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Characterization and modeling of hydrology and climatology in paramo ecosystems in Colombia

A study of the paramos and climate change impact on
these ecosystems as a water resource

Lovisa Nilsson och Julia Tholander



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A study of the paramos and climate change impact on these ecosystems as
a water resource

Authors:

Lovisa Nilsson and Julia Tholander

The Master's Programme in Environmental and Water Engineering,
Uppsala University and The Swedish University of Agricultural Sciences

Supervisors:

Erasmus A. Rodriguez Sandoval, Universidad Nacional de Colombia, and
Fernando Jaramillo, Stockholm University

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Abstract

Paramos are unique ecosystems situated in the tropical Andes at an elevation of 2800-4800 meters above sea level. They are home to a variety of endemic species and have a great water regulating capacity and supply around 80 % of the population in Colombia with freshwater. These ecosystems have been found to be particularly vulnerable towards climate change, which is a major challenge when it comes to safeguarding this water source. This study aimed to investigate paramos on three spatial scales: the large, medium and small scale. The large scale aimed at investigating the paramos of Colombia on a national level, the medium scale aimed at modeling the hydrology of a small paramo catchment, and the small scale aimed at exploring the general landscape and methods for monitoring the hydroclimate.

At the national scale, the paramos were characterized based on hydrological and climatological variables, in the end focusing on precipitation and discharge, and producing descriptive statistics, in addition to finding temporal trends. The aim was to describe the paramos of Colombia hydroclimatologically on a spatial and temporal scale to get a more updated and comprehensive picture of the hydrology in these ecosystems and to investigate whether any possible relationships between the hydroclimatic variables could be detected that could affect the water availability, that is, if there were any signs of climatic forcing and hydrological response. Another aim was to investigate whether any significant trends could be seen in historical data and if there were any signs of climate change or ENSO (El Niño Southern Oscillation) events affecting the time series. The results showed that there was a large range in the amount of annual precipitation, between 500 and 5000 mm/yr, depending on the location of the precipitation station. The annual precipitation differed with up to around 2000 and 3500 mm/yr within and between different paramo regions, respectively. The annual mean daily discharge ranged between 0 and 25-30 m³/s and the total annual specific discharge ranged between 0 and 2500 mm/yr. It was not possible to detect any general, common temporal trend in neither precipitation nor discharge for all of the stations and the majority of the trends for individual stations were not significant. However, most locations that did present significant trends in precipitation showed an increase rather than a decrease, on a monthly rather than an annual scale. The trends that were significant for discharge were also increasing. No evident relationship between precipitation and discharge could be detected in neither amount nor pattern or trend over time, although some similarities and common traits could be found. Some local maxima and minima in precipitation and discharge coincided with ENSO events, but whether the significant trends are due to climate change remains unclear. The changes that were seen could have an impact on societies that are close to and rely on the paramos, but more studies on a seasonal and monthly scale are needed.

At the medium scale, the HBV light model was used to simulate the hydrology in the small paramo catchment called Monterredondo. The aim was to investigate how a parsimonious model like the HBV model would perform compared to the more comprehensive SWAT model, which previously succeeded in modeling the hydrology in this watershed. Since the data is scarce in these regions, a simpler model could be more desirable. The results showed that the HBV was sufficient for

the task, receiving a NSE value of 0.81 (calibration period) and 0.56 (validation period), and able to perform almost as well as the SWAT model, which received NSE values of 0.83 (calibration period) and 0.59 (validation period). Furthermore, since the paramos are vulnerable towards climate change, it was considered important to investigate how discharge might be affected by climate change. Future climate simulations towards the end of the century representing two emission scenarios, SSP2-4.5 and SSP5-8.5, were performed with data from the general circulation models EC-Earth3-CC (Europe) and MRI-ESM2-0 (Japan). The results from the EC-Earth3-CC model indicate a change towards drier dry seasons and wetter wet seasons. On an annual scale, it shows a decrease in discharge, but no change in annual precipitation. The MRI-ESM2-0 model was not considered reliable due to the large distance between the catchment area in question and the location where the data came from.

Large uncertainties are associated with the data quality and quantity for both parts of this study. This is a well-known issue in these quite unapproachable locations, which is why the small scale investigation focused on learning more about the monitoring of these ecosystems. A horizontal precipitation station was built to capture horizontal precipitation. Even if built as a rather rough structure, it seemed to work and could be useful for future investigations. The results showed that horizontal precipitation contributed with a non-negligible amount to the total precipitation.

In summary, there is a risk that climate changes will have an impact on the water resources, due to drier dry seasons and wetter wet seasons. This could lead to water shortages in periods, but more studies are necessary to confirm the result. It is especially important to investigate more variables such as land use, soil moisture and radiation. It is also important to study more paramo areas in detail since they respond differently towards climate change.

Keywords: paramo, hydrology, climate change, precipitation, discharge, modeling, characterization, HBV, ENSO

Referat

Paramos är unika ekosystem som ligger på en höjd av 2800-4800 meter över havet i de tropiska Anderna. De är hem för en mängd olika endemiska arter och har en stor vattenreglerande förmåga och försörjer cirka 80 % av befolkningen i Colombia med dricksvatten. Dessa ekosystem har visat sig vara särskilt sårbara för klimatförändringar, vilket innebär en stor utmaning när det kommer till att skydda paramos som vattenkälla. Denna studie syftade till att undersöka paramos på tre rumsliga skalor: stor, medelstor och liten skala. Den stora skalan syftar till att undersöka paramos i Colombia på nationell nivå, den medelstora skalan syftar till att modellera hydrologin i ett litet paramoavrinningsområde, och den lilla skalan syftar till att utforska det allmänna landskapet och metoder för att övervaka hydroklimatologin.

På nationell skala karaktäriserades paramos utifrån hydrologiska och klimatologiska variabler, i slutändan med fokus på nederbörd och avrinning, genom att producera beskrivande statistik, och därtill hitta trender över tid. Syftet var att beskriva paramos i Colombia hydroklimatologiskt i en rumslig och tidsmässig skala för att få en mer uppdaterad och heltäckande bild av hydrologin i dessa ekosystem och för att undersöka om möjliga samband mellan de hydroklimatologiska variablerna kunde upptäckas som skulle kunna påverka vattentillgången, det vill säga om det fanns några tecken på klimatpåverkan och hydrologisk respons. Ett annat syfte var att undersöka om statistiskt signifikanta trender kunde ses i historiska data och om det fanns tecken på att klimatförändringar eller ENSO-händelser (El Niño Southern Oscillation) påverkade tidsserierna. Resultatet visade att det fanns ett stort spann i uppmätt årsnederbörd, mellan 500 och 5000 mm/år, beroende på nederbördsstationens lokalisering. Årsnederbörden skiljde sig med upp till cirka 2000 och 3500 mm/år inom respektive mellan olika paramoregioner. Det årliga medeldygnsfloppet låg mellan 0 och 25-30 m³/s och det totala årliga specifika flödet låg mellan 0 och 2500 mm/år. Det var inte möjligt att upptäcka någon generell, gemensam tidsmässig trend i varken nederbörd eller avrinning för samtliga stationer och majoriteten av trenderna för enskilda stationer var inte signifikanta. De flesta platser som faktiskt visade signifikanta trender i nederbörd visade en ökning snarare än en minskning, på månadsbasis snarare än årsbasis. Trenderna som var signifikanta för avrinning visade också en ökning. Inget uppenbart samband mellan nederbörd och avrinning kunde ses i varken kvantitet, mönster eller trend över tid, även om vissa likheter och gemensamma egenskaper kunde hittas. Vissa lokala maxima och minima i nederbörd sammanföll med ENSO-händelser, men huruvida de signifikanta trenderna beror på klimatförändringar är fortfarande oklart. De förändringar som kunde identifieras kan ha en inverkan på samhällen som är nära och förlitar sig på paramos, men fler studier på säsong- och månadsskala behövs.

På den medelstora skalan användes HBV-lightmodellen för att simulera hydrologin i ett litet paramoavrinningsområde kallat Monterredondo. Syftet var att undersöka hur en mindre komplex modell som HBV-modellen kunde prestera jämfört med den mer omfattande SWAT-modellen, som tidigare lyckats modellera hydrologin i samma avrinningsområde. Eftersom mängden data i dessa regioner är begränsad kan en mindre komplex modell vara att föredra. Resultaten visade att HBV presterade tillräckligt bra för uppgiften då modellen erhöll ett NSE-värde på

0,81 (kalibreringsperioden) och 0,56 (valideringsperioden) och kunde prestera nästan lika bra som SWAT-modellen, som erhöll NSE-värden på 0,83 (kalibreringsperioden) och 0,59 (valideringsperioden). Då paramos är sårbara för klimatförändringar ansågs det dessutom viktigt att undersöka hur avrinningen kan påverkas av klimatförändringar. Simuleringar för framtida klimat motsvarande slutet av seklet modellerades med två utsläppsscenarier, SSP2-4.5 och SSP5-8.5. De representerades med data från de allmänna cirkulationsmodellerna EC-Earth3-CC (Europa) och MRI-ESM2-0 (Japan). Resultaten från EC-Earth3-CC-modellen indikerade en förändring mot torrare torrperioder och blötare regnperioder. På en årsskala visade modellen en minskning i avrinning, men ingen förändring i årsnederbörd. MRI-ESM2-0-modellen bedömdes inte vara tillförlitlig på grund av det stora avståndet mellan det aktuella avrinningssområdet och platsen där datan kom ifrån.

Stora osäkerheter är förknippade med datakvalitet och kvantitet för båda delarna av denna studie. Detta är ett välkänt problem på dessa ganska otillgängliga platser, varför den småskaliga utredningen fokuserade på att öka förståelsen om den hydroklimatologiska övervakningen i dessa ekosystem. En horisontell nederbördsstation byggdes för att fånga horisontell nederbörd. Även om den byggdes med en ganska grov struktur, verkade den fungera och kan potentiellt vara användbar för framtida undersökningar. Resultaten visade att horisontell nederbörd bidrog med en icke försumbar mängd till den totala nederbörden.

Sammanfattningsvis finns det en risk att klimatförändringarna påverkar vattenresurserna, på grund av att torrperioderna blir torrare och regnperioderna blir blötare. Detta kan leda till en periodvis vattenbrist, men fler studier krävs för att bekräfta resultatet. Det är särskilt viktigt att undersöka fler variabler som markanvändning, markfuktighet och strålning. Det är också viktigt att studera fler paramoområden i detalj eftersom de reagerar olika på klimatförändringar.

Nyckelord: paramo, hydrologi, klimatförändringar, nederbörd, avrinning, modellering, karaktärisering, HBV, ENSO

Populärvetenskaplig sammanfattning

Paramos kallas de speciella ekosystem som är belägna högt uppe i den sydamerikanska bergskedjan Anderna, i länder som Chile, Ecuador, Peru och Colombia. Dessa ekosystem har en säregen karaktär med bland annat unik växtlighet. Vattnet som kommer in i dessa ekosystem lagras väl i bland annat laguner och de särskilt anpassade växterna och när det sedan rinner genom dess landskap har det bra kvalitet och ger ett vattenflöde som kommer mycket regelbundet. I och med detta är det många samhällen som förlitar sig på paramos för sin dricksvattenförsörjning. Dessa ekosystem är alltså av stor vikt för samhällena i Anderna, men är dessvärre samtidigt extra känsliga för störningar, såsom klimatförändringar, varför det är av stor betydelse att undersöka hur de kan komma att påverkas i framtiden.

För att få en bättre bild av paramoområdenas egenskaper och undersöka om det går att se effekter av klimatförändringarna redan idag gjordes en karaktärisering och trendanalys på regn och vattenflöde. Denna del av studien avsåg att täcka upp alla paramoområden i hela Colombia, vilket inte var möjligt då det visade sig att det inte fanns tillräckligt med data. Det gick inte att se några tydliga och entydiga historiska trender, men de enstaka trender som var betydande pekade mest på ökade regnmängder och ökat vattenflöde. Inget starkt samband mellan regn och flöde kunde dock uttydas. Vad gäller kvantitet i regn och flöde, kunde en stor variation mellan de olika paramoområdena eller mätstationerna ses. Vissa platser får till exempel nästan fem gånger så mycket regn som andra och flödet kan också skilja sig mycket. Detta tyder på att klimatförändringarna kommer att påverka dessa områden väldigt olika, beroende på var i Colombia de ligger.

Det gjordes också en undersökning på ett specifikt paramoområde som ligger ganska nära huvudstaden Bogotá och som står för en stor andel av vattenförsörjningen till staden. I denna del av studien användes den hydrologiska modellen HBV för att simulera hur vattenföringen kan förändras i framtiden. HBV är en relativt enkel modell, vilket var en av orsakerna till varför den valdes - i paramoområdena finns det nämligen mycket begränsat med data, så om det finns en modell som klarar av att modellera vattnet med begränsad data vore det att föredra. Det visade sig att HBV-modellen klarade av uppgiften nästan lika bra som den mer avancerade modellen SWAT. Resultatet från framtidssimuleringarna visade att det finns en risk att torrsäsongerna blir torrare medan våtsäsongerna blir blötare och att det totalt sett inte kommer att gå att ta ut lika mycket vatten från just detta paramoområde, vilket skulle kunna leda till periodvis vattenbrist.

Två fältbesök gjordes också till nationalparken Chingaza för att få mer kunskap om ekosystemen och om hur mätningar går till, samt för att bidra till uppstarten av installation av nya mätinstrument i området.

Sammanfattningsvis finns det en risk att vattenresurserna påverkas av klimatförändringarna, men fler studier behöver genomföras för att säkerställa detta. Framför allt behöver fler variabler än nederbörd, temperatur och vattenföring undersökas, som till exempel markanvändning, markfuktighet och solinstrålning. Fler paramoområden behöver också undersökas mer i detalj då det finns en så stor variation mellan dem.

Preface

This master thesis project rounds off our years at the Master's Programme in Environmental and Water Engineering at Uppsala University and the Swedish University of Agricultural Sciences. The project was performed as a Minor Field Study in collaboration with Universidad Nacional de Colombia in Bogotá. It is the work of Lovisa Nilsson, who is responsible for the modeling part and Julia Tholander, who is responsible for the characterization part. The project is worth 30 credits per student. The supervisors have been Erasmo A. Rodriguez Sandoval from Universidad Nacional de Colombia and Fernando Jaramillo from Stockholm University. The subject reviewer has been Benjamin Fischer from Uppsala university.

We would like to express our warmest gratitude to our supervisor and contact person in Colombia Erasmo Rodriguez, who has supported us from the beginning to the end, and who especially was a wonderful resource during our visit in Colombia and also made sure we had time to enjoy and explore his country. The fact that you have always had our best interests in mind, not only academically, has been indispensable. We would also like to thank our dear friends Roger Guio, David Jacobsson and Hanna Pierrau who always took their time to discuss the project and to give us invaluable help.

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Lovisa Nilsson and Julia Tholander
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Contents

Words, acronyms and definitions	1
1 Introduction	2
1.1 Climate change	3
1.2 El Niño Southern Oscillation (ENSO)	3
1.3 Previous studies and importance of this study	5
1.4 Aims and research questions	13
1.4.1 Aims	13
1.4.2 Research questions	14
2 Tools and materials	15
2.1 Characterization	15
2.1.1 Data	15
2.1.2 R and Microsoft Excel	15
2.1.3 ArcMap	16
2.1.4 Clim pact	16
2.2 Modeling	16
2.2.1 Data	16
2.2.2 Hydrological models	18
3 Study areas	22
3.1 Characterization: Colombia and its paramos	22
3.2 Modeling: Chingaza National Park	23
4 Methods	26
4.1 Characterization	26
4.1.1 Data collection and selection	26
4.1.2 Data quality screening and station exclusion	30
4.1.3 Final analyses and results	37
4.1.3.1 Precipitation	37
4.1.3.2 Discharge	38
4.2 Modeling	40
4.2.1 Study area delineation	40
4.2.2 Field visit	42
4.2.3 Model comparison	42
4.2.3.1 Data preparation	42
4.2.3.2 Model calibration	45
4.2.3.3 Uncertainties in discharge	46
4.2.4 Future runoff predictions	50
4.2.4.1 Calibration	50
4.2.4.2 Future discharge simulations	51
4.3 Field visit	53

5	Results	55
5.1	Characterization	55
5.1.1	Precipitation	55
5.1.2	Discharge	65
5.1.3	Comparison of precipitation and discharge	68
5.2	Modeling	69
5.2.1	Model comparison and evaluation of the HBV model	69
5.2.1.1	Water balance uncertainties	69
5.2.1.2	Sensitivity analysis	71
5.2.1.3	SWAT and HBV model comparison	72
5.2.2	Future runoff predictions	73
5.3	Field visit	78
6	Discussion	79
6.1	Characterization	79
6.1.1	Precipitation	79
6.1.2	Discharge	83
6.1.3	Comparison of precipitation and discharge	84
6.1.4	Uncertainties	85
6.1.5	Data scarcity	88
6.1.6	Limitations and further research	88
6.2	Modeling	89
6.2.1	Model comparison	89
6.2.2	Future climate predictions	91
6.2.3	Data uncertainties and model evaluation	93
6.2.4	Limitations and further research	96
6.3	General discussion	97
6.3.1	General limitations and further research	99
7	Conclusions	100
7.1	Characterization	100
7.2	Modeling	101
7.3	General conclusions	101
	References	103
A	Appendix	i
A.1	ENSO events	i
A.2	HBV model parameter settings	i
A.3	Modeling data analysis	i
A.4	Plots for scaling precipitation	iii
A.5	Cross section geometry	ix

Words, acronyms and definitions

C1-9: Cluster 1 to 9, the clusters into which the measuring stations are divided

Catchment/Watershed/Basin: Meaning the area where water is collected by the natural landscape. In this paper, the words catchment, watershed and basin are used as synonyms.

CNP: Chingaza National Park

Complejo: The smallest unit that the paramos are divided into.

Cordillera: Spanish word for mountain range (Cordillera Occidental: the Western Mountain Range, Cordillera Central: the Central Mountain Range, Cordillera Oriental: the Eastern Mountain Range)

Discharge/Runoff: The words discharge and runoff are used as synonyms in this paper.

Endemic: Species that are found in a particular geographical region and nowhere else in the world.

ENSO: El Niño Southern Oscillation

GCM: General Circulation Models. Models that simulate the response of global climate systems induced from climate warming.

IPCC: Intergovernmental Panel on Climate Change

ITCZ: InterTropical Convergence Zone

Leaf area index: Defined as the area of one side of the leaf per ground area.

Orogeny: A geological process where a section of the earth's crust is folded and deformed by compression which forms a mountain range.

S1-6: Season 1 to 6, the seasons that the year is divided into according to wet and dry seasons (S1: Feb-Mar, S2: Apr-May, S3: Jun-Jul, S4: Aug-Sep, S5: Oct-Nov, S6: Dec-Jan)

SSP: Shared socioeconomic pathways.

1 Introduction

At present, as many as 2.2 billion people do not have access to safely managed drinking water, according to the United Nations (UN) (United Nations n.d.). Furthermore, lack of water could force 700 million people to move by 2030. "Clean water and sanitation" is the UN's sixth sustainable development goal (SDG6), formulated to tackle this type of problems. SDG6 includes targets to, for example, "achieve universal and equitable access to safe and affordable drinking water for all, and protect and restore water-related ecosystems, including mountains, forests, wetlands, rivers, aquifers and lakes" (ibid.).

In Colombia, many societies rely on so-called paramos for their water supply (Ruiz, Martinson, and Vergara 2012, Impulse 2019). Paramos are ecosystems that are situated above the treeline and below the glaciers, and extend over the higher elevations of the northern Andes in countries like Peru, Venezuela, Colombia and Ecuador (Ochoa-Tocachi et al. 2016). Because of local characteristics, the elevation limits of the ecosystem vary between 2800 and 4800 meters above sea level (Morales Rivas et al., Madriñán, Cortés, and Richardson 2013).

Paramos are characterized by neotropical open alpine grasslands and the landscape is dominated by glacier-formed valleys and plains. There is also a large variety of lakes, wetlands and peat bogs, as well as small forest patches and shrubberies (Ochoa-Tocachi et al. 2016). The formation of the paramos was enabled by the Andean orogeny, since the evolution of these ecosystems is dependent on that the Andean mountain range could reach a sufficient elevation. The vegetation forms a unique ecosystem with many endemic species, and the paramos have been described as biodiversity hotspots since they host such a vast range of different species (Madriñán, Cortés, and Richardson 2013). Figure 1 shows a typical paramo landscape with valleys and cliffs. In the foreground a Frailejon grows, which is a typical plant in the paramo ecosystem. These plants have adapted to keep water in their trunk. Their growth rate is very slow, approximately 1 cm/yr making them very vulnerable to climate and land use change (Cárdenas 2016).



Figure 1: Picture showing a typical paramo landscape.

The paramos' special characteristics in general make these ecosystems extra sensitive towards even small disturbances in climate, water and biological systems (Flores-López et al. 2016), including those disturbances caused by anthropogenic activities, such as land use change. There are both national and international interests in learning more about, protecting, preserving and restoring the paramos (Morales Rivas et al. 2007). For example, there is an international interest for paramos from Ramsar - the inter-governmental wetland convention - since paramos contain many wetlands. The goal of Ramsar is to achieve a wise use and conservation of wetlands because of their diversity and productivity (Ramsar n.d.). In 2002 there were nine sites in Colombia listed by Ramsar as Wetlands of National Importance, two of which are located within the paramo ecosystems (Ramsar Sites Information Service 2002.)

1.1 Climate change

The Intergovernmental Panel on Climate Change (IPCC) has previously reported the possible future climate outcomes through Representative Concentration Pathways (RCP). As part of their work on an updated assessment report (AR6) they have produced a new framework for reporting possible future climate outcomes (SMHI 2021a). This framework goes under the name of Shared Socioeconomic Pathways (SSP) and these five scenarios are supposed to better recount possible future climates based on how society can evolve for certain concentrations of greenhouse gas emissions to be realistic (SMHI 2021b). The scenarios SSP3-7 and SSP5-8.5 describe scenarios where the world's countries do not work according to any climate policy and they are sometimes described as "business as usual", with high and very high emissions. The intermediate scenarios SSP4-6.0 and SSP2-4.5 are believed to be possible with the current policies, and the scenario representing the least climate change - SSP1-1.9 - reflects the mitigation needed to meet the Paris agreement with the goal to limit the temperature increase to 1.5 °C. (European Commission n.d., Peters and Hausfather 2020). For this study, the scenarios SSP5-8.5 and SSP2-4.5 were selected. These scenarios are often recurrent in literature, for example, in Vogel (2021), Cresso (2020), Urrutia and Vuille (2009), and are interesting since they represent both the "worst case scenario" and a more probable scenario.

1.2 El Niño Southern Oscillation (ENSO)

El Niño is a meteorological and oceanographic phenomenon recurring in an irregular pattern every 2-7 years. The phenomenon occurs due to a smaller than normal air pressure difference between the western and eastern parts of the Pacific Ocean, leading to weaker trade winds from the west coast of South America. This results in less surface water being transported away from the coast and towards the west. A consequence of this is that not as much cold and nutrient rich water will replace the water transported away from the coast as usually is the case, so the surface water along the South American coast is warmer than normal. These recurrent shifts back and forth in surface temperature and weather are called the El Niño Southern Oscillation (ENSO).

El Niño is described as the warm phase of ENSO. The warmer surface water and the weaker oceanic circulation during El Niño result in heavier precipitation over eastern or western equatorial South America. The mechanism behind this is that the lower atmosphere is heated up by the warmer surface water and this in turn leads to more cloud formation, followed by increased precipitation. La Niña is a phenomenon occurring in between El Niño events or normal conditions. As opposed to El Niño, La Niña is characterized by strong trade winds enabling more cold water than normal to enter the coastal areas of western South America. Therefore, it is described as the cold phase of ENSO. La Niña results in droughts in these regions. In other words, El Niño and La Niña alter the temperature of the surface water and the weather conditions in South America, so that they deviate from normal circumstances (Nationalencyklopedin n.d.).

The effects of ENSO described above are true for Ecuador and Peru. However, in the Pacific, Caribbean and Andean regions of Colombia (see Figure 2) the opposite effects are seen, that is, El Niño brings droughts by resulting in higher temperatures, less precipitation and discharge, lower moisture content in the soil and less humid air. La Niña on the other hand brings floods by causing the opposite conditions. Moreover, there are studies suggesting that the ENSO events will become both more frequent and more extreme due to climate change, although the science behind this is not completely certain (NOAA 2020).

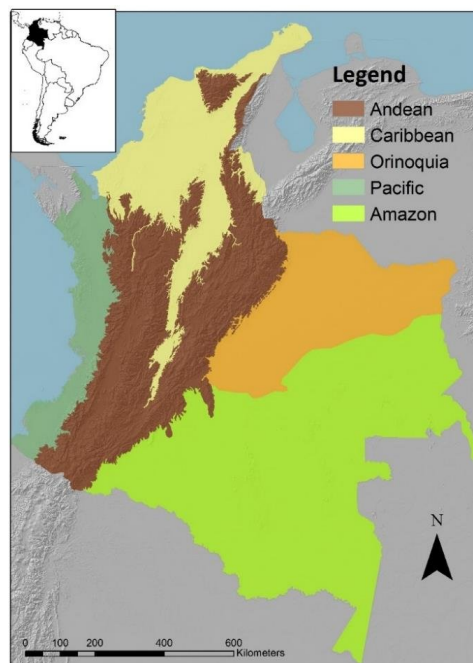


Figure 2: Map of Colombia showing the country's location in South America and its five natural regions (Source: Etter et al. 2018).

1.3 Previous studies and importance of this study

The paramo regions contribute with as much as 80 % of the water consumed in Bogotá (Ruiz, Martinson, and Vergara 2012) and 80 % of the total water supply in Colombia (Impulse 2019). Considering how crucial paramos are for hydrological purposes, their vulnerability is a major challenge. Therefore, it is of high priority to preserve the paramos, and hence it is important to investigate these areas regarding the hydrology and learn how they could respond to climate change. Climate change and land use changes caused by humans lead to increased stress on the paramo ecosystems, causing erosion as well as habitat and biodiversity loss. This will further likely have a significant impact on hydrology. Moreover, changes in glacier dynamics because of climate change, as well as snow cover, vegetation and land management changes, will affect the water regulation capacity of these ecosystems (Buytaert et al 2006, Ruiz, Martinson, and Vergara 2012).

According to Williams and Jackson (2007), an analysis of the IPCC's climate change scenarios showed an imminent risk that new climate conditions will evolve in South America, especially in tropical and subtropical areas, with a possible alteration in the precipitation patterns across the paramo regions along with an increase in the average temperature. Among other things this could potentially lead to a gradual drying of the currently wet soils, which would speed up the decomposition of organic matter. Instead of being a CO₂ sink, the paramos could transform into a greenhouse gas emission source (Cresso 2020).

Globally, the paramo ecosystems were among the least investigated ecosystems up until around the 2000s, after which there was a boom in the research, partly because more people over time have realized how critical they are for water regulation. Consequently, the knowledge of hydrological processes in the paramos and the effect of for example climate change on these processes has grown. Although some studies have provided robust hydrological insights on a small scale, there is still a need for upscaling these findings and getting a more comprehensive and even deeper understanding (Correa et al. 2020, Hofstede et al. 2014). Hofstede et al. (2014) mentioned that, at least at the time of writing, conclusions on the effect of climate change on hydrology in the paramos emanated from "logical assumptions" rather than "empirical evidence". Some examples of such logical assumptions are that climate change could affect the water balance and the possibility of wetlands to work as water reservoirs (Buytaert et al. 2006), that it could affect the soil content and fluxes of organic matter if paramos are replaced by Andean forest, and that it could extend the area suitable for agriculture and therefore diminish the paramo area (Buytaert et al. 2010). Hence, there is still a lack of knowledge regarding the impact of climate change on the hydrology of the paramos (Hofstede et al. 2014).

In the research about paramos an important aspect is the interplay between the different factors that contribute to the favourable hydrological traits of the paramos. These factors include the climate, the vegetation, and the soil (Hofstede et al. 2014, Correa

et al. 2020). In the paramos the climate is mainly known for being wet due to rather high precipitation and low evapotranspiration, the vegetation is dense and structurally intricate with a landscape containing bogs that can store water and organic matter, and the soil contains a lot of organic materials as well. Hofstede et al. (2014) stated that if for example the climate changes, the vegetation and soil changes as well, which would have an impact on the hydrology. They pointed out that the effect of climate change on the hydrology could, in theory, be confirmed through the vegetation and soil, since the water regulating capacity of the paramos is thanks to the soil being rich in organic matter and the protective vegetation. Hence, a shift in vegetation and/or faster degradation of organic matter in the soil due to climate change would make it more difficult for the paramos to hold water. Additionally, the organic matter in the soil in the mountains is believed to be extra vulnerable to temperature increases and if it is degraded faster due to higher temperature it is believed the hydrologic regulation in the catchments and the streamflow regimes can change. However, no research showing these effects empirically exist. (Hofstede et al. 2014)

Although many studies date back to around ten years ago, a study as recent as from 2021 argues that research on climate change and its possible effects on crucial ecosystem services provided by paramos is still sparse (Diazgranados et al. 2021). Up until now the impacts of climate change on paramos have been investigated in several ways, from various angles, but Diazgranados et al. (2021) claim that research treating the question of how climate change affects important ecosystem services provided by the paramos remains insufficient. They therefore sought to do an overall quantification of the effect of climate change on the different cultural, provisional, regulating and supporting ecosystem services (such as leisure, food production, erosion regulation and soil formation), through looking at how the plants that help sustain these ecosystem services were affected. They concluded that water regulation was one of the ecosystem services with the biggest estimated losses. This further emphasizes the need for more research on the effect of climate change on specifically hydrology.

In *Los páramos andinos - ¿Qué sabemos?: Estado de conocimiento sobre el impacto del cambio climático en el ecosistema páramo* (Hofstede et al. 2014), a report focusing on the effect of climate change on paramos in Colombia, Ecuador and Peru, it is emphasized that there is a perceptible lack of knowledge about climate change and how it is manifested. In other words, the understanding of what can happen and what has already happened in the paramos as a consequence of climate change is inadequate. One thing, however, is claimed to be known and it is that climate change is occurring in the paramos and that there are apparent signs of it already. For instance, various studies agree and state that the temperature has risen in the paramos and that this increase is greater in the paramos than in other types of ecosystems. Nevertheless, climate change overall is expressed differently in different places, and therefore it is a challenge to find out how it impacts a certain paramo. In particular, precipitation is one of the variables for which it is difficult to see any obvious trends. For example, it is unclear how total precipitation is affected by climate change. Trends towards more precipitation have been seen in several paramos, but the quantity has varied considerably between different sites.

Hofstede et al. write:

”Due to the uncertainties about the precipitation patterns under different climate change scenarios, the enormous spatial variability, and the lack of monitoring data of streamflow, in reality one cannot generalize the effect of climate change on the water regulation and the streamflows in the future. Different models have resulted in predictions that vary between little change, better water availability and important reductions. The only valid conclusion is that climate change entails much uncertainty about the hydrology in the Andes.” (p. 105-106, English translation)

All in all, according to Hofstede et al. (2014), it is, in fact, too difficult to determine whether the precipitation is increasing or decreasing, and it is even more challenging to say what time will bring. However, there is agreement regarding the seasonality, that is, that the seasons are getting more extreme with more intense precipitation during wet seasons and longer dry seasons. The uncertainty about the effects of climate change can mainly be attributed to the great geographical differences in the Andean mountains, the challenge of using climate models in mountainous areas and the lack of meteorological stations that gather long time series of data. Hofstede et al. (2014) also express that if, or as long as, more reliable information about the amount and distribution of precipitation is not available the effect of climate change on the paramos is only hypothetical. (Hofstede et al. 2014)

It is possible that a lot has happened since *Los páramos andinos - ¿Qué sabemos?: Estado de conocimiento sobre el impacto del cambio climático en el ecosistema páramo* (Hofstede et al. 2014) was published, and they also recognized that a lot was happening in the research field of paramos and climate change at the time of writing, but at least then they claimed that there was not a strong evidence base of observations and most knowledge was derived from possible scenarios and models, from application of information from one site somewhere in the world onto another site, and from logical suppositions and speculations.

More research on the effects of climate change and the connection and interplay between social, biophysical and hydroclimatic circumstances is also desired. Furthermore, there is a need to overcome the difficulties with gathering data long-term, to transfer knowledge to paramo regions lacking a monitoring system and to take into account the fact that the processes are inconstant (Correa et al. 2020).

According to Ruiz, Martinson, and Vergara (2012) it is possible to observe historical trends in for example precipitation and temperature that imply that climate change has already had an impact in the mountain areas, at least in the paramo that they looked at, which was located in the central Andean mountain range of Colombia. They investigated several variables, namely different measures of temperature, precipitation, sunshine and relative humidity, to discover potentially visible historical trends. However, there are more variables of interest for hydrology, such as horizontal precipitation, evapo(transpi)ration, radiation, wind speed, soil moisture, water storage, and runoff. These variables are interesting because they can also affect the retention, regulation and availability of water in different ways. For example, horizontal precipitation could be a

major contributor to water collection in the paramos, the relation between precipitation and evapotranspiration determines the effective water (Morales Rivas et al. 2007), the relationship between precipitation, evaporation and radiation can be used to determine a precipitation-runoff relationship (Solomon 1967) and soil moisture is a factor that affects how much water the soil can hold and how much water turns into discharge (Brauer et al. 2013). Additionally, an equation for evaporation was developed using sunshine, temperature, humidity and wind speed observations (FAO n.d.). By investigating as many of these supplementary variables as possible in this project, the prospect is that the results will be more comprehensive, accurate and reliable when it comes to climate change and its possible effects on hydrology and water availability.

Moreover, in a literature review, Palomo (2017) concluded that, in general, the southern continents were under-represented and South America came fourth out of the six continents when it came to number of articles about the effects of climate change on ecosystem services (such as water availability) in high mountain areas. Additionally, in South America most articles concentrated on Peru. So far, it also seems like much research about paramos has been carried out in Ecuador (Lelieveld 2020, Espinosa and Rivera 2016, Buytaert et al. 2006). Moreover, Palomo (2017) saw a particular need for more research in tropical areas.

Furthermore, the focus of many studies has been on the impact of land use change and not on the effect of climate change on hydrology (Correa et al. 2019, Céleri and Feyen 2009, Morales Rivas et al. 2007). For example, *Atlas de páramos de Colombia* primarily brings up human land use as a threat to the paramos. Climate change is mentioned more briefly in relation to rising temperatures (ibid.). In addition, Hofstede et al. (2014) state that many studies in Colombia are about the geography and geomorphology, whereas the focus has been different in the bordering countries Venezuela and Ecuador. That is, fewer studies have seemingly been conducted in Colombia, and the focus has been different.

What is more, many of the studies in Colombia have only looked at one or a few paramos, usually in Chingaza National Park (CNP) (Cresso 2020, Sanchez, Posada, and Smith 2014) or the central Andean mountain range (Ruiz, Martinson, and Vergara 2012, Hofstede, Ximena Mondragón Castillo, and Rocha Osorio 1995), and are therefore only on a rather local scale. This has made it apparent that the ecological processes in separate paramos are very diverse and distinct and therefore it is difficult or impossible to apply knowledge from one paramo, on another paramo. Hence, Hofstede et al. (2014) concluded that replication and validation of studies on the paramos' functioning is lacking. Moreover, according to them, most of the paramo areas (complejos) in Colombia were being studied at the time, but the paramos in Sierra Nevada and Cordillera Occidental were under-represented. Hence, few studies have been a national investigation of all the paramos in Colombia. This study will therefore attempt to be more comprehensive than most other existing studies, since its ambition is to cover all the main paramos within Colombia, and to have another focus, namely on the impact of climate change on hydrology.

The only work found that has looked at the paramos on a national scale in Colombia is *Atlas de páramos de Colombia* from 2007 (henceforth referred to as "the atlas"), published by Instituto de Investigación de Recursos Biológicos Alexander von Humboldt, IAVH (Morales Rivas et al. 2007). The aim of this atlas was to gather the most relevant knowledge of for example location, land use, precipitation pattern and amount, temperature, geology, flora and fauna, and socioeconomic and cultural aspects of Colombia's paramos from the numerous smaller and more niched studies that have been conducted. It covers general information about Colombia and the paramos with respect to for example geography, hydrography, climate, soils and ecology as well as specific information about the 34 "complejos" that they have divided Colombia's paramos into. Among other things, the specific information includes the ecological background, such as climate characteristics like precipitation and temperature. Since the information about the different complejos has been gathered from different studies, the amount and detail of the information varies. Using information from different sources can also be problematic since it has previously been highlighted that there is a need for comparable data (Céleri and Feyen 2009). Moreover, the atlas inconsistently presents either a single value or an upper and lower value of the annual amount of precipitation in each complejo, not showing the temporal variations on different time scales. Neither does the atlas compare the different paramo regions that much, which would give a better idea of the spatial differences.

The effects of climate change are expected to vary notably and no general description of them can be made, since it is uncertain how for example precipitation is affected by climate change. There are studies pointing to that greater evapotranspiration along with a concurrent increase in precipitation will cancel each other (Buytaert and De Bièvre 2012). However, there is a stronger opinion that the seasons will get stronger and that there will be more severe water deficits in some places (Hofstede et al. 2014). Places where the precipitation has decreased rather than increased, at the same time as the evapotranspiration has increased, are likely even more at risk of water shortages (Ruiz et al. 2011). Something that affects for example precipitation is ENSO, as previously mentioned in Section 1.2. According to some studies, anthropogenically induced climate change is believed to have an influence on ENSO by making ENSO events more common and more extreme. However, whether this is the case is still very uncertain according to the IPCC and there is no unanimity between researchers about it. Some studies even say the opposite, that is, that ENSO events will become weaker (NOAA 2020, DiLiberto 2021).

