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INFLUENCE OF CLIMATE CHANGE ON THE WATER AVAILABILITY OVER THE EASTERN SIDE OF COLOMBIA

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Abstract

Global climate change is one of the greatest concerns of humanity given the great impact that it has over the future sustainable development. The eastern region of Colombia is very susceptible to the effects of climate change due to its high diversity of fauna and flora and the potential direct impact on economic activities and the pressure on water resources. No research has been carried out focusing on the predicted changes on climate in the next decades on the eastern region of Colombia due to the unavailability of proper records and lack of technical and scientific focus on this region. This PhD is focused on the eastern region of Colombia and the practical development of this work was composed of three stages and the results from these phases led to the publication of three different articles which are the main body of this study. The first stage was focused on a systematic review of the climate characteristics over the last decades at eastern Colombia including a data survey and evaluation of the historical available data records. In the second stage, the Statistical Downscaling Model (SDSM) was used as a tool for downscaling meteorological data statistically over four representative water districts at the eastern side of Colombia. Here, data from the two Global Climate Models CanESM2 and IPSL-CM5A-MR, which are part of the CMIP5-project have been used to project future maximum and minimum temperature, precipitation and relative humidity for the periods 2021–2050 and 2071–2100. For both models, the Representative Concentration Pathways RCP2.6 and RCP8.5 were considered, representing two different possible future emission trajectories and radiative forcings. In the third stage, the results of the second stage together with the hydrological model BROOK90 and complementary data were utilized to determine the future changes in the water balance components in the previously selected four water districts in Eastern Colombia.

The general results showed that for many regions located at eastern Colombia, data records are insufficient to develop a reliable climate analysis that can lead to accurate projections; but at the four selected water districts, a consistency analysis showed that the data records in these areas are considered a good source of input data to perform further analysis such a climate modeling. The climate regional downscaling procedure indicated that maximum and minimum temperature are projected to increase, as it was expected, this for both used Global Climate Models and both Representative Concentration Pathways; relative humidity shows a decreasing trend for all scenarios and all regions; and precipitation shows a slight decrease over three regions and an increase over the highest region. The results of the simulation for the period 2071–2100 show a more drastic change when compared to the baseline period of observations. Regarding the analysis of water-budget components, the results determined that the temporal and spatial distribution of water balance components will be considerably affected by the changing climate. A reduction in the generated streamflow for all of the studied water districts is shown and changes in the evapotranspiration and stored water showed different range of magnitudes for each region according to both the climate scenario as well as the characteristics of soil and land use for each area. The results of spatial change of the water balance components showed a direct link to the geography of each region. Soil moisture will reduce considerably in the next decades, and the percentage of decrease varied for each scenario. This research project is conceived as part of the first steps in the creation of available technical information to address the problem of adaptation to climate change on the eastern side of Colombia.

Zusammenfassung

Der globale Klimawandel ist eines der größten Anliegen der Menschheit angesichts der großen Auswirkungen, die er auf die zukünftige nachhaltige Entwicklung hat. Die östliche Region Kolumbiens ist aufgrund ihrer großen Vielfalt an Fauna und Flora und der potenziellen direkten Auswirkungen auf die Wirtschaftstätigkeit sehr anfällig für die Auswirkungen des Klimawandels und es gibt bisher praktisch keine Untersuchungen zu den voraussichtlichen Klimaveränderungen für die nächsten Jahrzehnte in für diese Region. Diese Doktorarbeit konzentriert sich auf die östliche Region Kolumbiens und die praktische Entwicklung dieses Promotionsprojekts bestand aus drei Phasen, und die Ergebnisse dieser Phasen führten zur Veröffentlichung von drei Artikeln, die den Hauptteil dieser Studie bilden. Die erste Phase konzentriert sich auf eine systematische Überprüfung der Klimaeigenschaften der letzten Jahrzehnte in Ostkolumbien, einschließlich einer Bewertung der verfügbaren historischen Daten. In der zweiten Phase wurde das statistische Klimamodell SDSM als Instrument zur statistischen Projektion meteorologischer Daten in vier repräsentativen Wasserbezirken im östlichen Teil Kolumbiens verwendet. Hier wurden Daten aus den beiden globalen Klimamodellen CanESM2 und IPSL-CM5A-MR, die Teil des CMIP5-Projekts sind, verwendet, um die maximalen und minimalen Temperaturen, Niederschläge und die relative Luftfeuchtigkeit für die Zeiträume 2021–2050 und 2071–2100 zu projizieren. Für beide Modelle wurden die Emissionsszenarien RCP2.6 und RCP8.5 berücksichtigt. In der dritten Phase wurden die Ergebnisse der zweiten Phase zusammen mit dem hydrologischen Modell BROOK90 und ergänzenden Daten verwendet, um zukünftige Änderungen der Wasserhaushaltskomponenten in den zuvor ausgewählten vier Wasserbezirken in Ostkolumbien zu bestimmen.

Die allgemeine Ergebnisse zeigten, dass für viele Regionen in Ostkolumbien die Datensätze nicht ausreichen, um eine zuverlässige Klimaanalyse zu entwickeln, welche zu genauen Projektionen führt. In den vier ausgewählten Wasserbezirken ergab eine Konsistenzanalyse jedoch, dass die Datensätze in diesen Bereichen als eine gute Quelle für Eingabedaten zur weiteren Analyse betrachtet werden können. Das regionale statistische-downscalling Verfahren ergab, dass in den kommenden Jahrzehnten ein Anstieg der maximalen und minimalen Temperatur prognostiziert wird, sowohl für die beiden verwendeten globalen Klimamodelle als auch die Emissionsszenarien. Die relative Luftfeuchtigkeit zeigt für alle Szenarien und Wasserbezirke einen abnehmenden Trend. Der Niederschlag zeigt eine leichte Minderung in drei Regionen und einen Anstieg in der Region, die sich auf der höchsten Höhe befindet. In Bezug auf die Analyse der Komponenten des Wasserhaushalts ergaben die Ergebnisse, dass die zeitliche und räumliche Verteilung der Komponenten des Wasserhaushalts erheblich vom Klimawandel beeinflusst wird. Es wird eine Verringerung der erzeugten hydrologischen Flüsse für alle analysierten Wasserbezirke gezeigt. Die Evapotranspiration und das Reservewasser variieren für jede Region entsprechend dem verwendeten Klimaszenario sowie den Eigenschaften des Bodens und seiner Verwendung für jedes Gebiet. Die Ergebnisse der räumlichen Veränderung der Komponenten des Wasserhaushalts zeigten einen direkten Zusammenhang mit der Geographie jeder Region. Die Bodenfeuchtigkeit wird in den kommenden Jahrzehnten erheblich abnehmen. Dieses Forschungsprojekt ist als Teil der ersten Schritte zur Schaffung technischer Informationen konzipiert, die verfügbar sind, um das Problem der Anpassung an den Klimawandel in der östlichen Region Kolumbiens anzugehen.

Resumen

El cambio climático es una de las mayores preocupaciones de la humanidad a nivel global dado el gran impacto que tendrá sobre la futura sostenibilidad del desarrollo socioeconómico y ambiental. La región oriental de Colombia presenta una alta vulnerabilidad a los efectos del cambio climático debido a su gran diversidad de fauna y flora y el potencial impacto directo en las actividades económicas. Hasta el momento, prácticamente no se han realizado investigaciones orientadas a los cambios climáticos proyectados en Colombia para las próximas décadas sobre esta región, debido a la falta de datos y de enfoque técnico y científico en esta región. Este proyecto de investigación se centra en la región oriental de Colombia y se compone de tres fases. Los resultados de estas secciones condujeron a la publicación de tres artículos diferentes que son el cuerpo principal de este estudio. La primera sección se centra en una revisión sistemática de las características climáticas en las últimas décadas en el oriente de Colombia, que incluye una evaluación de los datos históricos disponibles. En la segunda sección, el modelo climático de anidación estadística SDSM se utilizó como una herramienta para proyectar estadísticamente los datos meteorológicos en cuatro distritos de agua representativos en el sector oriental de Colombia. Aquí, los datos de los dos modelos climáticos globales CanESM2 e IPSL-CM5A-MR, que forman parte del proyecto CMIP5, se han utilizado para proyectar las temperaturas máximas y mínimas, la precipitación y la humedad relativa para los períodos 2021–2050 y 2071–2100. Para ambos modelos, se consideraron los escenarios de emisión RCP2.6 y RCP8.5. En la tercera sección, los resultados de la segunda sección junto con el modelo hidrológico BROOK90 y datos complementarios se utilizaron para determinar los cambios futuros en los componentes del balance hídrico en los mismos cuatro distritos de agua en el este de Colombia.

Los resultados mostraron que para muchas regiones ubicadas en el este de Colombia los registros de datos son insuficientes para desarrollar un análisis climático confiable que conduzca a proyecciones precisas, pero en los cuatro distritos de agua seleccionados, un análisis de consistencia mostró que los registros de datos en estas áreas se consideran una buena fuente de datos de entrada para realizar análisis adicionales. El procedimiento de anidación estadística regional indicó que se pronostica un aumento en la temperatura máxima y mínima en las próximas décadas, esto para ambos modelos climáticos globales utilizados y para las los escenarios de emisión; la humedad relativa muestra una tendencia decreciente para todos los escenarios y todas las regiones; y la precipitación muestra una ligera disminución en tres regiones y un aumento en la región ubicada a más altura. Como se esperaba, los resultados de la simulación para el período 2071–2100 muestran un cambio más drástico en comparación con el período de referencia. Con respecto al análisis de los componentes del balance hídrico, los resultados determinaron que la distribución temporal y espacial de los componentes del balance hídrico se verá considerablemente afectada por el cambio climático. Se muestra una reducción en los flujos hidrológicos generados para todos los distritos de agua estudiados. La evapotranspiración y el agua de reserva varían para cada región de acuerdo con el escenario climático usado, así como las características del suelo y el uso de éste para cada área. Los resultados del cambio espacial de los componentes del balance hídrico mostraron un vínculo directo con la geografía de cada región. La humedad del suelo se reducirá considerablemente en las próximas décadas. Este proyecto de investigación es concebido como parte de los primeros pasos en la creación de información técnica disponible para abordar el problema de la adaptación al cambio climático en la región oriental de Colombia.

“Para encontrar la plenitud céntrate en lo que amas
y persigue lo que crees”

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1. INTRODUCTION

This PhD research project was developed with the financial support of a scholarship provided by the German Academic Exchange Service (DAAD, for its acronym in German). The project had the main objective of determining the change on the water budget over the eastern region of Colombia under climate change scenarios (RCP 2.6 and RCP 8.5) in two periods of time (2021–2050 and 2071–2100). This was analyzed based on the projected change of the hydroclimate variables precipitation, relative humidity, maximum and minimum temperature on four representative regions characterized as individual water districts on the east side and in the middle of Colombia. The low amount of available data throughout the Eastern region and its configuration together with the intended approach of showing the potential change of available water on a regional scale, lead to the development of this study over several water districts instead of the selection of one river basin.

1.1. Structure

This report is written and presented as PhD-Thesis in the accumulated-Thesis modality, wherewith it bases its central content on the three articles that were published in scientific journals and are the result of the research project developed in this PhD. The content presented in the first part of this report serves mainly to give a context of prior information to the articles presented in chapter 7. Considering that the work carried out in this research project is mainly intended to generate future projections of the possible scenarios of water availability over the study area, the first chapters presented in this report are largely based on the description of the current situation regarding climate and water management throughout the Colombian territory, this serves to give context to the projections resulting from the research project and to provide a good overview of water in Colombia to a first time reader. Thus, the content of this report is structured as shown below:

Chapters 1-6: General background, description of the problematic and an overview of the current situation of the water resource in Colombia and its general impact in the development of a growing Colombian economy.

Chapter 7: Published articles. ·
- Assessment of regional and historical climate records for a water budget approach in eastern Colombia
- Projected climate changes in four different regions in Colombia
- Projected changes in the water budget for eastern Colombia due to climate change

Chapters 8-9: General results of the research project and conclusions.

1.2. Motivation

Colombia is one of the richest countries in water resources. Its climate presents varied conditions with the coldest weather being located on its high mountains and the warmest at sea level. The high climate variability throughout its several regions is determined by its complex geography; however, there is also the influence of general circulation patterns. The eastern region of Colombia is very susceptible to the effects of climate change due to its high diversity of fauna and flora, the potential direct impact on economic activities and the pressure on water resources. The interest over the eastern side of the country is based to the lack of detailed climate studies throughout this region; a few previous studies have been carried out in Colombia mostly over the central and northern part of the country, where most of the climate records are available; but a research on a water budget approach was found necessary over this area to determine on a regional scale the possible change in the availability of water during the coming decades, especially for a developing country like Colombia due to the strong link of this resource to the economy, the environment, and the social conditions in the country and considering the growing pressure on water resources for the population and the industrial activities.

The issue of climate change in Colombia is only recently beginning to be understood as a topic of economic and social development. Therefore, the integration of this problem within the planning and investment processes of the productive sectors and in the territories are only now just beginning. As a result, the country might be missing out on some opportunities to improve their responsiveness to changes in weather conditions and reduce their vulnerability to such events. Adaptation and mitigation to climate change need to be addressed though the implementation of articulated strategies at both sectoral and territorial levels. This is necessary in order to achieve management-shared and coordinated resources which would in turn enable adequate decision-making. In order to make this vision a reality, it is necessary to implement technical studies, strategies, and programs which include long, medium and short-term visions. It is essential to create water resource management models designed to address the conditions associated with climate change and the variabilities derived from it. In this sense, the analysis of future climate scenarios in Colombia might offer valuable information. Along the same lines, there should be more vulnerability studies conducted on different physical aspects such as meteorological drought, water resources, forest ecosystems and coastal zones. Analysis of the productive sectors (including agriculture, energy, and industry) as well as of human settlements and the population will furthermore be very important in the coming years.

This research project is intended to create available technical information to address the problem of adaptation to climate change on the eastern side of Colombia. These results will be useful for development planners and decision makers when planning management strategies regarding to adaptation and mitigation of climate change for the studied regions

2. BACKGROUND

2.1. Global climate

The climate system is a complex system consisting of the atmosphere, the earth's surface, the hydrosphere (including the cryosphere) the lithosphere and the biosphere, and the interactions amongst them. The notion of climate refers to the state of the atmospheric component. Climate does not describe eventual episodes of the state of the atmosphere nor does it describe the temporal sequence of the particular states of the atmosphere. Climate describes the oscillation limits of the state variables that can characterize the components of the climate system. This includes recurrences of events, mean values and trends, i.e. statistics regarding the state of the climate system. Usually, the waiting period for the statistical definition of climate is 30 years (Chen & Chen 2013). Climate evolution is defined by internal dynamics of the climate system as well as external factors called climate forcings. These external factors include both endogenous terrestrial factors (such as volcanic eruptions) and exogenous factors (such as variations in levels of solar activity or changes in the eccentricity of Earth's orbit). Changes in the physical-chemical composition of the human-induced atmosphere are also to be included with these factors.

The energy source of the climate system is solar radiation. This radiation influences the energy content of the elements of the climate system. Elements of the climate system constantly exchange mass and energy. Thanks to the different sizes and thermal capacities of each link in this system, each of these components has different inertial characteristics. For the atmosphere, the time of energy relaxation is in the order of days; for the surface of the Earth, in months; the surface of the ocean, in years / tens of years; while the deepest depths of the ocean is in the order of hundreds of years. The energy balance of the earth defines the characteristics of the planetary climate. Changes in the balance of incoming and outgoing radiation cause changes in the statistical moments of the so-called climate balance. The radiative balance of the Earth is disturbed if the incident solar radiation is changed. For example, when the Earth’s orbit experiences changes, the Earth’s albedo also experiences changes. Additionally, changes in the structure of clouds, changes in the particulate composition of the atmosphere, or changes in the plant cover of the Earth's surface modify the emission of long-wave radiation from Earth (Stern et al. 2016).

2.2. Climate of South America

The chief controlling factors of the climate of South America include: the triangular shape of the continent, which is most broad near the equator and narrows as one moves southward; the lofty mountain ranges which run along the continent’s western border; and the cold ocean current off of the Pacific coast. The broadening of the land-mass near the equator in addition to the absence of high mountains along the Atlantic coastline exposes the greater portion of the vast northern and northeastern sections of the continent to the influence of the northeast and southeast trades. This ensures a remarkably uniform climate with very small temperature ranges over the whole region (Garreaud et al. 2009). The mountains running along the west coast of South America encourage rainfall on their windward slopes and form a clearly defined barrier between the climates of the narrow Pacific coastal zone and those of the eastern slopes and plains. The mean annual ranges of temperature are very small throughout South America. Over the northern portion of the continent (including Peru, northern Bolivia, and the greater portion of Brazil). South of the Tropic of Capricorn and east of the Andes, the ranges increase to between 30° and 40° in northern Argentina. By contrast to these larger ranges in the continental interior on the eastern side of the Andes, the mean annual ranges in Chile are less than 20°.

The entirety of the narrow western coastal strip thus has a very moderate climate. Even in the higher latitudes, the winters are very mild and the summers distinctly cool (Marengo et al. 2009). One of the most noteworthy facts in connection with the temperatures of South America is the negative temperatures found near the equator off of the western coastline; at - 10°, this anomaly is due to the Peruvian or Humboldt Current: a cold ocean water stream flowing up from the Antarctic. The effect of this cold water upon the temperature of the continent is seen in the presence of a negative anomaly of more than 2° along the coasts of both Chile and Peru.

The west coast, located within the trade-wind latitudes from about 4° to about 30° south, is very dry. This region is shut off from the trade winds and the great Cordillera mountain ranges on the east and has prevailing southerly winds. As long as southerly winds and a cool ocean current follow the coast, the coastal strip will be both dry and barren. As soon as the winds and current turn away from the shore, the previously barren shores will become covered in vegetation. Analogous examples can be observed on the western coast of the North American continent and the western coast of the African continent. Although it very seldom rains along the desert coastal strip, rain and snowfall do occur on the mountains of Peru and Bolivia during the summer. North of latitudes 3°/4° South, there is abundant rainfall from the equatorial rain belt. This rainfall amounts up to 160 inches a year on the Colombian coast located north of the equator (Garreaud 2009).

2.3. Climate of Colombia and atmospheric circulation patterns

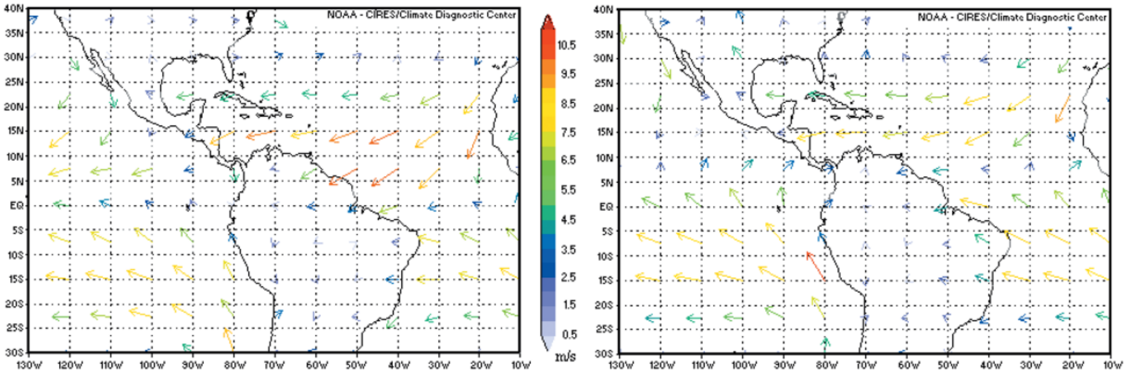
Colombia's specific geographical location in the tropical zone makes this territory a region that is highly receptive to the energy that the Sun transfers to Earth. Most of the Earth's solar energy is absorbed in the tropics alone. This energy is transferred to the atmosphere which sets up the engine that determines the displacement of air between the equatorial and polar latitudes through a southern circulation (Ruiz et al. 2018). In the tropical zone winds are developed near the Earth's surface from the northeast and southeast; these winds are commonly referred to as trade winds, and they are a direct result of the Coriolis Effect generated by the Earth's rotation around the axis that passes through its poles. The encounter of these winds near the equator forces the equatorial warm air to rise, according to the so-called ascending branch of Hadley's Cell. This upward movement causes the air to cool by expansion, a condition that favors condensation and therefore induces the development of clouds (IDEAM, 2005).

In the high troposphere, air moves away from the equator in the form of a return current towards the poles; again, the force of the Coriolis Effect intervenes causing a deviation from this current. In the northern hemisphere, the direction of that current is progressively oriented towards the northeast; whereas in the southern hemisphere, the direction of that current is progressively oriented towards the southeast. Some of this air descends back into the belts of high subtropical pressures at up to 30° latitude. This causes the compressed air to heat and reduces cloud development. In the vicinity of the surface, the winds in these regions are generally variable and weak before they become the trade winds that will afterwards reach Ecuador. In this way, a southern circuit is formed in each hemisphere in the movement of air through a large convective cell known as Hadley's Cell. Another part of the returning air coming from Ecuador does not undergo this downward movement at the 30° latitudes; here, the movement of air continues to higher latitudes, until the persistent action of the Coriolis Effect's force transforms this return current into a west flow at the mid-latitudes. In the zonal circulation along the parallels, there are three convection and rain zones (Dargan et al. 2007). The first zone is located in the Congo region of Africa; the second zone is located over the Amazon; and the third zone is located over Southeast Asia, where also the warmest ocean waters are also located.

2.3.1. Trade Winds

The trade winds blow throughout almost all tropical regions that extend between high-pressure belts and low equatorial pressures. In the northern hemisphere, the air heading towards the equator is diverted to the right by the force of the Coriolis Effect and forms the Northeast Trade Winds. Similarly, in the southern hemisphere, the deviation to the left forms the Southeast Trade Winds. These winds may vary in direction by local topography and friction effects; however, they are known for their persistence and regularity (Vera et al. 2006). Over the oceans, they are characterized by the presence of cluster clouds whose base is about one kilometer away and its top up to two kilometers high.

The drop of air (subsidence) in the subtropical high-pressure belts produces the inversion of temperature that persists in a part of the air's path to the equator. This in turn separates the moist air from the trade winds, located below, from the warm and very dry air located above. This investment acts as a kind of cap that limits the development of clouds, especially over the oceans. As air approaches the equator, the Northeast and Southeast Trade Winds converge over a narrow area called the Inner Tropical Convergence Zone - ITCZ; in this zone the inversion weakens and the air rises, this is observed in Fig. 1. The vertical development of the clouds increases, and the instability extends to higher altitudes. Precipitation becomes both stronger and more frequent.



February

August

Figure 1. Average surface wind fields for the months of February and August, based on the Reanalysis data NCEP / NCAR, for the period 1968-1996. Adapted from Climatological Atlas of Colombia (in Spanish), Retrieved July 18, 2019, from http://documentacion.ideam.gov.co/openbiblio/bvirtual/019711/AtlasClimatico1.pdf

2.3.2. The Inner Tropical Convergence Zone

The ITCZ is defined as a narrow zonal band of vigorous convection. It is manifested through the development of clusters- which has been widely confirmed by the use of satellite images. The ITCZ furthermore signals the convergence between the air of the northern and southern hemispheres. At the ITCZ, northeast trade winds (originating as a flow around the upper North Atlantic) meet the southeastern trade winds (formed as a flow around the high South Pacific and South Atlantic). The flow from the upper South Pacific routinely crosses the equator and recurves to the east. In such cases, these winds are known as the “equatorial southwests” or “wests”, as is frequently seen on Colombia's Pacific coast. Due to the convergent flow, the ITCZ is an area that experiences maximum cloud coverage and rain (Armenteras-Pascual et al 2011).

Observations have indicated that within the ITCZ, precipitation greatly exceeds the moisture supplied by evaporation from the ocean below. Thus, much of the steam needed to maintain convection in the ITCZ is supplied by the convergent flow of tropical Easter trade winds in the low troposphere. This large-scale flow provides the latent heat needed for convection; convective heating in turn produces the large-scale pressure field that maintains low-level flow. In fact, the ITCZ rarely appears over the oceans as a long continuous band of compact convective cloudiness, and it is almost never centered in Ecuador. Rather, it consists of a number of different clusters of clouds at a scale of hundreds of kilometers which are separated by relatively clear sky regions (Münnich and Neelin 2005). The intensity of the ITCZ is also very variable: both in space and in time. The Inner Tropical Convergence Zone moves latitudinally, following the apparent displacement of the Sun with respect to the Earth with a delay of approximately two months. Over Colombia and neighboring areas (Fig. 5), the segment of the eastern Pacific Ocean reaches its extreme southern position at 2° North in latitude between January and February. While in December, this segment is located a little further north, but this extreme position can reach 5° South in latitude during El Niño-Southern Oscillation events.

The continental segment appears to be both fractional and independent of the previous one, it is located between 5° and 10°South in latitude. Between March and May, the Pacific segment moves towards the north and its position near the coast is between 2° and 7° North in latitude. The mainland branch connects with the Atlantic Ocean segment between March and April forming a single system that ranks between 5° South in latitude and 1° North in latitude to the eastern portion of the country. These two segments are joined through poorly-organized convective conglomerates over the Andean region (Garcia and Kayano 2010). The Pacific segment at the beginning of June is located at 8° North in latitude; by the end of August, the Pacific segment is located at 10° North in latitude. Throughout this transition period, the Pacific segment penetrates the Caribbean region. The continental segment presents a Southwest-Northeast inclination over the eastern border of the national territory, moving northwards from Ecuador to 8° North in latitude. Between September and November, the Pacific segment begins its southward shift and positions are recorded from 11° to 7° North in latitude. Around this time, the continental branch also begins its journey southward, moving from the position of 8° North in latitude to Ecuador over the Orinoquia and Amazon regions. Here, it slowly loses its inclination until it almost coincides with the lines of the parallels. In this situation, the two segments of the ITCZ are also connected by means of convective clusters. Average location of ITCZ in January and July is shown in Fig. 2. As it passes through the different regions, the ITCZ determines the rainy seasons in Colombia.

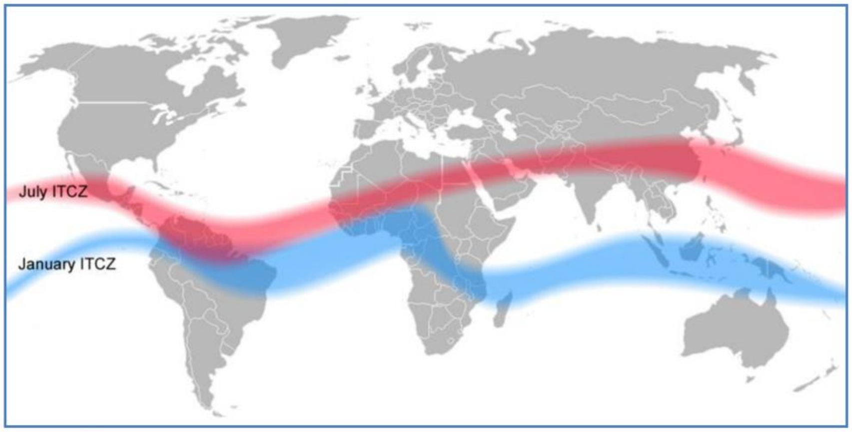


Figure 1. Average position of the ITCZ for the periods January and July. Adapted from Climatological Atlas of Colombia (in Spanish), Retrieved August 18, 2019, from http://documentacion.ideam.gov.co/openbiblio/bvirtual/019711/AtlasClimatico1.pdf

2.3.3. Amazon Synoptic Systems

Between May and November (particularly in the middle of the calendar year), it is relatively common for cold frontal areas to move to areas that are close to 20° in latitude. Over the oceans, cold air is significantly modified through warming on sea surfaces which weakens the front in its movement towards the equator. While over surfaces of water, transformation is slower, becoming an increasingly shallow frontal area. At the ends of these frontal areas, winds tend to come from the east on both sides of the front, however, the speeds tend to be higher on the cold side. These areas have been referred to as shear zones. The ends of cold masses of air can cause large time disturbances at the local level.

In South America, cold masses often move between 5° latitude while occasionally crossing over the equator. Cold air temperatures tend to stay more over this area longer than over the ocean. Cold masses commonly advance faster and further north along the eastern sides of the barrier formed by the Andes Mountains. As this air moves into tropical areas, it becomes unstable and forms lines of instability, which in turn gives rise to organized convection in the Colombian Amazon (Poveda et al. 2006). Occasionally when these systems are particularly intense, they can change the states of the weather along the Cordillera Oriental and parts of the Colombian Orinoquia. This situation is reinforced by dynamic conditions of the high troposphere. This is characterized by strong westerly winds and subtropical jet stream. The subtropical jet stream is a weather phenomenon in which the air mass moves northeast crossing into areas of lower pressure thus intensifying winds during the winter season of the northern hemisphere. Another system that directly influences the atmospheric circulation of the southeast of the country is the Amazon Low (Ruiz et al. 2018). The Amazon Low corresponds to the low-pressure system at low levels of the Amazon basin. Its origins are rooted in the latent heat of the condensation and the complementary effect that the Andes Mountains have in channelling the flow of the Northeast trade winds. This semi-permanent system moves from northern Bolivia (1,008 hPa) in January to the extreme southeast of Colombia (1,011 to 1,015 hPa) in July. This movement combined with the march of the solar cycle to the north results in a weakening of the low over the Amazon basin. This low intensifies convection and consequently precipitation in southern Colombia. It is furthermore responsible for the temporary displacement of the Inner Tropical Convergence Zone to the south. During these unusual events, we observe southerly winds over the southeast of Colombia and southern Venezuela (Santos et al. 2017).

2.3.4. Mesoscale Convective Systems and local climate factors

Convection is the main raining process in the tropics as the most important mechanism for heat transport to higher levels. Convection also provides the basic link for maintaining the general circulation of the atmosphere. The convective clouds in the tropics change their distribution, height, and thickness day by day. They are often organized in bands which are parallel or perpendicular to the wind. Although in some cases, they show no apparent organization. The satellite images have shown large convective conglomerates, almost stationary, in the interior of South America (particularly over the Amazon and over the eastern part of the tropical Pacific Ocean) during the rainy season- especially throughout the months of May and June. These convective systems are very similar to those of mid-latitudes, have a minimum life cycle of 18 to 36 hours, and result in cloudy skies with precipitation of varied intensity (Santos et al. 2017). They therefore decrease the daytime amplitude of the temperature from the absence of direct solar radiation.

Weather and weather-identifying characteristics don't just depend on large-scale atmospheric circulation. They are also conditioned by local particularities. These particularities include: those that result from the effects associated with the differentiation between the physical behavior of land, water, valley, and mountain surfaces; those caused by mountainous barriers to atmospheric circulation; and also, by those resulting from territory modified by land use as is the case with accelerated urban development (Beniston 2006).

2.3.5. Land-Sea Breeze

The thermal properties of the earth and water are different. The earth and the objects above it will heat up and cool down quickly; however, water does these slowly. Water temperatures do not vary much from day to day or week to week; the most significant changes are seasonal in nature. As the sun radiates over the earth-water interface, solar radiation penetrates several meters through the water. Solar radiation reaching the Earth's surface will only heat the first few meters, and at that, quickly. Adjacent air heats up, becomes less dense and rises. Cold air over water moves inland and local circulation develops from the water (sea, lakes and wide rivers), known as "sea breeze" or "water-to-land breeze. At night, the air on the earth cools rapidly due to irradiation, which causes the earth's temperature to drop faster than that of the adjacent body of Water. This creates a return flow called "land breeze" (Ortiz et al. 2018). Wind speeds in a terrestrial breeze are light while wind speeds at sea can be very accelerated. Differential pressure on land and water causes sea breezes. With these sea breezes (during the day), the pressure on the heated ground is less than the pressure on the colder water. In contrast, with the earthly breezes (at night) the opposite happens.

2.3.6. Mountain-Valley Breeze

The mountains and valleys are unevenly heated throughout the day. In the early hours of the morning, the sun warms and illuminates one eastern side of the mountain, while the other side still remains dark and cold. The air rises above the illuminated side and descends on the dark side. At noon, the sun's rays fall on both sides and warm them up. At the end of the afternoon, the situation is similar to that which occurs in the morning, but in reverse. After dark, as the air cools due to earth's cooling, the air descends into the valley from the highest hills (Tian et al. 2005). This differential warming generates rising winds, this can be observed in Fig. 3.

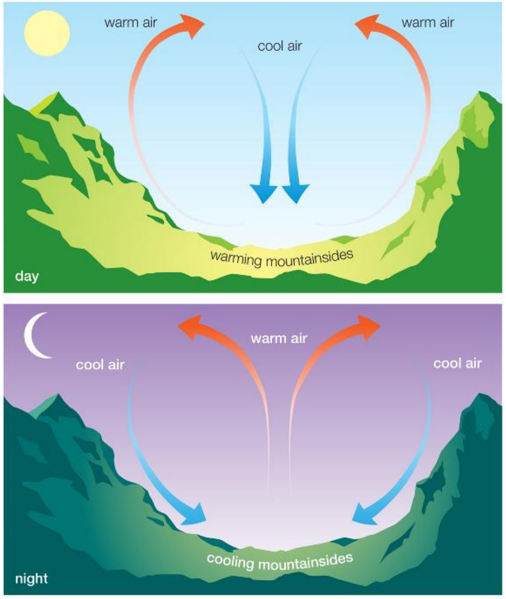


Figure 3. Valley and mountain breeze. Adapted from Encyclopedia Britannica, Retrieved November 28, 2019, from https://www.britannica.com/science/valley-breeze

2.3.7. Orographic Ascent

Air tends to rise over an obstacle that presents itself in its path. Although sometimes, air tries to make its way around the different sides of the obstacle. If an inversion of high temperature (warm air over cold air) covers the highest elevation, then the air will try to find its way along the sides of the mountain. When airflow is blocked, air recirculation occurs. During the night, the hills and mountains produce downward wind flows because the air is colder at higher elevations. The downwinds are usually light. However, under the right conditions, faster winds can occur (Roe 2005). Effects of orographic ascent over Colombia can be seen in the Fig. 4.

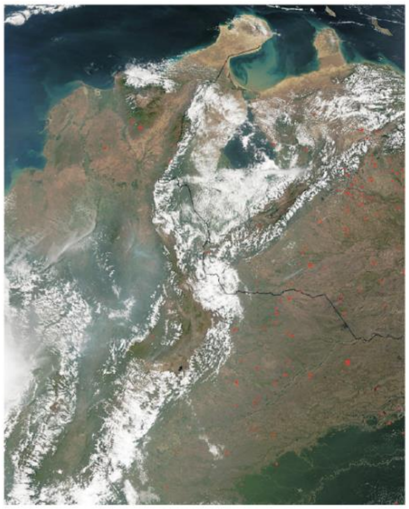


Figure 4. Orographic clouds formed in the Central and eastern Cordilleras observed from satellite images from 13.03.2004. Adapted from Climatological Atlas of Colombia (in Spanish), Retrieved December 10, 2019, from http://documentacion.ideam.gov.co/openbiblio/bvirtual/019711/AtlasClimatico1.pdf

2.4. Climate Variability

The climates in Colombia are characterized for having tropical rainforests, savannas, steppes, deserts and mountain climate, mountain climate further divided into hot, temperate, cold and Paramo. Sometimes, the weather of Colombia is altered by the seasons in the northern hemisphere. Annual precipitation in Colombia is distributed in areas with low values (less than 500mm per year) in the Guajira, to sectors with rainfall exceeding 9000mm per year (especially in sectors of the Pacific region). The Caribbean Region is characterized by rainfall between May and November; coinciding with the Eastern Wave Season and tropical cyclones; the last twin (October - November) being the maximum of precipitation volumes. The Andean region is partially monomodal and in other bimodal regions with two precipitation maximums especially associated with the double pass of the main system governing precipitation in Colombia, the ITCZ (Ruiz et al 2008). The first time of focus is structured on the period of April-May and the second time of focus is structured on the period of October-November. The Eastern Plains and the Amazon manifest a precipitation of a monomodal type. The Amazon receives its precipitation maximums in the middle of the year, while the Eastern Plaines receive its precipitation maximums at the beginning of the year when the ITCZ is located in the south of the country. Meanwhile, the peaceful region is characterized by maintaining near-constant rainfall throughout the year.

The average temperature in Colombia is highly influenced by the orography, and each region maintains an average temperature throughout the year (Mattar et al. 2013). The orography causes the higher temperature to be lower and vice versa. For this reason, it is represented by the thermal floors. A major phenomenon causing year-on-year climate variability is the so-called El Niño-Southern Oscillation - ENSO and La Niña phenomenon. These phenomena cause considerable variations in precipitation (at the local level) in Colombia. However, as mentioned before, the climate variability phenomena that most strongly govern Colombia's climate are largely controlled by the ITCZ and also by the dynamics of the Pacific and Atlantic Oceans. This results in a complex hydrological response that, among other aspects, makes it difficult to build climate change scenarios, (or rather scenarios which support decision-making to determine water resource behavior) in the face of pressures of climate change climate variability with low levels of uncertainty. Colombia has precipitation and climate variability regimes across the entire country. With such variable seasonality between regions, the effects of climate change are not homogeneously perceived in the Colombian territory (IDEAM 2005).

2.5. Colombian Meteorological Network

The weather network in Colombia consists of the set of stations conveniently distributed throughout Colombia where different phenomena and atmospheric elements necessary in determining the state of time and climate in the different regions are observed, measured, and/or recorded.

Currently, weather observation, weather measurement, and weather monitoring systems in Colombia are operated by the Institute of Hydrology, Meteorology and Environmental Studies of Colombia – IDEAM. For administrative purposes, the network is operated through different operational areas, located in the main cities of the country (IDEAM 2015). The networks that make up the National Meteorological Network are classified into different groups according to their function. Below is a brief description of these networks, all of which can be seen in Figure 5.
<u>Pluviometric Network:</u> It is the most covered network nationally and consists of 1,315 active stations, where the precipitation is measured through the use of continuous records (rain gauges).
<u>Climate Network:</u> This network is made up of the so-called weather stations in which other weather-related variables- such as temperature, air humidity characteristics, solar brightness, and wind (direction, travel, and evaporation are observed in order to obtain the variability)- are used for climate monitoring and study. In these weather stations, data is taken three times per day or continuously recorded.
<u>Agrometeorological Network:</u> The stations are distributed in existing agricultural areas and located within experimental stations or applied research institutes dedicated to agriculture, horticulture, livestock, forestry and edaphology.

