The Impact of Climate Change and Climate Variability on Groundwater Recharge in the Cauca Valley, Colombia

MSc thesis by Michiel Feijt

2015

Soil Physics and Land Management

WAGENINGEN UNIVERSITY
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The Impact of Climate Change and Climate Variability on Areal Groundwater Recharge in Colombia's Largest Sugar Cane Region, Valle del Cauca

Master thesis Soil Physics and Land Management Group
submitted in fulfilment of the degree of Master of Science in
International Land and Water Management at
Wageningen University, the Netherlands

Study program:
MSc International Land and Water Management

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09/2015

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Abstract

The Cauca Valley is Colombia's largest sugar-cane producing area and this thirsty crop has a high demand for water whole year round. During the dry seasons when the surface water table is too low for water diversion, the farmers need to switch to groundwater extracting for irrigation. The impact of the irrigation activities on the groundwater resources combined with the pressure of climate change and the El Niño Southern Oscillation phenomenon ENSO is unknown.

The purpose of this study is to investigate the effects of long term climate change and short term climate variability on groundwater recharge in a selected study area in the Cauca Valley, Colombia. Furthermore to propose adaptation measures in order to mitigate the impact of climate change. To achieve this meteorological data for precipitation and temperature was collected. Climate scenarios were developed by adjusting these data based on climate change projections published by Institute of Hydrology, Meteorology and Environmental Studies of Colombia. The developed climate change scenarios represent the extreme 8.5 Representative Concentration Pathway as described in the most recent Fifth Assessment Report of the IPCC. The climate variability scenarios were developed using historical climate data sets, which were resampled using the Nearest Neighbour strategy to generate new synthetic sequences.

To adjust the data sets several steps were taken using four different software tools. First the data was analysed using the Standardized Precipitation Index to compare the weather stations. Second the data was processed in Delft-FEWS, this is a climate forecasting GUI which is used for spatial and temporal interpolation over the study area. Third, the generated grid was processed in a python script that computes recharge over the study area based on climate conditions and surface characteristics. And at last, this resulted in output files which contain recharge values and can be visualized and used for calculations in iMOD. This is a hydrogeological model based on MODFLOW and served as a tool in order to analyse and visualize the data.

The results of this research reveal that despite the projected increase in precipitation by IDEAM, the recharge for the study area declines for the developed climate scenarios. Therefore adaptation measures are proposed to keep the state of groundwater sustainable and adapt to extremes in dry weather conditions for the future. These measures are in line with a by the Colombian Government of Environment developed conceptual framework of climate change which could be implemented by the water and agricultural sectors.

This research is conducted in the context of the ESCACES project initiated by Deltares institute for applied research in the field of water, environmental authority Corporación Autónoma Regional del Valle del Cauca, UNESCO-IHE Institute for Water Education and Netherlands Enterprise Agency to encourage entrepreneurs in sustainable, agrarian, innovative and international business.

Acknowledgement

First of all, I would like to express my very great appreciation to my supervisors Marta Faneca Sànchez MSc and Micha Werner PhD for giving their time so generously. Their valuable and constructive suggestions during the planning and development of this research work, their useful critiques, and patient guidance has been very much appreciated.

I am particularly grateful for the feedback on my work given by dr.ir Martine van der Ploeg as my supervisor from Wageningen University, and for helping me organizing the information and assistance in keeping my progress on schedule.

I would also like to extend my special thanks to ing. Héctor Fabio Aristizábal for offering me a working space for three months in the Water Resources Group of Corporación Autónoma Regional del Valle del Cauca in Santiago de Cali. This made it possible to collect the data for this research. And I wish to thank ing. Guillermo Céspedes López for helping me settling in Santiago the Cali and his valuable suggestions to improve my work.

Finally, I wish to thank my parents for their support and encouragement throughout my study.

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1. Introduction

Water is essential for life, but its availability at a sustainable quality and quantity is threatened by many factors, of which climate plays a leading role (IPCC, 2007). Climate change and climate variability have been linked to global changes and show remarkable effects on the hydrological cycle. It is expected that due to climate change the availability of groundwater resources will significantly change (García González, 2007). This is a problem that has global impact on people, industries and the environment. In 2008, the IPCC identified several gaps in knowledge related to climate change and climate variability in relation to the availability of water resources. The knowledge gaps were prioritized in need for further research. From these identified knowledge gaps, the most important one was the need the improve understanding of climate change and variability on the effects of groundwater resources (Bates et al. 2008). The prioritization of this knowledge gap is because groundwater is the world's largest storage of fresh water and functions in many regions as the main source for fresh water and water reserve. Therefore, it has a key role in sustaining primal human needs such as access to drinking water, food production and other ecosystem services (Taylor et al. 2013). The IPCC emphasizes in their report that currently there is not enough information available on how groundwater levels will develop under climate change, and how it is affecting the current climate variability. The changes will result in economic losses, social and environmental issues, especially the agricultural sector will be heavily affected by changes in food production (Vincent, 2007; Brown and Funk, 2008). The effects of climate change and variability have a direct impact on the groundwater recharge due to change in infiltration by precipitation and indirect by groundwater extraction due to human activity. This is already shown on a large scale in India and the Western United States where due to changes in climate patterns and human activity the groundwater levels are declining (Scott and Shah, 2004). On the other side, there are also studies that show that the intensification of rainfall due to climate change leads to an increase in recharge, mainly in arid and semi-arid areas (Taylor et al. 2009). Evidence shows that climate change reached a point of no return due to the production of carbon emissions. It is alarming that even if we stop the production of carbon emission immediately that the process of warming of the oceans cannot be stopped (Blunden and Arndt, 2015). For this reason, information of local and regional impacts of climate change on hydrological processes and water resources are becoming more important.

To see how these global changes and issues have an impact on the regional scale the following research is conducted. The problem of the impact of climate on the recharge is studied by using several research tools and hydrogeological model. This model is applied in the study area situated in Colombia's largest sugar cane producing regions Valle del Cauca. In this region the agricultural sector is depending on groundwater resources for irrigation.

1.1 Background

The geographical location of Colombia brings complex hydro-climatological features. Colombia has a lot of influences from the atmospheric circulations over the Pacific Ocean and the Caribbean Sea, the Orinoco and Amazon River basins and the strong topographical gradient. These conditions have a lot of influence on the atmospheric circulations (Poveda et al. 2001; Poveda, 2010). This combined with the increasing temperature of the oceans influences the atmosphere and affect natural phenomena's like the El Niño Southern Oscillation (ENSO). Several studies link the hydrological conditions in Colombia with the extreme phases of ENSO (Mesa & Poveda, 1997; Carvajal, 2004; Poveda, 2004). For Colombia warmer sea surface temperature (SST) refers to an El Niño which is associated with an reduction of precipitation and droughts (Jiménez et al., 1998; Poveda, 2010; Córdoba-Machado et al. 2015). The cold SST phase is referred to "La Niña" and is associated with an increase of precipitation. However, due to the variations in climate through the country, the effects of the SST phase can be different through the country. Studies show that during El Niño northern, central and western Colombia are associated with a significant decrease in rainfall during the whole year. The south-western region of Colombia shows the opposite behaviour. This illustrates the complexity and diversity of the climate in Colombia.

