk or correcting the problem, from the system (ecosystem) but from the consequences, although it is recognized that the impact studies may help to identify relevant indicators and to determine some thresholds of vulnerability. Examples of the previous idea are the indicators for the hydric resources of the chapter 3 of IPCC_AR 5 (Jiménez et al. 2014), that evaluate, at global scale, the reduction of the renewable and underground hydric resources, the exposition to floods, changes in water demand for irrigation, changes in the regime of the rivers flow from permanent to intermittent or vice versa and water scarcity. In accordance with Brooks (2003), it is possible to differentiate between one and another approximation, based on the differences between social vulnerability, which can be placed within the risk management frame.

A more comprehensive approach to vulnerability assessment, was made by the USA Forest Service, whom with the purpose to differentiate the biophysical elements from the social-economic studies of vulnerability, denominated the “natural” factor as the sensibility of the system and the anthropogenic factors as risks, so from the combination of both groups of indicators they obtained a measure of the total sensibility, from the system as well from the potentially affected populations (Furniss et al. 2013). In this exercise they made a differentiation between damping and stressor factors. The first refers to those that increase the resilience capacity of the system, this is, those reducing its sensibility, and the stressors are the factors increasing the sensibility of the system to phenomenon (Furniss et al 2013). Another approach to biophysical indicators of vulnerability of species was proposed by NatureServe, and has been successfully applied to different ecosystems (Ohlemüller et al. 2008; Lawler et al. 2009; Pacifici et al. 2015) with emphasis on biodiversity. Differing from those indexes, this work focusses on goods and services that ecosystem functioning provides to human beings.

Despite the concept of social-ecological systems reflects the idea that human actions and social structures are comprehensive with nature and, therefore, any distinction between social systems and nature ones is arbitrary (Berkes & Folke 1998), it is clear that natural systems refer to those supporting the biological and biophysical processes, whereas the social systems are based in rules and institutions mediating the use of human resources, like the knowledge and ethics systems that interpret natural systems from a anthropocentric perspective (Adger 2006). In this context it is clear the difference between the social vulnerability, for example, to environmental changes associated to climate change and the vulnerability of the environment itself. Nevertheless, the narrow relationship existing between the ecosystem services and the human welfare enhances a trend to confuse them or to assimilate as if they were the same thing. Hence, if an ecosystem provider of environmental services is highly vulnerable to a given hazard, the community that depends of these environmental services will also be to the extent that this service is affected.

In concordance, a perspective in the vulnerability assessment should be the biophysical vulnerability assessment of strategic ecosystems, since these may determine the grade of sustainability of the population they are strategic to (Agudelo 2007). This implies that vulnerability must be defined from a series of biophysical variables, based on each specific system, considering that biophysical vulnerability is a function of the intrinsic susceptibility grade of the system to a natural hazard or phenomenon and its capability of resilience, as to the frequency and the magnitude of the hazard.

An advantage of studies of vulnerability of natural systems in function of biophysical variables is that, it is possible to find some homogeneity on the stress or perturbation factors as those capable of alter their functioning or their structure. Meanwhile, a vulnerability assessment of socio-economic systems may incorporate large number of variables and stress factors that may differ among scales (local, regional or global) and among specific cases, according to the hazards they are submitted to, due to its geographical location and other social-economic and cultural specific characteristics of the system, which are independent between them (Füssel 2005).

However, a separated analysis does not imply to ignore the narrow interdependence of these two dimensions since any decision with political heritage, cultural or as repercussion of the economic external conditions, has consequences over nearby ecosystems, either in terms of conservation or degradation. That is why, besides insisting on the necessity of study the vulnerability of natural systems based on biophysical variables, we also suggest prioritize the systems, through a characterization or classification of the ecosystems, according to the kind and the importance of the environmental goods and services they provide, or the amount of benefited population with the services they generate. In other words, all the ecosystems and remnants of natural vegetation are important, but exist some that provide vital and limited resources, such as fresh water, food and rough material, among others, so they constitute strategic ecosystems for the human survival and the environmental sustainability of the society.

### 1.3.3 Assessment of biophysical vulnerability of ecosystems

In this study we propose a series of parameters and variables as indicators to assess the biophysical vulnerability of ecosystems. Also it is proposed an assessment method and, as an example, as a study case of the assessment of hydrological vulnerability of paramo ecosystems to climate change, in order to make an objective, replicable and comparable assessment of the ecosystems biophysical vulnerability.

The assessment of ecosystems biophysical vulnerability must focus on the study of the intrinsic vulnerability of a specific ecosystem, to hazards, making the distinction between current and future vulnerability (Brooks 2003; Füssel 2005). Therefore, we present some indicators and a method for study the vulnerability of hydrological functioning of ecosystems, as an example, which determines the quantity and the continuity of water supply by the ecosystem. In this context, the hazard could be the reduction or loss of the mentioned ecosystem services, as changes on its water yield or the hydrological regulation capacity, as a consequence of climate change. According to Buytaert et al. (2010) changes in the climate regime of paramo ecosystems might generate big changes on vegetation, specifically on the diversity of species and the fragmentation of the ecosystems, effects on the soil and the organic matter stored and big changes in the hydrological cycle of these ecosystems. This implies that a number of biophysical factors determine the vulnerability of ecosystems to climate change.

To delimit the object of study it is recommendable to define the values or characteristics the study is focus on, which is, the intrinsic biophysical variables that control the ecosystem vulnerability, as indicated above, and the working scale, since, the values may vary from the available water to supply a population or for electric generation, recreational, landscape values or the conservation of aquatic species. Accordingly, to assess the hydrological sensibility of ecosystems, it is necessary to identify the areas, in this case hydrographic basins as the spatial integral unity and representative of the ecosystem, where it is possible to measure the inputs, internal flows, and water outputs. These measurements allow to understand how the ecosystems function under the current climate regimens and to project, through simulation models, their responses to climate change in terms of changes in the hydrological processes and their magnitude, measurable as water yield and their responses to rainfall events.

The exposition of ecosystem is determined, in part, by the changes occurred (i.e. changes in land use), and by the magnitude, frequency, duration, and the spatial extension of the hazard (climate change). Therefore, it is necessary to know the current conditions, values and behavior of meteorological variables at the spot, as base line, and then considering hypothetical scenarios in accordance to regional and local trends of climate change, essentially changes in precipitation and temperature, among other variables that, according to the characteristics of the ecosystem, be relevant to determine the water inputs or outputs. In this case, the hydrological modeling tool allows for the simulation of changes, without introducing them to the ecosystem or even, without these ones have occurred indeed.

From the above, the hydrological vulnerability of an ecosystem to climate change, is a function of the exposition grade, the climate, the soils, the topography and the vegetation, as well as the human activities, -land uses- that may affect the resilience of the system. For the specific case of tropical high mountains ecosystems, the considered variables for the analysis of their hydrological vulnerability, whose significance will be verified in the validation of the model in paramo ecosystems, are: hydro-meteorological variables, at least temperature, precipitation and discharge; alterations of the natural vegetation and hydro-physical characteristics of soils. For this exercise, the mentioned variables were measured in the field, included the horizontal precipitation inputs.

From the vulnerability concept and the selected variables, we developed a conceptual model that integrates the values of the vulnerability variables and allows to determine, through sensibility tests, calibration and validation, the relevance of each variable and their grade of control over the response variable that, in this case, is the discharge of the studied basin (Figure 1-3). At the same time, the calibration process of the hydrological model allows to determine the incidence grade of the different variables over the sensibility of the hydrological processes over the variable of response (i.e. discharge). In this context it is important to separate the effects caused by changes in land use from those caused merely by climate change. Therefore, the calibration of the parameters and its validation, are performed for the same representative basins of the three Colombian paramos: one of them undisturbed, another one slightly intervened with extensive cattle and another one very intervened even nowadays (agriculture and cattle, with an intense soil degradation).

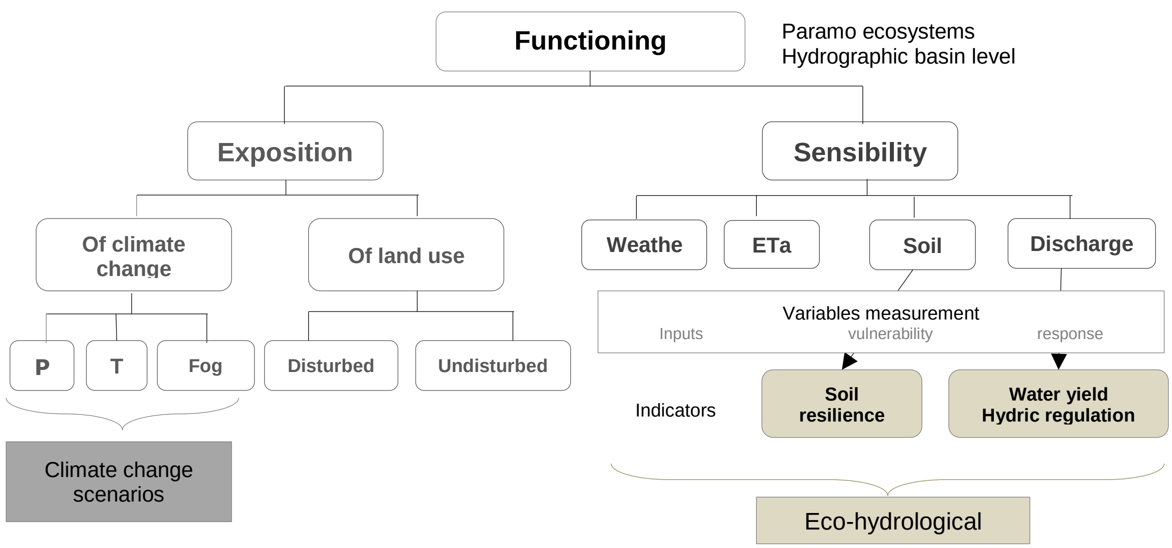


Figure 1-3. Conceptual model to evaluate the hydrological vulnerability of an ecosystem to climate change.

Once the hydrological model is calibrated and validated with the actual conditions, based on field measurements, it is possible to determine the vulnerability of the ecosystem, by inducting changes in the input variables. For projections it is used hypothetic scenarios of climate change, based on the analysis and predictions about the expected changes in temperature and precipitation for the Colombian high mountain, developed by experts, considering the future scenarios proposed by the IPCC and existing weather data (Ruiz et al. 2012; Carmona & Poveda 2014; Ruiz 2010). This allows to identify an inflexion point, from which the level of exposition -understood as the set of expected or projected changes in climatic variables-, generate significant alterations in terms of changes in hydrological processes (flows) and the response of the basin (discharge) to the excitations generated to the system, according to hypothetical scenarios, and also it will allow to estimate the magnitude of those changes.

The hydrological vulnerability of each basin, representative of hydrological functioning of the ecosystem, will be defined for the magnitude of the alterations on its hydrological response as a consequence of climate change, according to the level of alteration or the impact of some variables of vulnerability. In this way, the vulnerability levels, generally expressed as high, medium or low, may be defined based on the relative changes, regards to the regimes of the discharges taken as base line.

## 1.4 Conclusions

So far, most of studies of vulnerability to climate change have assessed vulnerability of populations, from the social-economic and anthropocentric perspective, with exceptions like the approximation of NatureServe. This assessment is subjective to the impacts caused on population due to the occurrence of a specific phenomenon, but does not consider the effects that climate change might have in the future over the goods and services that the strategical ecosystems provide us, i.e., an assessment of intrinsic vulnerability of the ecosystem.

As this approach may not determine the proper vulnerability of ecosystems, in this document we propose to evaluate vulnerability from a set of biophysical variables, which allows to measure the degree of vulnerability of a given ecosystem, according to its specific characteristics. Similarly, it is proposed a methodological approach, based on a conceptual model, to evaluate the vulnerability of specific ecosystem (e.g. hydrological vulnerability), based on control biophysical variables.

By applying the model, it is possible to determine the magnitude of the changes that different exposition scenarios to climate change may generate over the ecosystem, according to its sensibility and the alteration of variables and processes in the ecosystem.

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# 2. Fog and occult precipitation contribution to the water balance of paramo ecosystems: spatio-temporal distribution and impact on basin water yield

## Abstract

Paramos are high-altitudinal neotropical ecosystems with a high runoff ratio, located in the upper regions of the northern Andes. Fog occurrence is common in the paramos and occurs by the cooling of near-surface moist air, as it is forced to higher elevations by topography. Fog inputs to the system is thought to generate an additional water input into the terrestrial water balance, though this flux has rarely been quantified. We present results of monitoring of occult precipitation, understood as the combination of fog and drizzle inputs, for at least 7 months at several sites within three paramos in Colombia: three sites in Romerales (Quindío), two in Chingaza (Cundinamarca) and one in Belmira (Antioquia), combined with meteorological and soil moisture monitoring. Potential occult precipitation inputs were measured with cylindrical fog gauges with a cover on top. We find that potential occult precipitation inputs represent between 7 and 28% of rainfall inputs to the study sites. Our results also show that fog inputs have a large temporal and spatial variability, both within one site and between sites, which make it difficult to upscale and quantify at a catchment scale. Nevertheless, potential fog inputs are important for downstream water supply given that these inputs are especially concentrated during periods with low rainfall. We also find evidence for an increase in soil moisture related to occult precipitation during a dry period in Romerales paramo.

Keywords: fog inputs, occult precipitation, high mountain ecosystems, paramo hydrology, passive fog gauges

## 2.1 Introduction

Paramos are grassland ecosystems located in the upper parts of the tropical Andes extending from northern Peru to Venezuela, and occurring between the tree-line and glaciers. Paramos are recognized by their physical and biotical characteristics, particularly the dominance of grass and shrub vegetation, their specific cold and wet climatic conditions and their ability to store water and organic matter in the soil (Young et al., 2011). Those characteristics make them a permanent source of water and an atmospheric carbon sink

(Hofstede et al., 2003), due, in part, to the low decomposition rates of organic matter (Díaz-Granados et al., 2005).

Because of their geographic location, weather conditions are dominated by low temperatures, high air moisture conditions and low evapotranspiration, related to the permanence of low clouds and fog and a low leaf area index (1.3 $m^2/m^2$ on average) (Azocar and Rada, 1993; Cavieres et al., 2000; García-Varela and Rada, 2003; Rada et al., 1998). Because of the frequent presence of low clouds in the paramos, occult precipitation can be a significant water input (Díaz-Granados et al., 2005), therefore contributing to the high water yield and high runoff ratio recognized from these ecosystems (Tobón, 2009), understanding the runoff ratio as the proportion between total inputs and the water yield of the basin (Hino et al., 1988). The importance of water and nutrients entering the terrestrial system through occult precipitation, as well as their role in the hydrological cycle, has been recognized since early last century (Katata, 2014).

The fog is defined as water droplets or ice crystals suspended in the atmosphere near the earth surface, reducing horizontal visibility to less than 1 km (NOAA, 1995). In the tropical zone, fog occurs when moist air masses are cool enough for water to become liquid in very small droplets, which are suspended in the air and carried by the wind. Eventually, these droplets are intercepted by the surface of plants (Katata, 2014). Besides the fog, the drizzle, composed of droplets with size between 100 to 400 µm that fall at low velocities (0.25 – 2 $m.s^{-1}$) (Pruppacher and Klett, 1978), even in light winds, tend to fall in a wide angle, so they are collected more efficiently by the fog gauge than by the rain gauge, which makes it impossible to separate them from the fog inputs. Therefore we assume that both are part of the occult precipitation (Holwerda et al., 2010), even though there is an approximation to elucidate the role of occult precipitation in comparison to fog and rain is by using stable isotopes (Schmid et al., 2011).

The role of occult precipitation in high mountain ecosystems is twofold. It contributes directly to the catchment water balance when the water deposited on vegetation drips to the ground after overcoming the storage capacity of the leaves (Fu et al., 2016; Liu et al., 2014). But fog water on the surface of the leaves also reduces transpiration (Katata, 2014; Konrad et al., 2015; Sawaske and Freyberg, 2015), which seems to be related to solar radiation reduction and the increase of atmospheric moisture (Bruijnzeel et al., 2011). Air masses' daytime motions play a significant role in the functioning of high-altitude ecosystems and are considered key to the preservation of high- altitude environments (Ruiz et al., 2008). During late morning and early afternoon, atmospherically unstable conditions prevail in tropical high montane ecosystems, producing turbulence and vertical mixing. The induced atmospheric motions transport significant amounts of water vapour from lower to higher altitudes in the lower atmosphere, increasing the relative humidity in high-altitude environments, forming fog and mid-level clouds, and initiating convective cloud clusters (Ruiz et al., 2012). However, as the diurnal dynamics of this process is driven by differences in temperature and humidity between higher and lower altitudes, it is difficult to predict and to quantify.

The formation, dispersion and deposition of fog are the result of complex interactions between microphysical, thermodynamic, and dynamic processes (Gultepe et al., 2007). At local level, adequate conditions must exist for fog inputs to the system, such as wind speed and direction, duration and frequency of fog and characteristics of fog and drizzle as the amount and droplet size distribution and liquid water content. Also, the topography, elevation and terrain orientation play a role (Ritter et al., 2005). It is therefore important to evaluate the specific conditions of the different sites for potential occult precipitation inputs (Frumau et al., 2011) and its spatial and temporal variability.

Although there are several human activities that affect fog presence, frequency and deposition, such as land-use change and ecosystem degradation, in the last decades, climate change has become a major concern for the hydrological functioning of tropical high mountain ecosystems (Bruijnzeel et al., 2011). Among the expected impacts of climate change on the paramos are decreases in the frequency of low clouds and fog as a result of changes in atmospheric stability, which will reduce occult precipitation and increase solar energy that can accelerate the hydrological cycle and increase evapotranspiration. Additionally, changes in ecosystem structure might change some of their hydrological functions, such as the rainfall interception or soil infiltration (Locatelli, 2006). These will have effects on the water-related ecosystem services of paramos (Ruiz et al., 2011).

Despite the importance of fog for these tropical high mountain ecosystems, and the increasing threat of climate change, little is known about the magnitude of fog inputs, its spatial and temporal distribution and its contribution to the hydrological regimes of paramo ecosystems. Accordingly, this paper shows the results of an investigation, in which we separately studied and quantified potential inputs by occult precipitation and rainfall in three paramo ecosystems in Colombia, determined the spatial and temporal distribution of occult precipitation, and assessed its contribution to water yield from paramos.

## 2.2 Methodology

### 2.2.1 Study area

This study was conducted in three Colombian paramos: Chingaza (Cundinamarca) located in the Eastern Cordillera, Belmira (Antioquia) and Romerales (Quindío), on the Central Cordillera (Figure 2-1). These paramos have differences in their weather, orientation and altitudinal range, which results also in differences in the presence of fog and occult precipitation contribution to the ecosystem. Table 2-1 presents the climatic characteristics of the study sites, according to the measurements made during two years (2014 and 2015).

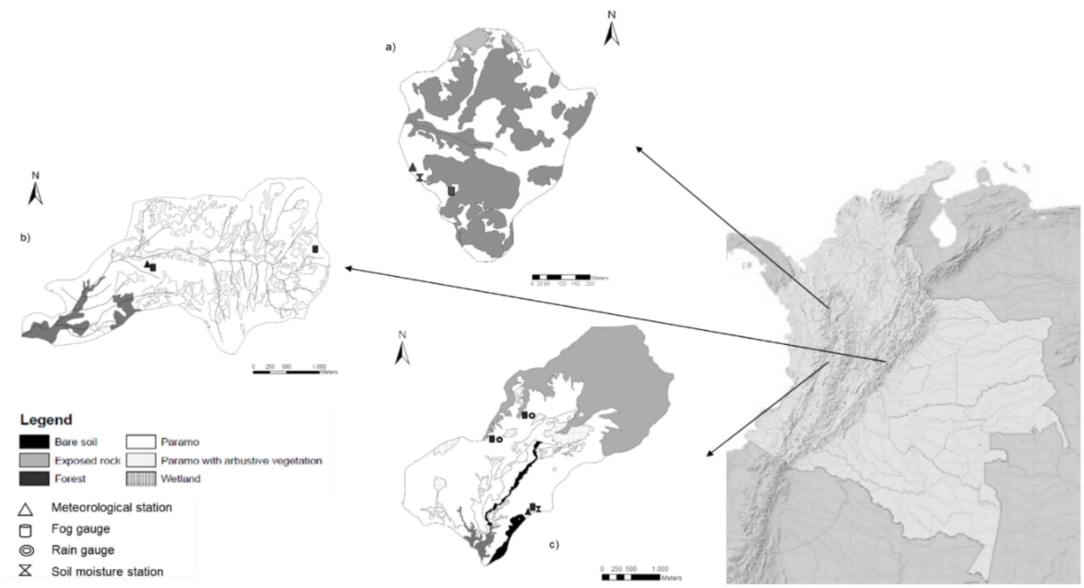



Figure 2-1. Localization of study area, where a) Belmira paramo, b) Chingaza paramo and c) Romerales paramo, and the stations inside each one.

Table 2-1. Climatic characteristics of study sites

| Paramo | Altitudinal range (masl) | Temperature (°C) | | | Air humidity (%) | | Solar rad. ($W.m^{-2}$) | | Wind speed ($m.s^{-1}$) | | Water yield (mm) | Rainfall (mm) | Occult precipitation (mm) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Avg. | Max | Min | Avg. | Min | Avg. | Max | Avg. | Max | | | |
| Belmira | 3000-3200 | 10 | 19 | 4 | 92 | 41 | 328 | 1436 | 3 | 10 | 886 | 1478 | 125 |
| Chingaza | 3150- 3750 | 11 | 26 | 2 | 85 | 30 | 271 | 1005 | 3 | 16 | 1979 | 3098 | 212 |
| Romerales | 3700- 4150 | 5 | 13 | 1 | 91 | 14 | 257 | 1390 | 4 | 16 | 380 | 970 | 120 |

### 2.2.2 Field measurements

Various methods exist to quantify potential fog inputs, including passive fog gauges (Katata, 2014; Villegas et al., 2007), that provide a standardized indicator of occult precipitation conditions and not attempt to imitate the fog water interception by a particular object (Juvik and Nullet, 1995). In this study, we used cylindrical fog gauges that have proved more efficient in forests and natural ecosystems than one-dimensional screens, as they are multidirectional (Juvik and Nullet, 1995). The fog gauges have a diameter of 12 cm and 39 cm of effective height, with a conical aluminium cover of 55 cm diameter to minimize the contribution of rainfall. We considered as the collector area = 0.0735 $m^2$, half of the cylinder since not all the cylinder face the fog at the time. Under the cylinder, we installed a tipping bucket rain gauge (Texas instruments ®), with Tynitag ® dataloggers recording data every 5 minutes.

The measurements were carried at different sites within the three studied paramos (Table 2-1). We also installed automatic weather stations (Campbell scientific ®) to measure precipitation, solar radiation, air temperature, air humidity, atmospheric pressure, and volumetric soil moisture at different soil depths (5, 25, 50 and 100 cm), using Time Domain Reflectometry, and recording every 15 minutes. The water yield of the catchments was measured every 5 minutes with Solinst ® level and baro-loggers at the closing point, where previously we improved the channels, as rectangular weirs.

Table 2-2. Characteristics of fog stations in the studied paramos

| Paramo | Station | Latitude (N) | Longitude (W) | Altitude (m) | Sampled period | Instruments |
|---|---|---|---|---|---|---|
| Chingaza | Estación | 4°45.96’ | 73°49.625’ | 3570 | 01/01 to 31/12, 2009 | Met. Station, fog gauge |
| | Laguna Seca | 4°47.81’ | 73°48.125’ | 3730 | 01/01 to 31/12, 2009 | Fog gauge |
| Belmira | Belmira | 6°39.673' | 75°40.378' | 3118 | 01/10/2015 to 30/04/2016 | Met. Station, fog gauge, TDR |
| Romerales | Filo | 4°40.250' | 75°25.154' | 3840 | 01/09/2014 to 06/02/2016 | Met. Station, fog gauge, TDR |
| | Plan de la Cueva | 4°41.714' | 75°24.482' | 4040 | 01/05/2015 to 06/02/2016 | Fog and rain gauges |
| | Piedra Gorda | 4°41.132' | 75°24.880' | 3964 | 08/06/2015 to 06/02/2016 | Fog and rain gauges |

### 2.2.3 Data analysis

The potential occult precipitation inputs were calculated by defining the collector area as the area exposed to the wind direction, i.e. half of the product of the internal diameter and the height. Although each fog gauge had a cover to prevent the inputs by rainfall, we decided to omit the fog input records during rainfall events with wind speed greater than 4 $m.sec^{-1}$ (Villegas et al., 2007), in order to corrected for the effect of the strong winds that tend to increase the angle of rainfall with respect to the vertical, making it very likely that rainfall drops intercept the fog gauge.

We analysed the occult precipitation, rainfall and discharge on a monthly basis and calculated the runoff ratio, as the proportion of total inputs, i.e. rainfall plus occult precipitation, that leaves the basin as runoff (Runoff / inputs).

Usually the fog presence in high mountain implies a sort of meteorological conditions previous and during its occurrence; therefore, the measurements of occult precipitation should be related to lower temperatures, atmospheric pressure, and solar radiation, while the wind speed, relative humidity it's expected to increase. In order to test that expected behaviour, we selected three of the largest occult precipitation events (when the fog gauges captured more than 0.5 $mm.hour^{-1}$) in our datasets, in order to find relationships among them, using the lagged cross-correlation analysis between occult precipitation and atmospheric pressure, temperature, solar radiation, relative humidity and wind speed measured at the weather stations.

Finally, we selected some dry spells (one or more consecutive dry days) in each site and assessed the soil moisture content at different soil depths (5, 15, 25 and 50 cm) against the potential occult precipitation inputs. The studied ecosystems are highly humid and their soils have properties (Chapter 4) that allow them to maintain high soil moisture content, so during the rainy season the soils are mostly saturated, but also it is not possible to separate the effect of fog inputs from rainfall in soil moisture. For dry days, we have into account, besides the days without rain, those with less than 1 $mm.day^{-1}$ of rainfall, since the average interception in these ecosystems is around 0.8 mm (C. Tobón, personal communication), so this amount of rainfall does not reach the soil surface, therefore, has none effect on soil moisture.