People living in the rural areas are facing an uncertain future due to climate change. There are testimonies from every part of the Andean mountains of the various effects of climate change that these populations have noticed. All of them recount that the seasons have become more unpredictable, which in turn affects the communities' agricultural habits and production. Nonetheless, overall the changes seen differ greatly. (Hofstede et al. 2014)

There are previous studies investigating the effects of climate change on paramos in specifically Colombia. Some signs of climate change in Colombia have already been reported. A discrepancy in precipitation trends between different geographical areas has been noted (Anderson et al. 2011). For example, increases of up to 10 % in precipitation by the end of the century in Cordillera Oriental and the areas that face the Pacific Ocean, and decreases of up to the same size in the altiplanos and the interandean valleys have been reported by Pabón Caicedo (2012). Moreover, observations from climatic stations in Colombia suggest that the monthly precipitation has declined with 5-10 mm (Castaño-Urbe 2002). The characterization method in this study has similarities with the study by Ruiz, Martinson, and Vergara (2012). However, they only investigated a part of Cordillera Central. They obtained results indicating that the precipitation had decreased significantly with 7-11 % per decade at the higher elevations on particularly the western slope. This corresponded to a quantity of -135 to -180 mm/decade. Conversely, the precipitation had increased at the lower elevations, according to data from a pair of meteorological stations. No significant change in number of dry days was observed, whereas the maximum daily precipitation indicated an increase.

On the other hand, model results from different models showing possible future precipitation do not agree (Hofstede et al. 2014). Using different scenarios it has been projected that during the last third of the century some parts of Colombia will experience decreases of more than 30, sometimes more than 50 %, in precipitation compared with the standard period 1961-1990. On the other hand, some other parts, like the foot of the eastern slope of the eastern Andean mountain range could instead experience an increase of more than 30 % (Pabón Caicedo 2012).

For Colombian paramos specifically, Ruiz et al. (2011) have shown an overall change nationally with increases in total precipitation in Cordillera Occidental, decreases in Cordillera Oriental, and no change, however more extreme events, in one of the paramos in Cordillera Central (Ruiz et al. 2008). In contrast, fewer extreme events have also been reported for Colombian paramos (Hofstede et al. 2014). According to Buytaert et al. (2010) the reason behind that there is less precipitation in Cordillera Oriental is that the winds from the Caribbean have become drier.

On a smaller scale, Cresso (2020) performed a study in the Chingaza paramo region in 2020 to find out how future climate change would affect the spatial distribution of the paramos. She investigated the change in temperature and precipitation, which are variables of high importance for hydrology. The result indicated a change towards drier dry seasons and wetter wet seasons, and that a smaller area than before would be suitable for paramo ecosystems.

The HBV (Hydrologiska Byråns Vattenbalansavdelning) model has been used by Sucozhañay and Céleri (2018) in a small paramo catchment (7.53 km²) in southern Ecuador. They investigated the importance of rain gauge distribution on the modeling result, using a network of 12 rain gauges. They found that the NSE value, a measuring the model performance, improved from 0.31 to 0.80 for the calibration period and from 0.14 to 0.73 for the validation period by increasing the quality of the rainfall data. The conclusion

was that model uncertainties are highly related to spatial rainfall and therefore, to the amount and location of rain gauges.

The HBV model has also been used in Colombia, for example in the large basin of Rio Cauca, located between the mountain ranges Cordillera Occidental and Cordillera Central (Häggström et al. 1988). The model was used on the upper part of the basin, covering an area of 16 284 km² where some of the area overlaps with paramo vegetation. Since the basin was that vast, it was divided into four smaller sub basins. The performance was measured with the R² value and for the calibration period, the R² value varied between 0.78 to 0.93 for the different subbasins.

Furthermore, a model called TOPMODEL was used in (2016) to model the hydrology of a watershed in Chingaza National Park. The TOPMODEL is also a conceptual model like the HBV model, but in addition to the climate variables it also requires a digital elevation model. The model is perhaps more physically based than the HBV model since the parameters can be measured in situ. The conclusions from this study was that the TOPMODEL was able to represent the hydrology of the watershed in CNP with a NSE value of 0.76 for the calibration period. (Gil and Tobón 2016)

Moreover, Flores-López et al. (2016) performed a study about climate change impact on a paramo watershed with sparse data in the Peruvian Andes by calibrating a model called Water Evaluation and Planning (WEAP). The WEAP model can create spatially-based models that calculate changes in hydrology by including climate change conditions and human-made infrastructure. The total area investigated in this study was 4280 km² where 198 km² were within the paramo areas. The model was divided into two sub models, one constituting the paramo area and the other containing the surroundings. The model managed to successfully simulate the streamflow according to the NSE value for the area surrounding the paramos, but for the paramo regions, the NSE value was only 0.25 during the calibration period. The main conclusion was that while the change in temperature and precipitation could be expected to impact the water availability from the paramo regions, the current land use had the most important influence on the amount of water coming from the paramo regions. This is an important finding, which, however cannot be directly adapted for another watershed, because, like Cresso (2020) points out, even if the paramos experience similarities, there are a lot of local differences in both climate and environment. More studies like Flores-López et al. (2016)'s are necessary to understand the possible future challenges that the paramos of Colombia face.

Another important contribution is Vogel's study in Chingaza National Park (Vogel 2021). The purpose was to examine the impacts of climate change on water availability using the Soil and Water Assessment Tool (SWAT). The study investigated two scenarios based on the climate scenarios SSP2-4.5 and SSP5-8.5, together with two land cover change scenarios. The simulation indicated a significant loss in runoff for both scenarios. However, there are hundreds of parameters that can be adjusted in the SWAT model (ibid.), which makes the model complex for the user and brings a large risk of over-parameterization. There is also a larger amount of required input data in the SWAT

model compared with the less complex HBV model - and the data availability in the paramo regions is often limited, which is why the use of a more parsimonious model could be more desirable, if still being able to produce reliable results. Furthermore, Vogel (2021) investigated the climate scenarios based on the General Circulation Models (GCMs) MRI-ESM2-0, CNRM-CM6-1, and BCC-CSM2-MR, which have proven to work well for projecting climate change in South America. However, there are 40 GCMs released in the CMIP6, which all have different strengths. For example the EC-Earth3-CC (Wyser n.d.) is a GCM, which due to its qualities is often used to simulate the Magdalena Cauca basin in Colombia, which contains most of the paramo areas (Lopera Muñoz 2021).

A study performed by Bizuneh et al. (2021) in three different watersheds in Ethiopia found that the SWAT model performed better than the HBV model, with respect to the performance value NSE that was used, in all three watersheds and neither model was able to represent the daily variations of the hydrograph during high and low intensity rainfall events. It was suggested that both models needed further improvements during extreme weather events, including evaluation based on seasons, which could improve the simulations of hydrology in the extreme events. However, different models are appropriate for different basins (Bizuneh et al. 2021), which is why it would be interesting to investigate the HBV model's performance in a small watershed in Colombia as well.

There are several studies stating that horizontal precipitation could constitute a highly important contributor, even one of the primary contributors, to the water cycle (Morales Rivas et al. 2007, Cárdenas et al. 2017, Gómez Elorza 2016). For example, Cárdenas et al. (2017) reported that in some paramos in Colombia fog and drizzle contributed with 7-28 % of the total precipitation and Gómez Elorza (2016) suggested that the contribution from horizontal precipitation can be up to around 60 % of the total hydrological response of a basin located in paramos. Nonetheless, there are quite few studies where data of observed horizontal precipitation has been gathered and where the amount and proportion of water from horizontal precipitation has been estimated, so this is still uncertain. There are also many challenges with trying to determine the amount of horizontal precipitation since it varies considerably in space and time and it is therefore challenging to obtain a value that can be applied to a bigger area (Cárdenas et al. 2017).

In conclusion, there is limited national and regional knowledge about the paramo ecosystems and their hydrology in Colombia since most studies regarding paramos have been conducted in other countries and/or at a local scale. Although there exists an atlas that has approached Colombia's paramos on a national scale, it is 1) based on information from various separate studies, 2) only describes hydroclimatology briefly, not analyzing spatial and temporal differences very much, and 3) dates back to 2007. On a large (national) scale, this study will therefore contribute by attempting to use the same methodology for all the paramo areas and investigating more variables, both hydrological and climatological ones (such as evapo(transpi)ration, radiation, wind speed, and runoff), in more detail, as well as including more recent data than the atlas. This would give a more consistent and comprehensive picture of some hydroclimatic variables, and

therefore of the hydrology, in the paramos of Colombia. This study will also, hopefully, bring more clarity to the possible changes in hydroclimatic variables that climate change gives rise to in the paramos, and in that way help fill in some of the knowledge gaps that exist when it comes to climate change and its effect on hydrology and the paramos as a water resource. Moreover, on a medium (catchment) scale the investigations of this study will be carried out in the same region as Cresso's (2020) and Vogel's (2021), but will focus on hydrology and hydroclimatic change, instead of the paramos' expansion like Cresso (2020), and use another hydrological model than Vogel (2021), with other GCMs. This study will also explore the HBV model, which is a simpler model than the SWAT model with respect to model structure and the input information needed, and then compare the models' results. Lastly, at a small scale (plot scale) two field visits were conducted to gain more knowledge about the paramo ecosystems and to perform initial hydroclimatological measurements to support the establishment of a monitoring network in a small watershed located in La Laja, close to CNP. The plot scale part of this study also included an investigation of the measurement and quantification of the contribution of horizontal precipitation to the total precipitation. These three spatial scales contribute with a more comprehensive picture of the hydrology and the climate's influence on the paramo ecosystems of Colombia.

1.4 Aims and research questions

1.4.1 Aims

There are two main aims for this project. The first aim is to characterize the paramos of Colombia on a national scale from a hydrological perspective, based on observed data for some hydrological and climatological variables (such as precipitation, temperature, evapotranspiration, relative humidity, radiation, wind speed and discharge), using a common methodology for all paramos. This includes producing plots and descriptive statistics that can explain the spatial characteristics, temporal trends and variability of these ecosystems. The idea is that this could give a more updated and complete picture of the hydrology in the Colombian paramos on a national scale. The spatial characterization focuses on the differences between different paramos, whereas the temporal characterization focuses on seasonality and changes in primarily annual total precipitation.

The second main aim is to evaluate the HBV model for the Monterredondo catchment and compare the NSE value with the value received by the SWAT model for the same catchment. The idea is to try a simpler model than the SWAT model for a small catchment in the paramo ecosystems. If the model works sufficiently well, it could be valuable for other discharge simulations where data is scarce. Another goal is to investigate with the HBV model the implications of expected changes in precipitation and temperature for future runoff. Investigating how the discharge might change due to climate change is of great importance since a lot of people depend on the runoff from these ecosystems for their water supply.

1.4.2 Research questions

Characterization of hydrological and climatological variables in paramos

- Which mean and median values and ranges between minimum, maximum and the 25 and 75 % quantiles in precipitation, temperature, evapotranspiration, relative humidity, radiation, wind speed and discharge characterize the paramos in Colombia on a regional and national scale, mainly on an annual basis, over a period of at least 25 years?
- Can any possible relationships be detected between the variables that could affect water availability, and if so which?
- Can climate change already be detected by analyzing historical data? Are there any statistically significant trends in the variables mentioned above? Do any trends seem connected to ENSO events?

Modeling of the future hydrology

- With respect to the NSE value, is HBV a sufficient model for modeling a watershed in the Chingaza National Park? How is HBV performing compared to the SWAT model?
- Based on the climate scenarios SSP2-4.5 and SSP5-8.5, what will be the possible effects of these changes on the discharge during the years 2022-2099?

Measurement and contribution of horizontal precipitation

- Is it possible to build a device that determines the amount of horizontal precipitation in a small paramo catchment? If so, how large is the contribution from horizontal precipitation to the total precipitation?

2 Tools and materials

2.1 Characterization

Statistical analyses are needed for various reasons and purposes. Firstly, the availability and quality of observed data need to be evaluated to ensure that the main analyses are based on a robust and reliable set of data. Secondly, statistics and characteristics of a large number of geographically dispersed measuring stations are useful for an objective grouping of the stations according to their measurements and physiographic characteristics. Thirdly, statistical analyses are crucial for evaluating the hydroclimato-logical spatial characteristics as well as temporal trends of the paramos, such as annual, seasonal and monthly values and trends over time.

2.1.1 Data

Table 1 shows the data that was processed in R, Microsoft Excel, Climpack and ArcMap and the corresponding sources. The data consisted of shapefiles of the paramo areas produced by Instituto de Investigación de Recursos Biológicos Alexander von Humboldt (IAVH 2012a) and of the national hydrometeorological stations from Instituto de Hidrología, Meteorología y Estudios Ambientales (IDEAM 2022a). Daily data for the hydroclimatic variables precipitation (PT), temperature (TS), evaporation (ET), relative humidity (HR), discharge (QL) and wind speed (VD) were also obtained from IDEAM (2022).

Table 1: Table with the data used in the characterization.

Data	Sources	Home pages	Last accessed
Station shapefile and hydroclimatic variables	IDEAM (Instituto de Hidrología, Meteorología y Estudios Ambientales)	DHIME - Consulta y Descarga de Datos Hidrometeorológicos http://dhime.ideam.gov.co/atencionciudadano/	Data provided by UNAL 2022-02-07
Paramo shapefile Identificación cartográfica de los páramos de Colombia a escala 1:100.000 (versión a junio de 2012)	IAVH (Instituto de investigación de recursos biológicos Alexander von Humboldt and Ministerio de Ambiente y Desarrollo Sostenible, Bogotá D.C. Colombia) Proyecto: Actualización del Atlas de Páramos de Colombia. Convenio Interadministrativo de Asociación 11-103.	http://www.humboldt.org.co/es/actualidad/item/109-nueva-cartografia-de-los-paramos-de-colombia-diversidad-territorio-e-historia https://www.aregis.com/home/item.html?id=166474b8fa84158a9ca3d34423b33b8	Data provided by supervisor 2022-01-17

2.1.2 R and Microsoft Excel

For statistical analyses the programs R and Microsoft Excel can be used. Both programs allow for gathering, handling, processing and analyses of data to be carried out. For example, various statistical variables, such as mean, median, maximum and minimum values, can be calculated from sets. The programs can also be used to carry out other statistical analyses, such as trend tests. One frequently applied trend test in hydroclimatology is the Mann-Kendall test and Sen's slope estimator. From this non-parametric test a p-value for significance and a Sen's slope value for the direction and magnitude of change, can be obtained. The significance is determined according to a given confidence level. A common confidence level is 95 %, which requires a p-value of less than 0.05 for the trend to be considered significant. The type and quantitative implication of the trend is described by the Sen's slope value, which is positive if the trend is increasing and negative if it is decreasing (Ali et al. 2019).

2.1.3 ArcMap

ArcMap is a program belonging to Esri's ArcGIS Desktop package. The application can be used to for example create maps and process, analyze and view geographical information. ArcMap was used to visualize the location of the paramo regions and the hydroclimatic measuring stations and to select the stations based on proximity to the paramos (Esri ArcGIS Desktop n.d.).

2.1.4 Climpack

Climdex is a project on climate led by University of New South Wales in cooperation with other climate actors (University of New South Wales n.d.[a]). They have developed a tool called Climpack, written in the R language, which can be used to calculate the so called Climdex indices. Climpack can either be downloaded as a software or used directly on the website in a web-based version (University of New South Wales n.d.[b]). For example, daily observed precipitation and temperature from measuring stations can be used as input data. The indices are annual and sometimes monthly statistics of precipitation and temperature. They are meant to facilitate the comprehension of weather extremes and how they vary in time and space (University of New South Wales n.d.[c]). A few examples of Climdex indices are: number of very heavy rain days, maximum 5-day precipitation and mean daily minimum temperature. The results are downloaded as Excel files with lists of the indices and PDFs with plots of the indices (Herold n.d.).

2.2 Modeling

Modeling the hydrology is a useful tool for both short and long term forecasts. There are many different models available which require different sorts of input data.

2.2.1 Data

Table 2 shows all the data and sources that were processed in Arcmap, HBV light and in Excel. The source for the data for the climate variables were EAAB who presented the data as daily values in excel sheets. The data from the different climate models were downloaded as NC files and converted to excel sheets using MATLAB. The climate data consisted of the coordinates from where the data was projected from together with precipitation and temperature in daily values.

Table 2: Table showing the data sources used in this study.

Data	Sources	Home pages	Last accessed
Climate variables (Temperature, precipitation, discharge)	EAAB (Water and Sanitation Utility of Bogotá)	Available at: https://www.acueducto.com.co	Data provided by supervisor 2022-01-17
Shape files (Location of stations, paramo distribution and CNP)	SIAC (Sistema de Información Ambiental de Colombia) IDEAM (Instituto de Hidrología, Meteorología y Estudios Ambientales)	Available at: http://www.siac.gov.co/ (DHIME - Consulta y Descarga de Datos Hidrometeorológicos) Available at: http://dhime.ideam.gov.co/atencionciudadano/	Data provided by supervisor 2022-01-17
Climate model EC-Earth3-CC (Europe)	EC-Earth community	(Döscher et al. 2022) Available at: https://cds.climate.copernicus.eu/cdsapp#!/home	2022-07-15
Climate model MRI-ESM2-0 (Japan)	Meteorological Research Institute	(Yukimoto et al. 2019) Available at: https://cds.climate.copernicus.eu/cdsapp#!/home	2022-07-15
DEM (Digital elevation model)	ALOS PALSAR	Available at: https://thegeoict.com/blog/2019/10/28/downloading-12-5-m-alos-palsar-high-resolution-dem/	2022-03-15

The discharge data that is used in this project is derived from the main watercourse that flows through the Monterredondo catchment, called River Chuza. At the outlet of this stream, a limnigraph, which measures the water level continuously, is installed. These water level measurements have then been used by the Bogotá water utility company (EAAB) to calculate the discharge time series that is later used in this project. In these calculations, historical rating curves are used by EAAB to convert the water stage (level) into discharge values. The limnigraph is showed in Figure 3. The stream is approximately 9.8 m wide and has a varying depth with its deepest point at 0.59 m.



Figure 3: The limnigraph in green is continuously measuring the water level.

2.2.2 Hydrological models

Different hydrological models often generate different responses for the same basin, therefore, choosing the best and most appropriate model to simulate the hydrological process of a particular basin has always been a challenge (Bizuneh et al. 2021). In this section the two hydrological models HBV and SWAT will be presented, with extra focus on the HBV model which is the model used in this project.

The HBV light model The HBV model is a widely used conceptual model with moderate data input that is mainly used for short and long term forecasting (Häggström et al. 1988). In 2005, the model had been applied in more than 30 countries over the world (Jan Seibert 2005), including in the high Andes in Ecuador where the model was able to simulate the hydrology well (Lelieveld 2020). The model only requires data for temperature, precipitation and discharge, rendering it very suitable for catchments with low data availability (Jan Seibert 2005). The model was initially developed at the Swedish Meteorological and Hydrological Institute (SMHI) (Sucozhañay and Céleri 2018). The version "*HBV light*" was developed at Uppsala University in 1993, with the main goal of being user-friendly thanks to an easy to use interface. Since then the HBV light model has been updated many times (Seibert and Vis 2012).

HBV can be used as a lumped model, treating the whole catchment as one unit, or as a semi-distributed model dividing the catchment into different sub catchments according to elevation and/or vegetation (Seibert and Vis 2012). The HBV light model contains four different so called routines that describe different processes: the snow routine, the soil routine, the response function (also called groundwater routine/response routine) and the routing routine, which work together to simulate the runoff (Häggström et al. 1988) (Seibert and Vis 2012). Figure 4 shows a conceptual drawing of the HBV model structure.

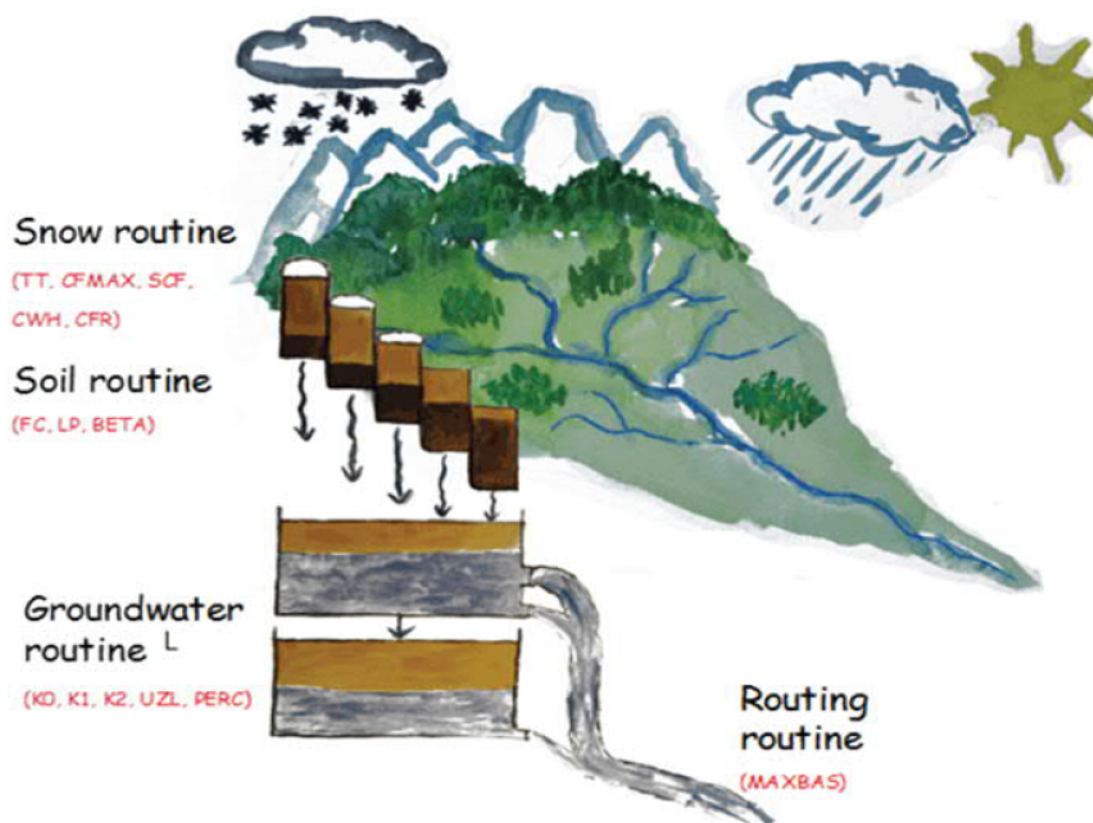


Figure 4: Conceptual drawing of the HBV model. The text in red lists the parameters that are linked to the routines above. Source: Petra Seibert (n.d).

The first routine is the snow routine, which represents the precipitation and whether it falls as snow or rain. It also controls the accumulation of snow and the rate of refreezing and snow melt (Seibert and Vis 2012). The parameter TT translates to the threshold temperature and controls whether the precipitation falls as snow or rain. It is therefore naturally close to 0 °C. TT also controls the snow melt - a lower TT means that the snow melt begins at a lower temperature. The factor SCF accounts for systematic measurement errors during snowfall and it also compensates for evaporation losses from the snowpack, which are otherwise not accounted for explicitly. CFMAX is a shape parameter that influences the timing of the peaks in the hydrograph and also influences

the snow melt. The freezing coefficient, CRF, controls the refreezing in the snow pack, and the water holding capacity CWH influences both the maximum water content that can be held within the snow pack and the response time (University of Zurich n.d.).

The water from the snow routine passes on to the soil routine (Häggström et al. 1988). This routine is parameterized by three parameters, F_C , BETA and LP. F_C represents the field capacity and measures the maximum amount of moisture that the soil can store in mm. The actual soil moisture can be anything between zero and the value of F_C (University of Zurich n.d.). BETA is a shape parameter that influences how much of the water from the snow routine that becomes runoff and how much that contributes to an increase in the soil moisture. The parameter LP defines a threshold for the water content in the soil box above which the actual evapotranspiration is equal to the potential evapotranspiration. A higher value of LP results in a lower actual evapotranspiration and therefore more water remains in the soil box, which will ultimately be routed into discharge (University of Zurich n.d., Häggström et al. 1988). In summary, these three parameters determine what happens with the water from the snow routine - either it is stored in the soil box, evaporated or contributes to runoff in the next routine.

The groundwater routine is responsible for converting the excess water from the soil routine into runoff. It also controls direct precipitation and evaporation for open water bodies. HBV light offers different setups for this routine. Here the default settings will be explained, where the routine includes an upper and a lower reservoir (groundwater boxes). The upper reservoir represents shallow ground water that reacts quickly to precipitation or snow melt, and the lower reservoir represents deeper ground water associated with the base flow. This makes it possible to derive the fast and slow recession processes that are typical for hydrographs. The groundwater routine consists of five parameters: Perc, UZL, K0, K1 and K2. The percolation capacity Perc defines the maximum percolation rate between the upper and lower reservoir. As long as Perc is not exceeded, all of the recharge goes down to the lower groundwater box. The outflow from the lower groundwater box is described by a linear equation where the outflow depends on the water level in the box multiplied by a constant K2. If Perc is exceeded, the water level in the upper groundwater box starts to rise. This activates outflow Q1 which is described by a linear equation with the water level in the upper box and the constant K1. If the water level in the upper reservoir exceeds the limit UZL it activates the outflow Q0, linear with the constant K0. All these outflows contribute to the total runoff. (University of Zurich n.d.)

Lastly, the total runoff is passed through the routine called the routing routine where the parameter MAXBAS is used to lower or delay the water flow. A higher value of MAXBAS gives a subdued and time-shifted flow while a low value equals a faster process (Bergström 1990).

The HBV model uses a warming-up period instead of initial states (Jan Seibert 2005). The model is normally calibrated using a manual trial and error approach. According to Häggström et al. (1988) daily discharge data from 5-10 years is enough. The unit used by HBV light is always mm/time unit. It is possible to use the model with monthly,

daily or sub daily values, as long as the time intervals are even. The output from HBV light is displayed in the result file which contains values for total runoff, the runoff contributions from the different reservoirs, actual evapotranspiration, snow and snow cover, soil moisture and recharge for the time step decided.

SWAT model The Soil and Water Assessment Tool (SWAT) is a physically-based, semi-distributed model developed to predict the impact of land use management on hydrology. The user is able to divide the basin into subbasins, which are further divided into a series of hydrological response units (HRU), where the soil and land use are assumed to be uniform (Bizuneh et al. 2021). Then the discharge is calculated by solving the water balance for each unique HRU and then put together for the whole basin. How many subbasins that are necessary is dependent on the basin area and how detailed the stream network is, and can be decided by the user. In Vogel (2021) - that investigated climate change in Chingaza National Park - 37 subbasins were created. As input data, the SWAT model requires elevation data, soil classification data, land use data, precipitation, maximum and minimum temperature, solar radiation, wind speed and relative humidity (Vogel 2021), which is significantly more than the HBV model requires. There are hundreds of parameters in SWAT, however only a few were used in Vogel (2021). One of the advantages with the SWAT model is the possibility to incorporate variables using the platform ArcGIS (ibid.). Moreover, the SWAT model is able to estimate evapotranspiration and hydrological features such as surface runoff, peak rate, groundwater flow, lateral flow and transmission losses (Bizuneh et al. 2021).

Comparison To assess how well the models are performing there are several objective functions to choose from in the HBV light interface. In this project the Nash-Sutcliffe efficiency (NSE) coefficient (also called Reff) has been used. This function (see Equation 1) is widely used in hydrology, and more importantly also by Vogel (2021) in the SWAT model, which makes the comparison easier.

$$NSE = \frac{\sum(O_i - O_m)^2 - \sum(S_i - O_i)^2}{\sum(O_i - O_m)^2} \quad (1)$$

where O_i is the observed discharge in every time step, O_m is the mean observed discharge over the whole evaluation period, and S_i is the simulated discharge in every time step. (Stehr et al. 2008)

To be able to perform the comparison, the same objective function was also used when simulating the runoff with the HBV model. The NSE can vary from $-\infty$ to 1 where 1 indicates a perfect fit, meaning that the model manages to captures the variability of the observed data. A NSE value ≤ 0 indicates that the mean value of the observed discharge gives a better prediction than the model itself (Ritter and Muñoz-Carpena 2013). A model is considered to have a satisfactory performance if the NSE is 0.5 or higher, according to Christiansen (2012).

3 Study areas

This study has investigated the paramo areas on different spatial scales: A large scale, containing all the paramos of Colombia, a medium scale, exploring the hydrology of a paramo catchment and a small scale focusing on the local environment.

3.1 Characterization: Colombia and its paramos

For the characterization part of this study, all of the paramos in Colombia were taken into consideration. Colombia is a country found in the northwestern corner of the South American continent, with coasts towards the Pacific Ocean in the west and the Caribbean Sea in the north. In the east the country borders to Venezuela and Brazil, in the south to Peru and Ecuador and in the west, between the two coasts, to Panamá (see Figure 2). The equator passes through its southern/southeastern parts. The different regions of the country experience different climates and have their distinct geological, ecological and topographical characteristics. For example, some of the mountain tops in the Colombian Andes are so high that they have glaciers (Morales Rivas et al. 2007).

The Andean mountains cover around one third of the country, and cross from the southwest to the northeast as three different mountain ranges, whereas the rest of the landscape is rather flat. The paramos are located in Cordillera Oriental (the Eastern Ranges), Cordillera Central (the Central Ranges), Cordillera Occidental (the Western Ranges), Nariño-Putumayo in the south, and Sierra Nevada de Santa Marta in the north (ibid.). In 2011, the paramos constituted an area of 1 925 410 ha, that is, approximately 2 % of Colombia's total area (Rivera Ospina and C. Rodríguez 2011). The mountainous areas are of hydrological importance since they make up places where the water can flow in different directions, eventually forming bigger streams and rivers. The orography, direction, elevation and branching of the mountain ranges, together with the precipitation patterns in different parts of the country, generate an intricate network of basins and catchment areas. The five big catchment areas in Colombia are Caribe, Pacífico, Amazonas, Orinoco and Catatumbo. (Morales Rivas et al. 2007)

The climate in Colombia is affected by the great atmospheric air masses that come from north and south of the equator and meet in Colombia. This results in a cyclicity of climatological events and the air masses control when the wet and dry seasons take place. Additionally, the translocations and shifts of the intertropical convergence zone (ITCZ), the trade winds, and local processes like convection and condensation play a role in affecting the climate. The trade winds with the greatest influence originate from the north- and southeast. What drives all the climatic processes is the solar radiation. Since Colombia is by the equator, the solar radiation and hence also the mean temperature do not vary considerably throughout the year. Instead, the temperature differences over the course of a day are far greater. The precipitation differs substantially between different places in the country. The total annual precipitation can vary between less than 200 and more than 9000 mm/yr depending on location. Some parts of the country

experience a bimodal precipitation pattern, that is, two wet seasons, that roughly occur in April-May and October-November, while others only experience one wet season, a unimodal precipitation pattern, around June-July (Morales Rivas et al. 2007). According to Mejía et al. (1999), the ITCZ mainly gives two wet seasons in the central part of the country.

Looking at the paramos specifically, they demonstrate a climate that changes very much when it comes to precipitation, temperature, relative humidity and wind, et cetera. The mean annual temperatures are low, often under 9 °C. Within a year, the mean temperature during different months is rather constant, but when it comes to the temperature during a day the difference between the maximum and minimum temperature is notable. The total annual precipitation and the annual rain pattern vary appreciably between different paramos. According to *Atlas de páramos de Colombia*, the mean annual precipitation over several years for the paramos has ranged between roughly 700 and 5000 mm/yr (ibid.). In comparison, according to Correa et al. (2020) the annual mean, maximum and minimum precipitation in the paramos of Colombia have been reported to be 1640 mm/yr, 4087 mm/yr and 798 mm/yr. Moreover, some paramos exhibit a unimodal precipitation pattern with only one wet season, whereas others exhibit a bimodal precipitation pattern with two wet seasons. The wettest paramo regions are on the outer slopes of Cordillera Oriental and Cordillera Occidental, that is, the eastern slope of Cordillera Oriental and the western slope of Cordillera Occidental, whereas the inner slopes of the mountain ranges are drier. Some parts of the western slope of Cordillera Oriental are described as the driest. At the time of writing the atlas, it was highlighted that horizontal precipitation was thought to be an important contributor to the total water amount in the paramos, but that there was no research quantifying this amount. (ibid.)

In the paramos it is very humid and clouds and fog are prevalent. This contributes to a low actual evapotranspiration. Therefore the water added through precipitation exceeds the amount lost through evapotranspiration in most of the paramos. Furthermore, the radiation is high and the wind is unpredictable in both direction and strength. (ibid.)

The activities that deteriorate the paramos do so by for example causing erosion, changes in the soil, such as drying, and changes in the ground cover, such as decreasing the amount of typical paramo vegetation, reducing the moisture- or water-holding capacity and humidity, increasing the evaporation, and worsening the water quality. The effects of these changes are noticed in the form of for example imbalances in water regulation. (ibid.). One thing that is expected to deteriorate the paramos is climate change.

3.2 Modeling: Chingaza National Park

For the hydrological modeling part, a paramo watershed called Monterredondo in Chingaza National Park (CNP) was chosen. CNP is located on the eastern mountain range of the Andes in Colombia, that is the Cordillera Oriental, and less than 70 km east of

Bogotá. The paramos in this area are situated above approximately 3200 m, where the vegetation changes from high-elevation mountain forests to the alpine paramo grasslands, and below 3900 m (Sanchez, Posada, and Smith 2014). The total area of CNP is approximately 766 km², out of which 645 km² can be classified as paramos (Vogel 2021). Different activities such as glacial actions, geological processes like orogeny and volcanic actions have worked together to create a varying topography with deep valleys and jagged peaks (Cresso 2020). The mountains was formed from Devonian sedimentary rocks and contains limestone, silt stone and sandstone, and can have slopes as steep as 30 % (Gil and Tobón 2016). CNP is an important freshwater source for the societies nearby, additionally to being home to over 2000 diverse plant species, many of which are endemic (Sanchez, Posada, and Smith 2014). A plan called “*National Development Plan of Colombia*” is protecting the area from destructive anthropogenic activities. However, human activities such as agriculture, grazing, water extraction, and so forth, are still occurring in the park to some extent (Cresso 2020).

The most common soils in CNP are Andisol, Entisol, Inceptisole and Histosol, which most are homogeneous and nutrient-rich volcanic soils. The low temperature and atmospheric pressure together with the high humidity decrease the microbial decomposition rate which leads to the accumulation of organic matter. The amount of organic matter can be up to 38% and gives the soil a dark colour. It has also a high porosity of 80%. This together gives the soil great water retention and storage capacities (90% in saturation conditions). The depth of the soil can vary from a few centimeters to several meters (effective depth down to 1.2m), which depends on the topography and other geological factors. (ibid.) (Gil and Tobón 2016)

The annual mean temperature and precipitation in CNP are around 11 °C and 2000-3100 mm, with some local variations due to micro climates. The inter annual temperature variations are quite small while the daily air temperature can fluctuate between 2 °C and 26 °C, with the greatest variations during the dry season due to less prominent cloudiness Cárdenas (2016). The evapotranspiration is relatively low approximately 300 mm/year in another watershed in CNP, according to Gil and Tobón (2016) and between 650mm/year and 900 mm/year in cordillera oriental, according to Morales Rivas et al. (2007) which can be explained by the presence of low clouds and fog and the low leaf area index (Cárdenas 2016). Because of the paramos’ elevation, orographic precipitation is common and occurs when the mountain range blocks the horizontal air movement, forcing the air to rise upwards. The change in temperature and air pressure forms orographic clouds with intense precipitation, which, annually contribute with 4500 mm of rainfall on the eastern slope of the Andes and decline gradually to 1500 mm on the western side (Cresso 2020). The precipitation is characterized by an unimodal pattern with two main seasons: the wet season between April and November (where 60 % of the rain falls between May and August) and a short dry season from December to late February or early March where only 17 % of the annual precipitation takes place (Morales Rivas et al. 2007).

The location of CNP and the Monterredondo catchment - that is the catchment chosen for the modeling - is shown in the map in Figure 5 below with Monterredondo catchment highlighted in red. It can be seen in the figure that the boundaries of the park do not completely follow the outline of the paramo ecosystem, but there is a large overlap.

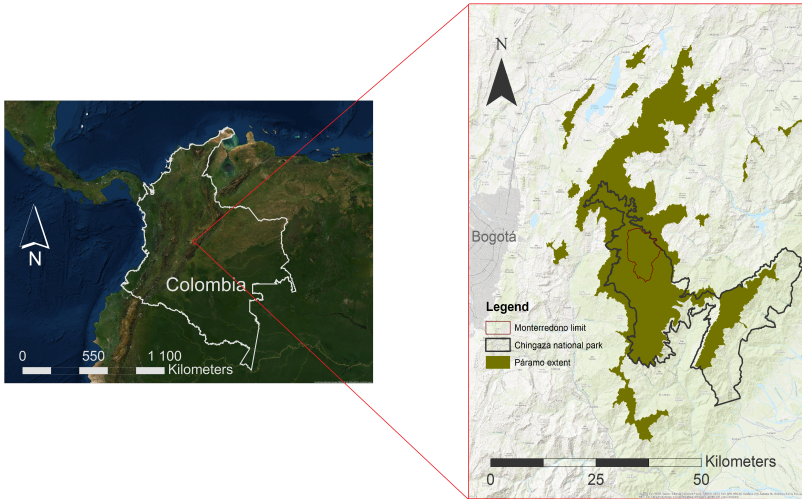


Figure 5: Map showing the location of Chingaza National Park and Monterredondo catchment.