The Cauca Valley is a region in the department "Valle del Cauca" located near the Pacific Ocean in the southwest region of the country. The location close to the Pacific Ocean and between the mountain ranges of the Andes makes it one of the regions most affected by climate in Colombia (Jiménez et al. 2012). Due to climate change and climate variability it is expected that the water availability in the Cauca Valley will change (Jimenez, 2012; Carvajal, 2013). Climate projections show that the Cauca Valley will get a warmer climate and depending on the season an increase or decrease in rainfall (IDEAM, 2015). How this affects the groundwater resources is unknown. Another challenge is how the usage of the groundwater by the agricultural sector can continue while maintaining economic development (Jimenez, 2012). These challenges are shown in a study to quantify the vulnerability of the Rio Cauca River basin published in 2013. The study indicates that the agricultural sector in the Cauca Valley is vulnerable to climate change and variability and "requires immediate attention to taking priority actions and adaptation measures for the sector, to maintain its competitiveness and income for farming communities" (CIAT, 2013). The analyses show that production systems with greater technological support tend to have a better adaptive capacity and are less sensitive to the changing climate. This observation indicates that investments in technologies and production systems could be the best adaptation strategy in the region to ensure high productivity in the future. Moreover, at the end of 2013 the department of the Cauca Valley with the support of the Ministry of Agriculture has started the Agricultural Development Plan which has led to investments in irrigation network to enhance the agricultural production.

Project background

This thesis is conducted within the context of the ESCACES project (Evaluación de las aguas Subterráneas en Condiciones climÁtiCas ExtremaS). The objective of the project is to improve understanding of the hydrogeological system of the Cauca Valley through data analyses and river-wetland-aquifer relationships. This project was initiated by Deltares - an independent institute for applied research in the field of water and subsurface and the Corporación Autónoma Regional del Valle del Cauca (CVC) which is a regional environmental authority in the Cauca Valley. The project is carried out in collaboration with UNESCO-IHE Institute for Water Education, and supported by the Netherlands Entrepreneurial Agency.

1.2 Problem statement

Due to climate change it is unknown how the groundwater resources will develop in the future in the Cauca Valley. Together with an expansion of the agricultural sector during the last few decades the pressure on the groundwater resources has increased (Giraldo, 2014). The most important crop in this area is sugar cane, which has an extremely high demand for water and belongs to the group of the thirstiest crops (FAO, 56). Several million people live in the Cauca Valley and they will be affected by the change in climate as well as the agriculture sector which has an important contribution to the economy (Jimenez, 2012). Therefore, there is a need for this study to examine the impact of changes in climate on the groundwater resources. This study is conducted in a selected study area within in the southern region of the Cauca Valley.

1.3 Research Questions

To investigate the problem of climate change on the effects of groundwater recharge the following research questions are formulated:

Main question

"What is the impact of climate variability on groundwater recharge in Cauca Valley, how is that affected by climate change, and how can adaptation strategies contribute to mitigating that change?

Sub questions

1) What are the effects of climate change and climate variability on the groundwater recharge in the study area in the Cauca Valley?
    a) What is the future climate projection for the Cauca Valley and how does this affect the groundwater recharge in the study area?
    b) What is the impact of extreme dry years on the groundwater recharge in the study area?
2) Which indicators can be used to measure the sustainability of the groundwater recharge?
3) Which adaptation strategies can be adopted by the public and private sector to improve the state of the groundwater?

1.4 Objective of the study

This research seeks to answer the question how climate change and climate variability influences the groundwater recharge rate of the groundwater resources in the study area in the Cauca Valley in Colombia. Moreover it seeks to answer which measures could be implemented by the agricultural and water management sector, including private and public sectors, in order to adapt to the changes in the groundwater resources.

To answer the research questions this study aims to succeed in the following objectives. The overall objective of this research is to collect climate data and use it to develop climate scenarios to calculate recharge rates for the study area. Then the study aims to propose an indicator which can be used to estimate the sustainability of the groundwater. The recharge rates are used to calculate a sustainability indicator to analyse the change in state of the groundwater over a certain time period of time. Finally climate change adaptation strategies are presented which are in line with national policies in Colombia.

2. Concepts and Definitions

2.1 Study Area Description

The study area is located in the department Valle del Cauca (Cauca Valley department) within the brown rectangle of
Figure 1 and has a surface of 47km^2. The study area includes a subsurface layer with an average depth of 120 meter which is designated as "Unit A" where the recharge is studied. The study area is situated between approximate 880 meter and 1000 meter above sea level in a valley which is formed between two Andean mountain ranges Cordillera Occidental and Cordillera Central.

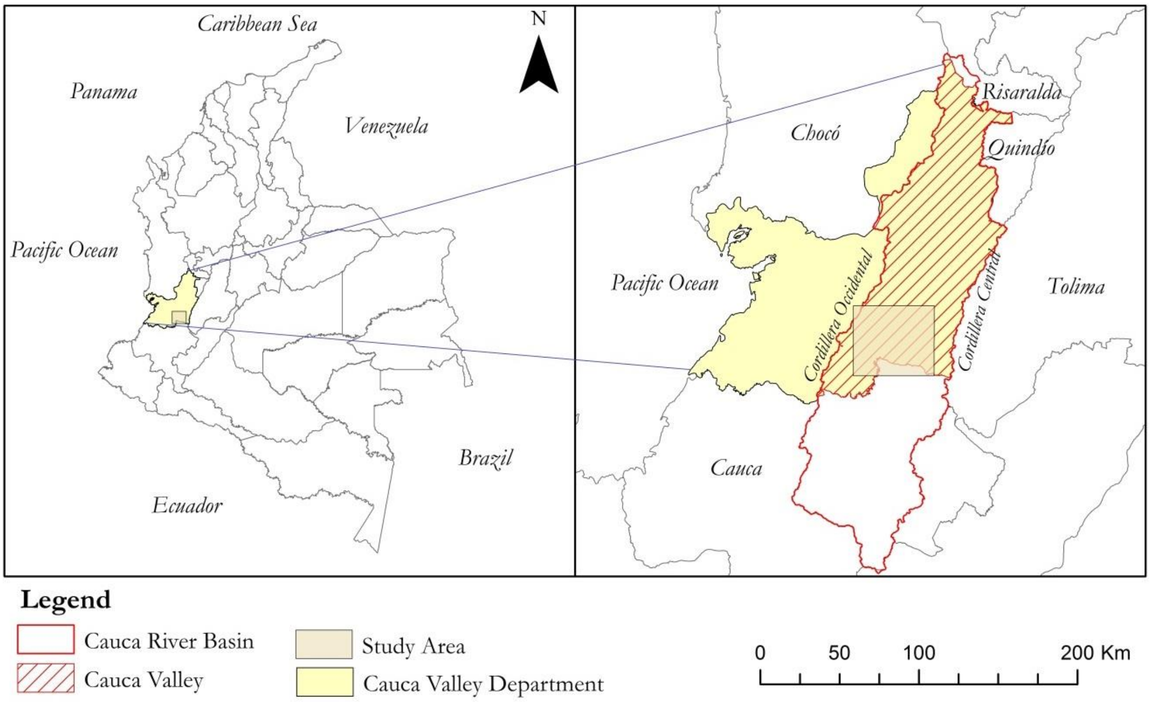


Figure 1 The location of the study area is shown in the brown rectangle and includes approximate 120 meter subsurface. The red hatched area is the Cauca Valley, situated in the Department Valle del Cauca (yellow) Source: author.

The study area was selected because it is one of the most intensive used areas in the Cauca River Basin, in terms of agriculture, water consumption, human pressures and urbanization of the cities Santiago de Cali, Jamundí and Palmira. The department is located in the southwest of Colombia between 3° 05' and 5° 01' latitude N, 75° 42' and 77° 33' longitude and named after the "Rio Cauca" the second most important river of Colombia after the Magdalena River. The department borders five other departments, with Chocó, Risaralda and Quindío to the north, Tolima to the east, Cauca to the south and facing the Pacific Ocean in the west.

The climate in the Cauca Valley department is characterized as tropical with relatively high temperatures and uniform precipitation throughout the year. The Cordillera Occidental divides the department into two regions, with on the west side of the mountain range the Pacific coast which is humid and full of jungle. And the Cauca Valley on the east side of the mountain range of approximate 50 kilometre wide towards the Cordillera Central. The Cauca Valley has a bimodal rainfall regime, which means that there are two rainy and two dry seasons per year (Table 1). The first wet season starts after a transitions period of 40 days in March and ends at the end of May (MAM). This is followed by a dry season June, July, August (JJA), which runs until the middle of August and is followed again by three wetter months September, October, November (SON) (Cenicaña, 2010).