## 2.3 Results

### 2.3.1 Spatial and temporal distribution of horizontal precipitation

The corrections to exclude wind-driven rain, i.e, the exclusion of the records of fog gauges when there was rain and wind speed higher than 4 $m.s^{-1}$, affected between 8 and 15% of initial records, the lower in Romerales and the higher in Belmira. There are marked intraday and seasonal patterns of fog interception between the three sites. One of the most evident differences is the number of days without occult precipitation and rainfall measurements (Table 2-3), while in Chingaza is less than 20% of the days during a year, Belmira has around 23% of the days without fog but 56% of the days without rainfall. On the other hand, Romerales presents more than half of the days without any of those.

Table 2-3. Days without occult precipitation or rainfall records in each studied paramo

| | | Days recorded | Days without occult precipitation | | Days without rainfall | |
|---|---|---|---|---|---|---|
| Paramo | | | number | proportion (%) | number | proportion (%) |
| Chingaza | | 365 | 59 | 16 | 64 | 18 |
| Belmira | | 208 | 48 | 23 | 117 | 56 |
| Romerales | Filo | 517 | 282 | 55 | 218 | 42 |
| | P_cueva | 278 | 157 | 56 | 145 | 52 |
| | Piedra_G | 230 | 150 | 65 | 119 | 52 |

In Chingaza, although the stations were relatively close from each other, the altitudinal difference between them explains the higher values found at Laguna Seca station, although there are no significant differences between these sites ($p> 0.05$) and temporal trends in distribution are similar between them (Figure 2-2a). January and February were the months with the highest potential occult precipitation inputs, however, between November and January inputs occurred preferably around midnight, and the rest of the year they occurred primarily in the morning and close to sunset from April to October. In Belmira, fog mostly occurred during the night and early morning, with few records during daylight hours, except in March, the month with the higher occult precipitation records during the measured period, with largest inputs early afternoon (Figure 2-2b). In paramo of Romerales, the highest occult precipitation inputs occurred in June, for the three stations, with another peak in October and November. The largest values were recorded at Filo station. In this paramo, the hours at which occult precipitation deposition occurs show erratic patterns (Figure 2-2c), with big changes in short periods of time. However, diurnal peaks dominate from August to March, for all stations with small variations among them (Figure 2-2d, for station Plan de la Cueva as an example).

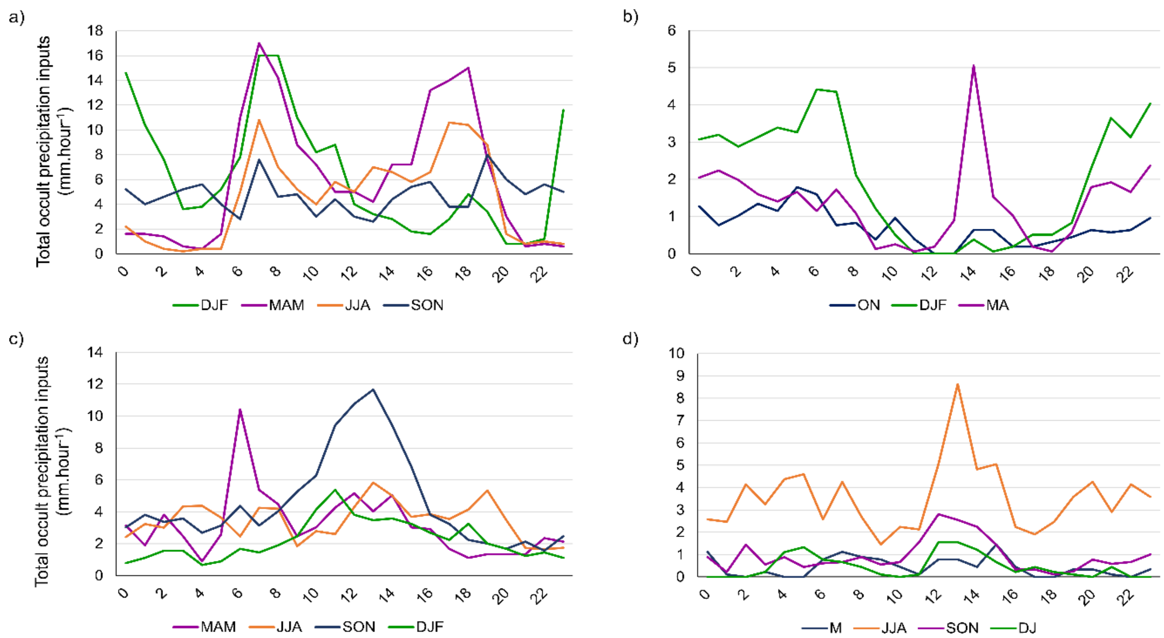


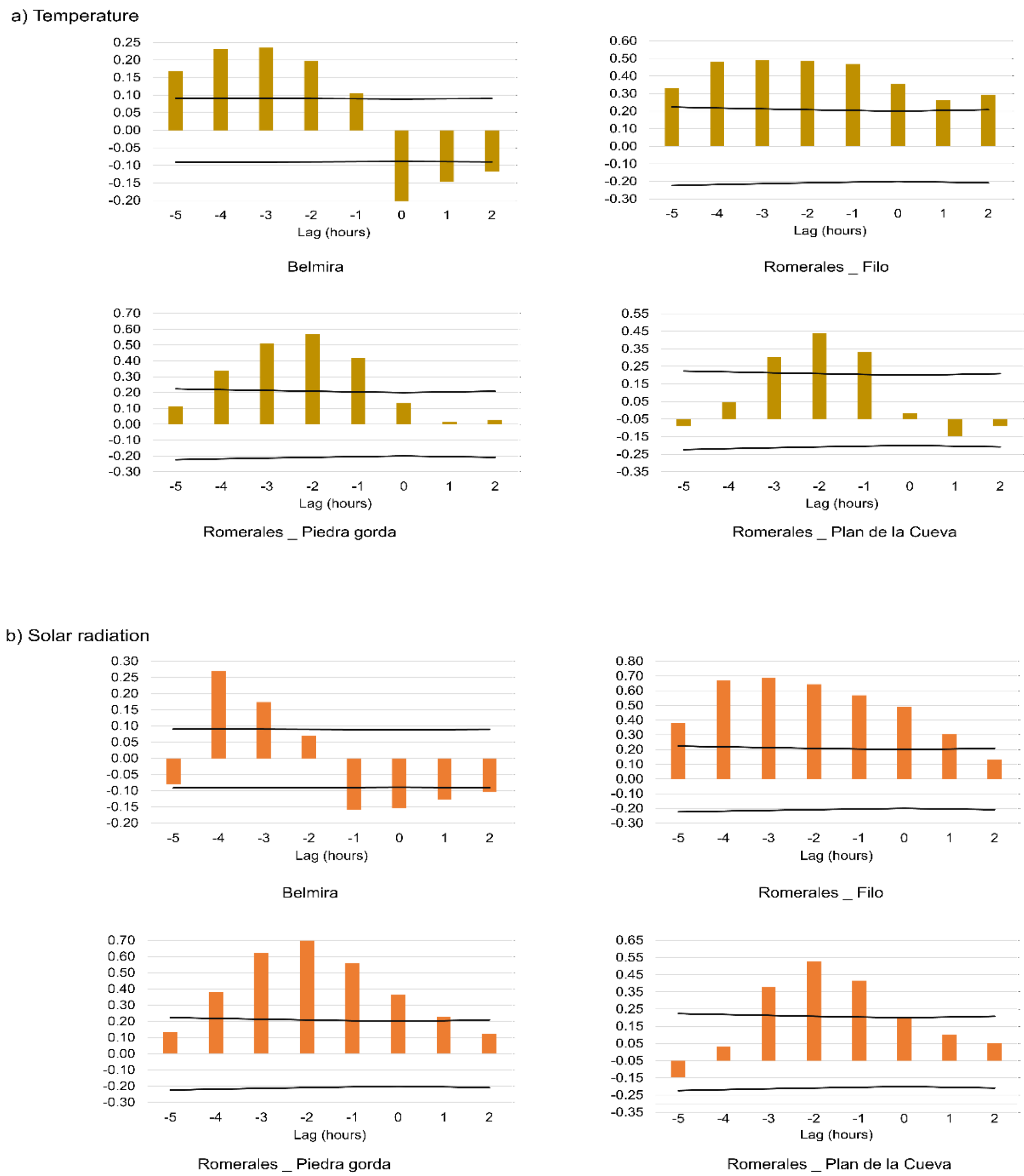

Figure 2-2. Mean diurnal courses of occult precipitation, grouped by trimesters in: a) Chingaza (Laguna Seca), b) Belmira, c) Romerales_Filo and d) Romerales_Plan de la Cueva

### 2.3.2 Relationship between horizontal precipitation and meteorological variables

There are important differences in the relationships between the three studied paramos. Chingaza is a wet site, with constant presence of fog. In the recorded time series of occult precipitation of this site it is difficult to identify individual events, i.e. records of more than 0.5 mm in one hour. Instead, a continuous occult precipitation inputs of small magnitude (e.g. 0.12 $mm.hour^{-1}$) was observed. For the same reason, after selecting some of the events with higher occult precipitation records, no significant correlation was found with climatic variables such as atmospheric pressure, solar radiation, temperature, relative humidity and wind speed (not shown).

In contrast, events in Romerales and Belmira are significantly correlated with the assessed meteorological variables, but every site has its own behaviour, i.e, the lagged correlations have a clear tendency, but the lag might change between stations (Figure 2-

3). In Belmira we analysed three fog events occurred during: 03/12/2015 to 05/12/2015, 20/02/2016 and 09/03/2016 to 10/03/2016. In Romerales we selected three events for the three sites simultaneously: 22/06/2015, 26/06/2015 to 27/06/2015 and 01/11/2015 to 03/11/2015. The lagged correlation was assessed at hourly temporal resolution.



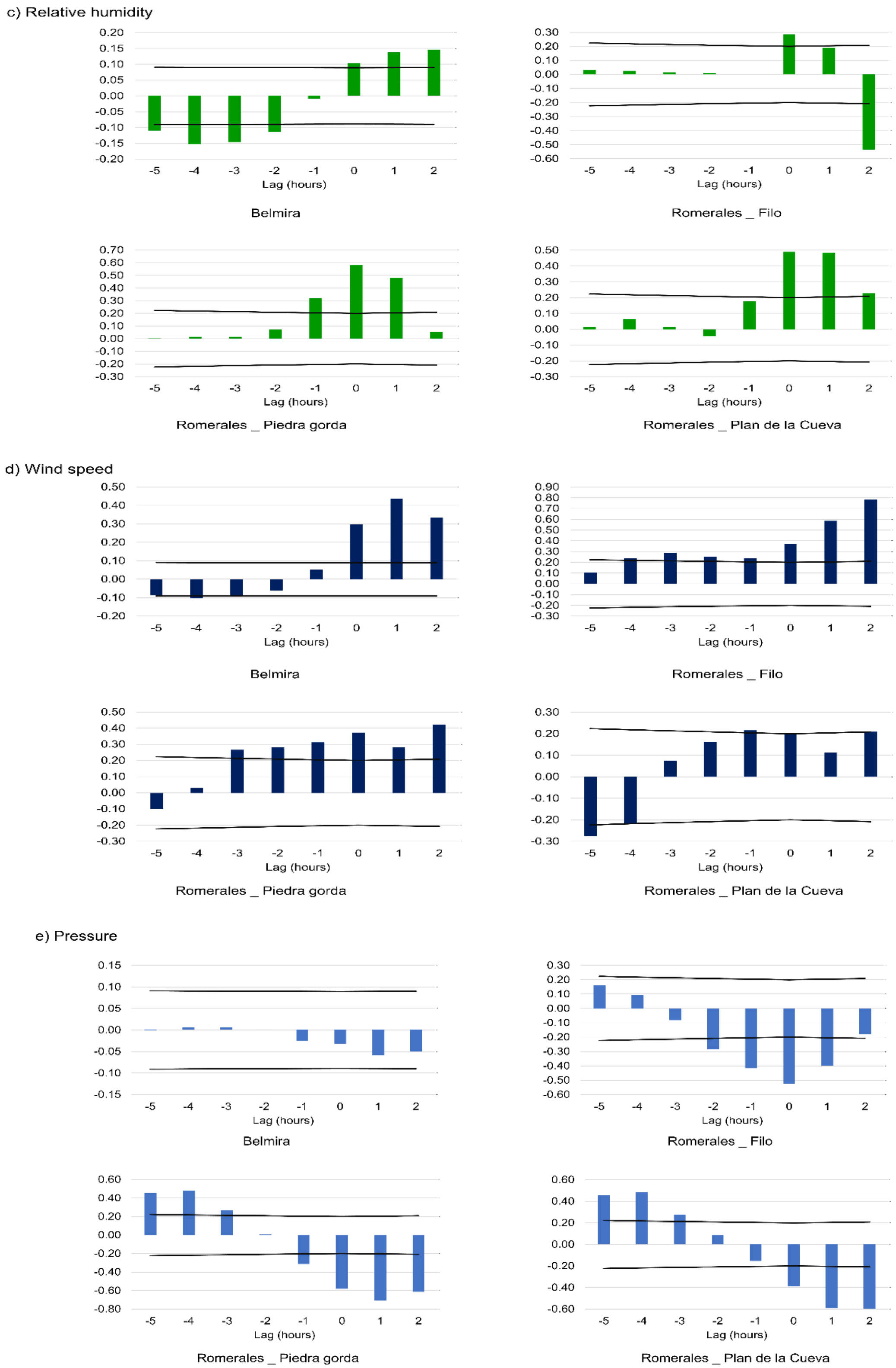



Figure 2-3. Lagged correlations between occult precipitation events and a) temperature, b) solar radiation, c) relative humidity, d) wind speed and e) atmospheric pressure, and their 95% confidence boundaries for Romerales and Belmira

The results indicate that when the fog passes, besides depositing water droplets, it changes the weather conditions: the air temperature and solar radiation has positive correlation around two hours before the fog event, which makes sense from a meteorological perspective, since this weather conditions heat the local air mases, promoting their buoyancy to be replaced by humid and cooler air masses ascending the mountain. During and after the fog event, correlations with solar radiation diminishes, as expected, but the correlation is still positive in Romerales, while in Belmira it is negative (Figure 2-3a and 2-3b). The correlation with relative humidity and wind speed is positive during and after the fog event (Figure 2-3c and 2-3d), while the correlation with atmospheric pressure is negative during and around the event (in Filo and Piedra Gorda is significant before, during and after the event, in Plan de la Cueva is significant during and after the fog event). These last correlations show significant increased pressure 3 to 5 hours before the fog event, which is consistent with orographic lifting. However, in Belmira the correlation between fog or occult precipitation events and atmospheric pressure is not significant (Figure 2-3e).

### 2.3.3 Contributions of horizontal precipitation and its relationship with the discharge

Table 2-4 presents the total of rainfall, occult precipitation and discharge measured at each site, and the proportions among them.

Table 2-4 Rainfall, occult precipitation, discharge and water yield for the stations in the studied paramos

| | Rainfall (mm) | Occult precipitation (mm) | % of occult precipitation over total inputs | Discharge (mm) | WY (D/R) |
|---|---|---|---|---|---|
| Chingaza (1 year) | 3398 | Est.: 214<br>L_Seca: 228 | Est.: 6.3<br>L_Seca: 6.7 | 2292 | 67.5% |
| Belmira (7 months) | 852 | 97 | 11.4 | 495 | 63.2% |
| Romerales (7 months) | Filo: 426<br>P_C: 587<br>P_G: 384 | Filo: 128<br>P_C: 119<br>P_G: 92 | Filo: 27.8<br>P_C: 25.9<br>P_G: 20.0 | 140 | 34.7% |

In Chingaza, there are no significant differences between sites in annual occult precipitation inputs, however inputs were not homogeneous along the year: Occult precipitation was higher in January and February, which are the months with the lowest inputs by rainfall (Figure 2-4a).

In Belmira occult precipitation ratios in relation to the rainfall measured in the basin vary widely between the wettest months (October and November) where occult precipitation was low, and the dry season, especially in December when occult precipitation contributed with 60% of rainfall (Figure 2-4b).

In Romerales, for the 7 months (June 2015 to January 2016) occult precipitation data were simultaneously recorded at the three stations. In this paramo, the months with the highest inputs of occult precipitation match with the wettest months, i.e., the temporal distribution of occult precipitation is similar to the rainfall patterns, with peaks in October-November and in June-July. It should be noticed that occult precipitation was higher in Plan de la Cueva in June and July, but at the end of the year (November and December) was exceeded by the occult precipitation inputs in Filo, while the rainfall in Plan de la Cueva was always higher than the other two sites. Figure 2-4c presents the relationship between occult precipitation and rainfall for the three stations in the paramo of Romerales. No discernible patterns between the stations can be found, and neither between the dry and rainy seasons.

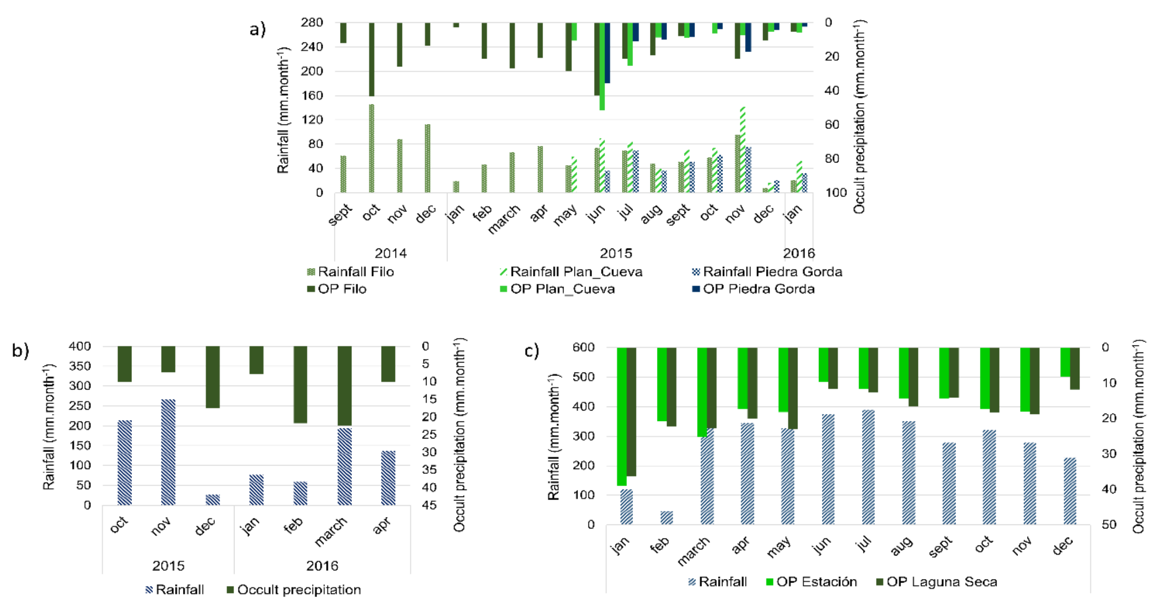



Figure 2-4. Measured occult precipitation and rainfall in studied paramos: a) Romerales, b) Belmira and c) Chingaza

The relations shown in Figure 2-4 highlight the importance of occult precipitation inputs in paramo ecosystems, particularly when those potential inputs occur during dry spells and in a relatively dry site as Romerales is. That is the reason we did not find the effect of occult precipitation inputs on soil moisture in the other two paramos: Chingaza is a wet paramo whit rainfall and fog most of time, so its soils are wet most of time. Belmira, on the other side, potential fog inputs are more commons than rainfall (Table 3), but the quantities were not enough to show a recharge on soil moisture during the period of measurements.

Although measurements of discharge do not allow the separation of different sources of water between rainfall and occult precipitation, we found that during long dry spells (consecutive days with less than 1 $mm.day^{-1}$ of rainfall), occult precipitation inputs are clearly accompanied by an increase in soil moisture (Figure 2-5), which implies that these inputs are entering the ecosystems. In the studied paramos, increases in volumetric soil moisture were observed after dense fog events, indicating that fog interception by paramo vegetation in these events contributes not only to the canopy wetness, but also drips to the soil surface and increase soil moisture. At the soil surface increases were of the order of 0.033 $m^3.m^{-3}$, while at subsurface soil layers, soil moisture increased 0.026 $m^3.m^{-3}$, in average, with inputs decreasing with soil depth.

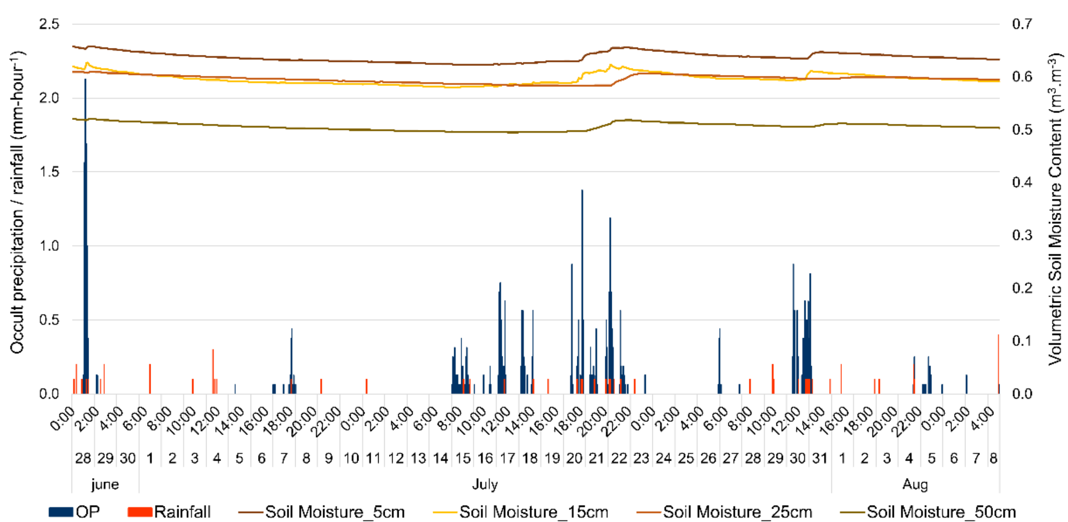



Figure 2-5. Increases in soil moisture due to fog inputs in a dry spell between 28-06 and 08-08, 2015 in Romerales paramo, measured at Filo station

## 2.4 Discussion

The water inputs via occult precipitation in Colombian paramos are extremely variable, both in time and in space. Although Błaś et al. (2002) found well defined diurnal and annual cycles of fog presence in Western Sudety Mts., Poland, the fog they studied has a different origin (humid maritime air masses), which is probably more stable because it responds to meso and macro scale atmospheric circulation. By contrast, fog in tropical high mountain depends on specific local weather conditions resulting in orographic cloud formation (Nair et al., 2010), but also of humid air masses that usually come from valleys of major rivers located at large distances (hundreds of kilometres) of the sites where it is deposited. Therefore, the fog presence in high mountain, and particularly in paramos, depends on the air humidity generated by another ecosystems downslope of the paramo. This explain why the fog and occult precipitation we measured does not exhibit a consistent pattern of distribution in time, i.e., a diurnal or annual cycle. Although they do not mention fog distribution, Buytaert et al. (2006) found large variability in rainfall inputs and no seasonal patterns in Ecuador paramo, which was related to the characteristics of the events.

It has been shown that fog follows the predominant directions of air movement (Błaś et al., 2002). It is likely that the same phenomenon occurred in the studied sites, because the wind direction indicates the path that these humid air masses follow. Similarly, there is a relationship between wind speed and occult precipitation, since the high wind speeds can avoid the drops deposition on vegetation (Bruijnzeel and Proctor, 1995). In our study, we found that nearby stations with some altitudinal differences like those in Chingaza indeed show differences, both in the magnitude of the records and in the hours with the higher deposition in different months of the year. In Romerales even stronger differences are observed. In addition to altitudinal differences between stations, we found topographical differences that influence wind direction and, consequently, the pathway of the humid air currents.

The presence of low clouds or fog masses that generate occult precipitation in paramo ecosystems, affect local meteorological conditions by reducing the solar radiation and temperature (Schneider, 1972). This is associated with reductions in atmospheric pressure because the mass of moist air which produces fog reduces its temperature and pressure as a result of an adiabatic expansion, as it is forced to higher elevations (Gultepe et al., 2007). This is evident when we analyse and correlate some fog events in Romerales and Belmira with those meteorological variables (Figure 3). This tendencies have also been found in Canary Islands in Spain, where temperature decreased and air humidity raised with fog presence (Marzol-Jaén et al., 2010).

Inputs by occult precipitation in these ecosystems are considerable. Although the paramo of Chingaza is one of the wettest paramos, the occult precipitation represents, on average, almost 7% of additional water to rainfall inputs, and is especially important in January and February, which are de driest months. In the paramo of Romerales, occult precipitation inputs vary between 20 and 28% of additional water to the received by rainfall. Meanwhile, in Belmira the occult precipitation represents an additional 11% to the rainfall inputs during the measured months, and increasingly important as a complementary input to rainfall in the driest months, which agree with that found in Californian mountains and in tropical forest in southwestern China (Fu et al., 2016; Liu et al., 2014; Sawaske and Freyberg, 2015), but is higher than what Schmid et al. (2011) found in a tropical montane cloud forest in Costa Rica. These results confirm that the interception of fog or occult precipitation in paramos is an important source of water, as already had been confirmed for other high mountain ecosystems (Cavelier and Goldstein, 1989; Holwerda et al., 2010). However, there are differences in the reported magnitudes and the time of year in which most fog or occult precipitation is deposited. In this study we found a significant contribution of occult precipitation to the system during the time of lower rainfall in Belmira and Chingaza paramos, which matches with reports made for cloud forests in Central America (Holder, 2004; Ritter et al., 2005). But Romerales shows an opposite behaviour, with the largest occult precipitation inputs registered during the months with greater rainfall.