The majority (80 %) of the water supply in Bogotá comes from the CNP (Ruiz, Martinson, and Vergara 2012). This is because the paramo ecosystems in CNP have an extraordinarily high rainfall-runoff ratio. There are several reasons for this:

- The precipitation intensity in CNP is usually constant, but relatively low, which causes the rain to infiltrate the soil instead of going off as surface runoff. (Cárdenas 2016)
- There is a high organic content in the soil that is typical for the Andean paramos. This creates optimal conditions for water storage and water regulating capacity. The characteristics of the soil are one of the most important factors for the continuous baseflow Buytaert et al. (2006).
- The vegetation of the paramos has a unique plant structure with a low leaf area index which prevents evapotranspiration caused by the high radiation at these high elevations (Cresso 2020). In the foreground in Figure 1 a Frailejon, which is a typical plant in the paramo ecosystem known for its water storing capacities, is seen.
- The varying topography with deep valleys and jagged peaks promotes water being collected in lagoons and lakes (ibid., Vogel 2021).

4 Methods

4.1 Characterization

The characterization of the paramos in space and time was carried out mainly by writing code in R to make calculations and produce graphs (found in authors' supplementary materials, supplied upon request). Microsoft Excel and ArcMap were used as complementary tools. For some of the investigation of trends over time, Climpack was used. The purpose was to get a better understanding of the quantitative values of different variables in different paramo regions and to investigate whether these values have changed over time. The method description of the characterization below is divided into the same parts as the work consisted of: Data collection and selection, Data quality screening and station exclusion, and Final analyses and results.

4.1.1 Data collection and selection

This section describes how data was gathered and then separated out based on different criteria (see Figure 13).

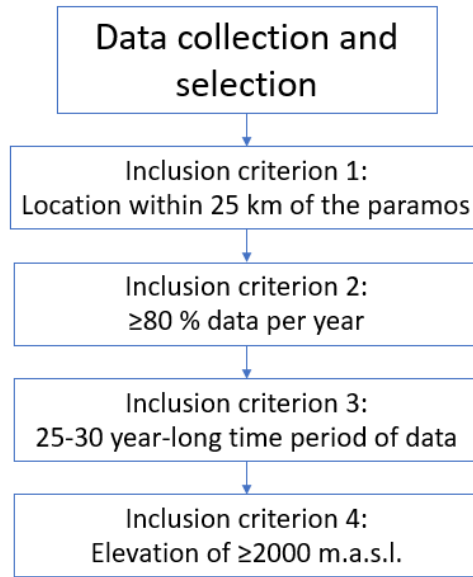


Figure 6: Flow chart showing the method for data selection using inclusion criteria.

First, the list of all hydrometeorologic measuring stations in Colombia ("Catálogo Nacional de Estaciones") was downloaded as a point shapefile from the Instituto de Hidrología, Meteorología y Estudios Ambientales (IDEAM), that is, The Institute of Hydrology, Meteorology and Environmental Studies, which is a government agency of the Ministry of Environment and Sustainable Development of Colombia (IDEAM 2022a). Moreover, a polygon shapefile for the geographical extent of the paramos in Colombia was obtained

from Instituto de Investigación de Recursos Biológicos Alexander von Humboldt (IAVH 2012b). These two shapefiles were imported into ArcMap, onto a basemap of Colombia, and by using the tool *Selection By Location* all the stations (points) lying within the paramo areas (polygon) were selected. Out of a total of 4499 stations 140 were within the paramos. Additionally, the same tool was used to select all the stations located in or within 25 km of the paramos. Out of the 4499 stations 1835 fulfilled this selection criterion. These 1835 stations were exported from a table in ArcMap to Excel using *Table to Excel*. Excel files with the stations containing data for the variables precipitation (PT), temperature (TS), evaporation (ET), relative humidity (HR), discharge (QL) and wind speed (VD) were supplied from IDEAM (2022). Using the match tool in Microsoft Excel, the two lists of stations were matched for each of the mentioned variables and the corresponding coordinates were extracted from the second file, generating a table with stations with available data for every variable. The tables were imported into ArcMap using *Excel to Table* and plotted in the original map containing a basemap, the paramo shapefile and all the national stations lying within 25 km of the paramos. This gave a visual perception of the location and density of stations for each variable. In Table 3, a summary of the number of stations with available data for each variable can be seen.

Table 3: Number of stations with available data for each variable.

Variable	Number of stations
Precipitation (PT)	1065
Temperature (TS)	272
Evaporation (ET)	208
Relative humidity (HR)	270
Discharge (QL)	354
Wind speed (VD)	69

Furthermore, some additional criteria were applied to the stations for each variable. This was done using R. One inclusion criterion was that the stations should contain at least 80 % data for each year. Another criterion that was applied was to have a time series of at least 25 years. The numbers of stations with at least 80 % data for each year were therefore plotted for every year between 1950 and 2017, before and after which data was limited or not downloaded. Next, the number of stations for different 25-30 year-long periods around the peak in number of stations with sufficient data were counted for each variable to find a common optimal time period. The time period that appeared to be the best choice was 1987-2012, that is, a period of 26 years, but other 26-year long periods that sufficiently overlapped part of this time period could also be accepted. Table 4 shows the whole possible time period around the peak in number of stations, the 26-year long time periods with most stations and the number of stations before and after application of the exclusion criteria.

Table 4: Possible time period and approximate station count in that period, followed by the time period with most stations available and the corresponding number of stations after application of the exclusion criteria.

Variable	Possible time period	Station count (approx.)	Optimum time period to apply criteria to (26 years)	Station count after application of criteria
Precipitation (PT)	1984-2015	600	1987-2012	252
Discharge (QL)	1980-2011 (1976-2014)	170 150	1986-2011	43
Temperature (TS)	1987-2014 1983-2016	120 80	1987-2012 1989-2014 1990-2015	12 12 12
Evaporation (EV)	1979-2015	55	1988-2013 1990-2015	4 4
Relative humidity (HR)	1983-2016	-	1989-2014	5
Wind speed (VD)	1982-2004	6	no optimal period found	0-1

From Table 4 it became apparent that few variables had enough stations for a national analysis to be performed. The study therefore had to be constrained to only cover precipitation and discharge.

Further station selection and data screening was first done for precipitation, that is, the variable with most stations. For these stations the inclusion criterion that the stations should be located at an elevation of at least 2000 meters above sea level was added. An elevation of 2000 meters above sea level was chosen since stations at a lower elevation would not represent the high-elevation paramo ecosystems as well, and because the precipitation pattern changes around this elevation, from increasing with height up to approximately this elevation to decreasing with height above this elevation (Mejía et al. 1999). After the application of these inclusion criteria only 87 out of 252 stations measuring precipitation remained. These 87 stations were then plotted in ArcMap to evaluate the spatial distribution. It became clear that no stations were left for the northernmost paramos of the "complejo" Perijá, belonging to Cordillera Oriental, and of the "complejo" Sierra Nevada de Santa Marta. A few smaller "complejos" in the southern part of Cordillera Oriental and in the central part of the Cordillera Occidental also lacked stations with sufficient data (see Figure 7). Therefore, the spatial scope of the project was forced to be decreased.

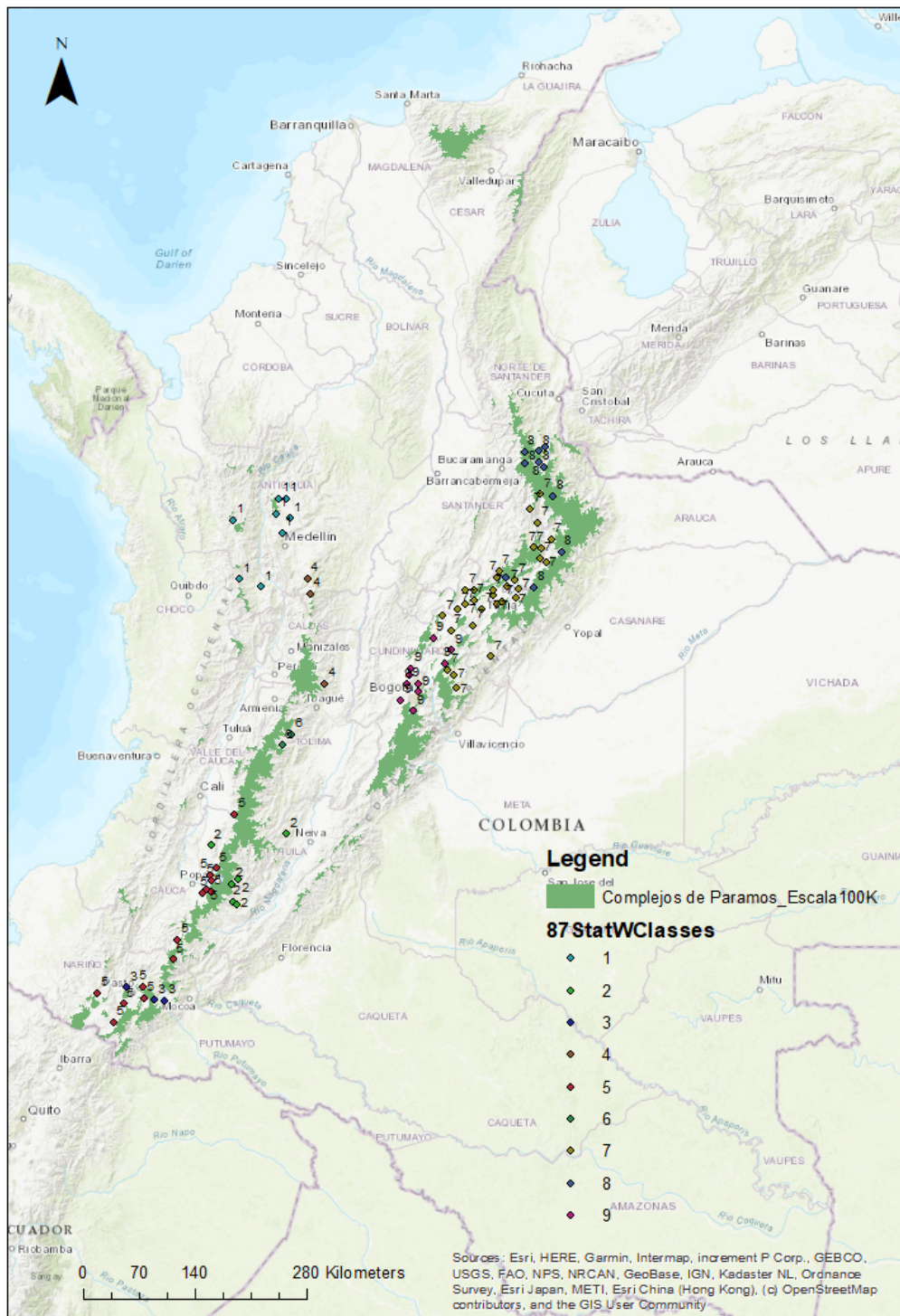


Figure 7: Map with the paramo areas in green (IAVH 2012a) and the 87 remaining precipitation stations assigned to nine different clusters.

4.1.2 Data quality screening and station exclusion

The next step consisted of data quality screening of the remaining precipitation stations following the method seen in Figure 8.

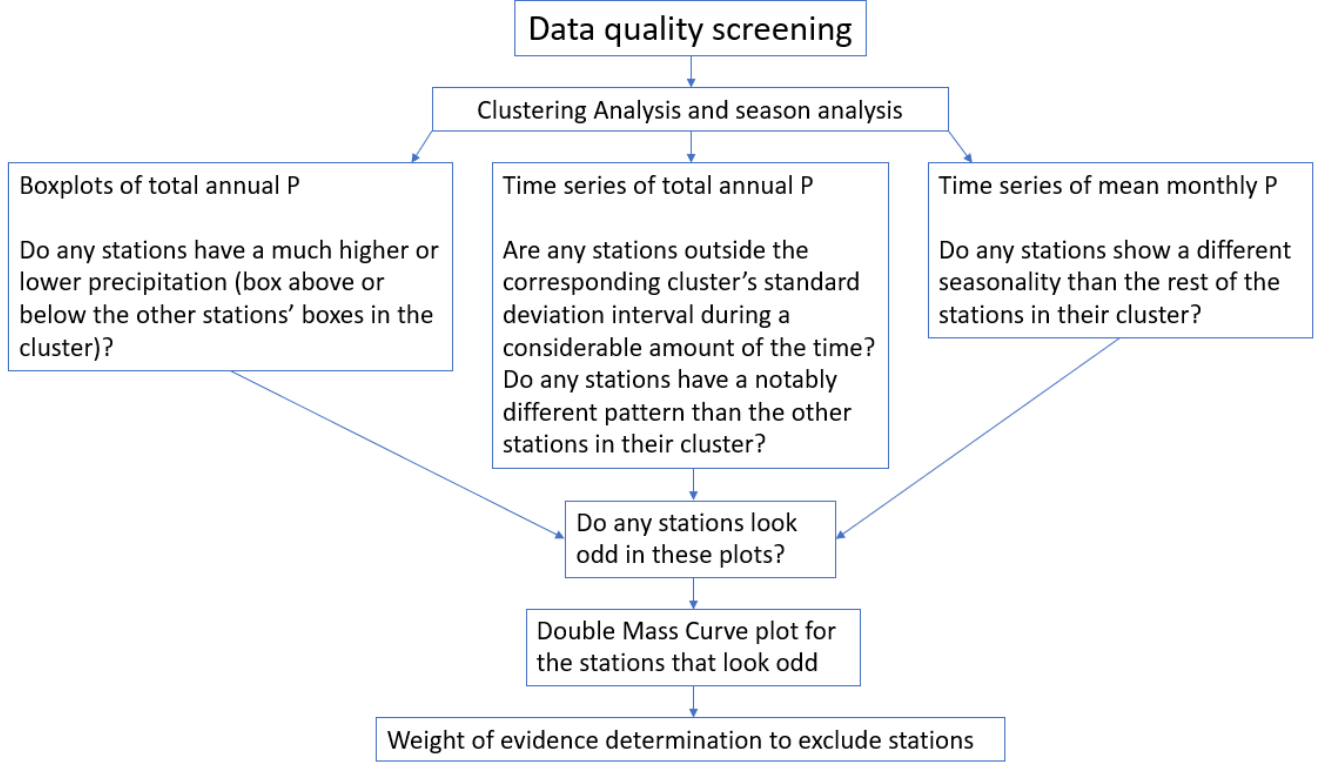


Figure 8: Flow chart showing the method for data quality screening.

To be able to visualize the data screening results and make a comparison easier the stations were divided into smaller groups, so called clusters. This was done by first dividing the stations into regions according to which mountain range (Cordillera Occidental, Central or Oriental) they belonged to and thereafter running a regionwise Clustering Analysis in Microsoft Excel. Other than mountain range or region, the Clustering Analysis included latitude, longitude, elevation and mean annual precipitation as input. The resulting clusters were then evaluated geographically in ArcMap and for two stations the cluster was adjusted based on the judgement that they had been assigned to a cluster where the rest of the stations were much further away than stations from other clusters. The clustering analysis resulted in nine clusters (see Figure 7) with 2-31 stations in each.

Once the clusters were set, the data quality screening was conducted. It consisted of using the daily precipitation data, in some cases first aggregating it, and making boxplots and time series plots on an annual, seasonal and monthly scale, and of producing Double Mass Curves using the cumulative sum of the precipitation. In a Double Mass Curve

the cumulative sum of data for a hydrologic variable from one station is plotted against the mean cumulative sum of data for the same hydrologic variable for all stations within an area that the individual station belongs to. They are plotted against each other since stations that are quite close to each other are expected to have a spatial correlation. The plot is then used to discover potential changes in the slope, or the relationship, that indicate some kind of disturbance in the time series of the individual station. It is a way to make sure that the data used is consistent (Searcy and Hardison 1960).

Both amount of precipitation and number of days with precipitation, defined as days with more than 0.2 mm of precipitation, were investigated. Moreover, the mean precipitation and the upper and lower limit of the standard deviation for each cluster, as well as vertical lines indicating strong or very strong ENSO events (El Niño and La Niña), between 1987 and 2012 were plotted in some of the figures (see Appendix A.1 for a list of the ENSO events included). The plots were made for each cluster and each station. To facilitate the analyses the stations not only obtained abbreviated ID:s, but were also assigned a specific colour to be used throughout the analyses.

The seasons were not given beforehand. Therefore a separate analysis was done using the plots with monthly precipitation. Through these it became evident that the seasonality varied between different stations, but that in general they could be divided into two groups; some that had two wet seasons, one in April-May and one in October-November, and some that had only one wet season in June-July. Since these wet seasons each consisted of two months the rest of the months during the year were divided into two months as well in order to make a comparison between the seasons easier. Table 5 shows how the months were divided into seasons.

Table 5: Division of months into different seasons.

Season	Months
S1	Feb-Mar
S2	Apr-May
S3	Jun-Jul
S4	Aug-Sep
S5	Oct-Nov
S6	Dec-Jan

For the statistical analyses of seasonal and monthly precipitation, only months with at least 75 % data were included, this to have data for at least three of the four weeks in a month. The maximum amount of days of missing data per month was set to 7 days, since 25 % missing data in the month with the least days (February with its 28 days) corresponds to 7 days and 25 % missing data in the months with the most days (January, March, May, July, August, October and December with their 31 days) corresponds to 7.75 days. The total annual, seasonal and monthly precipitation were calculated by summing all the daily precipitation, ignoring missing data since the criteria of at least 80 % data in a year and at least 75 % data in a month had already been applied.

To investigate wet and dry seasons for the different paramos, time series plots with the mean monthly precipitation calculated over at least 15 years of the 26 year-long period, depending on data availability for each month each year (as some months are excluded if they have more than 25 % missing data), as well as the number of days with precipitation ($P > 0.2$ mm) were plotted clusterwise for each station.

All the plots were visually assessed to determine if any stations showed deviating characteristics or patterns and therefore should be excluded from further analyses. The plots that were primarily used for the exclusion of stations were the boxplot and time series plot of total annual precipitation and the time series plot of total monthly precipitation. The assessment of the stations using the boxplot was based on if a station showed a much lower or higher precipitation than the other stations in its cluster (see Figure 9).

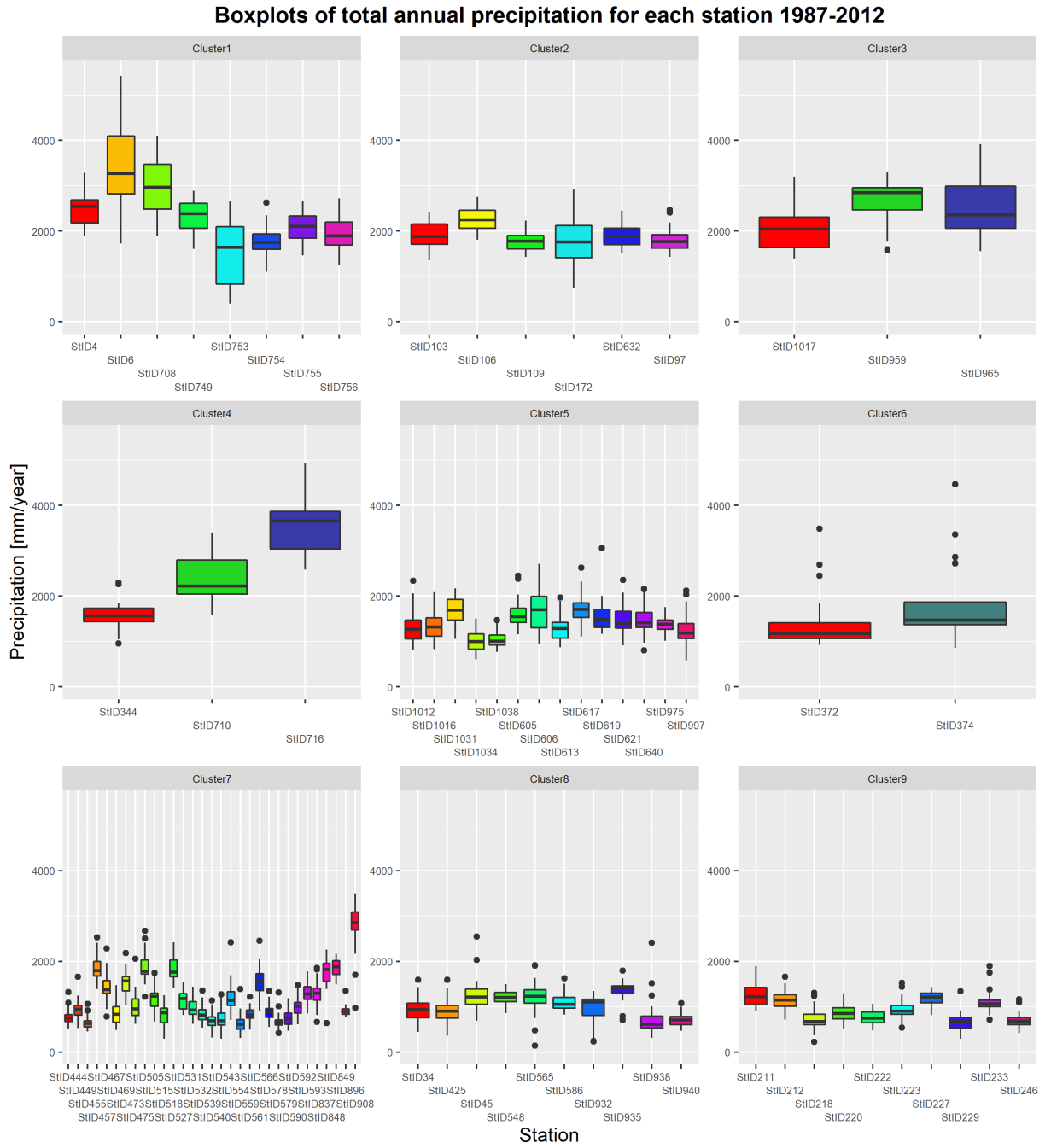


Figure 9: Boxplots based on total annual precipitation for each station 1987-2012 plotted clusterwise. The colours indicate the different stations.

In Figure 9 it can be seen that some stations have boxes that are situated notably above or below the boxes for other stations in the same cluster. Considering the general variability in each cluster, some stations stood out more than others, such as StID6 (yellow) and StID753 (light blue) in Cluster 1 and StID908 (red, far right) in Cluster 7.

The assessment of the stations using the time series plot with total annual precipitation was based on if a station was outside the standard deviation interval for the cluster it belonged to during a considerable amount of the time and/or had a notably different pattern than the other stations in the cluster (see Figure 10).

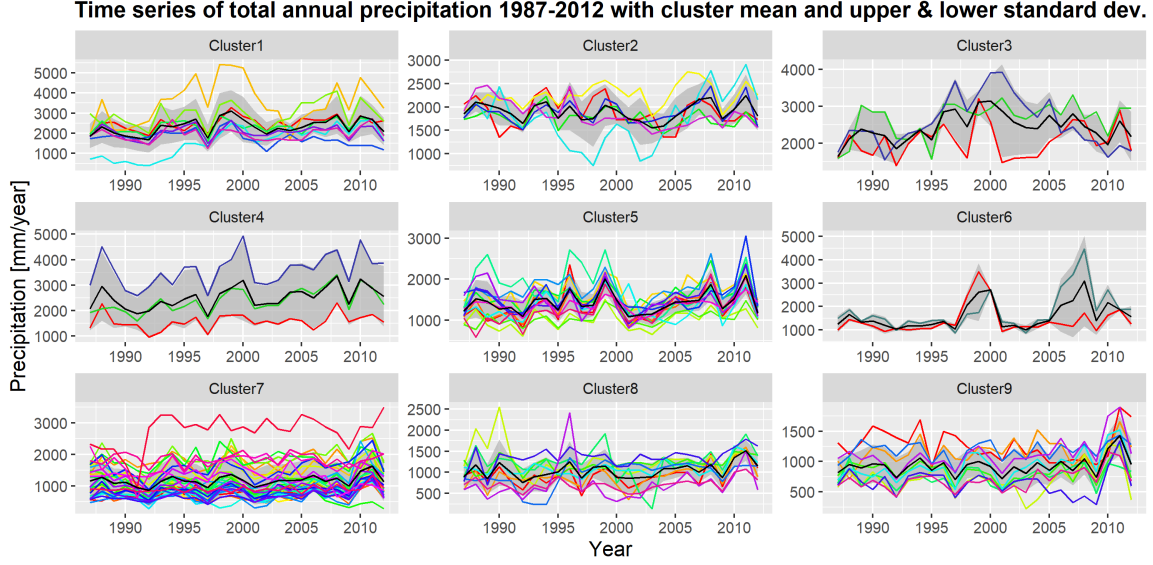


Figure 10: Time series of total annual precipitation for each station 1987-2012 plotted clusterwise. The black line corresponds to the mean precipitation and the grey band corresponds to the area between the upper and lower standard deviation in each cluster. The colours indicate the different stations.

Figure 10 shows that there are a few stations that are outside the standard deviation interval a major part of the time or that show a quite differing pattern from the rest of the stations. For example, the yellow station in Cluster 1 (StID6), the light blue stations in Cluster 1 and 2 (StID753 and StID172), respectively, as well as the red stations in Cluster 3 and Cluster 7 (StID1017 and StID908), respectively, are rather off compared with the other stations in their clusters.

The assessment of the stations using the time series plot with total monthly precipitation was based on if a station showed a different seasonality than the rest of the stations in its cluster (see Figure 11).

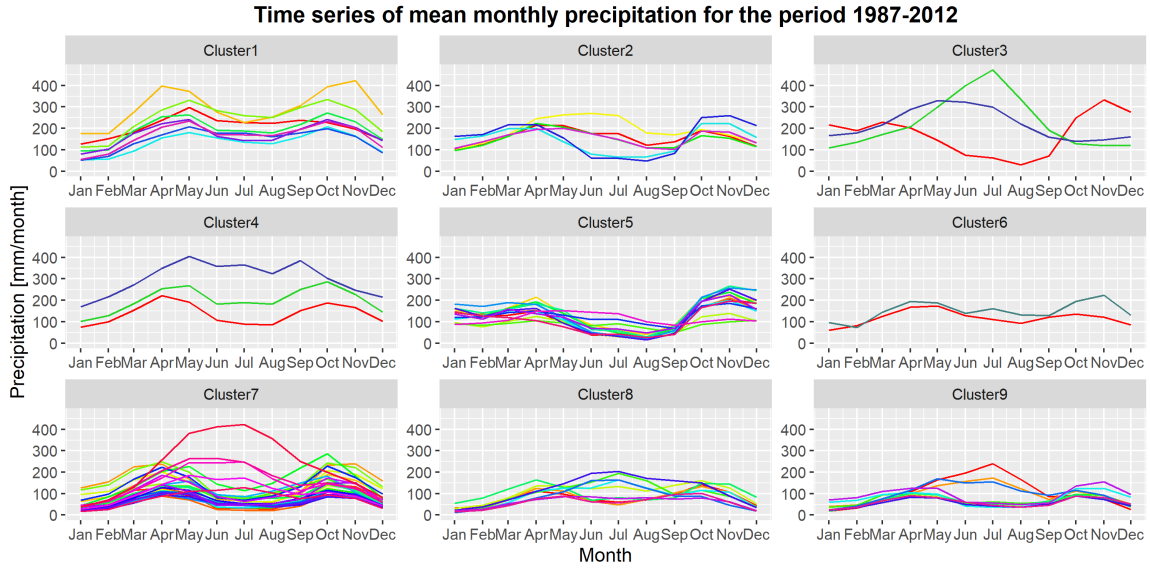


Figure 11: Time series of mean monthly precipitation for each station for the period 1987-2012 plotted clusterwise.

From Figure 11 different seasonalities were accepted in the same cluster as long as there were more stations showing the same seasonality. Although there were merely three stations in Cluster 3, the red station (StID1017) was questioned since it had the opposite seasonality pattern when comparing it with the two other stations in the same cluster.

The stations that were deemed "odd", that is, the stations that were deviating substantially from the rest of the stations in their corresponding cluster in the three plots above, were further assessed in Double Mass Curve plots (DMCs). This was done by plotting an odd station's cumulative precipitation over the 26 year-long time period against the mean cumulative precipitation of all the "normal" stations (that did not look strange in the previous plots) in the corresponding cluster (see Figure 12).

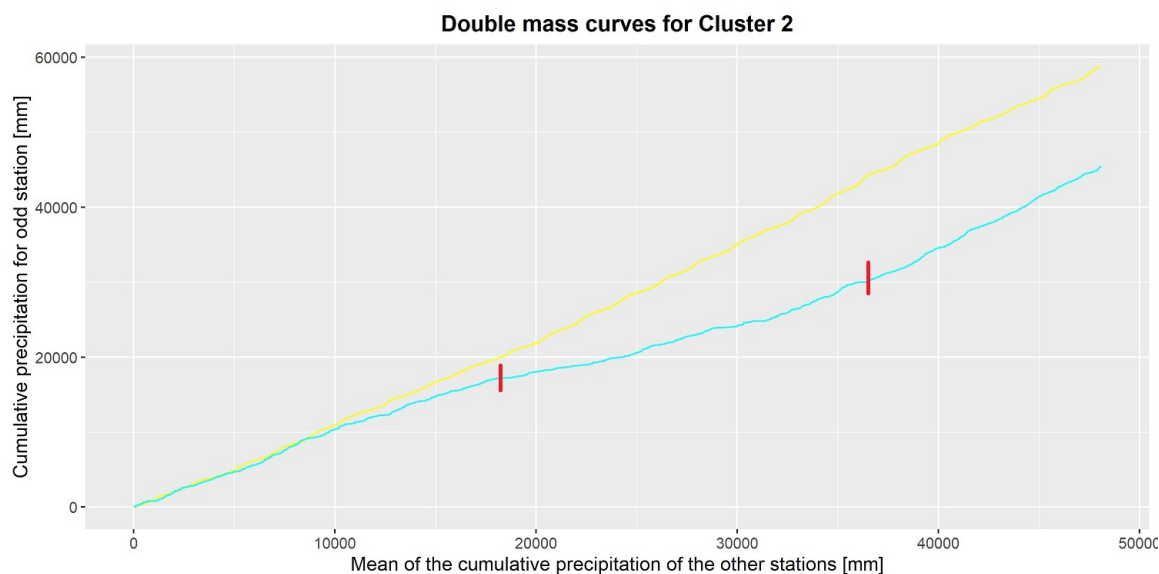


Figure 12: Double Mass Curve plot with cumulative precipitation of the odd stations against the mean cumulative precipitation for the rest of the stations in the cluster. Shown in this example is the Double Mass Curve for Cluster 2 and the stations StID106 (yellow) and StID172 (light blue). Points where the slope changes are marked with red lines.

Figure 12 represents an example to demonstrate how a Double Mass Curve plot can be interpreted. In the figure Double Mass curves for two stations in Cluster 2 can be seen. The curve for the yellow station (StID106) shows a rather consistent slope whereas the light blue one (StID172) has two "breaks" (marked in red) where the slope changes considerably.

After a weight of evidence determination, the final decision on which stations were to be excluded was taken. Hence, a station could be kept although the Double Mass Curve did not look optimal if it looked fine in the other plots and could add to the variability and cover some of the heterogeneity within a cluster. The stations that appeared strange in both the Double Mass Curve plot and one or more of the other plots were excluded from further analyses. For example, in the case of the light blue station (StID172) in Cluster 2, seen in Figure 10 and Figure 12 above, it was removed from the rest of the analyses after the information from the different plots were weighed together. After the full data quality screening procedure had been executed 80 out of the 87 precipitation stations remained.

The 43 discharge stations that had enough available data between 1986 and 2011 (see Table 4) , were reduced to 12 stations when the inclusion criterion of a station elevation of at least 2000 meters above sea level was applied. Due to the already low number of discharge stations, no such data quality screening as that for the precipitation stations was carried out.

4.1.3 Final analyses and results

In this section it is described how the final selection of stations from the section above were handled to characterize the paramos and find possible trends.

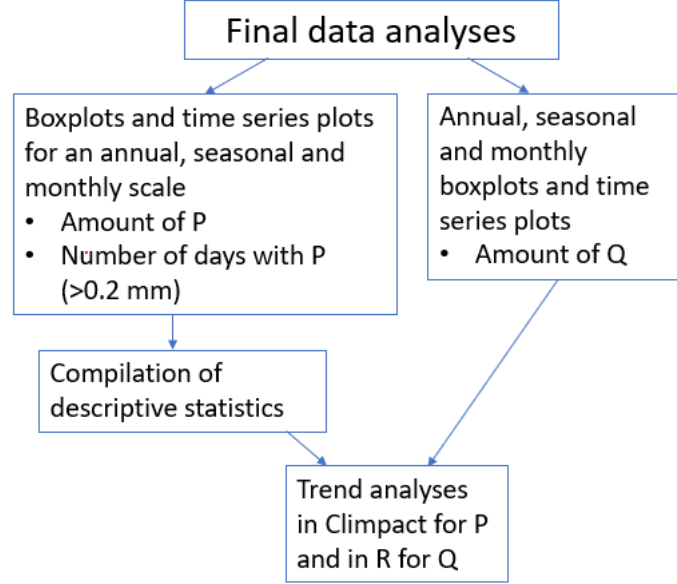


Figure 13: Flow chart showing the method for the final data analyses.

4.1.3.1 Precipitation

Following the data quality screening and exclusion of stations the same procedure was carried out for the remaining stations resulting in the same type of plots, except for that no Double Mass Curve plots were produced. The plots were used together with statistical commands in R to achieve more detailed quantitative information about each cluster. Such information included a compilation of descriptive statistics for each cluster, such as highest and lowest median precipitation and the range in-between, mean, maximum and minimum precipitation, highest and lowest 25 % (Q1 or Q25) and 75 % (Q3 or Q75) quantile, the biggest and smallest interquartile ranges and seasonality that could explain their precipitation characteristics and variability better. A comparison was then done between the clusters to investigate where the most and the least precipitation occurs and whether the seasonality differs between the clusters.

Next, for the investigation of changes over time, one station per cluster was chosen to represent the whole cluster. These stations were chosen using the new version of Figure 10, that is a time series plot of total annual precipitation, that resulted from excluding some stations, see Figure 24 in Section 5.1. The stations that visually seemed closest to, and most accurately followed, the black line corresponding to the mean precipitation of the cluster, were picked as representative stations. For these stations data and station

information were compiled in different text files to be run in Climpack. The station information files consisted of the station name, the station's coordinates and individually chosen specifications for some of the indices, whereas the data files contained year, month, day, daily precipitation and maximum and minimum daily temperature. Since the calculation of the precipitation indices was not reliant on temperature data, arbitrary dummy data was used for all the input data that had anything to do with temperature. The produced plots and Excel sheets were then searched for trends for different indices, see Section 5.1.

4.1.3.2 Discharge

To characterize the paramos based on discharge and to get a better idea of the possible effect of precipitation on streamflow, the twelve discharge stations that fulfilled all the inclusion criteria were processed. First, they were included in the same map as the precipitation stations (see Figure 14) and assigned to represent the different clusters. Cluster 6 was excluded from this analysis because no discharge station was located close to the precipitation stations in this cluster. Some discharge stations were used to represent more than one cluster because of proximity. Similar plots as the ones made for the precipitation stations were produced, but instead of using summation, the annual mean daily discharge (in $\text{m}^3/\text{s}/\text{day}$) for different time spans was calculated, and for finding possible trends the R tool *sen.slope* was used instead of Climpack.

To enable a comparison between the precipitation and discharge patterns and between different clusters and streams the total annual amount of specific discharge was then calculated. This was done by first multiplying all daily mean discharge values in m^3/s with the number of seconds in a day (24 hours = 86400 s) to get the volume of water each day. These daily volumes were then summed for each year. Thereafter, information about the size of the catchment areas for each discharge station was gathered and then the discharge in m^3/yr was divided by this area in m^2 and multiplied with 1000, obtaining a total annual specific discharge yield with the unit mm/yr . The discharge stations for which no catchment area size could be obtained, were excluded from this analysis. This meant that Cluster 8 and 9 had no stations left that could be used in a comparison of total annual precipitation and total annual discharge nor in a comparison of the discharge between the clusters. A time series plot and a table with trend test results (from using the *sen.slope* tool in R) for the specific discharge were produced for the remaining discharge stations.

The plots and tables for annual mean daily discharge and total annual specific discharge were analyzed with regard to amount, patterns and trends. They were also compared with the precipitation results, with a focus on comparing total annual precipitation with total annual specific discharge. The amount, patterns and trends in specific discharge were also compared between different clusters.