Table 1

Rainfall Calendar Cauca Valley department

Temporada	Primera temporada seca 16 diciembre - 15 febrero (62 días)											Transición 16 febrero - 25 marzo (40 días)								Primera temporada lluviosa 26 marzo - 25 mayo (61 días)												Transición 26 may. -15 jun. (20 días)				
Mes	Dic.		Enero						Febrero						Marzo						Abril						Mayo						Junio			
Década*	36		1		2		3		4		5		6		7		8		9		10		11		12		13		14		15		16		17	
Péntada**	71	72	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34
Día	16										15	16							25	26											25	26				15

Temporada	Segunda temporada seca 16 junio - 15 agosto (61 días)												Transición 16 agosto - 5 octubre (50 días)										Segunda temporada lluviosa 6 octubre - 5 diciembre (61 días)												Trans. 6-15 dic.	
Mes	Junio		Julio						Agosto						Septiembre						Octubre						Noviembre						Diciembre			
Década*	18		19		20		21		22		23		24		25		26		27		28		29		30		31		32		33		34		35	
Péntada**	35	36	37	38	39	40	41	42	43	44	45	46	47	48	49	50	51	52	53	54	55	56	57	58	59	60	61	62	63	64	65	66	67	68	69	70
Día	16											15	16									5	6											5	6	15

Source: Cenicaña, 2010

The formation of the Cauca Valley between the Cordilleras took millions of years. First the Valley was filled with tertiary sediment from erosion of the Western and Central Cordilleras (Figure 2). Then sediment transport of the Cauca River and its tributaries deposited quaternary sediments which are mainly found at the foothills of the mountains together with large alluvial fans. This process developed a layer 1000 meter thick and is divided into three levels, which are called Unit A, B and C. Unit A has an average depth of 120 meter, followed by Unit B with a depth ranging from 120 to 200 meters. Unit B is an impermeable layer of fine silt and clay, which prevents water from infiltrating to Unit C. Unit B is important for protecting the water in Unit C against pollution. Because of the low vulnerability and excellent water quality Unit C is seen as an important groundwater reserve and therefore protected by legislations against excessive groundwater abstraction.

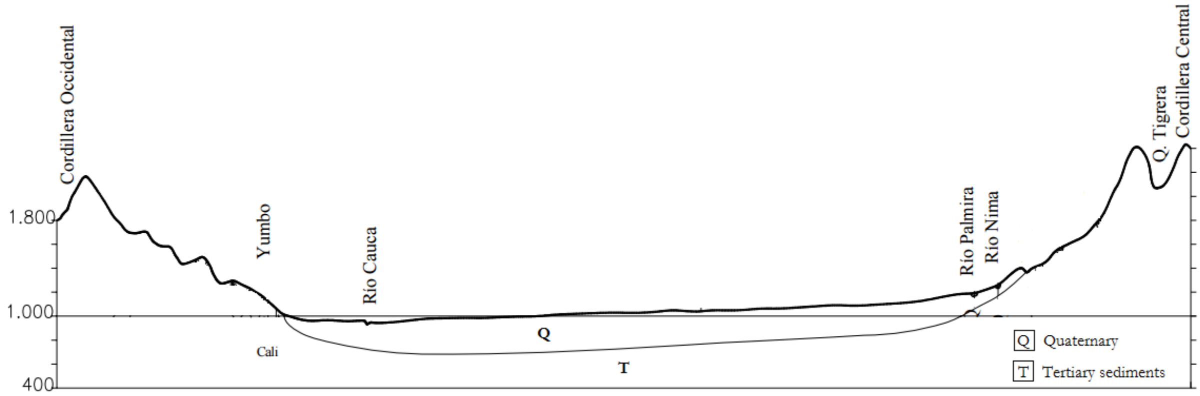


Figure 2 Cross section of the Cauca Valley (Gilboa and Guerrero, 1987; CVC, 2010).

The capital of the department is Santiago de Cali which is after Bogotá and Medellín the third biggest city in population of the country with 2.3 million inhabitants (CIA, 2014). The department is considered with a GDP of 9.3% as one of the most important departments of Colombia after the departments Bogotá and Antioquia (Banco de la República, 2009). The biggest contribution to the economy come from the sectors services, industry and agriculture (BPS, 2014).

The agricultural sector covers the majority of the surface in the Cauca Valley with approximate 69%. The most commonly cultivated crop is sugar cane and its exploitation goes back to the sixteenth century. It has characterised the valley over the centuries on its landscape and culture due to the construction of irrigation canals and water storage reservoirs. Over the years, sugarcane became the most important crop of the region and it created new opportunity to develop new industries such as ethanol production for fuel. This economical developed caused an increase in population and pressures on the environment in Cauca Valley. Nowadays sugar cane has an even bigger role in the economy of Colombia with and export value of over 369 million US$ in 2006 (Escobar and Cristina).

According to the WWF Report "Agricultural Water Use and River Basin Conservation" sugar cane is one of the four thirstiest crops together with, cotton, rice and wheat. The water consumption by sugar cane varies according to the stage of development between 1200 and 1500 millimetre per year. Crop growth goes through three stages which are called the initial, mid-season and late-season stage. These stages are expressed in crop coefficients named Kc values, which indicate the amount of water a crop needs during a specific stage. Sugar cane has the value of 1.25 the highest Kc value during mid-stage compared to other crops. The mid-stage for sugar cane takes at least 180 to 220 days depending on cane type. Because a growing cycle takes between the 320 and 480 days the cultivation of sugar cane demands a high amount of water all year round (FAO-56). Depending on the humid and wind conditions the Kc ranges between 1.1 and 1.6 during mid-stage where the crop is full strength and needs consumes the most water (Allen et al, 1998). According to the Colombian Sugarcane Research Center (Cenicaña) the average Kc value for sugarcane during the complete grow cycle is Kc 0.7. This value includes the initial, mid-season and late-season stages (Gonzáles et al., 2011). Besides the demand for water, the root depth also has an important impact on the water cycle. Sugar cane can grow up to 2.5 to 3 meters high. The roots can develop a length that reaches between 1.2 and 2 meters deep. The deep roots intercept water which cannot percolate deeper to recharge the groundwater. This can influence river flows as it intercepts run-off from the catchment into rivers (WWF, 2006).

2.2 Concept of Groundwater Recharge

Groundwater recharge is the central concept of this research. It is an important part of the hydrological cycle where precipitation infiltrates into the soil and replenishes groundwater supplies. It is defined as the volume of water that ingress into the saturated area of the soil where it becomes part of the groundwater reserves. Not all the precipitation will lead to recharge and it is depending on many factors. Figure 3 shows an overview of the studied water fluxes in the study area which impact the groundwater recharge. It should be noted that for this study recharge is studied using a vertical water balance approach and horizontal subsurface movement is not taken into account.