In this study we found evidence of soil moisture recharge by water inputs from occult precipitation during dry spells in Romerales, which to our knowledge has not been reported for any site, including cloud forests, although some authors refer to fog inputs as canopy drip, increasing net precipitation inside cloud forests (Bruijnzeel, 2001; Cavelier et al., 1996; Tanaka et al., 2010). By measuring volumetric soil moisture under the vegetation, at short time scales, it was observed that large fog events produced enough dripping to allow for soil water recharge in studied paramos, which is consistent with that found by Liu et al. (2005) using isotopic analysis in a tropical seasonal rain forest of China. Although these increases are only reflected when soil moisture is below saturation, it seems that the presence of fog, during or after rainfall events, highly contributed to soil moisture, which in turn, will be reflected as discharge, mainly at wet conditions. Nevertheless, to differentiate the source of soil moisture recharge between fog and rainfall it is necessary to use a chemical technique, such as isotopes (Schmid et al., 2011).

## 2.5 Conclusions

Colombian paramos receive a high amount of rainfall (over 1000 mm.year$^{-1}$), despite of this, the occult precipitation is an important additional input (of between 6 and 28% of rainfall) that interacts with the soil, recharging soil moisture.

For analysed fog events, clear correlations were found with temperature, solar radiation, relative humidity, wind speed and atmospheric pressure. Despite the correlations present similar tendencies, there are differences between stations and between paramos. In general, the two or three hours before the fog event give the meteorological conditions to determine that it occurs: high pressure, high solar radiation and temperature, which influence the presence of winds with greater speed during the fog event.

Temporal and spatial patterns of potential occult precipitation inputs are very variable, not only between paramos, but also within stations in the same paramo. These results indicate that fog and occult precipitation in tropical high mountain is a complex, variable and a difficult phenomenon to understand.

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# 3. Ecophysiology of frailejones (*Espeletia spp.*) and its contribution to the hydrological functioning of paramo ecosystems


## Abstract

Paramos are high elevation tropical ecosystems in northern Andes. Species of the genus *Espeletia*, known as frailejones, are one of the most conspicuous growth forms (megaphytes), representative of vegetation of the northern paramos. We studied their physiology in two Colombian paramos, to identify the conductive tissues inside the stems, estimate their allometric relationship, and measured sap flow using the heat ratio method. *Espeletia* have a central pith which increases with height, as the size of secondary xylem decreases. Frailejones respond quickly to the changing environmental conditions of paramos such as solar radiation and fog presence, but after a while, sap flow tends to decrease, a particular behavior of their transpiration processes, that occurs chaotically over time, including sap flow at night. The water lost through *Espeletia* transpiration, is 21% of the outputs through superficial runoff and 12.6% of precipitation, in ecosystems with 60% of water yield. We determine by radiocarbon the mean growth rates of *E. hartwgiana* between 3.8 and 6.9 cm.year$^{-1}$.



Keywords: Andean high mountain, frailejón, growth rate of *Espeletia*, paramo, sap flow


## 3.1 Introduction

Paramos are ecosystems in the higher peaks of the Andes, between the tree line and the glaciers, and are present from Venezuela to northern Peru, distributed as biogeographical islands (Hofstede et al. 2003). Due to altitudinal elevation where they occur, the predominant climate is characterized by low temperatures with wide daily range of temperature and large water availability. This is the main reason of the hydric stability and the interaction between hydric and thermic factors, as the main elements determining the growth and metabolic activity of plants in these ecosystems (Azocar & Rada 1993). These ecosystems are characterized as an open shrubby vegetation inside a grasslands matrix, with high levels of vegetation endemism attributed to their fragmented distribution in the landscape (Young et al. 2011).

One of the most outstanding eco-hydrological feature of the paramo ecosystems is its high water regulation and the highest water yield (Q/P), of about 63%, as compared to those of tropical dry forest (19% on average), the tropical rain forest (42% on average), and the cloud forests (57%) (Tobón 2009). Characteristics such as low temperatures, high relative humidity and well developed organic soils that occur with high moisture content, are the main factors controlling this condition. Additional factors contributing to this large water yield and regulation of the paramos, are low evapotranspiration, due to the presence of fog and low clouds, and a low leaf area index, of about 1.3 (Azocar & Rada 1993; Cavieres et al. 2000; García-Varela & Rada 2003; Rada et al. 1998). Moreover, some physiological adaptations found in tropical high mountain plants include high nightly respiration (Azocar & Rada 1993), high photosynthetic capacity (Goldstein et al. 1994), and short duration changes in the open degree of stomata, caused by variations in radiation, and the momentary intensities of transpiration and conductance (Lösch & Schulze (1995), cited by Mora-Osejo (2001)).

Species of the genus *Espeletia*, known as frailejones, are one of the most conspicuous forms in the paramos of the northern Andes. The frailejones exhibit a giant caulirosular habit, one of the typical adaptive forms in this kind of environments (Cuatrecasas 1968; Azócar & Rada 2007). Other morphological characteristics of these plants are the dead leaves that remain attached to the plants after leaf senescence, as a strategy of this plant to insulate the stem, to prevent freezing and to retain nutrients. Additionally, the central pith accumulates large amount of water, thus it can provide water to the transpiring leaves and the foliar pubescence under specific demanding conditions (Nobel & Goldstein 1992; Rojas-Zamora et al. 2013; Rada et al. 1985; García-Varela & Rada 2003).

The water stored in the pith can maintain the average intensity of transpiration for about 2.5 continuous hours, but this may vary according to the species (Goldstein et al. 1994). This explains the fast recovery of transpiration rates after a reduction or a total suspension of transpiration under unfavorable environmental conditions (Larcher 1995). The distribution of the pith and the xylem along the stem of frailejones is not homogenous (figure 3-1a): the pith is narrow in the base of the plant and becomes broader to the top; while the xylem becomes wider toward the base, which is the oldest part of the plant, as a consequence of its secondary growth via the vascular cambium (Trautner 1962; Rock 1972). A recent study (Rock, personal communication) has shown that the caulerosulan *Espeletia* exhibit a Primary Thickening Meristem (PTM) similar to those described in monocots by DeMason (1983), thus accounting for the massive amount of pith beneath the stem tip, as is shown in figure 3-1b.

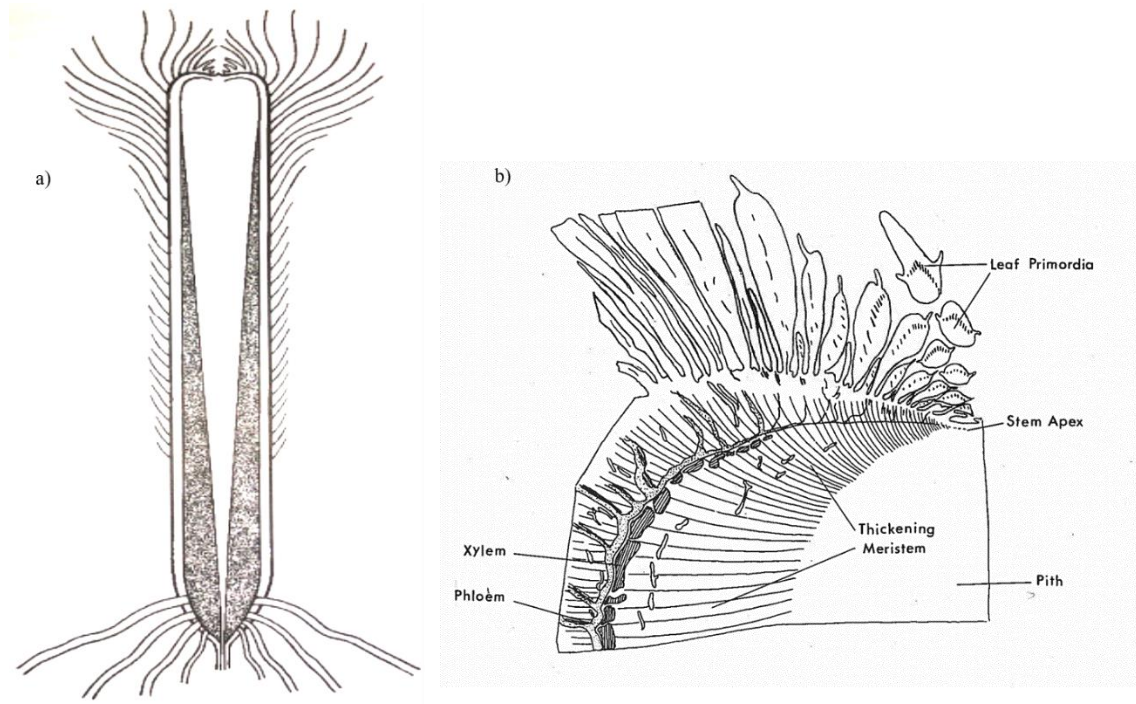


Figure 3-1. a) Longitudinal section of *Espeletia hartwegiana*, according to Weber (1962). Taken from Mora-Osejo (2001); b) Sketch through the longitudinal stem tip of *E. schultzii,* showing the Thickening Meristem and formation of the massive pith characterizing the megaphytic growth form typical of the genus.

The pubescence or trichomes on the leaves of *Espeletia* spp. increases its temperature by 5°C (Meinzer & Goldstein 1985), and protects the photosynthetic mesophyll of the plant of damage by overeating and UV radiation during sunny days reflecting the shorter UV wavelengths of the incident radiation (Lange et al. 1981). The trichomes of the leaves also have undulations that reduce transpiration (Roth 1973). In addition, transpiration may also be reduced by the presence of areolate cavities on the lower surfaces of *Espeletia* leaves, resulting in stomatal crypts located under mesophyll units (areoles) as shown in figure 3-2 (Rock 1972).

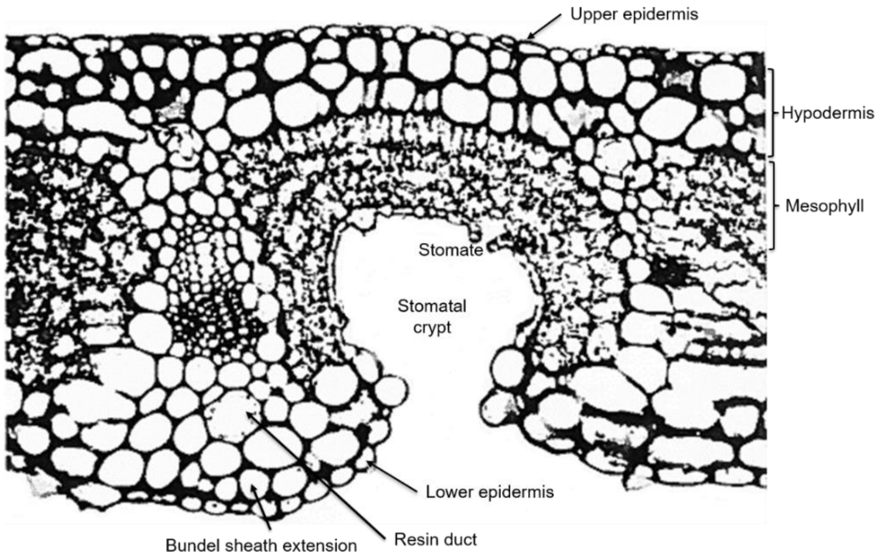


Figure 3-2. A cross section of a typical mature *Espeletia* leaf, showing the upper epidermis, a multilayered hypodermis, mesophyll, a resin duct in a bundle sheath extension, a stomatal crypt, and an open stomate. 100X. (Rock 1972).

Water is important to the physiology of plants because it participates in all physiological processes. Plants, and in particular, *Espeletia spp* require large quantities of water in non-woody tissues such as the stem pith, leaves and roots, where it can comprises between 70 to 95% of the biomass (Lambers et al. 2008). Transpiration is an inevitable consequence of photosynthesis, but it also has important effects on the leaf's energy balance, since as water evaporates from mesophyll cell surfaces, it cools the leaf. Without this mechanism, the temperature of leaves could rise to lethal levels (Lambers et al. 2008). In most species of *Espeletia*, including the megaphytic species, the top of the leaves consists of a single layer of upper epidermis and one or more layers of hypodermal cells which function as water storage as shown in figure 3-2 (Rock 1972).

Although there seems to be some understanding about the physiology of *Espeletia*, most of these studies have focused on describing morphological issues, as shown above, but few study the proper physiological functioning, such as sap flow or plant transpiration, related to specific site conditions of climate and soils. On the other hand, the time needed for establishment or recovery of paramo vegetation, soils and hydrology after any alteration is an unknown but necessary information (Ramsay 2014), given the importance of these ecosystems for human activities and the alterations they have suffered. In this context the age and growth rates of Espeletia as an ecological indicator have been understudied. Given the importance of understand the functioning of *Espeletia*, its growth rate, and the magnitude of water flow inside the plant resulting from transpiration, we have pursued a comprehensive study of the physiognomy, physiology and the eco-hydrological relationships between *Espeletia* and the particular meteorological conditions of the paramos, and its contribution of overall hydrological functioning of paramo ecosystems.

## 3.2 Methodology

### 3.2.1 Study sites

This work was conducted in March and April, 2016 in two paramos of Colombia: Romerales (04°40'52.8 N, 75°24'52.1 W, between 3600 and 4200 masl) and paramo of Belmira (06°39'44.6 N, 75°40'27.0 W, between 3050 and 3200 masl), both located over the Central Andean range in Colombia. The species of frailejon studied were *E. hartwegiana* in Romerales, and *E. occidentalis* in Belmira. On each paramo we measured the allometric inner relationships of frailejones and collected vegetative samples to conduct radiocarbon dating.

In both paramos we installed meteorological stations (Davis® and Campbell Sci® weather station), to measure precipitation, temperature, relative humidity, solar radiation, wind speed and direction at 15 minute intervals. We also installed soil stations to measure soil moisture and temperature (Decagon®) at four depths in the soil profile in Belmira: 5, 15, 25 and 35 cm, since soils are shallow.

### 3.2.2 Growth of *Espeletia spp*: allometric relationships and age

The inner distribution of tissues in frailejon stems is important; not knowing this relationship may lead to errors in the sap flow measurement, since there is a risk of inserting needles in a different area of the xylem. Therefore, for a better understanding of the inner distribution of xylem of frailejons based on the observations of Weber (1962), cited by Mora-Osejo (2001), we used the principle of allometric growth, in which the relative growth of a part of one organism is proportional to the relative growth of the whole organism or any of its parts (Gayon 2000); meaning $\left(\frac{1}{\mathrm{y}}\right)\frac{\partial \mathrm{y}}{\partial \mathrm{t}} = k\left(\frac{1}{\mathrm{x}}\right)\frac{\partial \mathrm{x}}{\partial \mathrm{t}}$, which results in the allometric function $y = cx^K$, where *y* is the biological variable to be estimated, in function of the variable *x* with a scaling *k*, and with the constant *c* (integration constant) which is characteristic of the given organism (Huxley 1932; Thompson 1917).

We measured and sampled the pith diameter and the width of xylem at different heights of the plants, using an increment borer of 5mm diameter. The data were adjusted to the allometric equation by regression to estimate parameters c and k. To meet the statistical assumptions of heterocedasticity, with no autocorrelation and normality, the expression $y = cx^K$ was linearized. The resulting equation $ln(y) = ln(c) + k * ln(x)$, satisfy the above statistical assumptions. Nevertheless, when the original model is recovered using antilogarithms, a bias is induced. To correct this bias, we used the mean square error (*MSE*) suggested by Zapata et al. (2001). After this correction, the new equation is $ln(y) = ln(c) + 0{,}5 * CME + k * ln(x)$

In the Romerales paramo we made 43 measurements at different heights, between the base of the plants and 200 cm, while in Belmira we made 42 measurements between 0 and 125 cm of plant height.

To determine the age of *Espeletia*, we sampled 3 individuals of different heights, assuming different ages according to the heights (65, 105 and 210 cm). Samples (of about 40 mg) were taken (march 5, 2016) from the inner part of the stem base of selected plants, by using an increment borer, taking special care to sample only the oldest wood. However, with the eldest plant we had an ambiguous result, so we used a second adjacent sample to determine the real age (del_Valle et al. 2014). Samples were analyzed in the International Chemical Analysis Inc. laboratory at Miami (Florida, USA), through the AMS radiocarbon analysis, from which the age of each individual was stated, using the software CaliBomb and the post-nuclear bomb peak radiocarbon content curve in North Hemisphere Zone 2 (NHZ2) (Reimer et al. 2004).

### 3.2.3 Temperature of the plants and leaves

We made measurements of leaves temperature in 6 individuals in each paramo, classified into three height categories: tall (over 120 cm), medium (61 - 120 cm) and low (0 - 60 cm). Also, in each individual we measured the temperature on both sides of the leaves, separated in three groups according to its position in the rosette: apical, adult and senescent leaves at the base of the rosette. Measurements were made continuously during two days, using type T thermocouples, connected to a CR1000 data logger to record data every 15 minutes.

In order to relate the measured values of leaf temperature with meteorological variables measured in a nearby weather station, we used a linear model with two indicator variables: height of the plant and position of the leaves in the rosette. With the data set and using principal component analysis, we ran a linear regression using the IBM_SPSS®

statistical software, testing the criteria of normality, no collinearity, additivity and homogeneity of variance, with a significance level of $p > 0.05$.

### 3.2.4 Sap flow measurements

Transpiration rates in *E. occidentalis* and *E. hartwegiana* were measured applying the Heat Ratio Method (HRM) (Burgess et al. 2001), with adaptations to the specific morphological conditions of *Espeletia* in relation to the standard measure of sapflow in woody species. Based on the results from the prior study of the physiological characteristics of these plants, sensors length was reduced to 1.2 cm. We installed one sapflow station in each paramo. Every station had 8 sensors located in 4 vigorous plants (two sensors in each plant), connected to a CR1000 data logger (Campbell Sci ®). Although the conventional method recommends measure at different depths of transverse axis of xylem, in order to determine the differential speeds of sap inside it, in this study we measured the average flow, since the xylem is very narrow to put more than one thermocouple inside it.

## 3.3 Results

### 3.3.1 Allometric internal relations

The total diameter of stem and the width of bark for both studied species of *Espeletia* have a low relationship with height. Contrary, the diameter of pith and the width of xylem show a clear dependence with height of stem in both species studied (Figure 3-3 a, b). Table 3-1 shows the allometric equations.

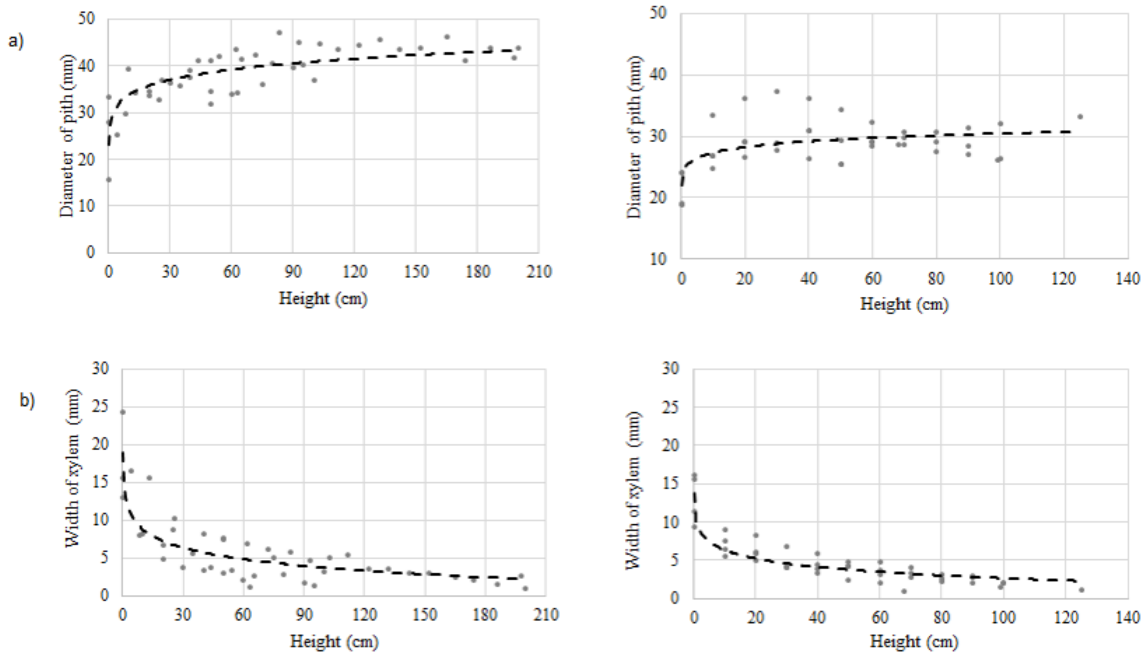


Figure 3-3. Relationship between frailejones: a) height (cm) and the diameter of pith (mm); b) height and the width of xylem (mm) in *E. hartwegiana* (left) and *E. occidentalis* (right)

Table 3-1. Allometric models of height (cm) with diameter of pith (mm) and with the width of xylem to *E. hartwegiana* and *E. occidentalis*

| Relationship | *Species* | Model | $R^2$ |
|---|---|---|---|
| Height (cm) - diameter of pith (mm) | *E. hartwegiana* | $y$=28.127x$^{0,083}$ | 0.521 |
| | *E. occidentalis* | $y$=24.701x$^{0,047}$ | 0.336 |
| Height (cm) - width of xylem (mm) | *E. hartwegiana* | $y$=14.694x$^{-0,29}$ | 0.596 |
| | *E. occidentalis* | y=9.96x$^{-0,259}$ | 0.740 |

### 3.3.2 Age of *E. hartwegiana*

The samples for dating were taken in February 5, 2016 (considered as 2015.5). Table 3-2 shows the ages of *E. hartwegiana* individuals, including the R3' sample, dated to determine the real germination year of the taller plant. The smaller and younger has a growth rate in height of 5.9 cm.year$^{-1}$, while the intermediate and the tallest have similar ages but very different growth rates in height (3.8 and 6.9 cm.year$^{-1}$, respectively). Meanwhile, the stem diameter at the base seems to grow unrelated to height between 0.24 and 0.49 cm.year$^{-1}$.

Table 3-2. Estimated ages by $^{14}C$ of three E. hartwegiana and their growth rates

| Sample | *R1* | *R2* | *R3* |
|---|---|---|---|
| Height to the base of the rosette (cm) | 65 | 105 | 210 |
| Diameter in the base of stem (cm) | 5.37 | 6.74 | 9.14 |
| F14C ± SD | 1.0731 ± 0.0025 | 1.1903 ± 0.0035 | 1.211 ± 0.0035 |
| Estimated year of germination, calibrated ($^{14}C$) | 2004.1 | 1987.1 | 1985.02 |
| Age (years) | 11 | 28 | 30 |
| Mean growth rate in height *h*/age ($cm.year^{-1}$) | 5.9 | 3.8 | 6.9 |
| Mean growth rate in diameter d/age ($cm.year^{-1}$) | 0.49 | 0.24 | 0.30 |

### 3.3.3 Temperature of the air, leaves and soils

There is no significant difference between mean temperatures measured in the bundle and undersides of leaves. Since the stomata are located on the underside, the measurements of temperature focused on this side. The model with grouped data from both paramos showed a better fit; thus, it can be used for the two species of *Espeletia*.

According to the validated model, the temperature on the underside of leaves ($Tl_e$ in °C) is a function of air temperature ($T$ in °C), relative humidity of atmosphere ($RH$ in %), wind speed ($Ws$ in $m.s^{-1}$), solar radiation ($Rad$ in $Watts.m^{-2}$) and the indicator variable apical leaves ($IV_L$*: 0, 1*). The other indicator variables (middle leaves and height of plant) were not significant to the model, therefore not taken into account in the model. Based on observations and field data, we established that apical leaves are 20% of total leaves. Equation 1 shows the model obtained for the underside ($Tle$, $R^2 = 0.848$) and equation 2 presents the model for the inner temperature of leaves ($Tl_i$ in °C) with $R^2 = 0.935$.

$$Tl_e = -4{,}441 + 0{,}926(T) + 0{,}06(RH) - 0{,}186(Ws) + 0{,}005(Rad) + 1{,}153(IV_L) \quad (1)$$

$$Tli = -20{,}705 + 1{,}457(T) + 0{,}111(RH) + 0{,}008(Rad) \quad (2)$$

With the measurements and observations made in Belmira paramo, it was possible to establish the temperature of soils in its superficial portion -derived from volcanic ashes and of dark color-. The soil temperature follows air temperature, with a wide diurnal fluctuation, and sharp decrease with soil depth (Table 3-3, Figure 3-4a). Measurements showed that soil temperature has a sinusoidal behavior, with frequencies decreasing with soil depth and night time.

Table 3-3. Maximum, minimum and mean temperature amplitude of the diurnal fluctuation measured at different soil depths, inside the frailejones, on the undersides of frailejones leaves, inside the marcescent leaves and in the air in the paramo of Belmira.

| Temperature in °C | Air | Leaves underside | Marcescent leaves | Frailejon inside | Soil at 5 cm | Soil at 15 cm | Soil at 35 cm |
|---|---|---|---|---|---|---|---|
| Mean diurnal fluctuation | 7.9 | 11.5 | 2.9 | 5.1 | 5.7 | 1.2 | 0.52 |
| Maximum | 19.6 | 22.0 | 13.7 | 17.0 | 23.7 | 16.6 | 15.00 |
| Minimum | 5.20 | 10.5 | 10.8 | 7.9 | 12.7 | 12.4 | 12.80 |

Air temperature has the biggest daily fluctuation, with a mean amplitude of 8°C, but its behavior is similar to that measured inside the frailejones, although wider ranges were observed during the lower rainfall periods (Figure 3-4b).

The records of soil moisture show that even in dry periods, the deeper layers remain close to saturation, while the superficial ones, with bigger temporal variations, never had volumetric moisture contents below 0.5 ($cm^3.cm^{-3}$) during the period studied (Figure 3-4c). Likewise, the minimum temperature in soil, at any depth, remained over 12°C (Figure 3-4a).

Additionally, measurements of temperature below and inside the mid vein of mature leaves and inside the marcescent leaves of the same plant, shows that temperature fluctuations underside the leaves is even lower than inside the plant stem (Figure 3-5).