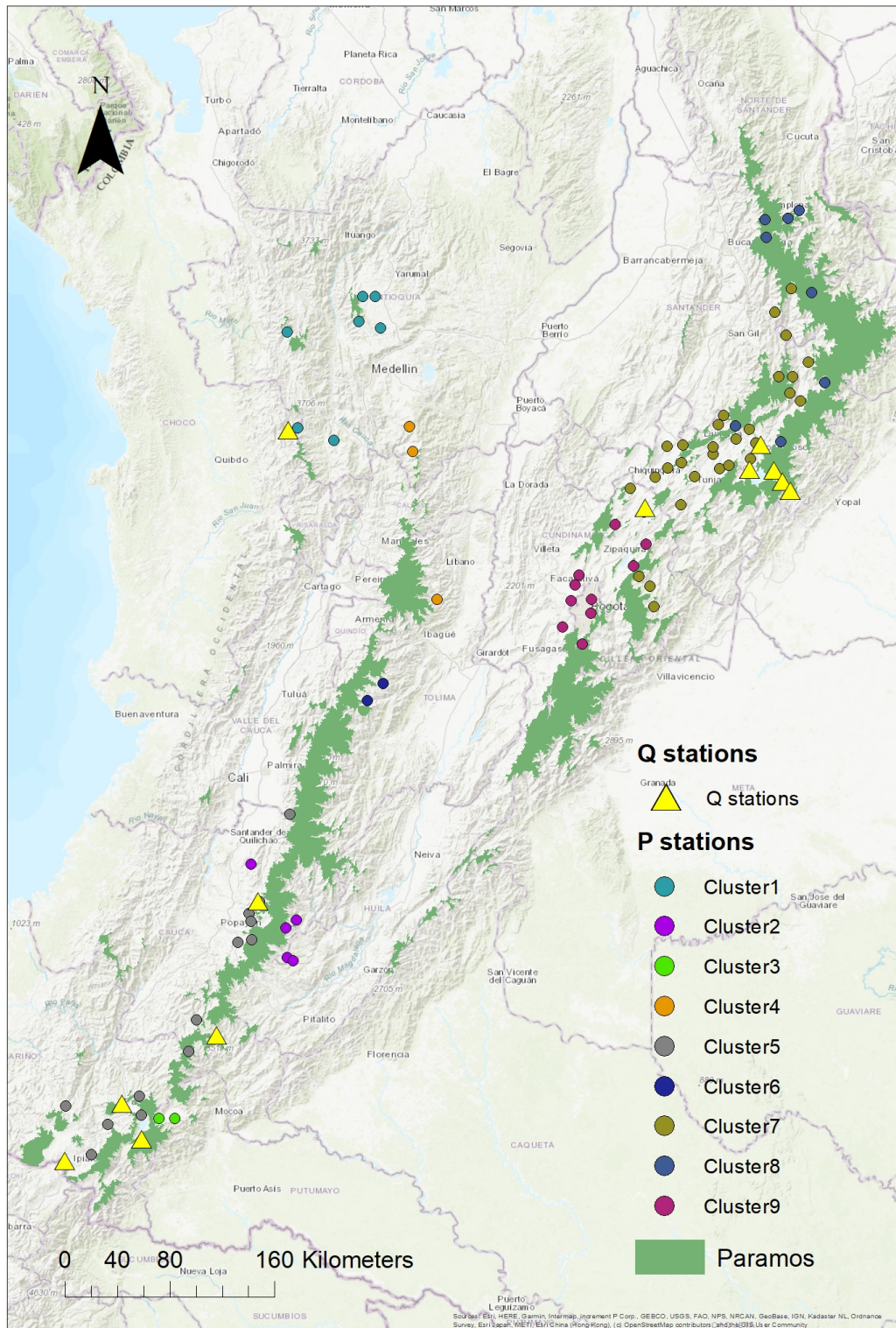


Figure 14: Map with the paramo areas and the 80 remaining precipitation stations (*P* stations), assigned to nine different clusters, along with the 12 discharge stations (*Q* stations).

4.2 Modeling

In the modeling part the HBV light model was used to model the discharge of the Monterredondo catchment. The modeling had two main purposes: first, to compare the HBV model with SWAT, and second, to simulate the future discharge based on different climate scenarios. This section is divided into four major parts; Study area delineation, Field visit, Model comparison and Future runoff simulations.

4.2.1 Study area delineation

The Monterredondo catchment in the northern part of CNP was chosen for the modeling part because of the availability of daily discharge and precipitation data and also to be able to carry out the comparison between the SWAT model and HBV light, since the SWAT model was used by Vogel (2021) for the Monterredondo watershed. The catchment was delineated in ArcMap using a high resolution Digital Elevation Model (DEM) from ALOS PALSAR, provided by the Alaska Satellite Facility and NASA's data distribution center EOSDIS (Earth Observing System Data and Information System) (The Geo-ICT Blog n.d.). The area of the catchment measured 60.40 km² which corresponds to a relatively small watershed. The outlet is on an elevation of approximately 3000 meters above sea level while the highest point in the catchment is on 3850 meters above sea level. According to Buytaert et al. (2006) a small basin is often more homogeneous which makes it easier to establish a more correct water balance. Figure 15 shows the delineated watershed.

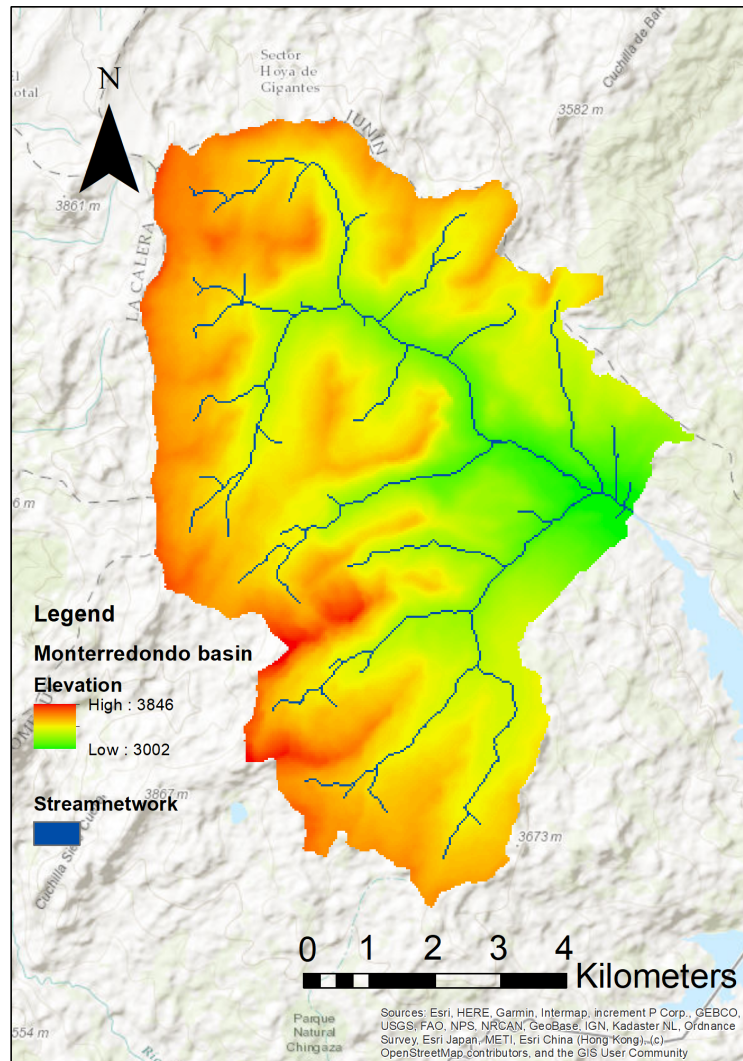


Figure 15: Monterredondo catchment and the stream network inside the watershed.

After the delineation, it could be confirmed that the watershed only contained ecosystems characterized as paramos, which is good since the study aimed to investigate paramos' with respect to the hydrology, and other ecosystem types within the watershed would make the investigation more complicated. Figure 5 in Section 3.2 shows a map of the location of the Monterredondo catchment in red and CNP in grey. As shown in the map, the catchment is completely within the paramo areas.

4.2.2 Field visit

To get familiar with the unique paramo ecosystem type and get an idea of how to represent the paramo watershed in the HBV model, field visits were carried out in CNP. The HBV light interface gives the user choices for deciding the model structure. It is possible to include different vegetation and/or elevation zones, lakes and/or glaciers, which could be of interest. The unique vegetation could be observed, as well as the dark soil and topography with jagged cliffs and valleys. Urban areas were rare. Some lakes existed, for example Lake Chingaza, which has given the name to the park. The vegetation varied slightly with elevation, which was expected since the paramo areas are situated where the landscape goes from forests to a more alpine vegetation. After the field visit and also by studying maps and pictures, it became clear that the Monterredondo watershed, in fact, was quite homogeneous, without any large lakes or urban or agricultural areas. There was however a small lake within the catchment, known as Laguna Seca. After the field visit, it was decided that it would probably be enough with a simpler model structure. Since the park was relatively homogeneous, it was decided that subbasins and vegetation zones could be excluded from the HBV model setup, and since glaciers and large lakes were missing, these were not included in the setup either. During the visit, a continuous base flow could be observed from the moist soils, and a fast response towards rainfall. Due to the soils characteristics of high organic content and porous properties, a high infiltration is expected, which could be observed in the field.

4.2.3 Model comparison

This section explains the method for the model comparison. The goal was to compare the performance of the HBV and the SWAT models by using the results from Vogel (2021) where the SWAT model was used and successfully simulated the discharge for the Monterredondo watershed. The same watershed has therefore been used for the HBV model, and as far as possible, the same input data (the same time periods and stations), has been used to make a fair comparison of the model performances.

4.2.3.1 Data preparation

The HBV light model requires two input data files. The first file contains potential evaporation and the second one contains precipitation, temperature and discharge, known as the PTQ file. There are also a few optional files, for example the mean temperature file and others necessary if the catchment would include sub basins or glaciers, which after the field visit, was not considered necessary for this project. This section explains how the two essential files (the evaporation file and the PTQ file) were obtained.

Figure 16 below shows a map of all the stations which were used in Vogel (2021). To distinguish which of these stations that were included or excluded in this project, the included stations are marked in red and the excluded in grey.

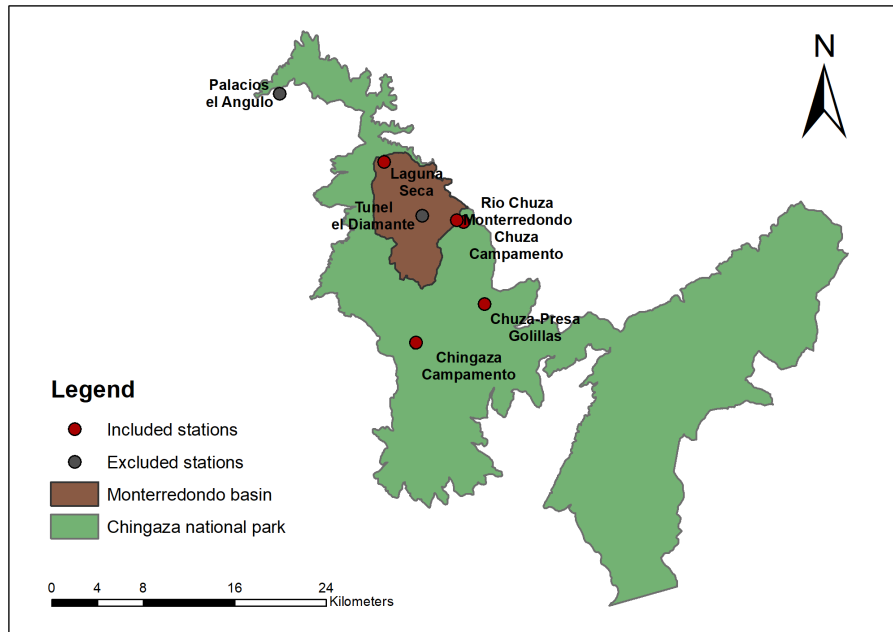


Figure 16: Map of the Monterredondo watershed and CNP showing the available stations and which were included or excluded in this study.

Evaporation The potential evaporation file needed can contain either 12 monthly mean values of potential evaporation, mean values for each day during the year, or values for each time step that cover the whole time period. For this project 12 monthly values were considered to be enough, this because temperature - and therefore evaporation - does not have a large inter annual variation and since Lelieveld (2020) obtained good results for a similar catchment in the Ecuadorian Andes using the HBV light model and a potential evaporation file containing only 12 monthly mean values.

To calculate the monthly potential evaporation, the same temperature stations that were included in the SWAT model were considered in this analysis as well. However, it was necessary to have only one temperature time series that would represent the whole catchment, and to obtain this the Thiessen polygon method was chosen. It is a method that gives a weight to stations based on their spatial distribution. It can be interpreted as the higher the weight, the more representative is the station, based on the location in the catchment. The weight can take a value between zero and one and can be seen as a proportion of the whole catchment. The time series is then multiplied by the associated weight. This method is described in Jan Seibert (2005) and used by Lelieveld (2020), and was therefore considered suitable for this catchment as well. The method was applied using ArcMap and the built in *Thiessen polygons tool*.

To carry out a fair model comparison it is desirable that the input data for the two models is as similar as possible. The same stations and time periods that were used as temperature input in the SWAT model were therefore chosen for calculating the potential evaporation. In the first calibration attempt, the input data consisted of the same temperature data as the SWAT model had used, with just a few exceptions. The result obtained was very poor, with a NSE value of -0.0038. Because of this, a simple data screening of the available input data was carried out, and a lot of data gaps were found. To avoid these gaps, only temperature data from 2013 was used, since this was the only year with no data gaps. The different weights that the stations received are presented in Table 6. The location of the stations can be seen in the map in Figure 16. The data screening can be found in Appendix A.3

Table 6: The weight for each temperature station obtained from the Thiessen polygon method.

Station	Weight
Laguna Seca	0.772
Chingaza Campamento	0.086
Chuza Preza Golillas	0.141

The weights received for each station were then used to obtain one single time series of daily temperature values. These were transformed into monthly mean values and further into potential evaporation. For this transformation, the Thorntwaite method was chosen. The method was developed by Thorntwaite in 1984 and uses an empirical relationship between air temperature and evaporation (Lelieveld 2020). This implies that the monthly average temperature from the watershed in question, is the only data needed. The method has also been used by Lelieveld (2020) and the steps are described in his paper. As a last step, the evaporation had to be corrected for the latitude, which was carried out using the factors from Rodríguez (2020).

Precipitation, temperature and discharge There was a number of stations available for precipitation data, and to merge the data from the different stations into one time series, the Thiessen polygon method was used again in ArcMap. First, the model was calibrated with the exact same precipitation time series as was used to calibrate the SWAT model. This led to a result with a NSE value of -0.0038. (See also the procedure of the potential evaporation, as the same situation occurred with the temperature data). A simple data screening found stations with a lot of missing data, which is why it was decided to only include stations with at least 80 % available data. Stations fulfilling this criterion were used in the Thiessen polygon method again and the different weights that the stations received are presented in Table 7. The location of the stations can be seen in the map in Figure 16. The data screening can be found in Appendix A.3, together with Double Mass Curves that was made to see if any station exhibited an unusual behavior. The double mass curves plot showed no unexpected behavior, except that some stations seem to receive more precipitation than others.

Table 7: The weight for each precipitation station obtained from the Thiessen polygon method.

Station	Weight
Laguna Seca	0.436
Chuza Campamento	0.540
Chuza Presa-Golillas	0.024

The temperature in CNP is generally too high for the precipitation to fall as snow, which is why the snow routine in the HBV model was not used. The precipitation simply passes through the routine as rain. Hence, the temperature in the PTQ file is not important since it is only used by the snow routine, and since no representative temperature series existed for the whole time period either way, the temperature in the PTQ file was simply put to 10 °C through the whole time period.

The Monterredondo catchment only has one available discharge station in the river Chuza, and the data from this station was used as discharge input data in the PTQ file to compare with the simulated discharge. In the HBV model, the unit is in mm/time unit, also known as specific discharge, which was used in every aspect of the modeling parts.

The HBV model can be used without any measured discharge data, but it is necessary if an objective function will be used to evaluate the performance of the model.

4.2.3.2 Model calibration

The input data files explained above were used in the HBV interface and the GAP optimization tool was used to reach the best NSE value possible. GAP optimization is an option to use in the HBV light user interface, where the model tries to find the best suited parameter values within the range specified (Jan Seibert 2005). Table 8 shows the ranges within which the different parameters were allowed. The parameter ranges were chosen with guidance from Seibert (2000), Lelieveld (2020), Seibert and Vis (2016) and Abebe, Ogden, and Pradhan (2010). The HBV model was calibrated using 2010 as warming up year and 2011-2015 as calibration years. For validation the years 2016-2017 were used. Otherwise, the model was run with the default structure. Since the model was calibrated with a PTQ file containing daily input values, the output was also daily values. To be able to compare the result with the SWAT model, NSE values for monthly output values were calculated manually in Excel using Equation 1, see Section 2.2.2.

Table 8: Parameter range overview in the GAP optimization.

Parameter	Description	Unit	Lower limit	Upper limit
TT	Threshold temperature	Degrees Celsius	-2	2.5
CFMAX	Degree-day factor	mm / (C*day)	5	15
SFCF	Snowfall correction factor	[-]	0.5	5
CFR	Refreezing coefficient	[-]	0.1	2
CWH	Water holding capacity	[-]	0.05	0.1
FC	Maximun storage in soil box	mm	300	750
LP	Threshold for reduction of evaporation	[-]	0	1
BETA	Shape coefficient	[-]	0.1	2
PERC	Maximal flow from upper to lower box	mm/day	0	5
UZL	Maximal storage in the soil upper zone	mm	0	75
K0	Recession coefficient (upper box, upper outflow)	/day	0.01	0.9
K1	Recession coefficient (upper box, lower outflow)	/ day	0.01	0.3
K2	Recession coefficient (lower box)	/ day	0.001	0.1
MAXBAS	Routing, length of weighting function	day	1	5

To make sure the model was performing sufficiently well, the water balance was checked after every simulation using the simple water balance equation below (Equation 2). Unfortunately, the water balance did not close for most of the simulations.

$$\Delta S = P - Q - E_{pot} \quad (2)$$

In Equation 2 above, ΔS symbolises change in discharge. P means precipitation, Q means discharge and E_{pot} means potential evaporation. The unit is mm/time unit for all variables. A sensitivity analysis for the input data and some simple changes in the model structure were made. This was carried out by changing the input data of potential evaporation, precipitation and discharge one by one with $\pm 10\%$, and then comparing the NSE values and the difference between the simulated and observed discharge. The influence of the model structure was studied by changing the default number of ground-water boxes from two to one and three. It is also possible to alter the parameterization settings, by changing from using the parameters UZL and K0 to only using one parameter Alpha, the effect of which also was investigated.

4.2.3.3 Uncertainties in discharge

The uncertainty in the discharge time series was thought to be an explanation for the water balance errors and was therefore examined closer. The errors in the water balance can be found in results section, 5.2.1.1.

The discharges in natural waterways are rarely monitored directly. Instead, the stream flows are estimated by measuring the water level (stage) at a known cross-section and then converting the water level to discharge by using a predefined stage-discharge relationship. A rating curve is a common way to derive a relationship like this and is normally obtained by using a set of on-site stage-discharge measurements, called gaugings. (Le Coz et al. 2014)

To assess the uncertainties of the available discharge time series in River Chuza, a rating curve was created using the BaRatin method. It is an application of the Bayesian estimations, which are especially powerful when there is little data available. The use of a well defined prior (the assumptions or estimations possible to make before taking into account the measurements, here the cross-section geometry) can give reasonable estimations, even when there are few data points available (Cipora 2019). The advantage of the BaRatin method is that it allows for the construction of a stage-discharge rating curve together with an uncertainty band. It combines the knowledge of the hydraulic controls of the cross-sectional area and the information regarding the uncertainty of the water level and discharge measurements. The BaRatin method derives a likelihood function that takes into account the uncertainty of the individual measurement points. The prior knowledge of the hydraulic controls in the considered cross-section and the likelihood equation are then combined into a posterior distribution, which then contains all relevant information about the parameters after adding the uncertainties from the measurements. As a last step Markov chain Monte-Carlo simulations are used to estimate the posterior probability density functions of the parameters for the rating curve (Le Coz et al. 2014).

Since the cross-section of Rio Chuza, where water levels are measured, does not have a precisely known geometry, the option “unknown” cross-section was chosen in the BaRatin interface. This creates the prior rating curve, consisting of the values and uncertainties that are associated with the cross-section and the hydraulic controls.

The discharge can be expressed as an exponential function, Equation 3, that holds for common uniform channel controls.

$$Q = a * (H - H_0)^b \quad (3)$$

where H is the measured water level and H_0 is the level zero for water level measurements where the discharge is equal to zero. a and b are two coefficients related to the channel and hydraulic control. Q is the discharge.

For Rio Chuza, as a result of the characteristics of the cross-section and hydraulic controls, these parameters received the following uncertainties, constituting the limits for the prior rating curve.

$$a = 8.080 \pm 0.092$$

$$H_0 = 0.01 \pm 0.013$$

$$b = 2.280 \pm 0.089$$

To create the posterior rating curve, the measured stage-discharge points, with their associated uncertainties from the measurement devices, were included; the water level was given an uncertainty of ± 1 cm, and the discharge measurements were given an uncertainty of 10 %, which are known errors for the measurement devices used. From this information, the BaRatin tool draws the likelihood equation, and after the Markov chain Monte-Carlo simulations, the most probable rating curve, called $Q_{maxpost}$, and the 95 % confidence interval for the posterior rating curve, are given. The posterior rating curve then contains the uncertainties both from the prior rating curve and the uncertainties related to the measurement points.

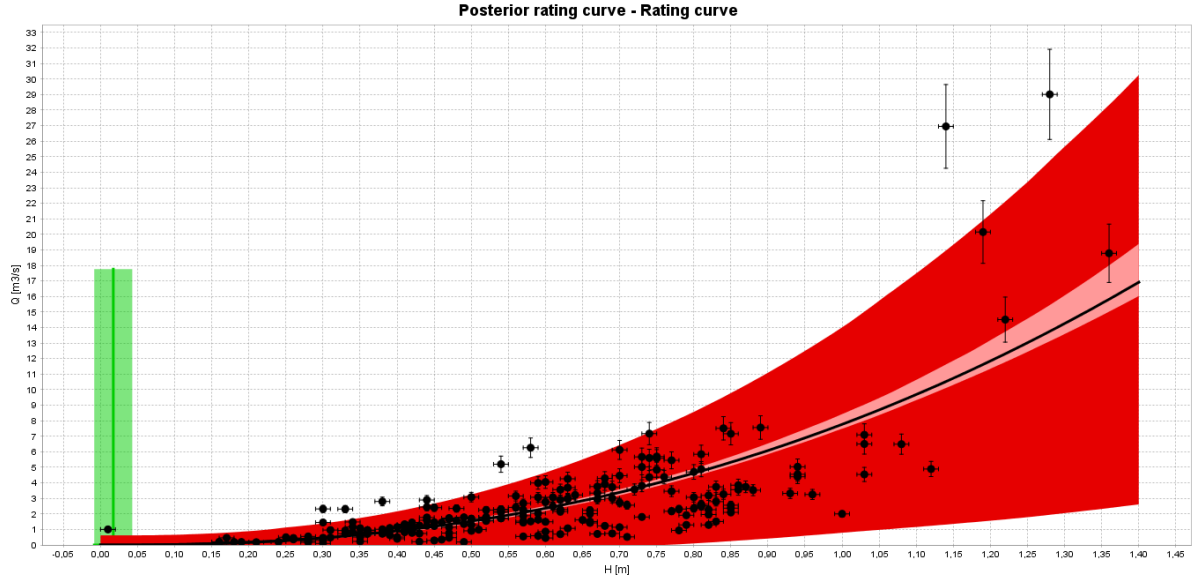


Figure 17: The prior rating curve in pink and the posterior rating curve in red, both with a confidence interval of 95 %. The black dots are the measurement points (the bars show the uncertainty for each measurement point). The green area shows the uncertainty associated with the zero water level. The black line shows the most probable rating curve called $Q_{maxpost}$.

As shown in Figure 17, the conversion from water level to discharge is associated with a lot of uncertainties in Rio Chuza, especially for the higher water levels. For example, when the water level measures 100 cm, the discharge can vary between 1 and 18 m³/s within a confidence interval of 95 %.

An exceedance curve (the level duration curve) that shows how probable it is that a certain water level is exceeded was created to show more detail, see Figure 18.

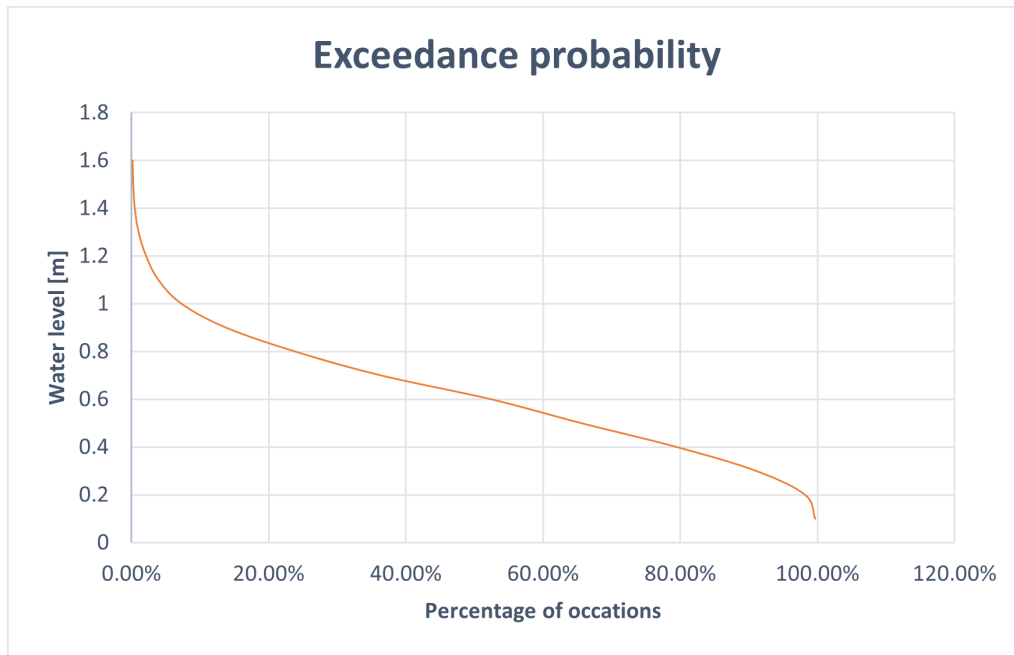


Figure 18: Exceedance curve that shows the probability of the water levels to be exceeded.

To investigate if the uncertainties in discharge measurements are large enough to explain the errors in the water balance, an example was calculated. High flows were defined as the flows that are exceeded 10 % of the occasions. This corresponds to a water level of 0.95 m, see Figure 18. This water level further corresponds to a discharge of approximately $6.8 \text{ m}^3/\text{s}$, see Figure 17. These flows, when taking into account the uncertainties from the Baratin curve in Figure 17, can be as high as approximately $12.5 \text{ m}^3/\text{s}$, meaning an increase of 83 %. The high flows, defined as the flows that are exceeded 10 % of the times, was therefore increased with 83 % and a new water balance was calculated. A flowchart summarizing the method presented in this chapter can be seen below in Figure 19.

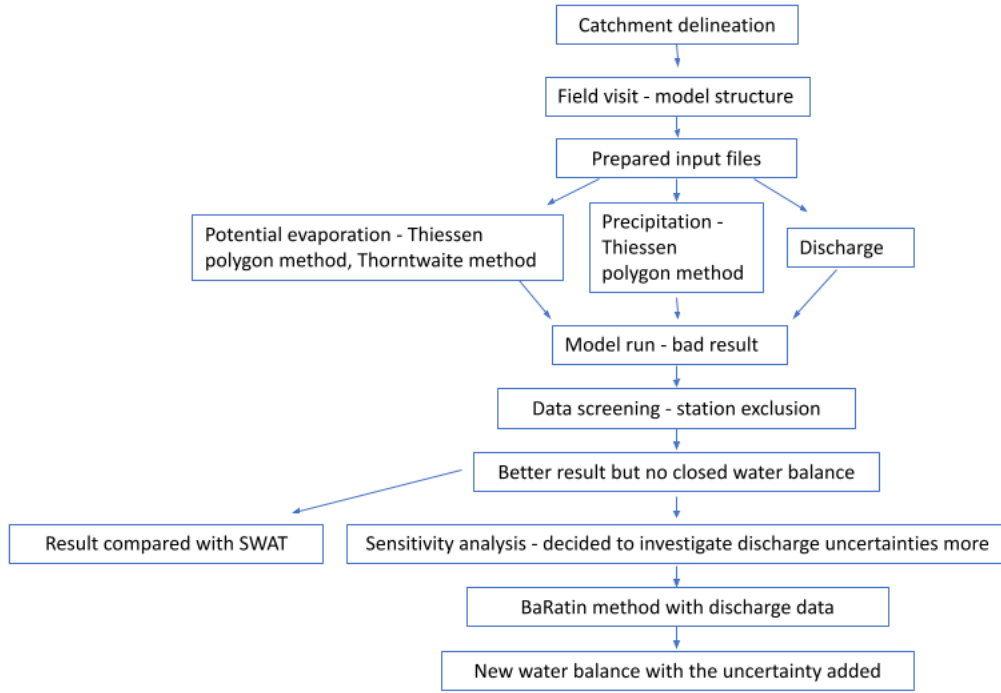


Figure 19: Summary of the method in the comparison analysis.

4.2.4 Future runoff predictions

The Monterredondo catchment was chosen to investigate how the discharge might change in the future due to climate change. Longer precipitation and discharge time series from the years 2000 to 2021 were received from EAAB and used in this part of the project. There was no available temperature data series that could supply additional information, which is why the same potential evaporation file was used for this part of the project as was calculated and used in the model comparison analysis.

4.2.4.1 Calibration

A data screening was performed for the available precipitation stations, Laguna Mar-rons, Cuchilla Golillas, Presa Golillas, Chuza Campamento, La Playa, Laguna Seca, La Cascada, Barajas and Tunel el Diamante. For every station except Presa Golillas and Chuza Campamento more than 25 % of the data was missing, which was why only these stations were used in the Thiessen polygon method. Chuza Campamento received a weight of 0.97, meaning 97 % of the catchment area is closer to Chuza Campamento than Presa Golillas, and precipitation measured at Presa Golillas would only have a small influence. This data screening is available in Appendix A.3. It was therefore decided that Chuza Campamento would be the only station that would be used for the precipitation series. Since there is a quite large elevation gradient in the Monterredondo catchment, an analysis in Excel was made to investigate the possibility of a relationship between elevation and precipitation within the catchment, using boxplots and linear

trends for the stations within the catchment. The analysis found a relationship between elevation and precipitation for the months May, June, October and November. These months had a large difference between the precipitation measured on the station on the lowest elevation and the precipitation measured on the station located on the highest elevation. They also had a good linear fit. For these months average scaling factors were calculated and later used to scale the months in the precipitation series for Chuza Campamento. The boxplots, linear trends and scaling factors for the different months can be found in Appendix A.4.

Table 9 shows the difference between the original non-scaled precipitation time series and the scaled time series.

Table 9: Comparison between scaled and not scaled precipitation time series. "Average Q diff" is the average difference in observed vs simulated discharge by the HBV model.

Method	NSE	Average Q diff [mm/yr]
Not scaled	0.56	- 123
Scaled	0.56	- 50.0

As seen in Table 9, the NSE value is the same for both versions, but the average difference in discharge is larger for the version that is not scaled. Therefore, it was considered most reasonable to continue working with the scaled version of the precipitation series and let this version of the precipitation calibrate the HBV model for the future predictions.

Through some test runs a decision was made for the following settings: 2006-2011 to be used as warming up years, 2011-2017 as calibration period and 2018-2021 as validation period. This was because the years before 2006 had significantly larger data gaps in the discharge series. It also became clear that this setup resulted in a combination of high NSE and a low difference between simulated and measured discharge values, which of course is desirable.

The GAP optimization tool was used to find the most optimal parameter settings, which were then saved to be used for the predictions. These settings can be found in Appendix A.2. The best result regarding the NSE was a calibration period with a NSE value of 0.56, a validation period with a NSE of 0.61 and an average discharge difference between the simulated and observed discharge of 300 mm, calculated for the validation period.

4.2.4.2 Future discharge simulations

General Circulation Models (GCMs) are numerical models that represent the physical processes in the ocean, atmosphere and on the land surface using a three dimensional grid stretched over the world. They are the most advanced tools available for simulating the climate change response due to increasing greenhouse gas emissions (IPCC n.d.). For this project, daily precipitation and minimum and maximum temperature were downloaded from (European Commission et al. n.d.) for the years 2022-2099. The data

was from the GCMs EC-Earth3-CC (Europe) and MRI-ESM2-0 (Japan) for the climate scenarios SSP2-4.5 and SSP5-8.5. EC-Earth3 is a globally used model that is often used for simulating the Magdalena Cauca basin in Colombia (which contains most of the paramo areas) (Muñoz, Céleri, and Feyen 2016). The MRI-ESM2-0 (Japan) model was used among other models in Vogel (2021) because of its accuracy in predicting temperature and precipitation in South America. The location closest to Monterredondo was chosen to download data from, in order to limit spatial errors. However, as seen in the map in Figure 20, the location from which the MRI-ESM2-0 data is taken from is still quite far from the Monterredondo catchment area. The MRI-ESM2-0 is approximately 100 km from Monterredondo while EC-Earth3 is only 8 km away (measured with the measurement tool in ArcMap).

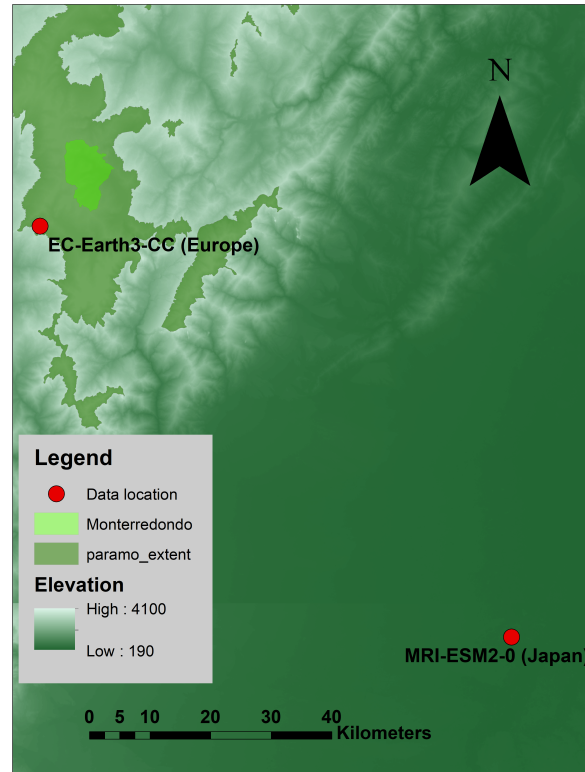


Figure 20: Map showing the Monterredondo catchment and the locations from which the data from the two different models were taken.

The data was analyzed in 20-year normal periods, four periods in total, with exception for the last period from 2082-2099 that is only 18 years. This was done to be able to compare the simulated discharge with the observed discharge values that were approximately twenty years in total, and also to be able to detect changes in time. For the four different time periods, models and scenarios, the potential evaporation was calculated using the Thorntwaite and the temperature files as described in the model comparison

part in Section 4.2.3.1. The PTQ file for each time period was created using the projected precipitation from the different models and scenarios with the temperature set to 10 °C. The parameter settings obtained from the calibration were used for all the simulations, and the default model settings were used as well. To receive the simulated future discharge, the model was run for the four time periods, the two scenarios SSP2-4.5 and SSP5-8.5 and the two models EC-Earth3-CC (Europe) and MRI-ESM2-0, in total 16 times.

A flowchart summarizing the method presented in this chapter can be seen below in Figure 21.

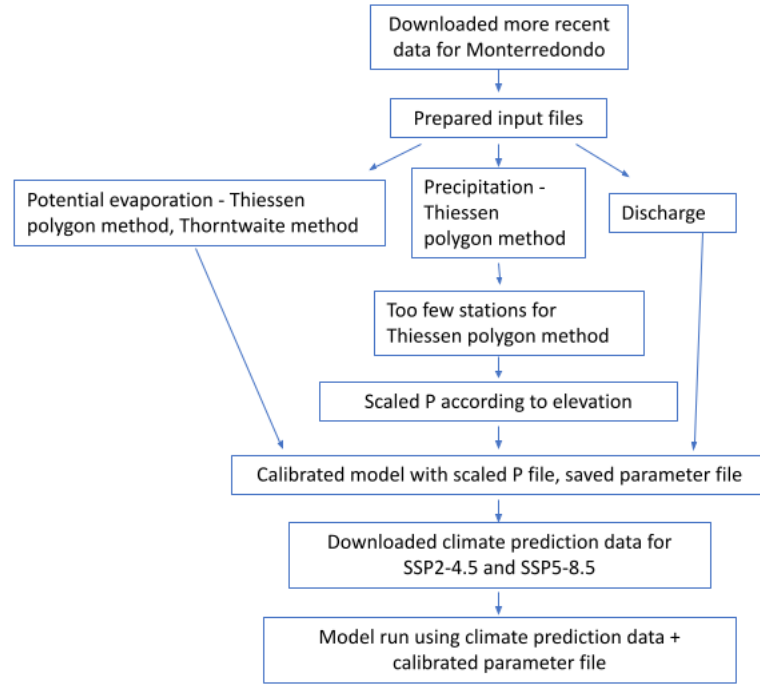


Figure 21: Summarize of the method in the comparison analysis.

4.3 Field visit

To get familiar with the unique paramo ecosystem type, field visits were carried out in Chingaza, specifically in La Laja. Discharge measurements by tracers were conducted in small streams using conductivity meters and salt dilutions. This to gain knowledge of a well used method for measuring discharge. One of the purposes with the field visit was to install a weather station that was able to measure temperature, precipitation, wind speed and direction, solar radiation, amongst other climate variables. This station did not arrive in time, but locations of its placement were discussed and decided. Placements of three different rain gauges were also suggested.

Horizontal precipitation brings an important contribution to the total precipitation at the high elevations at which you find paramos. This is considered to be an issue when measuring precipitation with regular devices such as rain gauges, since the rain gauges often are unable to capture the horizontal precipitation and hence underestimate the precipitation. To get a deeper understanding of this phenomenon, a horizontal precipitation measuring station was built, see Figure 22.



Figure 22: *Horizontal precipitation station built to get a better understanding of the contribution of water from horizontal precipitation.*

The vertical area of the station measured approximately 100x90 cm and the roof - protecting from vertical precipitation and tilted to avoid collection of water on top - measured approximately 90x50 cm. Below the screen 10 different water bottles, calibrated and marked with volume indications, were placed to collect the water. The bottles were emptied once every week and the volume noted down. The volumes were then converted to mm/m² using the volumes and the screen area. Then the horizontal precipitation in mm/d was calculated. Lastly, the obtained value for horizontal precipitation was divided by the sum of the historical daily average precipitation and the horizontal precipitation value to get the contribution from horizontal precipitation.