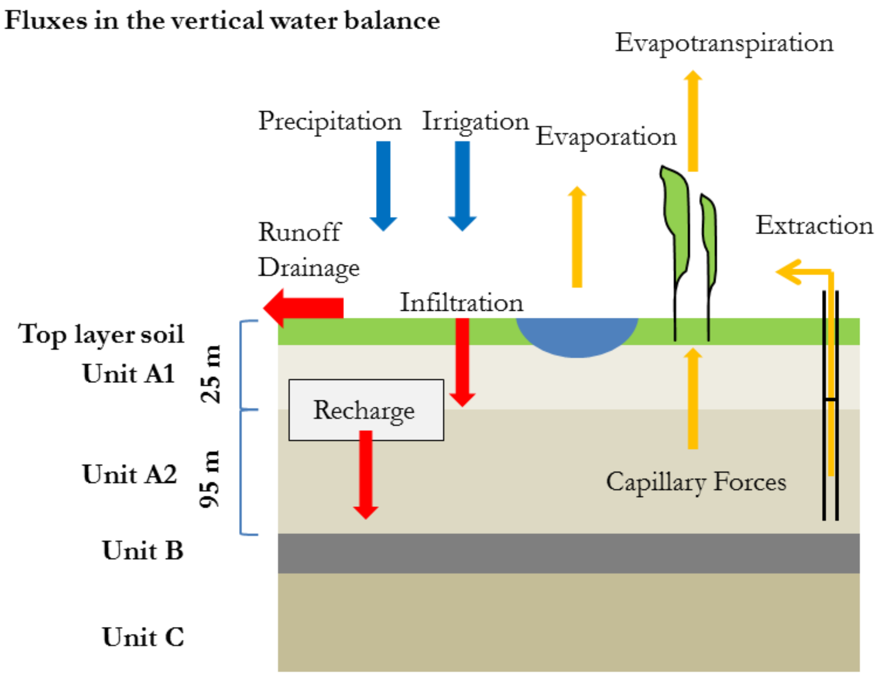


Figure 3 Schematic representation of the water fluxes and layers of the study area.

The amount of water that infiltrates into the soil is calculated using the Curve Number Method (curve number, or CN). The curve number is an empirical parameter and developed by the USDA Natural Resources Conservation Service (USDA, 1986). This approach divides the precipitation into the components infiltration and runoff. Infiltration is our main interest because this volume may lead to recharge.

Runoff is calculated with the formula:

$$Q = \frac{(P - 0.05S_{max})^2}{(P + 0.8S_{max})}$$

Where
Q = Runoff (mm)
P = Rainfall (mm)

S_{max}= Potential maximum retention after runoff begins (mm)

S_{max} is related to the soil and land cover conditions of the watershed through the curve number. Curve number has a range of 30 to 100 and is selected from a table developed by (USDA, 1986). The table describes the curve number depending on soil type, soil infiltration and land use resulting in:

$$S_{max} = \frac{1000}{CN} - 10$$

Then the infiltration is the difference between the precipitation and runoff and calculated by subtracting runoff from the precipitation

$$I = P - Q$$

Overview of the infiltration process

Figure 4 shows the procedure when the fluxes precipitation or irrigated water enters the study area. Precipitation is the main input flux and in this study the main driver for groundwater recharge. The soil moisture, or water content, is also an important factor and quantifies the volume of water that is stored between the pores of the soil. Once water is infiltrated it enters the state "soil moisture" where it varies between field capacity and wilting point due to evapotranspiration. The water can leave the soil again by evapotranspiration which is a combined process of both evaporation from soil and plant surfaces and transpiration through plant canopies. In the evapotranspiration process, the water is transferred from the soil and plant surfaces into the atmosphere in the form of water vapour. If the soil moisture exceeds the maximum soil moisture capacity (field capacity) water will infiltrate deeper into the ground below the root zone (extinction depth). There it cannot be reached anymore by the roots of the plants and cannot leave anymore by evapotranspiration. If this occurs then the water is recharged to the groundwater. However, if the groundwater level is above the extinction depth it can be added again to the soil moisture by capillary rise where the water could leave the soil by evapotranspiration.

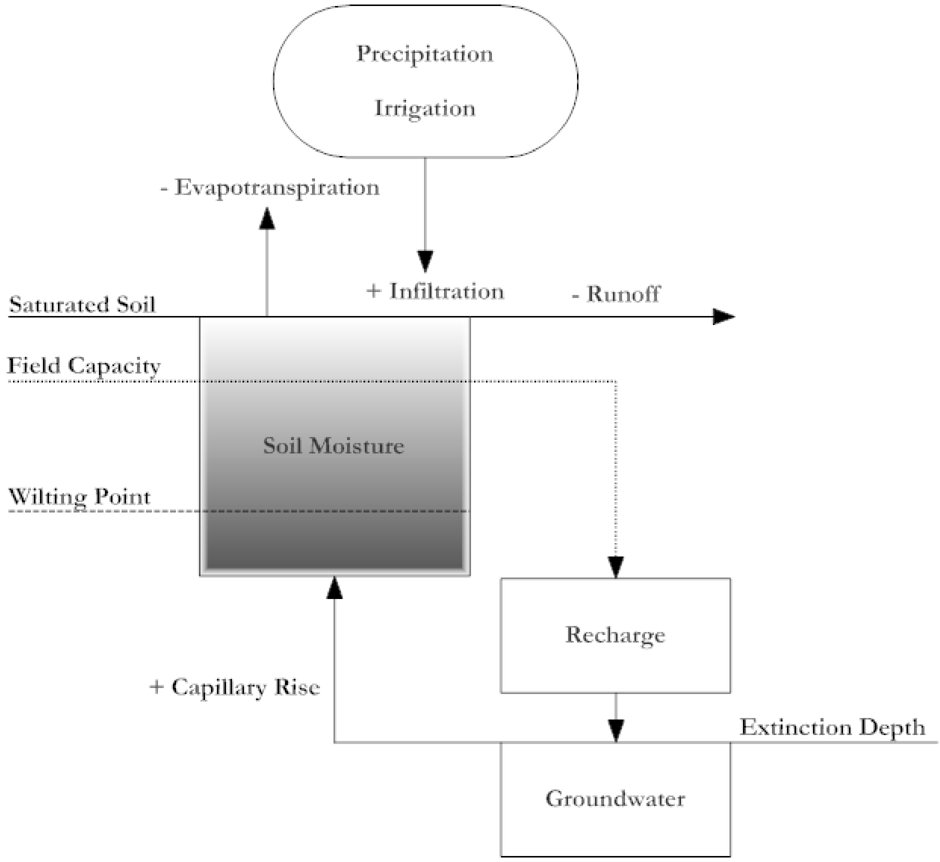


Figure 4 Schematic representation from water fluxes entering and leaving the system. Source: Author.

Climate
Climate is defined by the IPCC as "the average weather in terms of the mean over a certain time-span and a certain area". This is often measured over a period of at least thirty years. Climate change refers to a change in the state of the climate and occurs for decades or longer periods (IPCC, 2007). The climate variability is observed over a relatively short period of time and refers to monthly, seasonal and annual values with regard to the average. Climate variability includes inter seasonal variations (variations of two or three months) and annual (year on year). This means that climate fluctuates above or below long-term averages (FAO; Cenicaña, 2008).

Depletion
Groundwater depletion forms an important aspect for this research since it indicates the state of the groundwater. Depletion exists in many regions and is therefore described and defined by several authors with different terminology. Depletion is sometimes referred to as groundwater mining or groundwater overdraft (Korus and Burbach, 2009). Harou and Lund (2008) define depletion as "overdraft" referring to "long-term groundwater extraction at unsustainable rates manifested by steadily decreasing regional groundwater levels over a period long enough to overlook seasonal and drought effects". Konikow and Kendy (2005) refer to depletion to describe groundwater overdraft that causes "persistent head declines in renewable aquifers" and add that "groundwater depletion consists of a reduction of aquifer volume or a reduction in the usable volume of fresh groundwater within an aquifer". In this research groundwater depletion is

defined as when the groundwater extraction is exceeding the groundwater recharge, and analysed by calculating the volume being extracted divided by the volume being recharged.

Drought

Due to climate variability in the Cauca Valley droughts play an important role for the agricultural sector. In general the farmers divide water from the rivers and streams but during dry seasons the surface water is declined and to low so then have to switch to groundwater extraction. If a drought occurs is heavily depending on the impact it has on the water users, the demand for water in terms of quantity and quality and the availability at a particular location. This can be different for every industry or individual and makes it hard to make one definition (IPCC, 2007). Because of this difference, there are in general three different types of drought which can be associated with changes in meteorological, soil, and hydrological conditions (Figure 5). The first type of drought is a metrological drought, where the amount of precipitation falls below average over a prolonged period of time. Second, we can define an agricultural drought when there is a period below normal soil moisture that does not match the water requirements of a cultivated crop. Finally, we talk about hydrological drought when the river stream flows, ground water levels, lakes and reservoirs are below normal. In this research, the meteorological conditions are taken as a starting point and used to analyse the impact on the hydrological conditions.