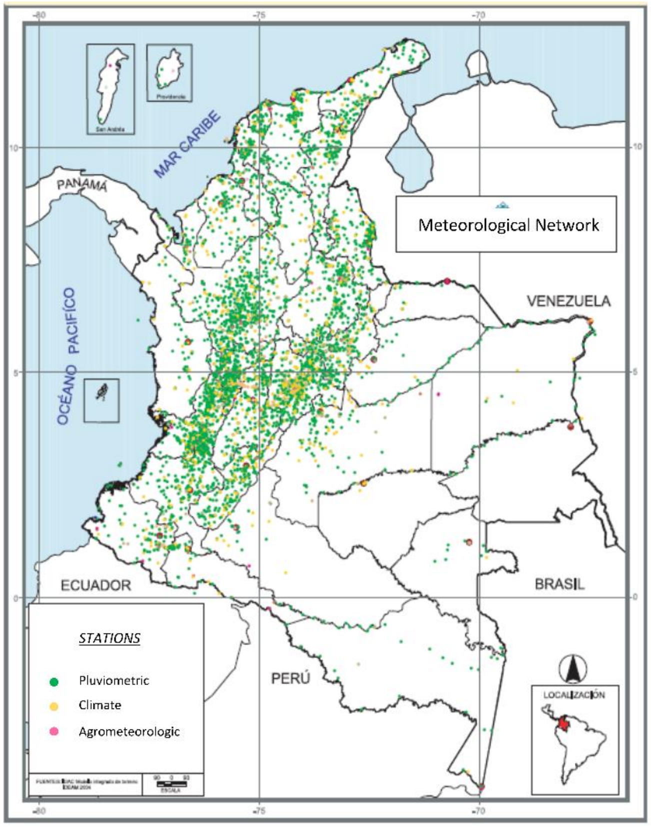


Figure 5. Meteorological network in Colombia. Adapted from Colombian Water National Study (in spanish), Retrieved December 18, 2019, from http://www.ideam.gov.co/solicitud-de-informacion

3. STUDY AREA

This analysis is focused on the macro water districts located throughout the eastern region of Colombia which are both distributed in different climate zones and which have varied geographical characteristics. A macro water district is a local area that includes several watersheds. It is delimited on a geographical, economic, and political basis and planned to maintain a constant water supply for the cities, municipalities, and communities that are located in its area. The east side of Colombia is hot in most of its extension, with average temperatures ranging from12 to 34°C. The eastern side of the country borders Venezuela; the Amazon is located to the south; extensive valleys and the Andean mountains are located on the mid-eastern side; and coastal plains are located towards the higher north (Ruiz 2008). Along the eastern side of the country, many different climates can be observed ranging from desert climates to super-humid climates. Moreover, in some of the water districts located throughout this area, different climate conditions coexist with each other. A more complete description of the climate over this region can be found in the articles presented in the chapter 7. The area of the water districts in the eastern region has extensions ranging from 2245 km2 and up to 42,650 km2. The topography along the studied area is highly variable and includes the Andean Mountains in the middle northeast, the coastal plains to the high north, and extensive valleys to the southeast (Sanchez-Cuervo et al. 2012).

The analysis conducted in the first article of this project (section 7.1) led to the focus into four representative areas. These areas were characterized as individual water districts (all located throughout the east side and middle regions of Colombia) with different geographic and climatic conditions. They were selected due to each region’s variability of geographic and climate and climate conditions and the availability of enough data for analysis. The delimitation of these water districts is shown in the Figure 1 together with the climate classification of the country made regarding the Lang’s index; I = Pr/Tm, where Pr is the mean annual precipitation amount and Tm is the mean annual temperature. These regions are named: Alta Guajira, Bajo Meta, Rio Catatumbo and Sabana de Bogota and lie between 74°56′13” and 66°82′29” west longitude, and between 12°24′40” north and 2°18′25” south latitudes. A brief description of these four regions will be discussed in detail in the following paragraphs.

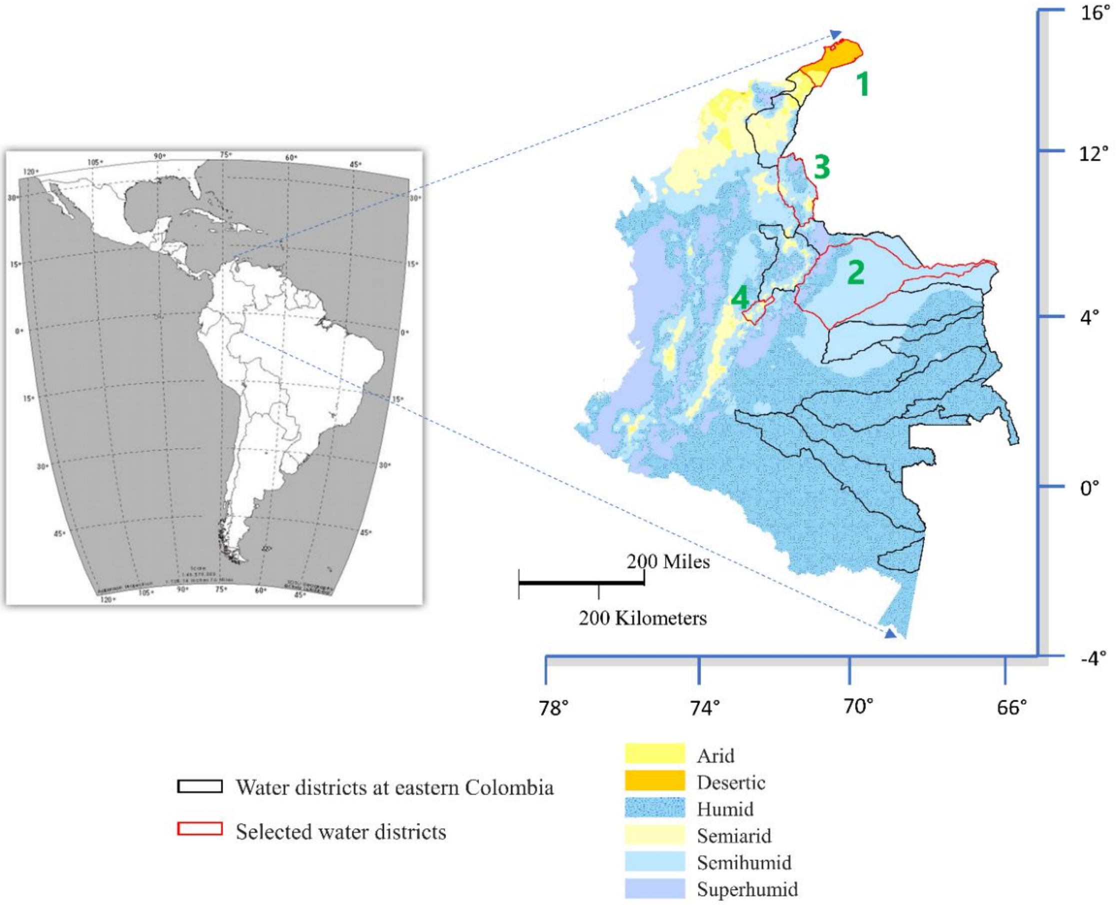


Figure 6. Location of water districts at eastern Colombia. 1) Alta Guajira, 2) Bajo Meta, 3) Rio Catatumbo, 4) Sabana de Bogota

3.1. Alta Guajira

This region consists of arid plains, whose dryness is caused by the rain shadow of the Mountain Sierra Nevada de Santa Marta. The headwaters of the Cesar River are located to the far south; this water flows south towards the Magdalena River. Alta Guajira covers the northernmost part of the peninsula, with mostly scarce semi-desert vegetation. It has only one isolated, low-altitude mountain range, the Serranía of Macuira (865 m above sea level). The Middle Guajira region is mostly flat, with hills protruding in some areas; it also has a mostly arid environment. The temperature averages for La Guajira range between 22° and 30°C, with a maximum average temperature of up to 42°C. There is only rain between the months of September and December. The climate of La Guajira provides for a very typical semi-desert vegetation, consisting mostly of thorny shrubs and cactus. It is the driest area in Colombia.

The economy of the Region of La Guajira is based on the exploitation of mineral resources including but not limited to coal, natural gas, and salt. Utility industry production includes electricity, gas, potable water, transport and communications. Education, health, community service and domestic services account for 9.60% of the total revenue. The region also has activity in the industries of agriculture, silviculture, and fishing, followed by commerce, hotel, and restaurant industries. Additional commodities produced in this region include tobacco, coffee, yuca, plantain, coconuts, yam, arracacha, oil palm, and sugar (Vides-Prado et al. 2018).

3.2. Bajo Meta

The territory of Bajo Meta consists of a mountainous part and the foothill-plains. The mountainous part lies to the west, on the slopes of the Eastern mountain range, and rises to heights of 4,000 m above sea level. The flattest part is located in the center and east of the region, with heights ranging from 110 m to 230 m. This area is covered by forest. The vegetation found in Bajo Meta consists mostly of that found in natural savannah environments. However, exceptions are given to the mountainous environments and their foothills. Here, the soil is fertile and suitable for agriculture. The flatter regions of Bajo Meta do not have this advantage since they are prone to flooding throughout the year. The Casanare's hydrographic network is made up of rivers, streams and pipes that drain west-east towards the Meta River.

The temperature in Bajo Meta ranges from 22 to 27°C. The climate changes from a humid climate in the foothill Plain, a cold climate in the Andean Mountains, and a tropical climate in the savannah area (about 27°C, rainy in winter, dry in summer). Traditionally ranching, livestock, and rice cultivation have all been very important industries in the territory of Casanare in Bajo Meta. The oil industry (in particular drilling) has also been a prominent industry of Bajo Meta (Richani 2010).

3.3. Rio Catatumbo

Rio Catatumbo has a distinct, varied geographic landscape. The landscape of this region is composed of mountainous areas, deserts, plateaus, plains, as well as hills. The landscape and climate create an environment that is fertile. The territory is criss-crossed by rivers and lagoons. The zone around the Catatumbo River has temperatures averaging 24 °C; the climate here is both warm and humid. The zone around the city of Cúcuta has a climate that varies from dry to very dry. In the mountainous areas, the climate can vary from temperate to cold.

A rich hydrographic system crosses the region. This hydrographic system contains three river basins of great importance: the Catatumbo river is located to the north, the Magdalena river is located to the west, and the Orinoco river is located in the southwest. The economy of the region at Rio Catatumbo is supported by commercial activity, banking services, and the transport services sector which is dependent on activities on the international border. Rio Catatumbo has been exploited for its natural resources; these include resources such as coal (which is at times procured by illegal means), oil, and other resources. These activities and resources are the main focus and export of the region (Richani 2010). These resources are most often directed to neighboring countries such as Venezuela and Ecuador. Agriculture is also a stable basis of the economy with products such as cotton, rice, and tobacco.

3.4. Sabana de Bogota

Sabana de Bogota (which means Bogotá Savanna) is a montane savanna located in the southwestern part of the larger Andean Plateau in the center of Colombia. The Bogotá Savanna has an average altitude of 2,550 meters. The savanna is situated in the eastern ranges of the Colombian Andes. It is part of the watershed of Bogotá River. Other rivers, such as the Subachoque, Bojacá, Fucha, and Tunjuelo Rivers (all of which are tributaries of the Bogotá River), form smaller valleys with very fertile soil dedicated to agriculture and cattle breeding and production.

The average temperature of the Andean Plateau is 14 °C, however, this can fluctuate between 0° and 24 °C. The dry and rainy seasons alternate frequently during the year. Despite the continuous urbanization and industrial activities, the Bogotá Savanna is a rich biodiverse area with many registered bird species. The most outstanding natural resources of the Cundinamarca Department are coal and salt. The region also produces lime, iron, and sulfur (Acosta 2010).

4. CLIMATE CHANGE

4.1. Global climate change

Climate change, according to the definition by the Intergovernmental Panel on Climate Change - IPCC, refers to any change in climate over time whether due to natural variability or as a result of human activity (IPCC 2014). This definition is thought to clash with that given by the United Nations Framework Convention on Climate Change - UNFCCC. According to the latter's definition, climate change is a change of climate attributed directly or indirectly to human activity, that alters the composition of the global atmosphere, and that is in addition to natural climate variability over comparable time periods. For the Institute of Hydrology, Meteorology and Environmental Studies of Colombia – IDEAM, the change in the climate can determine differences in the average values of a climate factor, that is, its change can be shown as a new normal climate and, therefore, lead to an adjustment in human activities.

Over the past few years, multiple studies have reported the increase in the frequency and intensity of extreme phenomena of climate variability in the world. The International Disaster Centre indicated that between 1900 and 2005, the occurrence of disasters associated with hydrometeorological phenomena had grown exponentially, a trend that had been exacerbated since the 1970s and 1980s. It could be argued that from these disasters, the world began to face new risk, and that climate scenarios can be demonstrated regardless of the scientific certainty of the relationship between climate change and climate variability phenomena (Jones et al. 2004).

Global climate change is now one of humanity's greatest concerns. Global climate change has an enormous impact on the future sustainability of humanity's socio-economic and environmental development. Climate change was first strongly observed a few decades ago (Folland 1990). These different observations indicated that global warming of the planet had not only occurred over the last century, but also that there was an increase in extreme conditions resulting in droughts (Jones et al., 2004). All of these factors had consequent impacts on human health, food security, access to natural resources from population displacement. Based on these facts, the scientific community has made a great effort to develop models that allow the climate system to be simulated and capable of reproducing the observed changes in order to finally determine the factors that contribute to climate change. Furthermore, the scientific community hopes to analyze this information in different socio-economic emission scenarios that are used to drive models in the future. According to the IPCC, a climate change scenario is a climate response under an assumption of greenhouse gas emissions into the atmosphere; therefore, depending on the scenario analyzed, a different change in weather patterns, induced by higher or lower gas emission throughout the 21st century, is allowed (Solomon 2007).

4.2. Climate Change in Colombia

Colombia has been no stranger to dramatic changes in the global climate. Colombia, as a country with insignificant industrial development, does not emit a high enough quantity of greenhouse gases to qualify it as a decisive player on the impact of the composition of the planet's high atmosphere; however, the country is expected to be a very affected area with climate change. The Colombian Andes and other mountainous areas are particularly vulnerable to these changes (Barros 2008).

Long-term trends in climatological variables have been analyzed, especially air temperature and precipitation. (Pabon 2012; Benavides et al. 2007; Mayorga et al. 2011; Pabon 2003; MAVDT-IDEAM-UNDP 2010; Carvajal et al 2014). A synthesis of the results establishes that, during the second half of the 20th century, in various regions of the country the average air temperature will increase at a rate of 0.1-0.2° per decade, while precipitation presented changes between -4% and 6% per decade, although the sectors with decrease or increase are different according to the authors. One of the clearest expressions of global warming and climate change in the Colombian territory is the reduction of the area of mountain glaciers. Between 1940 and 1985, eight glaciers disappeared in Colombia. Recent estimates of glacial retreat (MAVDT-IDEAM-UNDP, 2010), based on observations from the first decade of the 21st century, indicate a rate of 20-25 meters per year and project a disappearance of glaciers by 2040s. A more detailed description and overview of the historical climate over the study-areas in this study can be seen in the articles shown in the section 7.1 and 7.2 of this report.

Industrial and economic activity in Colombia has been, as in many other countries, directly linked to climate change in reference to its generation, impact, mitigation, and adaptation. At the beginning of the last decade of the 20th century, there was extensive economic growth in Colombia (Perez et al. 2010). These large economic changes included significant tariff reduction, the elimination of prior licensing practices, the legality of private participation in supply and administration, easier access to external credit for businesses, as well as major developments in the public capitals of the country. In terms of vulnerability, the effects of this industry on climate change were negative; there were frequent problems with land compaction, and the ground experienced a reduction in water absorption. This made the land more vulnerable to increased erosion, reducing its capacity to regenerate itself.

5. WATER RESOURCES SITUATION IN COLOMBIA

5.1. Water Supply in Colombia

Water Supply is defined as the water available through water sources that deliver the water to the aqueducts that provide drinking water to the Colombian population. Colombia is recognized for its abundant availability of water resources. However, in hydrological terms the national territory is not homogeneous (Furlong 2013). The different hydrographic areas of the country harbor sensitive differences that affect the vulnerability of both the system as well as the socioeconomic structure. Only a few of the aqueducts are supplied with only groundwater, as seen in Figure 7; the vast majority of aqueducts are supplied with a surface source with groundwater coming in second as a source. Regarding the spatial distribution of the available water, this can be better visualized in Figure 8, where the distribution of yearly average water yield is shown; in this figure and the similar posterior figures, the analyzed water districts in this study are also located to have a general context for each region. The water yield is defined as the amount of freshwater derived from unregulated flow measurements for a given geographic area over a defined period of time. The freshwater flow (yield) is generated from a combination of base flow, interflow and overland flow originating from groundwater, precipitation, and/or snowpack (IDEAM 2015).

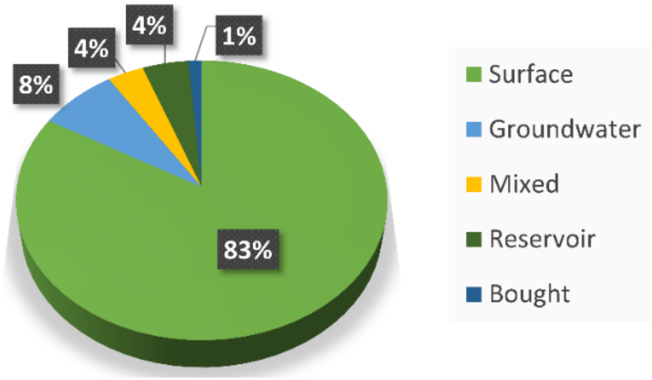


Figure 7. Sources of supplied water. Elaborated from Colombian Water National Study (in spanish), Retrieved December 15, 2019, from http://documentacion.ideam.gov.co/openbiblio/bvirtual/023080/ENA_2014.pdf.

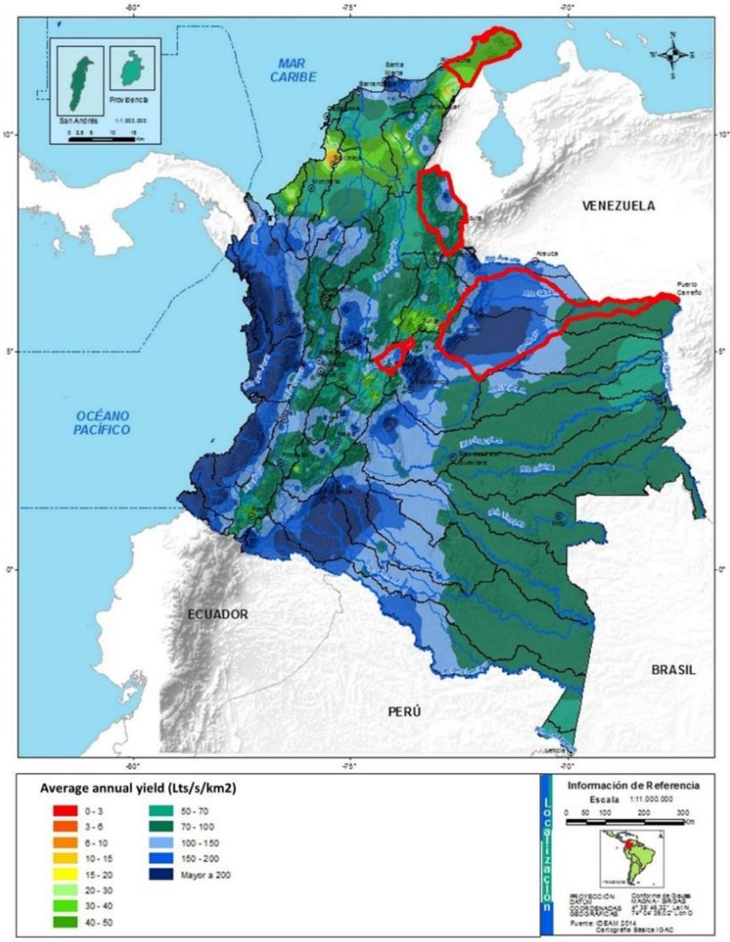


Figure 8. Average annual water yield in Colombia. Adapted from Colombian Water National Study (in spanish), Retrieved December 18, 2019, from http://documentacion.ideam.gov.co/openbiblio/bvirtual/023080/ENA_2014.pdf.

5.2. Water Demand in Colombia

The total water demand in Colombia corresponds to the sum of the volume of water used for the different purposes: domestic, services, preservation of fauna and flora, agricultural, livestock, recreational, industrial, energy, mining and hydrocarbons, fishing, mariculture and aquaculture, navigation, transport and return flow. In Figure 9, the estimated synthesis of water use for the year 2012 in Colombia is presented (Blanco 2008); the volumes of water used in the country are evaluated by productive sectors and as a whole. The values were calculated from the data provided by the National Study of Water (IDEAM 2015).

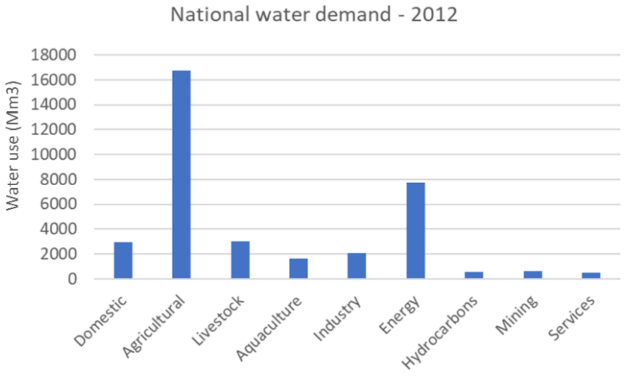


Figure 9. Sources of supplied water. Adapted from Colombian Water National Study (in spanish), Retrieved December 18, 2019, from http://documentacion.ideam.gov.co/openbiblio/bvirtual/023080/ENA_2014.pdf.

National water demand reached 35,987 million m3 (Mm3) in 2012 (IDEAM 2015). Figure 10 furthermore shows the average annual water demand for the entire Colombian territory; identifying the volumes of used water for activities as a whole. In 2012, the agricultural sector used 16,760.33 million m3 and 46.6% of the total volume of water used in the country; it is the sector that demands the most water resources in the country. Water use for power generation was estimated at 21.5%, the livestock sector estimated at 8.5%, and domestic use estimated at 8.3%. The concept of water use involves both extraction and also stored water not available for other uses.

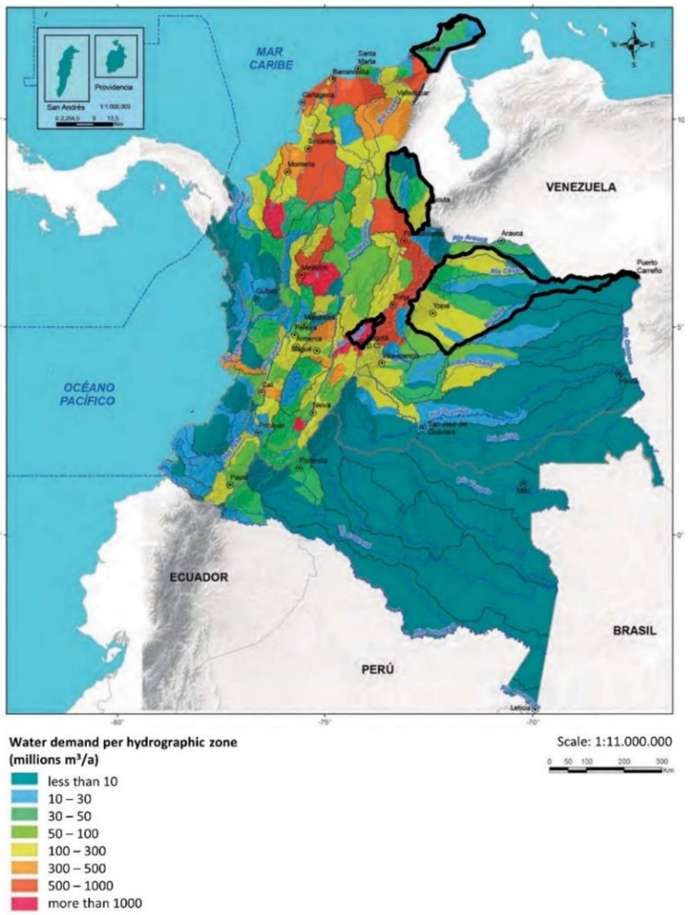


Figure 10. Water demand in Colombia. Adapted from Colombian Water National Study (in spanish), Retrieved December 15, 2019, from http://documentacion.ideam.gov.co/openbiblio/bvirtual/023080/ENA_2014.pdf.

5.3. Demographic growth

It is important to note that factors unrelated to climate change may have a comparable impact on water resources with regards to the same consequences of climate change. One such example is increased anthropogenic pressure on the resource hydric. In Colombia, population growth is already a threat to the current water resources. The steady increase of the Colombian population shown in the Figure 11 has reduced the annual per capita availability of water in Colombia from 60000 m3 per person per year in 1985 to only 40000 m3 per person per year in 2005 (Garcia 2015). If this trend continued, Colombia in only 40 years would have a water availability of 1000 m3 per person per year: this is in fact regarded internationally as a water scarcity crisis. When analyzing the population distribution throughout the Colombian territory. It has been observed that the highest demands for water are located in regions where the water supply is not very abundant. The productive sectors are strongly associated with these population densities. This suggests that the demand-to-water supply ratio is a vital factor in studying the state of the water resource and in projecting climate change scenarios. According to the population projections of the Colombian National Administrative Department of Statistics-DANE, the Colombian population will continue to grow, resulting in an increase in the demand for water in the country. Each Colombian, in addition to requiring water for their livelihood, requires water to sustain agriculture and industry that will provide them with the food, products, and services they demand throughout their life (Rosselli 2016). Higher water demands generate greater residual discharges, which unfortunately violates the quality of the water bodies in which they are discharged. Figure 12 also shows the influence of population growth on the four districts covered by this study.

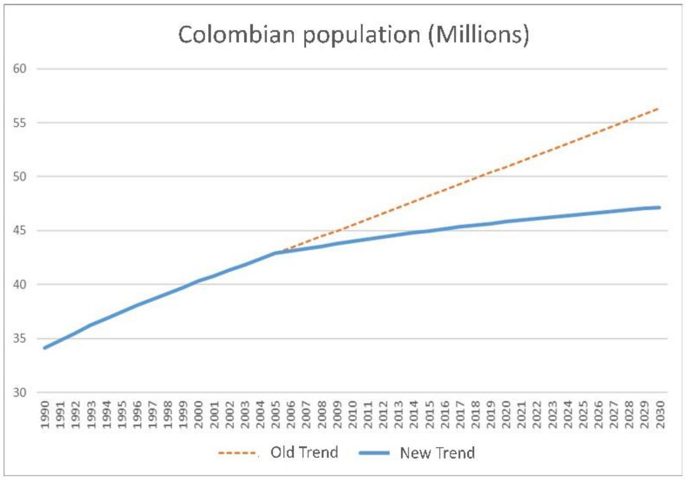


Figure 11. Trend of population growth. Adapted from New population data in Colombia (in spanish). Retrieved December 05, 2019, from https://focoeconomico.org/2019/04/02/nuevos-datos-de-poblacion-en-colombia-y-sus-implicancias-para-el-pib-tendencial/

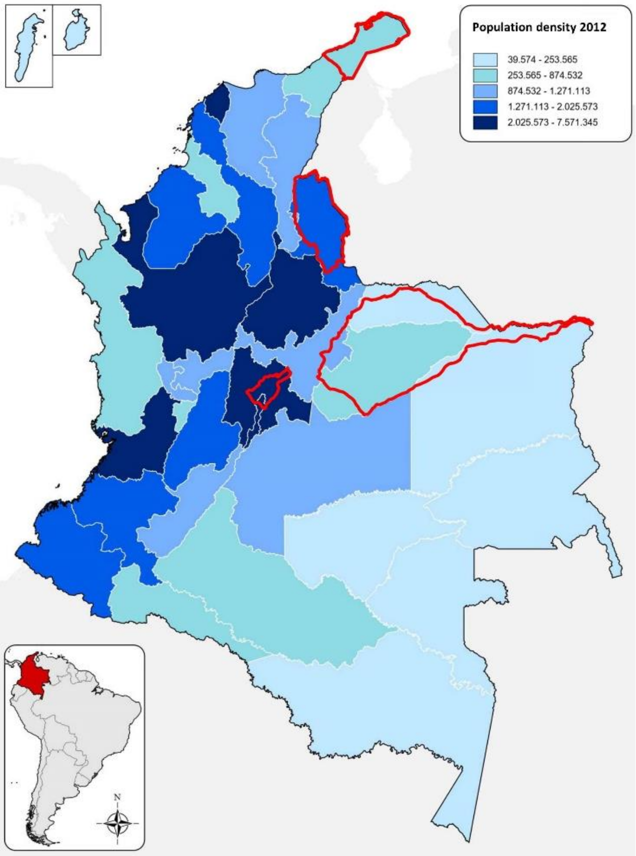


Figure 12. Population density in Colombia. Adapted from Population in Colombia, In Wikipedia, n.d., Retrieved November 15, 2019, from https://commons.wikimedia.org/wiki/File:Mapa_de_Colombia_(poblaci%C3%B3n_por_departamentos_2012).svg

5.4. Water Stress Index, WSI

The Water Stress Index - WSI is used in order to gain a clearer image of the relationship between water demand compared to the available water in a region (water supply). The WSI shows the amount of water used by different sectors in a given period (annual, monthly), and also through a spatial analysis unit (area, zone, subzone, etc.) in relation to the surface water available for the same temporal and space units (IDEAM 2015). It uses the following expression:

$$WSI = \left(\frac{Wd}{Sws}\right) * 100 \tag{1}$$

Where:
Sws = Surface water supply
Wd = Water demand, being Water demand the volume of water extracted for sectoral uses within a given period

$$Wd = \mathrm{Ch} + \mathrm{Cag} + \mathrm{Cin} + \mathrm{Css} + \mathrm{Cea} + \mathrm{Ce} + \mathrm{Ca} + \mathrm{Uea} \tag{2}$$

Where:
Ch: Human or domestic consumption
Cag: Agricultural sector consumption
Cin: Industrial sector consumption
Css: Consumption of the service sector
Ce: Energy sector consumption
Ca: Consumption of the acuicola sector
Uea: unconsumed extracted water

The spatial representation of the results of the average value of this indicator by region is illustrated in Figure 13.

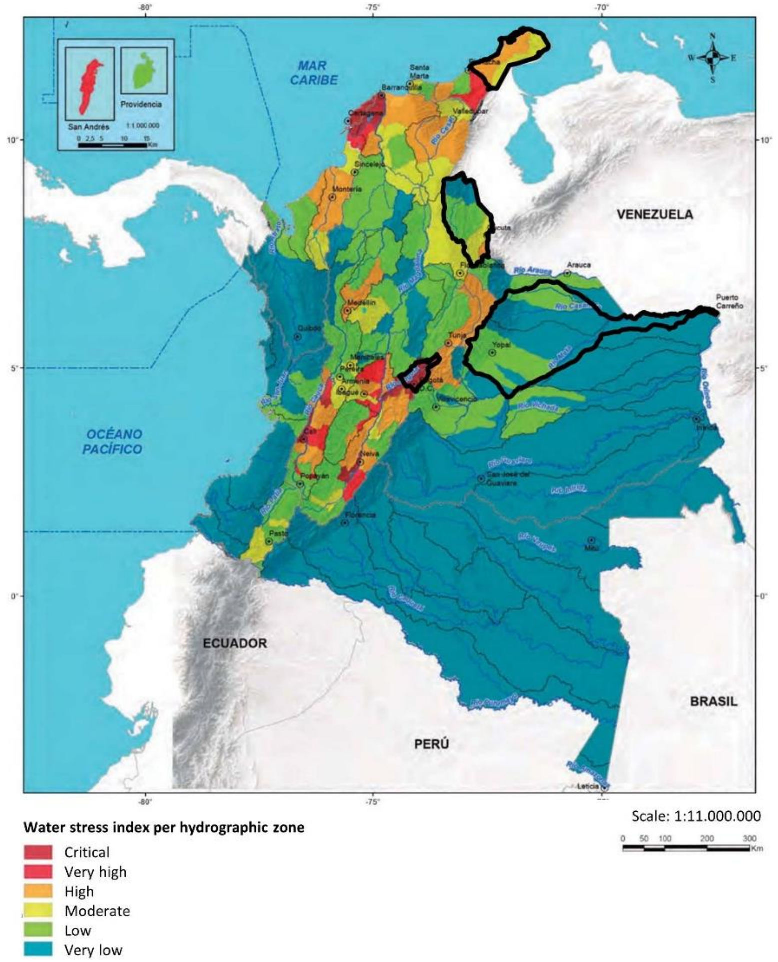


Figure 13. Water Stress Index – distribution. Adapted from Colombian Water National Study (in spanish), Retrieved December 18, 2019, from http://documentacion.ideam.gov.co/openbiblio/bvirtual/023080/ENA_2014.pdf.

5.5. Water Vulnerability Index, WVI:

The hydrological impact that climate change or any other factor that generates a water shortage within socio-economic sectors also depends on the level of vulnerability for each sector. This vulnerability can be represented through the Water Vulnerability Index - WVI. This indicator measures the degree of fragility of the hydro-system to maintain a necessary water supply, that in the case of threats such as long periods of drought or events such as el Nino, it could pose risks for shortages. (IDEAM 2015). The WVI is determined through a matrix of the relationship ranks between the Water Stress Index – WSI and the Water Retention Index – WRI. The categories of the WVI index are presented in Table 1 and the distribution of this index throughout the Colombian territory including the four water districts analyzed in this study can be seen in Figure 14. The WRI Index is a composite indicator developed to assess the capacity of the landscape to regulate and retain water passing through it. This indicator shows where there could be a deficit in the capacity of the landscape to retain water which, combined with rainfall extremes, could lead to higher flood risk or water scarcity.

Table 1. Categories of Water Vulnerability Index

WSI		**WIR**			
Value	Categorie	High	Moderate	Low	Very low
< 1	Very low	Very low	Low	Medium	Medium
1 - 10	Low	Low	Low	Medium	Medium
10 - 20	Moderate	Medium	Medium	High	High
20 - 50	High	Medium	High	High	Very high
50 - 100	Very high	Medium	High	High	Very high
> 100	Critic	Very high	Very high	Very high	Very high

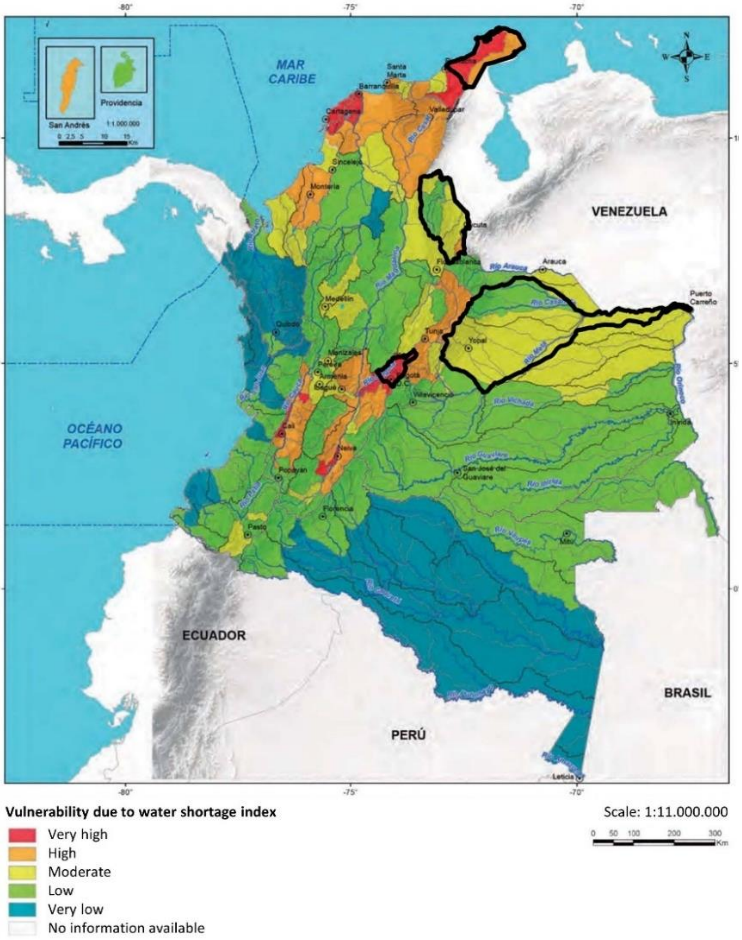


Figure 14. Water Vulneravility Index – distribution. Adapted from Colombian Water National Study (in spanish), Retrieved December 18, 2019, from http://documentacion.ideam.gov.co/openbiblio/bvirtual/023080/ENA_2014.pdf.

5.6. Hydropower Generation in Colombia

It is important to analyze the demand and supply of electricity in Colombia because the largest source of generation within Colombia is the country's hydraulic resources. If this resource is affected or decreased in the future, this could have a huge impact on the energy sector. A decrease in Colombia's hydraulic resources would significantly affect the country's growing economy and high demand for electricity.

5.6.1. Electric Energy Demand

The behavior of Colombia's electricity has always been closely related to the country's economic behavior. Every discontinuity in the percentage of growth in Figure 15 represents a major economic event, such as the 1992 electricity rationing, the 1999 economic recession, and the 2009 economic slowdown. According to the Colombian Energy Mining Planning Unit - UPME demand projections, an average growth of 2.9% is expected by 2020-2030 and higher growth for the following declines (Macias & Andrade 2013).

The central region of the country (where the district Sabana de Bogota is located) is where most of the hydroelectric generation is produced. This region experiences rainfall ranging from 1500 mm per year in inter-Andean valleys to 4000 mm per year in highlands and forests. This together with the mountainous geography that facilitates the construction of reservoirs has led to the development of the electrical system based on hydraulic generation (Tran et al. 2015). Currently, Colombia has an installed capacity of about 14.4 GW of which 69.9% is hydraulic generation, 24.8% gas thermal, 4.9% coal-fired thermal, 0.4% cogenerators and 0.1% wind, a graphical representation can be observed in the Figure 15.

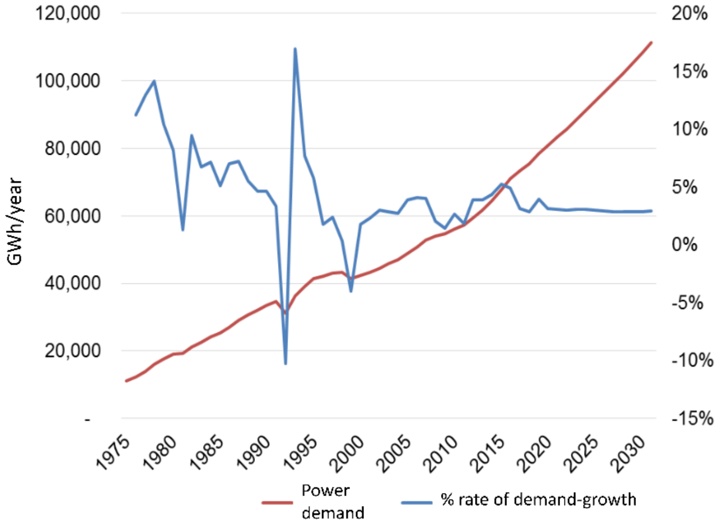


Figure 15. Trend of Energy demand in Colombia. Adapted from Study of Electricity Generation in Colombia under Climate Change Scenario (in spanish), Retrieved November 11, 2019, from http://www1.upme.gov.co/Documents/generacion_electrica_bajo_escenarios_cambio_climatico.pdf

5.6.2. Sources of power generation

Considering how important the hydrology system is to the country's energy supply; the following describes how its hydroelectric generation regime is constituted. Hydrological inputs that power the electrical system are concentrated in the Northwest and Central region (where the district Sabana de Bogota is located). As mentioned above, the region's level of input has been significantly affected by climatic phenomena, with notable instances occurring in the years 1997-98 and 2009-10.

In the year 2012, 44.737 million m3 water was used for the generation of hydropower. Of this,42,857 million m3 was used to generate large power plants and 1.880 billion m3 to generate small power plants. From this large volume, 97% was used to generate and almost immediately return water to water sources. The use of water for power generation is mainly concentrated in the central region of the national territory (Macias & Andrade 2013).