5 Results

5.1 Characterization

In the following section, different plots and summarizing tables are presented to highlight and compare the precipitation and discharge characteristics and behaviour within and between different clusters, and by extension, in different paramo regions.

5.1.1 Precipitation

The amount of annual precipitation varies notably both within and between clusters, with up to around 2000 mm/yr and 3500 mm/yr, respectively, as can be seen in Figure 23. However, in general, the paramos with stations belonging to Cluster 1-4 (northern part of Cordillera Occidental and the northern and eastern side of Cordillera Central) seem to experience more precipitation than the paramos with stations belonging to Cluster 5-9 (southern Cordillera Occidental, western slope of southern-central Cordillera Central, eastern slope of northern-central Cordillera Central and northern-central part of Cordillera Oriental), by rough calculations around 1100 mm/yr more (see Figure 14 in Section 4.1.3 for location of the different clusters). For stations in Cluster 1-4 the total annual precipitation generally exceeded or was close to 2000 mm/yr, whereas stations in Cluster 5-9 more often had a total annual precipitation between approximately 600 and slightly less than 2000 mm/yr in the years 1987-2012, with Cluster 8 and 9 generally experiencing the least precipitation. What is more, stations in Cluster 1, 3 and 4 imply a greater individual variability in total annual precipitation for the 26 years. For the same station the annual precipitation can vary considerably from year to year with up to around 1000 mm/yr. When it comes to variability between stations in the same cluster, it appears biggest for Cluster 1, 4 and 7.

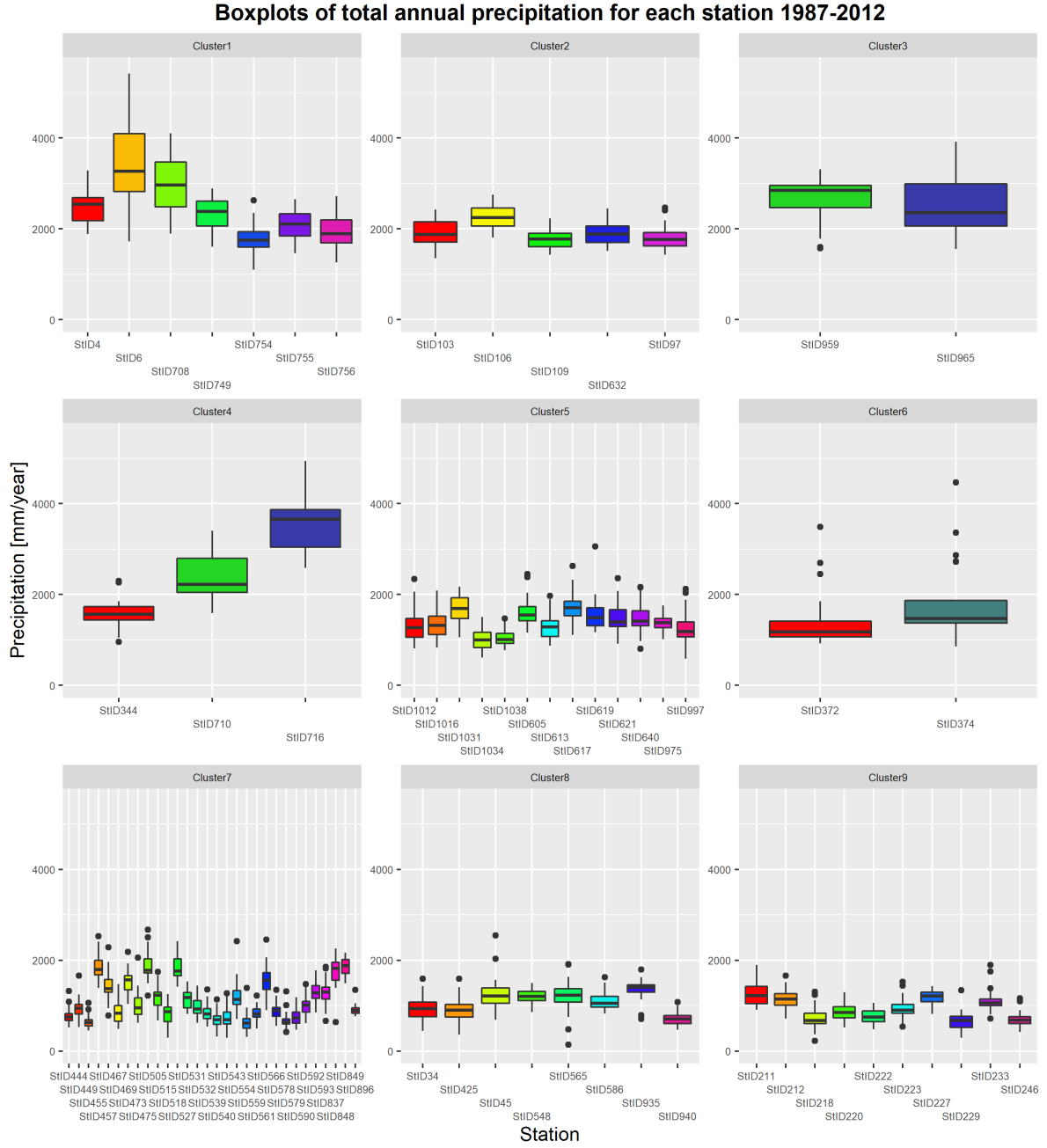


Figure 23: Boxplots based on total annual precipitation for each station 1987-2012 plotted clusterwise. The colours indicate the different stations.

Furthermore, the tendency of the stations in Cluster 5-9 to manifest a lower amount of total annual precipitation can also be noted in Figure 24. This figure also shows the changes in total annual precipitation over time between the years 1987 and 2012. The stations in Cluster 2, 5, 7, 8 and 9 seem to have a quite stable precipitation pattern over time, whereas stations in Cluster 1, 3, 4 and 6 have some rather drastic peaks and dips (local maxima and minima) in their total annual precipitation. Some of the peaks (local

maxima) appear to coincide with La Niña (blue vertical lines) and some of the dips (local minima) appear to coincide with El Niño (red vertical lines). However, in some cases this connection is not visible or as clear. Within some clusters several stations manifest rather similar precipitation patterns, such as the stations in Cluster 4, and/or quite similar precipitation quantities, like the stations in Cluster 2.

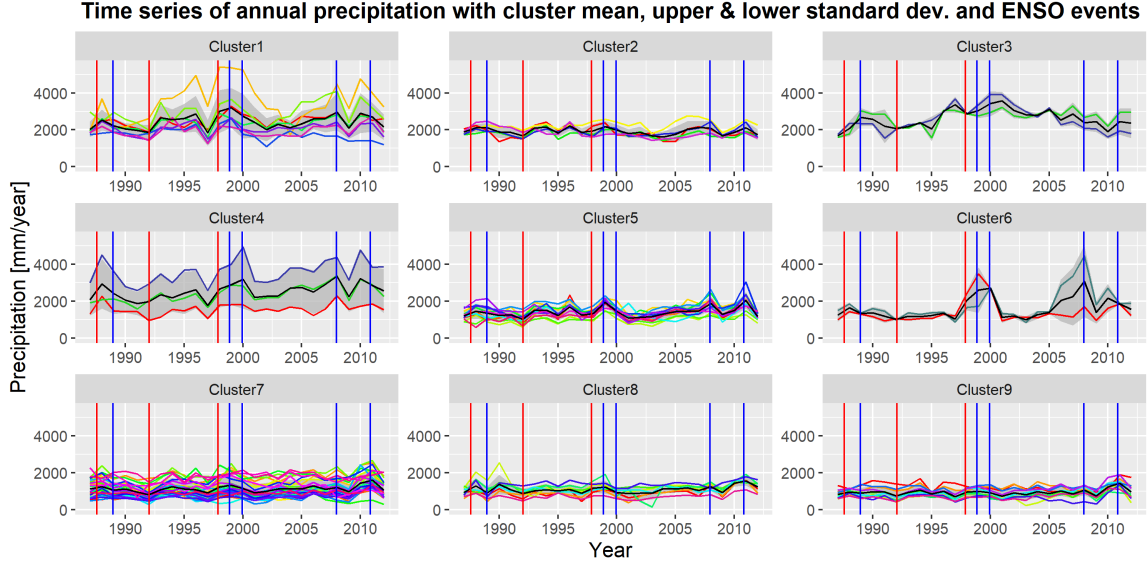


Figure 24: Time series of total annual precipitation for each station 1987-2012 plotted clusterwise. The black line corresponds to the mean precipitation for each cluster and the grey band corresponds to the upper and lower standard deviation. The red and blue vertical lines represent strong or very strong El Niño and La Niña events, respectively.

Figure 25 mainly conveys the seasonality in the areas where the different stations are located. The stations in Cluster 1, 4 and 6 quite consistently present a seasonality with two wet seasons (bimodal precipitation pattern), one in April-May (S2) and one in October-November (S5). The other clusters contain stations with varying seasonality patterns, several of which show the same seasonality as the stations in the three clusters mentioned above. However, an important number of stations seem to only have one wet season (unimodal precipitation pattern), occurring in predominantly May-June (S2-3) or June-July (S3) or all of these three months. This is the case mainly in Cluster 3, 7, 8 and 9 and somewhat less clearly in Cluster 5 and 2. Moreover, in Cluster 4 and 6 there is one station in each cluster showing a small increase in total monthly precipitation in June-July, although the general pattern for these stations is bimodal with two big peaks, one in April-May and one in October-November.

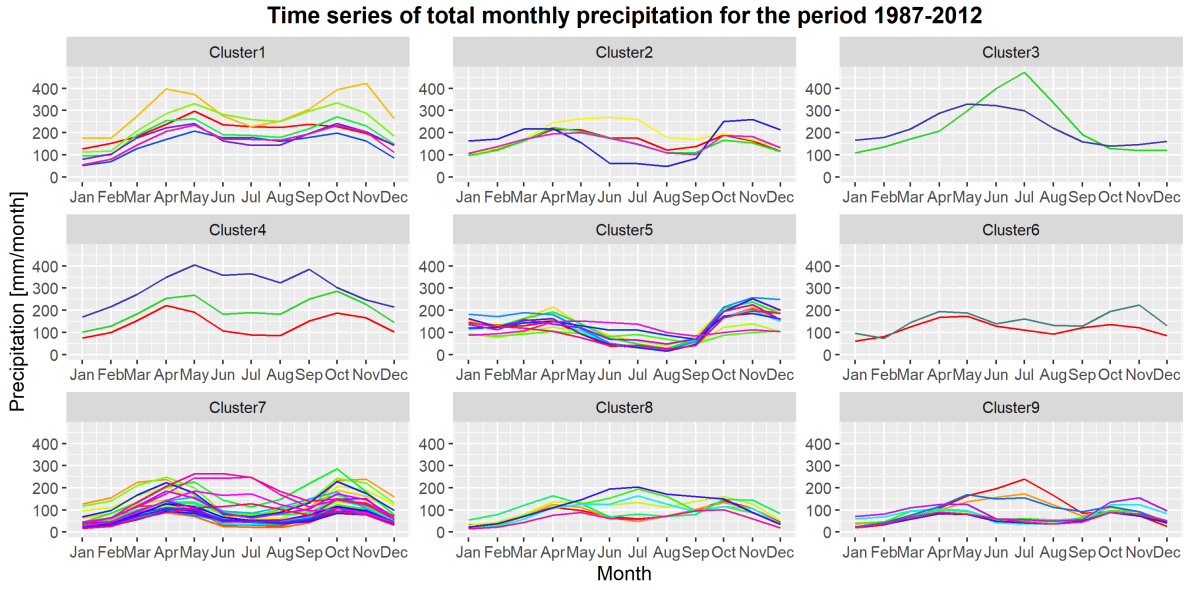


Figure 25: Time series of mean monthly precipitation for each station for the period 1987-2012 plotted clusterwise.

As for the number of days with precipitation (>0.2 mm/day) (see Figure 26) it seems to follow the same, or at least a similar, pattern as the amount of precipitation seen in Figure 25. This implies that both the amount of precipitation and the number of days with precipitation increase during the wet seasons.

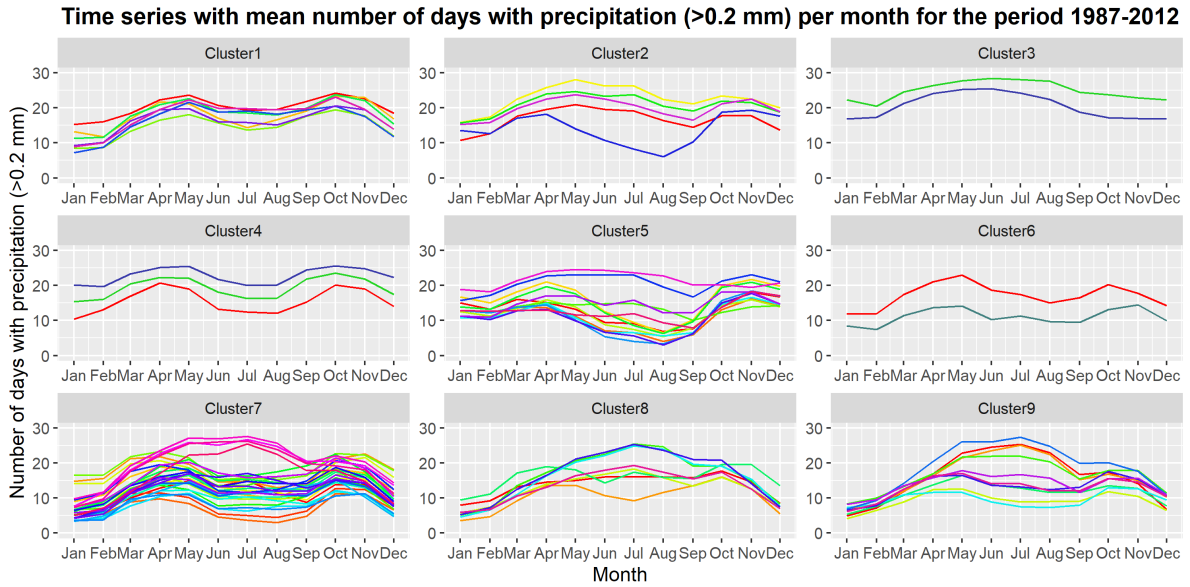


Figure 26: Time series of mean number of days with precipitation (>0.2 mm) per month for each station for the period 1987-2012 plotted clusterwise.

Table 10 presents a more detailed compilation of information regarding the seasonality based on both plots and statistical calculations, more or less describing what is seen in Figure 25 and 26, but also comparing the seasons between the clusters and indicating which season(s) receive/s the most precipitation in each cluster. Blue indicates highest value and orange indicates the lowest value. Generally, the same clusters (Cluster 1-4) that had the most total annual precipitation also had the most precipitation in the different seasons. More clusters with a bimodal precipitation pattern had most precipitation in S2 (April-May), but S5 (October-November) was not always far behind in terms of number of clusters and amount of precipitation.

Figure 27, in turn, visualizes the location of the precipitation stations with different seasonalities. Overall, the stations with a unimodal precipitation pattern are on, or at least closer to, the eastern slopes of the mountain ranges, whereas the stations with a bimodal precipitation pattern are more on the western sides of the mountain ranges. However, some stations with the opposite (bimodal/unimodal) precipitation patterns are in seemingly close proximity to each other. The four stations with a bimodal precipitation pattern, but small peaks in June-July (S3) are more scattered.

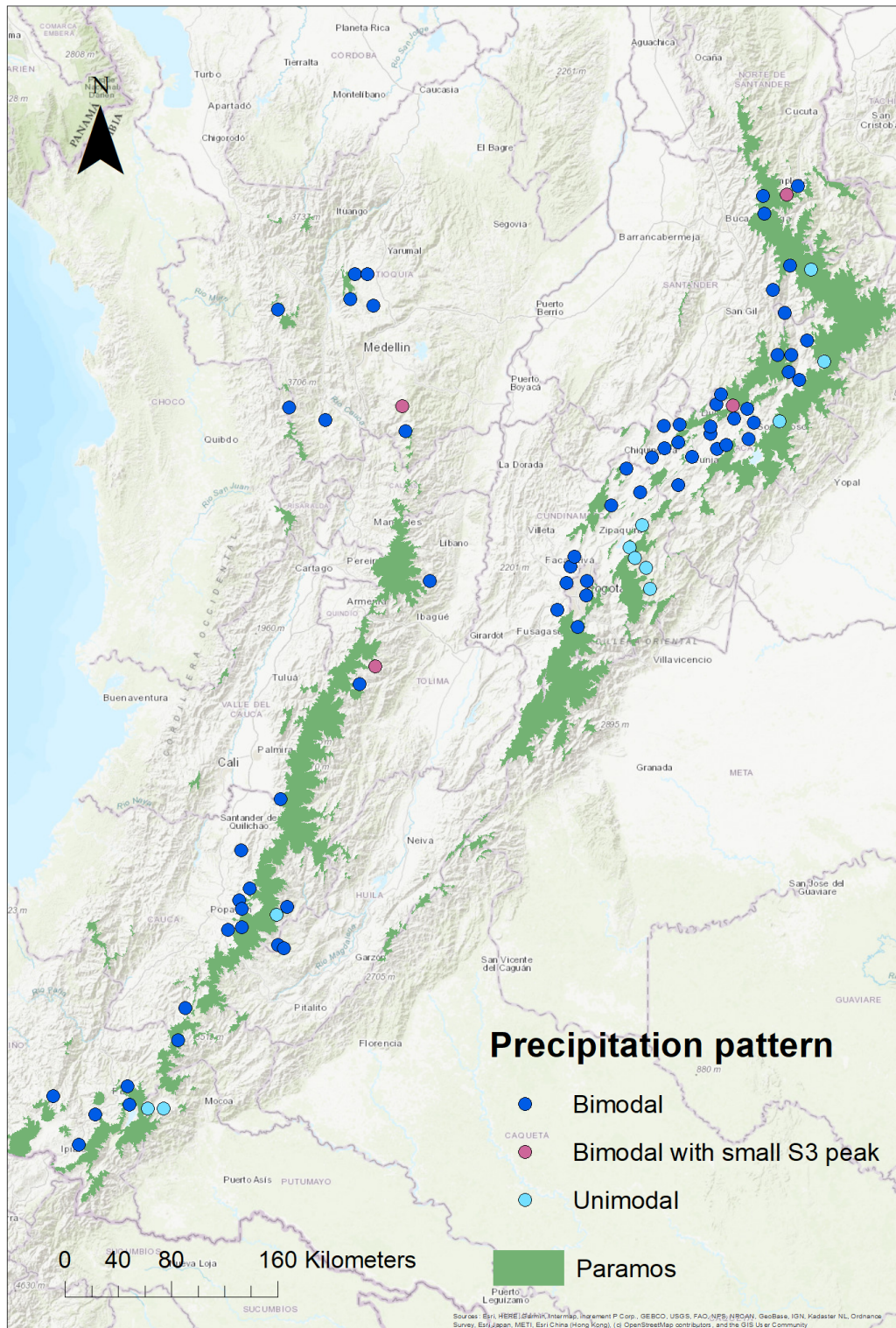


Figure 27: Map with the paramo areas and the precipitation stations divided according to seasonality, where dark blue indicates stations with a bimodal precipitation pattern, light blue indicates stations with a unimodal precipitation pattern and pink indicates stations with a bimodal precipitation pattern but that present a small increase in precipitation between the two wet seasons. Generally a bimodal precipitation pattern means precipitation peaks in April-May (S2) and October-November (S5) and a unimodal precipitation pattern means a precipitation peak in June-July (S3), but the months can differ slightly.

Table 10: Compilation of seasonality and average precipitation per season for each cluster. Blue indicates the cluster with the highest value and orange indicates the cluster with the lowest value. P = precipitation, *big variability, **wet days = days with more than 0.2 mm of precipitation (P>0.2 mm), bump = small peak during non-wet season.

	C1	C2	C3	C4	C5	C6	C7	C8	C9
Season(s) with most P (BP) <i>Comment</i>	S2 & S5 Bv* all seasons	S2 & S5	S3	S2 & S5 Bv S3	S2 & S5	S2 & S5	S2 & S5	S2 & S5 Bv S3	S2 & S5 Bv S3
Season(s) with most P (TS) <i>Exceptions</i>	S2 & S5	S2 & S5 Apr-Jul Mar-Apr	S3 May-Jun	S2 & S5 Bump Jul	S2 & S5 May-Jul & Nov	S2 & S5 Bump Nov	S2 & S5 Mar-May May-Jul	S2 & S5 Jun-Jul	S2 & S5 Jun-Jul
Number of wet days** <i>Exceptions</i> <i>Months with peaks</i>	S2 & S5 May & Oct	S2-S3 & S5 S2 & S5 (Apr)-May-(Jun) & Oct-Nov	S2-S3 May-June-(Jul-Aug)	S2 & S5 Apr-May & Oct	S2 & S5 S2-S3 Apr-May & Oct-Nov	S2 & S5 May & Oct-Nov	S2 & S5 S3 Apr-May & Oct-Nov May-Jul	S2 & S5 S3 Apr-May & Oct-(Nov) Jul	S2 & S5 S3 Apr-May & Oct-Nov (May-Jun)-Jul
Mean P [mm/season]									
S1	301	313	361	352	257	203	163	113	124
S2	532	427	565	562	265	362	279	238	215
S3	413	330	752	431	126	270	160	227	179
S4	429	234	453	459	99	237	161	215	135
S5	515	382	266	469	364	328	271	236	199
S6	254	254	281	272	298	184	105	71	86
Season with most P	S2	S2	S3	S2/S5	S5	S2	S2/S3/S5	S2/S3/S5	S2/S3/S5

Table 11 contains more detailed descriptive statistics for each cluster, not pointing out the individual stations. According to this summary, Cluster 3 and 4 have the overall highest precipitation, whereas Cluster 1 has the highest upper extreme values and includes the station with the biggest variability in the form of the biggest interquartile range.

Furthermore, for each statistical indicator the nine clusters were also compared, and the highest and lowest values are highlighted in blue and orange in Table 11. The overview of the table further supports the picture that Cluster 1-4 receive more precipitation than Cluster 5-9, as the left part of the table contains all the highest values and the right part contains all the lowest values. When comparing the mean annual precipitation for Cluster 1-4 and Cluster 5-9 it indicates a general difference of approximately 1100 mm/yr.

Table 11: Summary of the descriptive statistics for each cluster based on calculated total annual precipitation. Blue indicates the cluster with the highest value and orange indicates the cluster with the lowest value. IQR = interquartile range.

Statistic\Cluster	C1	C2	C3	C4	C5	C6	C7	C8	C9
Median [mm/yr]									
<i>Highest</i>	3264	2242	2844	3655	1712	1476	1882	1405	1219
<i>Lowest</i>	1745	1769	2352	1561	1002	1178	612	709	671
<i>Range</i>	1520	474	493	2093	710	298	1270	695	549
Mean [mm/yr]	2435	1931	2613	2517	1401	1599	1128	1091	932
Max [mm/yr]	5417	2753	3919	4938	3057	4463	2673	2546	1897
Min [mm/yr]	1100	1353	1550	956	584	858	292	141	225
Quantile [mm/yr]									
<i>Highest Q75</i>	4095	2456	2986	3870	1930	1871	2032	1461	1422
<i>Lowest Q75</i>	1930	1898	2954	1736	1140	1414	694	784	755
<i>Highest Q25</i>	2819	2061	2467	3039	1529	1370	1723	1296	1089
<i>Lowest Q25</i>	1594	1606	2058	1441	829	1066	502	605	518
IQR [mm/yr]									
<i>Biggest</i>	1276	441	929	831	462	500	394	338	375
<i>Smallest</i>	336	292	487	295	201	348	113	165	138

Table 12 includes the trends over time for the Climpack indices for precipitation. For the indices with a significant trend the p value and Sen's slope are indicated. The cells that are highlighted in orange connote a decreasing trend in precipitation, the ones highlighted in blue indicate an increasing trend and the ones highlighted in yellow indicate that there has been no change over time. From the table it becomes evident that most trends (~75 %) over time are not significant and that there are more cases

suggesting an increasing trend in precipitation rather than a decreasing trend or no change at all.

There are no significant changes in the number of consecutive wet and dry days for most of the representative stations (~ 89 % of the stations). Additionally, the annual and monthly number of days with precipitation greater than or equal to 10 and 20 mm have remained without any significant trend for most of the representative stations (~ 66 -78 % of the stations) as well. Moreover, there were more stations (33 %) showing significant trends in maximum monthly 1-day and 5-day precipitation total than for the corresponding indices on an annual scale, and the significant trends on a monthly scale were all increasing. Similarly, more stations manifested a significant trend in sum of daily precipitation equal to or greater than 1.0 mm on a monthly basis (44 %) than on a yearly basis, all of which were increasing. As for annual total precipitation divided by the number of wet days (when total $P \geq 1.0$ mm) 44 % of the representative stations displayed a significant increase. The rest of the indices present no significant trend or only a significant trend for one of the representative stations. One station that stands out in the sense that it shows several significantly *decreasing* trends is the station belonging to Cluster 3. It also has significantly increasing trends, but it has more significantly decreasing trends than increasing trends. Including the indices with trends that are not significant, half are decreasing and half are increasing for the representative station in Cluster 3.

The representative stations with most significant trends belong to Cluster 4, 6 and 3 (northern and southern Cordillera Central, mostly the eastern slope). For the stations in Cluster 4 and 6 (northern Cordillera Central) all the significant trends imply a wetter climate, whereas for the station in Cluster 3 (southern Cordillera Central) two of the indices imply a change for a wetter climate, four indices indicate a change to a drier climate and one index shows no change over time. The representative stations in Cluster 8 and 9 show no significant trends in any of the indices. The indices with most (56 %) representative stations showing a significant trend are the indices for monthly number of days when precipitation ≥ 10 mm (*r10mm*, *m*) and the maximum monthly 7-day precipitation total (*rx7day*, *m*), respectively, both of which increased significantly over the time period, except for two cases with no change in *r10mm*, *m*.

Important to note is that in Climpack the limit for what is considered a wet day is set higher than the limit of 0.2 mm used earlier in this analysis. In Climpack the corresponding value is 1.0 mm. This affects the calculation of number of wet and dry days.

Table 12: Climipact indices for trends in precipitation over time. The p value and Sen's slope are included where there is a significant trend. The cells that are highlighted in orange indicate a decreasing trend, the ones highlighted in blue indicate an increasing trend and the ones highlighted in yellow indicate that there has been no change (Sen's slope=0) over time. *Wet days = days with $P \geq 1.0$ mm.

Cluster INDEX\StID	C1 <i>StID4</i>	C2 <i>StID632</i>	C3 <i>StID959</i>	C4 <i>StID710</i>	C5 <i>StID1016</i>	C6 <i>StID374</i>	C7 <i>StID515</i>	C8 <i>StID586</i>	C9 <i>StID220</i>
Max. ann. # of consecutive dry days cdd						p=0.002, Sen=1.23			
Max. ann. # of consecutive wet days* cwd	p=0.029, Sen=0.24								
Ann. # of days when $P \geq 10$ mm r10mm, y				p=0.001, Sen=1.75	p=0.017, Sen=0.723				
Monthly # of days when $P \geq 10$ mm r10mm, m	p=0.043, Sen=0		p=0, Sen=0.01	p=0, Sen=0.01	p=0.033, Sen=0	p=0, Sen=0.011			
Ann. # of days when $P \geq 20$ mm r20mm, y				p=0.001, Sen=1.125		p=0.014, Sen=-0.882			
Monthly # of days when $P \geq 20$ mm r20mm, m			p=0.045, Sen=0	p=0, Sen=0.005		p=0, Sen=0.005	p=0.018, Sen=0		
Max. ann. 1-day P total rx1day, y			p=0.006, Sen=-1.6						
Max. monthly 1-day P total rx1day, m				p=0.008, Sen=0.025		p=0, Sen=0.049	p=0.018, Sen=0.019		
Max. ann. 5-day P total rx5day, y				p=0.05, Sen=1.28					
Max. monthly 5-day P total rx5day, m				p=0, Sen=0.072		p=0, Sen=0.115	p=0.046, Sen=0.037		
Max. ann. 7-day P total rx7day, y				p=0.042, Sen=1.785					
Max. monthly 7-day P total rx7day, m	p=0.029, Sen=0.046		p=0.044, Sen=0.071	p=0, Sen=0.097		p=0, Sen=0.128	p=0.046, Sen=0.044		
Ann. sum of daily $P \geq 1.0$ mm prcptot, y	p=0.014, Sen=0.135		p=0.002, Sen=0.231	p=0.001, Sen=44.779		p=0.01, Sen=0.152			
Monthly sum of daily $P \geq 1.0$ mm prcptot, m		p=0.031, Sen=0.097		p=0.006, Sen=0.099		p=0, Sen=0.656	p=0.025, Sen=0.086		
Ann. total P / # of wet days* sdi									
Ann. sum of daily $P > 95$ th percentile r95p									
Ann. sum of daily $P > 99$ th percentile r99p			p=0.021, Sen=-11.086						
100*r95p / PRCPTOT r95ptot			p=0.011, Sen=-0.769						
100*r99p / PRCPTOT r99ptot			p=0.011, Sen=-0.484						

5.1.2 Discharge

Some results were also produced for discharge. Figure 28 presents the annual mean daily discharge over time. Most of the stations have an annual mean daily discharge somewhere between 0 and 10 m³/s, but some reach discharge values of around 15 m³/s. Several of the stations demonstrate a drastic increase in discharge during the last years of the analyzed time period, some reaching discharge levels as high as 25-30 m³/s. For many of the stations the discharge seems rather stable over time, but for some there are signs of an increase (see orange stations in Cluster 1, 4, 8 and 9) or slight hints of a decrease (see the orange and purple stations in Cluster 5). As with precipitation some peaks (local maxima) coincide with La Niña and some dips (local minima) with El Niño, but there are cases where this connection is not clear or in a few cases the opposite is true.

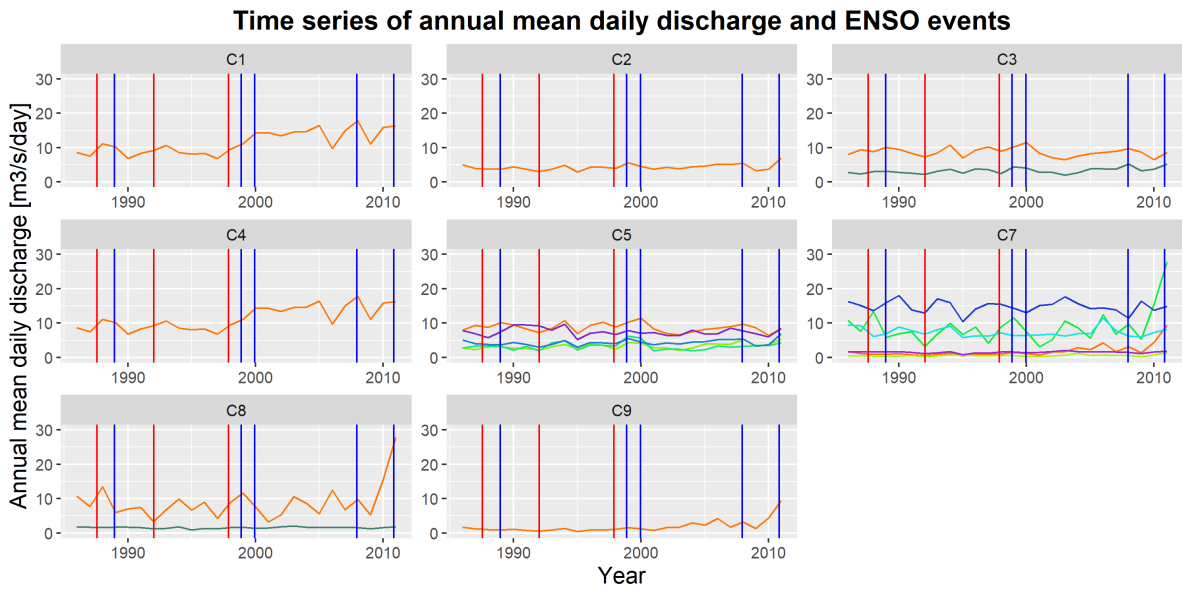


Figure 28: Time series of annual mean daily discharge for each station for the period 1986-2011 plotted clusterwise (C1-C9, except for C6). The red and blue vertical lines represent strong or very strong El Niño and La Niña events, respectively.

Figure 29 exhibits the total annual amount of specific discharge over time. Most of the stations have an accumulated annual specific discharge somewhere between 500 and 1500 mm/yr, but some reach discharge amounts of around 2000 mm/yr, and one stream only has a specific discharge of around 200 mm/yr. Several of the stations demonstrate a rather steep increase in discharge during the last years of the analyzed time period, one reaching discharge levels as high as approximately 2500 mm/yr. For several of the stations the discharge seems rather stable over time, but for some there are signs of an increase (see orange station in Cluster 1 and 4 and green station in Cluster 3) or slight hints of a decrease (see the orange and purple stations in Cluster 5). From the few stations that are included it seems Cluster 1, 4 and possibly 5 have streams with

the highest specific discharge, although it differs quite much between stations in Cluster 5. Cluster 7, 5, 3 and 2 seem to have streams with the lowest specific discharge or the generally lowest specific discharge, but in Cluster 5 and 7 the span is rather big.

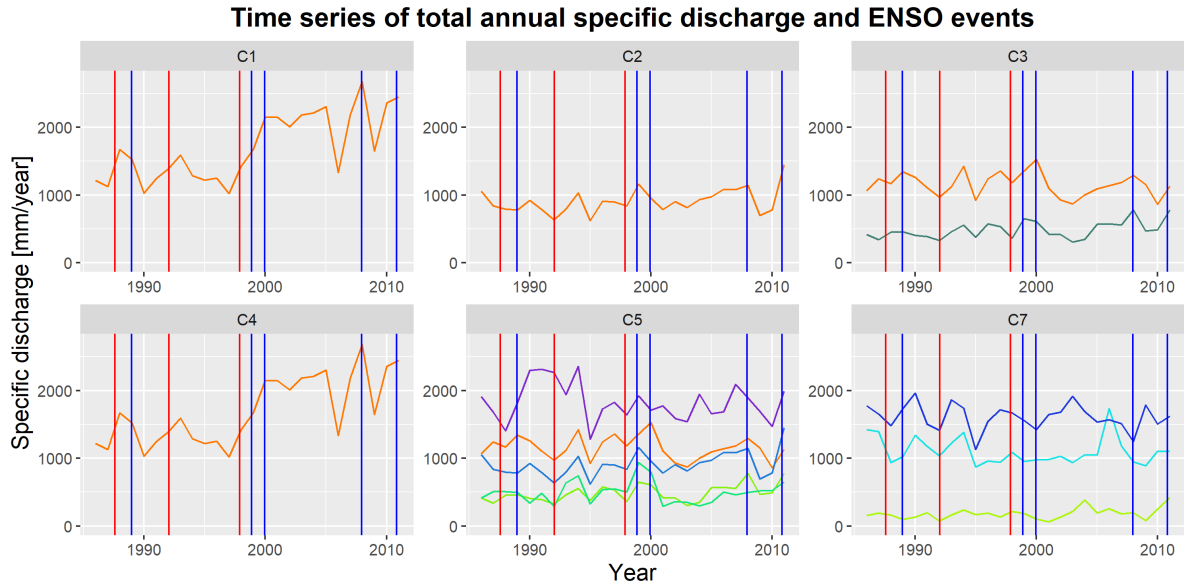


Figure 29: Time series of total annual specific discharge for each station for the period 1986-2011 plotted clusterwise (except for C6, C8 and C9). The red and blue vertical lines represent strong or very strong El Niño and La Niña events, respectively.

Table 13 shows the results from a Sen's slope trend test in R for the annual mean daily discharge. As some discharge stations represent more than one cluster only three of the twelve stations (25 %) show a significant trend for the time period between 1986 and 2011. There was a significant trend for one station in Cluster 1/4, for one in Cluster 3/5 and for one in Cluster 7/9. For all three stations the Sen's slope indicates an increase in discharge and this increase is the greatest for Cluster 1/4.

Table 14 indicates that out of the clusters and stations that were left for the calculation of specific discharge, the same show a significant increase over time when it comes to total annual specific discharge as for annual mean daily discharge. In fact, the pattern over time for annual mean daily discharge and total annual specific discharge are very similar (see Figure 28 and Figure 29).

Table 13: Results for the Sen's slope test in R. Cells highlighted in blue indicate a significantly increasing trend in annual mean daily discharge ($\text{m}^3/\text{s}/\text{day}$).

Cluster	ID	p-value	Sen's slope
C1	QID1	0.0000603	0.338
C2	QID5	0.113	0.040
C3	QID10	0.428	-0.030
	QID11	0.0173	0.055
C4	QID1b	0.0000603	0.338
C5	QID12	0.628	0.007
	QID10b	0.428	-0.030
	QID9	0.428	-0.034
	QID5b	0.113	0.040
	QID11b	0.0173	0.055
C7	QID8	0.724	0.001
	QID6	0.509	-0.031
	QID2	0.000585	0.076
	QID3	0.0580	0.009
	QID4	0.509	0.099
	QID7	0.402	-0.046
C8	QID8b	0.724	0.001
	QID4b	0.509	0.099
C9	QID2b	0.000585	0.076

Table 14: Results for the Sen's slope test in R. Cells highlighted in blue indicate a significantly increasing trend in total annual specific discharge (mm/yr).