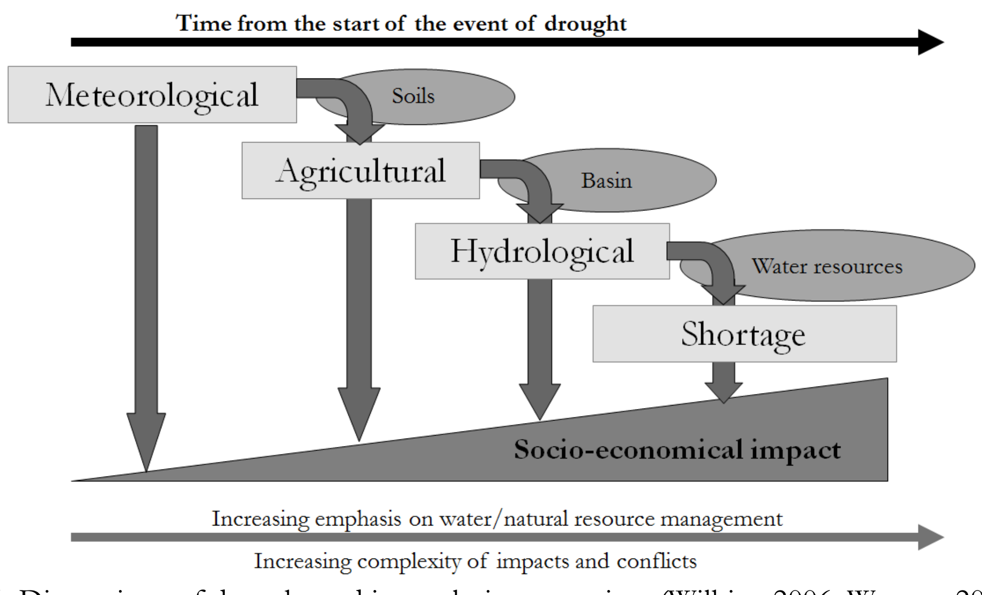


Figure 5. Dimensions of drought and its evolution over time (Wilhite, 2006; Werner, 2015)

Adaptation

Adaptations are management responses to risks associated with climate variability and climate change (Clifton et al. 2010). The IPCC 2007 defines adaptation as "Initiatives and measures to reduce the vulnerability of natural and human systems against expected climate change effects. This applies to policies and practices which can either reduce risks and / or realise opportunities associated with climate change. Climate change is recognized by the government of Colombia as a threat to social, economic and environmental development. To address these challenges, the National Planning Department (DNP), together with the support of Ministry of Environment and Sustainable Development (MED), the Institute of Hydrology and Environmental Studies (IDEAM) and the National Unit for Disaster Risk Management (UNGRD) developed the National Plan Adaptation to Climate Change (PNACCO). This is a conceptual framework that gives guidelines for developing adaptation plans to reduce climate vulnerability. The framework includes five principles how climate problems should be approached by the public and private sector. These key principles are used in this thesis to develop climate adaptation measures which could be applied in the Cauca Valley. In line with these principles, the Adaptation Support Tool developed by the European Environmental Agency (EEA) is used to identify concrete adaptation measures which are based on UKCIP, 2005; Adger et al. 2005; Prutsch et al. 2010; Brown et al. 2011).

Principles National Plan Adaptation to Climate Change (PNACCO)

This list provides an overview of adaptation measures proposed by the Ministry of Environment and Sustainable Development.

1. Implementation of adaptations measure which lead to measures that lead to restore ecosystems to provide ecosystem services, implementation of hard and soft technologies that reduce vulnerability for populations and infrastructure.
2. Combine adaptation with strengthen resilience since adaptation will not complete reduce the risks for climate variability.
3. Regional land use planning must include sustainable adaptive development.
4. Generate information and knowledge to measure risk for decision making for planned adaptation measures to reduce vulnerability and exposure.
5. Awareness raising about climate change in all public, private and population levels.

3. Methodology

This chapter provides an overview of the used methodologies in order to calculate the recharge and to propose adaptation measures to mitigate the effects of climate change. The chapter Concepts and Definitions gave a brief introduction of the used concepts to calculate recharge, but more variables and formulas are involved. The total process is divided into three steps:

1. **Data collection**
- The collection of historical precipitation and temperature data to make an initial data set of the Cauca Valley.
- Develop climate change and variability scenarios for different timescales in the future using the initial data set.

2. **Data processing**
- To calculate groundwater recharge using four different software tools.
- Calculation and visualization of the recharge in graphs and spatial maps.
- Scenario development and computing.

3. **Data analyses**
- To formulate groundwater sustainability indicator to calculate the impact of the scenarios on the state of the groundwater.
- To collect adaptation strategies that includes policies and technical measures that could be implemented to contribute to the sustainability of the groundwater.

3.1 Data Collection and Data Sources

To calculate the recharge for the study area two variables were needed. The first step of the research was to collect historical climate data of the variables:

- Daily precipitation values
- Daily temperature max, min and average values

The variables precipitation and temperature are essential because these are the main drivers for infiltration and evapotranspiration. Within the ESCACES project there was already climate data available to use but additional historical data was needed. The data was collected during a visit at the head office of environmental authority Corporación Autónoma Regional del Valle del Cauca (CVC) in Cali, Colombia. There is was possible to interact with workers and to use local networks such as intranet databases to complete the data set. This lead to additional data sources which are shown in Table 2. The visit in Cali made it possible to learn more about the study area in the Cauca Valley and to familiarize with the context of the project and to get an impression of the study area and culture of the region. These impressions were important for other parts of the research to see which climate adaptation measures could be implemented into the region.

Table 2

Overview of the different data sources

Dataset	Source	Description
Temperature	ESCACES (project) IDEAM (website) CVC (intranet database) WMO (website)	Daily temperature values of weather stations located in the Cauca Valley. Tmax, Tmin, Taverage between 1965-2013
Precipitation	ESCACES (project) IDEAM (website) CVC (intranet database)	Daily precipitation values of weather stations located in the Cauca Valley between 1965-2013

The precipitation data was collected from three different sources and combined into the "initial precipitation dataset" (Table 3). This dataset has daily values in millimetres rainfall between 1 January 1965 and 31 December 2013. The starting date is 1965 and has 28 stations with registrations increasing to 198 stations in 2013. The data set includes weather stations from the whole Cauca Valley and study area, and is used during the data processing phase for computing the Standardised Precipitation Index (SPI) and spatial interpolation between the weather stations.

Table 3

Data of the initial climate dataset

	Precipitation	Temperature
Time range	1965-2013	1973-2013
Interval	Daily	Daily
Number of stations	198 stations	40 stations
Unit	mm	°C
Format	CSV, notepad	notepad

For temperature data was available for the period 2000-2013 in the ESCACES project. Therefore additional data was needed for extending the time series as far as possible back in history. As a result, data was collected from two weather stations in the study area starting from 1973 and was combined with the dataset of ESCACES. These two stations were selected because they had the less missing values in comparison to other stations which had consecutive months or years of missing data. The missing values for the two weather stations were corrected by applying a linear interpolation when three or fewer days were missing between two dates by solving the formula:

$$y = y_0 + (y_1 - y_0)\frac{x - x_0}{x_1 - x_0}$$

During the data process phase, the temperature was also used for a spatial interpolation of the temperatures over the Cauca Valley. The availability of only two weather stations before the year 2000 is not ideal for this analysis since a higher number of weather stations would increase the accuracy of the interpolated grid.