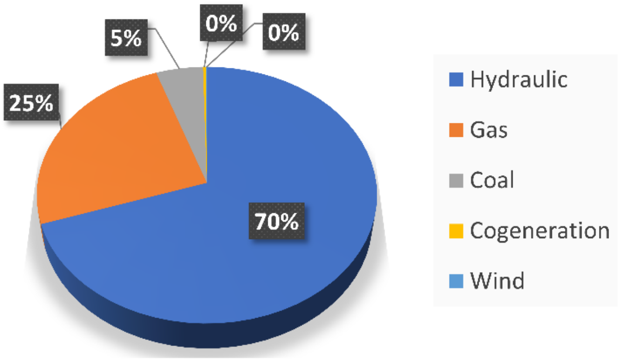


Figure 16. Sources of Energy generation in Colombia

If constant climate change generated a decrease in rainfall in Colombia, the country would be very likely to experience an energy deficit. Such a deficit would have a strong impact on economic development (Caspary 2009). The reduction in energy generation over time could result in higher production costs which might, in turn, be passed on to consumers; furthermore, this could cause an imbalance in the supply-demand ratio that affects all users and sectors who depend upon the water resource and the energy it generates.

6. METHODS

In the next paragraphs a brief description is made of the two main methods used in the development of the work that became the published articles, which are the core-work of this research project. These are the regional climate modeling-downscaling and the water-budget modeling.

6.1. Climate Modelling - Downscaling

Global Climate Models (GCMs) have been used for the purpose of estimating the effect that greenhouse gas emissions have on the global climate. GCMs describe physical elements and important processes in the atmosphere, ocean, and soil that occur within the climate system. The main disadvantage of using GCMs is their spatial resolution. This spatial resolution is adequate for a few 100 km. However, they do not capture regional and local meteorological details. In order to study the impacts of climate change on the regional level, it is necessary to predict changes on much finer scales. One of the best-known techniques to do this is through the use of Regional Climate Models (RCMs). The RCM is an atmospheric physics-based model to which boundary conditions are provided with the output of a GCM (Fowler et al. 2007). Downscaling technique is the method for creating local climate scenarios from GCM climate scenarios, and they are broadly classified into two categories: dynamic downscaling and statistical downscaling. Statistical downscaling methods construct statistical relationships between the large scale GCM outputs (predictors) and the catchment scale climate variables (predictands). The basic advantage of statistical downscaling is that it is computationally less demanding compared to dynamic downscaling. Wilby et al. (2002) and other authors have studied downscaling techniques and stated that by using this approach, GCM outputs can be changed into surface variables in the scale of a basin or smaller areas under study. According to Wilby and Wigley (2000), statistical downscaling is based on the assumption that the predictor–predictand relationships are valid under future climatic conditions. Predictor variables and their changes are well characterized by GCMs.

The Statistical Downscaling Model (SDSM), developed by Wilby et al (2002), is known as a decision support tool. It is a hybrid of regression-based and stochastic weather generators that perform the statistical representation for single-site stations of daily surface climate variables under current and future climate forcing. Wilby and Dawson (2013) have defined the tool as a conditional weather generator. The process of downscaling can be performed either unconditional, e.g., as with wet-day occurrence or air temperature; or conditional on an event, e.g., rainfall amounts are conditional to wet-day occurrence. In the first case, there is a direct linear relationship between the predictand Ai and the chosen predictors X_{ij} :

$$A_i = \delta_0 + \sum_{j=1}^{n} \delta_j X_{ij} + e_i \qquad (3)$$

In the case of a conditional procedure, an unconditional method is primarily assumed. In this case, the element W_i has a direct linear dependency on N predictors X_{ij} on day i:

$$W_i = \alpha_0 + \sum_{j=1}^{n} \alpha_j X_{ij} \qquad (4)$$

under the limit $0 \leq W_i \leq 1$, the event occurs when the stochastically generated random number $r \leq W_i$. Next, when the event occurrence is returned, the predictand amount P_i is derived from:

$$P_i^k = \beta_0 + \sum_{j=1}^{n} \beta_j X_{ij} + u_i \qquad (5)$$

In both processes, the predictors explain only part of the variability of the predictand and therefore the unsolved part (u_i) is used to add random noise to the simulated time series. The noise fraction is represented by the standard error which is assumed to be normally distributed (Gaussian). A pseudo-random number generator replicates values based on the normally distributed errors. The stochastic error is then added on a daily basis to the deterministic component. The noise adds local variance to the model and enables closer fitting for the variance of simulations with observations. In order to reflect the range of model uncertainty, the SDSM model enables the generation of several ensembles.

All transfer function coefficients (δ_j, α_j and β_j) are obtained by calibration of the local predictand against large-scale predictors. A screening procedure of candidate predictors is required in order to identify the most appropriate set of predictors (super-predictors) and downscaling coefficients. The transfer function relies on multiple linear regressions which can be optimized by either a dual simplex or ordinary least square (Wilby and Dawson 2007).

Based on the nature of the predictors, the predictor-predictand relationship can be mainly derived from two approaches, these are: Model Output Statistic -MOS or perfect prognosis (Wilby et al 2002; Wilby and Dawson 2007). In the first, predictors derived from the climate model (i.e., GCM) are used for both the development of the transfer function and simulation of future local climate. While in the perfect prognosis approach, the model is first trained using large-scale observations (i.e., reanalysis) and once the transfer function is defined, reanalysis predictors are then substituted by predictors derived from GCMs (Hussain et al. 2017; Saraf and Regulwar 2016). The MOS is usually preferred in classical statistical weather forecasts but in climate projections the climate models (i.e., either GCM or RCM) are forced towards observations. It is therefore reasonable to assume that simulated and observed climate states have a direct correspondence which can be directly related through perfect prognosis approach (Maraun et al 2010). Nevertheless, the perfect prognosis approach is the most widely adopted when applying SDSM and it was adopted in this study as well. For the use of the SDSM model in this study datasets of observed data, reanalysis data and GCM data were used.

6.1.1. Observed Data

The observed daily data of precipitation, maximum temperature (Tmax), minimum temperature (Tmin), and relative humidity (RH) was collected from 153 hydrometeorological stations along the studied regions. A larger amount of data was supplied by the Institute of Hydrology, Meteorology and Environmental Studies of Colombia - IDEAM. As result from the analysis performed in Article 1 of this study, only datasets with less than 30% of missing values for the time range of 1980–2015 were considered, complying with the minimum extension of records of 30 years as recommended by the World Meteorological Organization (WMO 2017) to obtain reliable statistics.

6.1.2. Reanalysis Data

The daily mean atmospheric variables were obtained from the National Centre for Environmental Prediction (NCEP-DOE 2) reanalysis dataset for the period from January 1980 to December 2015. The data has a resolution of 2.5° latitude × 2.5° longitude global grid and seventeen constant pressure levels in the vertical.

6.1.3. GCM Data

The selection of the GCMs was made on the basis of literature review and the availability of data. In a previous study, Bonilla-Ovallos and Mesa Sánchez (2017) evaluated the performance of the simulations of the Global Climate Models from the CMIP5-project compared with local observations. The two GCMs used in this study provided good performances in this analysis. The GCMs selected for this study are CanESM2 (2.79° latitude × 2.81° longitude) and IPSL-CM5A-MR (1.26° latitude × 2.5° longitude). CanESM2 was developed by the Canadian Centre for Climate Modelling and Analysis. The IPSL-CM5AMR was developed by The Institute Pierre Simon Laplace, France, respectively. The future Long-Term scenarios considered in this study are the Representative Concentration Pathways (RCPs) RCP2.6 and RCP8.5 representing two different possible future emission trajectories and radiative forcings. The RCP8.5 combines assumptions about high population and relatively slow income growth with modest rates of technological change and energy intensity improvements; in the long-term future, this is expected to lead to high energy demands and Greenhouse gases - GHG emissions in the absence of climate change policies. RCP8.5 corresponds to the pathway with the highest greenhouse gas emissions (Riahi 2011). It is important to notice that the concentration of CO2 continues to increase even after emissions slow and then drop. Carbon dioxide accumulates in the atmosphere and stays there for decades. The predictor variables are available and obtained for the period 1980–2005 for historical data, and the period 2021–2100 was used for the future projections of both models.

6.2. Water Budget Modelling

A water budget approach of the Earth's surface must be derived from climatic data averaged over several years. An approach of the water budget analysis over an area of interest represents an environmental-systematic approach to the hydrologic cycle, with emphasis on the transport, storage, and utilization of water (Muller & Grymes 2005). There are four submodelling systems describing the hydrologic cycle. The water balance model can contain one or more of them. These are, namely, an atmospheric water balance subsystem, a surface water balance subsystem, a soil water balance subsystem, and a groundwater balance subsystem. Depending upon the focus of the analysis, each subsystem can be modelled separately (Cumming Cockburn. Limited, 2001). In order to perform a water balance approach considering the future scenario for a specific region, hydrometeorological data together with additional information is required. In Figure 1, a basic scheme is shown with the minimum required data for a potential water balance analysis for a future scenario and the outputs of the method. The temporal resolution of the data depends on the approach for each case, but a high resolution is always preferred, and usually daily data is a reliable choice for most hydrometeorological data. The parameters named in the scheme as predictors refer to large-scale climate variables and local-scale or station-scale climate variables. These are typically derived from sea level pressure, geopotential height, wind fields, absolute or relative humidity, and temperature variables. These variables are archived in the grid resolution of operational and reanalysis climate models (Fung et al. 2011).

The model BROOK90 (Federer 2002) was used in this study for the water balance assessment in the historical and the different projected scenarios. BROOK90 is a deterministic, process-oriented, lumped parameter hydrologic model that can be used to simulate the water balance in most land surfaces at a daily time-step, year-round. The model has a strong physically based description that simulates the above and below liquid phases of the precipitation–evaporation–streamflow–ground water flow part of the hydrological cycle for a point-scale stand at a daily time-step (Combalicer et al. 2008). Input of daily precipitation and maximum and minimum temperatures is required for the use of the model. The model estimates interception and transpiration from a single layer (big leaf) plant canopy, soil and snow evaporation, and soil-water movement through one or more soil layers. The BROOK90 model calculates evaporation through the Shuttleworth–Wallace approach (Shuttleworth 1985), as well as an improvement of the Penman–Monteith equation. The characteristics of the soil water were determined using a modified approach of the Brooks and Corey (Brooks & Corey 1964), and Saxton (Saxton et al. 1986). The water movement through the soil was simulated using the Darcy–Richards equation. To calculate streamflow, the model used a simplified process—storm flow by source area flow or subsurface pipe-flow and delayed flow, from vertical or downslope soil drainage and first-order groundwater storage. A general water balance equation can be represented as follows:

$$PREC = EVAPOT + FLOW + STORAGE \qquad (6)$$

BROOK90 simulates vertical soil water movement and daily evapotranspiration for all land surfaces at all times of year using a process-oriented approach with physically-meaningful parameters. Only enough streamflow generation pathways are included to allow comparison with measured streamflow when available. BROOK90 can fill a wide range of needs. It was used in this study as a research tool to study the water budget and for predicting climate change effects. Additionally, it can be used as a water budget model for land managers, and as a fairly complex water budget model against which simpler models can be tested. BROOK90 has numerous parameters, but all parameters are provided externally and are generally physically meaningful. Parameter fitting is not necessary to obtain reasonable results. However, important parameters can be modified in order to improve the fit of simulated streamflow.

7. PUBLICATIONS

7.1. Assessment of regional and historical climate records for a water budget approach in eastern Colombia

water

MDPI

Article

Assessment of Regional and Historical Climate Records for a Water Budget Approach in Eastern Colombia

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Abstract: Regions located on the eastern side of Colombia are vulnerable to climate change due to the high diversity of fauna and flora located there, the potentially direct impact on agricultural activities, as well as the pressure on water resources. Limited research and work have been conducted to accurately create a description of the climate of these specific regions. The characteristics of the available records, which is valuable information, together with complementary data can be used to simulate the impacts of climate change and the effects it has on the water cycle. A description of the climate for the eastern region of Colombia was made and historical daily records from 669 hydrometeorological stations were considered in order to analyze the robustness and spatial distribution of the data. According to the available data, four of the water districts that compose the eastern region of the country were selected to show both a representative analysis of the climate variability and a consistency analysis using a cross-correlation procedure. A high percentage of missing values was found in the available records; however, with regards to the climatological analysis for the period from 1980 to 2015, 40% of missing values or less seems to be a good threshold for the datasets to be used. Temperature records show monthly small variations and a decreasing average rate from lower to higher elevations, i.e., 5 °C every 1000 m. Precipitation shows different patterns according to the region with monomodal and bimodal patterns. Correlations between datasets of the same region are positive and a significant correlation is obtained with temperature for stations at similar elevations or those located close to each other, and low correlations of precipitation are found. These data records are considered a good source of input data which could be used to perform further analysis such as a climate downscaling procedure, as well as a potential water budget approach for the four studied regions.

Keywords: Colombia; climate change; station data; mountain areas; correlation

1. Introduction

1.1. Overview

Climate change has a local and regional impact on hydrological regimes, and this directly affects ecological, social, and economic systems [1]. In addition, climate conditions and weather influence population health through several interrelated pathways. Extreme weather events can cause mortality and compromise water sources and crop production, leading to widespread food and water insecurity [2], moreover, climate has a significant influence on the geographic and seasonal distribution of pollutants [3].

Climate data is used as input information for studies in several areas of knowledge, but in some regions of the world, such as Colombia, these analyses are hindered by the difficulty of accessing accurate and complete hydrometeorological data at high temporal and spatial resolution. Researchers wishing to include climate variables as predictors in their studies generally have the option of using Earth observation (EO) climate data products such as those derived from satellites or model-based reanalysis data. EO climate data have the advantage of completeness, both temporal and spatial, and data can be available at a daily or even hourly resolution [4] without gaps and can be extracted for almost any location. The disadvantages of this source of data include the wide variation in the uncertainty of the estimates [5]. Weather conditions recorded at ground-based stations can still be considered the gold standard for meteorological data but are also subject to limitations such as the lack of maintaining routine record keeping can lead to significant data gaps, forcing researchers either to exclude outcome data reducing statistical power [6]. The current availability of long-term and high-quality instrumental climate data is still very limited in some parts of the world and this reduces the ability to carry out more reliable and long-term climate assessments to better understand, detect, predict, and respond to global climate variability and change [7]. Some of the available and accessible data does not reach the required standards of quality to be used to undertaking any climate analysis, applications, or services [8].

Local climate variations are governed by the regional physiographic conditions which are better represented for regional climate models (RCMs) or statistical downscaling techniques; these are not as accurately represented by direct global climate model (GCM) outputs due to coarse resolution [9]. Results from downscaling procedures are often used for hydrologic simulation models [10]. For these approaches, historical records that represent the climate variability of the region must be used for the validation and calibration of the models. Studies have shown that the choice of historical dataset can cause as much sensitivity in the resulting water balance as the choice of land surface model [11,12]. Hossain and Anagnostou [13] and Maggioni et al. [14] investigated the relative impact of model and rainfall forcing errors in hydrologic simulations by land surface models and found that both together contribute a large amount of the uncertainty in soil moisture estimates. Precipitation appears to cause the greatest sensitivity in runoff [15,16]. The assessment of climate change impacts on water resources is increasingly becoming an integral part of long-term natural resources planning [17]. All these aspects accentuate the importance of the characteristics of historic hydrometeorological records for climate studies over a selected region.

In Colombia, only a few studies have been carried out that reflect climate variability. Espinoza analyzed the spatio-temporal rainfall variability in the countries of the Amazon basin including Colombia [18]. Montealegre studied the rainfall variability associated with the El Niño Southern Oscillation [19,20] as well as Pavon and Torres [21]. However, limited work has been conducted to reach a valuable description of the climate on more specific regions, the features of the available records, as well as future climate projections.

There is a lack of specific information available over the eastern region of Colombia in regard to climate variation in general but, moreover, to the characteristics of the data that is available to use as a basic input to simulate the effects and impacts of climate change and the effects over the hydrological cycle over this area. This region presents high vulnerability to the effects of climate change due to its high diversity of fauna and flora since high mountain ecosystems are among the most sensitive environments to changes in global and regional climate [22]. Changes in climate have a potential direct impact on agricultural activities and pressure on water resources, additionally, productive areas over this region might experience changes in soils, desertification, and loss of their productive potential.

Due to the abovementioned factors, an analysis and systematic review of the climate characteristics over the last decades and the historical data records of the area becomes necessary with an aim to use it as input for a posterior regional climate analysis or water budget analysis. This study aims to provide this information as a data survey and evaluation, which counts as a proper first step to understand climate change over this studied area and improve the mitigation measures and response. Although this study is based only on survey and analysis of ground-based stations' data over the study area, a brief description of the steps to develop more detailed regional climate and water budget analysis is provided in the next section, in order to increase the understanding of the use of the reviewed data for further analysis.

1.2. Components of an Approach for a Water Budget Analysis

1.2.1. Climate Data

Climate data in the study areas either from models or historical records must be compiled and analyzed. There must be certainty that the data has gone through a quality control process to ensure the highest possible level of accuracy for the optimum use of this data by all possible means. Recommendations from the World Meteorological Organization (WMO) recommends that the required climate data for a long-term climate change assessment over a study area should ideally come from evenly distributed historical records and also along a period of a minimum of 30 years. The climatological standard normals, in addition to other variables, should only be calculated if there is available data for at least 25 of the 30 years, with no more than two consecutive missing years. Along the same lines, WMO recommends that monthly values should not be calculated if more than 10 daily values are missing, or five or more consecutive daily values are missing [23].

1.2.2. Regional Downscaling

Downscaling techniques include dynamic downscaling, which uses regional climate models (RCMs) driven by GCM outputs to generate climate information over a limited area; and also, statistical downscaling (SD), which uses statistical relationship between large scale climate predictors from GCMs and local scale predictand [24]. SD approaches are often used because of their relative ease of implementation. They require low computation and provide climate information at the equivalent of point climate observations [25]. Several studies have reviewed the characteristics of SD methods [26].

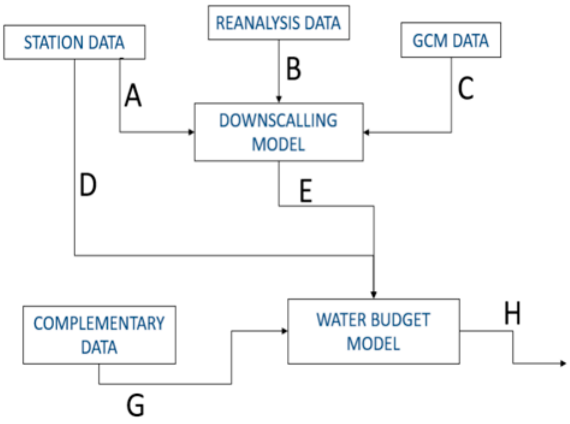
The SD models work with the assumption that the predictor and predictand relationship remains equally valid throughout the projection period. The result of SD is a synthesized daily weather series equivalent to station data, that makes it a suitable tool for impact assessment studies in areas such as water resources and hydrology [27,28]. Due to their suitability in impact and adaptation studies, statistical models, particularly regression-based models, have received more attention during the last decades [29]. On the basis of the statistical approach, statistical models are classified under the following three categories: weather typing, stochastic weather generator, and transfer function. In weather typing, local meteorological data are grouped in relation to the dominant patterns of atmospheric circulation and scenarios are developed by resampling from observed data [30]. Downscaling using stochastic and transfer function methods is performed by modifying parameters using weather generators and developing a statistical relationship between predictands and predictors, respectively. The input data for the SD model must be carefully analyzed since the statistical relationship between the predictors and predictands is the more important aspect in statistical models [31].

Several existing statistical downscaling methods have been applied in different climate regions and the results of these studies have shown that different methods have strengths in capturing different aspects of the downscaling [32]. Combining the results from diverse methods by weighting procedures can present a better performance than individual methods. A combination of techniques can include methods such as simple model average, linear regression, and artificial neural networks [33,34].

1.2.3. Water Budget Analysis

A water budget analysis of the Earth's surface must be derived from climatic data averaged over several years. An approach of the water budget analysis over an area of interest represents an environmental-systematic approach to the hydrologic cycle, with emphasis on the transport, storage, and utilization of water [35]. There are four submodelling systems describing the hydrologic cycle. The water balance model can contain one or more of them. These are, namely, an atmospheric water balance subsystem, a surface water balance subsystem, a soil water balance subsystem, and a groundwater balance subsystem. Depending upon the focus of the analysis, each subsystem can be modelled separately [36].

In order to perform a water balance approach considering the future scenario for a specific region, hydrometeorological data together with additional information is required. In Figure 1, a basic scheme is shown with the minimum required data for a potential water balance analysis for a future scenario and the outputs of the method. The temporal resolution of the data depends on the approach for each case, but a high resolution is always preferred and usually daily data is a reliable choice for most hydrometeorological data. The parameters named in the scheme as predictors refer to large-scale climate variables and local-scale or station-scale climate variables. These are typically derived from sea level pressure, geopotential height, wind fields, absolute or relative humidity, and temperature variables. These variables are archived in the grid resolution of operational and reanalysis climate models [37].



	Parameters	Time resolution
A	Precipitation Tmax, Tmin	Daily values
B	Predictors	Daily values
C	Predictors	Daily values
D	Radiation	Daily or monthly values
E	Precipitation Tmax, Tmin	Daily values, (delivered by model for future period)
G	Topography, Land use, Soil cover	-
H	Runoff, Evapotranspiration ,	Daily values, (delivered by model for future period)

Figure 1. Data flux diagram for a water budget approach.

2. Study Area

2.1. Location and General Description

A macro water district is a local area that includes several watersheds and is delimited on a geographical, economic, and political basis and planned to maintain a constant water supply for the cities, municipalities, and communities that are located in this area. This analysis is focused on the macro water districts located at the eastern region of Colombia which are distributed in different climate zones and which have varied geographical conditions, delimitation of these water districts is shown in the Figure 2. There, different climates along the eastern side from desertic to superhumid can be observed, in some of the water districts several climate conditions coexist. The climate classification was made regarding the Lang's index (I = Pr/Tm), where Pr is the mean annual precipitation amount and Tm is the mean annual temperature. The area of the water districts at the eastern region have extensions from 2245 km^2 up to 42,650 km^2, which lie between 74°56′13″ and 66°82′29″ W longitude, and between 12°24′40″ N and 2°18′225″ S latitudes. The topography along the studied area is highly variable and includes the Andean mountain ranges at the middle northeast, the coastal plains at the high north, and extensive valleys at the southeast.

2.2. Atmospheric Circulation Patterns

Colombia is located in the tropical region of South America. It is dominated by the great Amazon rainforest. In the climate conditions throughout the year, the continent is influenced by the so-called intertropical convergence zone (ITCZ) in the north, westerly winds in the south, and subtropical high-pressure systems over the Pacific and Atlantic oceans in the west and east, respectively [38]. In Colombia and its neighboring areas, the ITCZ intensity varies, both in space and time. It finds its meridional position at the latitude of two degrees north between January and February; after this, it moves towards the north and finds its position between the latitude of eight and 10 degrees north from June to August. From September until November, the ITCZ starts the path back to the south. As it passes through the different regions, the ITCZ determines the rainy seasons in Colombia. Convection is the main rainfall process in the tropics, and therefore, in Colombia, it is this the most important mechanism of heat transport towards higher levels. The synoptic systems of the Amazon also have an influence on the climate of the southeastern side of Colombia; cold masses move over South America between the five degrees of latitude crossing on some occasions to the equator.

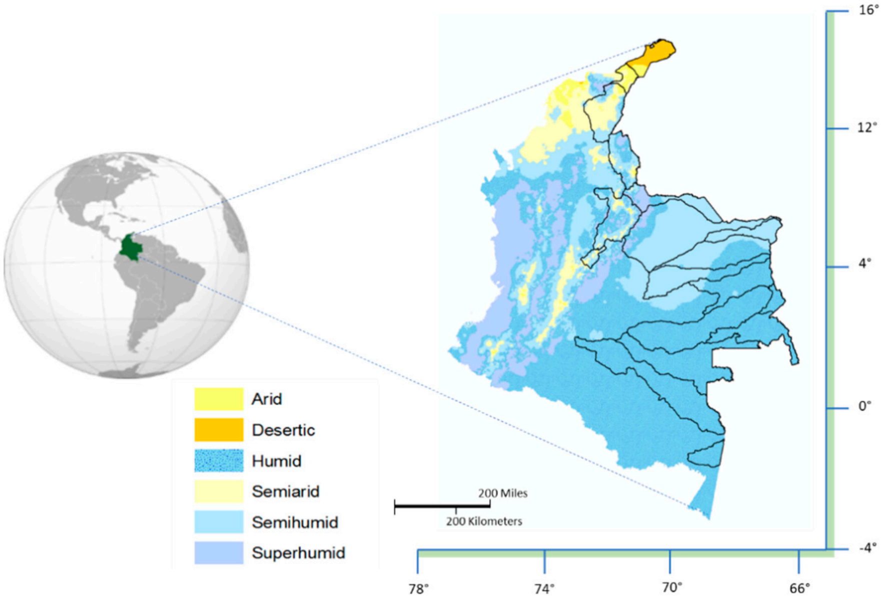


Figure 2. Water districts in the eastern side of Colombia and Lang's index climate classification.

The characteristics that identify the climate in Colombia are not only dependent on large-scale atmospheric circulation. They are also conditioned by the local particularities such as the effects associated with the differentiation between the physical behavior of valley and mountain surfaces, as well as those caused by mountain barriers to the atmospheric circulation, and orographic lift has also an important influence on climate at the mountain areas [39].

2.3. Climate

The Colombian climate is characterized as both tropical and isothermal due to its geographical location near the equator. The diversity of climates in Colombia is characterized as having tropical, rainforest, savanna, steppe, desert, and mountain climates. Each region maintains an average temperature throughout the year only presenting changes determined by precipitation during the rainy season caused by the ITCZ. Figure 2 showed the different climate zones of Colombia regarding the Lang's index.

3. Materials and Methods

In this study, not only is an assessment of the historical climate throughout the studied region performed, but also a description of the available data is conveyed with a major focus on the meteorological data. This is useful in determining how complete and coherent the data is in order to use it as input for posterior analysis such a climate projections and water budget analysis. In this section, the methods for a climate data survey and the analysis of it will be explained.

3.1. Data Availability

Historical daily records from 669 hydrometeorological stations located in the water districts in the eastern region of Colombia were obtained from the Institute of Hydrology, Meteorology and Environmental Studies of Colombia (IDEAM). The datasets from the stations consist mostly of precipitation records and to a lesser extent medium, minimum, and maximum temperature, relative humidity, as well as a very small amount of wind-speed records. The measurement periods for each station varies in the range of time from 1960 to 2015. A quality control of the datasets was previously conducted by IDEAM, this control consisted of an examination of repeated values, outliers, verification of the value according to the historical behavior of the variable, comparing total monthly and yearly values, and comparing with near stations and homogenization. For this study, a recheck of internal consistency and impossible values was performed to ensure its quality.

The datasets of the obtained data for every station in the studied region were analyzed to determine the missing values and the periods of data available. In this manner, a threshold of missing values was identified for the datasets which could be used in a water budget analysis in addition to identifying an appropriate historical period of time to be used as a baseline period; where there is more available data to work with.

3.2. Data Description

After determining a proper baseline period and the distribution of the data, a graphical description of the records was performed. Data were grouped according to elevation since geographical conditions could vary rapidly in the studied area, and data from stations at higher elevations could present a different range of values than those of stations located at lower elevations.

3.3. Consistency Analysis

A consistency analysis of the historical data was performed with the purpose of determining the relation and reciprocity between the historical time series from the stations. For this, the Pearson correlation coefficient was used; this coefficient is obtained as the covariance of the two variables divided by the product of their standard deviations according to Equation (1). It has a value between +1 and −1, where 1 is total positive linear correlation, 0 is no linear correlation, and −1 is total negative linear correlation.

$$r_{(x,y)} = \frac{cov(x,y)}{\sigma_x \sigma_y} \tag{1}$$

4. Results

4.1. Data Availability

Some of the data records obtained from the stations located in the study area contain data records for only a few years. It is important to detect the stations that contain a sufficient amount of data for posterior analysis. The number of stations with available data for a specific year was checked for every parameter on the studied region (Figure 3a). From the year 1980, there is a consistent amount of stations with robust data for all parameters, with the exception of wind speed. In the same way, the number of stations with available data for the period of 1980 to 2015 was determined considering a maximum percentage of missing values in the dataset (Figure 3b), e.g., the amount of stations with precipitation data for the period 1980 to 2015 with 20% or less of missing values is 374. From this graph, 40% of maximum missing values seems to be a good threshold for admitted missing values in the datasets with potential to be used in posterior analysis or studies in order to have a considerable amount of stations with representative data.

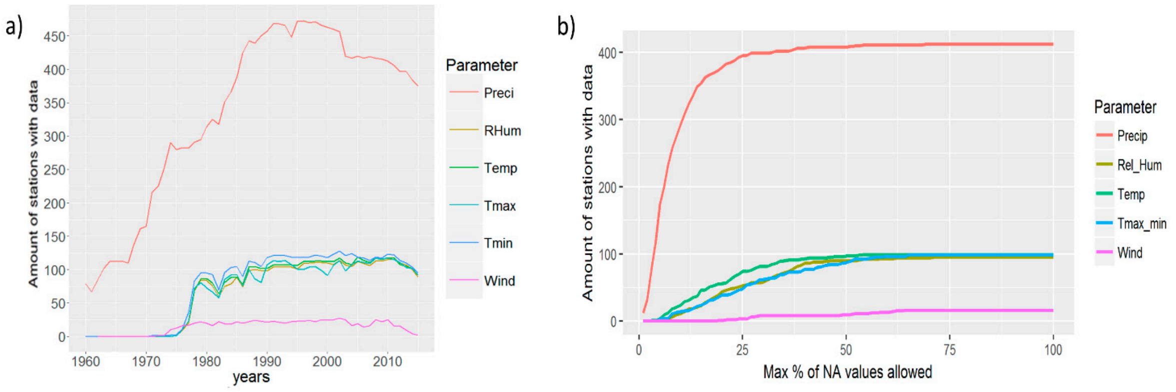


Figure 3. (**a**) Amount of stations with data for each year and (**b**) amount of stations with data for the period 1980 to 2015 considering a threshold of missing values in the dataset.

Considering only the stations that fulfill these conditions (data for the period of 1980 to 2015 and with a maximum of 40% of missing values), a distribution of them was observed for every parameter, as shown in Figure 4a. Distribution of the same stations regarding the altitude at which they are located (with no regards to their parameter) is observed in Figure 4b.

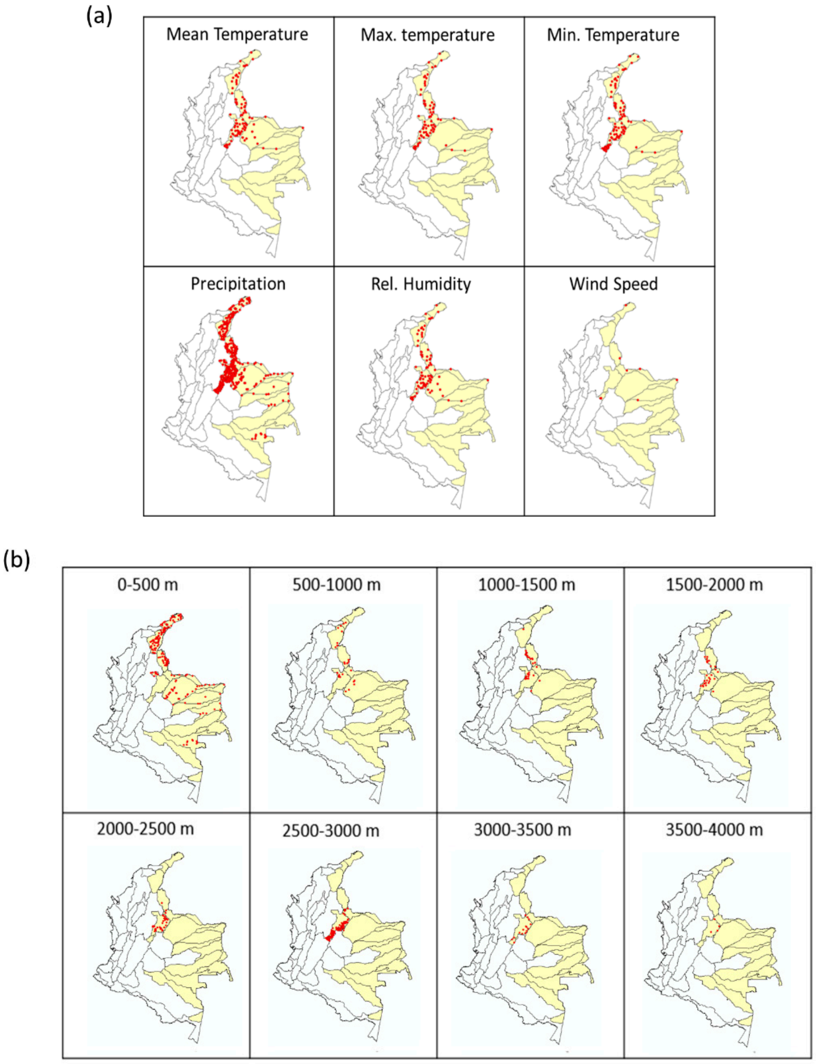


Figure 4. Location of stations with data after restrictions regarding to (**a**) parameter and (**b**) elevation.

Representative Areas

Considering the irregular distribution of stations observed in Figure 4, and that several of these water districts have no stations, and therefore no data availability, a group of four water districts that compose the eastern region of Colombia were selected for a more concentrated analysis, with each of these districts including different geographic and climate conditions. These water districts are Sabana de Bogota, Alta Guajira, Rio Catatubo, and Bajo Meta. In Table 1, the number of stations is shown with available data for each of these districts considering the restrictions established in the previous section, this is data for the period of 1980 to 2015 with less than 40% of missing values. This table also provides a brief description of the areas regarding climate characteristics and geographic aspects. Figure 5 shows the selected water districts and the distribution of the stations that register each variable.

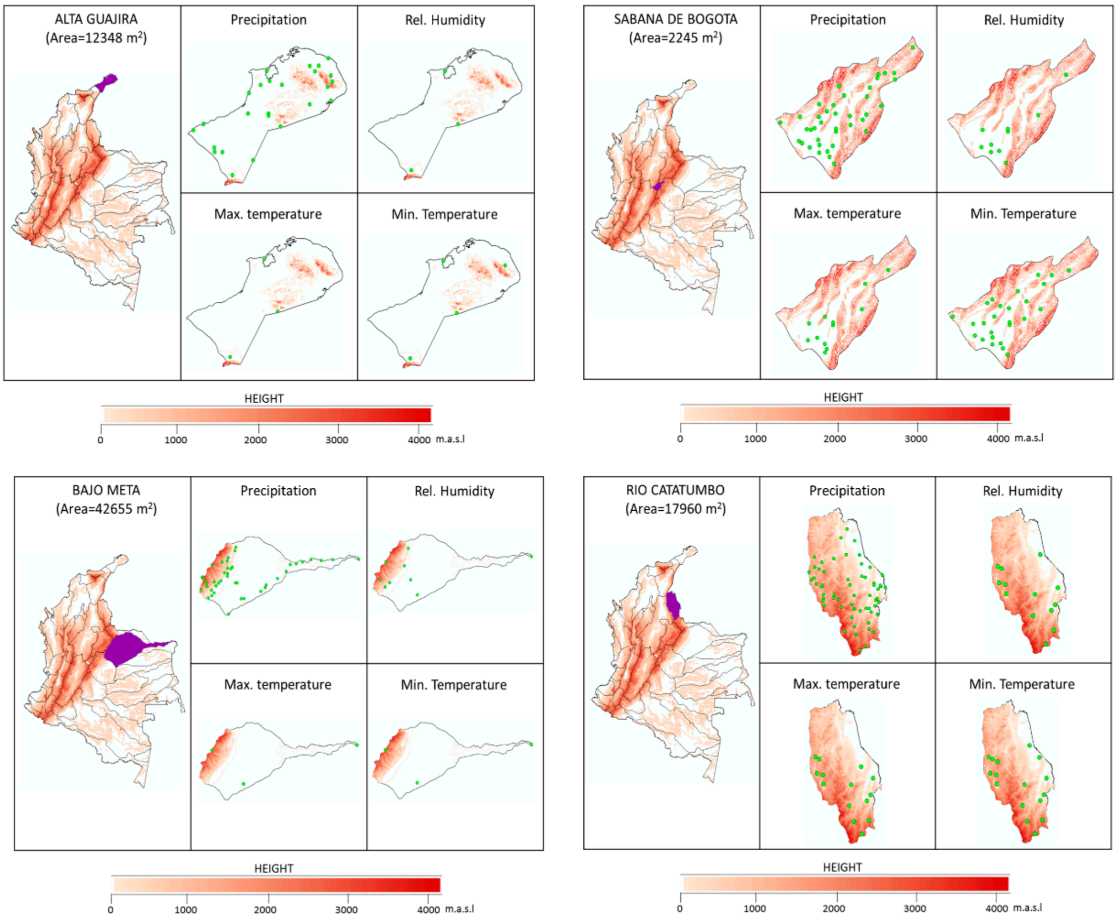


Figure 5. Distribution of stations regarding parameters for each of the 4 selected water districts.

Table 1. Number of stations with suitable data to be use in posterior analysis and description of selected areas.

Stations	**Alta Guajira**	**Bajo Meta**	**Rio Catatumbo**	**Sabana de Bogota**
N° Stations Precipitation	25	42	60	39
N° Stations Max. Temperature	3	3	14	12
N° Stations Min. Temperature	4	3	16	26
N° Stations Relative Humidity	3	9	13	10
Description				
Climate	arid, desertic	humid	semihumid	semihumid, semiarid
Area (km2)	12,348	42,655	17,960	2245
Min. Elevation (m.a.s.l.)	1	45	83	2540
Max. Elevation (m.a.s.l.)	390	3520	1740	3800
Mean monthly max. temperature (°C)	32.3	23.6	24.7	19.8
Mean monthly min. temperature (°C)	24.8	12.6	16.1	8.2
Mean yearly precipitation (mm)	346.8	2382.5	1447.9	832.4
Rainy seasons	May October	June	May, October	June

4.2. Data Description

A graphical description of the data records as regional climate time series for the four selected water districts with the predefined characteristics of less than 40% of missing values for period of time 1980 to 2015 are shown in Appendix A in terms of:

- Average monthly values for minimum and maximum temperature and relative humidity;
- Average accumulated monthly precipitation values;
- Average accumulated monthly precipitation values for each year in the mentioned period. These graphs are a good source to analyze seasonality, dry and wet periods for each of the studied areas;
- Probability density function with regards to each parameter. They offer a visual comparison of the variability of climate characteristics between the four selected areas.

This description of the average monthly and accumulated precipitation values is shown as a mean value of each variable for the group of stations located in each of the four water districts. Here, the data has been segregated as well regarding elevation in groups of stations at every 500 m. As explained before, this is done considering that a single area contains stations in a large range of elevations, and also that records at different heights might differ considerably.

4.3. Consistency Analysis

A cross-correlation procedure was performed in each of the four previously selected water districts, as well as for each parameter (precipitation, maximum temperature, minimum temperature, and relative humidity). Here, the Pearson correlation coefficient determines the linear correlation between every couple of time series of the same water district. The results are outlined in Appendix B. This section presents a graphical display of the cross-correlation results between datasets of all stations from the same district for each parameter versus the distance between the stations, in order to corroborate the consistency and congruence of the datasets.