### 3.3.4 Transpiration of *E. occidentalis* and *E. hartwegiana*

Sap flow measurements in frailejones show that transpiration is a discontinuous process during the day, contrary to what happens in other ecosystems. Among the factors controlling transpiration or sap flow in frailejones, are temperature and solar radiation, so these plants respond quickly to these environmental factors, taking into account the rapidly changing conditions of these factors in these environments, mostly related to the presence of fog or low clouds. Actually, a linear model evaluating the statistical assumptions mentioned previously with a significance level of p>0.05, shows that temperature (T in °C), solar radiation (Rad in $Watts.m^{-2}$) and the relative humidity (RH in %) explain 76% of sap velocity variation (Vs in $cm.h^{-1}$) measured at 1.2 cm depth in the plant (equation 3), $R^2$ = 0.765.

$$Vs = 0{,}907T - 0{,}002Rad - 0{,}09RH \quad (3)$$

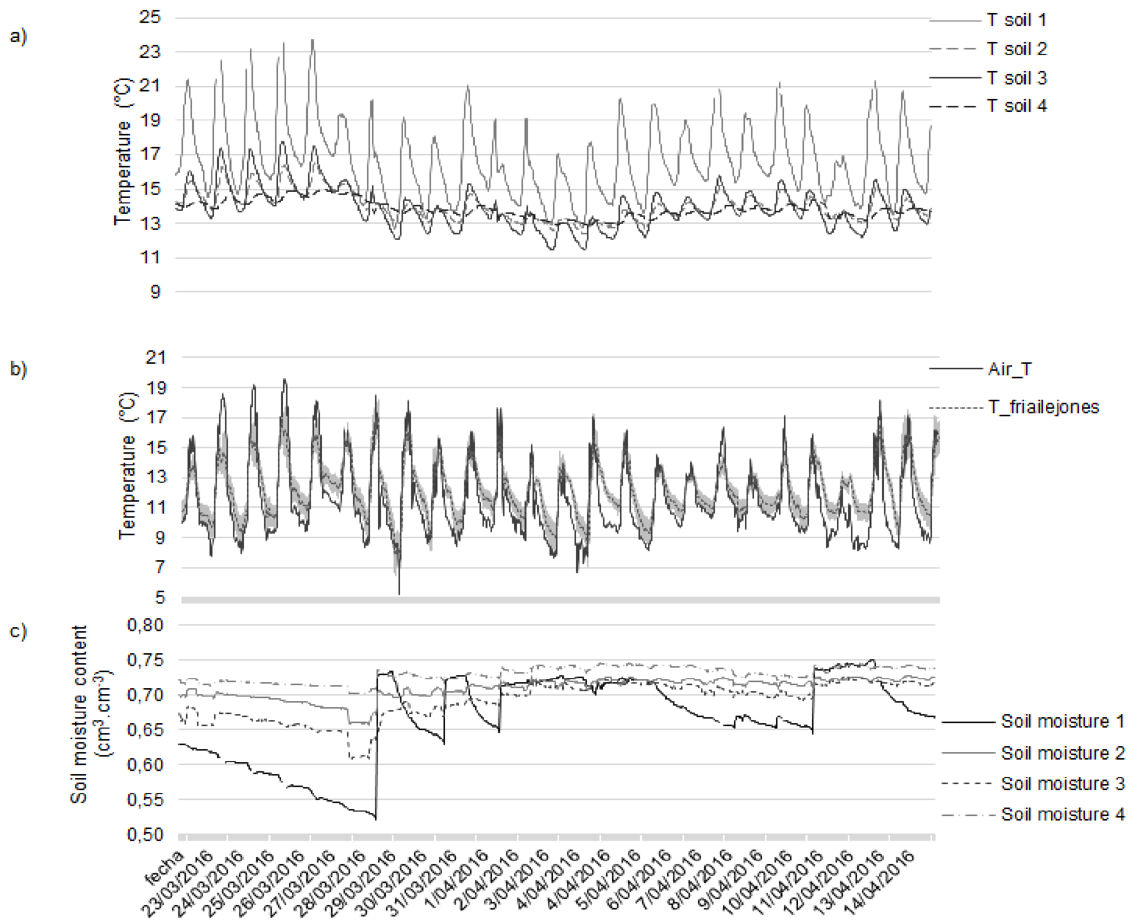


Figure 3-4. Soil temperature (°C) at different depths (a), temperature (°C) of air and inside the frailejones (b), and soil moisture content at different depths (c), measured during March-April 2016.

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For sunny days, even though the environmental stimulus is the same, sap flow, i.e., transpiration, tends to decrease, and sometimes it reaches zero. On the other hand, these plants move small quantities of water -on the order of 0.008 to 0.235 mm per hour in an adult plant- during the night (figure 3-6), probably this is done to recover the water reserves of the pith (Zweifel & Häsler 2001), and possibly the hypodermal layers of the leaves, since there was no evidence of such water movement during night time, possibly explained by the differences in water vapor saturation pressure between leaves and atmosphere or to wind speed (Snyder et al. 2003; Benyon 1999; Hogg & Hurdle 1997).

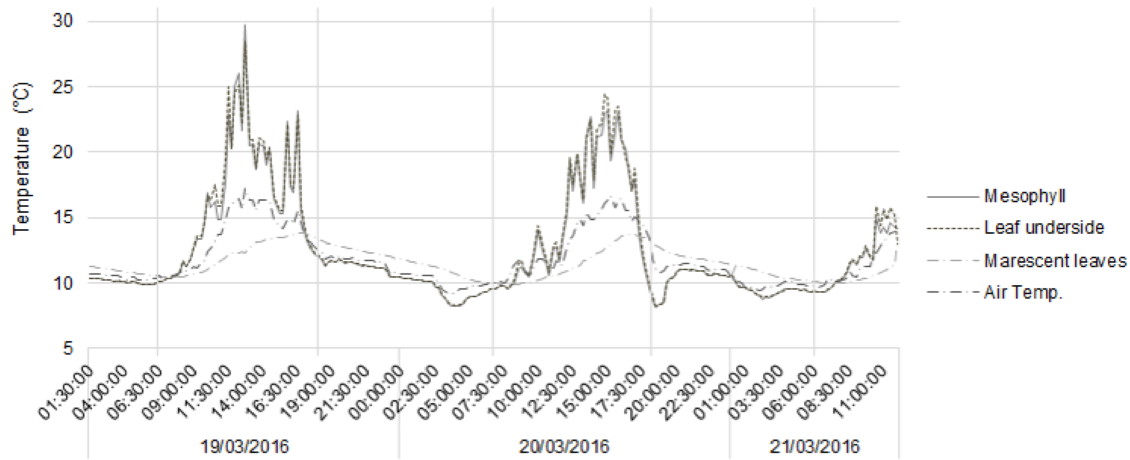


Figure 3-5. Air temperature and underside the leaves, in the mesophyll and in the marcescent leaves of frailejones, measures during 2.5 sunny days in March 2016. The vertical lines indicate the time of sunrise (6:30) and sunset (18:00).

According to the findings and extrapolating the sap flow velocity into water sheet for the entire watershed, it is estimated that the outputs of water through transpiration of *Espeletia* in a dry, sunny season, represents about 21% of outputs via basin discharge, in an ecosystem with 60% water yield.

## 3.4 Discussion

The anatomical adaptations of *Espeletia* to adverse environmental conditions of the paramos, where this genus evolved, occurred not only in its external structure but also internally: the pith thickens increases toward the top of the plant, due to primary thickening meristem. The two species of *Espeletia* studied show a clear allometric relationship between pith diameter and xylem width with plant height, as proposed by Weber (1962), cited by Mora-Osejo (2001). Frailejones possess primary thickening meristems (PTMs, see Figure 3-1) similar to those found in megaphytic monocots (DeMason, 1983). These thickening meristems occur just beneath the stem apical meristem, accounting for the massive pith tissue, located adjacent to the mature leaves of the rosette, where water is in large demand. Moreover, under adverse weather conditions, this supply of water remains for several hours until the water uptake from the soil is restored, thus preventing wilting. Although, in plants of the same species and height, measurements could have some differences, related to environmental factors or external causes, affecting the fit of models;

these results are very important for estimating sapflow, since this equation allows one to estimate the width of the conductive tissue where the sensors are installed, without the need of boring the plant.

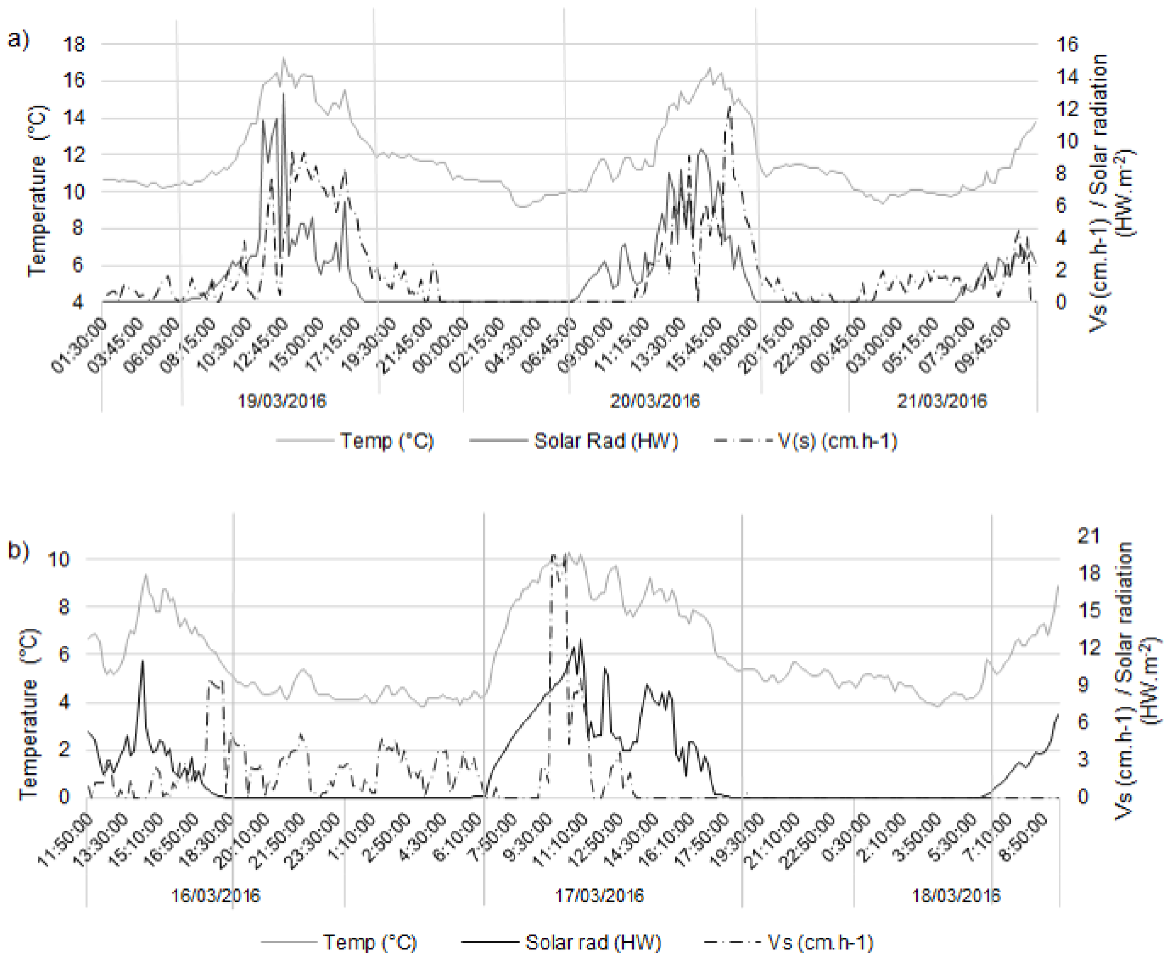


Figure 3-6. Relationship between temperature (° C), solar radiation (HWatts.m$^{-2}$) and sap flow velocity (cm.h$^{-1}$) measured during 2.5 sunny days in the paramo of Belmira (a) and 2 days in Romerales (b). The vertical lines indicate the time of sunrise (at 6:30 in Belmira, 6:00 in Romerales) and sunset (18:00 in both sites).

Temperature of leaves was measured in order to test the hypothesis that a small warming of the leaf surface is enough to increase the water vapor pressure gradient, after which transpiration occurs (Larcher 1995), as an adaptation mechanism to move water and minerals in plants under humid and cold environments as paramos are. However, when we relate the temperatures and the water vapor pressure with other meteorological variables and with the sapflow velocities in frailejones, there are no significant correlations, either instantaneous or lags.

On the other hand, keeping in mind that water moves through plant following a gradient, either of hydric potential, or of water vapor concentration (Lambers et al., 2008), we verify that in the continuous soil-plant-atmosphere in the paramo, neither the soil temperature nor the soil moisture content limit the water movement through the plant tissues, since the paramo of Belmira no longer presents temperatures near the freezing point, both in the atmosphere and in the soil; therefore, the plants are no longer subject to water stress generated by the cold and wet conditions pre-existing in paramos when this genus developed some of the adaptive features described. However, *Espeletia* retains these functional features, fixed by natural selection during evolution and adaptation to the normal specific climatic conditions of paramos (cold and wet). Therefore, the movement of water through *Espeletia* is mainly determined by local weather conditions. We also verify the effect of thermal insulation of marcescent leaves in frailejones, reported as one of the adaptation mechanisms of these plants to face the low environmental temperatures (Azocar and Rada, 1993; García-Varela and Rada, 2003; Meinzer and Goldstein, 1985; Rada et al., 1985). With regard to leaf temperatures compared to air temperature, our results are similar to those reported by Mora-Osejo (2001) for *E. grandiflora*: similar temperatures at night and the early hours at morning, but wide differences during the day, due to the high solar radiation received by leaves. The anatomical modifications exhibited by the succulent leaves typical of frailejones (water storage cells in the multiple hypodermal layers adjacent to the palisade cells of the mesophyll, distinctive stomatal crypts, and heavy, undulating layers of trichomes; see Figure 3-2) may be in response to such variations in high solar radiation exposure to the leaves.

Given the constraints in the paramos for the growth and development of frailejones, it has been assumed that their growth rates are extremely low, on the order of 1 $cm \cdot year^{-1}$ (Azócar and Rada, 2007), so the medium or large plants were considered as centenarians. A review of 15 studies on the current growth rates in height of *Espeletia* presents variations ranging from 0.2 to 14.8 $cm \cdot year^{-1}$ (Ramsay, 2014). So far, the estimation of age in frailejones has been based on two facts: (i) calculating the current periodical growth rates of height ($h$) between two consecutive measurements ($[h_2 - h_1] / [t_2 - t_1]$), where $t_1$ and $t_2$ are the dates of the measurements, (ii) and the assumption that taller frailejones are always older than those of lower height. In relation to fact (i), current growth rates are different from mean growth rates ($h$/age). The use of these small current growths of taller frailejones, as mean growths, tend to greatly overestimate the ages of frailejones. The ontogenetic growths of height are usually sigmoid-shaped curves, when this curve of an individual plant approaches maximum height, current growth tends to zero. The only way to calculate the mean growth of any organism, is to know its age. For wild trees and shrubs with secondary growth, there are two methods to know the age: annual growth rings, and radiocarbon. Trautner (1962) found annual growth rings in *E. neriifolia* in a seasonally dry paramo from Venezuela. However, we found no growth rings in our species, perhaps due to the absence of a dry season in paramos studied. The so named "bomb effect" on the radiocarbon content of the $CO_2$ in the atmosphere is a potent biogeochemistry tracer allowing dating with high precision organic materials produced since 1954 to the present (Reimer et al. 2004, del Valle et al. 2014). The use of this method allows us to determine for the first time the age and mean growth rates of three frailejones (*E. hartwegiana*).

So far, all estimates of the age of frailejones have been based on the false assumption that taller plants are older, but size (as height and diameter in *Espeletia*) are poor predictors of age in all organisms as shown in Table 3-2 in which two of the samples have similar age but almost 100% difference in height, nevertheless they were growing in the same paramo and under the same conditions. Despite the low number of *Espeletia* dated, we obtained mean height growth rates between 3.8 and 6.9 cm.year$^{-1}$, which agree with that found in Venezuelan paramos (Sarmiento et al., 2003). Radiocarbon emerges as an accurate, fast and cost-effective method to determine the age of the species of *Espeletia* without annual growth rings.

According to the environmental conditions of the habitat of frailejones, their low growth rate, we choose the HRM to estimate their transpiration, since it works well when the flow is low or close to zero (Bleby et al., 2004). Transpiration measured in the two *Espeletia* species using HRM, indicate that sapflow during the day is highly influenced by solar radiation and temperature, since soil moisture is not a limiting factor. However, it's interesting to see that periods of sapflow are discontinuous, opposite to what happens in trees, whose transpiration is continued while the environmental conditions are at non-limiting levels. It appears that species of *Espeletia* are adapted to respond very fast to environmental stimuli, meaning, they have a high photosynthetic capacity (Goldstein et al., 1994), necessary in tropical high mountain ecosystems, where unexpected changes caused by variations in radiation and fog presence, lead to short duration of stomata opening, which impacts on the momentary intensities in transpiration and conductance

(Lösch & Schulze 1995, cited by Mora-Osejo 2001). But also, frailejones seem to reach a level at which the sapflow is reduced or completely stopped, maybe as a mechanism of protection against the strong radiation, as suggested by their leaf anatomy. Small quantities of sapflow also occurs discontinuously during the night, which matched the reports of high nightly respiration in these plants (Azocar and Rada, 1993).

One of the more common explanations to the loss of water from leaves to atmosphere at night is the water vapor pressure differential (Becker, 1998; Benyon, 1999; Hogg and Hurdle, 1997; Snyder et al., 2003); but in this study, we established that there is no significant difference in water vapor pressure among frailejones leaves and the surrounding atmosphere, which makes sense in an ecosystem with high air humidity and soil moisture content. The more likely explanation to this nightly water flow is related to the inner reservoirs in the pith and the leaf hypodermal layers, since they provide water to transpiration during the day, but must be re-filled at night, because hydric relationships in trees are determined, in part, by the availability of inner reservoirs for transpiration (Zweifel and Häsler, 2001). It has been shown for several species that the static flow assumption in plants is not true (Snyder et al., 2003) and that the only possible explanation to the lags between water loss by leaves transpiration and water uptake by roots is the inner water storage (Goldstein et al., 1998; Schulze et al., 1985; Steppe et al., 2006). In few words, the amount of water leaving the paramos through transpiration of frailejones is very low, which helps to maintain the high water yield in these ecosystems: the high photosynthetic efficiency of frailejones influences a rapid response to appropriate environmental stimuli to its physiological functioning, but they also seem to have self-regulatory mechanisms that stop sapflow, even when stimuli, such as solar radiation and temperature remains. It does not mean the plants stop their physiological functions, instead they appear continue functioning by using their water storages. Consequently, the nightly sapflow observed in *Espeletia*, might indicate the re-filling of water in the pith and leaf hypodermal water-storage layers, the main water reservoirs of *Espeletia*.

## 3.5 Conclusions

We have verified some of the external and internal anatomical adaptations of the genus *Espeletia* to the environment where they evolved, which make them highly efficient in freezing avoidance and in the use of limiting resources in paramo ecosystems such as water and solar radiation. Some of the consequences of this last are low use of water for their functioning and a relative high mean growth rate, therefore, they may contribute considerably to the hydrological functioning and water yield to the paramo basins.

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# 4. Resilience of soils from paramo ecosystems to variability in rainfall regimes due to climate change


## Abstract

Paramos are montane Neotropical ecosystems of great importance for their large capacity for water regulation and yield, much of which is related to soil. These are usually deep, well developed and contain large amounts of soil organic matter, and some are under the influence of volcanic ashes; therefore, have unique hydro-physical properties and large capacity to store and retain water. However, climatic conditions are changing and, among the expected consequences for the tropical high mountain are the variations in the frequency and quantities of rainfall, resulting in long dry periods and high rainfall intensities. In order to determine the effects of these changes on the hydrological functioning of paramo ecosystems, specifically on their soils, we evaluate, through manipulated experiment, the resilience of soils from three different paramos in Colombia, to climate change, specifically to the presence of droughts. Moreover, soil hydro-physical properties were also investigated in order to understand and explain the results from the experiment, thus the changes on water holding capacity of studied soils. Results show that these organic soils influenced by volcanic ashes loss moisture faster during short drought periods, however for drought periods over 15 days, they retain more plant available water than soils without volcanic ashes. Moreover, the formers have greater ability to re-wet after long dry periods, therefore, they seem to be less vulnerable to climate change, under undisturbed conditions.



Keywords: Climate change, soil vulnerability, paramo ecosystems, soil moisture


## 4.1 Introduction

The paramo ecosystems located at the higher parts of the tropical Andes are noted for the high water yield, related to the exceptionally large capacity of soils to store and retain water (Buytaert et al., 2006). This is largely due to their high organic matter content and high porosity, attributed to the rather adverse climatic conditions (e.g. permanent low temperatures and high air humidity), which protrudes in low decomposition of soil organic matter (SOM). The latter is further enhanced by the abundance of amorphous alumino-silicates, released upon weathering of deposited volcanic ashes. (Mena et al., 2000; Tonneijck et al., 2009). Therefore, paramo ecosystems, with soils that commonly classify as Andosols, play an extremely important role in the hydrology of the Andes, acting as one of the largest water yield ecosystems for Andean population (Buytaert et al., 2006).

Most studies on the impacts of climate change on ecosystem hydrology focus on the aboveground compartment – the vegetation - and only relatively few paid attention to soils (Bruijnzeel, 2004). The latter studies largely concern expected increases in air temperature and atmospheric $CO_2$, and their effects on soil carbon and nitrogen dynamics, which may indirectly lead to changes in hydro-physical properties (Davidson & Janssens 2006; Qafoku 2015). In very few studies - if any – attention is paid to direct effects that relevant climate changes, such as lesser rainfall or increased length of drought periods, may have on these soil properties. Thus, a gap exists in the understanding of these impacts, specifically on the capacity of the soil to store and retain water, and the consequences that eventual changes in water holding capacity of paramo soils may have for the eco-hydrological functioning of these tropical ecosystems (Buytaert et al. 2010).

Current scenarios for climate change in the higher Andes predict increases in the length and frequency of droughts, in addition to an increase in temperature (Mena et al 2000; Urrutia & Vuille, 2009; Ruiz et al., 2011). From earlier studies on impacts of land use and concurrent soil degradation, it is known that the physical properties of paramo soils may be significantly affected by such droughts, due to a loss of porosity and eventual development of water repellency (Jaramillo 2006). Moreover, Climate change will likely change the soil water balance by increasing water demand through evaporation and transpiration, connected to the higher temperatures and changes in rainfall inputs (Föster, 2001). Both, land use and climate changes, may lead to a decrease in soil water retention and storage capacity, which might be reversible, but after crossing a threshold may become irreversible (Maeda et al. 1977; Mena et al. 2000). However, no systematic, experimental study exists on the impact of prolonged drought on hydro physical properties of paramo soils.

To provide some insight on these issues, we pursue an experimental approach to investigate the vulnerability of paramo soils to climate change. In this paper, results of the experiment are presented, together with field data from three paramos in Colombia. In the experiment, periods of drought and conditions during drying were chosen to closely resemble the actual field situation. Results are interpreted in terms of the vulnerability of the Colombian paramo ecosystems to changes in soil hydro-physical dynamics and concurrent catchment hydrology, as a result of climate change.

## 4.2 Methodology

### 4.2.1 Paramo sites

This study was conducted in three Colombian paramos: Chingaza (Cundinamarca) located in the Eastern Cordillera, Belmira (Antioquia) and Romerales (Quindío), on the Central Cordillera. These paramo ecosystems were selected, being representative for the range in soil and climate conditions of Colombian paramos (Table 4-1).

Differences on altitudes and exposition result in different climatic conditions among the three sites, as rainfall (Table 4-1) and fog inputs and soil organic matter accumulation, being the paramo of Chingaza the wettest one, with deeper soils (O, A, Bw and C with an average soil depth of 1.1 m) and higher SOM, followed by Romerales (A, Bw and C, with an average soil depth of 0.78 m) and Belmira, with relative low SOM soils (A, Bw and C), and average depth of 0.43 m.

Table 4-1. Main characteristics of studied ecosystems and soils.

| | |
|---|---|
| **Chingaza** | |
| Location 04° 39' 39.6 N 73° 50' 00.0 W | Altitude 3060 masl |
| Annual rainfall 3500 mm | Average temperature 12°C |
| Main soils classes (Soil Survey Staff 2004) | Developed from Glacier movements (Lahars), shales and sandstones, with high SOM, without volcanic ashes. Main soils classes are: Entisols, Inceptisols and Histosols (Vargas & Pedraza 2003, Rondón 2000, Rangel 2000) |
| Main vegetation species | E*speletia sp. Senecio garcibarrigae, Miconia wurdackii, Calamagrostis* sp., *Sphagnum magellanicum and Chusquea tessellata (*Premauer & Vargas 2004) |
| Predominant land use | Under conservation program, providing water for population in Bogotá (Colombia) |
| **Romerales** | |
| Location 04° 40' 52.8 N 75° 24' 52.1 W | Altitude 3770 masl |
| Annual rainfall 1200 mm | Average temperature 8°C |
| Main soils classes (Soil Survey Staff, 2004) | Soils are developed from moderately to weathered volcanic materials, with pyroclastic and basaltic material and abundant ashes deposited throughout the time. Main soils classes are Andisols, Inceptisols and few Histosols (Nelson 1957, IGAC 1995, Thouret et al 1985) |

| | | |
|---|---|---|
| Main vegetation species | *Calamagrostis effuse, Espeletia hartwegiana*, H*ypericum cf. laricifolium* y *Gynoxys sp. – Clethra revolute* (Rangel 2000, Alvear 2000) | |
| Predominant land use | Extensive cattle and some crops, which generates soil degradation. | |
| **Belmira** | | |
| Location 06° 39' 44.6 N 75° 40' 27.0 W | | Altitude 3089 masl |
| Annual rainfall 1850 mm | | Average temperature 11°C |
| Main soils classes (Soil Survey Staff, 2004) | Derived from igneous and metamorphic rocks, and granitic plutonic, partially covered by weathered volcanic ashes. Entissols and Inceptisols and few patches of Andisols (IGAC 1995) | |
| Main vegetation species | *Espeletia occidentalis*, *Monochaetum* sp., *Hesperomeles heterophylla*, *Diplostephium revolutum* and *Puya roldanii* (Parra & Valencia 1998) | |
| Predominant land use | Past extensive cattle and mining, result in a large soil degradation. From 1990, the paramo is under conservation program. | |

### 4.2.2 Measurements

In each paramo we measured precipitation over a two years period (2014 and 2015), on hourly basis, from which the former is considered as a "normal" year regarding ENSO phenomena, but during the second half of the following year (2015) occurred El Niño event, which slightly reduced rainfall in Colombia. To measure climatic conditions, we installed automatic weather stations at each paramo (Campbell Scientific ®), and two extra rainfall gauges (Texas instruments ®), randomly distributed within the studies catchments.