Because the climate data was collected from various sources it was needed to structure the data to similar formats, such as file extensions, timestamps and geographical location. This resulted in an initial dataset with all the collected precipitation and temperature values. The initial data set was used as a starting point to develop climate scenarios and process the data through the software tools.

3.2 Boundary Condition and Model Concept

The recharge is studied for the 47km^2 study area (Figure 1) and the approximate 120 meter subsurface layer underneath it (Unit A). It is assumed that the water flows vertically downwards until it reaches the impermeable layer of Unit B. This means that no horizontal movement of water of the subsurface layer is taken into account. To estimate the recharge, the study area is divided into 250 meter vertical grids which is schematic represented in Figure 6. These columns have an average depth of 120 meter and are varying depending on the upper head of Unit B.

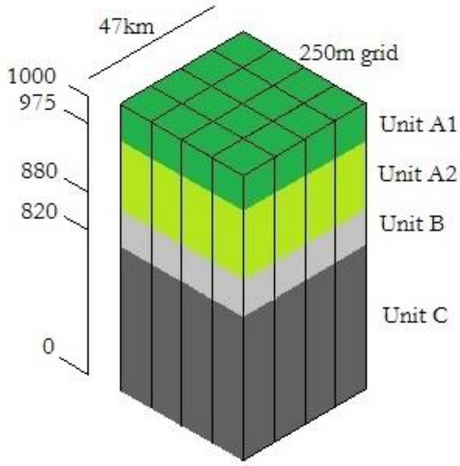


Figure 6 Schematic representatiation of the study area. The study area is visualized in the two green colors and include a subsurface layer of approximate 120 meter beneath the 47km^2 surface.

The top boundary condition of the study area is the water flux that becomes available from precipitation. As explained in the chapter Concepts and Definitions, precipitation entering the system is divided by the Curve Number into runoff and infiltration. Since only vertical movement is studied, runoff will not lead to infiltration into neighbouring cells. It is assumed that runoff water is drained from the cell and is added to surface water. Infiltration that may reach the groundwater flows downward through Unit A until it reaches the impermeable layer Unit B.

Only water from precipitation is taken into account for the recharge calculation. Water that infiltrates through rivers and streams is excluded from this research. The contribution from surface water is significant high, however, at date the model which calculates this volume is still in development within the ESACES project and not calibrated yet.

The choice for studying infiltration only for Unit A is by making the assumption that water cannot infiltrate through Unit B to replenish the confined aquifer of Unit C. However, as shown in Figure 7 Unit A and C seems to be connected at the alluvial fans close to the mountain slopes. Besides, the choice for studying Unit A is because the majority of the extraction wells are drilled in Unit A which has the biggest impact on the groundwater table.

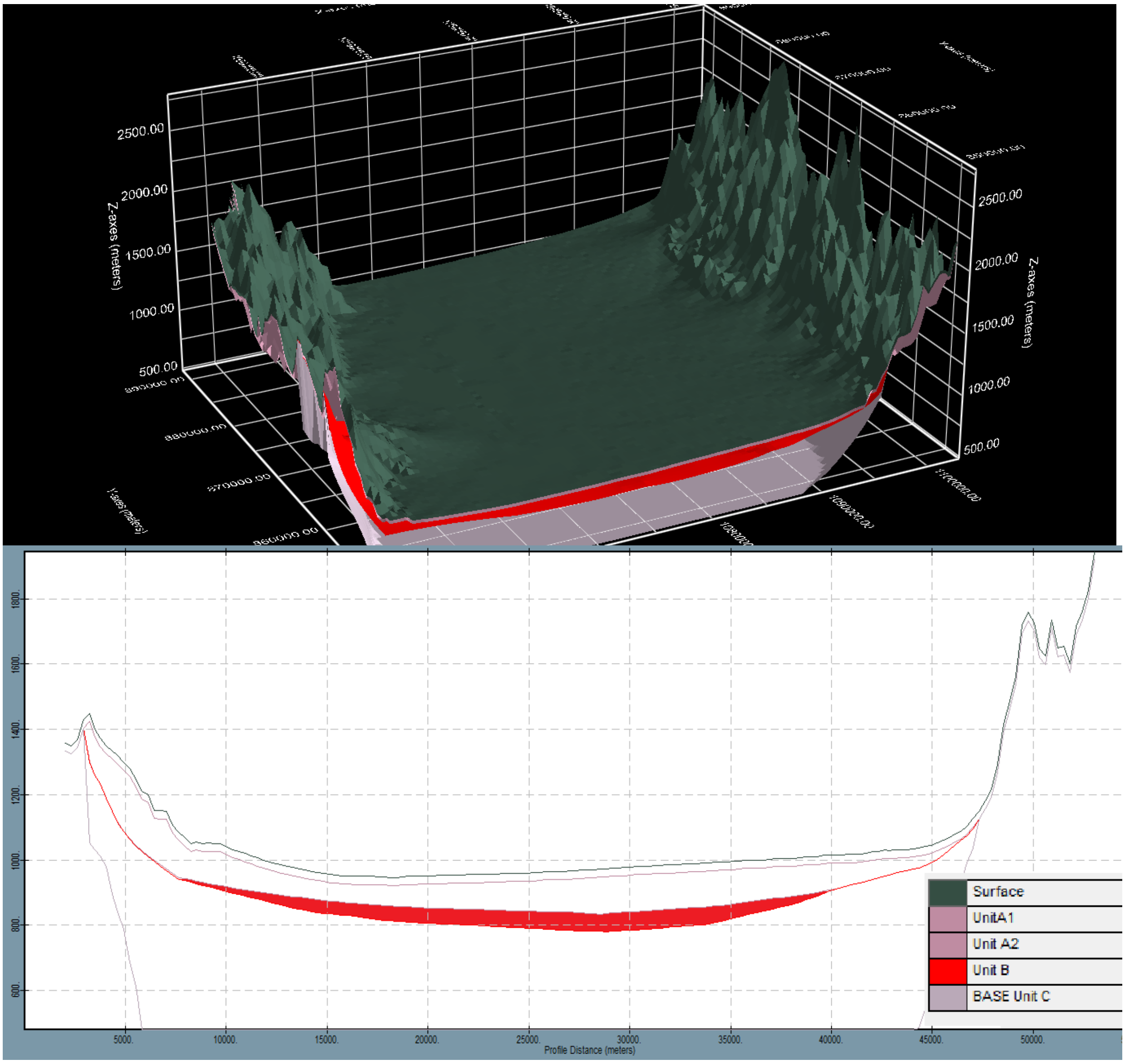


Figure 7 These figures show a 3D model and cross section of the study area. Unit B is clearly visible as forming a boundary between Unit A and C. However, Unit B is very thin closer to the mountain ranges where runoff from the mountains is able to replenish Unit C.
Note; 250meter grid cells are not visible in these figures.
Source: Author, images are captured using iMOD

Recharge is spatial and temporal estimated for every grid cell in the study area. To do this, the initial climate data set is processed in four steps using different software programs. This process is done for all the climate scenarios and demand accuracy because of the time consuming length of this process. The general steps of this process are presented in the flowchart of Figure 8. To generate the final results the software tools had to be used in the presented chronological order.

The used software tools are:

1. Standardized Precipitation Index Program (SPI)
   Used to standardize precipitation data to identify droughts and is used for scenario building.

2. Delft-FEWS
   A climate forecasting GUI initially developed for operational water management and hydrological forecasting. In this research it is used for spatial interpolation of the precipitation and temperature data and the preparation of input data for the Recharge script.

3. Recharge Script
   This is a Python based script developed in the ESCACES project. This script uses the interpolated temperature and precipitation maps created in Delft-FEWS, together with PCRaster maps containing characteristics of the study area, such as land use, root depth, to calculate recharge per grid cell. It generates output files which can be read and analysed in iMOD.