4.4. Complementary Data for a Water Budget Analysis

Discharge historical data can be also used for the process of calibration and validation of the model when a catchment-analysis approach is employed. A limited number of stream gauges are located throughout this region in order to measure the level of water surface and the discharge of the rivers; this corresponds to daily records for diverse periods in the years 1960 to 2015. Unfortunately, for the region, the number of measuring points is limited and the available data has large amounts of gaps.

Some models used for a water budget analysis approach require radiation data as an input. Historical records of the region from more than 50 stations are part of IDEAM database. This data is available as a monthly means for the whole period of the station service. Additionally, data from global databases is available which considers different periods, time, and spatial resolution. This data can be used to replace or complement the required data for a model. As main sources, high temporal resolution datasets of measurements from several stations in contrasting climatic zones around the world can be obtained from the World Radiation Monitoring Center (WRMC). Three-hourly resolution reanalysis data for a global grid in the period from July 1983 to December 2007 is available from the Global Energy and Water Exchanges (GEWEX) project. The surface solar radiation dataset, Heliosat (SARAH) is also an available dataset of satellite-based climatology of solar surface irradiance from satellite observations for the period of 1983 to 2013.

Detailed topography data for the area has been obtained from the Colombian geographical institute Agustin Codazzi and from the global elevation models available, such as the 30 arc-sec DEM for South America provided by the U.S. Geological Survey's Center for Earth Resources Observation and Science (EROS), or the Space Shuttle Radar Topography Mission (SRTM) created by NASA.

Vegetation and soil parameters which could be necessary for the use of the hydrological model or approach are available from the Colombian geographical institute Agustin Codazzi for the areas of interest or from global datasets such as the MODIS-products offered by the NASA LPDAAC collections accessed via the earth explorer of the U.S. Geological Survey or the global dataset of derived soil properties, 0.5-Degree Grid (ISRIC-WISE) created by NASA.

5. Discussion

A dense distribution of stations on the northeastern side of Colombia and a lower one on the southeastern side can be explained by the demographic distribution which follows this same pattern. A higher demographic density and a stronger economic activity in the central and northern part of the country (including agriculture and electricity generation activities such as hydropower) require a more detailed monitoring of climate variables. To the south, where the extensive valleys and Amazon rainforest are located, the economy is based more on extensive livestock farming and forestry exploitation; however, a denser distribution of stations in this area would be useful in order to create a more detailed and reliable climate prediction that can influence social and environmental conditions as well as other economic activities throughout the area, such as fishing and agriculture (corn, plantain, and rice). It should also be taken into consideration that several renewable energy projects and ecotourism projects are planned for this area in the future due to its large biodiversity.

The selection of the four analyzed water districts was made considering that they were the areas with more stations and data records out of all the eastern side of Colombia. There is a wide variability of climate and geography along this part of the Colombian territory and the selected four water districts for the analysis offer a good representative example of this variation with data records at different elevations and different climate zones. Areas, such as Sabana de Bogota or Rio Catatubo, offer wider and more accurate information due to their denser distribution of climate stations and stream gauges. In areas, such as Alta Guajira and Bajo Meta, a climate analysis or a water budget approach would offer higher uncertainty due to the low number of stations, and therefore also historical records, especially for parameters such as temperature and relative humidity.

Future studies at a local scale can use the results of this study as an overview of the climate and hydrometeorological data characteristics over the studied areas. In studies like the one performed by Nakaegawa [40] or Ospina [41], river discharge in the north of Colombia was analyzed using direct output from a GCM as a hydrometeorological input of the model, and similar studies could be performed in the four selected water districts at the east of Colombia considering the results of the current study in order to use the historical records from these areas to develop a regional climate downscaling or water budget analysis. The spatial and temporal data resolutions show acceptable characteristics for the purpose of performing reliable posterior analysis such as some developed through statistical regional downscaling on other areas with similar characteristics [31,32,42–44], or water budget analysis [45–49]. The use of a dynamical downscaling method could also provide more accurate results, but this approach demands much more intensive computational resources and require large volumes of data which are not available for the studied regions, thus, using a statistical downscaling technique is recommended as a first approach.

However, an individual and specific analysis for reduced areas must determine if data from the stations located include enough information to perform a suitable calibration and validation of the models to be used. A minimum of 30 years of records from the area is recommended for this purpose but the results presented in this study show a high amount of missing values in most of the existing datasets. This leads to the willingness to perform such analysis accepting a threshold of missing values. In this study, it was determined that around 40% of the data in the period between 1980 and 2015 accounted for this purpose; nevertheless, it should be noted that previous climate studies have been done with shorter periods of calibration and validation for the models, and also conducted by extrapolating the records from long distance neighbor stations.

For some of the water districts in eastern Colombia, it would not be possible to perform an analysis using only local records due to the low density of the available stations. For this, it is important and recommended to engage the government to foster interactions together with academia and interested scientists [50] in a cooperative effort to increase the improving climate data availability all over the country. As shown in Figure 4, it is clear that for some parameters there is almost no available records for the southern region. However, for all areas at eastern Colombia where no data is available or where there is data with a high percentage of missing values or short periods of measurements (and in general for any intended area to study), there is always the possibility for the data to be complemented from other sources in order to perform a climate or hydrological analysis. Spatial interpolation and extrapolation methods such as nearest neighbor, inverse distance weighting, splines, and geostatistical methods such as kriging and co-kriging can be used for complementing the required input data using information from near stations or global climate datasets. There are several projects that offer data at different space and temporal resolutions. Among them are Climate Data Online (by NOAA) which offers climate data from stations across the world dating back to the late 1800s, Climate Wizard (by The Nature Conservancy) with current and temperature and precipitation at 50 km resolution, CORDEX (a Coordinated Regional climate Downscaling Experiment) for a range of 20th- and 21st-century climate-related layers focused on different regions of the world at 0.5 deg resolution downscaled from GCM output, and WORLDCLIM in a 1 km resolution offers climate layers averaged from the period of 1950 to 2000 for the world.

Any posterior analysis should take into consideration the elevation of the stations in case a group of datasets from stations is intended to be used as input data. A group of stations at the range of 500 m of elevation show a desired correlation to be used together, but a group of stations with a higher difference in elevation is not recommended for the studied region. Along the same lines, the analysis performed in this study can be applied to other regions in Colombia to define the characteristics of the available hydrometeorological data, and the most suitable approach for climate studies that can include regional climate downscaling, hydrological analysis, or other studies that provide essential information in order to face adaptation and mitigation to climate change. In other regions in Colombia, such as the north and west, the coverage of climate stations is greater and the available historical records should offer a more suitable scenario to perform more accurate hydrometeorological analysis.

Regarding climate description in the four selected areas, the temperature shows a stable (not seasonal) behavior along the time with monthly small variations. As expected, the values of temperature decrease from lower to higher elevations with an average rate of 5 °C every 1000 m for the same region, and the relative humidity follows an almost direct proportional relationship with precipitation throughout the year for the four areas. In Appendix A (b), a bimodal precipitation regime is observed for the regions Alta Guajira and Rio Catatubo, due to the respective migration and recession of the ITCZ. A monomodal precipitation regime is observed for the regions of Sabana de Bogota and Bajo

Meta. Here, the wave produced by the migration of the ITCZ towards the north affects this region by producing precipitation from the month of April to the month of October. When the ITCZ migrates towards the southern hemisphere, the trade winds impact the area generating drought from the month of November to the month of March. The graphs created in the section c) of Appendix A are highly useful for identifying the dry/wet months and interdecadal precipitation-trends at the selected areas.

Results of the consistency analysis shown in Appendix B reveal that correlations between datasets of the same region are of high positive value for temperature. There is less correlation shown for relative humidity and very low correlation for precipitation as was expected. The graphs in Appendix B show higher correlations for stations at similar elevations and specifically for those located close to each other, which demonstrates the consistency of the datasets for the stations. These graphs are useful as support in order to select a correct group of stations for further studies over a specific area, for data interpolation or extrapolation purposes or for filling gaps in the data with records from nearby stations.

6. Conclusions

This study provides a description of the climate parameters of precipitation, maximum temperature, minimum temperature, and relative humidity in four selected water districts throughout the eastern side of Colombia using historical records from the period 1980 to 2015. The assessment of climate conditions focused on these areas due to the availability of data records which was found to be very deficient or even non-existing for a major part of the eastern Colombian territory. However, these four selected and analyzed water districts offer a representative overview of the climate of the eastern side of the country, each district with its very own unique geographical and climate conditions.

The historical records available for the four selected water districts are an acceptable source of input data. This information can be utilized to perform a posterior analysis (such as statistical climate downscaling procedure) or a potential water budget approach over an area/catchment of these regions, especially the water districts Sabana de Bogota and Rio Catatubo (this of course with regards to the availability and good correlation of datasets). The density of located stations at other regions throughout eastern Colombia is very low, and existing data in these areas must be deeply complemented using openly available external modeled datasets in order to perform a climate or water budget analysis over a reduced specific area.

The results from this study provide information which can be used on potential and more specific time spatial analysis throughout the region such as a regional downscaling or a water budget analysis, which would offer an outcome with impact on the environmental, social, and economic sectors. Potential studies analyzing climate change and hydrological effects throughout the eastern side of Colombia can provide valuable information regarding potential droughts, heatwaves, and water resources availability over these regions, which can be used to improve the response and to mitigate properly the impacts of global warming. However, a previous data survey is crucial, such as the one provided in this article, due to the lack of current reliable information. It is also recommended that the governmental agencies of Colombia support the network of stations in the area so that more accurate studies can be performed in the future.

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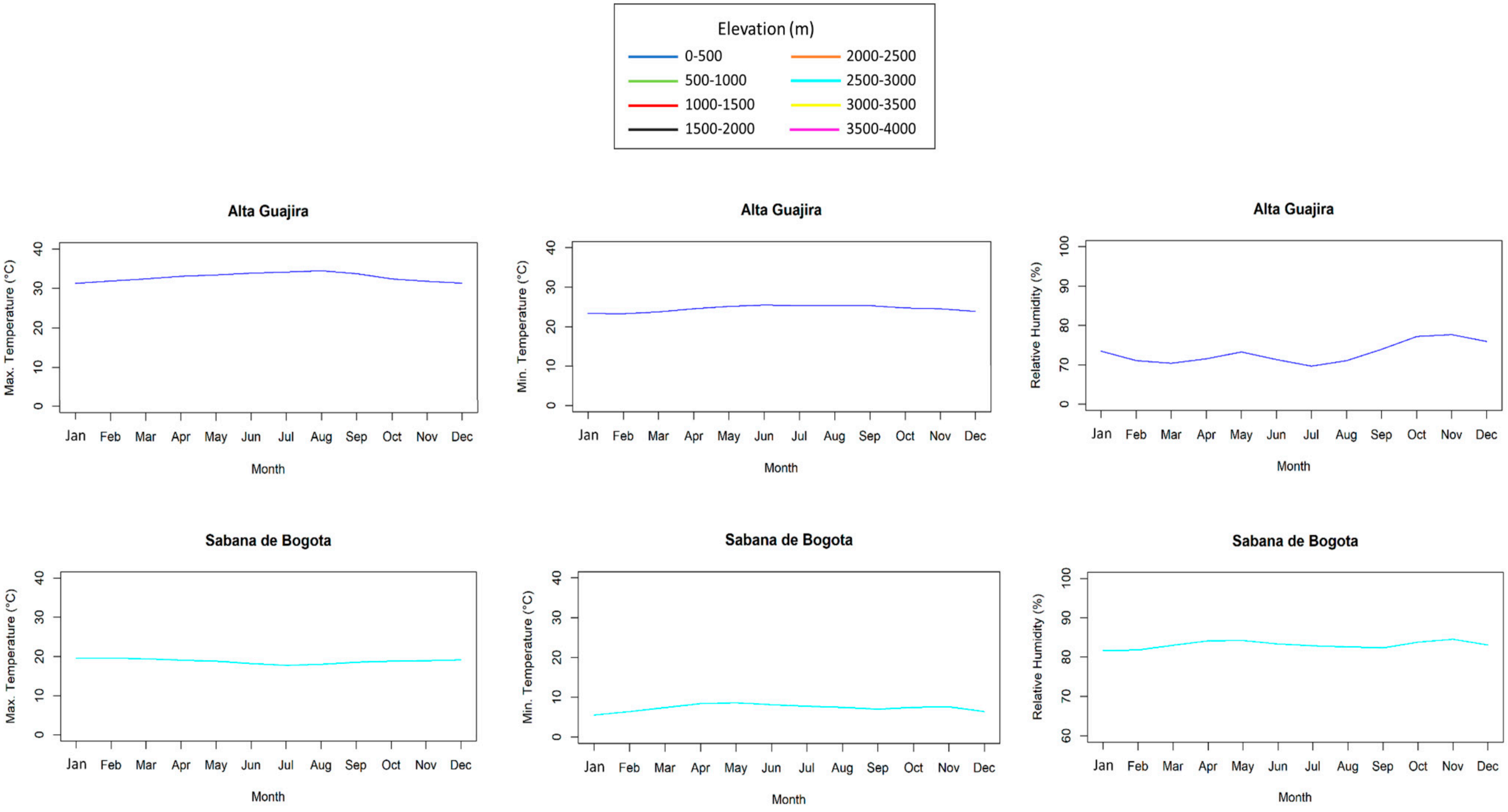
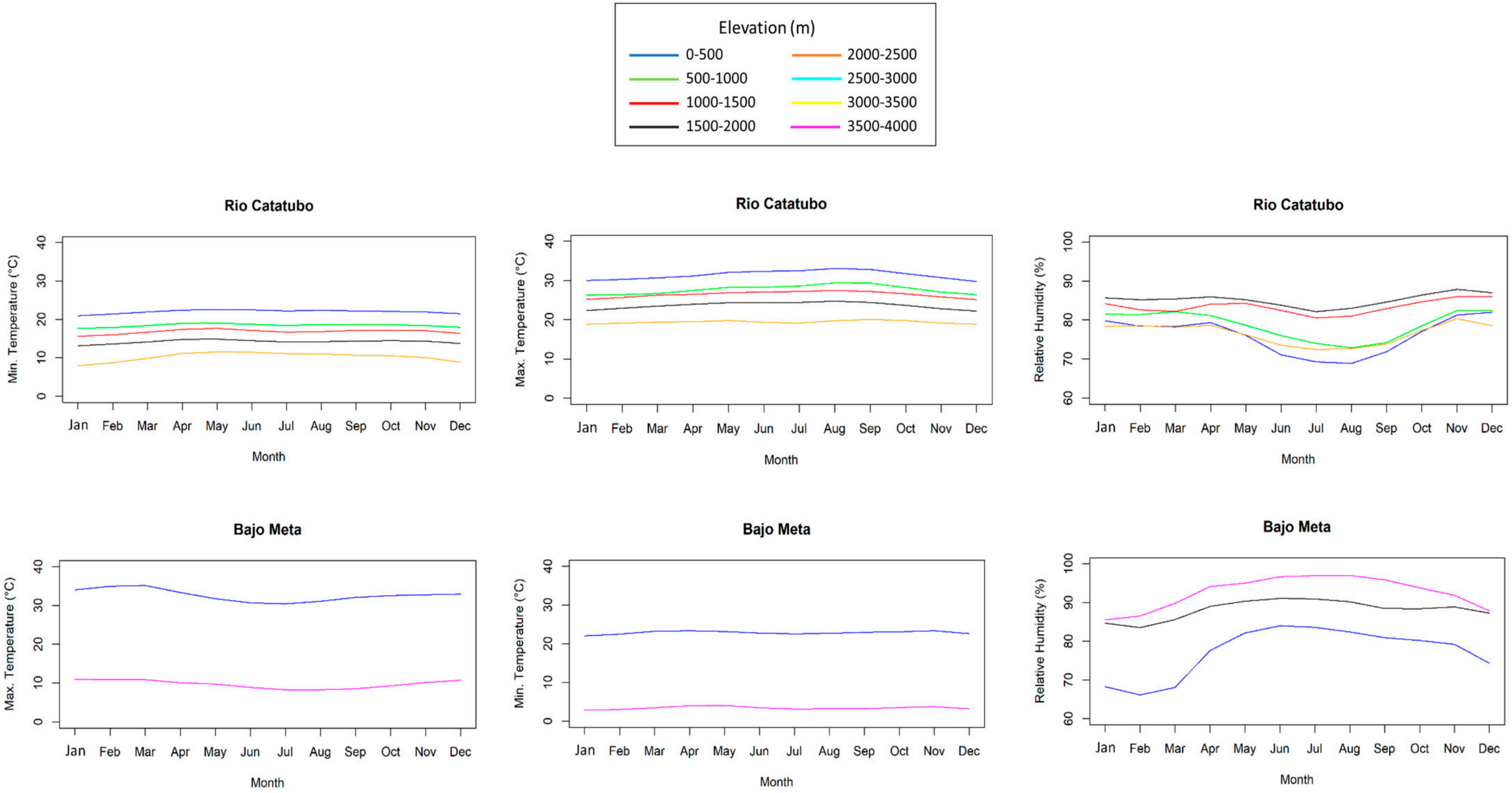
Conflicts of Interest: The authors declare no conflicts of interest.

Appendix A

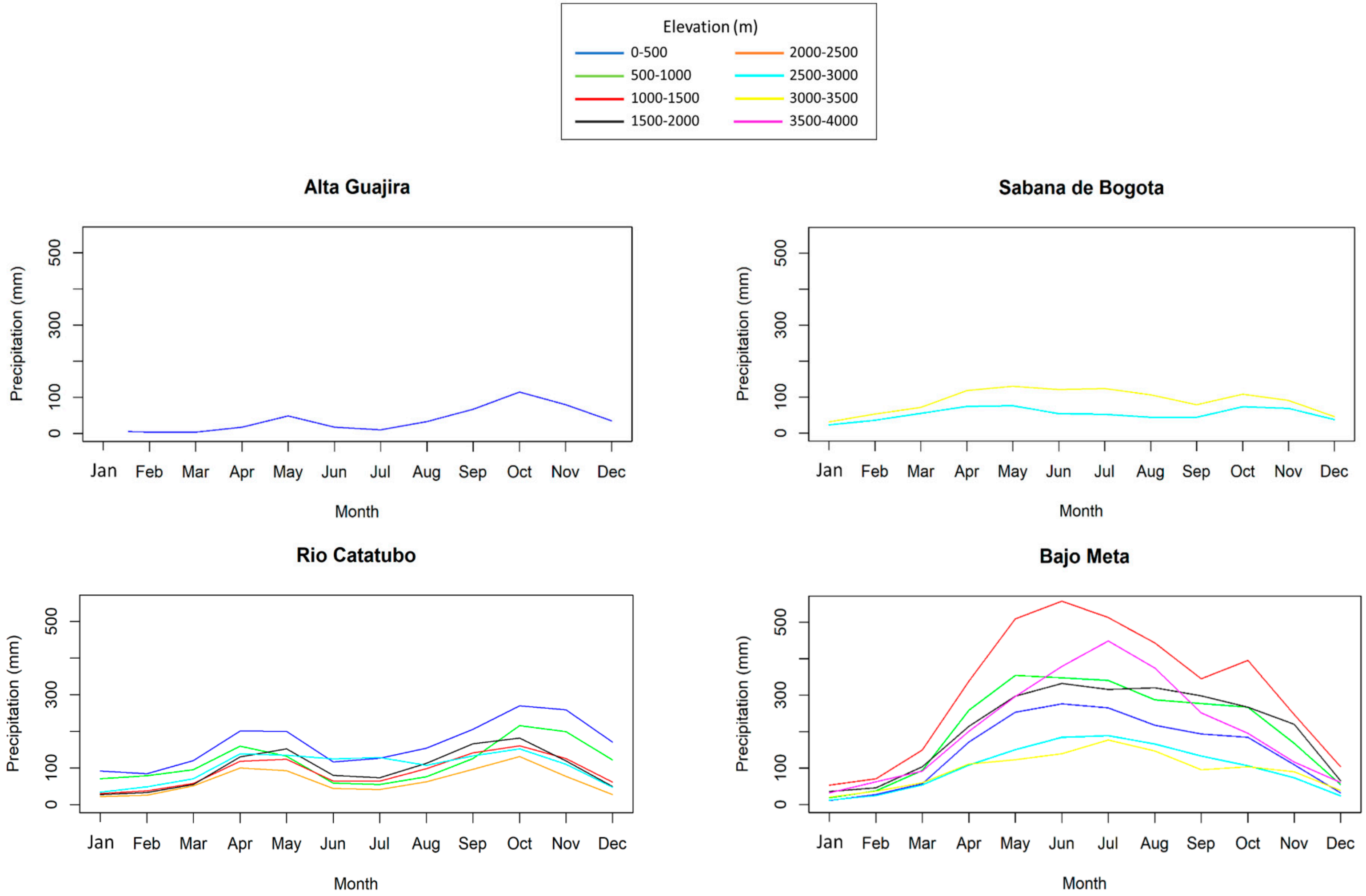
<u>Data records</u>

(a) Average monthly values (1980–2015):

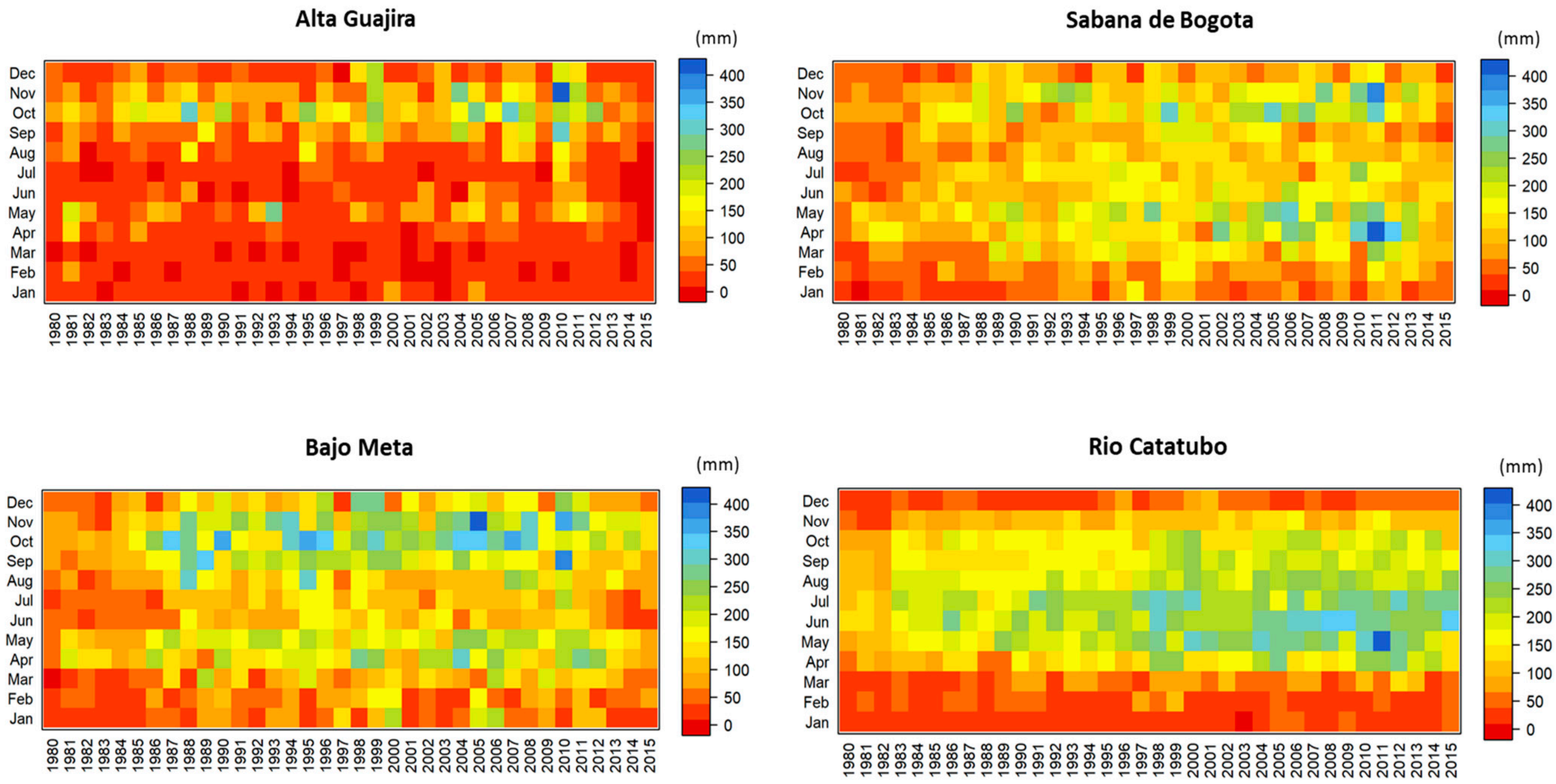



Elevation (m)
0-500
500-1000
1000-1500
1500-2000
2000-2500
2500-3000
3000-3500
3500-4000
Rio Catatubo
Min. Temperature (°C)
Rio Catatubo
Max. Temperature (°C)
Rio Catatubo
Relative Humidity (%)
Bajo Meta
Max. Temperature (°C)
Bajo Meta
Min. Temperature (°C)
Bajo Meta
Relative Humidity (%)
0
10
20
30
40
60
70
80
90
100
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
Month

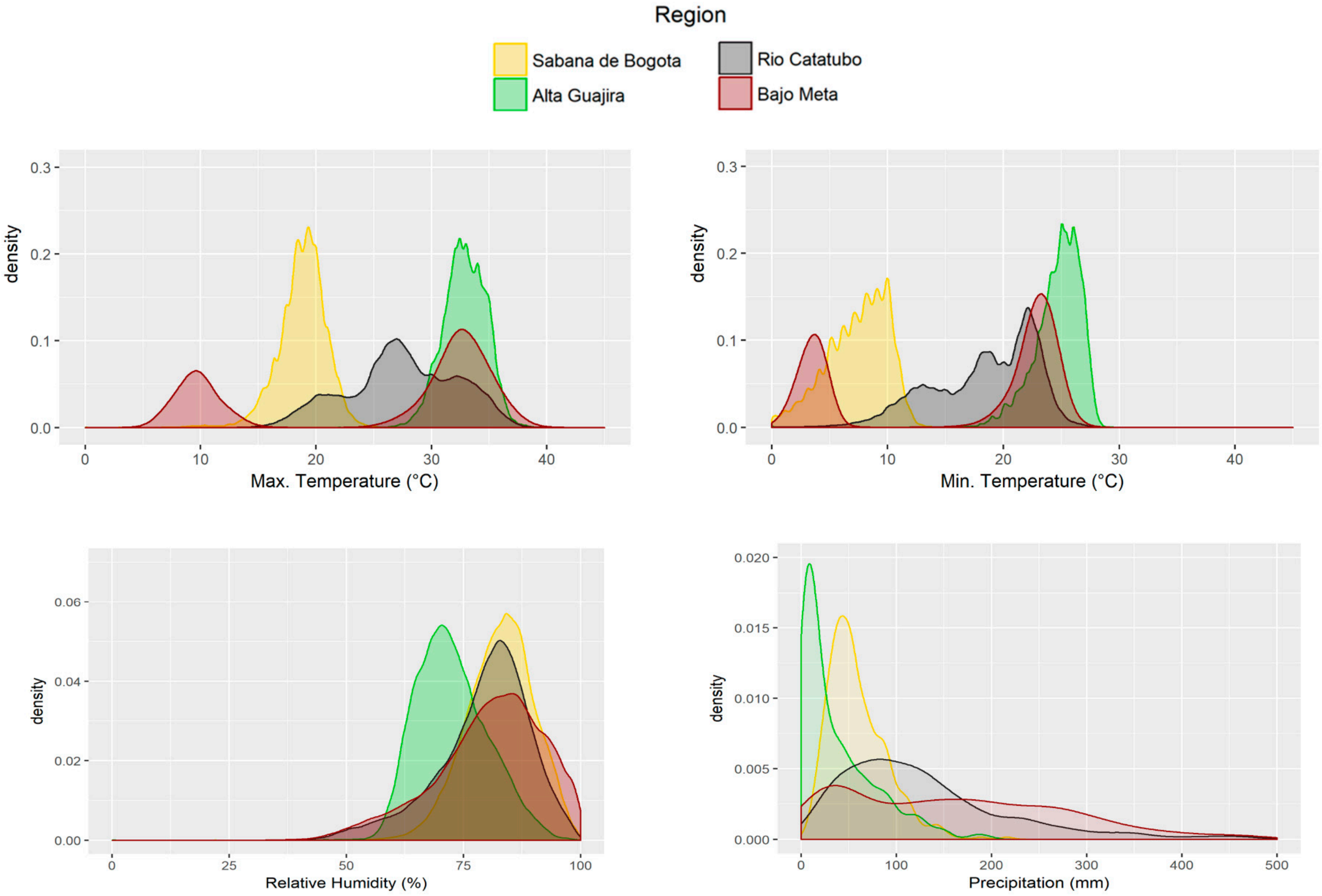
(b) Average accumulated monthly precipitation values (1980–2015):



(c) Average precipitation values for each year:



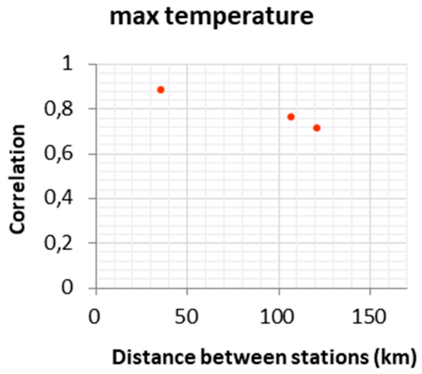
(d) Probability density regarding regions, for all parameters:

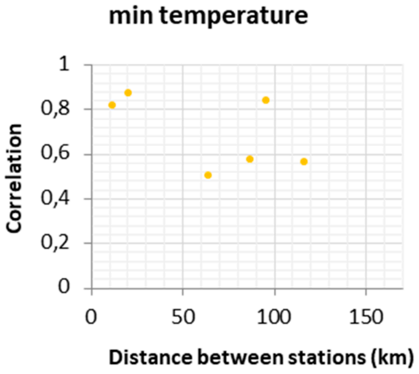


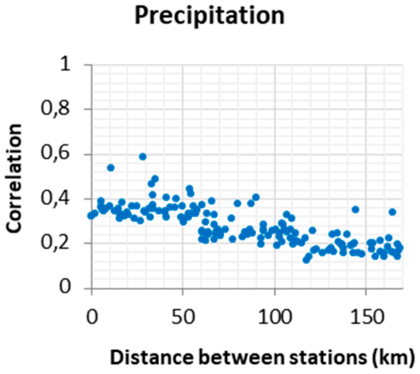
Appendix B

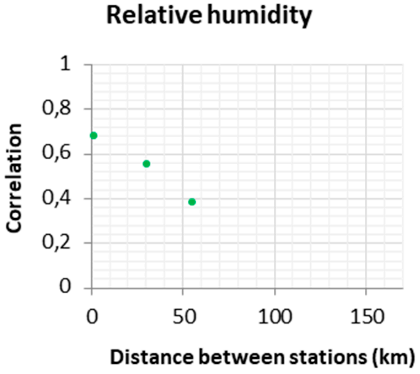
Correlations

-Alta Guajira:

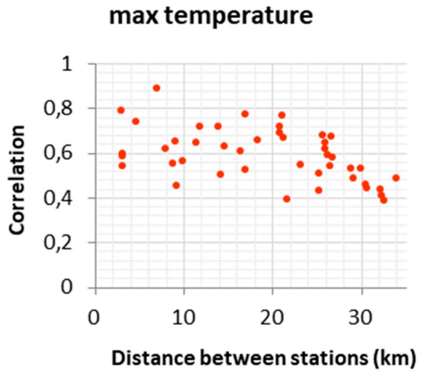


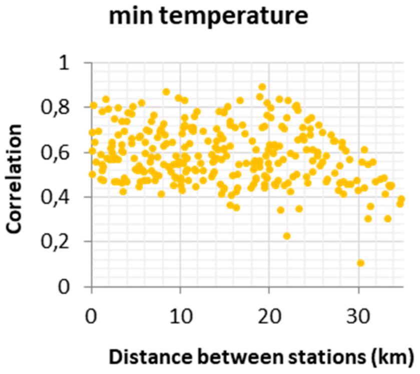


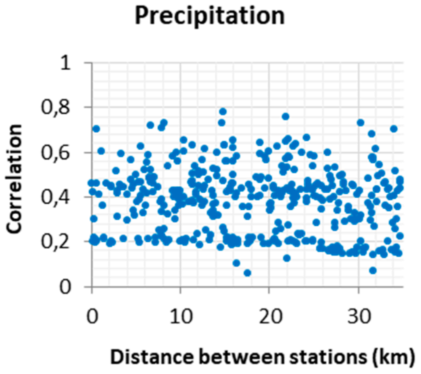


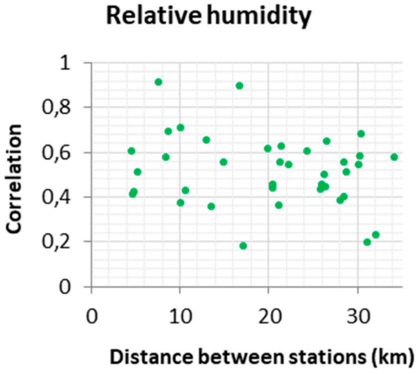


-Sabana de Bogota:

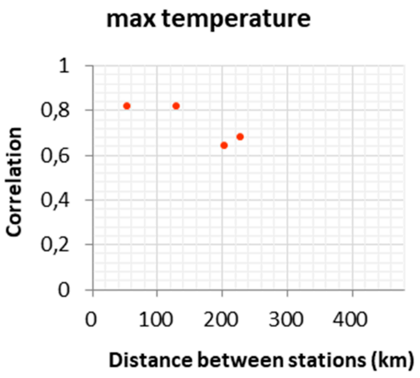


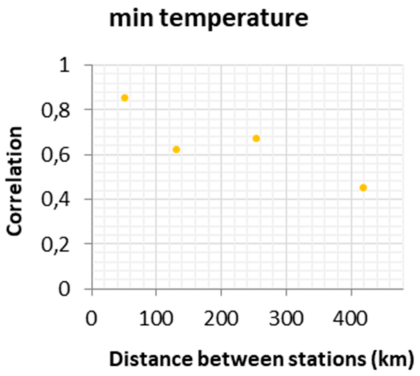


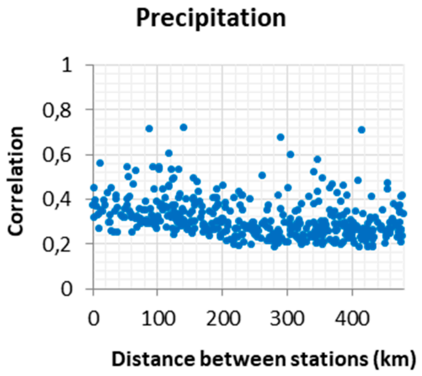


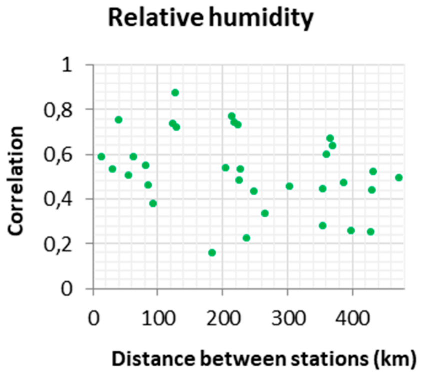


-Bajo Meta:

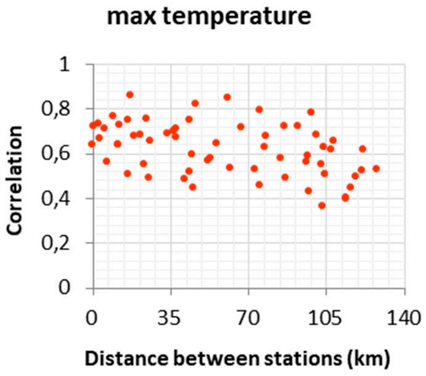

max temperature

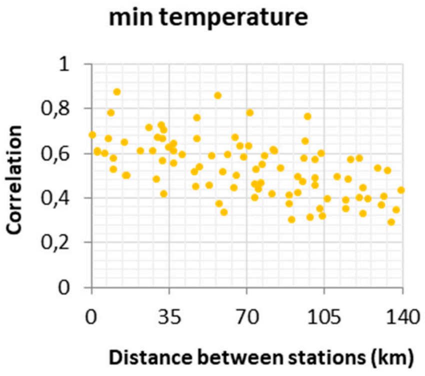

min temperature

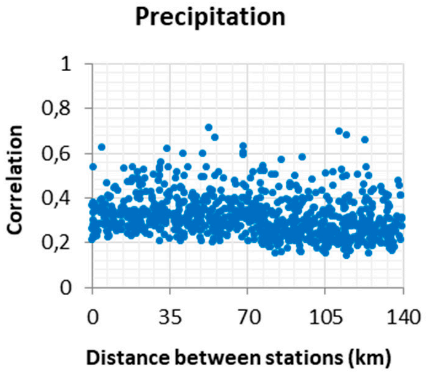

Precipitation

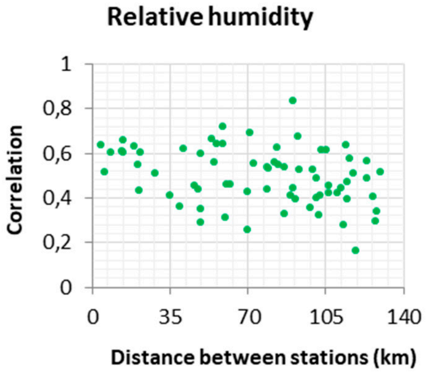

Relative humidity

-Rio Catatubo:


max temperature


min temperature


Precipitation


Relative humidity

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7.2. Projected climate changes in four different regions in Colombia

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Projected climate changes in four different regions in Colombia

Oscar D. Molina* and Christian Bernhofer

Abstract

Background: Considering the lack of research over this region the Statistical Downscaling Model (SDSM) was used as a tool for downscaling meteorological data statistically over four representative regions in the eastern side of Colombia. Data from the two Global Climate Models CanESM2 and IPSL-CM5A-MR, which are part of the CMIP5-project have been used to project future maximum and minimum temperature, precipitation and relative humidity for the periods 2021–2050 and 2071–2100. For both models, the Representative Concentration Pathways RCP2.6 and RCP8.5 were considered, representing two different possible future emission trajectories and radiative forcings. Predictor variables from the National Centre for Environmental Prediction (NCEP-DOE 2) reanalysis dataset, together with analyzed correlation coefficient (R) and root mean square error (RMSE) were used as performance indicators during the calibration and validation process.

Results: Results indicate that Maximum and minimum temperature is projected to increase for both Global Climate Models and both Representative Concentration Pathways; relative humidity shows a decreasing trend for all scenarios and all regions; and precipitation shows a slight decrease over three regions and an increase over the warmest region. As expected, the results of the simulation for the period 2071–2100 show a more drastic change when compared to the baseline period of observations.

Conclusions: The SDSM model proves to be efficient in the downscaling of maximum/minimum temperature as well as relative humidity over the studied regions; while showing a lower performance for precipitation, agreeing with the results for other statistical downscaling studies. The results of the projections offer good information for the evaluation of possible future-case scenarios and decision-making management.

Keywords: Downscaling, Colombia, SDSM, Climate change

Background

Global climate change is one of the greatest concerns of humanity given the great impact it has for the future sustainability of socioeconomic and environmental development. According to the Intergovernmental Panel on Climate Change (IPCC), a climate change scenario is a climate response under the assumption of emissions of greenhouse gases (GHG) into the atmosphere; therefore, depending on the scenario analyzed, a different change in meteorological patterns is allowed, induced by a greater or lesser emission of gases throughout the twenty-first century (Jones et al. 2004).