For soil properties determination and for the experiment, soil samples were collected at different sites within each paramo. Soil classes and soil horizons were the criteria used for soil sampling, which determines de number of sampling sites needed to represent the entire soil conditions at each paramo. Belmira has relatively homogeneous soils (very shallow and only two main soil classes); therefore, five specific sites were selected for sampling, as representative for soils at this paramo. Paramo of Chingaza has organic, well-developed, but less homogeneous soils, therefore 30 sites were selected for sampling. Finally, Romerales has organic and well developed and homogeneous soils, thus 9 sites were selected, as being representative for the soils classes found in this paramo.

In order to understand and discuss results from the experiment we investigate specific soil properties related to soil water dynamics. For soil texture, triplicate samples of 200g were collected from each site and soil horizon and subjected to a modified sieve–pipette sedimentation method (Gee & Bauder 1986). For bulk density, undisturbed samples were collected with stainless steel rings of 100 $cm^3$ at each site and soil horizon. The samples were weighed and oven-dried at 105°C for 48 hours, and bulk density was calculated as the ratio of the mass of the oven-dry sample to its bulk volume. Soil organic matter content (SOM) was determined in the laboratory using soil samples collected from each site and soil horizon, by analyzing them through the Weight Loss on Ignition method (Abella et al., 2007)

To determine the soil water retention curves (WRC), triplicate samples were collected from each soil horizon, at each site, by using metallic ring cores of 5 cm diameter and 1 cm height. In the laboratory, samples were saturated in a sand box with water. A pressure-plate apparatus was used to determine moisture contents associated with pressure heads from saturation up to 1500 kPa, weighing the samples after reaching equilibrium (Klute & Dirksen 1986). From the WRC measurements, plant available water (PAW) was determined for each sample, according to Tobón et al. (2010) and Saigusa et al. (1987).

Moreover, soil moisture was automatic measured at the different sites, and soil horizons (O, A, Bw and C), through Time Domain Reflectometry technique (TDR), using CS625 and CS616 TDR sensors (Campbell Scientific ®) horizontally installed at five different soil depths according to soil horizon distributions (5, 15, 25, 50 and 100 cm). Field measurements were calibrated according to Tobón et al (2010).

For the experiment, triplicate undisturbed soil samples (cores of 7.5 x 7.5 cm) were collected from each ecosystem, at the different sites and soil horizons (O, A and Bw) The experiment consisted of drying, previously saturated soil samples, for certain fixed periods, followed by rewetting and establishment of their moisture content upon being rewetted. Samples were saturated by putting them on a sand box with water for a number of days resulting that 15 days were sufficient to reach saturation conditions. Samples were subsequently subjected to droughts inside the ecohydrology laboratory (Universidad Nacional de Colombia), which was kept at a temperature of around 24°C and 18°C (day and night respectively), and at 65% and 85% air humidity during the day and night. Drying periods were successively increased as follows: 1, 3, 5, 8, 12, 15, 20, 30, 40, 50, 60, 70, 80, 90, 100, 120 and 130 days. After each drying period, samples were weighted and rewetted again during 15 days and immediately weighted, to establish their moisture content before starting the next cycle of drying. Samples were weighed on electronic balance (Scout Pro brand ®), with an accuracy of 0.01 gr.

### 4.2.3 Data analysis

Temporal trends of water loss by samples during drought events are expressed as cumulative values (%) and relative values for each drying period (%). The water content remaining in the samples after each drying period, as the average value for all samples from each site, is also shown, as the percentage of total moisture content of soils at saturation.

For comparison between results from the experiment and field conditions we used field data on soil water content from the A horizon, as an example, for the largest droughts occurring during the period of field measurements at Belmira, where largest drought periods last for 13, 14, 15 and 20 days, and Romerales, where droughts of 12, 14, 19 and 41 days were selected.

## 4.3 Results

### 4.3.1 Trends of precipitation in studied sites

The analysis of the frequency of dry spells, in this case, periods without rain or with less than 1 $mm.day^{-1}$ (Figure 4-1) recorded during a normal year without ENSO (2014) and a year with El Niño (2015), shows that in Belmira and Romerales a similar number of drought events occurred for 2014 (63 and 62 respectively), paradoxically these values decreased in the year El Niño. In Belmira half of these events last for one day, while in Romerales the events of 1, 2 and 3 days were common. As for the number of dry spells, Belmira registered the largest one, with 20 days, followed by one of 14 and the third of 9 days in 2014. In Romerales there were droughts of 14 and 12 continuous days (2014). As for 2015, there were periods of 15 and 13 days of draughts in Belmira, for Romerales there were 41 and 19 days. Meanwhile, Chingaza paramo shows the lower number of dry spells, where the largest drought was 10 and 16 days for 2014 and 2015 respectively.

### 4.3.2 Soil properties

Table 4-2 shows the average, maximum and minimum values of soil properties from each site and soil horizon down to a depth of horizon C. Soils from Chingaza show the highest values of SOM in all soil horizons, followed by soils in Romerales paramo. Minimum values were found for soils in Romerales and Belmira, in Bw and C soil layer. This indicates either that there is continuous addition of soil organic matter by vegetation of the paramos, or the rate of decomposition is lower than the addition, therefore it accumulates in the superficial soil layer.

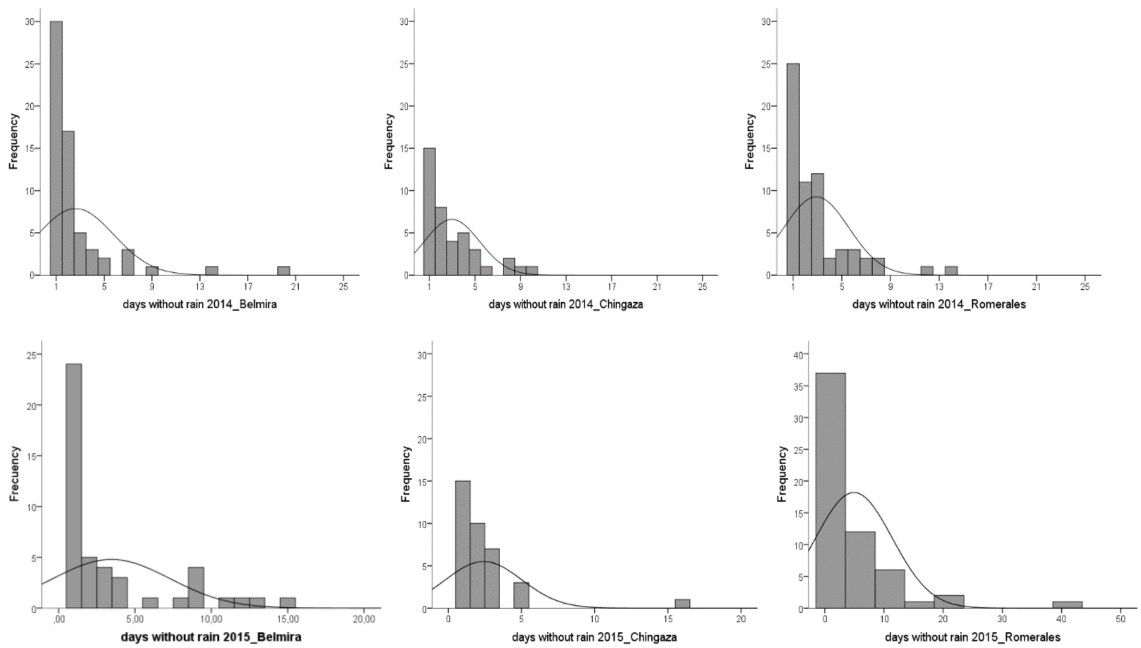


Figure 4-1. Frequency histograms for the number of dry spells in the studied sites during normal year (2014) and El Niño year (2015).

Bulk densities were relatively low throughout the soil profiles, for the three paramos, including the C horizon, which showed the highest BD. The lowest average and minimum values for BD were found in soils from Chingaza paramo (Table 2), followed by those in Belmira and Romerales, which seems to be related to the large SOM content and the volcanic ashes. Comparing BD mean values within the same profile, there were significant differences ($p < 0.05$) between different soil layers, for all sites.

Sandy loam to loamy textures dominate the particle size distribution of soils from studied ecosystems, throughout the soil profiles. Differences in texture between sites, reflect differences in SOM, where soils with higher SOM are loam to clay loam. In volcanic soils, sandy loam textures could be related to the aggregates formed by the organic matter moving through the soil profiles, hampering complete dispersion of mineral particles during textural analysis, resulting in an underestimation of clay content (Shoji et al. 1988).

Table 4-2. Values for soil organic matter and physical and hydraulic properties of soils from alpine tropical ecosystems in Colombia

| Paramo | Horizon | Avg. depth (cm) | Organic Matter Content (%) | | | BD ($g.cm^{-3}$) | | | Texture |
|---|---|---|---|---|---|---|---|---|---|
| | | | Avg. | Max | Min | Avg. | Max | Min | |
| Belmira | A | 18,5 | 19,37 | 27,84 | 13,38 | 0,565 | 0,804 | 0,359 | Sandy – sandy loam |
| | B | 22,9 | 8,82 | 10,62 | 6,78 | 0,701 | 0,842 | 0,527 | Sandy – sandy loam |
| | C | | | | | 0,714 | 0,846 | 0,585 | Sandy |
| Chingaza | O | 8,2 | 34,99 | 42,55 | 27,50 | 0,331 | 0,367 | 0,298 | Loam |
| | A | 14,4 | 26,89 | 34,30 | 20,52 | 0,407 | 0,486 | 0,331 | Loam |
| | B | 25,3 | 16,91 | 22,20 | 12,77 | 0,555 | 0,667 | 0,399 | Sandy clay loam |
| | C | 35,1 | 7,84 | 11,10 | 5,80 | 0,714 | 1,045 | 0,562 | Sandy clay loam |
| Romerales | A | 42,7 | 17,36 | 24,5 | 7,19 | 0,593 | 0,708 | 0,484 | Sandy loam |
| | B | 29,0 | 11,84 | 17,35 | 1,35 | 0,619 | 0,690 | 0,564 | Sandy loam |
| | C | | 4,434 | 6,01 | 1,64 | 0,915 | 1,180 | 0,680 | Sandy |

Water retention curves (WRC) of studied soils, showed similar tendencies for the three paramos, with a pronounced decrease curve at low suctions and very gentle at high suctions. This implies a large water releases at low suctions and more gradual releases at high suctions. Values differ slightly between the upper soil horizons (O and A) and subsurface one (Bw) soil layer, and between the three paramos (figure 4-2). Moreover, soils from these appeared to retain large amounts of residual water at wilting point (33%), indicating that studied soils trapped large amount of water in smaller pores or they have considerably large amount of these micropores. From the pore size distribution, we found that studied soils, in fact have larger percentage of micropores; except for undisturbed soils in Chingaza, which have a very large content of macropores (57% in A horizon).

Results from the PAW calculations indicate that soils from Chingaza have the largest PAW, followed by those in Romerales, with lowest values found in Belmira soils (table 4-3), which seems to be related to the amount of SOM at each soil horizon in studied paramos, plus de presence of volcanic ashes.

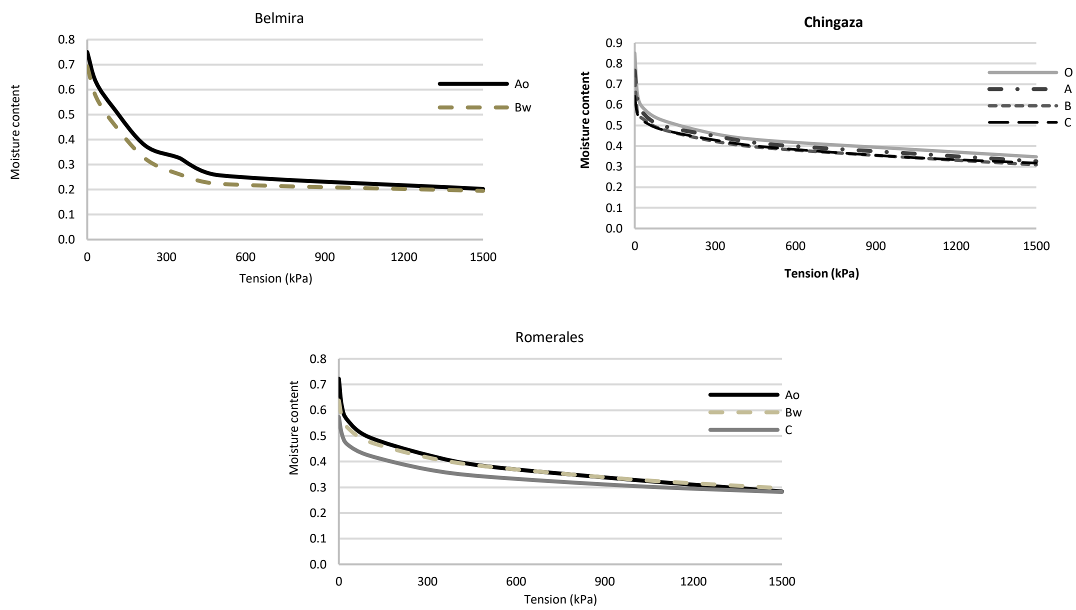


Figure 4-2. Representative water retention curves (WRC) for the sampled soil horizon, in the three paramos

Table 4-3. Volumetric soil moisture and plant available water (PAW), at field capacity and wilting point for studied soils.

| **PE** | **Horizon** | **Moisture content** | | | **PAW** |
|---|---|---|---|---|---|
| | | **10 kPa** | **33 kPa** | **1500 kPa** | |
| **Belmira** | A | | 0,61 | 0,26 | 0,35 |
| | Bw | | 0,54 | 0,22 | 0,32 |
| **Chingaza** | O (0 - 10 cm) | 0,65 | 0,59 | 0,30 | 0,35 |
| | A (11- 30 cm) | 0,62 | 0,56 | 0,28 | 0,34 |
| | B (31 - 60 cm) | 0,56 | 0,53 | 0,27 | 0,29 |
| | C (70 - 100 cm) | 0,55 | 0,52 | 0,32 | 0,23 |
| **Romerales** | A | 0,62 | 0,56 | 0,28 | 0,34 |
| | Bw | 0,58 | 0,53 | 0,30 | 0,28 |
| | C | 0,51 | 0,47 | 0,28 | 0,23 |

### 4.3.3 Soil water dynamics under drought conditions

Average values of the percentages of cumulative and relative loss of saturation capacity of soils from the three paramos are presented in Figure 4-3 to 4-5. Belmira soils appeared to be able to re-wet almost completely, to the initial conditions of saturation, for droughts up to 15 days. After this, the capacity to re-wet gently decreased to values near to water residual (30% out of the initial 67% of moisture capacity), when droughts lasted for 100 days in a row (Figure 4-3). Moreover, the spatial variability of the loss of soil water holding capacity is large, both with soil depth and sites (see Figure 4-3 b and c), implying that soils from this ecosystem are very heterogeneous in their properties; therefore, in their responses to processes as droughts and re-saturation.

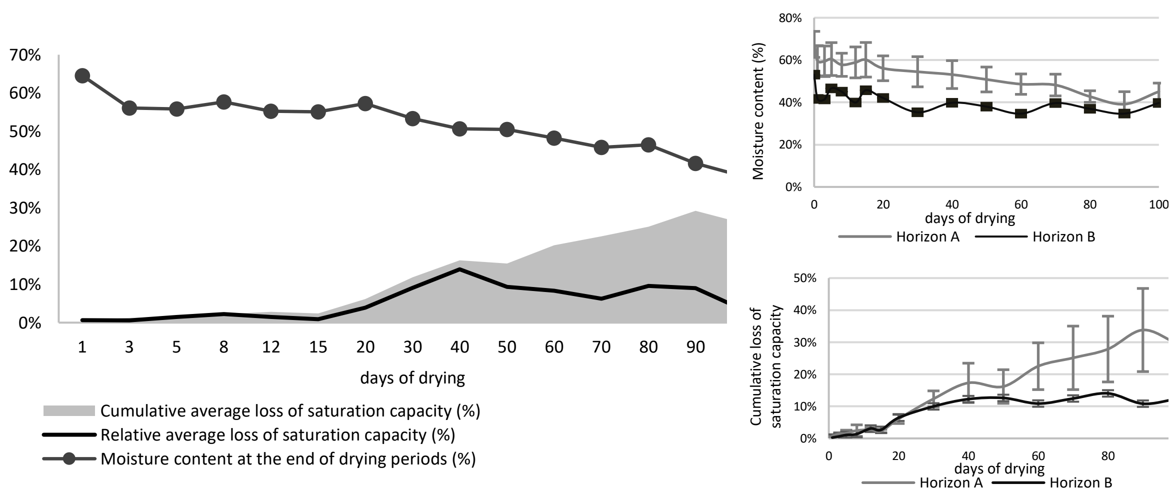


Figure 4-3. Loss of soil saturation capacity and soil water content from Belmira for the entire period of the soil drying experiment. The figure on the left shows the average values, while figures on the right show the tendencies for soil moisture and cumulative loss of saturation capacity, for the different soil horizons

Soils from Chingaza re-wetted completely, for drought periods up to 5 days only. After this, they slightly lose their capacity to re-wet, until a drought period of 100 days in a row, from where soils lost their capacity to restore the initial water conditions, losing more than 50% of their total water holding capacity (Figure 4-4). Noteworthy, the water content in soil samples was below 20% of their total water, after 130 drying days, which means that soil moisture decreased below water residual values. As expected, the moisture contents are higher in the organic (O) horizon, followed by the A horizon; however, the loss of saturation capacity, after 80 days, is higher on the O horizon, followed by the A. After 110 days of drying, all horizons have similar tendencies on water loss and capacity to re-wet (Figure 4-4).

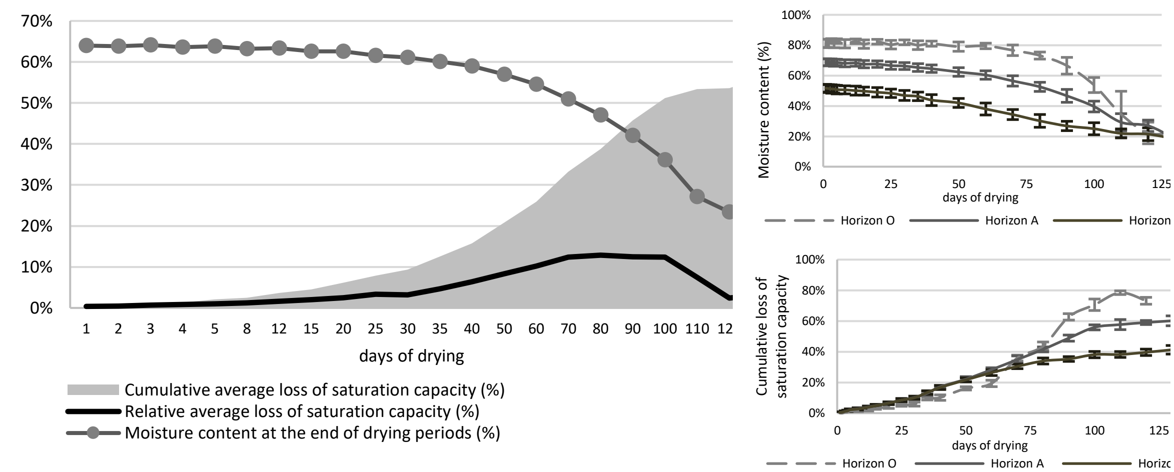


Figure 4-4. Loss of soil saturation capacity and soil water content from Chingaza, for the entire period of the soil drying experiment. The figure on the left shows the average values, while figures on the right show the tendencies for soil moisture and cumulative loss of saturation capacity, for the different soil horizons

In Romerales soils were capable of re-wet completely, to their initial conditions of saturation, for drought periods up to 20 days. After this, they were not capable of complete recover the initial capacity to re-saturation (Figure 4-5). Soils from these ecosystems show that after 120 days without rain, the soil water content was over 40% of their total water holding capacity, i.e., they only loss 20% of their saturation capacity. The A and Bw soil layers follow very similar trends; both in the rate of loss of water holding capacity and in soil moisture content after the different drying periods (Figure 4-5 b and c).

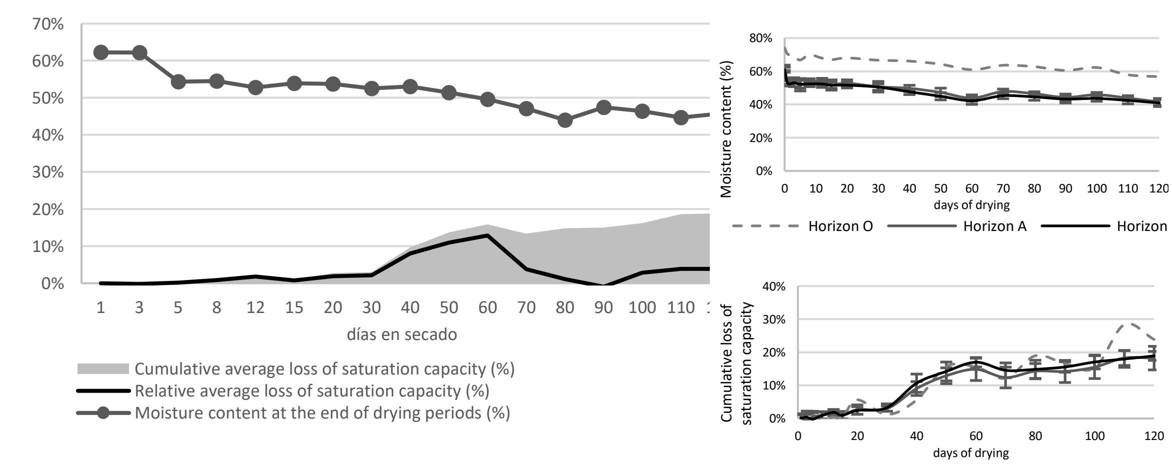


Figure 4-5. Loss of soil saturation capacity and soil water content from Romerales, for the entire period of the soil drying experiment. The figure on the left shows the average values, while figures on the right show the tendencies for soil moisture and cumulative loss of saturation capacity, for the different soil horizons

As indicated in Figures 4-4 to 4-6, studied soils derived from volcanic ashes mixed with organic matter, as those from Romerales and Belmira remained with available water after a drought of 100 days, while those from Chingaza, which are not influenced by volcanic ashes, had not available water, after this dry period, becoming soil moisture even below threshold values of witling point.

Results from the laboratory experiment, were compared with field measurements of soil water content at the horizon A, during the largest drought period observed in Belmira and Romerales paramos. Results show significant differences between the amounts and rates of water loss measured in the field and in the laboratory (Table 4-4). These values might change according to the site, being rates larger in Romerales, the time of the year, the vegetation, and additional inputs to soil moisture, as fog interception by vegetation.

Table 4-4. Water loss rates during drought events in daily volumetric moisture content (VMC) ($cm^3.cm^{-3}.day^{-1}$)

| Paramo | Laboratory experiment | | | Field measurements | | |
|---|---|---|---|---|---|---|
| | **days** | **VMC lost** | **rate** | **days** | **VMC lost** | **rate** |
| **Belmira** | 12 | 0,038 | 0,003 | 13 | 0,157 | 0,012 |
| | 15 | 0,032 | 0,002 | 14 | 0,119 | 0,009 |
| | 20 | 0,087 | 0,004 | 15 | 0,154 | 0,010 |
| | | | | 20 | 0,180 | 0,009 |
| | Average | | 0,003 | | | 0,010 |
| **Romerales** | 12 | 0,323 | 0,027 | 12 | 0,019 | 0,003 |
| | 15 | 0,343 | 0,023 | 14 | 0,006 | 0,001 |
| | 20 | 0,349 | 0,017 | 19 | 0,020 | 0,002 |
| | 40 | 0,434 | 0,011 | 41 | 0,017 | 0,001 |
| | Average | | 0,020 | | | 0,002 |

## 4.4 Discussion

Resilience of studied soils seems to be dependent upon the severity of the droughts and soil properties related to their capacity to store and retain water. Regarding the change on actual climatic conditions, it is clear from the GCMs that higher altitude ecosystems may be affected by climate change even more strongly than lowland sites (Foster, 2001); however, the length of droughts are very much site dependent (Föster, 2001). This applies for studied paramo ecosystems, where there was large variability between the length and frequency of droughts among paramos. From the precipitation records, in studied ecosystems, during 2014 (normal year) and 2015 (El Niño), it can be inferred that Chingaza is less vulnerable to changes in rainfall regimes, not only because it got the largest amount of annual rainfall during El Niño year, but also because it had less number of days without rainfall, and droughts are relatively short compared with those in the other two paramos. Contrary, Belmira got less annual rainfall in 2015, and more periods without rain, and had the largest drought period, even in the normal year. Although this may not be directly related to climate change, it provides an indication of tendencies on rainfall anomalies during El Niño Southern Oscillation phase.