Cluster	ID	p-value	Sen's slope
C1	QID1	5e-05	50.3
C2	QID5	0.113	8.25
C3	QID10	0.428	-4.02
	QID11	0.0275	7.33
C4	QID1b	5e-05	50.3
C5	QID12	0.628	0.839
	QID10b	0.428	-4.02
	QID9	0.454	-8.81
	QID5b	0.113	8.25
	QID11b	0.0275	7.33
C7	QID6	0.454	-5.24
	QID3	0.0641	2.81
	QID7	0.355	-5.29

5.1.3 Comparison of precipitation and discharge

When it comes to the amount of total annual precipitation and total annual specific discharge, Cluster 1-4 were the clusters with most precipitation (see Figure 23, Figure 24 and Table 11) and Cluster 1, 4 and possibly 5 had streams with the most specific discharge (see Figure 29). In other words, Cluster 1 and 4 seem to experience both a lot of precipitation and generate a lot of discharge in their surrounding areas. Cluster 5-9 seem to experience less precipitation, out of which Cluster 8 and 9 show the least precipitation (see Figure 23, Figure 24 and Table 11), and the stations with the least specific discharge or the generally lowest specific discharge are seen in Cluster 7, 5, 3 and 2 (see Figure 29), so the results for precipitation and discharge are not completely coherent and Cluster 5 and 7 have streams with both high and low specific discharge.

Some patterns over time, that is, increases, decreases, peaks and dips, coincide for precipitation and both annual mean daily discharge and total annual specific discharge (see Figure 24 and Figure 28 and 29). However, the patterns do not always coincide between all precipitation and discharge stations in a cluster. For instance, Cluster 1 and Cluster 4, that have the same discharge station, show a discrepancy between the precipitation and discharge patterns. There is a clear increase in discharge over time, which is not reflected in the precipitation pattern as most stations seem to have a rather stable precipitation over time, except for some periods with a notable, but temporary increase.

For discharge all clusters that have stations with a significant trend show increasing trends, whereas for precipitation most significant trends are increasing, but some are decreasing (see Table 12, Table 13 and Table 14). Both precipitation and discharge show mostly insignificant trends and they are both increasing and decreasing, but mostly increasing. No cluster has more than one stations with a significant trend in discharge. The clusters with one discharge station showing significant increases (Cluster 1/4, 3/5 and 7/9), also have mostly significantly increasing trends in precipitation indices, except for Cluster 3 and 9. The representative precipitation station in Cluster 3 has more indices showing significantly decreasing trends, and 50 % of the stations are showing increasing trends and 50 % are showing decreasing trends, if also looking at the trends that are not significant. The representative precipitation station in Cluster 9 does not have any indices with significant trends, but the majority of the trends are decreasing. Although Cluster 3 has one discharge stations with a significantly increasing trend, its other station has a decreasing trend, however not significant. Cluster 9's only discharge station, on the other hand, has a significantly increasing trend. Apart from the discharge station in Cluster 3, a few stations in Cluster 5 and 7 also show a decreasing, but statistically insignificant trend. All in all, the precipitation trends are not fully reflected in the discharge trends for the stations compared.

5.2 Modeling

5.2.1 Model comparison and evaluation of the HBV model

This section presents the result from the model comparison. During the comparison analysis between the SWAT and HBV model, some water balance uncertainties were encountered, which are presented below. A sensitivity analysis of the input data and changes in the model structure was also investigated, in addition to the performance comparison between the models. The result from these findings are presented in this section.

5.2.1.1 Water balance uncertainties

During the calibration of the HBV model - when using the same input data for temperature, discharge and precipitation as the SWAT model did - it became clear that the water balance for the input data did not close up, even though the NSE value of 0.81 (calibration period) was quite good. It would be expected that the water storage in the soil would vary between the years, but the water balance shows that the storage almost always has a positive value, indicating that the storage is increasing for almost every year. This error could also be visualized when comparing the difference in simulated and observed discharge - the simulated discharge values are always distinctly larger. Figure 30 shows the HBV water balance using the common input data. As seen in the figure, the water storage always has a positive value.

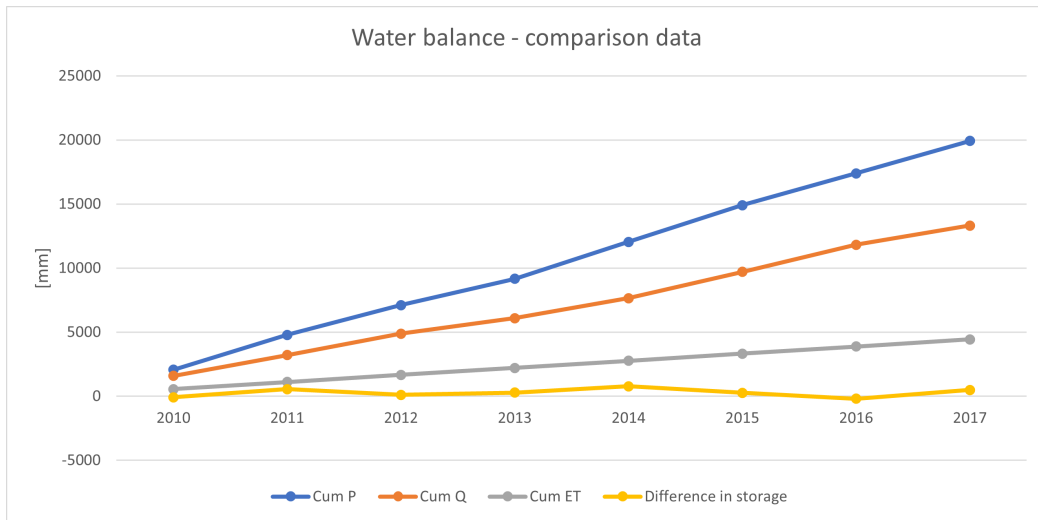


Figure 30: Water balance for the observed data. The cumulative precipitation, discharge and evapotranspiration compared with the difference in storage for each year. This graph shows the whole time period, warming up period and validation period included.

Table 15 and Table 16 below show the water balance in more detail.

Table 15: Water balance from the model comparison. The precipitation column contains the input data for the HBV model. Obs Q, meaning observed discharge values and Sim Q meaning simulated discharge values. To be able to see where the water ends up, the percentage of the precipitation is also shown for each year.

Year	Precipitation [mm/yr]	Obs Q [mm/yr]/ % of precipitation	Sim Q [mm/yr]/ % of precipitation	Sim Q - Obs Q [mm/yr]
2011	2725.8	1619.1 / 59%	2286.7 / 84%	667.6
2012	2327.1	1671.8 / 72%	1893 / 81%	221.1
2013	2053.9	1215.9 / 59%	1648.9 / 80%	433.1
2014	2876	1552.9 / 54%	2438.7 / 85%	885.8
2015	2867.3	2045.9 / 71%	2429.3 / 85%	383.4

As seen in Table 15, the simulated discharge is always larger than the observed discharge. The simulated discharge also holds a larger percentage of the precipitation than the observed discharge does, meaning more of the precipitation becomes discharge in the HBV model compared with the observed values.

Table 16: Continuation of the water balance from the model comparison. Epot, meaning potential evaporation and is the input data. AET, meaning actual evaporation and is the evaporation output produced by the HBV model. ΔS is the difference in storage. To see where the water ends up, the percentage of the precipitation is also shown for each year.

Year	Epot [mm/yr]/ % of precipitation	AET [mm/yr]/ % of precipitation	ΔS input [mm/yr]/ % of precipitation	ΔS output [mm/yr]/ % of precipitation
2011	553.9 / 20%	445.2 / 16%	552.7 / 20%	-6 / -0.2%
2012	553.9 / 24%	430.4 / 18%	101.4 / 4%	3.7 / 0.2%
2013	549.4 / 27%	410.1 / 20%	288.6 / 14%	-5.2 / -0.3%
2014	553.9 / 19%	431.2 / 15%	769.2 / 27%	6.1 / 0.2%
2015	553.9 / 19%	427.7 / 15%	267.5 / 9%	10.4 / 0.4%

The change in water storage, ΔS , was calculated using Equation 2 with both the input data and the output data. To obtain the ΔS for the input data, the observed discharge and potential evaporation were used, and to obtain the ΔS for the output data, the simulated discharge and actual evaporation were used in the same equation. As seen in Table 16, the ΔS for the input data is always increasing, while for the output data, the ΔS is varying, and has much smaller values. This indicates that the HBV model manages to close the water balance, but to do that, the discharge needs to be increased (see Table 15).

Table 17: The water balance after adjusting the high flows.

Year	Precipitation [mm/yr]	Original obs Q [mm/yr]	83% of high flows [mm/yr]	Adjusted obs Q [mm/yr]	Epot [mm/yr]	ΔS [mm/yr]
2011	2725.8	1619.1	234.1	1853.2	553.9	318.6
2012	2327.1	1671.8	340.5	2012.3	553.9	-239.1
2013	2053.9	1215.9	154.2	1370.0	549.4	134.4
2014	2876	1552.9	479.7	2032.6	553.9	289.5
2015	2867.3	2045.9	822.3	2868.2	553.9	-554.8

Table 17 shows the water balance after the high flows have been adjusted for the possible uncertainties that were found with the BaRatin method in Section 4.2.3.3. The high flows have a possible upper uncertainty of 83 %, which is why this increase has been added to the original data. After the adjustment, the water balance table shows a more stable water balance with a water storage that increases for some years and decreases for others. The total change in water storage for these five years is -51 mm, compared to the values before the adjustment when the change in water storage for the same five years was 1979 mm.

5.2.1.2 Sensitivity analysis

Table 18: Table that shows the result from the sensitivity analysis. The original structure includes two groundwater boxes.

Variable	Adjustment	NSE	Relative difference in NSE	Average difference in discharge [mm/yr]
Original	Original	0.591	-	518
Precipitation	+10%	0.456	22.8%	1042
Precipitation	-10%	0.624	5.6%	270
Discharge	+10%	0.617	4.4%	-15
Discharge	-10%	0.555	6.1%	680
Evaporation	+10%	0.594	0.5%	480
Evaporation	-10%	0.589	0.3%	552
Model structure	1 GWB	0.507	14.2%	518
Model structure	3 GWB	0.591	0.0%	518
tModel structure	Alfa	0.591	0.0%	518

Table 18 shows the results from the sensitivity analysis. The sensitivity analysis tested the HBV model's sensitivity towards changes in input data and simple changes in the model structure. The result shows that the model is most sensitive towards a lowering in precipitation, since it leads to the worst result. It also confirms the theory that the precipitation is overestimated or that the discharge is underestimated, since the NSE increases when the precipitation is decreased or the discharge is increased. These changes also obtain the lowest difference in discharge. Furthermore, the evaporation has a very low influence on the result. Another observation is that the model structure using two groundwater boxes is performing similarly to when three groundwater boxes

are used, indicating that using three groundwater boxes is unnecessarily complicated for mimicking the paramo system, whereas one groundwater box is too simple, since it leads to a worse result. Changing the parameterization to Alpha from UZL and K_0 does not influence the NSE. Hence, neither a change in model structure or parametrization changed the difference between simulated and observed discharge.

5.2.1.3 SWAT and HBV model comparison

Table 19: Comparison of SWAT and the HBV model with respect to the NSE values. These values are calculated from monthly simulated discharge data.

Model	Uncalibrated	Calibration	Validation
SWAT	-	0.83	0.59
HBV	0.47	0.81	0.56

Table 19 shows the NSE values for the SWAT model and the HBV model calculated using Equation 1, found in Section 2.2.2, for monthly simulated values. (Observe that the sensitivity analysis is performed on daily values, which is why the NSE values in Table 18 differ from the NSE values shown in Table 19). With regards to the NSE, the SWAT model is performing slightly better, with a NSE value during the calibration period of 0.83 and validation period of 0.59, compared to the HBV model who received NSE values of 0.81 during calibration period and 0.56 during the validation period. Figure 31 shows a plot with the calibration period and validation period starting in January 2016 for both models. It is clear that the models perform quite similarly.

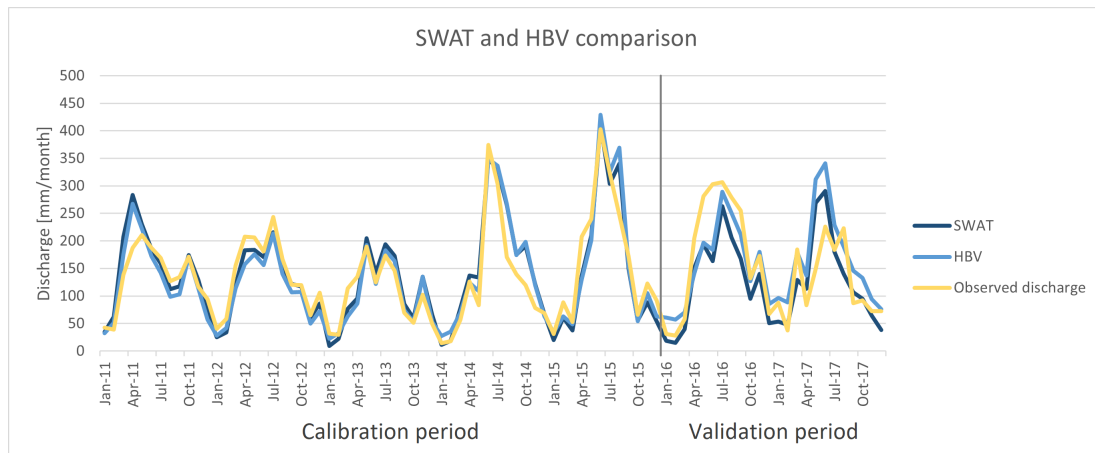


Figure 31: Comparison between the simulated discharge from the SWAT model and HBV together with the observed discharge data from the same time interval. The calibration and validation periods are separated with a line between December 2015 and January 2016.

5.2.2 Future runoff predictions

This section presents the results from the future runoff simulations. The figures for the different models (Figure 32 and Figure 33) show the future precipitation from the different scenarios SSP2-4.5 and SSP5-8.5 compared with the historical observed precipitation values for the years 2000-2020. The data from 2022-2099 is divided into four normal periods where the average precipitation during approximately 20 years is calculated for each month during the year. According to Figure 32, showing the precipitation from the EC-Earth3-CC (Europe) model, the wet seasons are getting wetter and the dry seasons are getting dryer, whereas the total volume of water does not seem to change much.

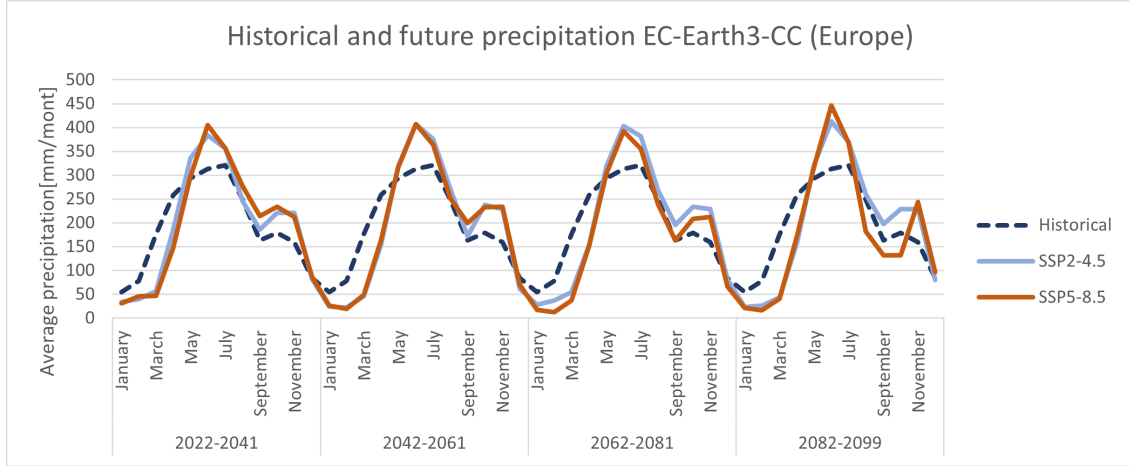


Figure 32: Future vs historical precipitation over 20 years. The historical precipitation is from the years 2000-2020.

Figure 33 shows the future predicted precipitation from the MIR-ESM2-0 model (Japan), with a quite similar trend as the EC-Earth3-CC (Europe) model seen in Figure 32. For the last period (2082-2099) it can be seen that the wet seasons are getting wetter, but the trend is less strong in the earlier time periods. For both the climate predictions EC-Earth3-CC and MRI-ESM2-0 the different scenarios SSP2-4.5 and SSP5-8.5 are very similar.

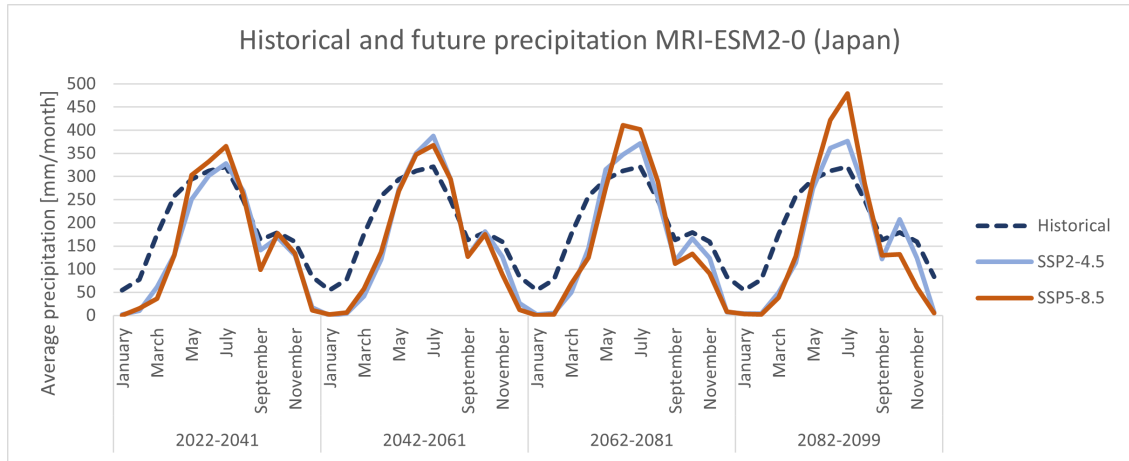


Figure 33: Future vs. historical precipitation divided into four normal periods. The historical precipitation is from the years 2000-2020.

Table 20: Precipitation statistics for the two climate scenarios SSP2-4.5 and SSP5-8.5 and the GCM's EC-Earth3-CC (Europe) and MRI-ESM2-0 (Japan). The Table shows the annual precipitation [mm/yr] in the rows called "SUM" and the monthly minimum and maximum values [mm/month] in the rows called "MIN" and "MAX" for the four different normal periods. Below are the historical values.

Years		EC-Earth3-CC SSP2-4.5	EC-Earth3-CC SSP5-8.5	MRI-ESM2-0 SSP2-4.5	MRI-ESM2-0 SSP5-8.5
2022-2041	SUM	2345	2352	1812	1866
-	MIN	34	31	2	0
-	MAX	383	405	328	366
2042-2061	SUM	2317	2329	1932	1885
-	MIN	22	19	0	3
-	MAX	407	407	387	368
2062-2081	SUM	2382	2157	1906	1918
-	MIN	28	12	2	0
-	MAX	403	392	372	411
2082-2099	SUM	2350	2166	1914	1977
-	MIN	23	16	4	2
-	MAX	413	446	377	479
2022-2099	Total SUM	9395	9004	7563	7645

		Historical values			
2000-2022	SUM	2326			
-	MIN	54			
-	MAX	321			

Table 20 shows precipitation statistics for both prediction models and the historical measured values for comparison. If the minimum values are compared it is clear that the dry seasons are getting dryer for every scenario and for all time periods. The wet

seasons are getting wetter for all time periods, scenarios and prediction models, but this trend is more clear for the EC-Earth3-CC model. Generally, the MRI-ESM2-0 model indicates less precipitation compared to the historical values, and to the EC-Earth3-CC model, which indicates no change in the annual amount of precipitation.

Figure 34 shows the predicted temperature for the SSP2-4.5 and SSP5-8.5 for the prediction models EC-Earth3-CC (Europe) and MRI-ESM2-0 (Japan) together with the historical values in the same graph. The historical values are the same temperature data from the year 2013 that was used to calculate the potential evaporation file. Here, the time series is repeated for the different time periods. Both prediction models indicate a large increase in temperature for both climate scenarios, out of which the MRI-ESM2-0 (Japan) prediction model indicates the largest increase.

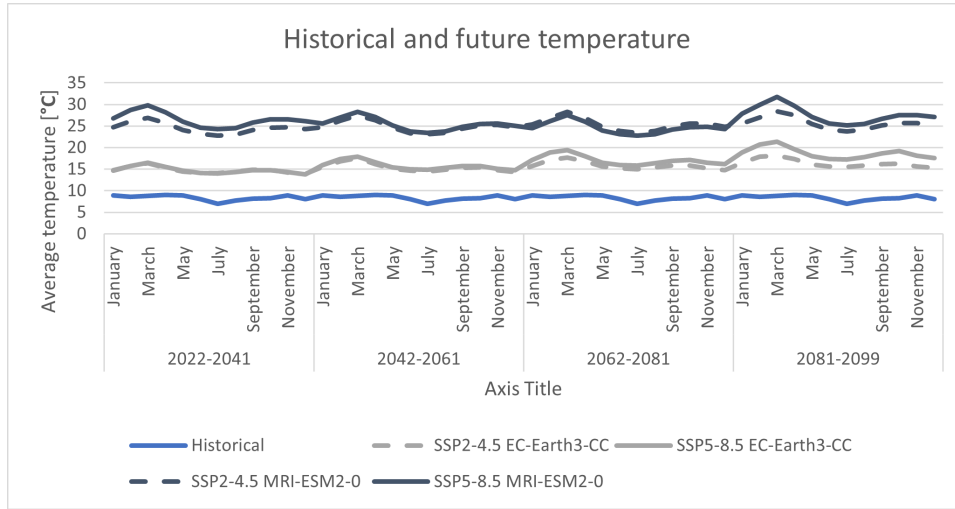


Figure 34: Future and historical mean temperature values over 20 years normal periods. The historical temperature is from the year 2013, which was used as calibration input data. The future temperatures are from the prediction models EC-Earth3-CC (Europe) and MRI-ESM2-0 (Japan).

Figure 35 and 36 show the historical and future discharge obtained from the HBV simulations for the different climate scenarios and prediction models compared with the measured values from the years 2000-2020, which then have been repeated for the different time periods. Figure 35 shows the graph for the EC-Earth3-CC (Europe) model. Like the precipitation pattern from the same time period, the discharge is lower for the dry periods and increases for the wet periods.

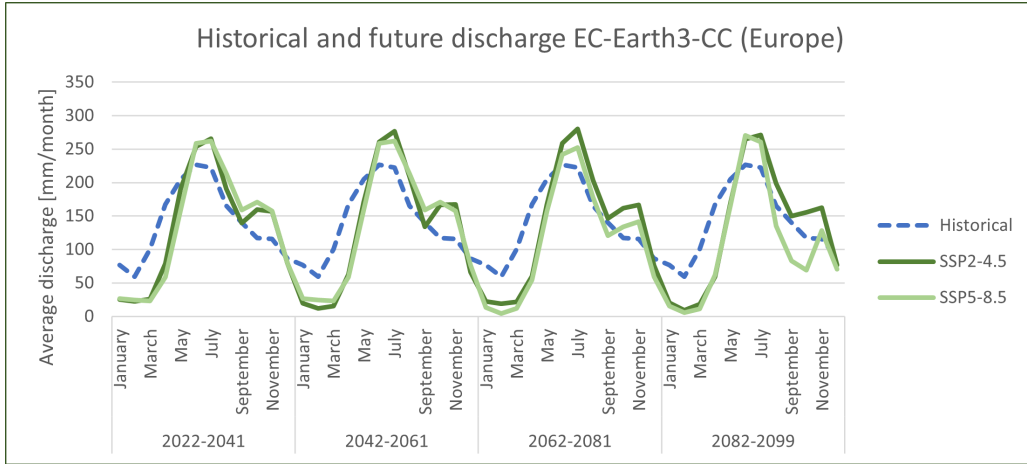


Figure 35: Future vs historical average discharge values over 20 years normal periods. The historical discharge is from the years 2000-2020.

Figure 36 shows the result from the MRI-ESM2-0 (Japan) model which also shows a similar pattern as the associated precipitation. There is generally less discharge compared to the measured historical values. This is a consequence of both less precipitation and higher evapotranspiration due to higher temperature.

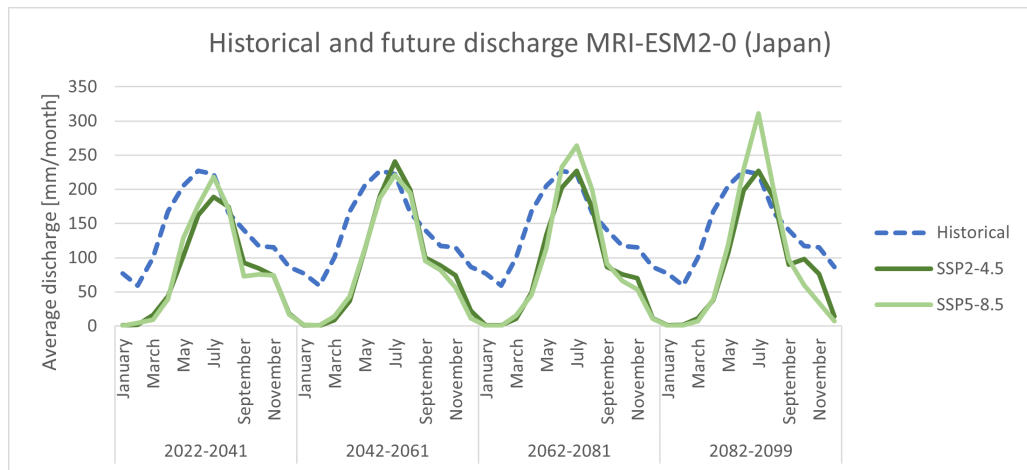


Figure 36: Future vs historical average discharge values over 20 years normal periods. The historical discharge is from the years 2000-2020.

Table 21: Discharge statistics for the two climate scenarios SSP2-4.5 and SSP5-8.5 and the GCM's EC-Earth3-CC (Europe) and MRI-ESM2-0 (Japan). The Table shows the annual precipitation [mm/yr] in the rows called "SUM" and the monthly minimum and maximum values [mm/month] in the rows called "MIN" and "MAX" for the four different normal periods. Below are the historical values.

Years		EC-Earth3-CC SSP2-4.5	EC-Earth3-CC SSP5-8.5	MRI-ESM2-0 SSP2-4.5	MRI-ESM2-0 SSP5-8.5
2022-2041	SUM	1588	1592	959	989
-	MIN	22	23	1	1
-	MAX	265	262	189	218
2042-2061	SUM	1561	1590	1075	1021
-	MIN	12	23	1	1
-	MAX	277	262	241	221
2062-2081	SUM	1582	1368	1040	1093
-	MIN	19	4	1	0
-	MAX	280	252	227	264
2082-2099	SUM	1555	1277	1050	1104
-	MIN	9	6	1	1
-	MAX	271	271	277	311
2022-2099	Total SUM	6286	5827	4124	4208

		Historical values			
2000-2022	SUM	1683			
-	MIN	59			
-	MAX	227			

Table 21 shows the monthly minimum and maximum discharge and an annual summation of the discharge values for the four different time periods, for the prediction models EC-Earth3-CC and MRI-ESM2-0 and the scenarios SSP2-4.5 and SSP5-8.5. It also shows the measured historical values for the years 2000-2022. For all scenarios, prediction models and time periods, the total simulated discharge is lower than the historical values. This is even more clear when comparing the historical values with the simulated discharge from the MRI-ESM2-0 prediction model where the simulated discharge is significantly lower than the historical. The result from the EC-Earth3-CC model shows an annual decrease in discharge between 90 and 400 mm depending on the scenario and time period. The highest decrease are from the SSP5-8.5 scenario for the last time period. The result from the different climate scenarios does not seem to differ within the prediction models - the values for MRI-ESM2-0 SSP2-4.5 and MRI-ESM2-0 SSP5-8.5 are quite similar, the same goes for EC-Earth3-CC with one exception. The total summation of EEC-Earth3-CC, SSP5-8.5 for the time period 2082-2099, is significantly lower than for SSP2-4.5 the same time period. This deviation can also be seen in Figure 35 where the simulated discharge suddenly decreases approximately around September only to increase again in November.

The flow duration curves shown in Figure 37 show a similar pattern - the simulated discharge is lower for both prediction models, a trend that is extra clear for the MRI-ESM2-0 model. The shape of the curves for the MRI-ESM2-0 model simulations are similar to the shape of the curve for the historical values, indicating that the discharge flows in a similar pattern. The EEC-Earth3-CC model on the other hand has a higher increase in moderately high flows (around 5 mm/day) and lower base and high flows.

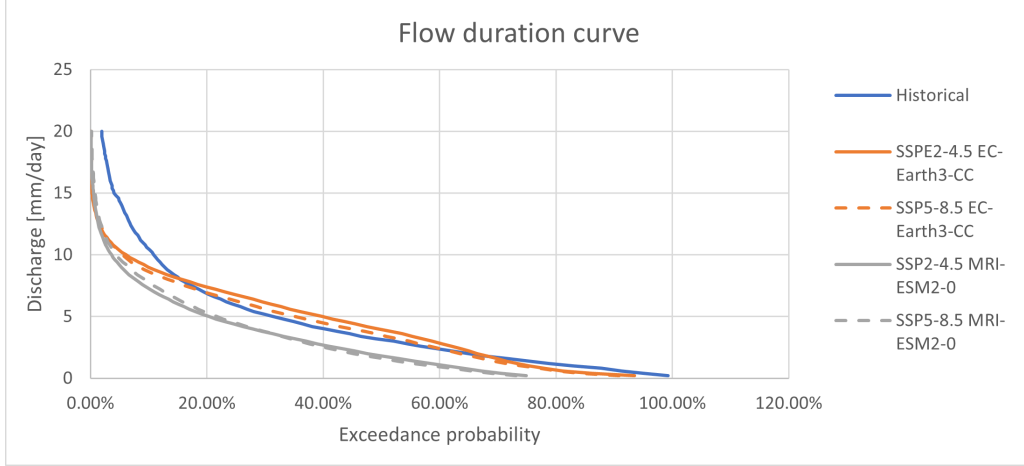


Figure 37: Flow duration curve shows the result from the discharge simulations.

5.3 Field visit

The horizontal precipitation measurement station measured the water volume during one week. The average volume measured 0.37 mm/d. Unfortunately, there is no active precipitation station close. For comparison, the historical average during the years 2000 to 2021 for station Chuza Campamento are 5.65 mm/d. According to these values, one would expect the horizontal precipitation to be up to 3.39 mm/d if it constituted 60 % of the total precipitation. The value received by the station is almost ten times lower, indicating that the station might be unreliable or that the horizontal precipitation didn't have such a big influence on the total precipitation in that particular area or during that particular week. Either way, the comparison is subject to a lot of errors, for example, the week when the station was measuring could have been a very dry week.

6 Discussion

6.1 Characterization

This part of the study aimed at characterizing the paramos of Colombia based on various hydroclimatic variables, and at exploring whether there were any significant trends over time for the variables that could be attributed at least partially to climate change or ENSO and that could affect water availability. Furthermore, the study aimed at investigating whether there were any signs of possible relationships between the variables. The results showed that in general, Cordillera Occidental and Cordillera Central received more precipitation than Cordillera Oriental. Moreover, some stations had a bimodal precipitation pattern whereas others had a unimodal precipitation pattern. There were no obvious trends over time for neither precipitation nor discharge, and the trends that were significant mostly indicated an increase in precipitation and discharge. The areas with most significant trends in precipitation were located in the northern and south-eastern part of Cordillera Central, whereas for discharge each Cordillera had a least one significant trend. For precipitation most of the trends that were significant represented a monthly scale rather than an annual scale. The Climact indices with most significant trends could indicate an increase in frequency, intensity or amount of precipitation. For the clusters with several discharge stations, the trend results were not consistent between stations with regards to significance and/or trend direction and magnitude. Moreover, there was no clear and unambiguous connection between the amount, patterns and trends in precipitation and discharge, although some similarities could be spotted. The other hydroclimatic variables (temperature, evapotranspiration, relative humidity, radiation, and wind speed) and all of the paramos of Colombia could not be analyzed on a national scale because of data scarcity.

This section will discuss the results from the spatial and temporal characterization of precipitation and discharge. Some uncertainties, data scarcity, limitations and suggestions for further research will also be discussed.

6.1.1 Precipitation

The results from the spatial analyses show that the quantity of annual precipitation for the Colombian paramos in general, and the areas in their vicinity, can range between around 500 and 5000 mm/yr according to this study (see Figure 23, Figure 24 and Table 11). This can be compared with the values 700 and 5000 mm/yr, between which the average total annual precipitation for the areas on the outskirts of the paramos is supposed to fluctuate according to the atlas (Morales Rivas et al. 2007). The upper limit is more or less the same, but the lower limit differs quite much. This disparity can either be due to an underestimation in this project's analyses because of missing data or due to the fact that many of the stations are not actually within the paramos. As mentioned briefly, underestimations can also arise if horizontal precipitation is not captured well enough. The disparity could also be due to that the precipitation values are taken from

different locations or time spans in this study compared with in the studies that the atlas is based on. Since it is not clear how the values in the atlas have been calculated, it is also a possibility that their lower limit is an overestimation or has some other source of error. However, it is probably more likely that the lower limit of 500 mm/yr is an underestimation, since paramos are known for having a high total annual precipitation. The results from this study are even further away from the ones in Correa et al. (2020) where the minimum precipitation was reported to be 798 mm/yr and the maximum precipitation was reported to be 4087 mm/yr. Here both the lower and upper limits differ, but the reasons behind this may be similar.

As for the quantity of precipitation for different paramo regions the results convey that, all in all, on an annual basis Cluster 1-4 experience more precipitation than Cluster 5-9, by rough calculations around 1100 mm/yr more (see Figure 23, Figure 24 and Table 11). This implies that there is more precipitation in the northern part of Cordillera Occidental and Cordillera Central (the western and central mountain ranges). The annual precipitation differed with up to around 2000 and 3500 mm/yr within and between different paramo regions, something that highlights the great variability in paramos. In the southern/central part of Cordillera Central seemingly more precipitation falls on the eastern side of the mountain range. This contradicts what is written in *Atlas de páramos de Colombia* (2007) about that the slopes facing the interandean plains are drier. These contradictory results might be explained by the fact that the southern/central part of the eastern slope of Cordillera Central faces, and is more exposed to, the Amazon rainforest which could have an influence on the precipitation in these areas. Cluster 5, with stations mostly spread out along the southern part of the western slope of Cordillera Central, and Cluster 6, with two stations on the central-northern eastern slope of the same mountain range, generally exhibit a medium precipitation compared with the other clusters. Cluster 7-9 that cover the northern and central part of Cordillera Oriental show a comparatively lower precipitation, although the stations within the biggest cluster, Cluster 7, have a large range of precipitation amounts. The lower amount of precipitation in Cordillera Oriental, is in line with the atlas that described that some areas on the western slope of Cordillera Oriental were the driest (Morales Rivas et al. 2007) and in the map with the stations (see Figure 7) it seems like most stations analyzed in this study are in fact on the western slope. The overall precipitation results also at least somewhat match the map of mean total annual precipitation for 1981-2010 in Colombia published by IDEAM (n.d.). One reason behind the differences between the clusters is likely the location of the different regions. Cordillera Occidental and Cordillera Central are probably more influenced by large-scale climate phenomena deriving from the Pacific Ocean and the Caribbean sea and the southern-central eastern slope of Cordillera Central also by the Amazon, whereas at least the western slope of the northern/central part of Cordillera Oriental is more protected from precipitation since it is more in the inland, further away from the coasts, and since much of the precipitation arising in Orinoquia and Amazonia probably falls on the eastern slope. It is possible that societies close to the paramo regions with less precipitation would suffer more from climate change.

For the same station the annual precipitation can vary considerably from year to year with up to around 1000 mm/yr (see Figure 23 and Figure 24). The interannual variability in total annual precipitation appears biggest for the regions that have the highest precipitation (see Figure 24). Especially Cluster 1, 6, 4 and 3 (northern Cordillera Occidental, northern-central Cordillera Central and the eastern slope of southern Cordillera Central) seem to have experienced some years with considerably higher precipitation, in some cases followed by quite dramatic decreases the subsequent years. Since some of the big peaks coincide with strong to very strong La Niña events, this is a plausible explanation for the drastic changes and big differences. Additionally, some of the dips in precipitation coincide with strong to very strong El Niño events. If ENSO is the explanation, the question is why other clusters do not seem as affected by these events. Nonetheless, this strong interannual variability could affect societies that rely on water from these paramos. Planning of for example agricultural activities could be a challenge since the water supply can become quite uneven and unreliable.