In order to estimate the effect that greenhouse gas emissions have on the global climate, Global Climate Models (GCMs) have been used for this purpose. GCMs describe physical elements and important processes in the atmosphere, ocean, and soil that occur within the climate system. The main disadvantage of GCMs is their spatial resolution, which is adequate for a few 100 km; thus, they do not capture regional and local meteorological details. In order to study the impacts of climate change on the regional level, it is necessary to predict changes on much finer scales. One of the best known techniques to do this is through the use of Regional Climate Models (RCMs). The RCM is an atmospheric physics-based model to which boundary conditions are provided with the output of a GCM. Downscaling technique is the method for creating local climate scenarios

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from GCM climate scenarios, and they are broadly classified into two categories: dynamic downscaling and statistical downscaling. Statistical downscaling methods construct statistical relationships between the large scale GCM outputs (predictors) and the catchment scale climate variables (predictands). The basic advantage of statistical downscaling is that it is computationally less demanding compared to dynamic downscaling. Wilby et al. (2002) and other authors have studied downscaling techniques and stated that by using this approach, GCM outputs can be changed into surface variables in the scale of a basin or smaller areas under study. According to Wilby and Wigley (2000), statistical downscaling is based on the assumption that the predictor–predictand relationships are valid under future climatic conditions, and predictor variables and their changes are well characterized by GCMs.

Worldwide, Colombia is one of the richest countries in water resources. Its climate presents varied conditions with the coldest weather being located on its snowy mountains and the warmest at sea level. Precipitation is governed by the double crossing of the Inter Tropical Convergence Zone (ITCZ); however, there is also the influence of trade winds and climatic variability events such as El Niño-La Niña, intra-seasonal Madden–Julian oscillation (MJO), among others. Regional physical-geographic factors such as orography also play a role (IDEAM 2005). These patterns of circulation and according to IPCC could be altered by the emission of greenhouse gases. Colombia is a country with relatively low industrial development, for this reason, the quantity of greenhouse gas emissions is not in a proportion that they have become a decisive factor on the effect of the composition of the high atmosphere of the planet. However, the country is expected to be very affected by climate change: especially the Colombian Andes (Perez et al. 2010). The eastern region of Colombia presents high vulnerability to the effects of climate change due to its high diversity of fauna and flora, potential direct impact on agricultural activities and the pressure on water resources.

Almost no research has been carried out focusing on the predicted changes on climate in Colombia for the next decades, especially on the eastern region. Only studies on related fields have been performed for other areas; Ruiz et al. (2008) analyzed the past change of climate during the last decades in a mountain basin on the west flank of the Colombian andean central mountain range, Nakaegawa and Vergara (2010) studied river discharge in the north of Colombia using direct output from a GCM as well as Ospina-Noreña et al. (2017), but there is no research for the east side and no regional downscaling approach have been carried out to determine a more accurate representation of the future climate in a specific region. With reference to the above factors and considering the great lack of detailed climate studies about Colombia, a research work is necessary to determine on a regional scale the possible change of climate variables such as precipitation, temperature, and relative humidity in Colombia for future decades. Additionally, this data must be compared against a reference period of historical records to comprehend the magnitude of the future climate change in the region and its potential impact.

Study area

The eastern side of Colombia borders Venezuela. It is characterized by different geographical and climate characteristics with a range of medium temperature from 12 to 34 °C. The Amazon Rainforest is located in the southernmost part; the extensive valleys and Andean Mountains are found in the middle-east region of the country; and coastal plains to the high north. The areas analyzed in this study comprises 4 macro water districts located at the eastern and middle side of Colombia: each area presenting different geographic and climate conditions. These two regions lie between 74° 56′ 13″ and 66° 82′ 29″ west longitude, and between 12° 24′ 40″ north and 2° 18′ 225″ south latitudes. These specific regions are shown in the Fig. 1 and were selected due to their variability of conditions and the sufficient availability of data for the analysis. Colombia is located in tropical South America, which is dominated by the Amazon Rainforest. Precipitation throughout the country is highly influenced by the Inter Tropical Convergence Zone—ITCZ; however, the climate is also conditioned by local particularities like those caused by mountain barriers to the atmospheric circulation.

Materials and methods

Datasets

Observed data

The observed daily data of precipitation, maximum temperature (Tmax), minimum temperature (Tmin), and relative humidity (RH) was collected from 153 hydrometeorological stations along the studied regions. A bigger amount of data was supplied by the Institute of Hydrology, Meteorology and Environmental Studies of Colombia (IDEAM) but only datasets with less than 30% of missing values for the time range of 1980–2015 were considered, complying with the minimum extension of records of 30 years, recommended by the World Meteorological Organization (WMO 2017), to obtain reliable statistics.

Reanalysis data

The daily mean atmospheric variables were obtained from the National Centre for Environmental Prediction

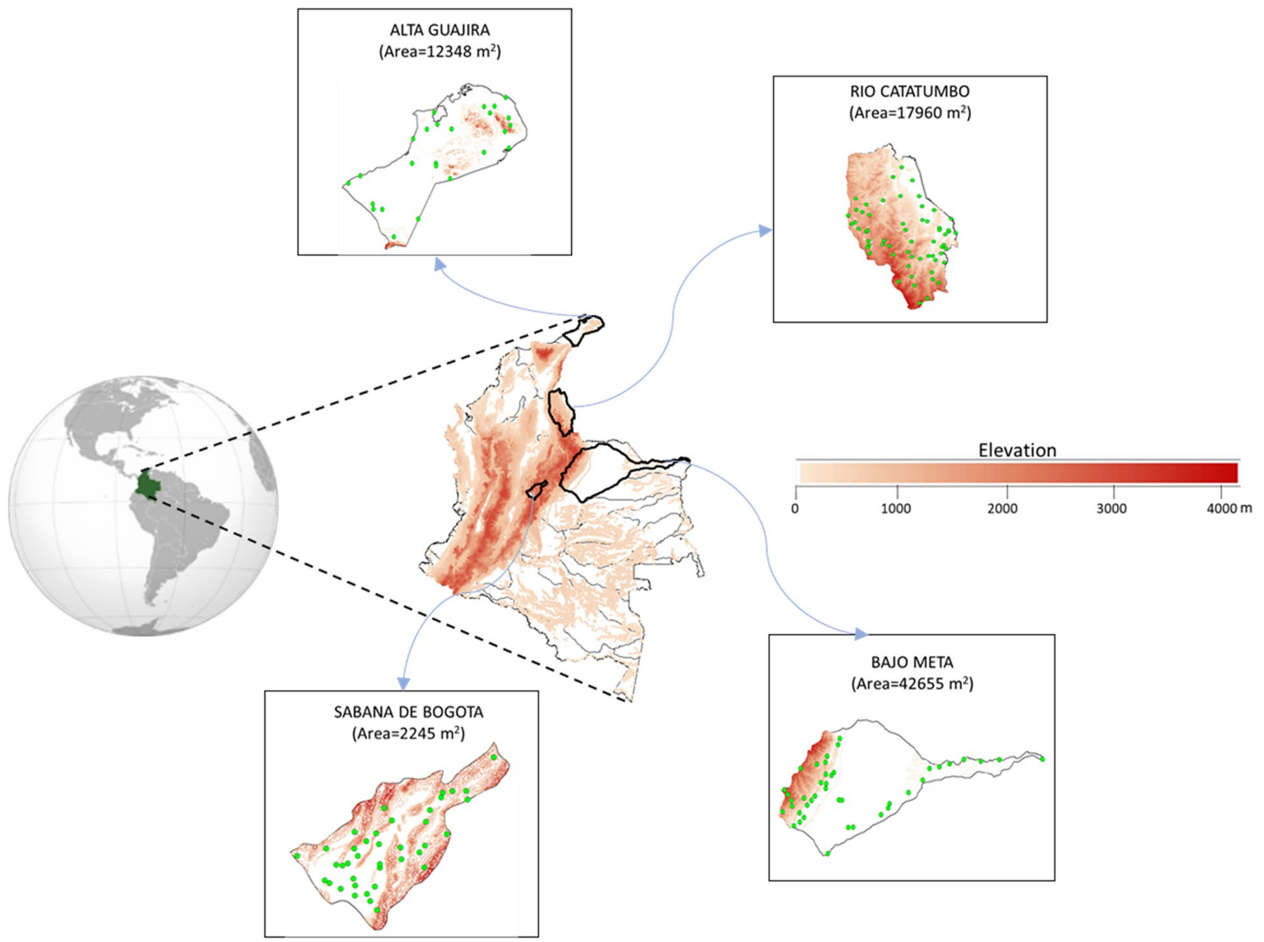


Fig. 1 Location of Colombia and the studied regions

(NCEP-DOE 2) reanalysis dataset for the period from January 1980 to December 2015. The data has a resolution of 2.5° latitude × 2.5° longitude global grid and seventeen constant pressure levels in the vertical.

GCM data

The selection of the GCM's is made on the basis of literature review and availability of data. In a previous study, Bonilla-Ovallos and Mesa Sánchez (2017) evaluated the performance of the simulations of Global Climate Models from the CMIP5-project compared with local observations, the two GCM used in this study showed a good performance in this analysis. The GCMs selected for this study are CanESM2 (2.79° latitude × 2.81° longitude) and IPSL-CM5A-MR (1.26° latitude × 2.5° longitude). CanESM2 is developed by Canadian Centre for Climate Modelling and Analysis, whereas IPSL-CM5A-MR by The Institut Pierre Simon Laplace, France, respectively. The future Long-Term scenarios considered in this study are the Representative Concentration Pathways (RCPs) RCP2.6 and RCP8.5 representing two different possible future emission trajectories and radiative forcings. The RCP8.5 combines assumptions about high population and relatively slow income growth with modest rates of technological change and energy intensity improvements, leading in the long term to high energy demand and GHG emissions in the absence of climate change policies. RCP8.5 thus corresponds to the pathway with the highest greenhouse gas emissions (Riahi 2011). The RCP 4.5 represents a scenario with lower concentration in the atmosphere of CO_2 than RCP 8.5, here the emissions peak around midcentury at around 50% higher than 2000 levels and then decline rapidly over 30 years. It is important to notice that concentration of CO_2 continues to increase even after emissions slow and then drop. Carbon dioxide accumulates in the atmosphere and stays there for decades.

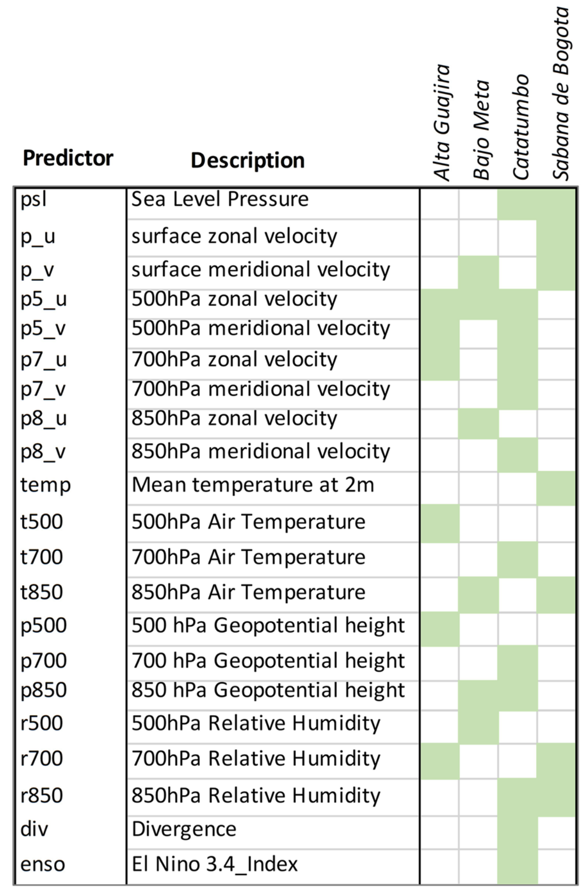
The predictor variables are available and obtained for the period 1980–2005 for historical data, and the period

2021–2100 was used for the future projections of both models (van Vuuren et al. 2011).

Statistical Downscaling Model (SDSM)

The Statistical Downscaling Model was developed by Wilby et al. (2002) as a tool for statistical downscaling method. There are many studies which have used SDMS in climate change impact assessments (Rajabi and Shabanlou 2013). The model uses a combination of stochastic weather generator (SWG) and multiple linear regression (MLR). The MLR establishes a statistical relationship between GCM predictor variables and local-scale predictand variables to produce regression parameters. These calibrated regression parameters are further used with NCEP and GCM predictor variables in SWG to simulate daily time series producing a better correlation with the observed predictand's time series.

In SDSM, there are three kinds of sub-models—monthly, seasonal and annual sub-models—that comprise the statistical/empirical relationship between the regional-scale variables (temperature and precipitation) and large-scale variables (Hussain et al. 2017). There are also two options within sub-models: conditional and unconditional sub-models. The conditional sub-models are used for the parameters that are dependent on the occurrence of other climate parameters, i.e. precipitation, evaporation, etc., while the unconditional models are used for independent climate parameters, i.e. temperature.



Predictor	Description	*Alta Guajira*	*Bajo Meta*	*Catatumbo*	*Sabana de Bogota*
psl	Sea Level Pressure			🟩	🟩
p_u	surface zonal velocity				🟩
p_v	surface meridional velocity		🟩		🟩
p5_u	500hPa zonal velocity	🟩	🟩	🟩	
p5_v	500hPa meridional velocity	🟩		🟩	
p7_u	700hPa zonal velocity	🟩		🟩	
p7_v	700hPa meridional velocity			🟩	
p8_u	850hPa zonal velocity		🟩		
p8_v	850hPa meridional velocity			🟩	
temp	Mean temperature at 2m				🟩
t500	500hPa Air Temperature	🟩			
t700	700hPa Air Temperature			🟩	
t850	850hPa Air Temperature		🟩		🟩
p500	500 hPa Geopotential height	🟩			
p700	700 hPa Geopotential height			🟩	
p850	850 hPa Geopotential height		🟩	🟩	
r500	500hPa Relative Humidity		🟩		
r700	700hPa Relative Humidity	🟩			🟩
r850	850hPa Relative Humidity			🟩	🟩
div	Divergence			🟩	
enso	El Nino 3.4_Index			🟩	

Fig. 2 Most used predictors for SDSM using inputs from NCEP-DOE 2

Screening of predictors

The direct relationship between predicted variables and large-scale predictors as independent variables is considered to define a multiple linear regression model. The screening of predictors is an essential step of statistical downscaling with SDSM (Wilby et al. 2002). For this, a correlation analysis was applied between predictands (precipitation, Tmax, Tmin, and RH) and daily data of 21 predictors based on explained variance, correlation coefficient, and the p value. In this way the best correlation between individual predictors and predictand was found. The predictor with the highest correlation was selected as main predictor, also called superpredictor, setting the significance level of $P < 0.05$ as default value. After selecting the main predictor, a second and third predictors were also selected based on highest correlation and explained variance. Similar studies have used the method performed in the current study for the selection of the appropriate predictors (Saddique et al. 2019; Khan and Coulibaly 2006; Gulacha and Mulungu 2017).

The correlation found between the predictand and predictors in the case of precipitation was low, this was expected considering other similar studies and the difficulties for downscaling with high accuracy daily precipitation (Hashmi et al. 2011; Huang et al. 2011; Meaurio et al. 2017). For regions at high elevation (Sabana de Bogota and Rio Catatumbo) superpredictor were found at 500 hPa while for regions at low elevations (Alta Guajira and Bajo Meta) superpredictors were found at surface level and 850 hPa. Figure 2 summarizes the results of the most used predictors due to its better correlation with the downscaled variables for each evaluated region.

Model performance

During the validation period, the four different variables were simulated using the NCEP data, as well as the historical data from both GCM datasets (CanESM2, IPSL-CM5A-MR) and compared with observations in order to evaluate the model performance in the different cases. For this, the correlation coefficient (R), root

Table 1 Performance of model for daily time series of Tmax, Tmin, RH, and precipitation during the calibration period (1981–2000)

	Tmax		Tmin		Rel. Humidity		Precipitation	
	R	RMSE	R	RMSE	R	RMSE	R	RMSE
Alta Guajira								
NCEP	0.78	0.8	0.72	0.73	0.65	11.87	0.27	6.23
Bajo Meta								
NCEP	0.66	1.14	0.61	0.82	0.54	5.13	0.25	34.61
Rio Catatubo								
NCEP	0.82	1.91	0.77	1.43	0.65	21.23	0.35	59.23
Sabana de Bogota								
NCEP	0.8	0.64	0.81	0.52	0.74	11.19	0.31	13.12

mean square error (RMSE) and normalized root mean square error (NRMSE) were used.

$$R = \frac{4\sum_{i=1}^{N}\left(P_i - \bar{P}\right)\cdot\left(O_i - \bar{\mathrm{O}}\right)}{\sqrt{\sum_{i=1}^{N}\left(P_i - \bar{P}\right)^2}\cdot\sqrt{\sum_{i=1}^{N}\left(O_i - \bar{\mathrm{O}}\right)^2}} \tag{1}$$

$$RMSE = \frac{\sqrt{\sum_{i=1}^{N}\left(O_i - P_i\right)^2}}{\sqrt{N}} \tag{2}$$

$$NRMSE = \frac{RMSE}{\bar{\mathrm{O}}} \tag{3}$$

where $\mathrm{O_i}$ and $\mathrm{P_i}$ are the observed and modeled values, respectively, $\bar{\mathrm{O}}$ and $\bar{\mathrm{P}}$ are the means of the observed and modeled values, respectively, and N is the number of data points. A Taylor diagram (Taylor 2001) is used as well to quantify the statistical relationship between observed and modeled data for each of the analyzed regions and scenarios. In this diagram, the relationship is represented by the correlation coefficient (R), the standard deviation (σ) and the centered root mean square difference (RMS), an independent diagram is shown for each parameter.

Results

Model calibration and validation

Based on the available datasets of observations, two daily data sets for the periods 1980–1999 and 2000–2015, were selected for the model calibration and validation, respectively. This for every station of the studied regions. SDSM is calibrated using observed station scale data (Tmax, Tmin, Precipitation and Relative Humidity) and sets of observed predictors, i.e., NCEP reanalysis datasets. A monthly sub-model was set for the process of calibration, which derives 12 different regression equations, one for each month, and the optimization of the best fit is performed by the ordinary Least Squares Method.

With the calibrated model for the period of 1980–1999, 20 daily ensembles for every variable were simulated for the periods of calibration and validation. The mean value of these 20 ensembles was compared with the observed data. The correlation coefficient and root mean square error were used as performance indicators during the calibration and validation process. Table 1 and the Taylor diagrams in Fig. 4 show the general model's performance during the calibration and validation periods. Here, the given R and RMSE values are taken as an average value for the group of stations that belong to each region. Some of the studied regions include stations in a wide range of elevation. Such is the case, for example, of the region Bajo Meta, with stations below 500 m and others above 3500 m of elevation. These groups of stations represent results in different ranges for each modeled variable. Figure 3 presents an example of the validation results concluded over an average result for a group of stations located in the range of 500 m of elevation for each region.

The Taylor diagrams provided in the Fig. 4 are a brief statistical summary of standard deviation, correlation coefficient and root mean square difference according to the results of SDSM for the downscaling of daily maximum and minimum temperature, relative humidity and precipitation.

Climatic scenarios generation

Data from the selected GCM models was used into the developed and calibrated SDSM model to simulate daily values of precipitation, Tmax, Tmin and relative humidity for two future periods: 2021–2050 and 2071–2100, this for both GCM and both Representative Concentration Pathways. Future changes in the variables were calculated by comparing them to a baseline period from 1981 to 2010. In the Figs. 5 and 6 a comparison of the

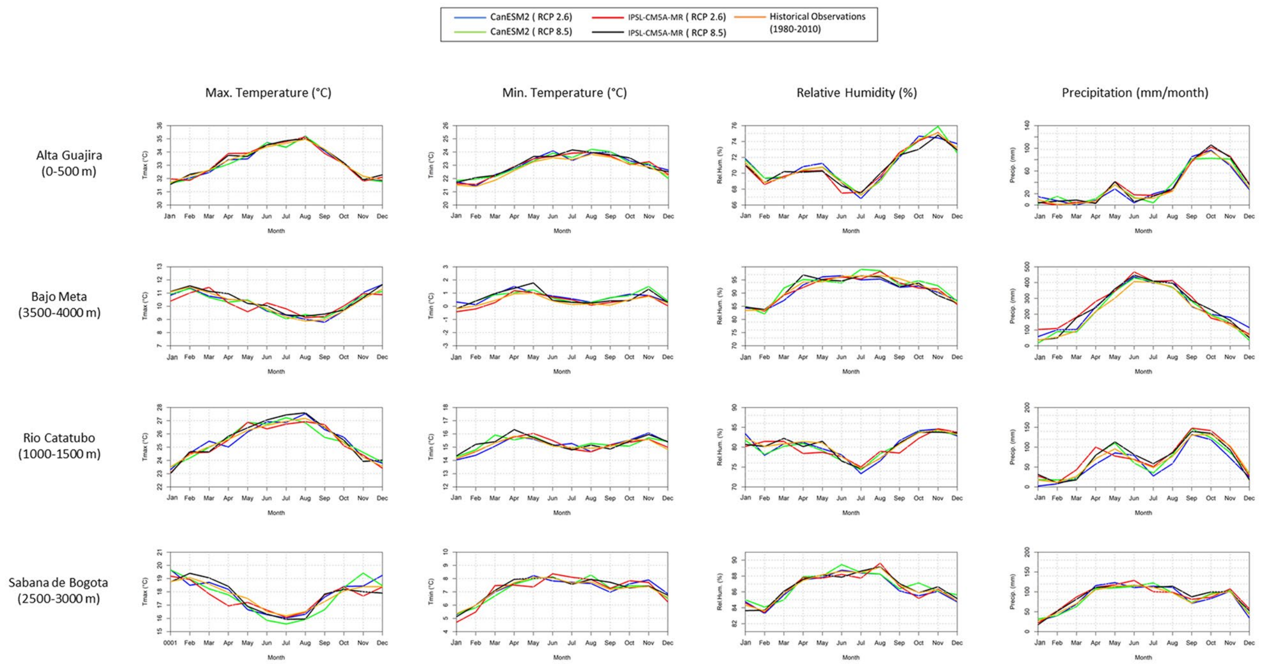


Fig. 3 Validation of SDSM for four water districts in a range of 500 m of elevation regarding to Tmax, Tmin, relative humidity and precipitation

simulated results is made with the baseline period of observations in 1981–2010. Using the mean value for the 30-year period, it is possible to calculate the relative increment or decrease for each projected variable in the future compared to the reference period of 1981–2010; these values can be observed in the Table 2.

Discussion

The results presented in Table 2 show an increase of both maximum and minimum temperature over the next decades as well as a decrease in relative humidity with a slight change of precipitation which will most likely decrease for most of the considered stations-especially in the last decades of the XXI century. In contrast to the case of temperature, difficulties to perform accurately a downscaling of daily precipitation agrees with the results of other studies (Huang et al. 2011; Nguyen et al. 2006; i.a., González-Rojí et al. 2019; Saraf and Regulwar 2016; Ahmadi et al. 2014; Saddique et al. 2019; Hussain et al. 2017; Cavazos and Hewitson 2005; Fiseha et al. 2012; Osma et al. 2015), also in these studies a low correlation in a regional scale between daily precipitation and different set of predictors was found, this creates a difficulty to adjust the model and calibrate it more accurately. That can be seen in this study in the Figs. 3 and 4. This partial inability of the statistical model of reproducing daily precipitation is also due to regional physical-geographic factors like interactions of atmospheric flow with topography, combined with land-use and land-cover changes that play a role in the formation of precipitation and show high variability in inter-annual basis. This confirms the high sensitivity of mountainous regions and the complex climate processes at play, which have been found as well in other studies (Gulacha and Mulungu 2017; Sigdel and Ma 2015; Mahmood and Babel 2013).

The projected increase in temperature as shown by the CanESM2 model, is slightly higher than the IPSL-CM5A-MR model, both for maximum and minimum temperature. Regarding the change of precipitation, Rio Catatubo, Bajo Meta and Alta Guajira show a general decrease over their area while Sabana de Bogota was the only region that presents an increase. However, it must be considered that these results are a mean average from all the stations located in each region and it is given in these terms in order to have a general overview of the different climate variables on each region on the future caused by different scenarios of greenhouse emissions and climate change. The projected values may relatively differ for each station with regards to the elevation where is located and regional physical-geographic factors such as orography.

In terms of geographic perspective, the greatest increase in maximum and minimum temperature is observed in Bajo Meta and Sabana de Bogota (which are mountainous regions), while the lowest increase is observed in the Alta Guajira region (which is located

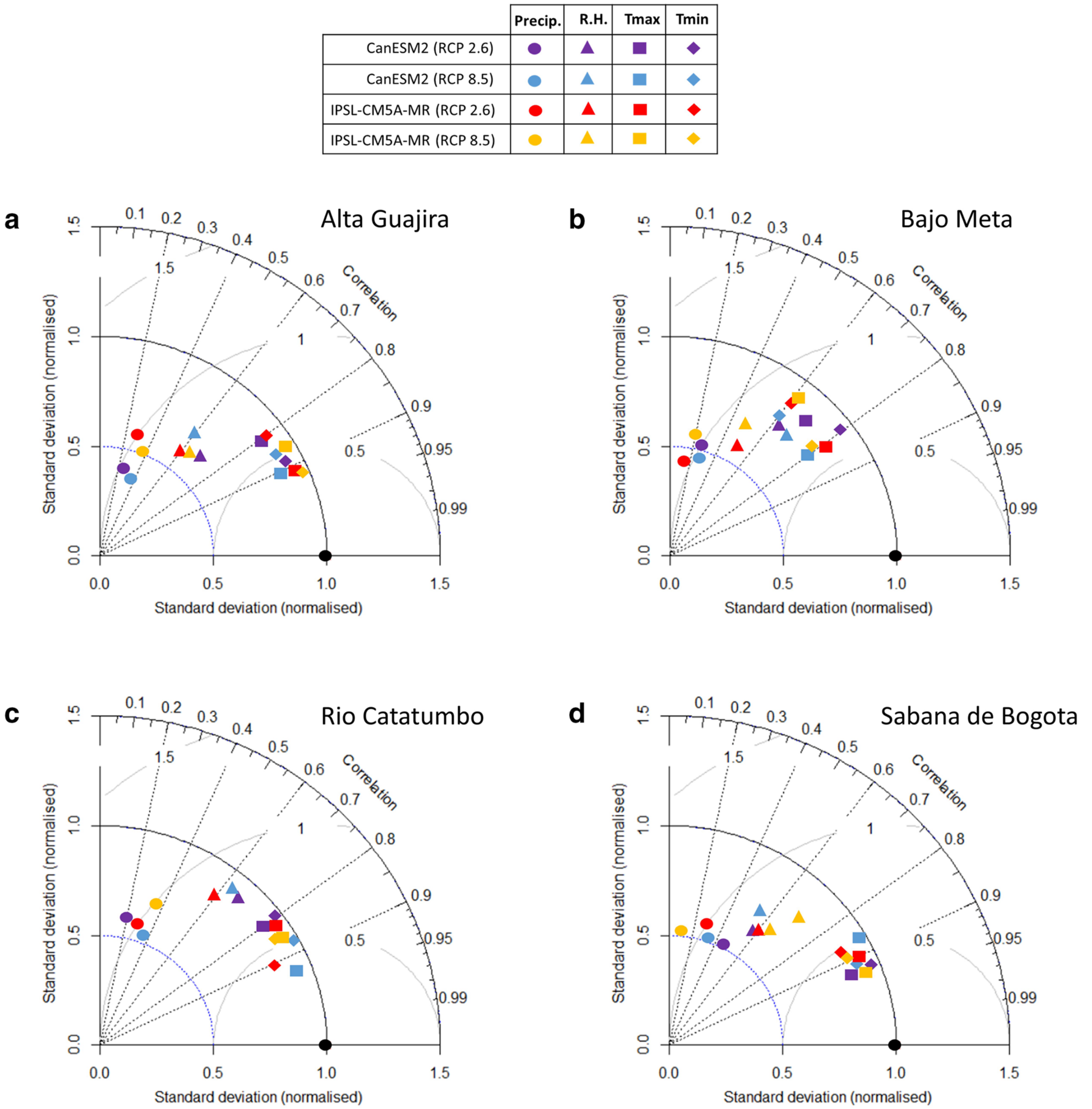


Fig. 4 Taylor diagrams for two GCMs and two scenarios during SDSM validation for all parameters in **a** Alta Guajira, **b** Bajo Meta, **c** Rio Catatumbo, **d** Sabana de Bogota

at the northern coast). In general, it is observed from the output of various scenarios that the mountainous stations with drier climate show a higher probability of rising temperatures during the coming decades. The projections obtained with the Representative Concentration Pathway RCP 8.5 were expected to show the highest increase in temperature compared with those made using the RCP 2.6. Since the first mentioned represents the worst-case scenario of greenhouse gas emissions for the first decades of XXI century, and this was in fact the result that was observed at most of the stations. This can be seen in the examples shown in Fig. 5; however, the maximum temperature that was projected using the model CanESM2 RCP2.6 is for some stations higher than the one obtained with RCP 8.5 with the model IPSL-CM5A-MR. This might indicate (in some degree) inconsistency or instability in the global projections of the models in some locations.

Considering the two different modeled periods and the characteristics of the different Representative Concentration Pathways (RCPs) the changes obtained for the

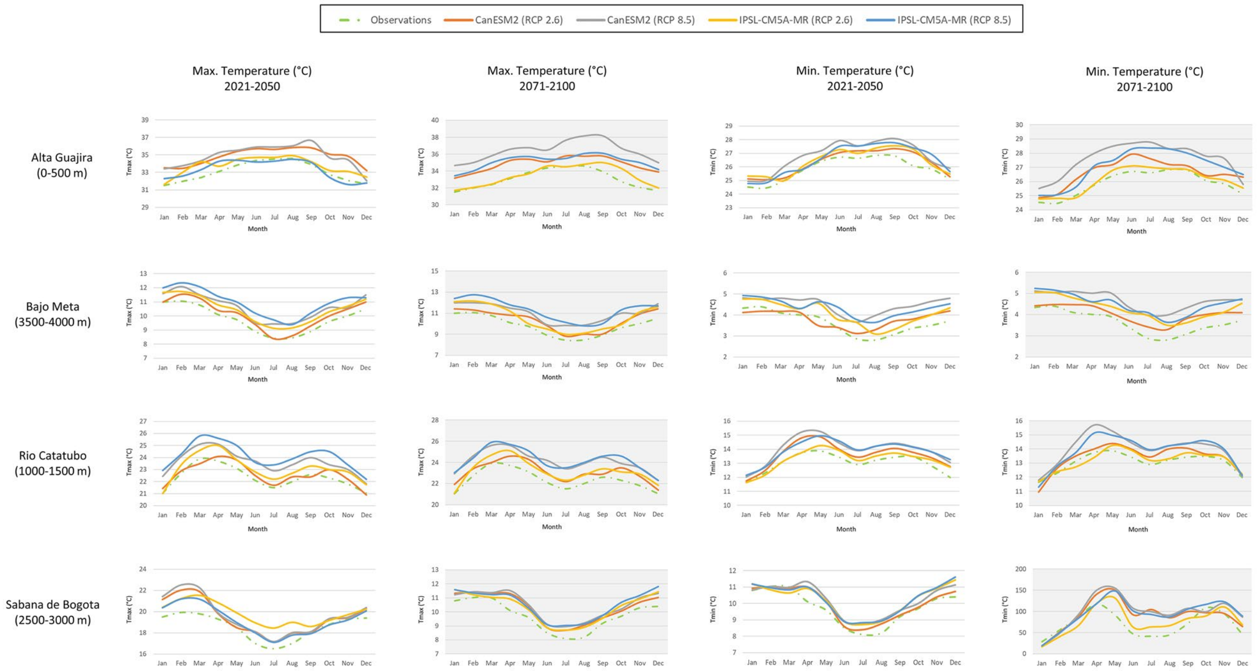


Fig. 5 Changes in Tmax and and precipitation at the four studied regions for the periods of 2021–2050 and 2071–2100, compared to the baseline period of 1981–2010

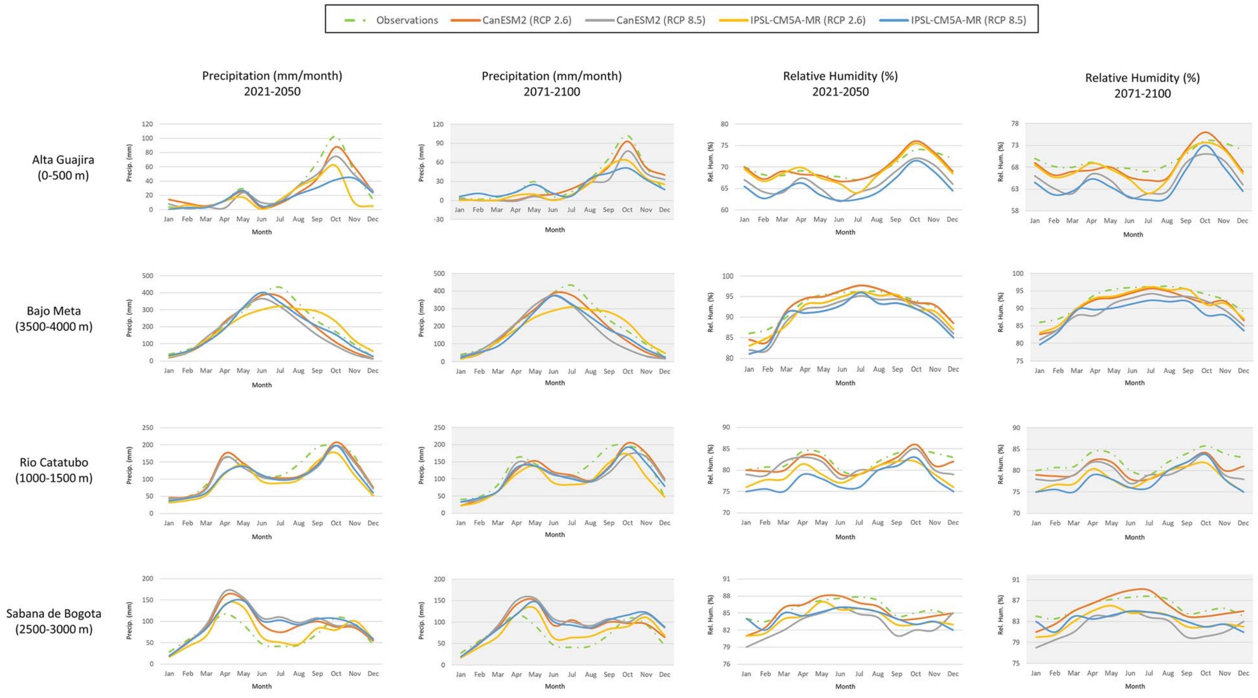


Fig. 6 Changes in relative humidity and precipitation at the four studied regions for the periods of 2021–2050 and 2071–2100, compared to the baseline period of 1981–2010

Table 2 Reductions and/or increases in °C for temperature and in % for relative humidity and precipitation for two future periods compared to the reference period of 1981–2010

	2020–2050	2070–2100	2020–2050	2070–2100	2020–2050	2070–2100	2020–2050	2070–2100
Alta Guajira								
CanESM2 (RCP 2.6)	0.3	0.5	0.6	0.7	− 2.3	− 3.1	0.5	− 3
CanESM2 (RCP 8.5)	0.7	1	1.3	1.5	− 6.3	− 7.1	− 0.4	− 1.6
IPSL-CM5A-MR (RCP 2.6)	0.4	0.8	0.9	1.1	− 3.5	− 4.3	0.1	− 4.1
IPSL-CM5A-MR (RCP 8.5)	0.8	1.4	1.1	1.3	− 2.9	− 3.7	− 0.4	− 1.9
Bajo Meta								
CanESM2 (RCP 2.6)	1.1	1.8	1.1	2.2	− 1.5	− 2.3	− 2.3	− 5
CanESM2 (RCP 8.5)	1.5	2.6	2.2	3.3	− 5.5	− 6.3	− 3.4	− 4.6
IPSL-CM5A-MR (RCP 2.6)	0.9	1.4	1.4	2.5	− 2.7	− 3.5	− 1.2	− 6.1
IPSL-CM5A-MR (RCP 8.5)	1.2	2.7	2	3.1	− 2.1	− 2.9	− 3.6	− 8.9
Rio Catatubo								
CanESM2 (RCP 2.6)	1.9	3.2	0.3	2	− 1.3	− 2.4	− 2	− 4
CanESM2 (RCP 8.5)	2.7	3.2	0.7	2.5	− 5.3	− 6.4	− 1.6	− 3.6
IPSL-CM5A-MR (RCP 2.6)	2.2	2.8	− 0.2	0.9	− 2.5	− 3.6	− 3.1	− 5.1
IPSL-CM5A-MR (RCP 8.5)	3.2	3.5	0.5	1.6	− 1.9	− 3	− 5.9	− 7.9
Sabana de Bogota								
CanESM2 (RCP 2.6)	2.6	2.9	1	1.7	− 3.1	− 5.2	1	2
CanESM2 (RCP 8.5)	3	3.6	2.1	2.8	− 7.1	− 9.2	2.4	3.4
IPSL-CM5A-MR (RCP 2.6)	1.7	2.2	1.3	2	− 4.3	− 6.4	− 0.1	0.9
IPSL-CM5A-MR (RCP 8.5)	2.1	2.7	1.9	2.6	− 3.7	− 5.8	1.9	3.2

period of 2071–2100 are, as expected, bigger than for the period 2021–2050 when compared to the baseline period of observations (1981–2010). A more detailed analysis of the spatial distribution of the projected climate changes shows that groups of station located at low elevations (below 1000 m) present a more spatially uniform results than those at higher elevations. This was the case for three of the four regions. More uniformity is also found for the period of 2071–2100 than for 2021–2050.

An important inference of the performed approach and as concluded in other studies (Gebrechorkos and Bernhofer 2019), the selection of the best fit predictors for a given predictand at a particular location, represents the key part of the modelling process and enables to accurately reproduce and predict the observed station data. The predictors that showed the best correlations with precipitation as predictand are related mostly with wind speed, geopotential, as well as high and relative humidity. This agrees with other studies using statistical downscaling methods (e.g., Hussain et al. 2017; Saraf and Regulwar 2016). A bias correction was not applied to the global climate data because it was found that bias correction methods might impair the advantages of circulation models by altering spatiotemporal field consistency, relations among variables, and by violating conservation principles. This might additionally neglect feedback mechanisms (Ehret et al. 2012); moreover, the resulting correlation coefficients found in the calibration and validation procedure were significant to assume a direct predictor-predictand relationship.

Since the projected scenarios for precipitation don't show a general tendency over the four studied regions, an alternative method is suggested for daily precipitation regional downscaling in order to compare the results or find higher accuracy e.g. generalized linear models or the use of neural network approach. In the same way, it is recommended that the results from this study be compared with other regional climate modeled datasets such as CORDEX in order to validate or complement the analysis of the results. The use of a dynamical downscaling method could provide more accurate results as well but this approach demands much more intensive computational resources and require large volumes of data which were not available for the studied regions.