Concerning the capacity of soils to retain water and re-wet after dry spells it was observed that for short dry periods, up to 15 days in a row, paramo soils do not loss considerably amounts of water and can re-saturate almost completely. However, differences existed between studied paramos, in their loss of water during the droughts and capacity to re-wet. Belmira soils, although they are partially disturbed and has less SOM, they were capable to re-wet almost completely, after droughts up to 15 days in a row, with more gently decaying curve of water loss during the experiment. Moreover, in a drought of 100 days, soils from this paramo lost only 30%, out of the total water storage capacity. Romerales soils seem to have similar tendencies, but the amount of water loss during droughts is much lower than soils from Belmira and Chingaza, and the capacity to re-wet last for droughts up to 120 days in a row, losing only 20% of their total water storage.

Contrary, soils from Chingaza, although they have the largest amount of SOM, among studied soils, they seem to be more vulnerable to climate change, in terms of drought lengths. Only for dry periods up to 5 days, soils were capable of re-wet to initial conditions, and which they were not capable of recovering their initial capacity to re-saturate completely. Moreover, after a drought of 100 days, soils have lost 50% of the initial water storage capacity and only 20% after a 130 dry days in a row.

Differences here, on soil capacity to store and retain water, may be explained by soil properties and soil disturbance, thus their resilience to be altered by climate change. Concerning soil properties, it is well known that SOM increases soil water retention and storage capacity (Buschiazzo et al. 2004; Rawls et al., 2003). This seems to be enhanced by the presence of volcanic ashes (Hincapie and Tobón, 2014; Mena et al., 2000; Tonneijck et al., 2009). Therefore, the abundance of SOM plus the presence of volcanic ashes in studied soils seem to reinforce their capacity to retain water for long dry periods without losing their capacity to re-wet, as those from Romerales and Belmira. Contrary, soils with high SOM, but without the influence of volcanic ashes, loss more water during the droughts, and resist shorter dry periods without being affected (only 5 days without rain).

Results from water retention capacity analysis indicate that studied soils have large capacity to retain water (Table 4-3); however, they also show large values for soil moisture content at wilting point, which is, large amounts of residual water, lasting in the soil a snot available for plants. These were larger for soil in Chingaza (non-volcanic soils) tan from Romerales, where soils have large amounts of volcanic ashes. This implies that among studied soils, those from Chingaza are more affected by rainfall anomalies (droughts) than those from Romerales and Belmira. However, specific conditions and properties of soils from Belmira, notably, shallow soils and sandy textures, have important implications for soil water dynamics under droughts.

Moreover, soils derived from volcanic ashes, shows a strong "hysteresis" when dried (Shoji et al. 1993), which is explained by the presence of inorganic non-crystalline materials such as allophone, making the greatest contribution to this irreversible change. Tsutsumi et al. (1977) compared the water retention at 33-1500 kPa of field-moist, air-dried and oven-dried Andosols and found that the irreversible reduction in the water retention occurred following the air-drying process. This partly explains the results here, where available water and the capacity of soils to re-wet, after each dry period, decreased, to a threshold where soil re-wetness was no longer possible. This is related to the fact that liquid and plastic limits of volcanic ash soils greatly decrease with drying, as compared to other mineral soils; however, the effect of drying on the liquid and plastic limits of soils is small when the soils are air-dried. Though liquid and plastic limits of volcanic ash soils are not affected by the decrease in the initial water content to a certain threshold, from where the process is irreversible (Tsutsumi et al. 1977; Shoji et al. 1993).

It is well known that Andosols retain a large amount of water in soil pores of varying size (Saigusa et al. 1987). However, when Andosols contain considerably amounts of organic matter, as those occurring in studied paramos, the capacity of soils to store and retain water increase (Buschiazzo et al. 2004), thus increase their capacity to recover from droughts. This partly explains the results here, where for droughts larger than 80 days in a row, soils without ashes (Chingaza) showed a deficit of plant available water, while the others, with volcanic ashes (Romerales and Belmira), remained with some available water. However, when they are affected by land use, soil porosity is diminished (Tobón et al. 2010), therefore disturbed soils, although they are of volcanic origin and have large amounts of organic matter, they are no longer capable of retain a considerable amount of available water (Huntington 2007; Buytaert et al. 2006; Tobón et al. 2010).

Several studies have demonstrated a positive relationship between soil organic matter content and water retention capacity, concluding that organic carbon plays a substantial role in defining water retention capacity of soils (Rawls et al., 2003). This may be related to the fact that organic matter affects the structure of soils (Rawls et al. 2003), improve soil aggregate formation and stability (Haynes & Beare 1996), and modifies the availability of adsorption of water by soil particles (Christensen 1996), therefore, it improves the capacity of soil to store and retain water (Hudson 1994; Rawls et al. 2003). Moreover, physical and chemical properties of organic matter influence the soil water retention, according to its quality (Huntington, 2007).

According to the “Birch effect”, when organic soils become dry during droughts or when they are dried in the laboratory, and after they rewet again, there is a considerably increase of humus decomposition and mineralization of organic matter (Birch 1964). Moreover, the water holding capacity of organic soils decreases as the decomposition of organic matter increases (Brandyk et al. 2003), which is related to the increases on the polymerization of humic substances. The interaction of these substances with the mineral fraction of soils, produce a decrease of soil water holding capacity to the point when it becomes hydrophobic (Silva & Mendoça 2007). However they tend to behave differently in relation to the maximum water holding capacity at low and high suctions, pending on the state of decomposition of SOM (Da Rocha et al. 2011) and the presence of other soil material. This explains the differences on reduction of water holding capacity of soils throughout the simulated droughts, between studied paramos. Additionally, the subsidence process of swelling and shrinkage of the soils, resulting from the drying and wetting process, produces a decrease in soil porosity and increase on soil density (Brandyk et al. 2003), which contributes to the reduction of the soil capacity to re-wet completely to the initial conditions, when subject to prolonged and continuous dry and wet seasons in the nature.

Finally, the rates of loss of water are significantly different between the laboratory results and the field measurements. In the case of Belmira, this might be due to the loss of water of soil by plant transpiration, since in the laboratory, samples were in shade and only lost water by evaporation, but the paramo has a lot of vegetation and receives high radiation. Romerales shows an opposite behaviour, with higher rates of water loss from analysed samples in the laboratory, but in the field, the losses of soil water are very low. An extra analysis shows that, in fact, the drought periods in this paramo match the periods of higher inputs of fog water from horizontal precipitation, so the soil retains large part of its moisture.

## 4.5 Conclusions

Although predictions of climate change by GCMs indicate water stress increases in many tropical regions and decreases in soil moisture, in studied paramos these changes seem to be site-dependent. During the studied period, paramo of Chingaza observed lower changes on the amount of precipitation and frequency and length of droughts, while Belmira had the larger changes, followed by Romerales. According to the results, in the absence of precipitation or when current rainfall regimes changes, there is a consequent loss of soil capacity to retain water and recover initial moisture conditions.

Studied soils from paramo ecosystems in Colombia have either high SOM without volcanic ashes or with volcanic ashes, and depending on this combination they exhibit specific soil properties as loamy soil textures, low bulk density, high saturated hydraulic conductivity and high water retention. According to these properties, they behave differently in the soil-water relationships. Both of them, appeared to loss large amounts of water in short droughts, but they were capable of re-wet completely after these periods. However, for longer dry periods, soils derived from volcanic ashes combined with organic matter, have greater resilience in terms of moisture storage and re-saturation capacity than those without ashes. Actually, after 80 days of drought, soils without ashes show a deficit of plant available water, while the other two keep available water up to 0.25 $cm^3.cm^{-3}$. The results are particularly interesting because soils derived from volcanic ash belong to the paramos that have been or still are subject of land uses different to conservation, affecting their initial physical properties. Therefore, paramos with soils with volcanic ashes and subject to land uses of conservation, are more resilient in terms of their hydro-physical properties, their water storage and re-saturation capacity.

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# 5. Hydrology of Colombian paramos: current and projected conditions, considering climate change scenarios

## Abstract

High mountain ecosystems are very important as water providers and regulators. In northern Andes, paramos are ecosystems highly recognized by their hydrological properties, however, there are not enough information about their current hydrological functioning or the expected changes on their hydrological processes, due to climate change. In this work, we present a characterization of hydro-meteorology of three Colombian paramos, analyzing their hydrological response, their water regulation capacity and their water yield. To evaluate the hydrological effects of climate change, we applied the WaSim hydrological model to each basin, with hourly temporal and 15m spatial resolutions, which is used to project their hydrological responses, considering six climate change scenarios for the medium term (two rainfall realizations for expected average and extreme dry years and the 2.5, 4.5 and 8.5 RCP for temperature anomalies), to assess the possible changes in the response of each paramo to climate variability. Our results show that soils and climatic characteristics of Colombian paramos are the key control for the hydrological functioning of these ecosystems with good water regulation and high water yield, over 60% in most cases. We also found that projected increases in temperature are more relevant than expected changes in rainfall regimes in studied high mountain ecosystems, and these changes in temperature determine the variations in hydrological response of paramos, increasing evapotranspiration and reducing the discharge.

Keywords: climate change, paramos hydrological functioning, water yield, tropical high mountain hydrology, WaSim hydrological model

## 5.1 Introduction

Mountains are complex and fragile ecosystems characterized by verticality, highly differentiated climatic conditions and often by an abundance of water and rich biodiversity (Becker 2005), thus, they are key elements of the global geosphere-biosphere system (Diaz et al. 2003) and, in particular, mountains are a key element of the hydrological cycle, being the source of many of the world's major river systems (Beniston et al. 1997), and providing life-sustaining water for most regions of the world (Diaz et al. 2003).

High-elevation mountain areas are generally water-rich but data-poor (Beniston et al., 1997), and are especially unknown in the tropical zone. Most studies on the hydrological functioning of basins in the tropical mountain ecosystems, have been especially focused in the effects of land cover changes on discharge (Yuan et al. 2012; Sun et al. 2006; Roa-García et al. 2011; Neupane et al. 2015; Negley & Eshleman 2006; Muñoz-Villers & McDonnell 2013; Molina et al. 2012; Li et al. 2007; Harden 2006; Gould et al. 2016; Brown et al. 2005); with paired basins, as one of the most used method to study the impacts of vegetation changes on water yield at different time scales (Brown et al. 2005; Tobón et al. 2010).

In the tropical region, montane ecosystems regulate the hydrological cycles of high-elevation areas (Goller et al. 2005), e.g. the paramos and other Andean headwater basins perform as important regulators, water and nutrient surplus and sustain base flow to the rivers descending to both the coastal regions and the Amazon basin (Molina et al. 2012; Buytaert et al. 2006). In Andean basins, paramos have a particular land cover that largely affects the hydrological processes (Guzmán et al. 2015). Paramos provide abundant high-quality water for downstream populations as well as a variety of other environmental services (Mosquera et al. 2015).

Paramos are located roughly between 11° north and 8° south latitude, forming discontinuous patches within the high mountains (Guzmán et al. 2015; Hofstede et al. 2003). They consist of accidented, mostly glacier formed valleys and plains with a large variety of lakes, peat bogs and wet grasslands intermingled with shrub lands and low-statured forest or shrubs patches (Buytaert et al. 2006). In northern Andes the species of *Espeletia spp*. are representative of paramos vegetation.

The historical climatic conditions of these ecosystems are characterized by average temperatures below 10°C, wide diurnal temperature range, cloudy skies, foggy days, high UV radiation amounts, low atmospheric pressure, strong winds, and continuous drizzles (Ruiz et al. 2008). The mechanism responsible for the excellent water regulation capacity of the paramos is very poorly understood, but, according to the main characteristics of these ecosystems, the hydrological behavior is mainly determined by soils (Chapter 4; Buytaert et al. 2005). Nevertheless, hydrological responses in mountainous landscapes, even in basins with comparable climatic and edaphic conditions, can be very diverse (Becker 2005), meaning that behavior is not comparable, scalable o generalizable to an entire ecosystem or a bigger basin (Goller et al. 2005).

Despite their important role as freshwater resources and their vulnerability to anthropogenic pressures and to climate change, our knowledge of the ecohydrology of tropical high mountain ecosystems, and in particular, of paramos, remains limited (Goldsmith et al. 2012; Buytaert et al. 2006; Célleri & Feyen 2009; Mosquera et al. 2015), which is exacerbated by the high spatial and temporal gradients and variability in their geographic and hydro-meteorological conditions (Ochoa-Tocachi et al. 2016). On the other hand, the lack of reliable long term data series puts serious constraints on the study of the climate changes in the paramo (Buytaert et al. 2006; Ruiz et al. 2012; Célleri & Feyen 2009).

High elevation environments are among the most sensitive to climatic changes occurring on a global scale and basins in mountain regions are particularly vulnerable (IDEAM 2011), since relatively small perturbations in global processes, can cascade down to produce changes in their hydrological cycle, to the complex fauna and flora, and the people that depend on those resources (Diaz et al. 2003). Tropical mountain ecosystems have been projected to experience faster rates of warming than surrounding lowlands (Ruiz 2015). Higher temperatures are likely to increase evapotranspiration and therefore the atmospheric water vapor content. This may result in changes in large-scale precipitation patterns and the frequency of extreme events. The changes in evapotranspiration and timing and intensity of precipitation are expected to strongly affect various types of water resources, particularly, soil moisture, stream flow, and groundwater storage (He et al. 2009; Buytaert et al. 2010). Additionally, a dryer climate and an increased seasonality may affect soil hydraulic properties, because the low temperatures and high moisture contribute to the slow rate of organic matter decomposition and mineralization. Changes in these environmental conditions will affect the soil organic matter content, its porosity and its water retention capacity, which in turn, will impact the water regulating capacity of paramo soils (chapter 4).

In montane ecosystems, a major consequence of the global increase in temperature is an upward shift of the ecosystem boundaries, which reduces the total area of the upper ecosystems (IDEAM 2011). The hydrological consequences of this process are ambiguous, and depend strongly on the vegetation that replaces the natural one in paramos (Buytaert et al. 2006). On the other hand, it is not clear how the disappearance of the snow cover above the paramos (glaciers) will affect their hydrology (Buytaert et al. 2006).

Hydrologic models were regarded as a powerful tool for predicting climate and land use and cover change impacts on watershed hydrology (He et al. 2009). In this case, we use GMC for temperature anomalies prediction, historical trending analysis for projections of precipitation, and the WaSim hydrological model to estimate the fluxes and eco-hydrological responses at basin level, having into account the current characteristics of each basin, and to estimate their hydrological response considering climate change. This work aims to understand the current hydrological functioning of paramos basins, and to predict, using the hydrologic model and the climate change projections (in temperature and precipitation), the expected changes in paramos hydrological functioning, in the medium term.

## 5.2 Methodology

### 5.2.1 Study sites

This chapter analyzes data from three Colombian paramos: Paramo of Chingaza (Cundinamarca) located in the Eastern Cordillera (04°39'39.6 N 73°50'00.0 W, between 3000 and 3460 masl), paramo of Romerales (Quindío, 04°40'52.8 N 75°24'52.1 W, between 3600 and 4200 masl) and Belmira (Antioquia, 06°39'44.6 N 75°40'27.0 W, 3050 and 3200 masl), on the Central Cordillera. In each paramo we selected a basin, where most of the vegetation is representative of paramo land cover. As inputs for the hydrological modeling of climate change scenarios, land cover is required; therefore, the basins land cover was mapped, based on Landsat images and GIS (Geographical Information System) software.

The basins were selected trying to obtain most of the land cover with typical paramo vegetation which is grasses and frailejones (*Espeletia spp.*); however, there are another type of covers such as wetlands, bare soils, shrub vegetation and cloud forests (figure 5-1).

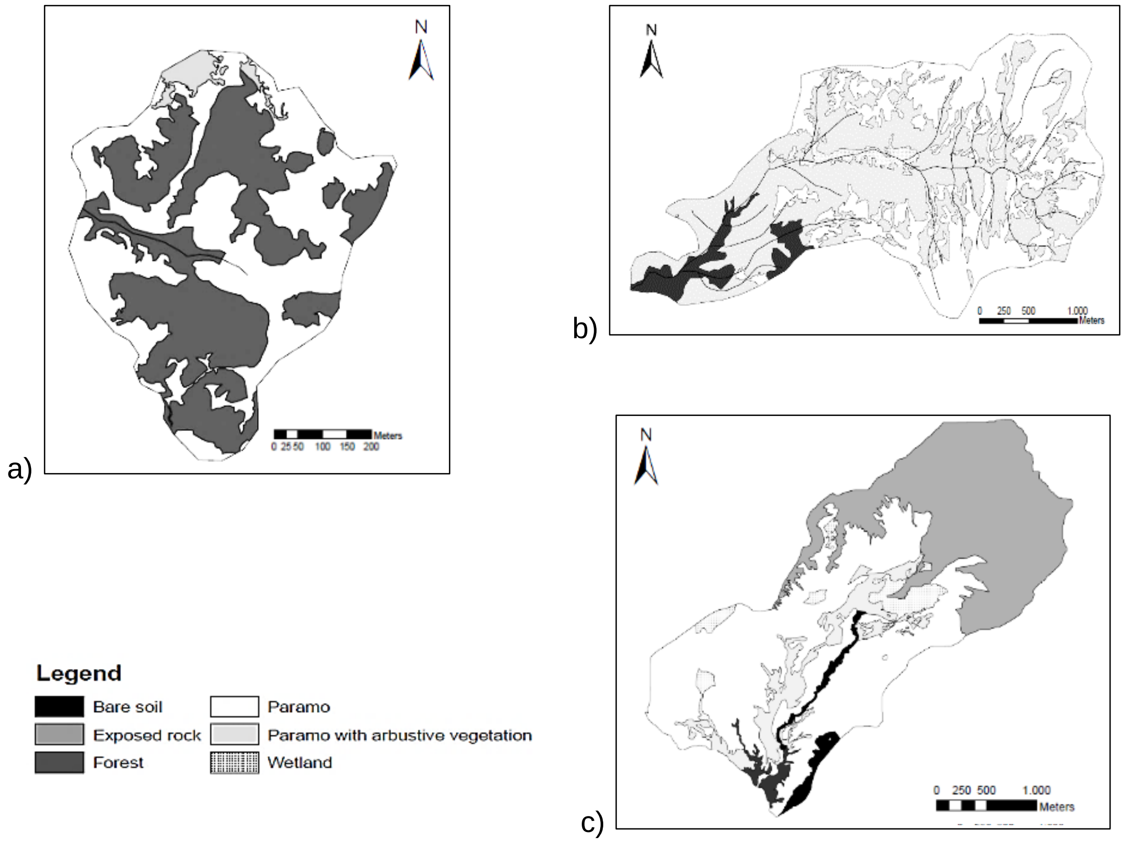


Figure 5-1. Land cover for the paramo basins: a) Belmira, b) Chingaza, c) Romerales

### 5.2.2 Measurement of hydro-climatic variables

In each paramo we measured hydro-climatic variables over two years period (2014 and 2015). The measured variables were precipitation, temperature, air humidity, solar radiation, wind speed and direction, with Davis ® and Campbell Sci ® weather stations, at 15 minute intervals. At each weather station we also measured horizontal precipitation using a cylindrical fog gauge connected to a rain gauge with a Tynitag ® data logger. We also installed a set of rain gauges with Tynitag ® data loggers, distributed in the basins, to determine the spatial distribution of precipitation. The discharge of the basin was measured with Solinst ® level and baro-logger at the closing point, where previously we improved the channels, as rectangular weirs.

To evaluate soil physical and hydraulic properties in each paramo, we selected several sampling sites according to the total area covered by the basin and soil homogeneity, so that the samples were representative of the general conditions of the sites. In each sampling site, we dig a soil pit down to the C horizon, and undisturbed soil samples were taken from each soil horizon (O, Ao and Bw) to determine bulk density, texture, organic matter content and saturated hydraulic conductivity. We also took samples to evaluate roots distribution density on the vertical profiles of soil.

### 5.2.3 Hydrological model

In order to simulate the hydrological functioning of studied paramo basin, we used the Water Balance Simulation Model –WaSim-, which is a distributed, deterministic, mainly physically based hydrologic model (Schulla 2013), and successfully used to model small or medium mountain basins (Kunstmann et al. 2004; Kleinn et al. 2005). The structure of the model is composed by sub-models, so it is possible to use or to disable some of them, according to the specific requirements. The first sub-model analyses the meteorological data, the second uses a digital elevation model of 15 m –DEM- and a land-use map to estimate interception, evapotranspiration, infiltration, runoff and inter-fluxes. The soil sub-model has two possibilities, one based on Topmodel and another based on Richards equations, which was the one used in this research, based on a conceptual model of lineal reservoir, since there is no evidence of the presence of aquifers in the studied basins.

The meteorological information required by the model was divided into calibration (2014) and validation (2015) data sets. The calibration allowed to define the parameters that best fit the hydrological representation of the model with the real behavior of each basin. The validation guaranties that estimated parameters represent in an ideal way the global hydrological behavior of the basin, instead of just represent the calibration period. The simulation was made with an hourly temporal resolution, which is adequate to describe the hydrological processes and the discharge dynamics during storm events in the studied basins.

Due to the characteristics of the model, most of the parameters used are measurable soil properties (depth, saturated hydraulic conductivity, roots density, Van Genuchten parameters derived from the moisture retention curves, measured and indicated in Chapter 4), which leaves only 6 parameters to calibrate: The decay constants of the surface runoff (Kdir), inter-fluxes (Kint) and the underground flows (Ksub), density of the drainage network (dr), the constant of the linear reservoir representing the underground flow (Qo), the thickness of the layers (L) in which the soil is divided for the solution of the Richards equations and the minimum time step -in seconds- to solve this equation. For the calibration of the parameters, we selected the initial range of values from those expected, according to the hydrologic features of the ecosystem and the information available in literature. From these values the model was run, comparing predictions by the model with field measurements, looking for the best possible adjustment between them. Further, the value of the first parameter was modified at the time, and the model was iteratively run, until the best fit was found. The value of the calibrated parameter was set, and the next parameter was calibrated, and so on until all of them were calibrated. Subsequently, each parameter was recalibrated, applying the same procedure, until the best performance of the model was obtained.

Model validation was aimed at demonstrating that the model was capable of predicting accurately the basin hydrology (discharge dynamics and quantities), based on new input data with the same temporal resolution and the parameter values identified during the calibration process. The efficiency criteria of the process are given by the closeness between simulated and observed discharge, that is, the capacity of the model to simulate discharge dynamics and amounts in each basin. Two criteria were applied: Graphical approach, using the hydrographs and the curves of duration of the simulated discharge against those observed in each basin, and a statistical criterion, by measuring the efficiency of the predictions through Nash-Sutcliffe coefficient (E):

$$E = 1 - \frac{\sum_{i=1}^{n} (X_{obs,i} - X_{model})^2}{\sum_{i=1}^{n} (X_{obs,i} - \overline{X_{obs}})^2}$$

where $X_{obs}$ is observed values and $X_{model}$ is modelled values at time/place i. Nash-Sutcliffe efficiencies can range from $-\infty$ to 1. An efficiency of 1 ($E = 1$) corresponds to a perfect match between model predictions and observations. An efficiency of 0 indicates that the model predictions are as accurate as the mean of the observed data, whereas an efficiency less than zero ($-\infty < E < 0$) occurs when the observed mean is a better predictor than the model.

### 5.2.4 Climate change scenarios for paramo ecosystems in Colombia

To project near-surface temperature anomalies to 2046-2065 scenario, we used the results of the work made by Ruiz (2015) for the Andes cordillera, with emphasis in tropical high mountain. For this purpose, he used several models to build a multi-model mean annual temperature anomalies, following a differential model weighting scheme, and considering the distribution of historical mean annual near-surface air temperature. After the analysis, the models used were NCAR:CCSM4, MPI:ESM, GFDL-CM3 and NASA:GISS-E2, weighted with 0.255, 0.507, 0.087 y 0.151 respectively (Ruiz 2015). The temperature anomalies are projected for all the representative concentration pathway

(RCP). The RCPs include four general trajectories of greenhouse gases emissions, concentrations and land use emissions until the year 2100, covering a span of increase in radiative forcing from 2.6 to 8.5 $W/m^2$ (IPCC_AR5 2014).

The temperature projections we used are the mean temperature. Even there is evidence of changes in extreme values of this variable for studied ecosystems (Ruiz et al. 2012), the knowledge on the behavior of transpiration of paramo vegetation (chapter 3), and the time of the day when the minimum temperature occurs (around 6 am), makes think that changes in minimum and maximum temperatures are not that significant for evapotranspiration, so the mean temperature is appropriate to project it.

To assess the changes in precipitation for the scenario 2046 - 2065 we analyze, following the suggestions of an expert (Ruiz, personal communication) changes in the mean and the variance, and significant trends in time series for the longest daily rainfall data available nearby the study sites (table 5-1). The evaluated variables for precipitation were annual total precipitation, total precipitation for the driest trimester and the wettest trimester, the precipitation registered in the rainiest day of each year, the number of dry days, the number of dry spells (one or more consecutive dry days) and the duration of the longest drought each year. For dry days, we have into account, besides the days without rain, those with less than 1 $mm.day^{-1}$ of precipitation, since the average interception in these ecosystems is around 0,8 mm (C. Tobón, personal communication), so this amount of rainfall do not reach the soil surface, therefore, has none effect on discharge.

Since the main concern about the changes in rainfall regimes is the effect of longest droughts over the ecohydrological functioning of paramos, we focused our analysis on this variable, so we estimate the cumulative distribution function of dry spells, and used the 95 percentile as a reference of the historical more critical drought events.

The reconstructions of precipitation realizations at medium term for the three study sites were based on: i) the tendencies shown by the historical series, ii) the correlations of the series with the inter-annual and inter-decadal variance, iii) the maximum drought periods estimated by the cumulative distribution function. This is, based on the information collected from each site, we reconstructed two hourly precipitation series of a year length: one represents the average of the projections for dry years, meaning that its occurrence is highly probable, and the second one is an extremely dry year or with an extreme temporal distribution, but according to the projections and the standard deviations, i.e. its occurrence is plausible in the medium term. The two realizations we made for each site are the upper and lower boundary conditions of the possible dry years in the medium term, which is the period between 2046 and 2065, according to IPCC (2014); therefore, the climatic sign for drought will be inside those scenarios. Also, is highly probable the occurrence of normal and wet years during the assessed period, but, since it does not affect the hydrological response of paramo basins, we don't consider them for our assessment.