4. iMOD,
   An on MODFLOW based hydrogeological software program which can be used for computing water balances and visualize groundwater levels to analyse recharge rates of the different climate scenarios.

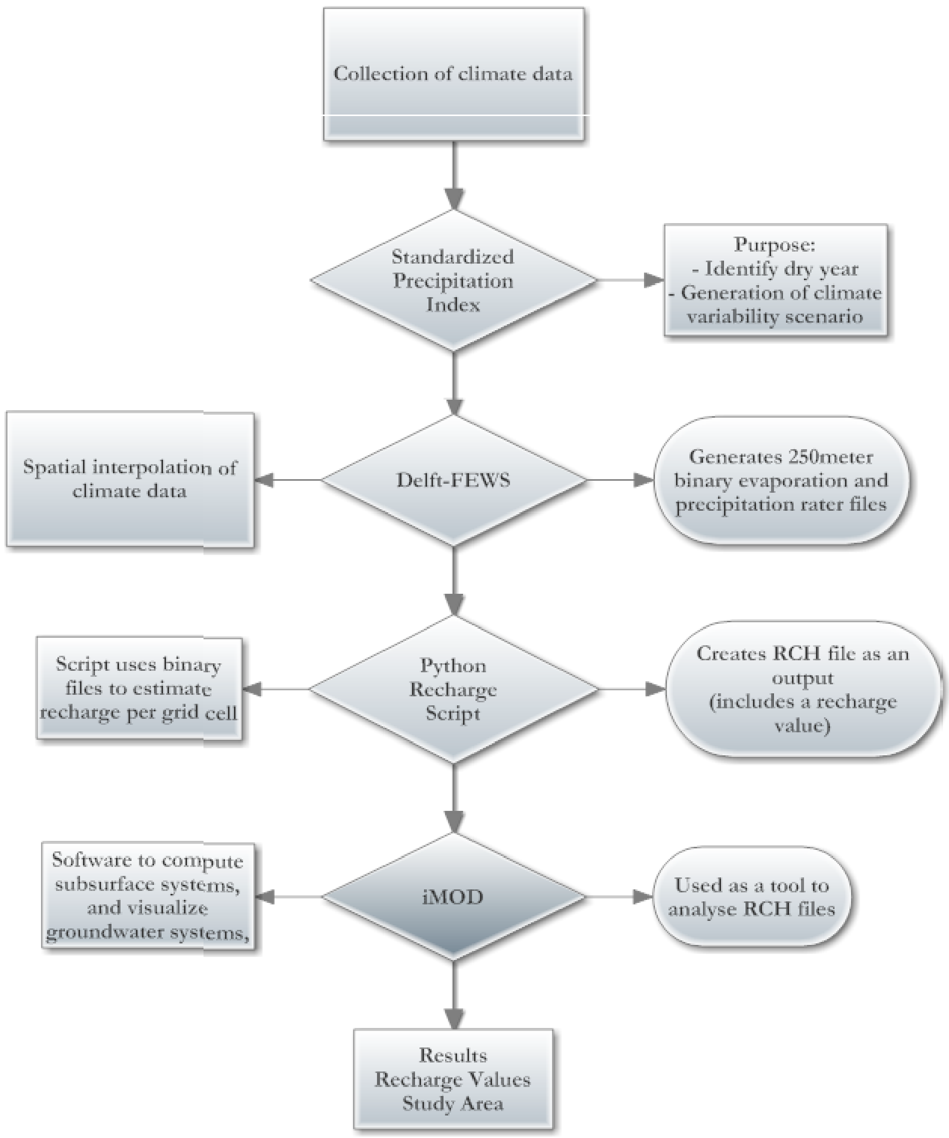


Figure 8 This workflow shows the order of taken steps to calculate recharge.

3.3 Used Research Tools for Data Analyses

3.3.1 Standardized Precipitation Index

The purpose of using the SPI is to identify a dry year in the collected climate data and to use this year to develop a climate variability scenario. There are a wide range of methodologies available to identify droughts but the choice for using the SPI is based on its simplicity and data availability. In contrast to other drought indexes such as the Palmer Drought Severity Index and Crop Moisture Index, the SPI only needs precipitation as an input parameter with a minimum of 30 and preferable 60 year or more of historical precipitation data (Edwards and McKee, 1997). The Standardized Precipitation Index (SPI) makes it possible to compare rainfall periods by standardizing the monthly totals of precipitation. The monthly totals are converted from absolute values into indexes ranging from -0.0 to +0.0. The index transforms the precipitation off different periods into a normal distribution with a mean of zero and a standard deviation of one. The SPI gives the amount of standard deviation of the mean. 95 % of the standard deviations are between SPI -2 and SPI +2 and approximate 64% between SPI -1 and SPI +2. When the precipitation values are indexed then this makes it easier to compare rainfall between different periods and different stations. Positive values indicate greater than the mean and represent wet periods where negative values indicate less than the mean and represent drought (Table 4). According to McKee and others (1993), a drought event occurs at any time the SPI is continuously negative and reaches intensity of -1.0 or less and the dry event ends when the SPI becomes positive.

Table 4

Weather conditions per SPI value

SPI Values	Category
≥ +2.00	Extremely Wet
+1.50 to +1.99	Very Wet
+1.00 to +1.49	Moderately Wet
-0.99 to +0.99	Normal
-1.00 to -1.49	Moderately Dry
-1.50 to -1.99	Severely Dry
≤ -2.00	Extremely Dry

Source: McKee et al. (1993)

3.3.2 Delft-FEWS

Delft-FEWS is a software infrastructure initially developed for operational water management and hydrological forecasting. Delft-FEWS provides an open shell system for managing the operational management process (Werner et al. 2013). Delft-FEWS can be deployed as the stand-alone environment, as a fully automated client-server application, or as a web service component within another forecasting system. It incorporates a set of data handling utilities to transform data with disparate spatial and temporal scales. In this study, it is used as a stand-alone environment and is not connected to an external real-time database. This stand-alone version was built in the ESCACES project to import and process climate data. This process includes workflows which are five steps in order to process the climate data and make it ready for the following software tool the Recharge Script (Appendix

Appendix 1). The purpose of using Delft-FEWS is to import the climate data to create precipitation and evaporation 250-meter grid files which are used as an input for the Recharge script. For the ESCACES project workflows are developed to interpolate the data. The general steps are following:

1. The climate data is imported into Delft-FEWS from a CSV, Notepad of Excel file containing precipitation and temperature values. These values have a weather station code to assign the climate data to the corresponding weather station, and a timestamp

with the yyyy-MM-dd hh:mm:ss format. To avoid errors during the import of the data, it is important to configure the system settings of the OS to this time format.

2. While the data is importing, Delft-FEWS runs a check in the background to identify outliers. Delft-FEWS compares the imported data against maximum and minimum set temperature and precipitation values for the region. If data exceeds this limit then a warning message is shown in the log GUI. The user can then decide to take action or ignore the message and continue with the next step.

3. When the data is imported the next workflow can be manually started which pre-process the data. During this step the daily data is aggraded in monthly values and added and saved in the Delft-FEWS database. From this database the further calculations are conducted.

4. Once the data is stored in the database the nest workflows can be ran. Because of high memory usage it is recommended to run the interpolation step by step over time periods of maximum 5 years, depending on the processor. As an example for this research, the initial climate data set of the years 2000-2013 is divided into 4 interpolation runs to complete starting from 2000-01-01 07:00 until 2003-12-31 07:00 (Appendix 2).

5. The first interpolation workflow is to process the precipitation data. This workflow makes monthly averages of the stations and interpolates these values using the closest distance interpolation method to get best linear unbiased prediction. Then for every station the difference between the monthly average and daily value is calculated. These differences are interpolated by inverse distance method. Then the result is added or subtracted to the monthly average to get the final result. Appendix 3 shows a daily step of the time serie visualized in a map. The GUI looks similar for the workflows temperature and recharge.