When it comes to the seasonality, the stations could roughly be divided into stations with a bimodal precipitation pattern, with wet seasons in April-May and October-November, and stations with a unimodal precipitation pattern, with a wet season in June-July (see Figure 25 and Table 10). This is something recognized by the atlas (Morales Rivas et al. 2007), too, although it does not give a clear general description of which paramos show which precipitation pattern. For this one needs to go into the details of each complejo. One of the reasons behind the differences in annual precipitation pattern seems to be the location of the stations, as the ones with a unimodal precipitation pattern are on, or at least closer to, the eastern slopes of the mountain ranges (specifically Cordillera Oriental and Cordillera Central), whereas the stations with a bimodal precipitation pattern are more on the western sides of the mountain ranges, and further away from Amazonia and Orinoquia (see Figure 27). The areas with a bimodal pattern might be located where the precipitation regimes are strongly influenced by the ITCZ movement throughout the year. On the other hand, the areas with a unimodal pattern might be more strongly influenced by the precipitation regime from the Amazonia and Orinoquia basins, which would make sense since the stations showing this pattern are generally located on the eastern part of Cordillera Oriental and Cordillera Central. According to Mejía et al. (1999), however, the ITCZ mainly gives two wet seasons in the central part of the country and this would not explain why there are some stations in Cordillera Central with a unimodal precipitation pattern and quite many with a bimodal precipitation in the western and southern extents of the country. Depending on how general this description from Mejía et al. is and on how they define the "central" part of country, it is possible that many stations could still be included in this area (see Figure 7). However, if the hypothesis that the paramos with a bimodal precipitation pattern are more influenced by the ITCZ and the ones with a unimodal precipitation pattern are more influenced by Amazonia and Orinoquia it is unclear how it can be that some stations with the opposite (bimodal/unimodal) precipitation patterns are sometimes in seemingly close proximity to each other (see Figure 27). This could indicate that very local processes could have an important role in the seasonality. For some stations, however, it was rather difficult

to say that they had a clearly bimodal or unimodal precipitation pattern. Some showed something somewhat inbetween or almost like a combination of both. Societies in areas with a bimodal precipitation pattern might not experience as much water stress during dry periods as the ones in areas with a unimodal precipitation pattern, since the time between the wet seasons is shorter. The precipitation seasonality could therefore be of importance in case climate change results in less precipitation and discharge in any of these areas.

The results from the temporal analyses show some trends in the precipitation between 1987 and 2012, however not consistent for all clusters and not significant in most cases (see Table 12). The inconsistency in the results might further prove how differently the precipitation can behave in different regions. The majority of the significant trends are increasing, indicating that the amount, frequency or intensity of precipitation is increasing. There are also more representative stations manifesting significantly increasing precipitation trends on a monthly scale than on an annual scale, which could indicate that climate change causes a change in precipitation that can only be seen on a monthly, or maybe seasonal scale, not on an annual scale. At the same time four representative stations (for Cluster 2, 4, 6 and 7) manifest a statistically significant increase in the total annual precipitation divided by the number of wet days (when total $P \geq 1.0$ mm), meaning either the total annual precipitation has increased or the number of wet days has decreased, or both. This cannot be seen by looking at the other related indices. Therefore it would have been interesting to complement the Climpack indices with the trends in total annual precipitation and number of wet days, separately.

The representative stations with most significant trends in precipitation belong to Cluster 4, 6 and 3 (northern and southern Cordillera Central, mostly the eastern slope). For the stations in Cluster 4 and 6 (northern Cordillera Central) all the significant trends imply a wetter climate, whereas for the station in Cluster 3 (southern Cordillera Central) three of the indices imply a change for a wetter climate, four indices indicate a change to a drier climate and one index shows no change over time. All in all, the significant precipitation trends were predominantly increasing. This has also been seen in other studies (Hofstede et al. 2014, Pabón Caicedo 2012). The results, however, at least partially contradict the ones from Ruiz et al. (2011), who reported an overall change nationally with increases in total precipitation in Cordillera Occidental, decreases in Cordillera Oriental, and no change, however more extreme events, in one of the paramos in Cordillera Central (Ruiz et al. 2008). This study rather shows stable precipitation or increases in Cordillera Occidental and Cordillera Oriental, however mostly not significant trends, and that Cordillera Central manifests most significant changes, mainly significantly increasing trends. Nonetheless, as most significant results concern Cordillera Central it makes sense to compare the results with some results for part of Cordillera Central from Ruiz, Martinson, and Vergara (2012) where the total annual precipitation was found to decrease significantly by -7 to -11 % per decade. Although this project also covered more than one decade, two and a half decades to be specific, it still did not get any such results, except for partially for Cluster 3, perhaps. The decrease reported by Ruiz, Martinson, and Vergara, however, was only seen for stations above a certain elevation on

the western slope of Cordillera Central, whereas the stations at lower elevations showed an increasing trend. Therefore, results might differ depending on slope and elevation in this study as well. This is something that could be worth investigating more.

The indices with most (five out of the nine or roughly 56 %) representative stations showing a significant trend are the indices for monthly number of days when precipitation ≥ 10 mm ($r10mm, m$) and the maximum monthly 7-day precipitation total ($rx7day, m$), both of which increased significantly over the time period, except for two cases with a significantly stable $r10mm, m$. This means that the precipitation intensity could have increased.

Important to note is that climate change is not expected to necessarily cause either a decrease or an increase in precipitation in all cases. Cresso (2020) rather denominates effects of climate change on precipitation as changes in precipitation patterns and they found that wet seasons are getting wetter and dry seasons are getting drier. Other studies also mention that the seasons are expected to get more extreme and less predictable. Hofstede et al. (2014) and Castaño-Urbe (2002) have obtained results pointing this way, since they reported decreases of 5-10 mm in monthly precipitation. It would be interesting to look into not only the annual trends, but also the seasonal and monthly trends, particularly since most of the significant trends in this study were significant on a monthly scale. Unfortunately, Climpack does not allow the user to define and specify their own seasons and in the result files the slope for the indices are given on a general monthly scale, seemingly lumping together the results for all the individual months, as well as for the seasons December-February, March-May, June-August and September-November. However, no p value specifying if the trend is significant or not is given for the indices on these monthly and seasonal scales, at least not for most of the indices, which makes them rather insipid. Whether the rather few significant trends that are seen are due to climate change or not therefore remains unclear.

6.1.2 Discharge

When it comes to the discharge quantity the annual mean daily discharge ranged between 0 and 25-30 m³/s (see Figure 28) and the total annual specific discharge ranged between 0 and 2500 mm/yr (see Figure 29). From a spatial perspective, the discharge can only be fairly compared using specific discharge. The clusters with the highest specific discharge, that is, Cluster 1, 4 and possibly 5, are located in the northern parts of Cordillera Occidental and Cordillera Central and on the western slope of the central part of Cordillera Central. The clusters with the lowest specific discharge were Cluster 2, 3 and possibly 7, located in the central part and on the southeastern slope of Cordillera Central, as well as on the central western slope of Cordillera Oriental. However, three clusters were missing from this spatial analysis because no catchment area sizes could be obtained for the calculation of specific discharge, making this analysis incomplete.

Regarding the temporal perspective, most stations showed a rather constant annual mean daily discharge or regular fluctuations, but some stations seemed to have an in-

creasing discharge and a few a possibly slightly decreasing discharge (see Figure 28). The only significant trends, however, were increasing, and only 25 % of the stations exhibited this significant trend (see Table 13). Several of the stations manifested a radical increase in discharge in the last years of the time period, which possibly could be connected to La Niña. Nonetheless, annual mean daily discharge could be a misleading measurement to use if the value is strongly affected by measurements from a few extreme events. If instead looking at total annual specific discharge, however, the results are very similar (see Figure 29 and Table 14), although this calculation is also subject to uncertainties. As with precipitation, it could be interesting to look into the discharge behaviour during different months and seasons as well, to investigate whether there are any critical trends on these time scales.

6.1.3 Comparison of precipitation and discharge

The results indicate that it is not necessarily the clusters with the most precipitation that have the highest specific discharge or vice versa. Admittedly, some of the clusters showing the highest precipitation also show the highest specific discharge and some of the clusters with the least precipitation show the lowest specific discharge, but this connection is not true for all clusters (see Figure 24 and Figure 29). Moreover, the specific discharge could not be calculated for three of the nine clusters. Therefore, the comparison of the amount of total annual precipitation and total annual specific discharge becomes somewhat misleading and uncertain, making any connection between precipitation and discharge more difficult to decipher. Therefore, it is not possible to claim that the same clusters that have the most precipitation also have the biggest specific discharge yield and vice versa. However, based on the clusters that could be compared, this claim does not seem to be entirely true.

The precipitation and discharge patterns coincide for some stations belonging to the same cluster, but not all. For example, the increase in discharge together with a concurrently seemingly quite stable precipitation for Cluster 1 and Cluster 4 could be discussed. If there are glaciers in the catchment area where the discharge data has been gathered for these clusters, it is possible that the significantly increasing discharge is caused by a faster and more expansive melting of the glaciers, rather than by an increase in the frequency, intensity or amount of precipitation. However, this depends on how big of a contribution glacier melt has on the discharge in the area. There is also a risk of data errors causing this rather big increase in discharge. The risk for data errors is especially big since no data quality screening of the discharge stations was conducted due to an already low number of stations fulfilling the inclusion criterion. However, these possible causes might not be enough to explain the trend completely. If there are other discharge stations close to the precipitation stations it would be valuable to investigate whether they show a similar trend, even though they would cover another time period or a shorter time span.

A water balance calculation for each cluster would be of interest, but since no control of whether the precipitation stations in a cluster were in the same catchment as the

discharge stations that were used to represent their cluster, no water balance could be approximated. Furthermore, considering that the BaRatin method indicated that there were large uncertainties in the discharge values, especially for high flows, for the small paramo catchment used in the modeling part (see Section 4.2.3.3), and the fact that no discharge gauge information was gathered for the discharge stations used in the characterization part, calculating the water balance would entail too high uncertainties which are not possible to account for in this project.

For precipitation, Cluster 3, 4 and 6 exhibit most significant trends (see Table 12). For discharge, Cluster 1/4, 3/5 and 7/9 have one station each with a significant trend (see Table 13 and Table 14). For all discharge stations the significant trends are increasing, and for the representative precipitation stations in Cluster 1, 2, 4, 5, 6 and 7 all the indices with significant trends are also increasing, except for a few indices with a significantly stable trend. However, for the representative precipitation station in Cluster 3, the significant trends for some of the indices indicate changes towards drier conditions. Here the relationship between precipitation and discharge is not clear and implies that the discharge is likely strongly affected by other factors than precipitation, or that the stations are not in the same catchment area, as previously discussed.

The Colombian Andes could both experience reductions (Diazgranados et al. 2021), increases or insignificant changes in water availability (Hofstede et al. 2014) and this rather general analysis on discharge points more towards the two latter options. The results could, however, be different if one would look at a monthly or seasonal scale and do an overall more detailed and comprehensive study. It is possible that the water availability issues that climate change could cause is more a question about timing than about amount. Additionally, not only decreasing water availability could have a negative impact on societies, but also increases, since it can cause for example flooding and land slides.

6.1.4 Uncertainties

One of the main aims of this study was to characterize the paramos of Colombia. Notwithstanding, not all of the stations included in the analyses are located within the paramos, and even though they are within 25 km of the paramos, those stations might not be entirely representative for these ecosystems since the landscape and the climate can change quite drastically even over small distances. All the main paramos of Colombia could not be covered either, since some of them either lacked measuring stations or did not have time series of data that fulfilled the criterion of minimum time period and maximum amount of missing data. For precipitation, these paramo regions that could not be covered included Sierra Nevada de Santa Marta, the southern and eastern part of Cordillera Oriental, the central and northern part of Cordillera Central and several of the small paramo areas belonging to Cordillera Occidental (see Figure 7).

Moreover, using representative stations for the analysis of trends in precipitation (that is, only analyzing the trend over time for one station per cluster) might not, in fact, be very representative for a cluster, especially not if the variability between stations in a cluster is big and the distances between the stations are large, as has been proven to be the case for some clusters. For example, as mentioned previously, Ruiz, Martinson, and Vergara (2012) noticed a discrepancy between stations at different elevations, and perhaps also between different slopes. If the amount of precipitation varies a lot between stations in the same cluster, descriptive statistics like cluster mean might be misleading.

Regarding the grouping of the precipitation stations with the help of Clustering Analysis, it became evident through the plots that this was more or less successful. It was expected that there would be a heterogeneity in the amount and pattern of precipitation within a cluster because of different factors such as location and elevation, but at the same time the clustering built on the idea and hope that some similarities would be present and enable an easier visualization and a more general characterization. Some stations within the same cluster also did, in fact, have common traits, such as the stations in Cluster 4 that had surprisingly similar precipitation patterns, although the annual amount of precipitation differed considerably between them (seen in Figure 24). Within some clusters the precipitation quantities were quite similar between different stations, in others the multiannual precipitation patterns were similar, in some both were true, and within some clusters there was a rather big diversity in precipitation amount and/or pattern. The seasonality was what made the grouping most questionable. Seasonality was not an aspect included in the Clustering Analysis, but in hindsight this might have been a good idea. Especially for Cluster 7-9 there was a clear disparity among the stations, where some stations had a bimodal precipitation pattern with wet seasons in April-May and October-November, whereas others had a unimodal pattern with a wet season in June-July (see Figure 25). This distinction might be important in an attempt to characterize the paramos and hence a recommendation for future studies could be to include information about seasonality during the grouping of the stations. Another thing that could possibly improve the grouping would be to separate stations based on elevation and on which slope of the mountain range they are on. This could be a good idea since it appears that paramos at different elevations and on different sides of the same mountain range can experience different precipitation amounts, patterns and trends (Morales Rivas et al. 2007). Additionally, it might not be optimal comparing clusters with a very different numbers of stations. An area with many stations is probably more likely to give a more reliable picture of the overall region, but at the same time giving a bigger range of values and making generalizations more challenging. The usefulness of the results and how much they convey about a region depends on how many stations there are, where they are located and how dispersed or dense they are.

Furthermore, with observed data inherent uncertainties come along. Getting good and reliable precipitation measurements is challenging, and even more so in paramo areas. Precipitation may be measured in different ways and with different devices at different locations. The measuring instruments might not capture all of the precipitation (for example horizontal precipitation) and the devices have their specific uncertainty to take

into account. Moreover, different methods for calculating the precipitation can lead to more or less reliable and accurate results (Padrón et al. 2015, Muñoz, Céleri, and Feyen 2016). Nature can also affect the measurements by for example blocking the entrance of precipitation into the device or by even overturning it, causing an underestimation or an interruption in the time series of data. Similar problems can be present for discharge measurements. For discharge, uncertainties also come along if the discharge is calculated using water levels or water velocities.

Another uncertainty lies in the calculation of total annual, seasonal and monthly precipitation for the boxplots and time series plots and in the calculation of the cumulative precipitation for the Double Mass Curve (DMC) plots. In all calculations the missing data was ignored since it was regarded too difficult and time consuming to try to fill in the data gaps. In the case of the total precipitation for different time spans, summing the daily precipitation was considered a better approach than calculating an average daily precipitation for the period of interest and then multiplying it by the number of days in said period, since the amount of precipitation can differ strongly from day to day. Summing still brings an uncertainty to the results since the risk of an underestimation is rather overhanging and since different stations have different proportions of missing data and can have missing data in different seasons. The inclusion criteria demanding at least 80 % data in a year and at least 75 % data in a month were meant to lower the risk of this kind of uncertainty, but for example a station with 20 % missing data compared with a station with 1 % missing data will still result in an unfair comparison, especially if the missing data for the first station is part of a wet season, whereas the missing data for the second station is during a dry season. In the case of cumulative sums, the problems are the same, but possibly even more evident. Missing data is also a problem when calculating annual mean daily discharge and total annual specific discharge.

The relationship between precipitation and discharge is complex, since precipitation cannot be directly translated into discharge. Hence, comparing the time series plots for precipitation and discharge does not necessarily say that much. Moreover, if an increased evapotranspiration cancels the increase in precipitation (Buytaert and De Bièvre 2012) it is possible that the increase in precipitation would not be reflected in the discharge behaviour. Worth mentioning is also that discharge is one of the hydroclimatic variables that is also affected by land use, making a cause-effect relationship between climate change and discharge perhaps even more difficult, since factors on land can have a strong influence on the discharge as well.

In the comparison between precipitation and discharge, a big uncertainty lies in the fact that the chosen discharge stations are very far away from many of the precipitation stations that belong to the clusters that they are supposed to represent (see Figure 14). As the connection between the precipitation stations and the discharge stations has not been confirmed, it could be that they do not belong to the same catchment area, which means that if they do not, the precipitation does not influence the discharge. Moreover, if the distance between the precipitation stations and the discharge stations is big a lot affecting the discharge could happen along the way from the precipitation station to the

discharge station, making it more difficult to find a relationship. For example, other local climates along the way could cause either losses or contributions of water, and there could be withdrawals or additions of water from human activities, like agriculture, on the way.

6.1.5 Data scarcity

The ambition to characterize the paramos and investigate trends on a national scale with much more recent data than in the atlas for all the variables precipitation, discharge, temperature, evapo(transpi)ration, relative humidity, wind speed, and radiation, proved unrealistic due to data scarcity and the time consumption it would entail to look at so many variables. The fact that, despite it being 2022, only time series up until 2011/2012 could be accepted for there to be as many stations with as little missing data as possible left, further proves the importance of installing more measuring stations in the paramos. The total area of the paramos plus the additional area included by accepting measuring stations at a distance within 25 km of the paramos is unknown. However, if this were to be calculated, one could get a rough estimation of the station density in mountainous areas in Colombia. This could in turn be compared with the station density in mountainous areas in other countries in other parts of the world, for example Sweden, to see how Colombia is doing in comparison and how extensive their monitoring network is in relation to other countries. It could also be compared with the World Meteorological Organization's recommended minimum densities of stations in the mountains, which they have specified for some types of stations, for example precipitation and discharge stations (WMO 2008). An option to overcome the problem with data scarcity would be to instead use reanalysis or remote sensing data to get more complete and comprehensive data to work with. Using remote sensing is something that was also advised by Altamiranda-Saavedra et al. (2020), who also identified limits in the data provided by IDEAM. Of course, using reanalysis and remote sensing data brings along its own uncertainties, and reanalysis still relies on observed data, too.

6.1.6 Limitations and further research

The data included in the project only extends between 1986/1987-2011/2012. Therefore, research on more recent data, if found, would be valuable, although this study found that data after 2012 was lacking with respect to missing data. One could, of course, apply less strict inclusion criterion, but this could affect the quality of the study. Another possibility would be to only include the stations with the longest time series, but this would instead decrease the spatial scope of the study. Moreover, future studies could include more variables, as was the initial plan for this project. In further research a more detailed Clustering Analysis, taking into account seasonality for different measuring stations, could also be carried out. Additionally, information about at what elevation and on which slope of the mountain ranges the measuring stations are located could be included in the study, either in the Clustering Analysis as well, or just as more background information to take into consideration when analyzing the results.

Furthermore, even though there were few signs of trends indicating less precipitation or discharge over time, it could be valuable to investigate whether there are any such trends when only looking at certain seasons or months over time. This could show if some parts of the year are getting wetter, whereas others are getting drier. The trend analysis could also be carried out for all stations, instead of only for a few representative stations, since this would give a more comprehensive picture making it easier to draw conclusions about general trends for different areas. Moreover, if climate change does affect ENSO, this is also a field for further research, since this study shows tendencies of ENSO events having a considerable influence on both precipitation and discharge in mountainous areas.

Moreover, more research to improve the reliability and accuracy of models, reanalysis data and remote sensing data in paramo areas would be valuable to facilitate characterizations of big areas. Because of the great variability within paramos it would still be important to incorporate or take into account observational data. Therefore, there needs to be a concurrent effort to improve the reliability and accuracy of observations.

6.2 Modeling

This part of the study aimed at investigating if the HBV model could be a sufficient model to simulate the hydrology in a small paramo catchment in the Colombian Andes. The model was compared with the SWAT model, which previously succeeded in modeling the hydrology in this catchment. The results showed that HBV was sufficient for the task and able to perform almost as well as the SWAT model. Furthermore, the HBV model was used for predicting possible changes in discharge due to climate change. The results from the future discharge simulations indicate a change towards drier dry seasons and wetter wet seasons, but on an annual scale, no change in total precipitation was seen. As for discharge, there is a decline in annual discharge by 90 to 410 mm/yr depending on scenario and time period (values from the EC-Earth3-C model). This decline has not been tested for significance, and the reliability of these figures will be discussed further in Section 6.2.3.

This section will discuss the result from the comparison analysis and the future discharge simulations. Some uncertainties will also be discussed.

6.2.1 Model comparison

During the model calibration, the HBV model provided satisfactory results receiving a NSE value of 0.81 for the calibration period. The NSE value for the validation period was lower, 0.56. However, a model is considered to have a satisfactory performance if the NSE is 0.5 or higher, according to Christiansen (2012) and Morasi et al. (2007). This indicates that the model succeeded in replicating the discharge, however only on a monthly basis, since only monthly values were used in this part of the study.

The result from the sensitivity analysis shows that the model is most sensitive towards changes in precipitation and discharge, and insensitive towards changes in potential

evaporation. The original structure of the HBV model with two groundwater boxes is also sufficient, since the same NSE value and difference in simulated and observed discharge was achieved regardless of whether two or three groundwater boxes were used. However, the result got worse when simplifying the structure to only one groundwater box. The investigation made by Lelieveld (2020) using the HBV model in the high Andes of Ecuador also found that the standard model structure achieved the highest model efficiency. Lelieveld (2020) also found that the model was most sensitive towards changes in precipitation and discharge data and less sensitive towards changes in potential evaporation. The study made by Lelieveld (2020) might not be the best to compare with though, since it was performed in Ecuador, and local differences influences a lot which model structure that is the most suitable.

The result from the model comparison shows that for the Monterredondo watershed, the models HBV light and SWAT perform quite similarly. This is somewhat unexpected since the SWAT model has more input data and is a more complex model, which could imply that it would represent the watershed more correctly. It rather seems like the additional information provided in the SWAT model is unnecessary for describing the hydrology in Monterredondo. It is by analyzing Figure 31 that one can see that it looks like the models are performing similarly, the curves for both models follow each other. However, the curve for observed data sometimes deviates. This indicates that the errors are within the input data and not within the models, (or that the models exhibit the same errors). There are a few occasions where the SWAT model performs better than the HBV model, for example during the validation period, in January to February 2016 and in June to July 2017. Lelieveld (2020) found that the HBV model had a slight tendency to underestimate high flows and overestimate low flows, which seems to be the case for the deviations in these cases as well. This is also coherent with the results from Temesgen Ayalew (2019) who compared HBV light and the SWAT model in three different basins in Ethiopia. They found that while the HBV tends to overestimate the low flows, the SWAT model underestimates the low flows and overestimates the high flows. It is possible that the SWAT model's ability to divide the catchment into subbasins and further into HRUs - compared to the HBV model's method of just treating the catchment as a whole - makes the model better at giving accurate responses to rain events. However, the HBV model is representing the hydrology of the Monterredondo catchment surprisingly well. This could imply that parsimonious models like HBV is enough for modeling the hydrology in small paramo watersheds in the high Andes. This could hopefully make modeling of these remote ecosystems easier and improve the hydrological knowledge and aid in decision making. One suggestion could be to use the HBV model when discharge, temperature and precipitation data are available, but other data types, such as soil characteristics, elevation and land use, are missing. If the data for discharge, precipitation and temperature are reliable, then the HBV would produce a reliable result. SWAT on the other hand requires data on more variables but produces a result with a slighter better NSE value, indicating that the model is more reliable. The SWAT model could therefore be used if there data on more variables available and the aim is to get as good of a model representation as possible.

6.2.2 Future climate predictions

The calibration of the HBV model for the future climate predictions also produced acceptable NSE results, with a NSE value for the calibration period of 0.56 and a NSE value for the validation period of 0.61. For this part of the project, the result improved when scaling the precipitation according to elevation compared to using the original unmodified precipitation series as precipitation input. However, it is not possible to say if this generally is a better method than the Thiessen polygon method. It depends on the data quality and the spatial distribution of the data.

The data from the EC-Earth3-CC (Europe) model shows an increase in temperature and a shift in precipitation with wetter wet seasons and drier dry seasons. There is not a big difference between the different scenarios SSP2-4.5 and SSP5-8.5. The result from the simulations shows that the discharge follows the same trend as precipitation, which is an expected output result from the model, since the discharge is a direct response of precipitation.

The result from the MRI-ESM2-0 (Japan) model shows a much higher increase in temperature and less precipitation in general than the EC-Earth3-CC (Europe) model does. The simulated discharge again shows the same trend as the precipitation with generally less discharge due to both less precipitation and higher evapotranspiration. Worth mentioning is that the minimum discharge for the MRI-ESM2-0 model shows values that are zero or close to zero which indicates that the river might dry up.

The projected temperature from the MRI-ESM2-0 model is unrealistically high compared to the historical values. This is probably because the data from the MRI-ESM2-0 model is taken from a location quite far away from the Monterredondo catchment, see Figure 20. This was one of the closest locations to the Monterredondo catchment that it was possible to find data from for the MRI-ESM2-0 model, at least from the website used. Since that location is at a much lower elevation, the data in itself is probably correct for that specific location (one would expect the temperature to be higher at lower elevations), although there is a risk that the data is not representative for the Monterredondo catchment. The temperature directly influences the potential evaporation which, if the temperature is too high also will be too high. A too high potential evaporation could lead to a decreased discharge. Luckily, according the results from the sensitivity analysis, the potential evaporation has a limited influence on the result. The reliability of the precipitation data is more important for the simulated discharge outcome.

Villavicencio is the name of a town not far from the place that the MRI-ESM2-0 model data is projected for. The climate in Villavicencio is tropical and the annual rainfall is 1120 mm, which is less than half of the annual precipitation measured in Monterredondo. The average temperature is around 25 °C with a low intraannual variation (Climate Data n.d.). Since the climate at this location is so different from the climate in Monterredondo it seems likely that the prediction data from this site is irrelevant, even if the model and precipitation and temperature data itself are correct. This would imply that the discharge modelled using the MRI-ESM2-0 model is not correct and should be

rejected.

If one still wished to use the data from the MRI-ESM2-0 model it is possible to scale both precipitation and temperature according to elevation and get more representative data. This was however not performed in this study, but could be made in future investigations, if desired.

The result from the EC-Earth3-CC (Europe) model is more relevant since the data at least is from within the paramo region. The temperature is still high compared to the historical values, but one important thing to remember is that the historical temperature data is only from one year, namely 2013, and the average yearly temperature is around 11 °C in Chingaza according to Cárdenas (2016). The result shows less precipitation during the dry season and more during the wet season, but annually no change in total volume. The discharge follows the same trend as the precipitation with less discharge during the dry season and more during the wet season, however, the total annual discharge is lower. There are results indicating that the river might dry up, with discharge values as low as 4 mm/month. This would have a severe impact on the ecosystem, since a lot of different organisms are dependent on the continuous water supply. For the water supply to the cities nearby, some consequences could be limited by building water reservoirs for collecting water during the wet seasons and storing it so that it could be distributed during the dry season. How large and severe the negative consequences of drier dry seasons would be has to be investigated further.

Urrutia and Vuille (2009) studied two climate change projections for the tropical Andes in Colombia using a regional climate model. Their projections indicated that there would be significant warming towards the end of the 21st century. In their highest emission scenario, the average annual surface temperature would increase by 4 to 5 °C. This is a lower change than the increase shown by EC-Earth3-CC (Europe) compared to the historical values, but consistent if compared to the literature value of a yearly average of 11 °C. They also predicted that the precipitation in the area would decrease by 400 to 1200 mm/yr for their highest emission scenario. The decrease in precipitation between the historical and SSP5-8.5 emission scenario for the last time period (period 2081-2099) in this study was approximately 160 mm/yr, which is a much lower decrease. However, they did also point out that the precipitation patterns were irregular with a lot of local differences.

One can still question the accuracy of the result, it depends on if EC-Earth3-CC (Europe) is a sufficient GCM for this watershed, or if the HBV has managed to simulate the discharge correctly. Even if the NSE was sufficient for the calibration and validation for this part, the NSE is not the only way of verifying a model's accuracy. The results from this paper are however in alignment with Cárdenas (2016) who studied the effect of climate change in three different paramo regions, CNP included. Their results showed prolonged and intensified seasonality in the Andean regions. The result is also in alignment with Cresso (2020) who predicted drier dry seasons and wetter wet seasons in two catchments in CNP. However, Cresso (2020) also found an increase in yearly precipitation, which is in contrast to the result from Vogel (2021). Vogel's (2021) results showed

that the precipitation and discharge would be significantly lower for both the dry and the wet season in the Monterredondo catchment.

Another study modeling Peruvian paramo ecosystems' hydrological response to climate change was conducted by Flores-López et al. (2016). Their result showed a decrease in water production due to changes in temperature and precipitation. However, they found that the anticipated land use changes in the area would be the primary driver behind the hydrological responses in the paramo.

To summarize, there is a big range of prediction results from climate change in the paramos, indicating the difficulties of simulating the effect of climate change in these regions. One aspect that speaks for this study is that it is a very local pilot study where it is clear where the prediction data comes from. Since there are many different microclimates in the Andes, the local data would be preferable when assessing how a certain catchment would be affected.

6.2.3 Data uncertainties and model evaluation

The result from the water balance analysis shows that there is a water balancing issue for the input data, since the water storage is increasing for every year. Reasons for this might be that the discharge station in Rio Chuza is underestimating the discharge, that the precipitation stations that were used are overestimating the precipitation, or that the potential evaporation is underestimated. The sensitivity analysis shows that the result is not very sensitive towards changes in potential evaporation, which is why this was not considered to be the issue. Furthermore, it is quite unusual that the measurements of precipitation are overestimated at these elevations, if anything, the precipitation is often underestimated due to the horizontal precipitation losses, therefore, the uncertainty analysis was focused on discharge. The question that remains is then: if the uncertainties of the discharge measurements are taken into account, does this explain the insufficient amount of discharge? To investigate this, the uncertainties in the discharge values were examined.

There are also some concerns regarding the water level measurements in River Chuza. A limnigraph should preferably be installed at a site where the cross-section is of a geometry that makes it easy to derive a relationship between the stage and the discharge. The cross section was measured 2022-02-10 and can be found in Appendix A.5, where it can be seen that it is not an easy geometry, for example not a square or triangle. It is also of interest to have a cross-section that does not change over time, for example due to vegetation, stones or loss of the bank sides by erosion. In some cases, a constructed weir with a well-known geometry - for example a triangular or rectangular one - is the most suitable, limiting the errors when converting the stage into discharge. At Rio Chuza no construction like that is installed, instead, a quite unsuitable site has been chosen, see Figure 3 in Section 2.2.1. A weir is not always feasible to install, but a more suitable site could probably be found. The water stream is shallow with large stones on the bottom that influence the level and flow rate, contributing to measurement uncertainties.

The limnigraph itself is placed on a foundation which, when becoming overflowed, will make the station underestimate the discharge. The stones on the bottom and/or the foundation could be causes of backwater flow, making the measurements of the water level uncertain. In addition, the cross-sectional area can easily be changed, for example due to bank erosion, vegetation or stones moving.

The large errors received with the BaRatin method were taken into account and the biggest possible error was added to the discharge (result in Table 17 in Section 5.2.1.1). The new water balance that was obtained behaved more like expected. However, there are a lot of uncertainties in this method. For example, the highest absolute uncertainty of 83 % was chosen, which is unlikely to be true for all the high flows (it is indeed a huge generalization). However, the result shows that the transformation of water levels into discharge are associated with large uncertainties in River Chuza, since completely different water balances can be obtained within the uncertainty span.

To summarize, the discharge series that is used for calibrating the HBV model in this thesis consists of two types of errors: First, the errors in the continuous water level measurements with the limnigraph that is placed at a quite unsuitable site. Second, the errors that are associated with converting these water level measurements into discharge, illustrated with the BaRatin method. Together this is believed to be enough to explain why the water balance does not close.

There is of course a possibility that there are some issues with the precipitation or temperature data as well. It would for example have been more desirable if the stations that existed within the area had less data gaps so that they could have been included, or if the spatial availability of data was improved. Lelieveld (2020), in line with Sucozhañay and Céleri (2018), also obtained a result that suggested that an increase in spatial distribution and density of rain gauges resulted in a more accurately modelled discharge. This was a more important factor than for example increasing the length of the time series used as input. A study made by Buytaert et al.(2006) investigated the spatial and temporal rainfall variability in paramo regions in Ecuador. They found that even if rain gauges within 400 meters of each other were correlated, the spatial variability was very high. Thiessen interpolation gave good results, but the results using Kriging interpolation were even better.

For this study, a small spatial rainfall analysis was conducted to investigate if there was a relationship between elevation and precipitation. The analysis found that there was a difference in precipitation between the different stations that, and for some of the months this difference could be correlated with the change in elevation. The Double Mass Curves showed that none of the stations included in the analysis were behaving unexpectedly, all stations followed the same pattern of dry and wet seasons and no curve had any abrupt change during the time period of the analysis. It is clear that some stations received more water than others. One explanation could be local micro climates and another, the elevation differences. No analysis was made to evaluate the measurement uncertainties for the rain gauges and it is unclear if the Chuza campamento station was able to represent the precipitation for the whole catchment, even if it was scaled for

spatial variability. It is also unclear whether the Thiessen polygon method was the best choice during the model comparison analysis, however, the annual precipitation for both the future climate predictions and the model comparison is within the span of 2000 to 3100 mm/year reported by Cárdenas (2016).

A more comprehensive analysis of how well the HBV model was able to represent the watershed could have been done by examining what proportions of the total runoff that were represented by the base flow and by water from more superficial soil layers, respectively. These values could then have been compared with literature values or measured data if this had been available. It would have been important to know more about the structure of the bedrock beneath the soil, to be able to judge if any water could possibly flow away in any other direction, and not end up in River Chuza. The catchment area was delineated using a DEM file, which might give false information about the water flow directions. It is possible that the water takes other ways than what has been assumed, which could lead to modeling errors. However, the NSE values obtained from the comparison analysis and future runoff simulations indicate that the model works sufficiently for this catchment and are close to the performance of other models. Also, since the water balance closes with the simulated values, it indicates that the model captures the hydrology well. The TOPMODEL was used for another catchment in CNP, where the climate and hydrological conditions could be assumed to be very similar. The TOPMODEL received a NSE value of 0.76 for the calibration period (the NSE value for the validation period is not clearly stated) (Gil and Tobón 2016), compared to the result from this study with NSE values for the calibration period of 0.59 (model comparison part) and 0.83 (future climate predictions). Another study performed by Häggström et al. (1988) using the HBV model in Colombia received R^2 values in the range 0.78 to 0.93 for different basins during the calibration period. The performance values of R^2 and NSE cannot be directly compared, but according to Bizuneh et al. (2021), a model is regarded as performing sufficiently well if the R^2 value is above 0.5. Lelieveld (2020) received a NSE value during the calibration period of 0.69 and a NSE value of 0.44 during the validation period for a paramo region in Ecuador. Another study carried out in paramo regions in Ecuador using the HBV model was performed by Sucozhañay and Céleri (2018). They received a NSE value of 0.80 during the calibration period and 0.73 during the validation period. These studies shows that the HBV model has performed sufficiently well in paramo regions in Ecuador and Colombia, and the NSE value is expected to be more or less the same as the values that were obtained in this study.

The NSE value clearly indicates that the model works sufficiently well, even if deeper analysis could be performed. If the model holds, and if the precipitation inserted in the model is assumed to be correct, it is very likely that the simulated discharge is correct. It could even be that the simulated discharge is more correct than the observed discharge. This statement is strengthened by the fact that the water balance was closed by the simulated discharge but not with the measured discharge. For the future discharge simulations, that would indicate that the simulated discharge is correct, but the comparison with the measured discharge is subject to a large uncertainty, since the measured

discharge is uncertain. This is important to keep in mind, since the decrease in annual discharge by 400 mm/yr then is not very certain. As for now, by only taking into account the result from this study, it is not possible to know how alarming the result is. New measurements of the discharge in Rio Chuza have to be made. One note however, is that the discharge simulations for the dry seasons seem to result in discharge values that approach zero, regardless of whether they are compared with the historical values or not. The most extreme simulation (EC-Earth3-CC, SSP5-8.5, years 2062-2081) shows a specific discharge of 4 mm/month. This is an important result, since it could have severe consequences on the ecosystem.

6.2.4 Limitations and further research

To confirm the suitability of the HBV model on the Monterredondo catchment it would be interesting to investigate other methods to confirm the model's accuracy, for example by applying other objective functions such as Spearmann Rank, KGE or R^2 , all available in the user interface in HBV light. There are also other ways of calculating the potential evaporation time series that could be interesting to investigate the influence of, for example the Blaney–Criddle equation and the Penman equation (Rijtema 1955).

The data availability is a major limitation of this study. If possible, more data, especially the spatial availability, would be desirable to improve.

One other limitation with the HBV model's ability to simulate the future discharge is that only temperature and precipitation can be taken into account. More realistically, other factors would also influence the discharge (solar radiation, wind speed and land use for example) and this is a clear limitation in the HBV model and in this study. This could be studied further by using another hydrology model with the ability to include more variables.

One weakness with the future discharge simulations is that the coordinates from which one of the prediction models' data came from is far away from the catchment and the result from his projection can therefore not be trustworthy. Hence, the result is only based on one model, making the result weaker. To confirm the change in discharge, it would be interesting to investigate the outcome of other prediction models in the HBV model. Furthermore, it would also be interesting to examine other climate scenarios, for example SSP1–1.9 which reflect the mitigation needed to meet the Paris agreement, to see if that limited climate change would be enough to preserve the paramos as a water resource. It would also be interesting to broaden this study into investigating more paramo areas, since the result from only one small paramo catchment can only be seen as a pilot study.

A simplification was made to treat the Monterredondo watershed as one unit. It is however possible to alter this in the HBV light interface, to include subbasins and vegetation zones. This simplification was made since the watershed appeared homogeneous enough, but it is possible that by including subbasins and vegetation zones, the model would give a better representation of the hydrology.

A more comprehensive analysis of how well the HBV model was able to represent the watershed could have been done by examining what proportions of the total runoff that were represented by the base flow and by water from more superficial soil layers, respectively.