For a more detailed analysis of the predictors and in order to identify potential better correlations with the historical records, the lagging of daily predictor variables could be applied as well as suggested for some authors (e.g., Harpham and Wilby 2005; Crawford et al. 2007) with the purpose of revealing hidden direct relationships between predictand and predictors; this is because predictors from distant grid-boxes may also influence the local climate in distinct time.

Conclusions

The results obtained during the process of calibration and validation define the model developed by SDSM as efficient in the downscaling of maximum/minimum temperature and relative humidity over the studied regions. With regards to precipitation the model shows a lower performance, which is not unusual compared to other statistical downscaling studies.

The GCMs used in this study show a projected increase of both maximum and minimum temperature over the next decades on the studied regions as well as a decrease in relative humidity with a slight change of precipitation with a most likely tendency to decrease for most of the considered stations, especially in the last decades of the XXI century.

The distribution density of stations into the studied regions (especially the Alta Guajira and Bajo Meta regions) is low when compared with other regions of the country. Even though these regions have importance regarding the agricultural and energy sector, there is still a higher attention on surveilling climate parameters in more urban areas in Colombia. The low amount of climate records and particularly those for temperature, relative humidity, radiation, and wind speed make it difficult to conduct a more proper technical climate analysis and thus creates higher uncertainties when calibrating climate models with the historical records for these regions.

Performing this study over four different regions offers a good opportunity to evaluate the performance of the tool SDSM over different geographic and climate conditions. Along the same lines, the results of the projections offer good information for the evaluation of possible future-case scenarios and decisions-making management. These results are useful for development planners, decision makers, as well as other stakeholders when planning and implementing appropriate management strategies regarding to adaptation and mitigation of climate change for these regions.

Abbreviations

SDSM: Statistical Downscaling Model; GCMs: Global Climate Models; Tmax: maximum temperature; Tmin: minimum temperature; RH: relative humidity; R: correlation coefficient; RMSE: root mean square error; NRMSE: normalized root mean square error; RMS: root mean square difference; NCEP: National Centre for Environmental Prediction; IPCC: Intergovernmental Panel on Climate Change; ITCZ: Inter Tropical Convergence Zone; MJO: Madden–Julian oscillation; IDEAM: Institute of Hydrology, Meteorology and Environmental Studies of Colombia; RCM: Regional Climate Models; WMO: World Meteorological Organization; RCP: Representative Concentration Pathway; GHG: greenhouse gases; MLR: multiple linear regression; NCEP: National Center for Environmental Prediction; SWG: stochastic weather generator.

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Authors' contributions

OM obtained, analyzed and interpreted the climate data and performed the modeling-task. CB contributed with co-planning, guidance and supervising the project and the manuscript. Both authors read and approved the final manuscript.

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The authors declare that they have no competing interests.

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Publisher's Note

7.3. Projected changes in the water budget for eastern Colombia due to climate change

water

MDPI

Article

Projected Changes in the Water Budget for Eastern Colombia Due to Climate Change

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Abstract: There is a lack of information about the effect of climate change on the water budget for the eastern side of Colombia, which is currently experiencing an increased pressure on its water resources due to the demand for food, industrial use, and human demand for drinking and hygiene. In this study, the lumped model BROOK90 was utilized with input based on the available historical and projected meteorological data, as well as land use and soil information. With this data, we were able to determine the changes in the water balance components in four different regions, representing four different water districts in Eastern Colombia. These four regions reflect four different sets of climate and geographic conditions. The projected data were obtained using the Statistical Downscaling Model (SDSM), in which two global climate models were used in addition to two different climate scenarios from each. These are the Representative Concentration Pathways (RCP) RCP 2.6 and RCP 8.5. Results showed that the temporal and spatial distribution of water balance components were considerably affected by the changing climate. A reduction in the generated streamflow for all of the studied regions is shown and changes in the evapotranspiration and stored water were varied for each region according to both the climate scenario as well as the characteristics of soil and land use for each area. The results of spatial change of the water balance components showed a direct link to the geography of each region. Soil moisture was reduced considerably in the next decades, and the percentage of decrease varied for each scenario.

Keywords: climate change; water budget; general circulation model; modeling; stream flow changes; soil water; RCP

1. Introduction

According to the Intergovernmental Panel on Climate Change [1], the amount of greenhouse gases released into the atmosphere might have an high influence on the global warming of Earth's surface over the next decades. These changes in climate can have long-term implications on social, economic, and ecological processes, while also affecting the natural development of ecosystems [2]. Thanks to advances in the modelling field as well as the physical understanding of the climate system-processes, more regional climate change projections have been developed for several regions of the world, throughout the last years. It is expected that the increment of average annual and seasonal temperatures in the tropics and subtropics will be higher than that in the mid-latitudes. On the other hand, average annual precipitation is expected to decrease in many regions located in mid-latitudes and subtropics. It is estimated that for each degree produced from global warming, there will be a reduction of at least 20% in hydric resources for approximately 7% of the global population [3].

Water budgets are a useful method for evaluating availability and sustainability of a water supply—it shows the balance between the water stored in an area and the water that flows into and out of the area. Observed changes in water budgets of an area over time can be used to assess the effects of climate variability and human activities on water resources. Furthermore, they provide a basis for assessing how natural or human-induced changes in one part of the hydrologic cycle might affect other aspects of the cycle [4]. A large number of published articles show the important impacts of climate change on water resources—some of which are related to the hydrological cycle, e.g., [5–9], while other studies are related to groundwater, recharge, changes in the vegetation cover, and the impact on ecosystems. Alterations in the climate will produce changes in the hydrological cycle, including an increase of evaporation due to higher temperatures, as well as an increase in global and regional evapotranspiration, which will be directly related to precipitation levels, spatiotemporal changes in rain distribution, vapor pressure deficit, and wind speed [10–12]. These features could have a negative influence on water sources.

Soil moisture variation is caused by rising temperatures and other climate variations; soil moisture affects agricultural productivity and has a negative influence on the land's ability to store carbon. Moreover, soil moisture information is valuable to a wide range of government agencies and private companies concerned with issues of weather and climate, runoff potential and flood control, soil erosion and slope failure, reservoir management, geotechnical engineering, and water quality. Soil moisture is a key variable in controlling the exchange of water and heat energy between the land surface and the atmosphere, through evaporation and plant transpiration.

The eastern region of Colombia is highly vulnerable to the effects of climate change, especially with regards to its high diversity of fauna and flora, the expansion of the agricultural frontier, in addition to pressure on water resources for industrial activities. When a dry climatic condition occurs in the country, the water yield reduces significantly, as compared to normal conditions; thus, the natural supply of the hydric resource in an average year and a dry year have regional differences that are important to consider [13]. This hydric shortage could affect areas including both the agriculture an energy sector. There is a lack of data and detailed climate studies throughout this region; therefore, research on a water budget approach is necessary to determine on a regional scale the possible change in the availability of water for future decades. This research can, thus, contribute valuable information to development planners, decision makers, researchers, and other stakeholders as to when to plan and implement appropriate management strategies for adapting to climate change in this area.

This study aims to determine the change of the water balance components under climate change scenarios (RCP 2.6 and RCP 8.5) in two periods of time (2021–2050 and 2071–2100), based on the modeling of climatic and hydrologic parameters on four representative regions characterized as individual water districts on the east side and in the middle of Colombia—regions with very different geographic and climatic conditions. Included complementary to this study, are descriptions of the soil moisture in the projected climate scenarios.

2. Study Area

The areas analyzed in this study comprises four representative areas characterized as individual water sectors on the east side and in the middle of Colombia with different geographic and climatic conditions. These regions lie between 74°56′13″ and 66°82′29″ west longitude, and between 12°24′40″ north and 2°18′225″ south latitudes. These regions are named Alta Guajira, Bajo Meta, Rio Catatumbo and Sabana de Bogota. They were selected due to each region's variability of conditions and the sufficient availability of data for analysis.

Colombia is located in the northwestern corner of South America, exhibiting complex geographical, environmental, and hydroecological features. Colombia is crossed by three rugged parallel ranges of the Andes Mountains—namely, the Eastern, Central, and Western Cordilleras. Precipitation along the country is highly influenced by the Inter Tropical Convergence Zone (ITCZ); however, the climate is also conditioned by local particularities like those caused by mountain barriers to the atmospheric circulation. On seasonal time scales, the displacement of the ITCZ exerts a strong control on the annual cycle of Colombia's hydroclimatology [14–16]. Some regions of the country experience a bimodal annual cycle of precipitation with distinct rainy seasons and dry seasons, while others experience a unimodal annual cycle, which result from the different passages of the ITCZ over those regions. Moisture transported from the Amazon basin encounters the orographic barrier of the Andes, thus, focusing and enhancing deep convection and rainfall in the eastern flank of the Cordillera, with the maximum rainfall occurring during June–August. The interannual variability of the diurnal cycle is dominated by the effects of both phases of El Niño Southern Oscillation (ENSO).

The east side of Colombia is hot in most of its extension, with a range of medium temperature from 12 to 34 °C. The eastern side of the country borders Venezuela, the Amazon is to the south, extensive valleys and the Andean mountains are on the mid-eastern side, and coastal plains towards the higher north. These plains are tropical grasslands that undergo seasonal flooding; they are suitable for livestock grazing and in some areas for the cultivation of crops. Additionally, major petroleum discoveries have been made in the eastern region.

3. Materials and Methods

3.1. Meteorological Data

Historical daily data of precipitation, maximum temperature, minimum temperature, and relative humidity from 153 hydrometeorological stations along the four studied regions was provided by the Institute of Hydrology, Meteorology and Environmental Studies of Colombia (IDEAM). From this, only datasets with less than 30% of missing values for the time range of 1980–2015 were considered for the analysis. This was used in concordance with the minimum extension of 30 year-records, which is recommended by the World Meteorological Organization [17] in order to obtain reliable statistics. Figure 1 and Table 1 show the location and description of the 4 analyzed regions or water districts; the climate characterization refers to Lang's Index (I = Pr/Tm), where Pr is the mean annual precipitation amount and Tm is the mean annual temperature. In some of these water districts, several climate conditions coexist.

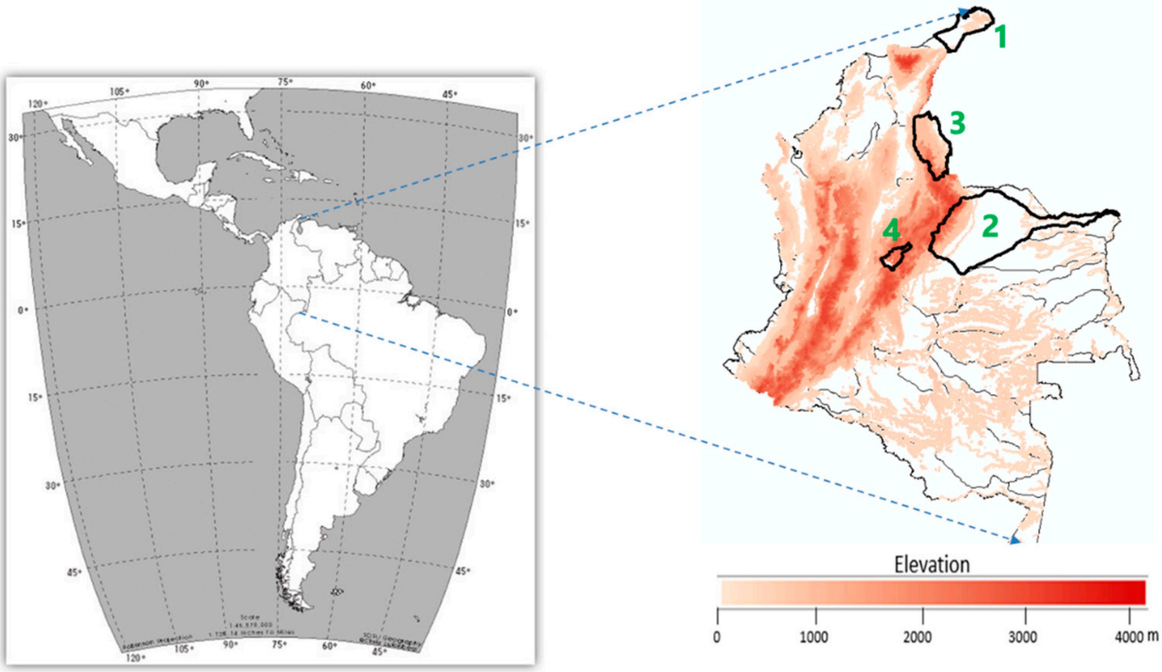

Figure 1. Location of the studied areas with elevation.

Table 1. Characteristics of the four analyzed regions.

	Region/Water District	Climate	Area (km^2)	N° of Stations (Precipitation)	Min. Elevation (m.a.s.l.)	Max. Elevation (m.a.s.l.)
1	Alta Guajira	arid, desertic	12,348	25	1	390
2	Bajo meta	semihumid	42,655	42	45	3520
3	Rio Catatumbo	humid	17,960	47	83	1740
4	Sabana de Bogota	semihumid, semiarid	2245	39	2540	3800

Projected daily data sets for the same variables and for the future periods 2021–2050 and 2071–2100 were created from a regional downscaling procedure [18], using the statistical downscaling model SDSM and datasets from two Global Climate Models (GCM), which are part of the CMIP5-project, the Global Climate Model CanESM2 developed by Canadian Centre for Climate Modelling and Analysis and the model IPSL-CM5A-MR developed by The Institut Pierre Simon Laplace. Both GCM included in the study (as most GCM used to date) used fundamental physical laws, which were then subjected to physical approximations like equations of Geophysical Fluid-Dynamics that are appropriate for describing the atmosphere and the ocean at large enough scales. The Representative Concentration Pathways—RCP 2.6 and RCP 8.5 were considered for both models, representing two different possible future emission trajectories and radiative forcings. The RCP 8.5 combines assumptions about high population and relatively slow income growth with modest rates of technological change and energy intensity improvements, leading to a high energy demands and greenhouse gas (GHG) emissions in the long term, in the absence of climate change policies. The RCP 2.6 might be described as the best case for limiting anthropogenic climate change. In this scenario, Global CO2 emissions peak by 2020 and decline to around zero by 2080. The concentrations in the atmosphere peak at around 440 ppm in midcentury and then slowly start declining.

3.2. Soil and Land Cover

The values of the different canopy and vegetation variables were taken from available local studies, and maps provided by IDEAM. Physical characteristics of the different types of soils for each region were obtained from regional studies in the areas. The overall available information about the general soil characteristics of the whole extension of the study sites was relatively low, most of the data used for the analysis corresponded to the maps provided by the IDEAM and the local authorities. Three of the studied regions, not including Alta guajira, were relatively similar in terms of soil properties but did show significant differences in terms of land cover. In these regions, numerous wetlands can be found along with some urban areas; however, grassland and tropical forest are the main land-cover types for all of regions, even though the portions differ.

3.3. Model

The model BROOK90 [19] was used in this study for the water balance assessment in the historical and the different projected scenarios. BROOK90 is a deterministic, process-oriented, lumped parameter hydrologic model that can be used to simulate the water balance in most land surfaces at a daily time-step, year-round. The model has a strong physically based description that simulates the above and below liquid phases of the precipitation–evaporation–streamflow–ground water flow part of the hydrological cycle for a point-scale stand at a daily time-step [20]. The BROOK90 model calculates evaporation through the Shuttleworth–Wallace approach [21], as well as an improvement of the Penman–Monteith equation. The characteristics of the soil water were determined using a modified approach of the Brooks and Corey [22], and Saxton et al. [23]. The water movement through the soil was simulated using the Darcy–Richards equation. To calculate streamflow, the model used a simplified process—storm flow by source area flow or subsurface pipe-flow and delayed flow, from vertical or downslope soil drainage and first-order groundwater storage. A general water balance equation can be represented as follows:

$$PREC = EVAPOT + FLOW + STORAGE \quad (1)$$

where *PREC* represents precipitation (mm), *EVAPOT* is the evapotranspiration (mm), *FLOW* is the corresponding simulated total streamflow (mm) derived from surface flow and groundwater flow, and *STORAGE* is the deep seepage loss from groundwater (mm). Applications of the BROOK90 model have been demonstrated in grasslands, temperate evergreen and deciduous forests [19], and cultivated lands [24], among various vegetations with satisfactory performance. The model is also applicable in the tropics after adjusting the parameters to local conditions.

3.4. Data-Grid and Interpolation

The study intends to show the change in water budget caused by climate change over the studied regions on a bigger scale than a watershed scale. For this reason, the study was focused primarily on water sectors that covered a much bigger extension of an area. This would give a wider overview and understanding of the availability of water for several cities and settlements located in and around these regions, as well as the productive activities developed in the area. With this purpose, the data from the stations (including historical and future data) were interpolated and converted into a 10 km × 10 km grid of datasets. This is an appropriate approach considering the irregular distribution of the stations and the highly variable geography of the areas. It further enables the possibility of conducting a water balance calculation in areas where no historical data are available, while also being located at different elevations from the station point. The data were interpolated using the Thin Plate Spline Method (TPS). This is a spline-based technique for data interpolation and smoothing and it has been proven to perform a good interpolation for precipitation data (Tait et al., 2006). For interpolation of scattered $z(x,y)$ data, the TPS is just a special case of Radial Basis Function (RBF) interpolation:

$$z(x,y) = p(x,y) + \sum_{i} l_i \, \phi(r) \quad (2)$$

where $p(x,y)$ is a polynomial function and ϕ is an RBF. In the case of TPS, $\phi = r^2 \ln(r)$. The water balance would be calculated for each of the grid points using BROOK90 and all available data. The results for the baseline historical period of 1981–2010 would be compared with the results obtained for the different projected scenarios, considering the two Representative Concentration Pathways RCP 2.6 and RCP 8.5, the two GCM, and the two projected periods 2021–2050 and 2071–2100. The comparison would allow one to visualize the expected differences in the availability of water for the future decades, due to the effects of climate change.

4. Results

The graphs provided in Appendix A show an overview of monthly average results for the 4 studied areas. Here, one can compare the three periods of time (historical baseline 1981–2010, future projections 2021–2050, and 2071–2100) for each area, each GCM, and each Representative Concentration Pathway. As an example, in Figure A1a of Appendix A, the results for the three periods of time in the Alta Guajira region and the scenario with the model CanESM2 and Representative Concentration Pathway RCP 2.6 can be observed. The results are expressed in terms of the water balance components given by Equation (1). Table 2 shows the relative increment or decrease for each projected component of the water balance in the different climate scenarios, compared to the reference period of 1981–2010.

Projected soil moisture for the 4 studied regions as an averaged monthly value can be seen in Figure 2, the results for the climate scenarios are then compared with the baseline period of 1981–2010.

Table 2. Percentual change of the water-balance components in the projected scenarios.

	Precipitation (mm)		**Streamflow (mm)**		**Evapotranspiration (mm)**		**Storage (mm)**	
	2021–2050	**2071–2100**	**2021–2050**	**2071–2100**	**2021–2050**	**2071–2100**	**2021–2050**	**2071–2100**
Alta Guajira								
CanESM2 (RCP 2.6)	9.12	3.68	17.73	35.07	13.73	−10.36	−22.34	−21.03
CanESM2 (RCP 8.5)	−0.88	−24.15	66	−22.75	−22.24	−26.74	−44.64	25.34
IPSL-CM5A-MR (RCP 2.6)	−35.22	−26.59	−1.97	−15.73	−4.37	−25.27	−28.88	14.41
IPSL-CM5A-MR (RCP 8.5)	−35.13	−22.07	−22.8	−52.77	−18.3	0.4	5.97	30.3
Bajo Meta								
CanESM2 (RCP 2.6)	−11.41	−11.58	−12.48	−12.81	−6.67	−5.29	7.74	6.52
CanESM2 (RCP 8.5)	−19.33	−20.73	−20.45	−22.52	−15.18	−13.06	16.3	14.85
IPSL-CM5A-MR (RCP 2.6)	−1.5	−6.91	−10.58	−15.85	18.12	27.03	−9.04	−18.09
IPSL-CM5A-MR (RCP 8.5)	−9.81	−17.67	−10.47	−19.93	7.67	8.43	−7.01	−6.17
Rio Catatubo								
CanESM2 (RCP 2.6)	−3.64	−2.44	−24.92	−23.93	17.15	18.45	4.13	3.04
CanESM2 (RCP 8.5)	−8.9	−10.57	−30.73	−39.7	12.41	17.78	9.42	11.35
IPSL-CM5A-MR (RCP 2.6)	−6.25	−5.92	−30.64	−30.53	17.57	18.02	6.82	6.59
IPSL-CM5A-MR (RCP 8.5)	−14.17	−13.68	−35.08	−40.32	6.24	12.24	14.67	14.4
Sabana de Bogota								
CanESM2 (RCP 2.6)	10.33	10.53	−16.18	−18.17	30.11	32.33	−3.6	−3.63
CanESM2 (RCP 8.5)	17.84	16.78	−24.59	−22.39	50.25	46.41	−7.82	−7.24
IPSL-CM5A-MR (RCP 2.6)	−2.57	−1.77	−15.27	−16.16	7.07	8.99	5.63	5.4
IPSL-CM5A-MR (RCP 8.5)	12.54	20.72	−20.8	−11.09	38.1	44.67	−4.76	−12.86

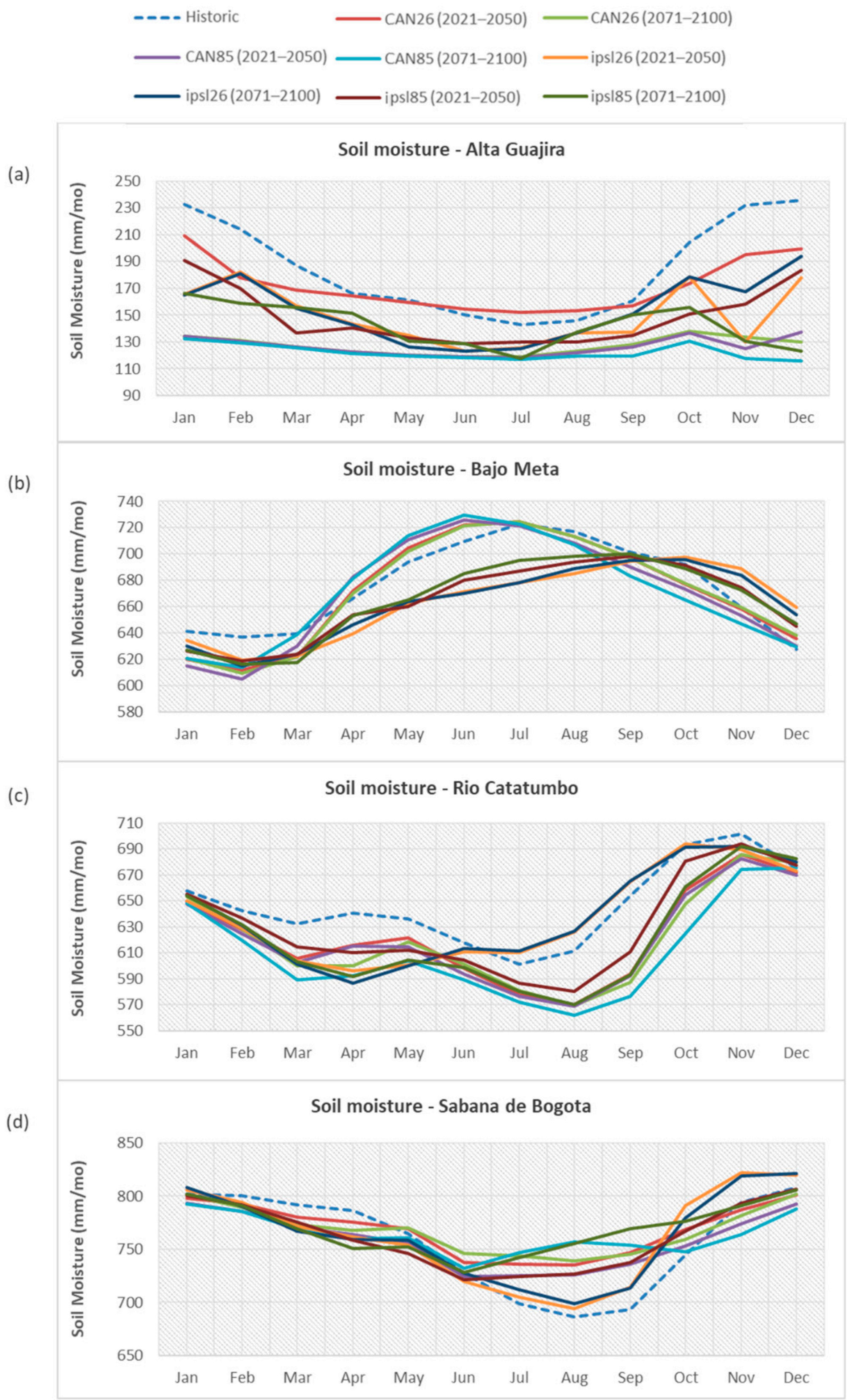

Figure 2. Monthly averaged soil moisture in (**a**) Alta Guajira; (**b**) Bajo Meta; (**c**) Rio Catatumbo; (**d**) Sabana de Bogota.

5. Discussion

In Appendices A and B, one can appreciate the notorious difference between the climate conditions and the water availability between the four studied regions, with regards to the historical period as well as to the projections. In general terms, the water balance components in the different regions showed different patterns magnitudes due to variability in precipitation along the Colombian territory. The region of Sabana de Bogota (Appendix A, m–p) showed a clear bimodal precipitation regime and the region Meta (Appendix A, e–h) showed a clear monomodal regime; the other two regions presented a not-so-clearly defined bimodal regime—these precipitation conditions were obedient to the displacement of the ITCZ over the regions.

The region of Alta Guajira being an arid/desert region shows very low levels of precipitation for most of the year. It reaches a peak of about 105 mm by the month of October, generates low levels of streamflow, since almost 85% of the total precipitation in the year is converted into evapotranspiration due to the high temperatures. In the first three months of the year, evapotranspiration can be almost 8 times larger than precipitation. During this time, the storage water produced as a consequence of the rainy season in the last months of the year is constantly being evaporated. The projections for Alta Guajira showed a decrease in precipitation, in general terms, and, therefore, a decrease in the other components of the water balance. This was the case for both projected periods of time of 2021–2050 and 2071–2100. Only the model CanESM2 with scenario RCP 2.6 showed a slight increment of precipitation in the short and long term.

From the four analyzed areas in this study, Bajo Meta presented the highest amount of rain on a yearly basis. In this region, the results showed an almost “normal” distribution of precipitation throughout the year for the historical records—presenting the highest values in the months of June and July with a peak of 430 mm/month and a non-rainy season at the end and beginning of the year. Most of the precipitation in Bajo Meta was converted into streamflow during the year (74.3%). This might be due to the characteristics of the soil (a predominant silty loam type for a big part of this region), which does not allow a big rate of infiltration. The projections for this region showed a decrease in precipitation, which led to a directly proportional decrease in streamflow; evaporation showed variable results depending on the model; CanESM2 indicated a slight decrease for both RCP scenarios, while IPSL-CM5A indicated the opposite. These results are reasonable considering that for the first model the decrease in precipitation was much bigger in magnitude than the second model.

The historical period indicates that in the region of Rio Catatumbo, half of the precipitation in the year was evaporated (50.7%) and a similar level was converted into streamflow (45.1%). In general terms, the projections for the future showed a slight decrease of the precipitation regimes, with around 6% from the model CanESM2 and around 9% from the model IPSL-CM5A but with a much higher decrease in the levels of streamflow produced by this precipitation. Evaporation in both models was projected to increase at levels of around 20% for the next decades. This was linked to the projected increase in the temperature for the region, which was close to 4 °C for the end of the century with the scenario RCP 8.5, according to the results from the regional downscaling procedure [18].

In the region of Sabana de Bogota, the historical period showed that 58% of the precipitation was evaporated while only 41% converted into streamflow. The typical clay type of soil predominant in a big part of the region was reflected in the low levels of stored water. Sabana de Bogota was the only one from the analyzed four regions where an increase of precipitation was projected for the next decades; Table 2 shows that the biggest increment was in the period of 2071–2100, with the model IPSL-CM5A and the scenario RCP 8.5. These projections showed that the levels of evaporation would increase in a considerable rate compared with the historical period. It was clear from Appendix A (m–p) that a bigger percentage of the projected precipitation would evaporate, compared with the historical baseline.

It is important to consider that the results obtained in this study and shown in Figure 2 and Appendix A are the averaged-out product of the results of each station in the region. This was made with the purpose of obtaining results in a macro-scale, to have a notion of the projected scenarios for water districts, where productive and social activities are planned in accordance with the available water in that area. An analysis for an individual station or an area of a much higher resolution could also show variable results, depending on the elevation of the studied area. The rasters produced in Appendix B are a useful representation of the spatial variability of the historical and projected results for two of the studied regions, when considering the geographical variation presented in each of them. As was said before, the spatial distribution density of meteorological stations at the other two regions was too low to allow a proper interpolation process to create a figure that reliably showed a representation of spatial variability of the results throughout the regions.

Figure 2 shows that, in general, soil moisture would be reduced considerably in the next decades, the percentage of decrease could vary for each scenario; the only exception was the region of Sabana de Bogota, where precipitation is projected to increase, which would result in an increase in the soil moisture. These results are important in relation to agricultural activities and the planning/use of soil for the next decades.

The lack of available historical records of discharge in the studied areas as well as the wide extent of these areas, made the performance of a respective process of calibration and validation of the water balance components that comprises all extensions of the studied areas unsuitable, however, an intensive review of the input data to the model was carried out to ensure an appropriate parameterization. This included a detailed selection of values regarding the information of soils in the studied areas, through technical information from the public and private sector. Information regarding vegetation comes mostly from Governmental institutes, as well as the detailed land use information that was also obtained from regional, territorial development plans. In the same way, a review of the results of the model and a comparison with results of other studies nearby, in tropical or similar areas was made [25–31], to verify the veracity of the results and ensure that they are within a correct range of magnitudes.

The main differences of both GCM that were used for a regional downscaling as a source of the projected climate data used in this study are their spatial resolution; CanESM2 with 2.79° latitude × 2.81° longitude and IPSL-CM5A-MR with 1.26° latitude × 2.5° longitude, as well as the model-components with which they were coupled; CanESM2 consists of a physical atmosphere–ocean model coupled to a terrestrial carbon model and an ocean carbon model, while the IPSL-CM5A-MR model couples four components of the Earth system, atmospheric dynamics and physics, ocean dynamics, sea ice dynamics and thermodynamics, and land surface. Moreover, every single GCM differs in the parametrization of the physical modeled processes, for this reason they offer varied results that might be more successfully correlated with real measurements in some areas than others. The model IPSL-CM5A, in spite of its slightly higher spatial resolution has shown a better performance than other models to identify extreme events in South America and other regions [32], but a lower performance to appropriately reproduce precipitation historical records in comparison with CanESM2 and other models, in Colombia and South America [33,34]. This agreed with the results of this study, where extreme events and seasonal precipitation was more clearly identifiable for the model IPSL-CM5A, especially in regions of lower elevations, where the model seemed to overestimate the projected change for the different variables.

Rainfall seasonality and its interannual variability have been observed to change in magnitude, timing, and duration, in the tropics [35]. As mentioned before, the climate in Colombia is conditioned by local particularities like those caused by mountain barriers to the atmospheric circulation but the annual cycle of Colombia's hydroclimatology is mostly influenced by the displacement of the ITCZ. The different passages of the ITCZ over the regions determine either a bimodal annual cycle of precipitation with distinct rainy seasons and dry seasons, while others experience a unimodal annual cycle that result from the moisture transported from the Amazon basin when it encounters the orographic barrier of the Andes. The seasonality of hydrological elements in the different water districts shows larger variability due to their different conditions of topography, hydrogeology, and vegetation. Higher regions like Sabana de Bogota or parts of Rio Catatumbo are highly dependent on altitude, and since there is no snow formation in any of the regions, there is no considerable time lag between the precipitation event, the stream flow, and the soil moisture, which can be observed in Figure 2 and Appendix A. A prolonged positive soil humidity in the humid regions seen in Figure 2 linked directly with rain events explained by a permeable soil and temperature that was not high enough to increase evapotranspiration for several months. Climate seasonality is a defining feature of many ecosystems, often characterized in the tropics by a distinct non-uniformity in their timing of annual rainfall. This results in one or two wet seasons during which most of the annual rainfall occurs, separated by prolonged dry periods. In regions like Bajo Meta or Rio Catatumbo, under conditions of relative water abundance, long-term evapotranspiration becomes limited by the potential evapotranspiration, while in arid regions like Alta Guajira, where the energy supply is high, precipitation is the main constraint to evapotranspiration. In the former case, water supply exceeds demand, while in the latter case water supply is outstripped by the demand [36]. In Alta Guajira a projected increase in mean temperature would likely lead to increase in the frequency and the intensity of seasonal droughts [37].

It is important to consider that although the RCP 2.6 scenario might be described as the best case for limiting anthropogenic GHG emissions, their atmospheric concentrations will continue to increase even after emissions slow down and then will eventually start to decrease [38]. Carbon dioxide accumulates in the atmosphere and stays there for decades. Even if emissions start reducing in 2020, the concentration continues increasing and starts falling very slowly, only after 2050. This might explain why in some of the results of RCP 2.6 in Table 2, a bigger percentual change is observed for the period 2020–2050 than for the period of 2070–2100. However, as expected, the results obtained for the projections in the scenario RCP 8.5 showed a higher projected change than those in the scenario 2.6, this is the case for the analyzed regions except in Alta Guajira with model CanESM2, where the results showed a slight increase in precipitation under scenario 2.6, and a negative change under scenario 8.5 and model IPSL-CM5A_MR. This could have been caused by the incapacity of the model to accurately predict changes of precipitation in very arid areas that are characterized by little but highly variable and unpredictable rainfall and has been shown in other studies like Zhao [39] who analyzed the performance of the GCM models used in the CMIP5-project in several arid regions of the world, or by Mingxia [40] which found similar results across dryland areas.

The inherent existence of uncertainty in every water budget approach must be taken into consideration. Uncertainty related to hydrological modeling is affected by the input data, validation data, model structure, and model parameters. In order to reduce the uncertainties as much as possible in the hydrological modeling in this study, a detailed parametrization of the model was intended for each of the grids cells that the regions were divided into. For this, soil, vegetation, land use, and topography data were taken from local private studies and maps provided by governmental institutions and the parameters were individually defined for each of the cell grids where the model was run individually.

The hydro-climatic model chain typically consists of the components—emission scenario, GCM, regional climate model or statistical downscaling, and hydrological model [41]. This study represents the last step of that chain, but all of these components constitute a potential uncertainty source for the results. The uncertainty associated with the individual components of this chain has been investigated by an increasing number of studies. In some of them, the GCM structure is identified as the dominant source of uncertainty, e.g., [42–44]. A common finding for other studies is that in the hydrological model, uncertainty is less important than other sources but cannot be ignored [45–47]. Ideally, the analysis of hydrologic change in future studies should comprehend the full suite of uncertainties associated with global climate modeling, climate downscaling, hydrologic modeling, and natural climate variability. In this manner, the water resources planning and management community can make more informed decisions. Parameter uncertainty estimation is one of the major challenges in hydrological modeling and analysis of future change for the water sector is an interdisciplinary endeavor [48]. Ongoing parallel efforts to monitor and verify water budget components would help to improve accuracy. Posterior analysis could be done in an effort to determine the magnitude of the uncertainty of the hydrological response to climate change. Due to the uncertainties associated with the study of climate change and the limitations of models in representing climate and hydrological response, the most trustworthy indicator is still the trends observed at the measuring stations while the predictions of models in a big scale like that in this study might only be used to have a general notion of trends for the studied variables under different potential climate conditions.

The main objective of this study was to provide an overview of water budget response to climate change for a region where no other studies have been performed, and where not so much information was available since the few existing studies in Colombia have been aimed at regions with a bigger density of available data. In the analyzed regions in this study and especially in Alta Guajira and Bajo Meta, there is a lack of observed data with sufficient detail and quality. We encourage the future improvement of collection and testing of reliable data in a range of spatial and temporal scales in these regions, since it is critical to improve our understanding of hydrological processes [49].

6. Conclusions

The model BROOK90, historical data, as well as projected meteorological data were used to determine the changes in the water balance components in four different regions, which represent the four water districts in Eastern Colombia. The four regions reflect four different climatic and geographic conditions. The projected data were obtained from a statistical regional downscaling procedure, where two GCMs (CanESM2 and IPSL-CM5A-MR) and two different climate scenarios from RCP 2.6 and RCP 8.5 were used.

Results have shown a potential reduction in the generated streamflow for all studied regions. The temporal distribution of water balance components was considerably affected by the changing climate, which moreover, might have a profound impact on the hydrological regimes in these regions. Changes in evapotranspiration and stored water could vary from each region, according to the climate scenario, and the characteristics of soil and land use for each area. Results of spatial change of the water balance components have shown a direct link to the geography of each region and how the values differed accordingly, at different elevations. Soil moisture would be reduced considerably in the next decades and the percentage of decrease could vary for each scenario. Only in the region of Sabana de Bogota did the results show the opposite—this agreed with the precipitation projections that are to increase and, therefore, also the soil moisture.

Application of the model BROOK90 proved to be valuable for water cycle analysis and for the purpose of this study in offering a general overview to the change of water balance components, throughout the east side of Colombia, due to future climate change. Prediction of the impact of climate change on water budget components is a transcendent, practical, and theoretical problem to which each country and its institutions should dedicate more resources—especially for countries and regions that are more vulnerable to climate change.

Uncertainties associated with the GCMs, hydrological models, and the approaches used in this study have a direct effect on the outcome, and they have to be considered and evaluated for the use of these results, in addition to their uses for future works. The results obtained in this study should be considered as indicative of the expected trend in water resources of the studied regions, as a result of climate change. These results might serve as a baseline information for creating mitigating measures. However, future work using other models and other techniques for the analysis of water resources throughout these areas is encouraged.

Author Contributions: Conceptualization, methodology, software, analysis, writing, O.M.; Software, review, T.T.L.; Supervision, review and guidance, C.B. All authors have read and agreed to the published version of the manuscript.

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Conflicts of Interest: The authors declare no conflict of interest.