Table 5-1. Stations used for historical analysis of precipitation and to create the scenarios for climate change

| Station name | Station code | Latitude | Longitude | Altitude | Series length | Source |
|---|---|---|---|---|---|---|
| Cenicafé | 2615502 | 0500 N | 7536 W | 1310 | 01-1942 to 12-2011 and 2015 | Cenicafé |
| El Cedral | 2613507 | 0442N | 7532W | 2120 | 01-1961 to 12-2006 and 2015 | Cenicafé |
| Belmira | 2701087 | 0637N | 7538W | 2540 | 01-1071 to 12-2015 | IDEAM |
| La Esperanza | 2120114 | 0448N | 7410W | 2555 | 01-1975 to 12-2013 | IDEAM |
| Emmanuel D’Alzon | 2120123 | 0442N | 7404W | 2520 | 01-1976 to 12-2015 | IDEAM |

Also, we induced a dry spell in the synthetic series: the 90 percentile for the average dry series and the 95 percentile for the extreme ones. It is possible that this is the biggest hydrological challenge those basins will face in the medium term, but its occurrence is plausible. For all the reconstructions, we used the measured data in every basin during 2015, since this was a very dry year (presented an average reduction of 34% in total annual precipitation, with respect to the annual multiannual mean), with the biggest ONI registered in the last 60 years. On that base, we induced the mentioned changes, but keeping the rainfall temporal distribution typical of every site.

## 5.3 Results

### 5.3.1 Hydro-climatic variables

Due to the inter-tropical location, the average temperature in Colombia is determined by the altitude, however, precipitation observes some variation throughout the year, which is controlled by the pass of the Inter-Tropical Convergence Zone. Two of the studied sites have the typical bimodal annual precipitation distribution with higher values of precipitation around April and October. However, Chingaza presents a monomodal distribution of precipitation, with a main peak in June. Nevertheless, the three paramos have the lowest precipitation inputs in December and January.

Despite the belief that the tropical regions have not significant variances in most meteorological variables, our results show that there are important differences between the maximum and minimum values registered, and those changes occur on daily basis. Table 2 shows the average, maximum and minimum values of some of the meteorological variables measured in the study sites, as well as the water yield estimated for each year. It is important to note that year 2015 was an El Niño year, so rainfall and basin discharge decreased, but some associated variables such as temperature, solar radiation and fog inputs, also change during this period (table 5-2). It is also important to note that the ENSO phenomenon occurrence does not match with a calendar year, however, the information given below depends on our field data availability.

Table 5-2. Meteorological variables measured at the three paramo basins, during 2014 and 2015.

| Paramo | Year | Temperature (°C) | | | Air humidity (%) | | Solar rad. ($W.m^{-2}$) | | Wind speed ($m.s^{-1}$) | | Rainfall (mm) | OP (mm) | Discharge (mm) | $D.P^{-1}$ |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Avg. | Max | Min | Avg. | Min | Avg. | Max | Avg. | Max | | | | |
| Belmira | 2014 | 10.3 | 18.8 | 4.2 | 91.8 | 45.0 | 334.3 | 1384 | 2.8 | 9.4 | 1511.0 | 129.1 | 931.9 | 0.62 |
| | 2015 | 10.5 | 18.7 | 4.0 | 92.0 | 36.0 | 322.5 | 1487 | 3.0 | 10.7 | 1445.8 | 121.1 | 840.2 | 0.58 |
| Chingaza | 2014 | 11.5 | 24.9 | 0.8 | 84.9 | 25.0 | 268.0 | 1019 | 2.7 | 13.8 | 3031.7 | 281.0 | 2069.3 | 0.68 |
| | 2015 | 11.1 | 26.7 | 2.3 | 85.1 | 34.0 | 274.0 | 990 | 4.1 | 18.1 | 3164.5 | 143.6 | 1888.2 | 0.60 |
| Romerales | 2014 | 5.2 | 13.1 | 0.0 | 90.9 | 13.4 | 254.4 | 1390 | 3.6 | 16.6 | 1106.8 | 122.1 | 519.3 | 0.47 |
| | 2015 | 5.4 | 13.5 | 1.1 | 90.5 | 14.7 | 258.8 | 1390 | 4.1 | 15.5 | 832.5 | 118.1 | 240.3 | 0.29 |

The diurnal cycles of some meteorological variables are good approximation of the behavior of some weather conditions of paramo ecosystems. Figure 5-2 presents those cycles for the three studied paramos. The atmospheric pressure cycle changes with the location and altitude, but in the three sites shows the typical bimodal cycle, with peaks around the mid-morning and before midnight. The diurnal cycles of temperature and relative humidity are opposite, according to the Clausius-Clapeyron equation, and temperature usually start rising after sunrise (around 6:00) until a maximum after midday and then decline, following the solar radiation cycle that starts with sunrise, has the higher value around midday and stops with sunset (around 18:00).

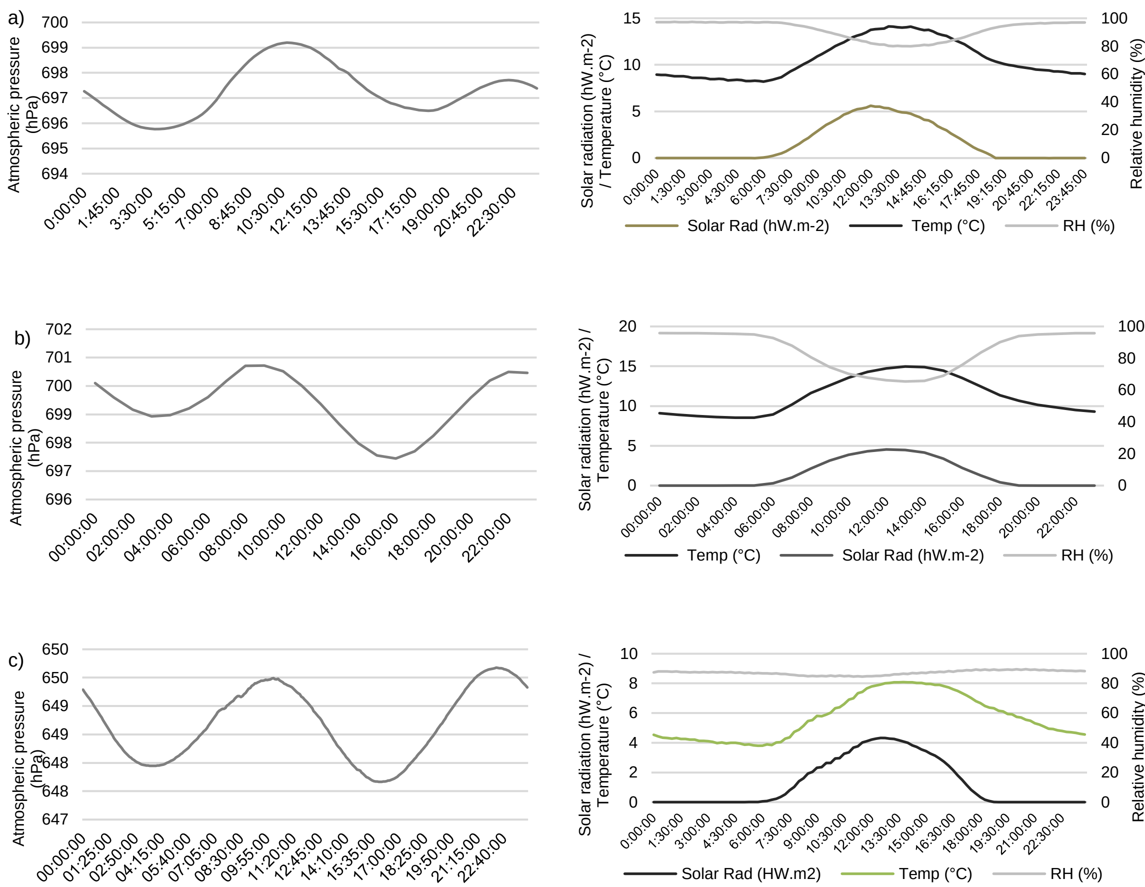


Figure 5-2. Diurnal cycles of atmospheric pressure (left) and the diurnal cycle of temperature, solar radiation and relative humidity (RH) (right) from a) Belmira, b) Chingaza, c) Romerales

The high water-regulation capacity of the paramo, is confirmed by analysis of the discharge data of the studied basins, with important differences among them. The lowest discharge in Belmira was registered in the dry period between December, 2015 and February, 2016, with a base flow over 18.8 mm.month$^{-1}$, compared with a mean of 73.4 mm.month$^{-1}$ during the total measured period and only 108 mm of rainfall during those three months (figure 5-3a). In Chingaza (figure 5-3b), the average discharge was 163.1 mm.month$^{-1}$, with the lowest values in February, 2014 (64.2 mm) when the rainfall was only 28.8 mm.month$^{-1}$ and January, 2015 (92.9 mm). Romerales, on the other hand, seems to retain more water in the soil than the water it releases to the discharge. This is clear when comparing the reduction in rainfall between 2014 and 2015 (in table 5-2), in the order of

25%, thus the reduction in measured discharge, during the same periods, around 54% (figure 5-3c).

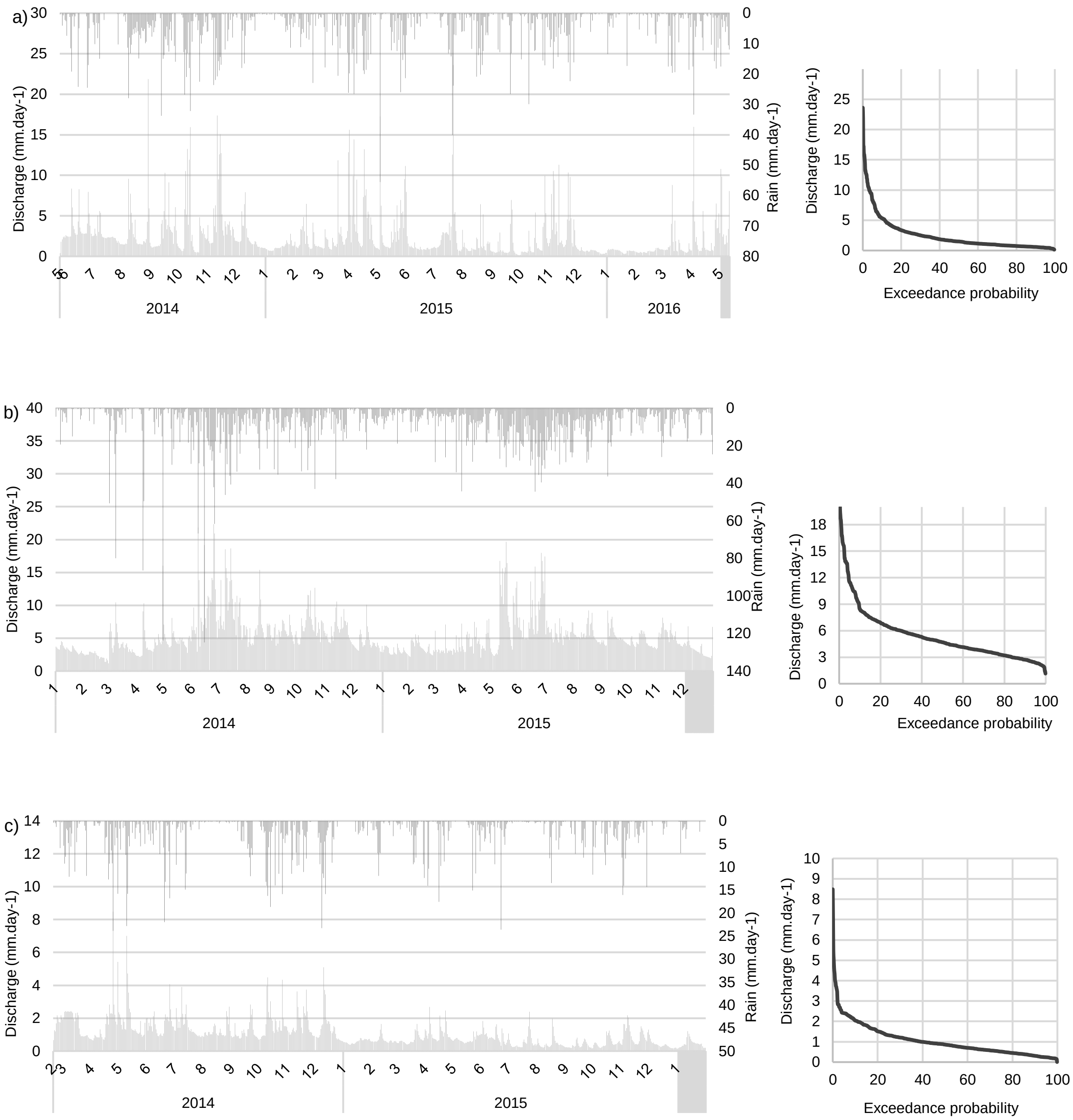


Figure 5-3. Daily rainfall, discharge (left) and the discharge duration curves (right) registered in the three basins: a) Belmira, b) Chingaza, c) Romerales

Figure 5-3 also presents the discharge duration curves, showing that Romerales is the paramo with lower discharge expressed as depth of water (mm), but also has the smallest contributions to total discharge from the storm events or peak flows. Different to Chingaza and Belmira, which show that in the lowest 5% of exceedance probability the changes are on the order of 48,3% (from 11.5 to 22.4 $mm.day^{-1}$) and 65% (from 8.3 to 23.6 $mm.day^{-1}$), respectively; implying that those basins present quick and significant peak flows during storm events. On the other hand, the upper 5% in exceedance probability, i.e., the base flows, show that in Romerales base flow decays faster during droughts (97%, from 0.24 to 0.005 $mm.day^{-1}$), Belmira loses 70% of its base flow during the same period (from 0.47 to 0.14 $mm.day^{-1}$), however, Chingaza basin presents a better water regulation, since its base flow has the lower reduction, of 52% (from 2.38 to 1.15 $mm.day^{-1}$).

### 5.3.2 Calibration and validation of hydrological model

During the calibration process we found the optimal parameters for the model, considering the Nash efficiency index (NSE), and the fidelity of the model to reproduce the amount of discharge for a period. Table 5-3 shows the results of the Nash-Sutcliffe coefficient and the ratio between the observed and the simulated discharges, obtained during the calibration and the validation periods for the three paramos.

Table 5-3. Nash-Sutcliffe (E) index and the relationship between the total discharges (observed and simulated) for the model calibration and validation, in different periods, for the three basins

| | **Calibration** | | **Validation** | |
|---|---|---|---|---|
| | E | Dobs/Dsim | E | Dobs/Dsim |
| Belmira | 0.51 | 0.90 | 0.49 | 0.90 |
| Chingaza | 0.29 | 0.90 | 0.23 | 0.83 |
| Romerales | 0.66 | 0.96 | 0.29 | 0.96 |

Figure 5-4 shows the fit between the modeled total discharges and the observed ones. The model has a good representation of the hydrological response of the basins in the means. Belmira had the best fit in both calibration and validation periods; despite in the hydrographs is possible to see that the model does not reach the observed peaks, in terms of exceedance probability it is not significant, since these two curves, observed and simulated, are very similar (figure 5-4a). On the contrary, Chingaza was very difficult to calibrate, and the discharges simulated are very different to the observed in wet periods were the model could not be at the same level of the observed base flow, overestimating it, but also during the dry periods the model underestimated the base flow (figure 5-4b). In Romerales the model also overestimated the discharge during wet periods and underestimated it on dry periods, but the differences were lower (figure 5-4c) and the ratio between the observed and the simulated discharge was the highest of the three modeled basins (table 5-3).

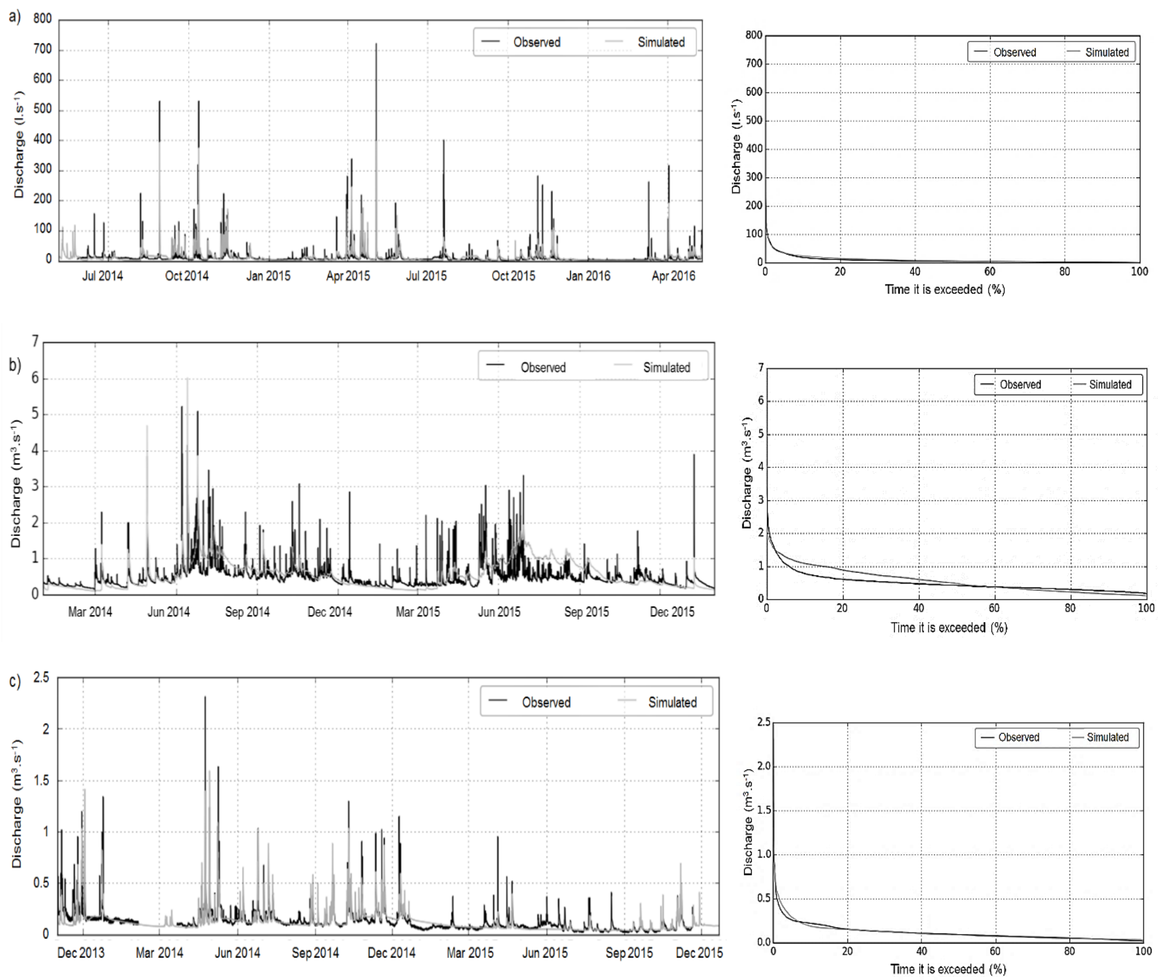


Figure 5-4. Observed and simulated hydrographs (left) and curves of duration (right) for the three basins: a) Belmira, b) Chingaza and c) Romerales for two years, corresponding to the period of calibration -the first year- and validation of the model parameters, the second.

### 5.3.3 Projection of future climatic scenarios for paramos in Colombia

The projections of average temperature anomalies for the three study sites and the four RCP or IPCC 5th report (IPCC_AR5 2014) are show in table 5-4.

The analysis of historical series of precipitation show similar signs and trends for the three sites: None of the analyzed stations show climate change signs, expressed as changes in the mean, the variance of total precipitation and on the distribution among wet and dry periods (trimesters). For the five studied stations, we found a strong sign of the inter-decadal (11 years) ($R^2$ between 0.28 and 0.46, average = 0.35) and the inter-annual (5 years) variation ($R^2$ between 0.12 and 0.35, average = 0.2), this last is similar to the average period of ENSO and to the correlation found between the precipitation variation and the Oceanic Niño Index -ONI-. Therefore, we can state that at least 50% of the natural temporal variation of precipitation is explained by the interannual and interdecadal cycles, determined by the occurrence of ENSO and sunspots.

Table 5-4. Average projected temperature anomalies for the studied basins for the period 2046 - 2065

| | Belmira | | | | Chingaza | | | | Romerales | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Models \ RCP** | **2.6** | **4.5** | **6.0** | **8.5** | **2.6** | **4.5** | **6.0** | **8.5** | **2.6** | **4.5** | **6.0** | **8.5** |
| NASA:GISS-E2 | 1.18 | 1.68 | 1.7 | 2.26 | 1.08 | 1.68 | 1.57 | 2.08 | 1.35 | 2.15 | 1.94 | 2.53 |
| MPI:ESM | 1.72 | 1.04 | | 3.07 | 1.72 | 1.12 | | 3.34 | 1.74 | 1.28 | | 3.16 |
| NCAR:CCSM4 | 1.38 | 1.8 | 1.8 | 2.5 | 1.42 | 1.84 | 1.9 | 2.62 | 1.42 | 1.87 | 1.9 | 2.58 |
| GFDL-CM3 | 2.2 | 2.68 | 2.45 | 3.29 | 2.5 | 3.14 | 2.71 | 3.78 | 2.25 | 2.85 | 2.53 | 3.48 |
| **Weighted Average** | **1.59** | **1.47** | | **2.82** | **1.61** | **1.56** | | **3.00** | **1.64** | **1.70** | | **2.94** |

Source: Ruiz (2015)

However, we did found a significant linear growing trend for the number of dry days and the dry spells, indicating changes in the temporal distribution of rainfall in El Cedral and in La Esperanza stations, so these changes were used for realizations in Romerales.

### 5.3.4 Changes on the hydrological functioning of paramos connected to climate change scenarios

The results of the model for 2015 are considered the base line to compare the results of the projections for a dry year for each paramo. For studied cases, it is clear that there are no significant differences between the projected average and extreme dry years, despite this last had longer dry spells and, in the case of Romerales, a bigger number of dry days; the results are related to the RCP projected (table 5-5).

In Belmira, despite there were no reduction in total annual precipitation, the modeled total discharge shows a reduction between 4 and 8%, according to the RCP. Outstanding in this paramo, most of the reduction in discharge is related to the proportional reduction in baseflow, whereas the modeled direct flow increased. Moreover, increases in estimated ET are between 6 and 13%. Chingaza shows smaller changes in total discharge, of between 4 and 6%, all of it related to the reductions in baseflow. Increases in ET are between 6 and 11%.

Table 5-5. Proportions of evapotranspiration (ET), discharge and water yield of projected scenarios with respect to results from 2015

| **Rainfall** | | **Average dry** | | | **Extreme dry** | | |
|---|---|---|---|---|---|---|---|
| **RCP** | | **2.6** | **4.5** | **8.5** | **2.6** | **4.5** | **8.5** |
| **Belmira** | Total discharge | 0.96 | 0.97 | 0.92 | 0.96 | 0.97 | 0.93 |
| | Base flow | 0.91 | 0.91 | 0.88 | 0.91 | 0.91 | 0.88 |
| | Direct flow | 1.27 | 1.28 | 1.17 | 1.27 | 1.28 | 1.17 |
| | ET | 1.07 | 1.06 | 1.13 | 1.07 | 1.06 | 1.13 |
| **Chingaza** | Total discharge | 0.96 | 0.96 | 0.94 | 0.96 | 0.96 | 0.94 |
| | Base flow | 0.96 | 0.96 | 0.94 | 0.96 | 0.96 | 0.94 |
| | Direct flow | 1.00 | 1.00 | 0.96 | 1.00 | 1.00 | 0.96 |
| | ET | 1.06 | 1.06 | 1.11 | 1.06 | 1.06 | 1.11 |
| **Romerales** | Total discharge | 0.66 | 0.64 | 0.61 | 0.66 | 0.66 | 0.61 |
| | Base flow | 0.70 | 0.70 | 0.66 | 0.70 | 0.68 | 0.66 |
| | Direct flow | 0.40 | 0.40 | 0.33 | 0.38 | 0.38 | 0.31 |
| | ET | 1.10 | 1.10 | 1.14 | 1.10 | 1.10 | 1.15 |

Romerales presents the biggest reduction in discharge, since this paramo has the highest probabilities of have significant changes in rainfall regimes. However, results indicate that the base flow reduction is much lower than reductions in direct flows, which matches with the response observed during the drought in 2015. ET increases between 10 and 15%. Due to the low water yield this paramo had in 2015 and the projected reduction in discharge with the variations due to climate change, the projected water yield for this basin is below 20%, which is very low for these kind of ecosystems; a clear effect of the land use this paramo has suffered for decades.

## 5.4 Discussion

Despite the small size of studied basins (Belmira 0.4 $Km^2$, Chingaza 7.5 $Km^2$ and Romerales 9.3 $Km^2$), the discharge was permanent in all of them during the two measured years, included a drought period due to a very strong El Niño in 2015-2016. The basins also showed the high water yield and good water regulation expected for these ecosystems, well known for its very large water surplus and sustained base flow (Buytaert et al. 2006). However, results indicate the hydrological system in Romerales paramo might be close to exceed its limit or its resilience to keep hydrologic regulation during severe or long drought periods. In contrast, Belmira, which is located at low altitude, has lower extension, with highly degraded soils and more patches of forest vegetation into a paramo matrix, not only keeps a continuous flow, but its base flow, even is very low, presents lower changes during the drought, which a sign of good hydrological regulation.