6.3 General discussion

Neither the characterization part nor the modeling part obtained results that showed that there had been or would be a change in annual precipitation. However, the modeling indicated that the wet seasons would become wetter and the dry seasons would become drier. The results from the characterization show some trends in the precipitation, however not consistent for all clusters and not significant in the majority of the cases. Most of the significant trends are increasing and there are more representative stations manifesting significantly increasing trends on a monthly scale than on an annual scale. Since annual trends generally are not significant whereas the monthly ones are to a greater extent, this implies that the significant increases on a monthly scale are counterbalanced by decreases in amount, intensity or frequency in precipitation in some of the months, something that a few of the Climact indices possibly indicated. More detailed analyses of the historical data could therefore be done on a monthly or seasonal scale and then it is possible that the results would demonstrate that dry seasons are getting drier and wet seasons are getting wetter on a national, or at least regional scale, as well. However, as of now the results from the characterization part can neither deny nor confirm the findings of more extreme seasons in the small scale modeling part.

If the wet and dry seasons are getting more extreme when it comes to precipitation, it could connote a strain on the societies that rely on the paramos as a water resource, as the supply could become more uneven and therefore less reliable throughout the year. More intense rain could also affect the water quality if it results in more contaminants being flushed into the streams and rivers, although this can be expected to happen to a larger extent downstream of the paramos where there is more human activity.

Another consequence of drier dry seasons could be, as Cresso (2020) mentioned, a gradual drying of the currently wet soils. This could speed up the decomposition of organic matter. Instead of being a CO₂ sink, the paramos could transform into a greenhouse gas emission source and if these emissions are considerable it could exacerbate climate change. The result from this study confirms that there is a risk that the dry seasons would get drier, which could lead to the situation described. However, longer and/or wetter wet seasons might slow down this process.

The modeling of the future discharge showed a decrease in annual discharge, while the characterization of historical data did not. In some cases the trend analysis of historical discharge data in the characterization part even reported significant increases in discharge. It is possible that the effect of climate change did not show in the historical data yet, but will be more evident later.

The results from the future climate predictions showed a decrease in discharge, more intense wet and dry seasons and higher average temperature (observe that the changes were not tested for significance and that the discharge values are subject to large errors, read Section 6.2.3) It is important to keep in mind that the future climate predictions are only pilot studies and it is important not to generalize and apply these results on all paramo regions. As Cresso (2020) points out, there are many resemblances between paramo ecosystems at different locations, but there are also large variations. Their different locations in the Andes put them in an unequal relation to the large-scale wind and climate systems and other forcing factors, which makes it impossible to treat the different paramos as one single ecosystem. Climate change will therefore affect paramo regions differently, depending on where they are located and the specific hydroclimatic conditions prevailing at those sites. The result from the characterization confirms the large variations in hydroclimatology for the paramos at different sites.

The future climate simulations demonstrated a quite clear correlation between discharge and precipitation in the different graphs and figures received (observe that no correlation tests have been performed). This is quite expected, since the HBV model is using the precipitation to calculate the expected discharge. The characterization part did not perform any correlation test between precipitation and discharge either, but by observing the graphs and by comparing the trend analyses, it could be observed that the variables exhibited some similarities in patterns and trends and had some common traits, but they were not entirely coherent and not clearly correlated. It was a bit unexpected, since precipitation in theory would have a major influence on discharge. In the case of characterization however, the discharge and precipitation stations are not necessarily in the same catchment, which would have a large influence on the correlation analysis. Furthermore, the paramo catchments used in the characterization analysis could include urban areas and/or water outtake for irrigation, hydroelectric plants, drinking water et cetera, which has not been investigated and would influence the water balance.

For both parts of this study observed precipitation was used. This entails uncertainties, for example due to a limited ability of the measuring instruments to catch horizontal precipitation. The rain gauges that are often used in these areas mainly catch the vertical precipitation, while the contribution from horizontal precipitation is lost. For this reason the horizontal precipitation station was built in La Laja, Chingaza, but it proved difficult to get a reliable result using such a "rough" construction. The station would need further improvements to get more accurate and precise results. For example, a bigger screen could be made to cover a larger area and closed tanks could be used to collect water so that the station would not be subject to losses due to evaporation or animals drinking it and to prevent overestimation due to accidental collection of vertical precipitation. It would also be desirable to install several stations like this in the same area, since one single station entails a lot of uncertainties, as there can be different microclimates within a quite small area. Moreover, measuring instruments in general that are located in the paramos are sometimes subject to very tough weather conditions, such as strong storms. This makes it even more difficult to gather data and therefore the instruments need to be robustly constructed to withstand these conditions.

The results received from the field visit measured 0.37 mm/d, which is approximately 6,1 % of the historical data from the same site. This is not within the interval of 7-28 % suggested by Cárdenas et al. (2017). According to Gómez Elorza (2016), the contribution to the hydrological response can be as high as 60 %, which is much higher than the measured values in this study. The result from the field visit is only from one week, so to get a more robust result, it is important to measure over a longer period of time. Even if the result is compared to the high value of 60 %, it could still be correct since the comparison between the measured values over only one week and a historical average over a long time is not a fair comparison. For example, what if the week of measuring was a dry week? Compared to Cárdenas et al. (2017) it seems like the result received in this study is reasonable, which would imply that the kind of structure built in this field visit served its purpose and, if improved, could be important for future research.

6.3.1 General limitations and further research

For both the characterization and modeling part the constriction of which variables could be included was quite strict. However, there are many other variables that influence hydrology, for example solar radiation, wind speed, soil characteristics and land use. If these variables were included, the results would be more comprehensive and representative with respect to climate change and paramo characteristics.

Moreover, longer time series would improve the reliability of the results for especially the characterization, but it is also possible that the HBV model would be more reliable if longer time series were used for the calibration. However, Lelieveld (2020) showed that the length of the input data only had a minor importance.

The horizontal precipitation station could be improved in several aspects. The containers for collection of water needed to be emptied continuously, there was a risk of collecting rain, and the water collection could be subject to evaporation and consumption by animals. Additionally, the small screen area could be subject to disturbances, for example, wind could have a large influence. For instance, humid air could easily blow past a small screen, while a screen that covers a larger area would be more representative. To better investigate how much influence horizontal precipitation has, a much more robust and precise structure would be needed, and a larger area would have to be covered.

One important question that was not investigated in this study is how climate change might affect the spatial distribution of the paramo areas. The area of these ecosystem have a direct influence on hydrology, which makes it an interesting aspect to investigate further. The result from Cresso (2020) showed that there is a large risk that the areas suitable for paramo ecosystem will decrease, especially during the dry seasons. This because, according to Cresso (2020) and in alignment with the result in this paper, the dry seasons will be drier.

7 Conclusions

7.1 Characterization

The quantity of precipitation for all the areas investigated ranged between approximately 500 and 5000 mm/yr and the amount could differ substantially both within and between clusters with up to approximately 2000 and 3500 mm/yr. Additionally, the annual precipitation for a single station could vary from year to year with up to around 1000 mm/yr. For the time period analyzed Cordillera Occidental and Cordillera Central generally exhibited more precipitation than Cordillera Oriental. As for seasonality most stations had a bimodal precipitation pattern with wet seasons roughly in April-May and October-November, but some had a unimodal precipitation pattern, generally with a wet season in June-July. The stations with a bimodal precipitation pattern were quite scattered, but the ones with a unimodal precipitation pattern seemed to be on, or at least closer to, the eastern slope of Cordillera Oriental and the southern eastern slope of Cordillera Central.

The annual mean daily discharge ranged between 0 and 25-30 m³/s and the total annual specific discharge ranged between 0 and 2500 mm/yr. The specific discharge was highest for the northern parts of Cordillera Occidental and Cordillera Central and the western slope of the central part of Cordillera Central, but it is not possible to draw the conclusion that the clusters with the highest precipitation also have the highest specific discharge.

Most of the trends in total annual precipitation, annual mean daily discharge and total annual specific discharge between 1986/1987 and 2011/2012 were not significant. The majority of the ones that were, implied wetter conditions. The fact that there were more significant trends on a monthly scale, than on an annual scale for precipitation, might indicate that potential effects of climate change are only detectable on a monthly or seasonal level. On an annual scale it is not evident that climate change had a big impact on the Colombian mountain areas during the analyzed time period. However, there are signs of ENSO events influencing at least precipitation quite strongly. No evident relationship between precipitation and discharge could be detected in neither amount nor pattern or trend over time, although some similarities and common traits could be found.

The results are not consistent and univocal enough for it to be possible to point out certain paramo areas as more sensitive to climate change. However, as Cluster 7, in the central part of Cordillera Oriental, both had among the least precipitation and the lowest specific discharges, this might imply that mainly the western slope of this area is at risk for problems with water supply. On the other hand, the northern and southeastern part of Cordillera Central showed most significant trends, but in these areas it seems like there is rather a risk for too much water.

7.2 Modeling

The model comparison part can deem the HBV model as sufficient for the Monterredondo watershed based on the NSE value. The model efficiency is a little higher for the more complex SWAT model, which also managed to, at a few occasions, better represent high and low flows, indicating that the SWAT model performs better for this watershed. When calibrating the model for the future predictions, this NSE result confirms that the HBV model is sufficient in this watershed.

There is an evident error in the input data that is used, since the water balance does not close. Most likely the error is due to the discharge measurements, since the measurement site is unsuitable for water level measurements and there are huge uncertainties in the conversion from water level to discharge.

The result from the sensitivity analysis shows that the model is less sensitive towards change in potential evaporation and more sensitive towards changes in discharge and precipitation. When it comes to model structure, the Monterredondo catchment is well represented with two or three groundwater boxes while one box is too simplistic.

The result from the future discharge simulations shows drier dry periods and wetter wet seasons with respect to both precipitation and discharge. The annual volume in discharge will also decrease. Since the measured discharge that the simulated discharge is compared to is subject to a lot of uncertainties, it is not possible to tell how alarming the decrease in discharge is. If the result is correct however, it could influence the water resources, leading to issues with flooding during wet season and the stream drying up during dry season. Some of these issues could perhaps be avoided with planning. For example, it might help to increase water storage abilities by building water reservoirs. To ensure this result, a deeper analysis of the discharge uncertainties is needed.

The precipitation changes is deemed to be more certain, even if no significance test have been performed. This because the historical precipitation is deemed to be more reliable. The precipitation results show drier dry seasons and wetter wet seasons.

7.3 General conclusions

Data scarcity is a big issue for all of the spatial scales investigated in this study. This limited the analyses. With observed data, there are many practical challenges, inherent uncertainties come along, and incomplete time series can be a problem. An option to overcome the problem with data scarcity would be to instead use reanalysis or remote sensing data to get more complete and comprehensive data to work with. The network of measuring stations could also be expanded.

The dry seasons are getting drier and the wet seasons are getting wetter according to the result from the future climate scenarios. The annual precipitation is not changing much while the result shows a decrease in annual discharge. The result from the characterization part can neither confirm nor deny this result, which implies that it might be a possible consequence of climate change for some paramo areas. Since the result from

the future climate scenarios is uncertain, especially when it comes to knowing how much less discharge there is to expect, and the characterization can neither confirm nor deny the result, it is not possible to know how alarming the consequences of climate change will be on the paramos as a water resource.

From both parts precipitation trends are visible. For the future discharge predictions, the result shows a trend towards drier dry seasons and wetter wet seasons, while the result from the characterization is not as unambiguous. It is however clear that there are changes happening in the precipitation patterns, and the future discharge predictions indicate that it is because of climate change. The majority of the changes in precipitation and discharge were insignificant in the national analyses, but the trends that were significant mostly indicated wetter conditions. The patterns over time appeared to be clearly influenced by ENSO events, but it was not as clear that the trends over time in historical data were attributed to climate change.

The result from future climate scenarios are only a pilot study and the result should not be generalized and applied to other paramo regions. The result from the characterization part confirms that there is a large variability between the different paramo regions. Climate change will likely therefore influence paramo regions differently, depending on their location and other characteristics, and on the specific hydroclimatic conditions prevailing at those sites.

The horizontal precipitation station constructed in the plot scale study would need some major improvements, but could be a valuable measurement device for future investigations. The results from using the station showed that horizontal precipitation did contribute to the total precipitation, but it is not possible to draw any conclusions as to how important the contribution of horizontal precipitation is in general.

All in all, as negative effects of climate change on the paramos as a water resource cannot be ruled out, the consequences it could have for the societies should not be ignored. Therefore, more knowledge is needed, and more preventative measures are recommended.

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A Appendix

A.1 ENSO events

Table A.1: Months and years for strong and *very strong ENSO events between 1987 and 2012.

El Niño events	La Niña events
Aug-Sep 1987	Nov-Dec 1988/Jan 1989
Jan-Feb 1992	Nov-Dec 1998
Nov-Dec 1997*	Nov-Dec 1999/Jan 2000
	Nov-Dec 2007/Jan 2008
	Oct-Nov 2010

A.2 HBV model parameter settings

Table A.2: The final parameter settings for the comparison analysis and the Future climate predictions.

Parameter	Comparison analysis	Future climate prediction
TT	0.50	0.63
CFMAX	15.00	14.76
SP	0	0
SFCF	4.87	4.53
CFR	1.57	0.57
CWH	0.08	0.07
FC	750	750
LP	0.00	0.05
BETA	0.26	0.25
PERC	2.12	4.78
UZL	73.89	2.87
K0	0.89	0.03
K1	0.20	0.25
K2	0.00	0.10

A.3 Modeling data analysis

Table A.3.1: Data screening for the precipitation stations available for the model comparison part. The table shows how many dates that have missing data each year.

Year	Chuza Campamento	Tunel el Diamante	Chingaza Campamento	Presa Golillas	Laguna Seca
2010	0	8	0	0	43
2011	0	203	0	0	2
2012	0	321	55	0	52
2013	0	328	76	0	0
2014	0	298	192	0	28
2015	0	168	276	0	141
2016	0	219	301	0	165
2017	0	246	279	0	156
Total missing	0	1791	1179	0	587
Percent missing	0	63	41	0	20

Table A.3.2: Data screening for the temperature stations available for the model comparison part. The table shows how many dates that have missing data each year.

Year	Chingaza Campamento	Laguna Seca	Presa Golillas
2010	0	0	29
2011	0	0	365
2012	224	214	270
2013	15	0	0
2014	176	0	182
2015	12	81	223
2016	0	366	0
2017	0	365	0
Total missing	427	1026	1069
Percent missing [%]	15	35	37

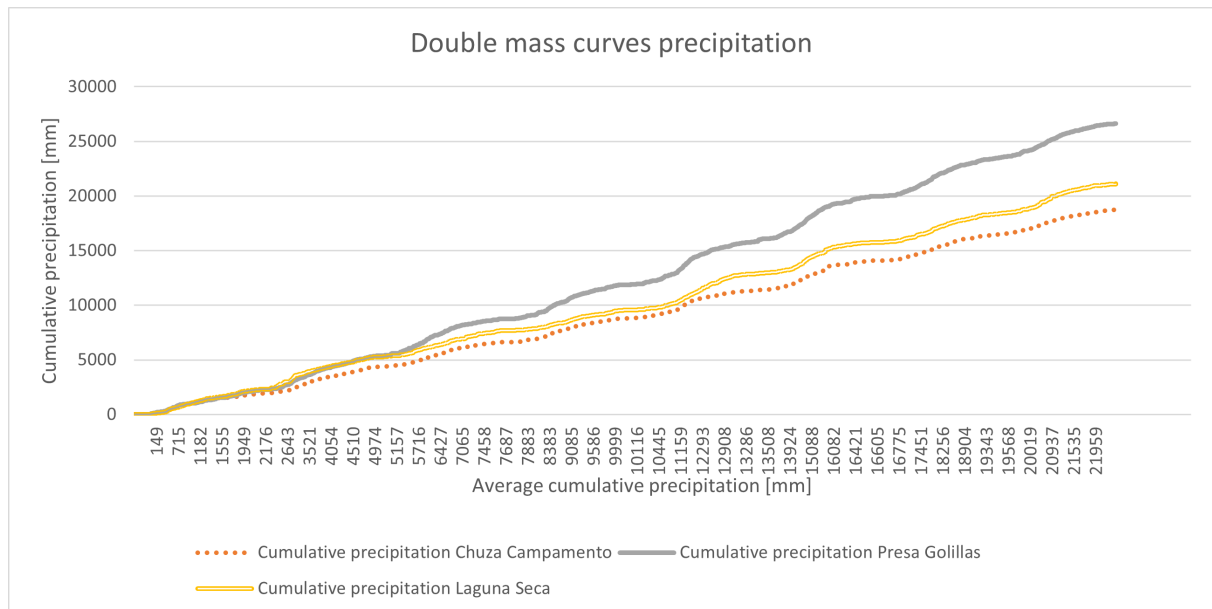


Figure A.3.1: Double Mass Curve for the precipitation stations that were included after the data selection.

Table A.3.3: Data screening for the precipitation stations available for the future discharge modeling part. The table shows how many dates that have missing data each year.

Year	Laguna marrons	Cuchilla Golillas	Presa Golillas	Chuza Campamento	La Playa	Laguna Seca	La Cascada	Barajas	Tunel el Diamante
2000	245	81	0	0	337	66	134	235	101
2001	153	188	0	0	365	79	177	248	34
2002	218	260	1	0	303	262	272	206	257
2003	80	212	0	0	70	58	127	191	55
2004	177	266	0	0	26	83	83	177	37
2005	46	15	0	4	199	120	143	74	0
2006	83	181	0	0	125	274	104	266	79
2007	125	152	0	0	191	277	24	202	77
2008	37	125	1	0	210	137	25	34	12
2009	9	18	0	0	213	63	68	50	7
2010	20	63	1	0	279	52	93	45	9
2011	27	9	0	1	321	2	39	8	198
2012	0	0	0	0	340	52	90	16	321
2013	0	0	0	0	280	0	0	64	322
2014	21	42	0	0	289	15	19	105	288
2015	8	209	0	0	108	151	69	152	160
2016	128	222	0	0	133	159	187	8	208
2017	56	140	0	0	77	151	211	152	239
2018	193	184	0	0	62	181	272	279	291
2019	215	200	0	0	59	223	275	199	304
2020	0	12	0	0	0	135	123	149	32
2021	162	161	0	0	135	157	254	211	128
Total missing	1943	2740	3	5	4122	2647	2789	3171	3159
Total missing [%]	24	34	0	0	51	33	35	39	39

A.4 Plots for scaling precipitation

Figure A.4.1 to A.4.12 show the boxplots and linear plots that were made to determine if a relationship between elevation and precipitation existed. This analysis was made for each month separately and only using stations within CNP. The analysis was made for the input data during the calibration part for the future climate scenarios, found in Section 4.2.4.1 .

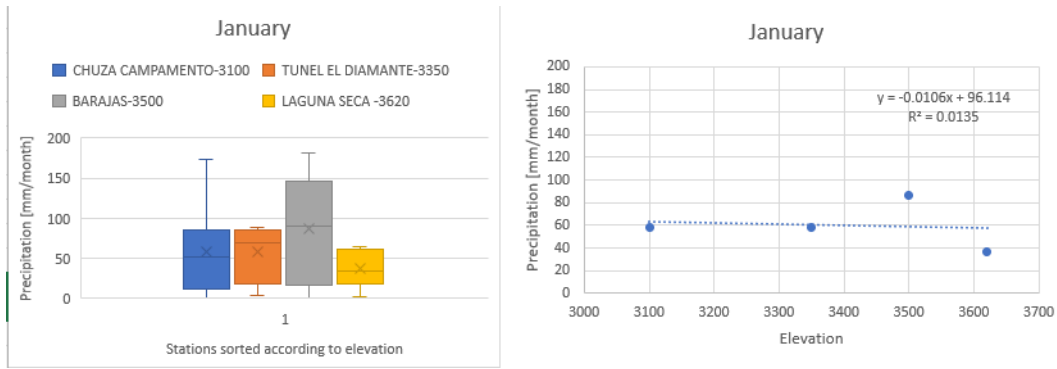


Figure A.4.1: January boxplot.

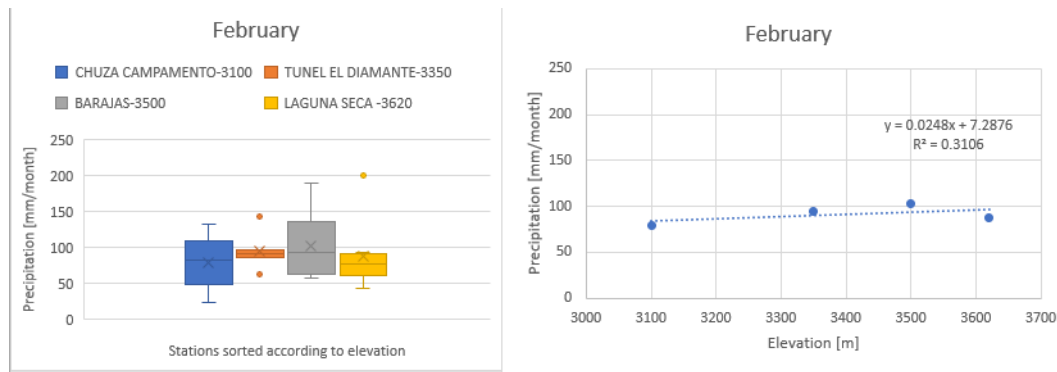


Figure A.4.2: February boxplot.

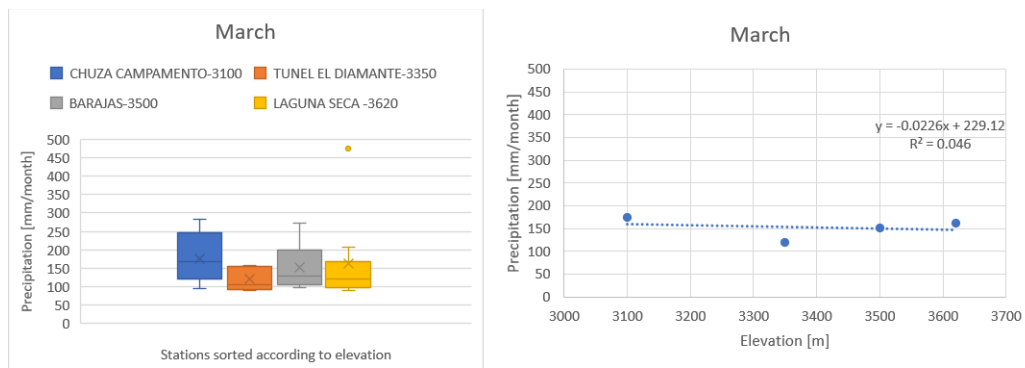


Figure A.4.3: March boxplot.

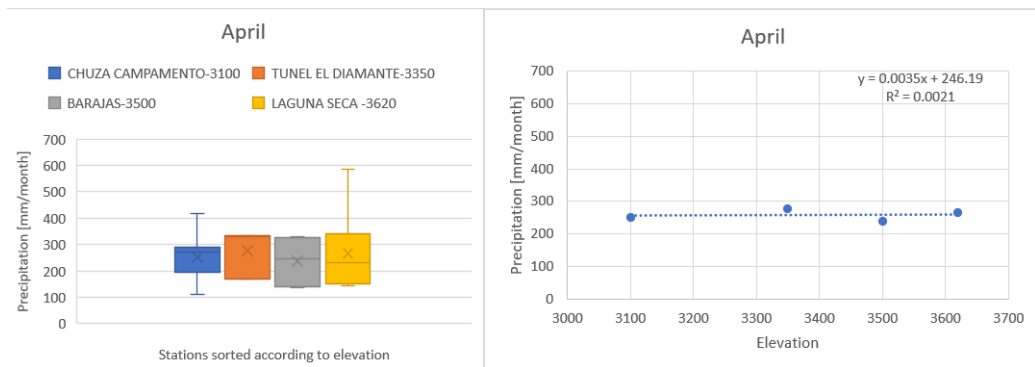


Figure A.4.4: April boxplot.

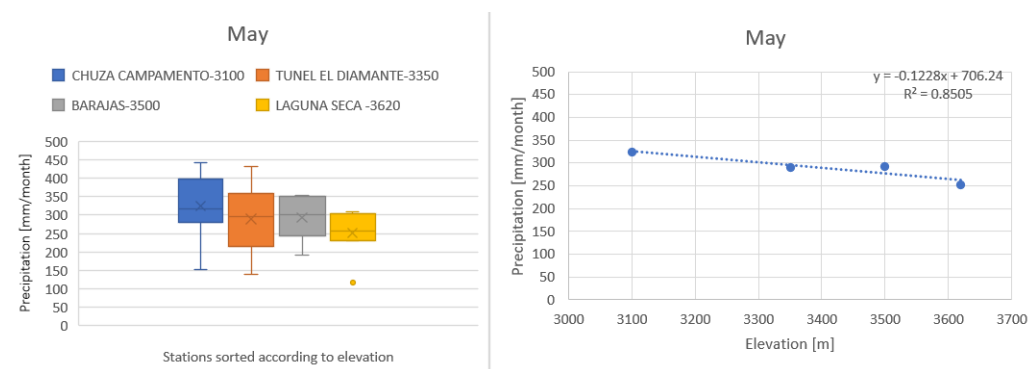


Figure A.4.5: May boxplot.

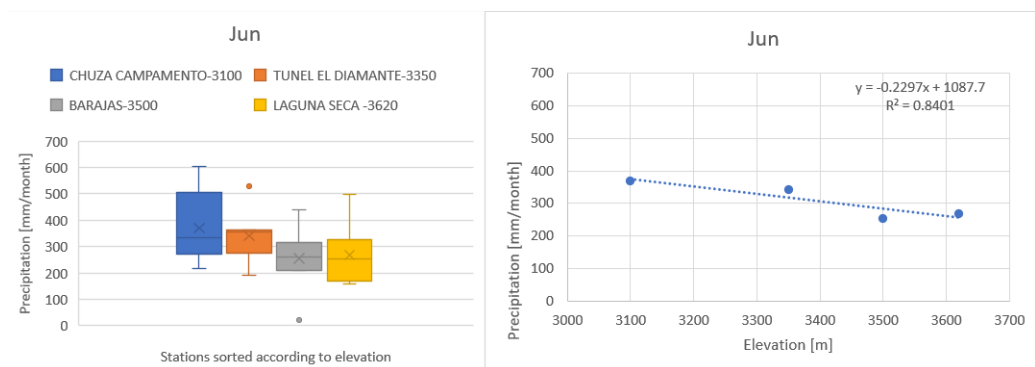


Figure A.4.6: June boxplot.

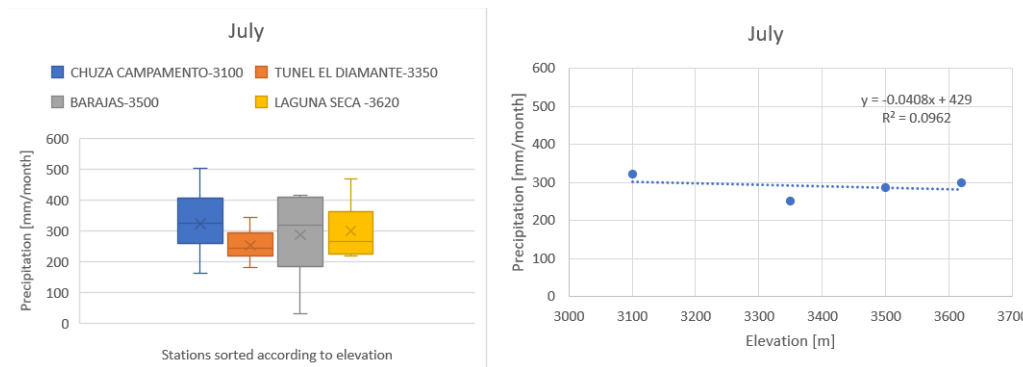


Figure A.4.7: July boxplot.

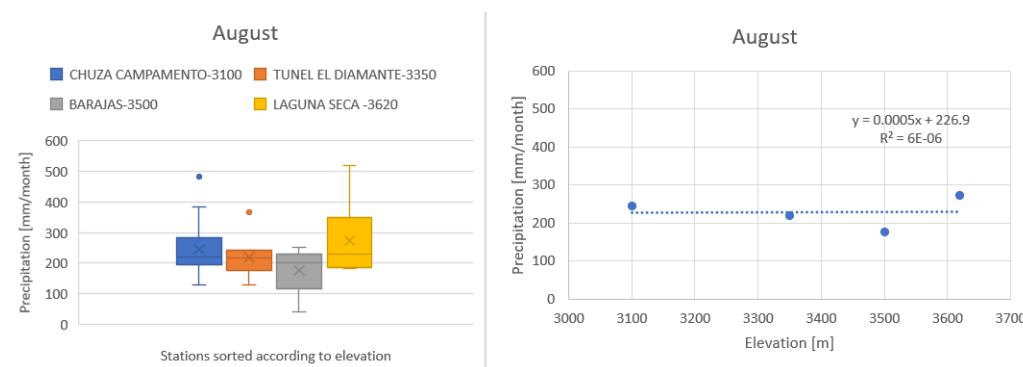


Figure A.4.8: August boxplot.

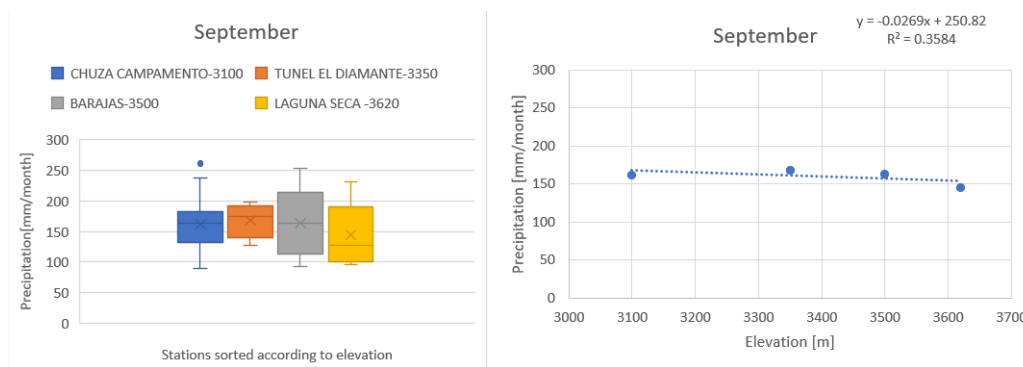


Figure A.4.9: September boxplot.

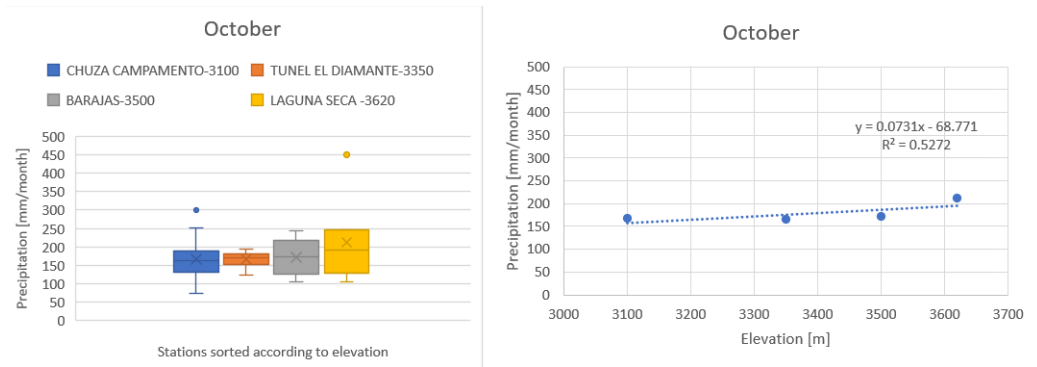


Figure A.4.10: October boxplot.

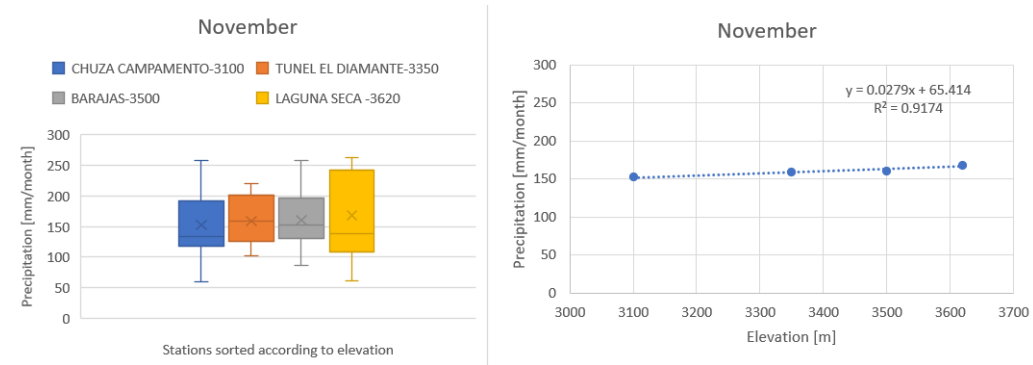


Figure A.4.11: November boxplot.

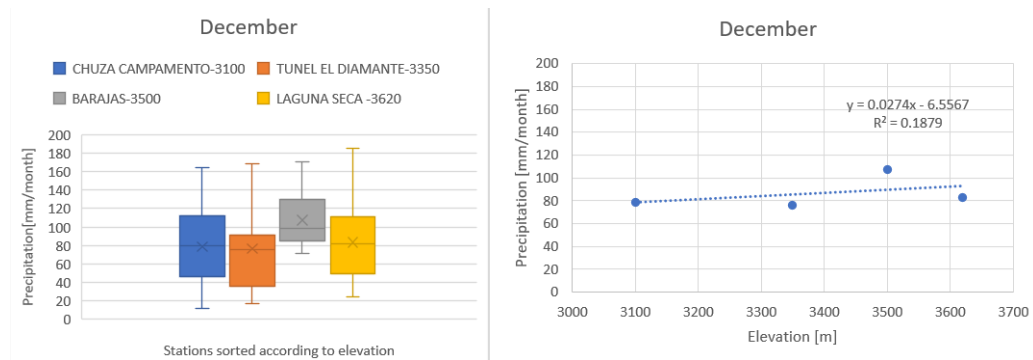


Figure A.4.12: December boxplot.

Table A.4: The scaling factors for the relevant months.

Month	Scaling factor
May	0.89
June	0.83
October	1.07
November	1.05

A.5 Cross section geometry

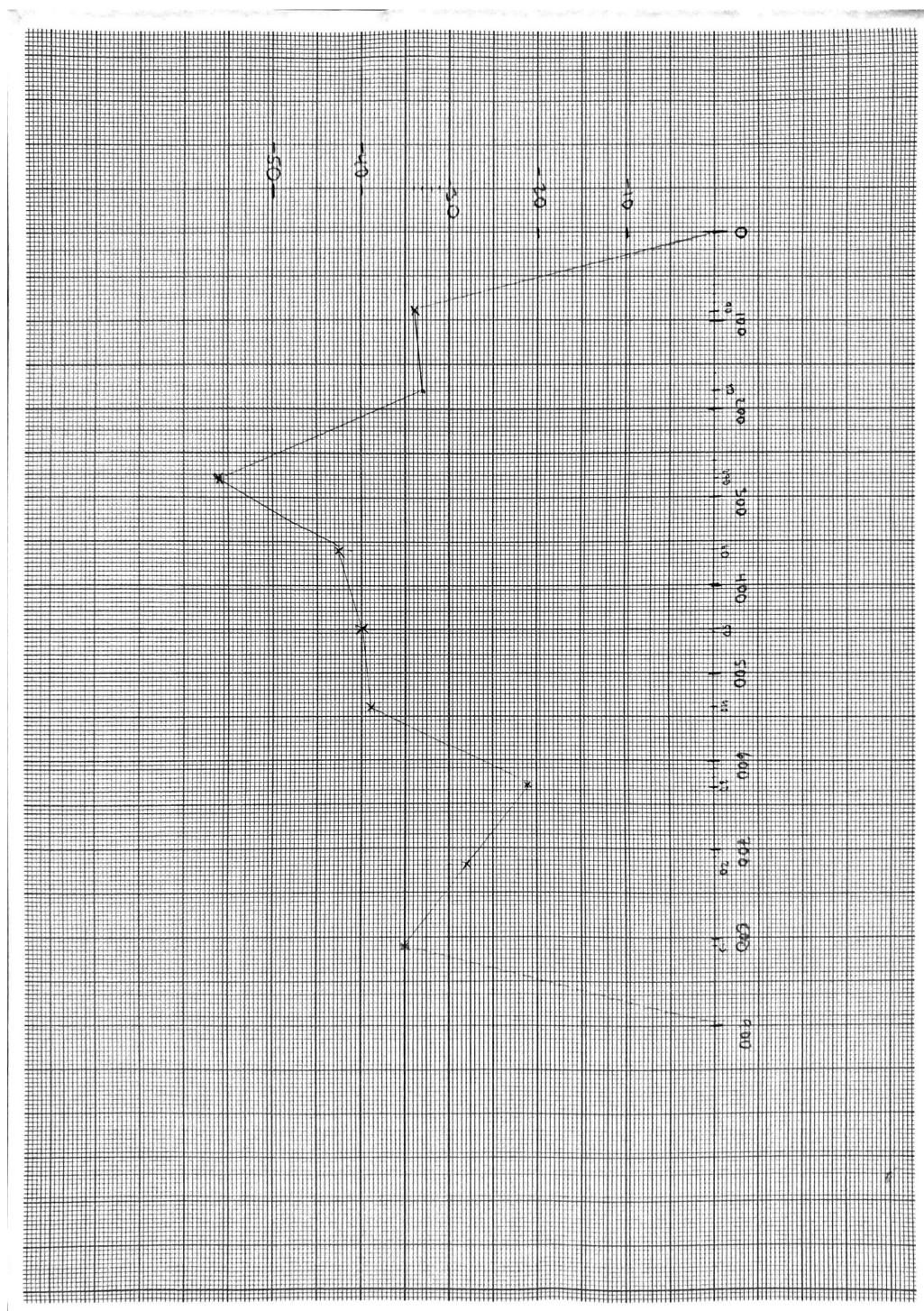


Figure A.5: The cross section where the limnigraph is installed.