Appendix A

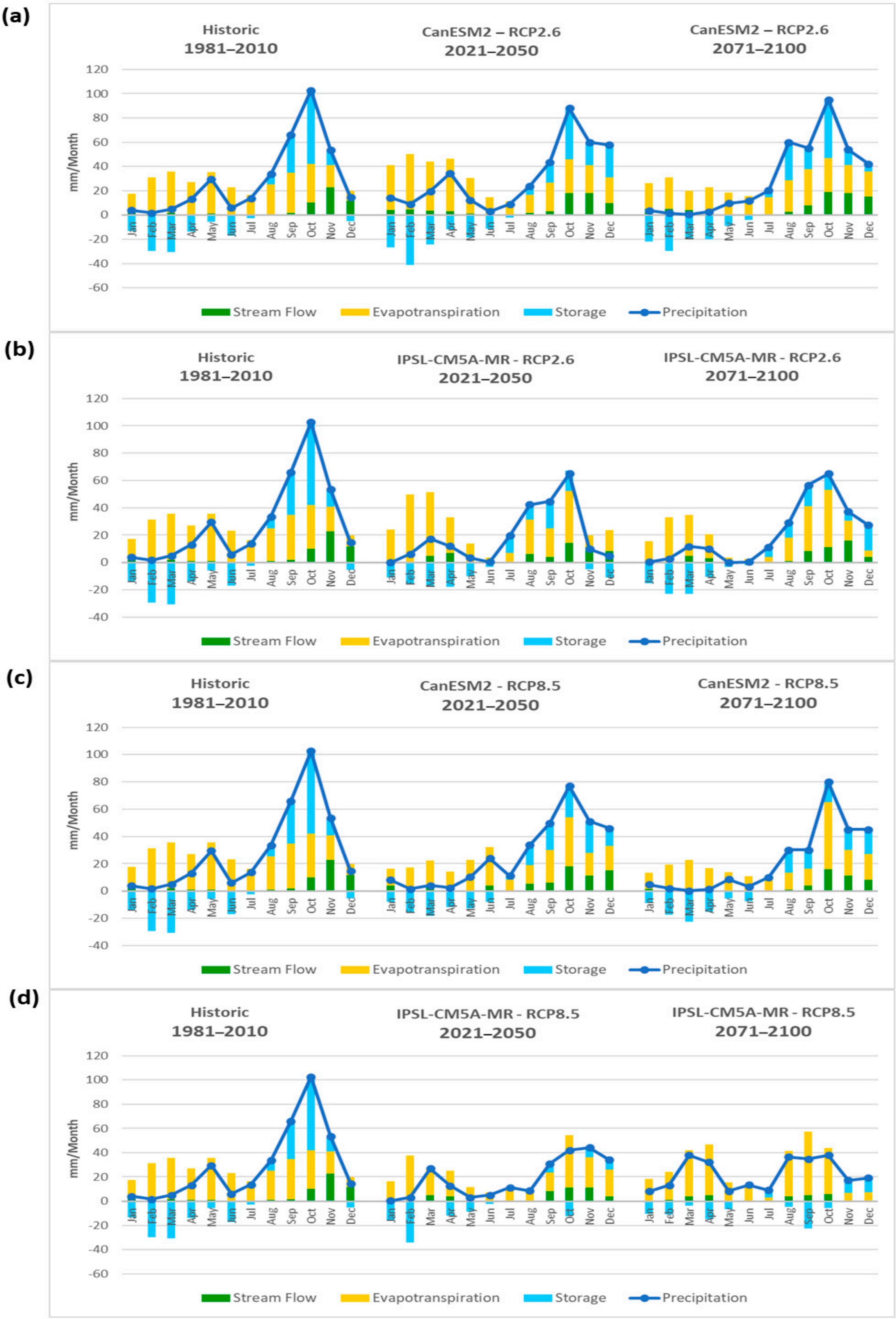

Figure A1. Alta Guajira.

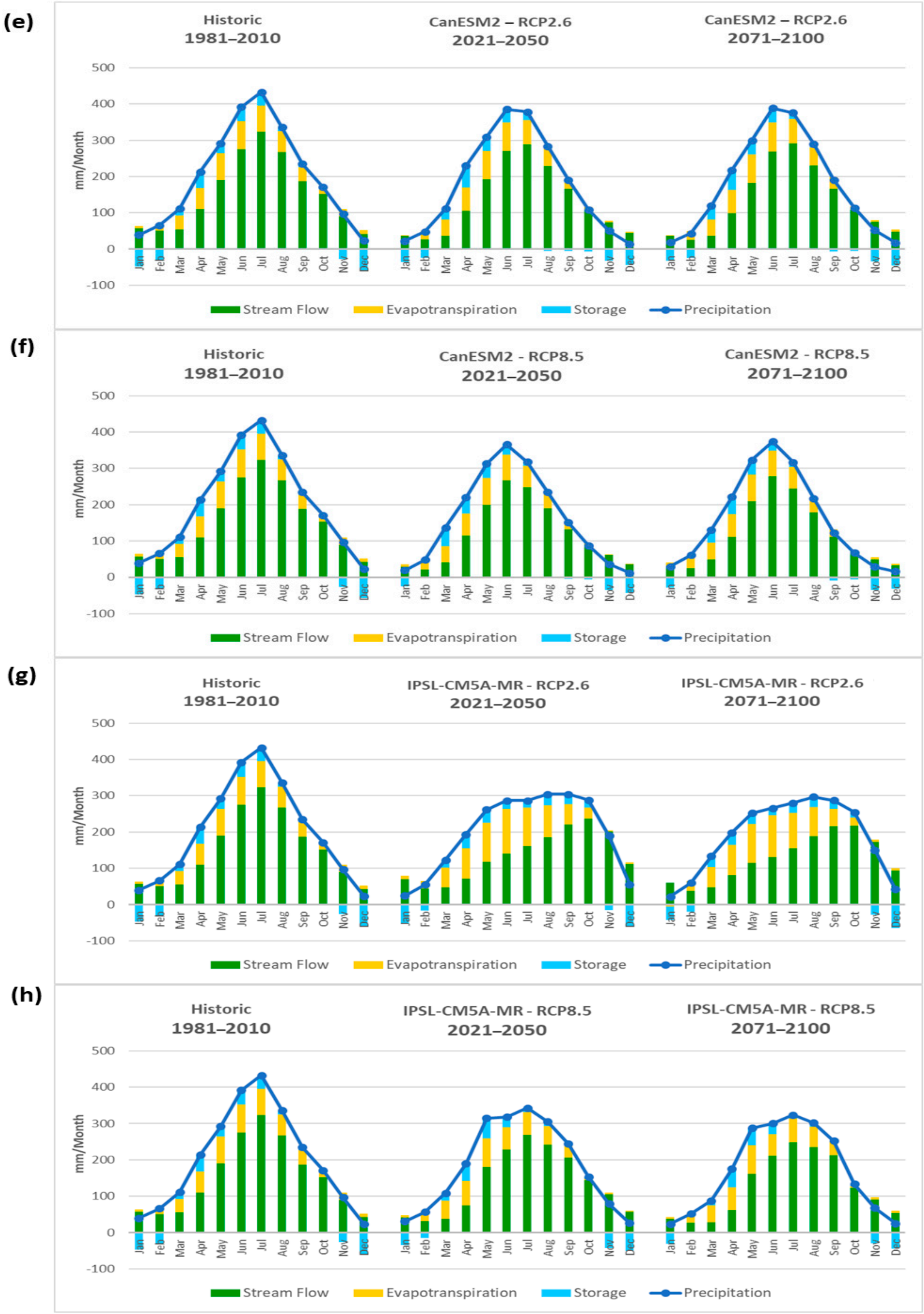

Figure A2. Bajo Meta.

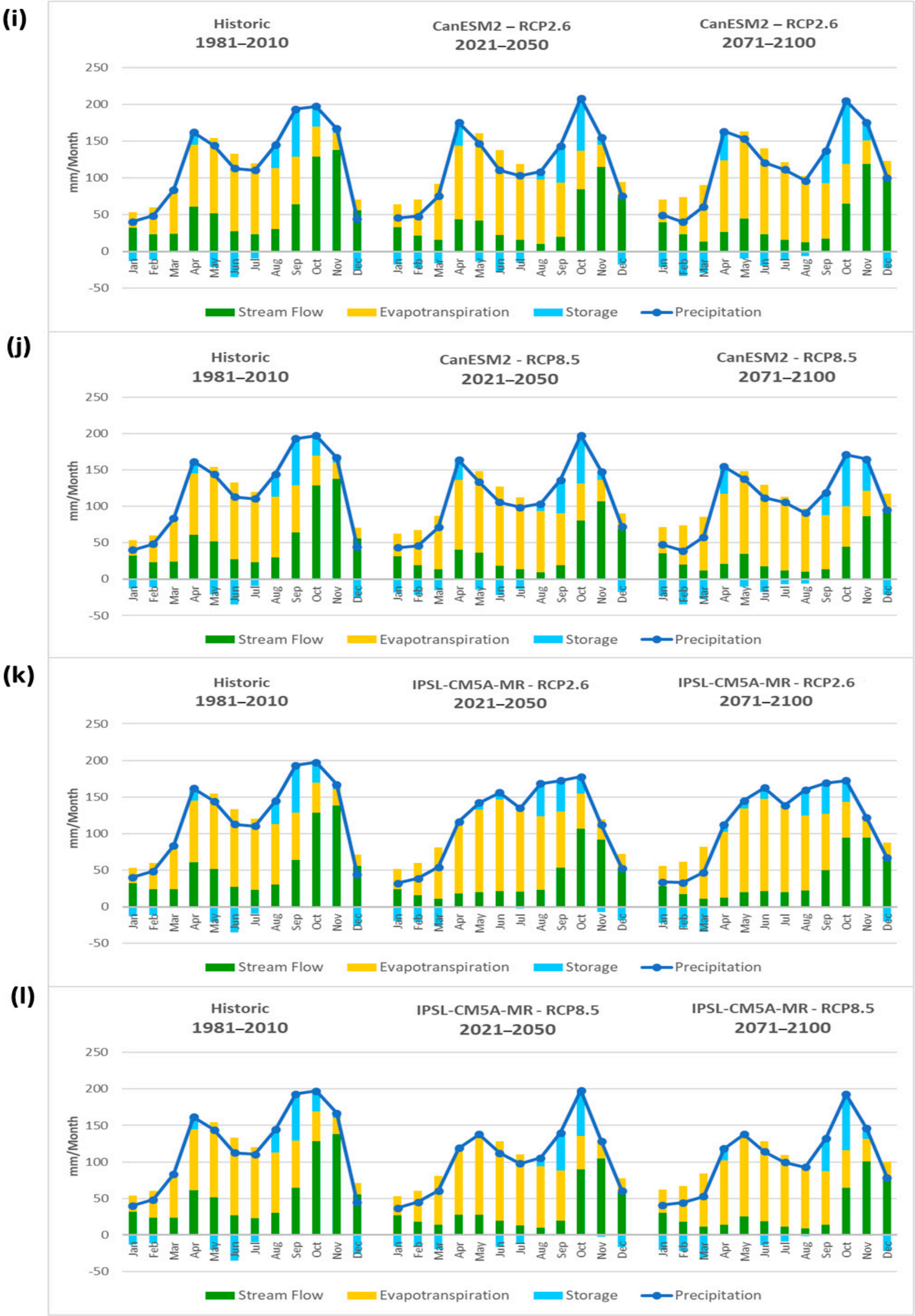

Figure A3. Rio Catatumbo.

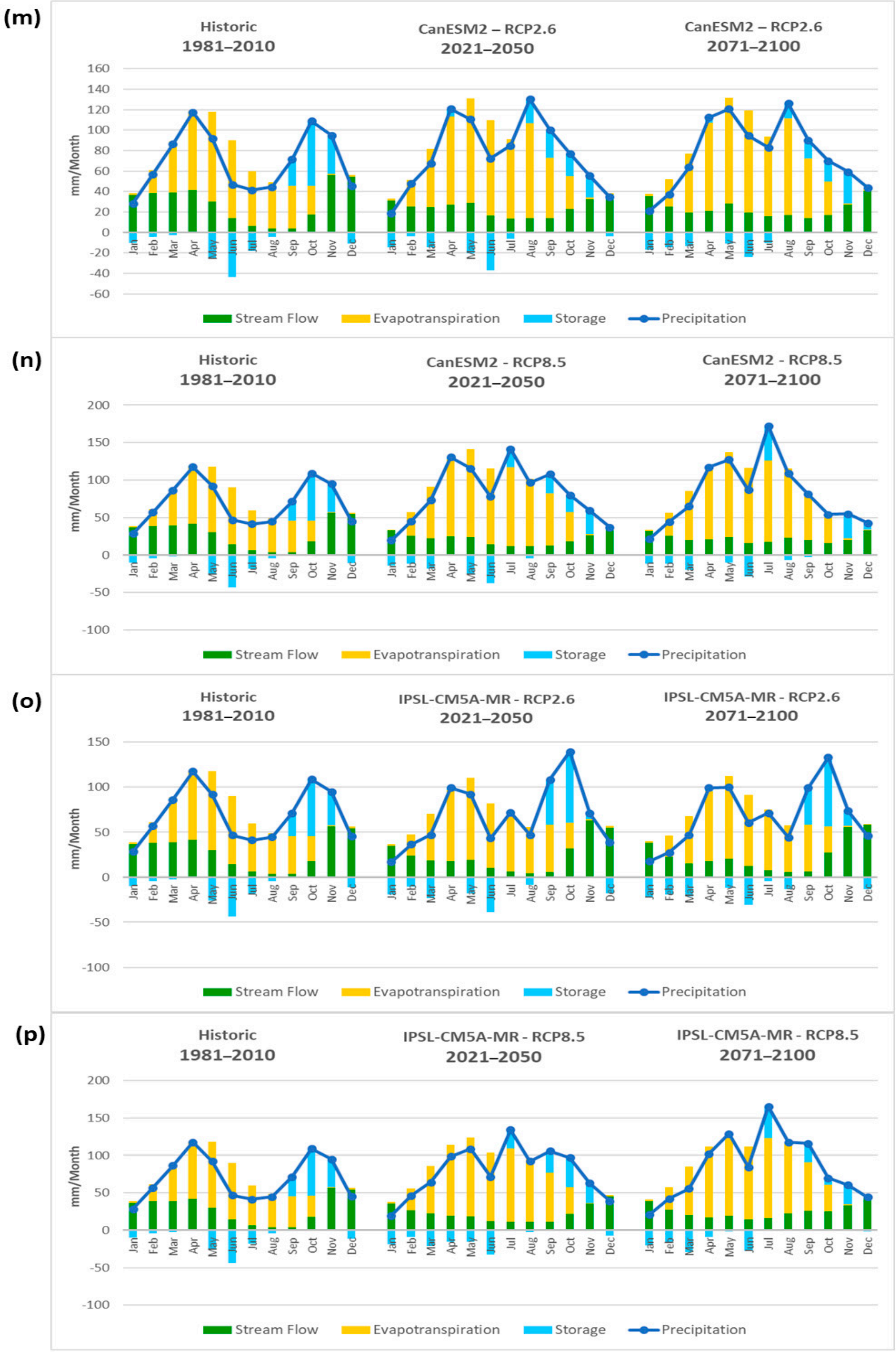

Figure A4. Sabana de Bogota.

Appendix B

Appendix B.1 Rio Catatumbo

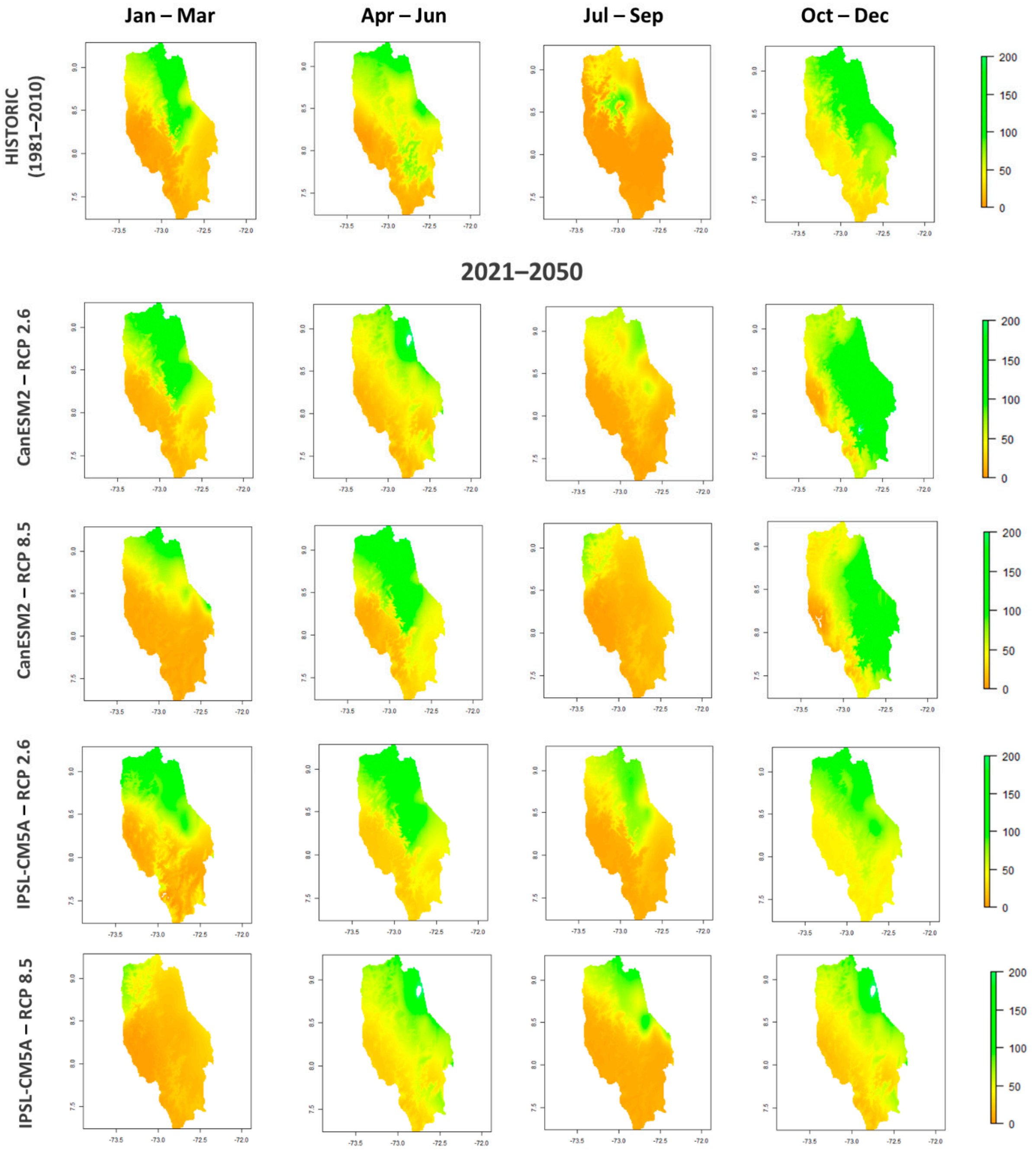

Figure A5. Stream Flow 2021–2050.

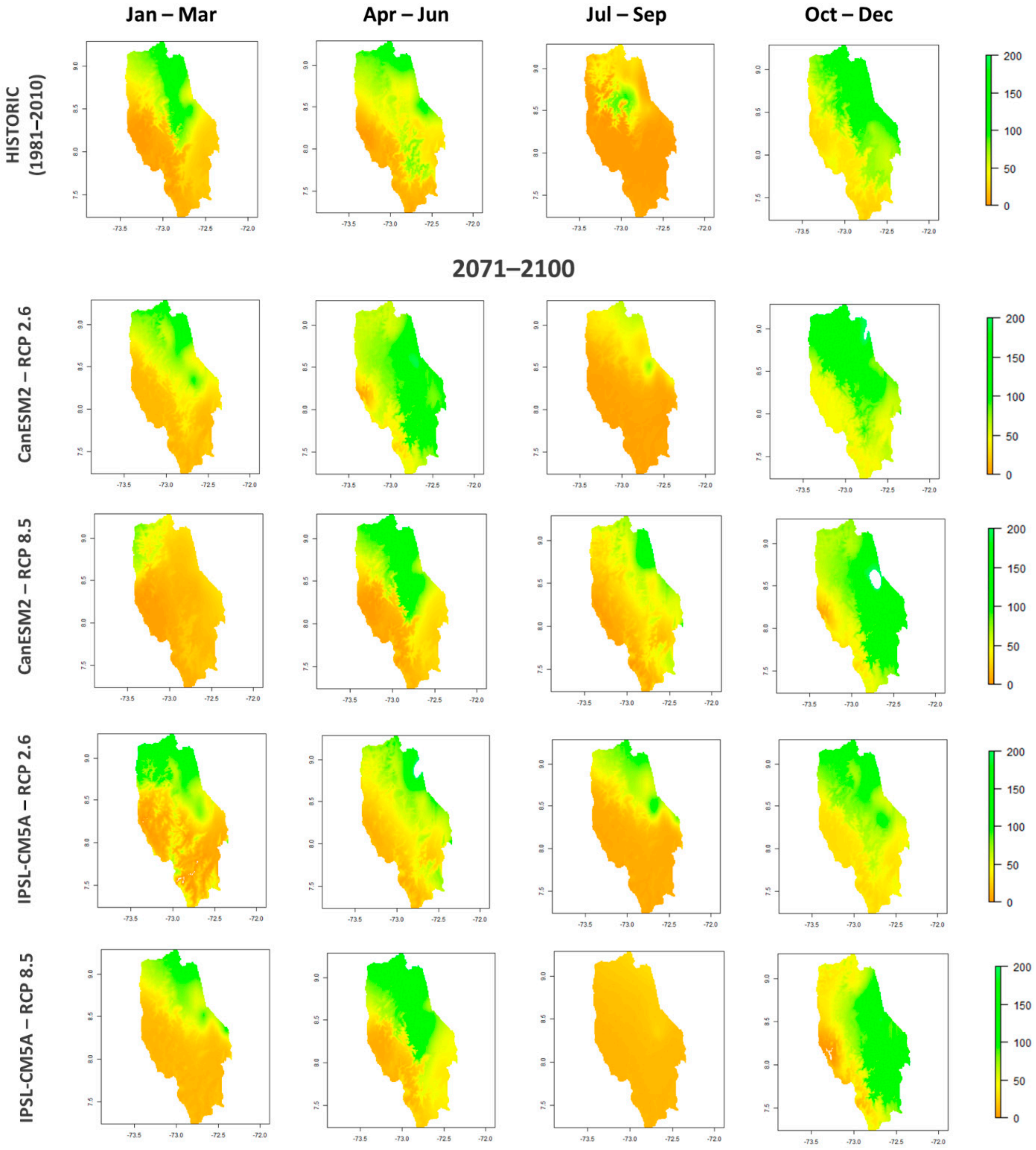

Figure A6. Stream Flow 2071–2100.

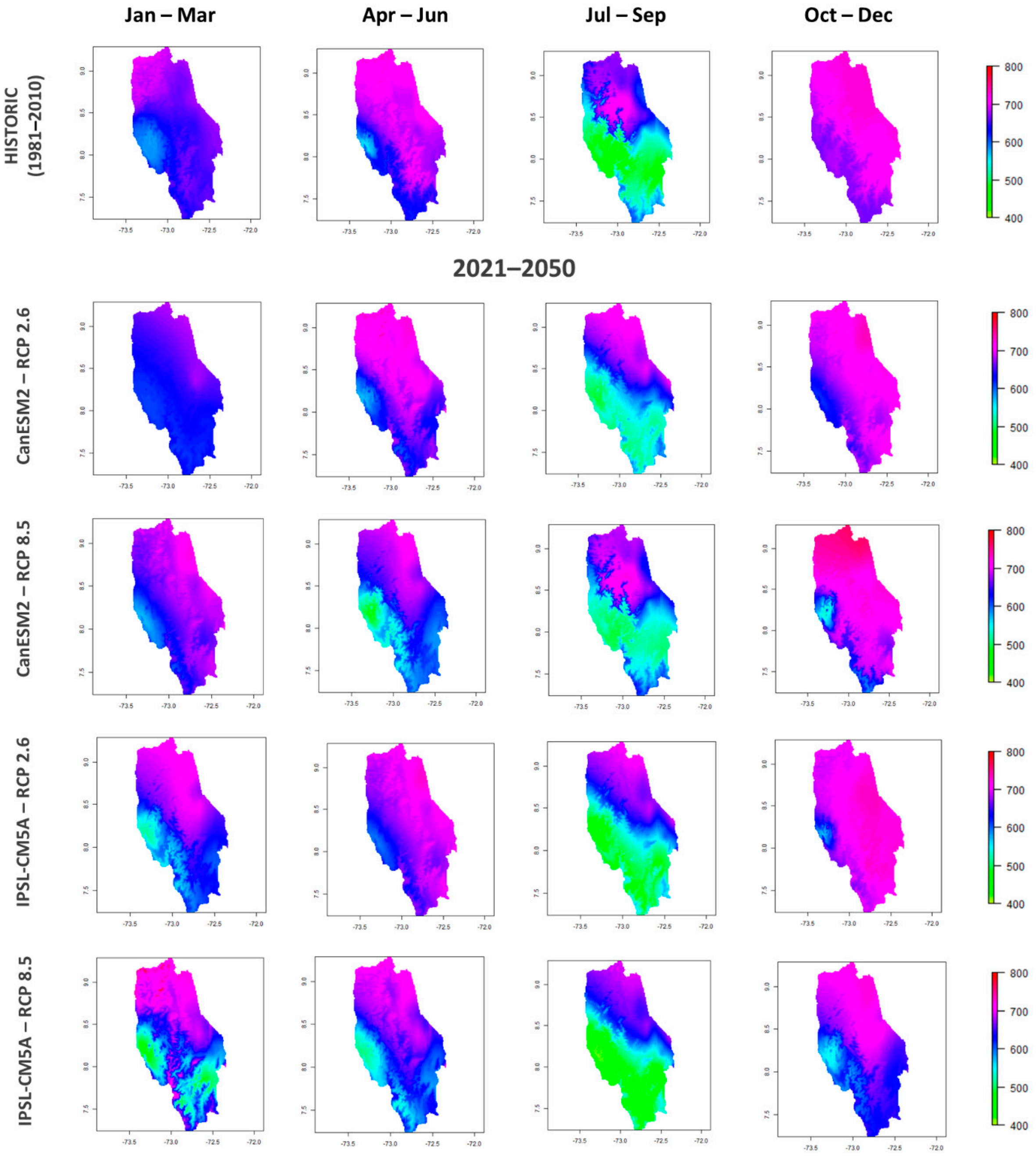

Figure A7. Soil Moisture 2021–2050.

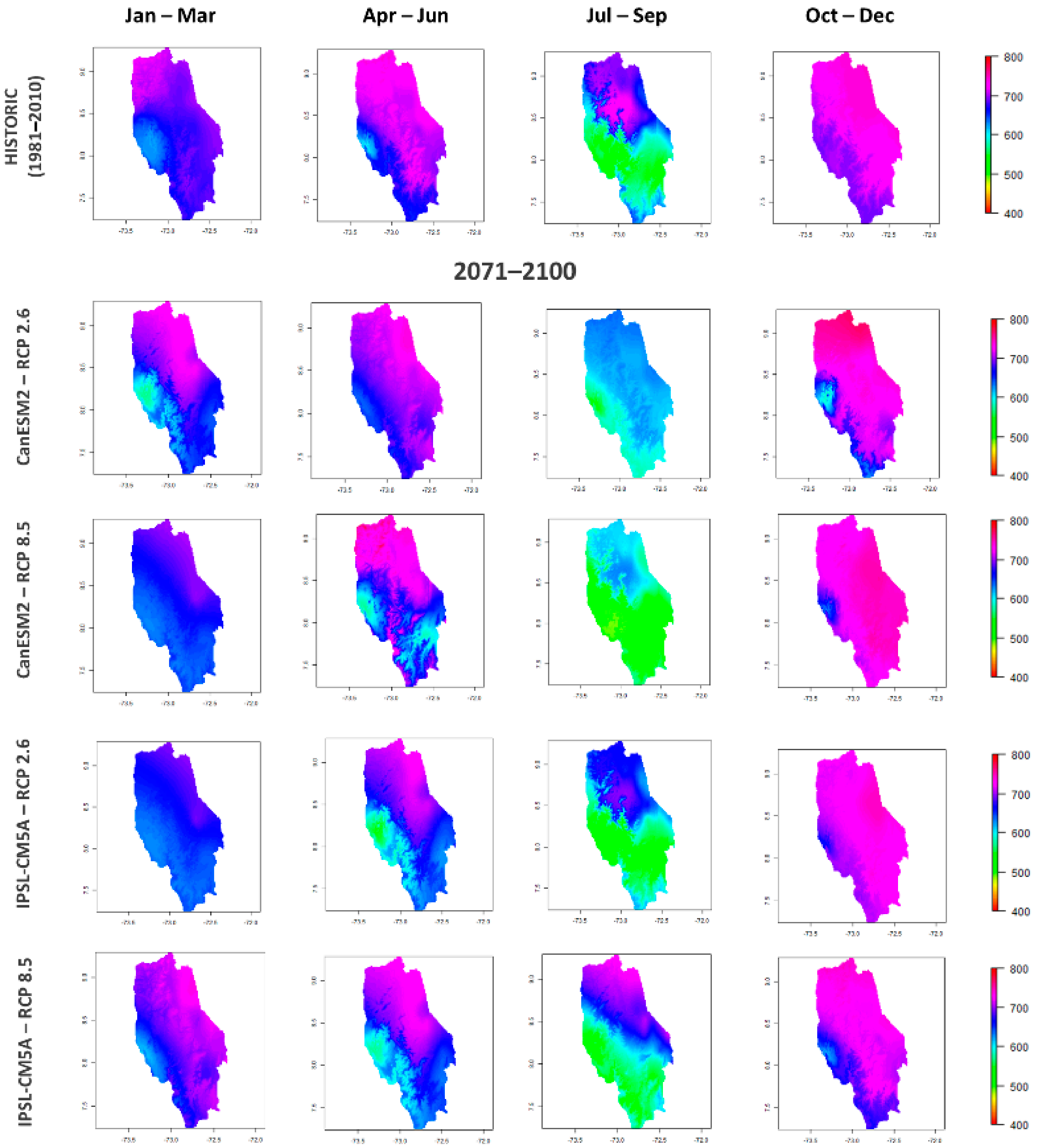

Figure A8. Soil Moisture 2071–2100.

Appendix B.2 Sabana de Bogota

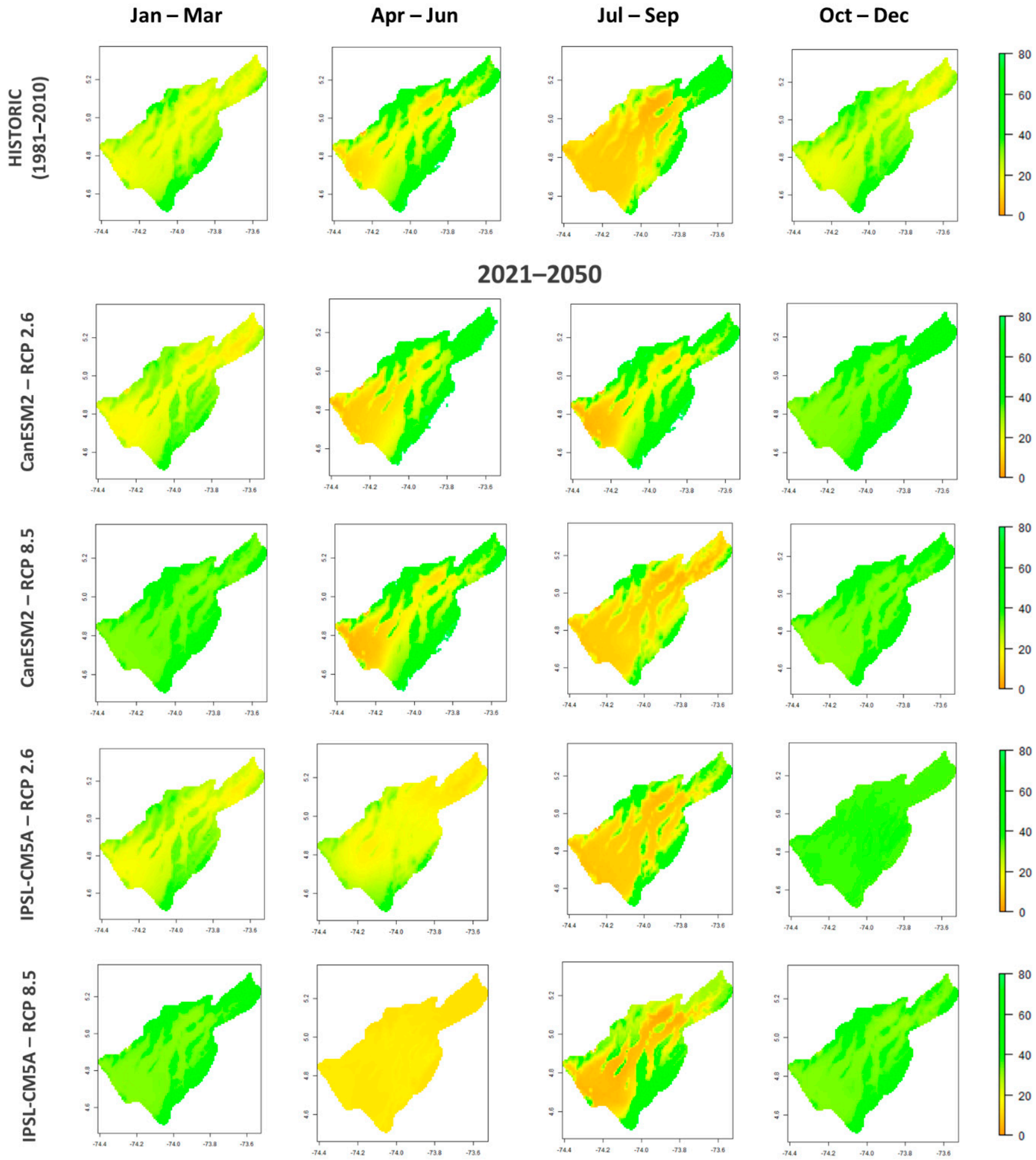

Figure A9. Stream Flow 2021–2050.

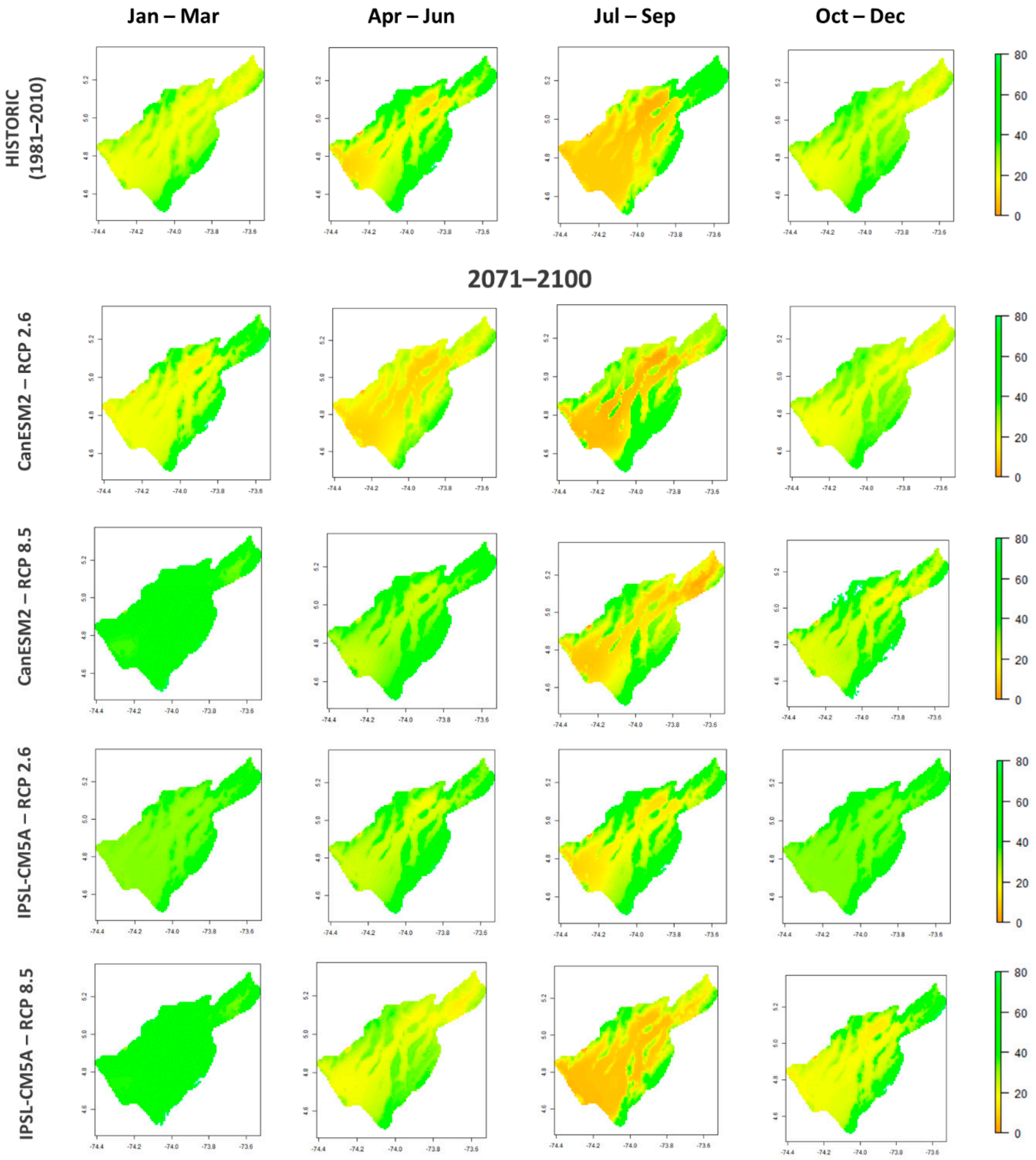

Figure A10. Stream Flow 2071–2100.

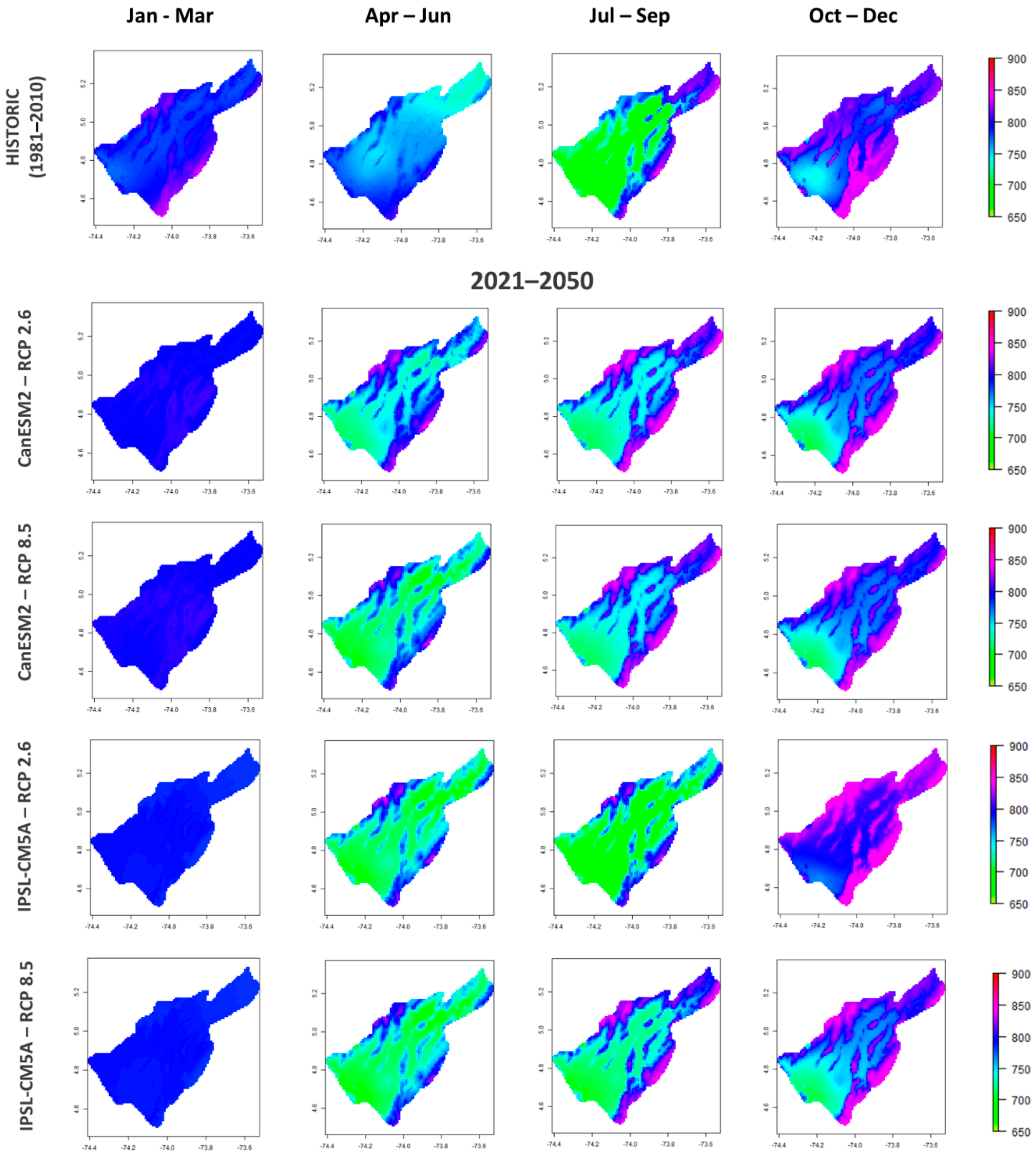

Figure A11. Soil Moisture 2021–2050.