Water yields were high, as expected for paramo ecosystems, considering its high humidity, low temperatures, presence of fog and low clouds, among other characteristics associated with high inputs of water by rains and horizontal precipitation and low evapotranspiration (Tobón et al. 2004). However, Romerales paramo is an exception because it has water yields below those expected values (of around 60% for paramos), which can be explained by the anthropic effect of extensive livestock that have been trampling these soils for decades, reducing infiltration and generating surface runoff and erosion (Bruijnzeel 2004). On the other hand, the deep soils, rich in organic matter and volcanic ashes observed in this paramo, have properties (chapter 3) that give it the ability to store large amounts of water, and keep it for long periods of time. The consequence is that, during prolonged droughts, these soils can remain with high moisture content, i.e. with plants available water and for evaporation in its upper portions, but do not generate interflows to release water, so the discharge could be reduced or even become temporarily dry. This matches with the observations of several authors who recognize that soils are closely related to the high water regulation capacity and the extraordinary water retention capacity in paramos (see Buytaert et al. 2006).

The precipitation intensity in paramos is low. During the measured period it was lower than 12 mm.hour$^{-1}$ at the 97 percentile, for the three sites. This means that peak flows are due to surface flows generated by saturation of soils during the wet seasons, more than to rainfall intensities higher than infiltration rates. The previous also explains why Romerales is the paramo with lower contribution of peak flows to the total discharge. Actually, in that paramo, we dug pits of until 1.2 m deep because we found buried soils, but the total depth of those soils is unknown.

The WaSim hydrological model has been used for the simulation of mountain basins and in studies of hydrological impacts of climate change (Beniston 2002; Cullmann et al.

2006; Jasper et al. 2004; Schulla 2013; Tolessa et al. 2016), but this might be the first study with detailed temporal and spatial resolution, due to the small size of the basins, which implies the hydrological responses occur very fast. Considering the temporal resolution used here for the model, which was hourly, and the differences in rainfall and discharge observed between the calibration (2014) and validation (2015) periods, we found a good performance of the model to simulate the different hydrological processes, represented by the discharge components, and their temporal variability. The biggest effort was focused on the drought periods, since those are the most critical, both, for the functioning of the paramos and for the people who uses the water they provide. During the droughts, despite the observed and the simulated base flows were not zero, there were significant differences among them, especially at the end of those periods when the base flow is mainly originated from the wetlands located in the headwater of the basins, and the model did not consider these wetlands, as an extra input. It is particularly interesting how the model was able of simulate the reduction of almost 50% in discharge of Romerales basin during the validation period (2015, Figure 5-4c), since such discharge reduction was twice the reduction of water inputs, while in the other two basins the discharge variability was proportional to the inputs.

Global climate models (GCMs) are extensively used to generate future climate scenarios to be used in the climate change impact studies on water resources, and then these downscaled climate projections are taken as input into the hydrological models to estimate climate change impact on basin runoff (Gädeke et al. 2014), as we did in this research. The climatic and hydrological projections made are approximations to what might happen in a 20 years period as horizon for medium term (2046-2065). According to Haque et al. (2015), the uncertainty linked to the choice of hydrological models is quite small in comparison with the GCM and realization uncertainty. According to these authors, one should not rely on one GCM or a single projection of a GCM or one hydrological model in climate change impact studies (Haque et al. 2015). That is why we choose to use six combinations of temperature projections and precipitation, as borders of a possible range of dry years with three levels of warming, considering the 2.6, 4.5 and 8.5 RCP. In other words, since we are interested in the hydrological consequences of dry years and increases in temperatures, we used a set of possible future scenarios to cover the conditions that paramos must face in the selected horizon. There are many other potential feedbacks related to physiological responses of vegetation and of soils to increasing CO2 and temperature that we did not considered here, since we have not enough information about their functioning, but that also might affect the hydrological response of paramo basins.

The hydrologic projections show that, as expected, an increase in temperature will lead to an increase in ET. This increase will be reflected in reductions in total discharge, however, the responses of the three studied basins differ among them, according to their own characteristics and history. The most critical is Romerales, this paramo seems to be close to its resilience hydrological point, and is severely affected by diminishes in rainfall and by long dry spells, responding with large reductions in its total discharge, since most of the water keep stored in soil, but, even in the most critical projected scenario the modeled discharge is never zero, for any of the studied basins.

## 5.5 Conclusions

Soils and climatic characteristics of Colombian paramos are the key control for the hydrological functioning of these ecosystems. Despite the anthropic activities affecting their natural properties (land cover and soils), paramos show a good water regulation, expressed in low proportion of peak flows and prolonged base flows, even after long or severe drought periods; which is related to the high organic matter content and volcanic ashes in some of them. Also, the estimated water yield, as the proportion of precipitation that becomes discharge, was over 60% for Chingaza and Belmira. Romerales, however, shows lower values, which is probably related to the complexity of hydrological processes in deep volcanic ash - organic soils.

The projected temperature scenarios for the three sites show average anomalies between 1.54 and 3 Celsius degrees, depending on the used RCP, for the medium term. Analysis of historical precipitation close to the studied paramos indicate that climate change is not affecting it, since there is no evidence of variability in the mean nor the variance of the variables; but there are significant linear trends in the number of dry days or dry spells for some of the stations, which might affect the temporal distribution of rainfall in the future: more dry days and more intense rainfalls. Around 50% of natural interannual and interdecadal variability of precipitation in tropical high mountain could be explained by the ENSO and sunspots cycles. However, there is still another 50% of that variability we cannot explain. Longer and of better quality series are needed to understand better this complex variable.

For the medium term, variations in projected hydrological responses of paramo basins are determined by the expected increases in temperature, which increase the evapotranspiration and, thus, reduce the amount of water outputs via discharge. Expected variations in rainfall appeared to be low, thus Belmira and Chingaza paramos seem not to be sensible to those changes. However, Romerales is highly sensitive to reductions in total rainfall and increases in dry days and dry spells, which is related to the high impact land uses during several decades in this basin, expressed in its low water yield.

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# 6. Eco-hydrological vulnerability of Colombian paramos to climate and land use changes

## 6.1 Introduction

Among the main global environmental problems the planet is facing nowadays are biodiversity loss, climate change, and increased freshwater consumption (Scheer et al. 2014). About 80% of the world's population already suffers serious threats to its water security and climate change can alter, even more, this freshwater availability, and therefore threaten water security (Settele et al. 2014). This is one of the main reasons to study threatened ecosystems, as paramos, which are one of the most important ecosystems in the Andes related to fresh water supply, especially in Colombia and the cities in northern Andes that take water from high mountains.

This work is focus in assess the hydrologic response of these ecosystems and understand the main factors controlling the processes associated to the hydrological regulation and water yield. This is an important input to take actions, considering the possible climate changes in the medium term, and the effects these changes might have on the functioning of paramo ecosystems; therefore, understanding those changes in the hydrological cycle will help on the identification of diverse impacts and risks, and they are conditioned by and interact with non-climatic drivers of change and water management responses (Jiménez et al. 2014).

In context, effects of climate change are usually assessed in terms of vulnerability. In this work ecosystems vulnerability is understood in terms of i) the relative state of the system with respect to a boundary conditions, after such it can be assumed that the system is damaged –resilience-, ii) the sensibility of the system and iii) the frequency distribution or the degree of exposure to a stress factor (Eakin & Luers 2006), in this case, the climate. For our purpose, the ecohydrological vulnerability of paramo ecosystems to climate change is defined as the relative change in total discharge and its components (peak and base flows) in response to variablily in temperature and rainfall, with respect to baseline conditions (Chapter 1).

Accordingly, the goal of this chapter is to answer the main questions of the project, based on the results of the research, presented in previous chapters.

i) What are the control variables in the assessment of eco-hydrological vulnerability of paramos to climate change, with different conditions of land use in Colombia?

ii) What are the most vulnerable eco-hydrological functions or processes of paramos to anthropic disturbances and stress factors related to climate change?

iii) What is the vulnerability of paramo ecosystems in Colombia to climate change and what is their resilience to such changes, based on different land uses and management?

## 6.2 Methodology

To answer the scientific questions and to achieve the objectives, we followed a comprehensive methodological procedure, starting by the characterization of hydro-climatic variables and hydrological processes, to understand and describe the hydrological functioning of studied paramos, under actual conditions. Further, we calibrate and validate a hydrological model, in order to simulate the ecohydrological effects of climate change for the three studied paramos. Therefore, having into account the measured variables, the assessed processes and the projections made to a medium term, considering climate change scenarios, in this chapter the gathered information is grouped and compared into three different categories: variables, processes and the ecosystem responses to climate change.

The first analysis, at variables level, was made with trimestral averages of climatic, edaphic and hydrological data. With the data set and using principal component analysis, we ran a linear regression using the IBM_SPSS ® statistical software, testing the criteria of normality, no collinearity, additivity and homogeneity of variance, with a significance level of $p > 0.05$, to determine, for each paramo, the set of variables which are significantly related to the response variable of the basin, i.e., discharge.

The variables measured and assessed in this research were divided into three groups: a) meteorological variables such as precipitation, temperature, relative humidity of air, solar radiation, wind speed and direction, atmospheric pressure and fog inputs. Those variables were measured in each study site for at least two years (2014 – 2015); b) soil variables, such as root distribution in the soil profile, organic matter content and physical soil properties: texture, bulk density, porosity, moisture retention capacity, saturated hydraulic conductivity and soil moisture; and c) the discharge as the response variable. The separation of discharge into base and direct flow was made following the method of Nathan & McMahon (1990), but to fit the parameters, instead of the values those authors proposed, the suggestions made by Eckhardt (2012), which gives better results. Due to the different nature of the measured variables, the analysis was made separately for meteorological and soil variables versus the discharge.

The second analysis is related to the comparisons and analysis of ecohydrological processes at different time scales. Those are evapotranspiration, surface runoff and basin responses to rainfall events and water regulation capacity.

In order to answer the third research question, we compare the results obtained for the studied basins at the current conditions and the responses with the climatic projections, considering climate change scenarios for dry years. As proposed in chapter 1, the hydrological vulnerability of each basin, representative of hydrological functioning of the entire ecosystem, will be defined for the magnitude of the alterations on its hydrological response as a consequence of climate change, according to the level of perturbation or to the impact of some variables of vulnerability. To do this, changes are divided by percentiles (P); so the changes equal or lower than $P_{20}$ will mean very low vulnerability, between $P_{20}$ and $P_{40}$ means low vulnerability, between $P_{40}$ and $P_{60}$ will be medium vulnerability, between $P_{60}$ and $P_{80}$ will be high vulnerability and changes over $P_{80}$ are considered as very high vulnerability.

## 6.3 Results and discussion

### 6.3.1 The variables for eco-hydrological vulnerability in paramos

Results indicate that when running the linear model with the method forward and the discharge as the dependent variable, all the variables meet the statistical assumptions, but most of them are not significant to explain the variability of the dependent variable.

For Belmira and Romerales, 97.5 and 90.2% (respectively) of the discharge variability was explained by the inputs, i.e., the sum of the rainfall and the horizontal precipitation, but any of the other variables were significant. In Chingaza, a model based only on the inputs explains 95.2% of discharge variability. However, for this paramo the relative humidity was also significant, and both variables showed an $R^2$=97.8.

With soil properties, the analysis was different since those are discrete measurements, at the different pits made in each paramo and for each soil horizon. We averaged the values for the entire soil profile, over the basin, and evaluated those values against the water yield and the base flow per area unit ($Km^2$). Results show that the only significant soil variable to predict water yield at basin level in studied paramos is organic matter content, variables with a positive and linear correlation. Contrary, other studied soil properties were not significant.

Results also indicate that base flow per unit area in studied paramos, is function of soils depth, saturated hydraulic conductivity (Ks) and average roots density, which makes sense since those variables control the infiltration rates, the movement of water into the soils and their water storage capacity (Tobón et al. 2010).

### 6.3.2 Vulnerability of ecohydrological processes in paramo ecosystems

**Evapotranspiration, ET**

The evaluation of influence of climatic variables on the discharge showed that temperature and solar radiation have none influence over the response of the basin, something unexpected since those variables directly affect the evapotranspiration, which is the main output of water from studied basins, after discharge. Moreover, an analysis of the simulated ET during the two years, one climatic normal year (2014) and the second with occurrence of El Niño (2015), showed that during the second year the reduction in discharge was directly related to the reduction in rainfall and increases in soil water storage, but did not show any significant increase in ET (Chapter 5). This means that increases of solar radiation or temperature related to a phenomenon as ENSO, does not imply a substantial increment in evapotranspiration, i.e. a significant reduction in the basin's discharge due to water loss through this process, at least in the medium term.

On the other hand, the results of measurements and data analysis of the dynamics and amounts of transpiration measured in frailejones (*Espeletia spp*.) in Belmira and in Romerales (Chapter 3), indicate that these plants, the tallest and more conspicuous among the paramo vegetation, moves to the atmosphere, in average, less than 12% of water inputs through rainfall. Moreover, an outstanding finding in this study related to evapotranspiration of *Espeletia* is that, frailejones are not active all day long, not even during the sunny and high temperature periods, or, considering the high capacity of water storage inside these plants, it is possible they continue with their physiological activities during the day using the water they store inside the leaves' mesophyll and in their pith, and then, after a while, they start moving water again to re-fill them as the result of an inherited behavior or an evolutionary characteristic, since paramo vegetation has evolved adapted to extreme weather conditions, and the plants are very efficient using their energy and the resources available, such as solar radiation and water. This means that changes in temperature of paramos, in the medium term, will not affect the transpiration rates of frailejones; therefore, relative higher temperatures will have no significant consequences over the water losses from these ecosystems through plant transpiration.

Accordingly, the biggest threat in this process is the change of land cover or of the predominant species in paramo ecosystems due to a combination of human impacts to natural vegetation and the global increases in temperature, resulting in an upward shift of the ecosystem boundaries (IDEAM 2011) or in a change in land cover with species of different ecosystems (Buytaert et al. 2006); in such case is highly probable evapotranspiration rates increases. In Belmira and Romerales it is possible to see how the anthropic alterations to natural vegetation and the fire, facilitate the presence of tree species from those ecosystems located below the paramo, like tropical montane cloud forest, which are adapted to conditions of higher temperatures, fastest growing and, perhaps, more efficient in their dispersion, to invade and transform the paramo ecosystems.

**Surface runoff and response to rain events**

Here we found that the large water storage capacity of soils, related to the high organic matter content, their high saturation capacity, and the low intensity of precipitation, result in a small contribution of surface runoff to the basin hydrological response, which agree with that found by Buytaert et al. (2005) in Ecuadorian paramos. Rain intensities during the measured period were below 12 $mm.hour^{-1}$, so most of the surface runoff occur due to soil saturation, not because the rainfall intensity surpasses the soil infiltration rate. Therefore, the magnitude of discharge response to big rainfall events varies according to the soil moisture content, i.e. if the soil is saturated the response is faster and higher than if the soil is relatively dry or at least below field capacity, because the rainfall recharge the soil moisture and, if in excess, it produces runoff.

The peak flow / base flow ratios calculated for the three paramos, gives values of 0.62, 0.24 and 0.12 for Belmira, Chingaza and Romerales, respectively, which are inversely related to the average depth of soils in each studied basin, i.e. deeper soils imply lower contributions of peak flow to total discharge; even although those soils have been disturbed by anthropic activities. Also, the peak flow / base flow ratio found is highly correlated with the contributions of peak flow to total discharge, graphically expressed in figure 1 and explained in the next point: water regulation.

**Water regulation**

One of the main characteristic of Colombian paramos is the weather conditions: low temperatures, high relative humidity, high solar radiation, relatively high inputs via rainfall (chapter 5), but also the presence of fog and horizontal precipitation as an additional input of water are very important hydrological variables (of over 11% of rainfall in all measured cases) that interacts with vegetation, reducing plant transpiration when the leaves are wet; but also with the soil, recharging soil moisture and providing water to the plants (chapter 2).

Studied soils from paramo ecosystems in Colombia have high SOM, with or without volcanic ashes, and depending on this combination they exhibit specific soil properties, but most important, they behave differently in terms of water retention and rewetting ability: For short droughts both of them loss large amounts of water, but they were capable of re-wet completely; however, for longer drought periods, soils derived from volcanic ashes combined with high organic matter, have greater resilience in terms of moisture storage and re-saturation capacity than those without ashes (chapter 4). In other words, Andisols, which are soils formed in volcanic areas and with a large water storage and retention capacity, limit the potential impact of land use management activities (conservation or restoration) on the water regulation function of catchments (Roa-García et al. 2011).

Romerales is the paramo with lower discharge expressed as depth of water (mm), but also has the smallest contributions to total discharge from the storm events or peak flows. Different to Chingaza and Belmira, whom in the lowest 5% of exceedance probability show changes on the order of 48,3% and 65%, respectively; meaning that those basins may present quick and significant peak flows during storm events (figure 6-1). However, for the three paramos, there is a relative low proportion of total flow corresponding to peak flows, since the break point is around or below 12%. Also, there are significant reductions of base flow during the drought, but despite the low size of the studied basins, they never dried out, during the study period, since the base flow at this point (higher 5%, see zoom in figure 6-1) seems to be maintained by the water stored of wetlands on the headwater. Although in this research we did not analyzed the contributions of wetlands to the eco-hydrological functioning of paramos, there is no doubt they play an important role in water regulation and supporting the base flow during the drought periods.

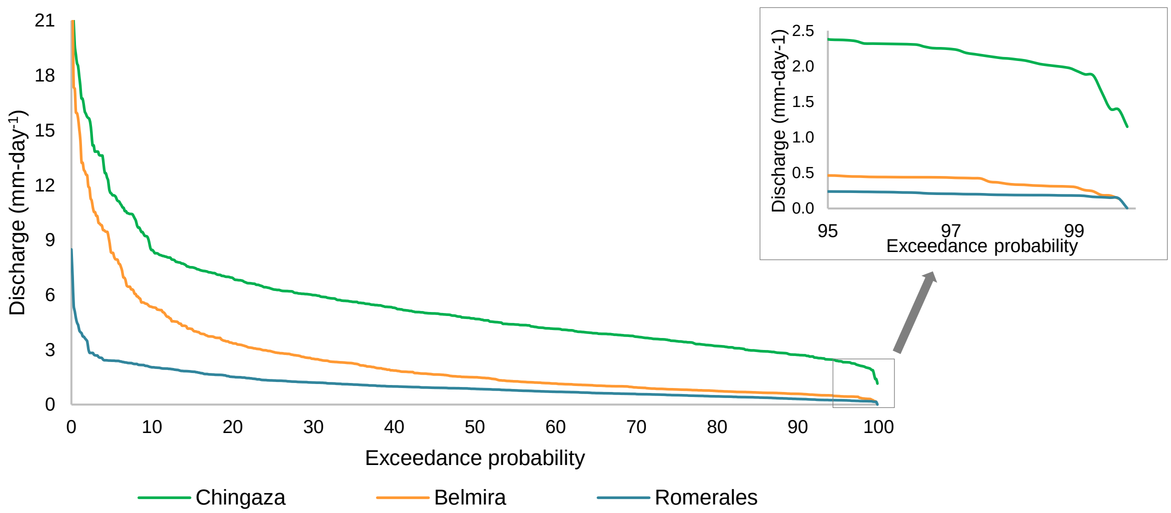


Figure 6-1. Discharge duration curve for the three paramos, with zoom in the highest 5% of exceedance probability

In general, the hydrological response of the studied basins might be explained by the soils physical properties, the relationship between soil organic matter content and volcanic ashes, the depth of their soils and the storage capacity of the wetlands inside the basin, especially if those wetlands are located at the headwater. Thus, the processes related to water regulation are highly vulnerable to anthropic activities which may alter or destroy some of these properties, including agricultural crops, burning, livestock and, in the most extreme case, mining. Climate change might also impact the soils by the occurrence of long drought periods, as we proved with the experiment presented in Ch. 4, but the evidences of time series of daily precipitation studied, from stations close to the study sites, show no significant changes on the historical total rainfall or in duration of drought periods, therefore, according to our predictions the probability that soil properties and soil conditions of paramos are affected by changes in the temporal distribution of precipitation is very low in the short and medium term. The increases in air temperature and atmospheric CO2, and their expected effects on soil carbon and nitrogen dynamics, may indirectly lead to changes in soil hydro-physical properties (Jones et al. 2005; Krol et al. 2006; Davidson & Janssens 2006; Vanhala et al. 2008; Müller et al. 2010; Castro et al. 2010; Hueso et al. 2011; Dymov et al. 2015; Qafoku 2015), another possible threat to consider, but those effects might be higher if they are combined with anthropic activities or with changes in natural land cover.

### 6.3.3 The vulnerability of paramo ecosystems

To assess the vulnerability, we must take into account the base line considered for comparison with projections, which is the climate conditions in 2015, since this was a dry year due to the occurrence of a very strong El Niño. Therefore, the projections used to determine and compare the expected changes for the three basins, as well as to define the hydrological vulnerability level of each studied paramo are the worst scenarios expected: an extreme dry year and the 8.5 RCP. Table 6-1 shows the values or every percentile of changes with respect to the base line.

Table 6-1. Percentiles of proportional changes and the defined vulnerability levels.

| Percentile | Value | Vulnerability level | Representative color |
|---|---|---|---|
| 20 | 5.9 | Very low | |
| 40 | 11.5 | Low | |
| 60 | 14.1 | Medium | |
| 80 | 36.2 | High | |
| 100 | 67 | Very high | |

Table 6-2 presents the results observed in 2015 and projected with the described scenario, for every paramo, and the proportional changes among them. The color scale is used to graphically represent the classification of each component, according to the levels of vulnerability defined in table 6-1.

Results indicate that evapotranspiration variations for the 8.5 RCP is the higher expected in the medium term, the changes vary between 11 and 14%, according to the extent and the land cover of each basin.

Considering the importance of soil properties in hydrological behavior of basins, it is expected that the most altered paramos by anthropic activities evidence the loss of some of their hydrological characteristics, as observed in Romerales. In terms of eco-hydrological vulnerability to climate change, the projected changes in paramo of Chingaza indicate a very low vulnerability and Belmira has a low one; while the changes in Romerales are critical, indicating a very high vulnerability to climate change.

Table 6-2. Base line, hydrological projections and relative changes for the studied paramos, considering the driest year and the 8.5 RCP scenario of climate change

| | | Belmira | Chingaza | Romerales |
|---|---|---|---|---|
| ET | 2015 (mm) | 629.1 | 926.3 | 642.4 |
| | Medium term projections (mm) | 710.1 | 1032.4 | 734.8 |
| | Change (%) | 12.9 | 11.4 | 14.4 |
| Base flow | 2015 (mm) | 719.5 | 2262.2 | 195.3 |
| | Medium term projections (mm) | 634.0 | 2128.4 | 127.9 |
| | Change (%) | -11.9 | -5.9 | -34.5 |
| Direct flow | 2015 (mm) | 132.5 | 3.7 | 29.8 |
| | Medium term projections (mm) | 155.4 | 3.5 | 9.8 |
| | Change (%) | 17.3 | -4 | -67 |
| Discharge | 2015 (mm) | 851.9 | 2265.9 | 225.1 |
| | Medium term projections (mm) | 789.4 | 2131.9 | 137.8 |
| | Change (%) | -7.3 | -5.9 | -38.8 |

As for Belmira, it is interesting since this paramo was subject to large disturbances until about 40 years ago, but the conservation program in the last decades shows good results, as this paramo exhibits the indicators, the hydrological functioning and the rates of future change of a well conserved one. This means that, despite the destruction of part of the natural vegetation and soils, in just a few decades the ecosystem has recover most of their properties and hydrological functioning. Also, it’s worthy to highlight the short time required for the the restoration; because due to the specific climatic conditions and the slow growth of the plants, it is belief that the restoration of degraded paramos may be very slow and take long time.

## 6.4 Summary and Conclusions

The control variables of eco-hydrological processes in paramo ecosystems are the precipitation, as a key control of total discharge; the soil organic matter content, as key control of water yield and a set of soil variables: depth, roots density and saturated hydraulic conductivity, as key control of base flow. In some places, precipitation is varying because of climate change, but in high mountain we found no evidences of significant alterations in this variable related to climate changes, and half of natural variation found is explainable by the ENSO and the sunspots cycles. However, soil properties controlling water yield and base flow are susceptible to be affected -both in negative or positive ways- by anthropic activities. That is why these ecosystems should be protected, to preserve their natural properties; nevertheless, the presence of volcanic ashes in soils give them a structure so strong that is capable of resist some of those harmful activities, keeping them with good hydrological functioning.

The eco-hydrologic processes analyzed were the evapotranspiration, the surface runoff and response to rain events and the water regulation. The analysis of evapotranspiration indicates that an increase in temperature, as the projected due to climate change, will not significantly affect evapotranspiration in paramos, meanwhile the paramo vegetation remains invariable; but it can be expected that changes in land cover of natural paramo vegetation by foreign species, might result in evapotranspiration increases and reductions of total discharge.

Surface runoff appeared to be highly correlated to soil properties and soil moisture content, more than with rainfall intensity, generally low; so, this process is more vulnerable to anthropic disturbances affecting soil properties, than to increases in rainfall intensities due to climate change. Moreover, soil properties play a very important role in determining the hydrological response of paramo basins. The water regulation of studied paramos is controlled by soils and, during severe drought periods, by the water stored in wetlands inside the basins. Although severe droughts might affect soil properties or the wetlands characteristics, the water regulation of paramos is more vulnerable, in medium term, to human uses affecting soils and wetlands, than to climate change.

In the medium term, the vulnerability of undisturbed or protected ecosystems of paramos to climate change is very low and low, as demonstrated by the results obtained in Chingaza and Belmira. Nevertheless, anthropic activities that affect or destroy the properties of soils, vegetation and, therefore, the hydrological functioning of paramos, are big threats to those ecosystems, which results in poor hydrological performances, the loss of the ecosystem resilience and a high to very high eco-hydrological vulnerability to climate change. On the other hand, Belmira is a good example of how highly disturbed paramos may reach good levels of restoration and recover their hydrological functions in a few decades of conservation efforts.

Conservation and restoration activities, when necessary, enhance the resilience of paramo ecosystems, i.e. act as buffers increasing the adaptive capacity of paramos to climate change, then, reducing their vulnerability.

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