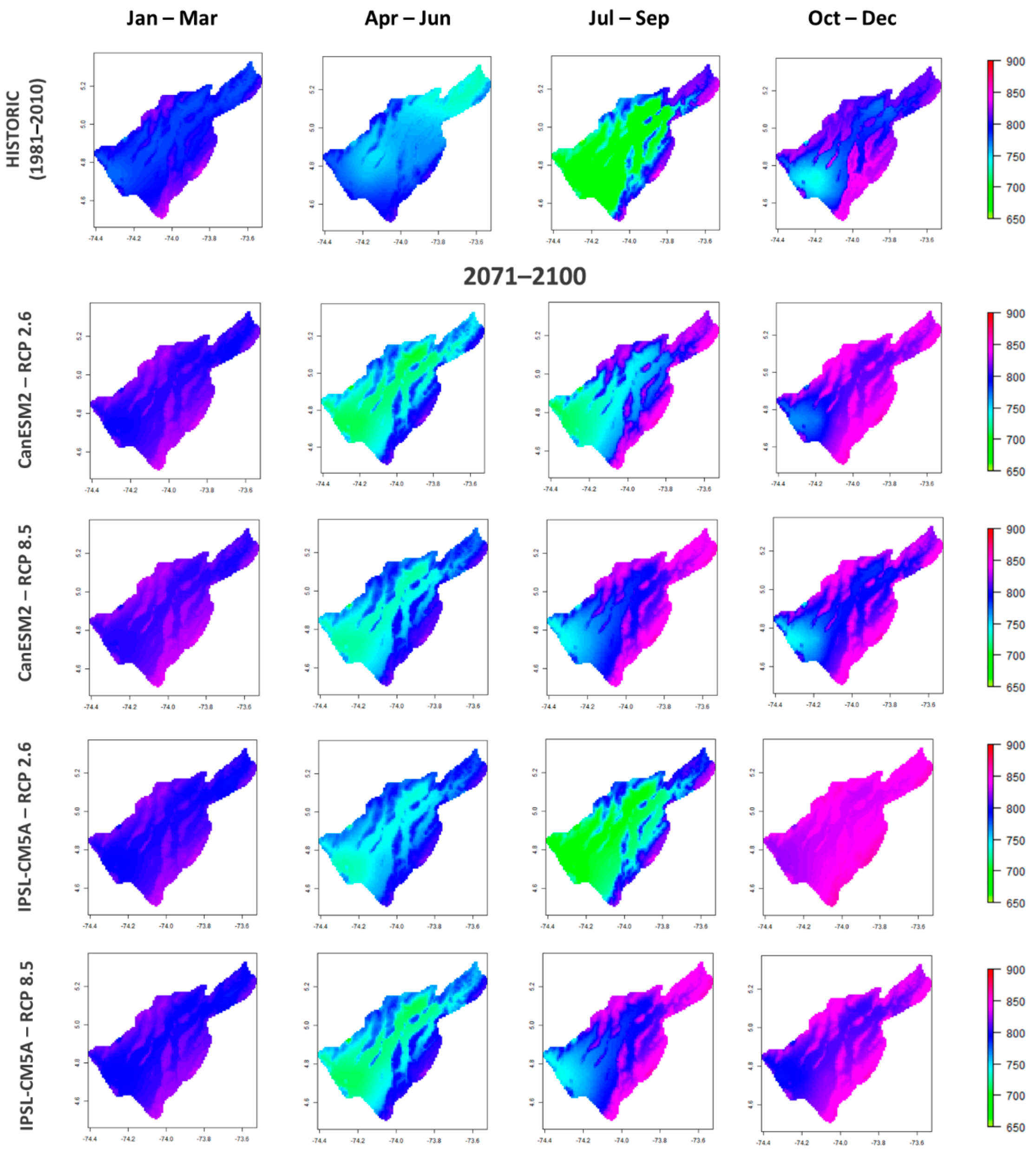

Figure A12. Soil Moisture 2071–2100.

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8. DISCUSSION

8.1. General analysis

The selection of the four analyzed water districts was made considering that they were the areas with more stations and data records out of all the eastern side of Colombia. There is a wide variability of climate and geography along this part of the Colombian territory and the selected four water districts for the analysis offer a good representative example of this variation with data records at different elevations and different climate zones. Areas, such as Sabana de Bogota or Rio Catatumbo, offer wider and more accurate information due to their denser distribution information due to their denser distribution of climate stations. A dense distribution of stations on the northeastern side of Colombia and a lower one on the southeastern side can be explained by the demographic distribution which follows this same pattern. A higher demographic density and stronger economic activity in the central and northern part of the country (including industry, agriculture, and hydropower generation) require a more detailed monitoring of climate variables. To the south, where the extensive valleys and Amazon rainforest are located, the economy is based more on extensive livestock farming and forestry exploitation; however, a denser distribution of stations in this area would be useful in order to create a more detailed and reliable climate prediction that can influence social and environmental conditions as well as other economic activities throughout the area, such as fishing and agriculture (corn, plantain, and rice). It should also be taken into consideration that several renewable energy projects and ecotourism projects are planned for this area in the future due to its large biodiversity. For the purpose of performing reliable posterior water budget analysis, it is determined from this study that the spatial and temporal data resolutions have good characteristics in some of the watersheds located in the analyzed water districts. However, the lack of discharge data is a decisive aspect for such analysis when compared to meteorological stations since there is a very small network of discharge stations, which can restrict the performance of the research-methods and increase the uncertainty in the results, like it was the case of this study. In the last decade, IDEAM has made recent efforts to strengthen the environmental monitoring-network in Colombia by installing new automatic stations distributed in sites representative of the main ecosystems and vulnerable areas of the country. Future planning for improving the network of stations is urgently needed for some of the water districts in southeastern Colombia. In these water districts, there is an extremely low density of available stations, and it is not suitable to perform accurate water-budget analysis using only current local records.

Along the four selected water districts are isothermal. Historical records of temperature were shown to decrease from lower to higher elevations with an average rate of 5 °C for every 1000 m of elevation in the same region; the relative humidity follows an almost direct proportional relationship with precipitation throughout the year for the four areas. The results from the publication shown in the section 7.1 determine that the datasets from stations located in the four studied water districts have plausible characteristics of correlation. This analysis was performed regarding the distance between the stations (considering vertical and horizontal axis); therefore, the data from one station should not be averaged together with the data from another station having a high difference of elevation. The results of the climate statistical downscaling show that maximum and minimum temperatures as well as relative humidity will increase over the next decades. Precipitation will slightly decrease for the water districts Alta Guajira, Bajo Meta and Rio Catatumbo. For the district Sabana de Bogota, precipitation will increase. The percentages of the changes can be seen in the publication shown in the section 7.2. Difficulties to accurately perform a downscaling of daily precipitation agree with the results of other studies (Huang et al. 2011; Nguyen et al. 2006; i.a., González-Rojí et al. 2019; Saraf and Regulwar 2016; Ahmadi et al. 2014; Saddique et al. 2019; Hussain et al. 2017; Cavazos and Hewitson 2005; Fiseha et al. 2012; Osma et al. 2015). These studies found a low correlation in a regional scale between daily precipitation and different sets of predictors.

This partial inability of the statistical model to reproduce daily precipitation is also due to regional physical-geographic factors such as interactions of atmospheric flow with topography, land-use, as well as land-cover changes that play a role in the formation of precipitation and which also show high variability in inter-annual basis. This confirms the high sensitivity of mountainous regions and the complex climate processes at play as has been found as well in other studies (Gulacha and Mulungu 2017; Sigdel and Ma 2015; Mahmood and Babel 2013). The projected increase in temperature as shown by the CanESM2 model is slightly higher than the IPSLCM5A-MR model both for maximum and minimum temperature. Regarding the change of precipitation, Rio Catatubo, Bajo Meta and Alta Guajira show a general decrease over their area while Sabana de Bogota was the only region that presents an increase. However, it must be considered that these results are a mean average from all the stations located in each region and it is given in these terms in order to have a general overview of the different climate variables on each region on the future caused by different scenarios of greenhouse emissions and climate change.

In terms of geographic perspective, the greatest increase in maximum and minimum temperature is observed in Bajo Meta and Sabana de Bogota (which are mountainous regions), while the lowest increase is observed in the Alta Guajira region (which is located at the northern coast). In general, it is observed from the output of various scenarios that the mountainous stations with drier climate show a higher probability of rising temperatures during the coming decades. The projections obtained with the Representative Concentration Pathway RCP 8.5 showed, as expected, a higher increase in temperature compared with those made using the RCP 2.6. Since the first mentioned represents the worst-case scenario of greenhouse gas emissions for the first decades of XXI century. However, the maximum temperature that was projected using the model CanESM2 RCP2.6 is higher for some stations than the one obtained with RCP 8.5 with the model IPSL-CM5A-MR. This might indicate (in some degree) inconsistency or instability in the global projections of the models in some locations.

Considering the two different modeled periods and the characteristics of the different Representative Concentration Pathways (RCPs) the changes obtained for the period of 2071–2100 are, in most cases, bigger than for the period 2021–2050 when compared to the baseline period of observations (1981–2010). An important inference of the performed approach and as concluded in other studies (Gebrechorkos and Bernhofer 2019), the selection of the best fit predictors for a given predictand at a particular location, represents the key part of the modelling process and enables one to accurately reproduce and predict the observed station data. The predictors that showed the best correlations with precipitation as predictand are related mostly with wind speed, geopotential, as well as high and relative humidity. This agrees with other studies using statistical downscaling methods (e.g., Hussain et al. 2017; Saraf and Regulwar 2016). A bias correction was not applied to the global climate data because it was found that bias correction methods might impair the advantages of circulation models by altering spatiotemporal field consistency, relations among variables, and by violating conservation principles. This might additionally neglect feedback mechanisms (Ehret et al. 2012); moreover, the resulting correlation coefficients found in the calibration and validation procedure were significant to assume a direct predictor-predictand relationship.

Since the projected scenarios for precipitation do not show a general tendency over the four studied regions, an alternative method is suggested for daily precipitation regional downscaling in order to compare the results or find higher accuracy e.g. generalized linear models or the use of neural network approach. In the same way, it is recommended that the results from this study be compared with other regional climate modeled datasets such as the coordinated regional climate downscaling experiment – CORDEX in order to validate or complement the analysis of the results. The straightforwardness of SDSM tool allows climate-impacts community, with relatively little knowledge of atmospheric physics, to create their own local or site-specific climate change scenarios. The use of a dynamical downscaling method could provide more accurate results as well but this approach demands much more intensive computational resources and requires large volumes of data which were not available for the studied regions. For a more detailed analysis of the predictors and in order to identify potential better correlations with the historical records, the lagging of daily predictor variables could be applied as well as suggested for some authors (e.g., Harpham and Wilby 2005; Crawford et al. 2007) with the purpose of revealing hidden direct relationships between predictand and predictors; this is because predictors from distant grid-boxes may also influence the local climate in distinct time.

The results from the statistical downscaling with SDSM and the hydrological modeling with BROOK90 show the notorious changes between the climate conditions and the water availability over the four studied water districts (with regards to the historical period as well as to the projections). In general terms, from the hydrological modeling performed in Article 3, the water balance components in the different regions showed different patterns and magnitudes due to variability in precipitation throughout the Colombian territory. The region of Sabana de Bogota showed a clear bimodal precipitation regime while the region Bajo Meta showed a clear monomodal regime. The other two regions presented a not-so-clearly defined regime; however, they showed a tendency to be bimodal. These precipitation conditions were obedient to the displacement of the ITCZ over the regions. The region of Alta Guajira (being an arid/desert region) shows very low levels of precipitation for most of the year. It reaches a peak of about 105 mm by the month of October. The region generates low levels of streamflow due to the fact that almost 85% of the total precipitation in the year is converted into evapotranspiration due to the high temperatures. In the first three months of the year, evapotranspiration can be almost 8 times greater than the level of precipitation. During this time, the storage water produced as a consequence of the rainy season in the last months of the year is constantly being evaporated. The projections for Alta Guajira showed a decrease in precipitation in general terms; therefore, it also shows a decrease in the other components of the water balance. This was the case for both projected periods of time of 2021–2050 and 2071–2100. Only the model CanESM2 with scenario RCP 2.6 showed a slight increment of precipitation in the short and long term.

From the four analyzed areas in this study, Bajo Meta presented the highest amount of rain on a yearly basis, presenting the highest values in the months of June and July with a peak of 430 mm/month and a non-rainy season at the end and beginning of the year. Most of the precipitation in Bajo Meta was converted into streamflow during the year (74.3%). This might be due to the characteristics of the soil (a predominant silty loam type for a big part of this region), which does not allow a big rate of infiltration. The projections for this region showed a decrease in precipitation, which led to a directly proportional decrease in streamflow; evaporation showed variable results depending on the model; CanESM2 indicated a slight decrease for both RCP scenarios, while IPSL-CM5A indicated the opposite. These results are reasonable considering that for the first model the decrease in precipitation was much bigger in magnitude than the second model. The historical period indicates that in the region of Rio Catatumbo, half of the precipitation in the year was evaporated (50.7%) and a similar level was converted into streamflow (45.1%). In general terms, the projections for the future showed a slight decrease of the precipitation regimes, with around 6% from the model CanESM2 and around 9% from the model IPSL-CM5A but with a much higher decrease in the levels of streamflow produced by this precipitation. Evaporation in both models was projected to increase at levels of around 20% for the next decades. In the region of Sabana de Bogota, the historical period showed that 58% of the precipitation was evaporated while only 41% converted into streamflow. The typical clay soil predominant in a big part of the region was reflected in the low levels of stored water. Sabana de Bogota was the only region from the analyzed four regions where an increase of precipitation was projected for the next decades; The biggest increment was projected for the period of 2071–2100, with the model IPSL-CM5A and the scenario RCP 8.5.

It is important to consider that the hydrological-modelling results obtained in this study, are the averaged-out product of the results of each station in the region. This was made with the purpose of obtaining results in a macro-scale, to have a notion of the projected scenarios for water districts where productive and social activities are planned in accordance with the available water in that area. An analysis for an individual station, watershed, or an area of higher resolution could also show variable results depending on the elevation of the studied area. The rasters produced in the third publication shown in the section 6 are a useful representation of the spatial variability of the historical and projected results for two of the studied regions when considering the geographical variation presented in each of them. As was said before, the spatial distribution density of meteorological stations at the other two regions was too low to allow a proper interpolation process to create a figure that reliably showed a representation of spatial variability of the results throughout the regions.

Results show as well that soil moisture would be reduced considerably in the next decades. The percentage of decrease could vary for each climate scenario. The only exception to this, was the region of Sabana de Bogota, where precipitation is projected to increase. This would result in an increase in soil moisture. These results are important in relation to agricultural activities and the planning/use of soil for the next decades. The lack of available historical records of discharge in the studied areas as well as the wide extent of these areas, made the performance of a respective process of calibration and validation of the water balance components that comprises all extensions of the studied areas unsuitable. However, an intensive review of the input data to the model was carried out to ensure an appropriate parameterization. This review included a detailed selection of statistics about the soil in the studied areas. The review was compiled through technical information from both the public and private sector. Information about vegetation comes mostly from governmental institutes. Detailed land use information was also obtained from regional territorial development plans. A review of the model's results and a comparison with results of other studies conducted nearby in tropical or similar areas (Bastidas et al. 2019; Leta et al. 2016; Louzada et al. 2018; Silva et al. 2016; Almeida et al. 2019; Schwerdtfeger et al. 2014; Escurra et al. 2014) was made to verify the veracity of the results. This review was also conducted to ensure that the results are both plausible and within a correct range of magnitudes.

Rainfall seasonality and its interannual variability have been observed to change in magnitude, timing, and duration, in the tropics (Feng et al. 2013). As mentioned before, the climate in Colombia is conditioned by local particularities like those caused by mountain barriers to the atmospheric circulation. The annual cycle of Colombia's hydroclimatology is mostly influenced by the displacement of the ITCZ. The different passages of the ITCZ over a region determine either a bimodal annual cycle of precipitation with distinct rainy seasons and dry seasons, or a unimodal annual cycle which results from the moisture transported from the Amazon basin when it encounters the orographic barrier of the Andes. The seasonality of hydrological elements in the different water districts shows larger variability due to their differences in topography, hydrogeology, and vegetation.

Climate conditions on higher regions like Sabana de Bogota or parts of Rio Catatumbo are very dependent on elevation, since there is no snow formation in any of the regions, there is no considerable time lag between the precipitation event, the stream flow, and the soil moisture. A prolonged positive soil humidity in humid regions linked directly with rain events is explained by a permeable soil and temperature that is not high enough to increase evapotranspiration for several months. Climate seasonality is a defining feature of many ecosystems, often characterized in the tropics by a distinct non-uniformity in their timing of annual rainfall. This results in one or two wet seasons (during which most of the annual rainfall occurs) separated by prolonged dry periods. In regions like Bajo Meta or Rio Catatumbo, under conditions of relative water abundance long-term evapotranspiration becomes limited by the potential evapotranspiration. In arid regions like Alta Guajira (where the energy available is high), precipitation is the main constraint to evapotranspiration. In the former case, water supply exceeds demand. However, in the latter's case, water supply is outstripped by the demand (Feng et al. 2012). In Alta Guajira a projected increase in mean temperature would likely lead to increase in the frequency and the intensity of seasonal droughts (Hartmann et al. 2013).

The two main differences between both of the GCMs that were used for a regional downscaling as a source of the projected climate data in this study are their spatial resolution as well as the model-components with which they were coupled. The model IPSL-CM5A, with its slightly higher spatial resolution has shown a better performance than other models to identify extreme events in South America and other regions (McSweeney et al. 2015); however, this model showed a lower performance to appropriately reproduce precipitation historical records in comparison with CanESM2 and other models, in Colombia and South America (Bonilla-Ovallos & Mesa 2017; Yin et al. 2012). This was in agreement with the results of this study. Both results found that extreme events and seasonal precipitation were more clearly identifiable for the model IPSL-CM5A, especially in regions of lower elevations where the model seemed to overestimate the projected change for the different variables.

It is important to consider that although the RCP 2.6 scenario might be described as the best case for limiting anthropogenic GHG emissions, their atmospheric concentrations will continue to increase even after emissions slow down and eventually start decreasing (MacDougall et al. 2013). Carbon dioxide accumulates in the atmosphere and stays there for decades. Even if emissions start reducing in 2020, the concentration continues increasing and starts falling very slowly: only after 2050. This might explain why in some of the results of RCP 2.6, a bigger percentual change is observed for the period 2020–2050 than for the period of 2070–2100. However, as expected, the results obtained for the projections in the scenario RCP 8.5 showed a higher projected change than those in the scenario 2.6. This has proven to be the case for most of the analyzed regions with exception given to Alta Guajira. The results of model CanESM2 showed a slight increase in precipitation for Alta Guajira under scenario 2.6, and a negative change under scenario 8.5 and model IPSL-CM5A_MR. This could have been caused by the incapacity of the model to accurately predict changes of precipitation in very arid areas that are characterized by little but highly variable and unpredictable rainfall. This was the case in other studies such as Zhao (Zhao et al. 2014) who analyzed the performance of the GCM models used in the CMIP5-project in several arid regions of the world. A study conducted by Ji (Ji et al. 2015) also found similar results across dryland areas.

The inherent existence of uncertainty in every water budget approach must be taken into consideration. Uncertainty related to hydrological modeling is affected by the input data, validation data, model structure, and model parameters. For the use of climate model SDSM, a robust downscaling scheme was followed in order to avoid unreliable representations and higher uncertainties of climate projections. For this: a significant amount of candidate predictors was considered, a detailed screening of predictors was applied, the predictor-predictand physical interactions were analyzed, the most appropriated period for both calibration and validation were adopted regarding the available data, and a proper metrics for validation was used according to the objectives of the study. In order to reduce uncertainties in the hydrological modeling of this study and conducting a locally relevant study with the best data available, a detailed parametrization of the model was intended for each of the grids cells that the regions were divided into. For this: soil, vegetation, land use, and topography data were taken from local private studies and maps provided by governmental institutions. The parameters were individually defined for each of the cell grids where the model was run individually. The hydro-climatic model chain typically consists of the components: emission scenario, GCM, regional climate model or statistical downscaling, and hydrological model (Muerth et al. 2013). This study represents all steps of that chain for the four studied water districts; however, all of these components constitute a potential uncertainty source for the results. The uncertainty associated with the individual components of this chain has been investigated by an increasing number of studies. In some of them, the GCM structure is identified as the dominant source of uncertainty, e.g., (Prudhomme et al. 2009; Hagemann et al. 2011; Dobler et al. 2011). A common finding for other studies is that the hydrological model shows uncertainty to be less important than other sources; nevertheless, uncertainty cannot be ignored (Thompson et al. 2013, Velázquez et al. 2013, Jobst et al. 2018). Ideally, the analysis of hydrologic change in future studies for these areas should comprehend the full suite of uncertainties associated with global climate modeling, climate downscaling, hydrologic modeling, and natural climate variability. In this manner, the water resources planning and management community can make more informed decisions. Parameter uncertainty estimation is one of the major challenges in hydrological modeling and analysis of future change for the water sector is an interdisciplinary endeavor (Clark et al. 2016). Ongoing parallel efforts to monitor and verify water budget components would help to improve accuracy. Posterior analysis could be done in an effort to determine the magnitude of the uncertainty of the hydrological response to climate change. Due to the uncertainties associated with the study of climate change and the limitations of models in representing climate and hydrological response, the most trustworthy indicator is still the trends observed at the measuring stations while the predictions of models in a big scale like that in this study might only be used to have a general notion of trends for the studied variables under different potential climate conditions.

8.2. Additional remarks

Hydrological basins form complex systems in which physical-geographical factors define the variability of the hydrological regime of surface currents. These factors can be classified into two groups: meteorological and related to land surface coverage. The main weather factors are precipitation, evaporation, and air/soil temperature. Factors related to land cover are made up of relief, soil, plant cover, the morphometric characteristics of the basin and waterways, as well as the hydrogeological structure of the underground basins. It is considered that the behavior of a region's average annual water supply is defined by the climatic conditions of the hydrological basins. The annual, semi-annual, and monthly supply is also influenced by the factors of the basin surface cover. These define groundwater concentration times, surface storage, and regulation characteristics. The characterization of extreme phenomena (floods and droughts) have particularly shown that the characteristics of the surface of terrain exert a direct influence. This means that the hydrological consequences of climate change depend not only on changes in precipitation patterns, but also on changes in the coverage and surface characteristics of the different basins.

It is of great interest to understand what effects climate change will have on extreme hydrological phenomena such as floods and droughts. To understand this complexity, hydrology constructs probabilistic density curves to characterize how often extreme flow values are presented in any given basin. These extreme flows (maximum or minimum) represent the critical conditions to which the different productive sectors of Colombia may be subjected. With probabilistic density curves, the most frequent water supply of Colombian rivers has been also defined (Domínguez et al. 2008; Ivanova & Corridor 2007). There are two patterns of water supply behavior in the country. The first is characterized by frequently low water availability and peak flow extremes as a critical phenomenon. The second, on the other hand, has high modal (frequent) modal water availability and their critical extremes correspond to minimum values. The first hydrological pattern is characteristic to the sector at the northern end of the country (where the water district Alta Guajira is located) and the northeastern area of the country (where the water district Rio Catatumbo is located). The second hydrological pattern is more characteristic to the eastern plains (where the water district Bajo Meta is located) and the central area of the country (where Sabana de Bogota is located). Because of the above, to understand the hydrological consequences of climate change it is necessary to understand changes in precipitation trends. Detailed analysis is also necessary to further understand alterations in the extreme flow rate. Some results of modelling in these regimes were presented in Colombia's third National Communication to the United Nations Framework Convention (IDEAM et al. 2017). These results revealed that the effects of climate change impacted the regime of extreme flows of Colombian rivers in different ways.

Without discussing the uncertainty of local weather scenarios, it is clear that climate change will benefit some regions with increases in rainfall and punish others with decreases in rainfall. Increases in rainfall that feed the flows of Colombian watersheds will cause a consequent increase in water supply, a decrease in their variability (increased regularity), and accentuation in the asymmetry of the flows from this water supply. On the other hand, a decrease in precipitation will lead to a decline in water supply and increased variability of this supply, making it more irregular over time. In the first scenario (increased water supply), with regards to regions whose present hydrological regime is positive asymmetry (such as Alta Guajira and Rio Catatumbo) there will be significant increases in the frequency of maximum flow rates and an attenuation in the severity of the minimum flow rates, the frequency of these flow rates occurring will be slightly increased. In the second scenario, with regards to regions with a hydrological regime of negative asymmetry (such as Sabana de Bogota and Bajo Meta), the results will be opposite to those of the first scenario. The low flow rates will be favored with an increase of their magnitude; but at the same time, these flow rates will experience a significant increase in their frequency. Lastly, the maximum flow rates will also increase in value but decrease in frequency. For the second scenario (decrease in water supply) the most important change is related to the increase in the temporary irregularity of the flows. This will cause a much more variable water supply than the current one. In addition, this scenario is also associated with increased severity of extreme phenomena (floods and droughts). In both scenarios, the impact for the existing infrastructure (bridges, dams, etc.) is significant since in the first case, the infrastructure will have to face higher maximum flows than those for which it was designed; while in the second scenario, infrastructure will have to face operating at lower minimum flow rates than are recorded in the current climate. It is clear that regions and districts without management mechanisms as well as those with underdeveloped hydrotechnical infrastructure will be more affected by climate change; however, one should bear in mind that factors not related to climate change may have greater impact on water resources to the same degree as climate change. In Colombia, as already mentioned, population growth is already a threat to the current water resource. The population's steady increase has led to an increase in anthropogenic pressure on water resources as well as a decrease in the availability of water per capita in Colombia. In the Figure 7 can be observed that the districts Sabana de Bogota and Rio Catatumbo have the highest population densities. This generates intense pressure on the available water. When comparing these densities with the availability of water through the WSI in Figure 7, it is observed that although Rio Catatumbo has a high population density, the demand for water has no critical value. In Bajo Meta, low demand for water resources is currently observed compared to supply. However, as previously mentioned, this would change in the following decades due to the increase in productive activities that are projected for this region; additionally, this study predicts a projected decrease in water in this region due to climate change. The Alta Guajira and Sabana de Bogota regions present the most critical values of water use today. This fact is mostly due to the demand for productive activities in Sabana de Bogota and the natural water deficit as is the case in Alta Guajira.

The hydrological impact of climate change on socio-economic sectors also depends on the vulnerability levels of each sector. Vulnerability is not only defined in terms of threats or impacts, but also by the patterns of a developing society: its degree of physical exposure, the distribution of its resources, the disasters previously suffered and its social institutions and government (IPCC 2014). The index of water vulnerability WVI shown in Figure 8 shows that the districts Sabana de Bogota and Alta Guajira are the most vulnerable; this coincides with the Water Stress Index today. In the case of Sabana de Bogota, this vulnerability is due to the intense demand for water from the different productive sectors as well as the region's high population density. However, according to the projections obtained, Savana de Bogota was the only state of the four studied where an increase in the availability of the hydrated resource is foreseeable., However it should be noted that Sabana de Bogota is likely to experience a population increase, particularly in the area surrounding the the capital of the country. This population increase will generate a demand for water greater than what is actually available. In the case of Alta Guajira, the future projection predicts a decrease in available water. Such a prediction produces a scenario of great concern due to the already existing water deficit that exists in this semi-desert region. In the Bajo Meta and Rio Catatumbo districts, the vulnerability of a water shortage has a medium to low value; however, measures must be taken to address the future decline in availability of the water resource in the coming decades.

The current evidence of the impact of climate change on the hydrology of different regions around the world is not yet clear. This is because the hydrological records we have are not detailed enough to clearly determine the trend of the flow rate regime. In addition, the hydrological basins act as filters that decrease the high variability of the climate. In cases where there are sufficient records the trends found in some cases there are increases in other cases there are decreases. These results do not always coincide with the trends detected in the precipitation series (Dominguez et al. 2010). However, the climate and hydrological projections obtained in this study (without pretending to be the absolute truth) allow to visualize the potential situations that could be experienced in the future. They are to be confirmed as the availability of the records increases throughout monitoring networks. It will also continue to provide an overview of the future availability of water resources in these four analyzed regions. Due to the potential impacts of climate change on water the economy, the environment, and the society in Colombia, it is essential to create water resource management models designed to address the conditions associated with climate change and the variabilities derived from it. The results offered in this study are part of the first steps in the creation of available technical information to address this problem on the eastern side of Colombia. Colombia has generated multiple studies that have allowed the country to deepen its knowledge of their water resources and the impact that climate change could have on them. As a provision of hydrometeorological and environmental information in the country, these studies have progressively improved in terms of their scope and level of detail. Similarly, the need to produce more regionalized information has become more apparent over the past few years. The phenomena of climate variability are steadily increasing on water resources within the national territory. To this extent, climate variability has become a key issue in steering resources towards the analysis of this problem. Relationships between these factors and local/regional conditions, impact analysis on hydrological response with regards of variability and climate change become highly complex and is therefore subject to high levels of uncertainty. However, despite this uncertainty, the information currently available points to the need to generate policies that allow immediate responses to water resource impacts associated with climate change and climate variability. The information from these studies can also serve as a guide for how water-use planning and land occupation can be structured in the long term future. Adapting to climate variability is part of the challenges of climate change.

The Integrated Water Resources Management - IWRM paradigm has been gaining acceptance through water as a resource and an ecosystem. This has become an important position within the priorities in decision-making and policy-making. Colombia does not shy away from this trend, as it has been advancing efforts to adopt the policy of comprehensive management of water resources through the Ministry of Environment and Sustainable Development and with the technical support of IDEAM (Ramirez-Villegas et al. 2012). This interest is likely to materialize in reducing the vulnerability of hydrological systems to climate change. Taking into account the new regulatory elements in the area of risk management and comprehensive management of the water resource (which have been started or have plans to be adopted in Colombia), the challenge of the government institutions consists of knowing the possible future effects of climate change through hydrological models, such as the one used in this study. A major issue in climate change adaptation lies in the strategic relationships between development models, disaster risk management, and land management. The 2014-2018 national development plan for Colombia and the one for 2018-2022 incorporated in its development model a strategy seeking to advance the implementation of the sustainable development goals. This was implemented with the goal of reducing environmental impacts and mitigating climate change. The plan defined among its strategic objectives "to achieve resilient growth and reduce vulnerability to disaster risks and climate change", establishing the following actions: knowledge management regarding the process of climate change and its impacts; and development planning for adaptation to climate change (integrating adaptation criteria into the planning instruments of territorial entities and sectors). In addition, actions were planned to mitigate climate change such as: agricultural development with sustainable practices, sustainable transport, the use of unconventional renewable energy/energy efficient technologies, sustainable/low-carbon industry, the provision of buildings and sustainable infrastructure, as well as a unified commitment to climate change mitigation. The plan also established strategies to advance climate change adaptation and enabling cross-cutting institutional actions to consolidate the National Climate Change Policy.

The National Climate Change Policy was created in 2014 and since then it has been proposed to articulate all of the efforts that the country has been developing for several years. These developments began in 2011 by several national institutions. The National Climate Change Policy provides new elements to strategically guide all efforts towards fulfilling the commitment made under the Paris Agreement. Its five strategic lines are based on the New Climate Economy which was a global reference exercise in which Colombia participated with six other countries. In addition to these strategic lines, the National Climate Change Policy supports the development of these strategies in four instrumental themes: Climate Change Management Planning; Information, Science, Technology and Innovation; Education; and lastly, Financing and Economic Instruments (Melo 2014). The fundamental challenges going forward is to continue the implementation of the National Climate Change Policy and developing the agreements built: and implementing both of these, while taking into account the realities of a country that will change in many respects and that requires us to live up to its new challenges. Social organizations, NGOs and universities have supported with great efforts through education, creating training processes, raising awareness, leading adaptation projects in the national territory, and articulating institutions of the state, local organizations, ethnic and peasant communities.

Unfortunately, not so much information is available regarding the effects of climate change for the eastern side of Colombia since the few existing studies in Colombia have been aimed at regions with a bigger density of available data. We encourage the future improvements of collection and testing of reliable data in a range of spatial and temporal scales in these regions, since it is critical to improve our understanding of hydrological processes. The results obtained in this study should be considered as indicative of the expected trend in water resources of the studied regions as a result of climate change. These results might serve as a contribution for a baseline of information for creating mitigating measures. However, future work using other models and other techniques for the analysis of water resources throughout these areas is encouraged. The information provided in this study is valuable regarding the analysis of potential droughts, heatwaves, and water resources availability over these regions. Along the same lines, it is a good source of information for the evaluation of possible future-case scenarios and decisions-making management. They can be used for development planners, decision makers, as well as other stakeholders when planning and implementing appropriate management strategies regarding response and mitigation and adaptation to the impacts of global warming for these regions.

9. GENERAL CONCLUSIONS

The assessment of climate data records was found to be very deficient or even non-existing for a major part of the eastern Colombian territory. However, the four selected and analyzed water districts offer a representative overview of the climate of the eastern side of the country: each district with its very own unique geographical and climate conditions. The historical records available for the four selected water districts are an acceptable source of input data especially the water districts for Sabana de Bogota and Rio Catatubo with regards to the availability of data and the good correlations found in the datasets. The density of located stations at other regions throughout eastern Colombia is very low, and existing data in these areas must be deeply complemented using openly available external modeled datasets in order to perform a climate or water budget analysis over a reduced specific area.

The Statistical Downscaling Model (SDSM) was used for downscaling meteorological data statistically over the studied four regions. For this, two GCMs (CanESM2 and IPSL-CM5A-MR) and two different climate scenarios from RCP 2.6 and RCP 8.5 were used representing two different possible future emission trajectories and radiative forcings. Results obtained during the process of calibration and validation define the model developed by SDSM as efficient in the downscaling of maximum/minimum temperature, as well as relative humidity over the studied regions. With regards to precipitation, the model shows a good but still lower performance, which is not unusual compared to other statistical downscaling studies. Performing this study over four different regions offers a good opportunity to evaluate the performance of the tool SDSM over different geographic and climate conditions. The GCMs used in this study show a projected increase of both maximum and minimum temperature over the next decades on the studied regions as well as a decrease in relative humidity with a slight change of precipitation with a tendency to most likely decrease for most of the considered stations, especially in the last decades of the XXI century.
The low amount of climate records and particularly those for temperature, relative humidity, radiation, and wind speed make it difficult to conduct a more proper technical climate analysis and thus creates higher uncertainties when calibrating climate models with the historical records for these regions.

The model BROOK90, historical data, as well as the projections obtained from the regional statistical downscaling procedure were used to determine the changes in the water balance components over the four different studied regions, which represent the four water districts along eastern Colombia. Results have shown a potential reduction in the generated streamflow for all of the studied regions with exception given only to the region of Sabana de Bogota- where climate projections showed a slight increase of precipitation and, therefore, the other components of water budget. The temporal distribution of water balance components was considerably affected by the changing climate, which moreover, shows a profound impact on the hydrological regimes in these regions. Changes in evapotranspiration and stored water vary from each region, according to the climate scenario, and the characteristics of soil/land use for each area. Results of spatial change of the water balance components have shown a direct link to the geography of each region and how the values differed accordingly, at different elevations. Projections show that soil moisture will be reduced considerably in the next decades, and also that the percentage of decrease could vary for each scenario.

The use of the hydraulic resource currently, assessed by means of the Water Stress Index, which expresses a relationship between the demand for water in relation to the available supply for each region of Colombia, presents critical values for the water districts located in Alta Guajira and Sabana de Bogota/ This is due to a deficit of water caused by natural climatic conditions for Alta Guajira and an extreme demand of water resources combined with high population density for Sabana de Bogota. The results of this study reveal, however, a more negative scenario for Alta Guajira. There is a predicted decrease in the water available for the coming decades in this region which worsens the already existing water deficit. In the Bajo Meta and Rio Catatumbo water districts there is currently a moderate use of the water resources considering their availability in these regions. However, it should be noted that it is equally necessary to adopt measures towards adaption to the projected decrease in water supply for the coming decades in these regions.

The application of the model BROOK90 proved to be valuable for water cycle analysis and for the purpose of this study in offering a general overview to the change of water balance components throughout the east side of Colombia due to future climate change. Prediction of the impact of climate change on water budget components is a transcendent, practical, and theoretical problem to which each country and its institutions should dedicate more resources: especially for countries and regions that are more vulnerable to climate change. Uncertainties associated with the GCMs, climate model, hydrological model, and the approaches used in this study have a direct effect on the outcome, and they must be considered and evaluated for the use of these results in addition to their uses for future works.

Despite Colombia's high water availability, a profound impact is contemplated at various levels due to the decline in water resources in the east of the country in the coming decades. This prediction was made considering the results of this study in addition to the already exploited vulnerability of several regions of the country for the purposes generated by climate change. Despite the negative outlook, the Colombian government is already in the process of creating policies, strategies and necessary changes response for the mitigation and adaptation to the impacts of global warming for the Eastern side of the country and in general for the whole territory.

The results obtained in this study should be considered as indicative of the expected trend in water resources of the studied regions as a result of climate change. These results might serve as a contribution for a baseline of information for creating mitigating measures. However, future work using other models and other techniques for the analysis of water resources throughout these areas is encouraged. The information provided as a result of this project is valuable regarding the analysis of potential droughts, heatwaves, and the availability of water resources throughout these regions. Along the same lines, it is a good source of information for the evaluation of possible future-case scenarios and decisions-making management. The results of this study can be used for development planners, decision makers, as well as other stakeholders when planning and implementing appropriate management strategies regarding response and mitigation and adaptation to the impacts of global warming for the studied regions.

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ABBREVIATIONS

FTA - Free Trade Agreements

GCM - Global Climate Models

IDEAM - Institute of Hydrology, Meteorology and Environmental Studies of Colombia

IPCC - Intergovernmental Panel on Climate Change

ITCZ – Inner Tropical Convergence Zone

MOS - Model Output Statistic

RCM - Regional Climate Models

RCP - Representative Concentration Pathways

SDSM - Statistical Downscaling Model

Sws - Surface water supply

Tmax - maximum temperature

UNFCCC - United Nations Framework Convention on Climate Change

UPME - Colombian Energy Mining Planning Unit

Wd - Water demand

WRI - Water Retention Index

WSI - Water Stress Index

WVI - Water Shortage Vulnerability Index

LIST OF PUBLICATIONS

Molina OD, Bernhofer C. (2019) Assessment of Regional and Historical Climate Records for a Water Budget Approach in Eastern Colombia. Water. 12. 42. https://doi.org/10.3390/w12010042

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