6. The next workflow uses the temperature max, min and average data to interpolate evaporation. To do this first the temperature is interpolated by using the inverse distance method, taking the elevation into account by applying the lapse factor. The lapse factor is a factor which increases or reduces the temperature by 0.6 degrees Celsius for every 100 meter difference in elevation. Since the weather stations are located by coordinate system Delft-FEWS applies the factors between the stations.

7. Now both evaporation as precipitation values are stored in the Delft-FEWS database.

8. By running the final workflow "Recarga", Delft-FEWS creates the input for the recharge script. It converts the stored data of the database into daily binary files. For every day one precipitation and one evaporation file is created.

9. These files are input files for the Recharge Script and contain for every cell of the 250meter grid in the study area a value which of either temperature, or evaporation. These binary files are the final output of Delft-FEWS and are named for precipitation

pptn0000.000 and evap0000.000 for evaporation. The name of the file changes for every day step e.g. evap0000.999 to evap0001.000, and so on.

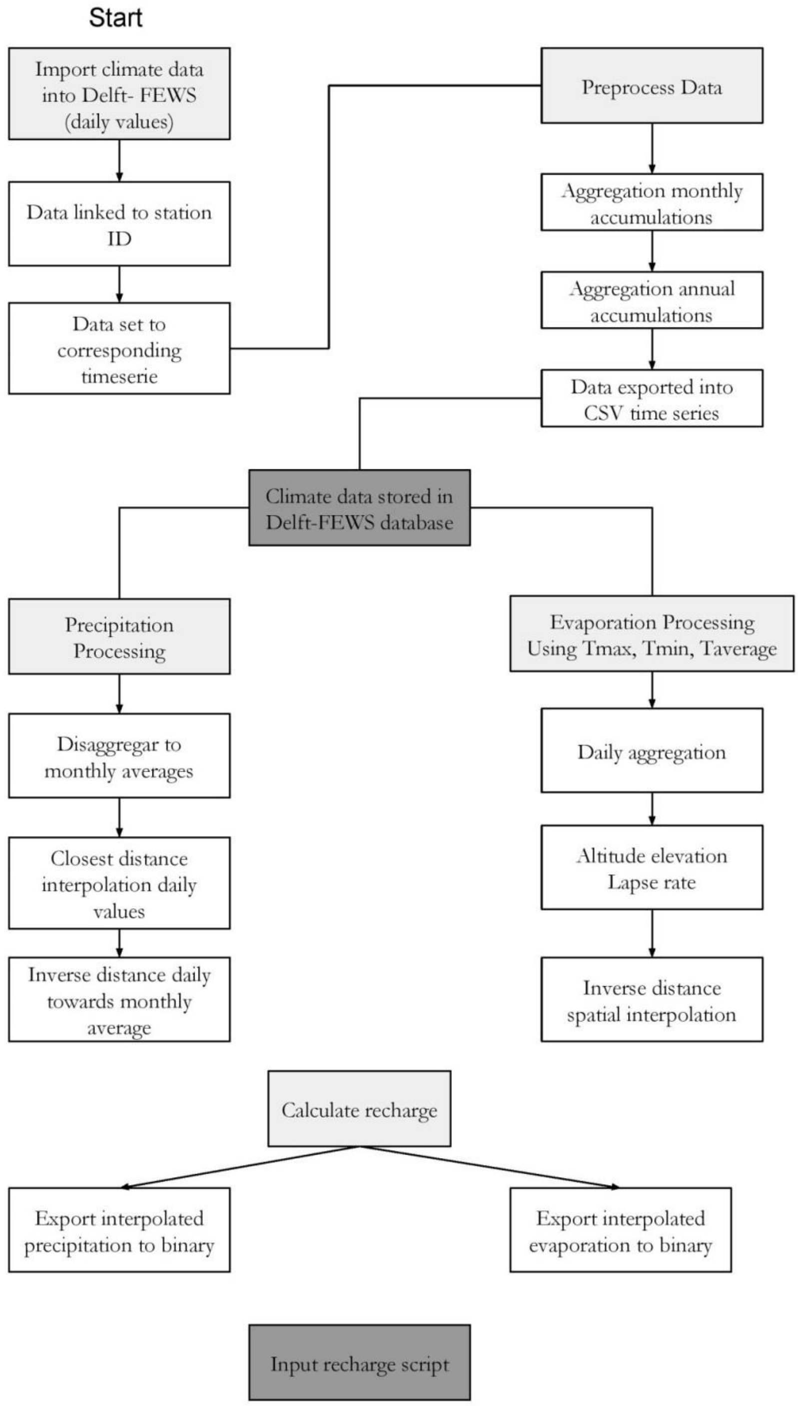


Figure 9 This flowchart shows the data processing in Delft-FEWS.

3.3.3 Recharge Script

The recharge script calculates the recharge for every grid cell in the Cauca Valley. The script first calculates the volume of water that infiltrates into the soil by using the Curve Number method. Then it calculates how much of the infiltrated water will recharge. As explained in the

Concepts and Definitions the infiltration is depending on the soil characteristics, land use and water fluxes. All the information of the characteristics is stored in PC Raster files and presented in Table 5. These characteristics are defined within the ESCACES project in collaboration with Cenicaña (Center for Research of Sugar Cane). This is a scientific based research institution in the field of sugar cane. Cenicaña is conducting research in the Cauca Valley since 1930 and has therefore a long record of reliable information.

The process starts with preparing a run file (Appendix 4) which tells the script where to read the input files and the destination folders to write the output files. The input files are stored in two folders, a "static folder" and "variable folder". Where the static folder contains the PC Raster files and the variable folder contains the in Delft-FEWS generated precipitation and evaporation files. For example, since the climate change scenario is computed over the period 2000-2013, the variable folder contains 5113 days * 2 (precipitation, and evaporation) = 10.226 files, plus two "map stack files" which tells the script which day stamp to assign. The script uses the map stack files to combine for every day step the precipitation, evaporation and PCRaster files to compute the recharge with the formulas in Table 6. Then at the end of a month the script generates an RCH.idf (recharge.idf) file. This file contains an accumulation of all the daily recharge values and is created at the end of every month. The RCH.idf files can be read in the next software tool iMOD. The runtime of the script over the period 2000-2013 takes between one and a half and two hours.

Table 5

Overview of the PCRaster files and containing information

Variable	Abbreviation	Description	Value (range)
MoistFieldCap	Moist. max	Moisture field capacity	0.0 - 0.216
DepthRootZone	d_{root}	Root zone depth at hill slope and flat areas	30-100 cm
Extinction Depth	d_{ext}	Subsurface location where moisture is protected from evaporation	100-120 cm
SurfSealFrac (Fraction sealed surface)	n/a	Fraction to reduce recharge in cells, for example in urban area	0 or 0.6
AutoIrrMoistFrac	n/a	If the soil moisture falls below this fraction, then the script applies irrigation.	0.5 or 0 (0 when there is no irrigation)
GWL	d_{GWL}	Groundwater level	100-1000 cm
CropFact	Kc	Crop coefficient	0.7-1.0
CurveNumber	CN	Curve Number	-
Land coverage	n/a	Describes the different types of land use	-
Evapotranspiration	Equation for estimation of the daily PETref based on the Hargreave's approach (Allen et al, 1998)		

$$PET_{Har} = 0.0023 \cdot (\frac{R_a}{\lambda}) \cdot \sqrt{(T_{max} - T_{\min})} \cdot (T_{mean} + 17.8)$$

Where

- R_a= Extra-terrestrial radiation
- λ = Latent heat of vaporisation
- Tmean = mean daily temperature °C
- Tmax = maximum daily temperature °C
- Tmin = minimum daily temperature °C

Table 6

Overview of the applied formulas in the Recharge script

Procedure	Formula
Capillary factor	$= \frac{d_{ext} - d_{GWL}}{d_{ext} - d_{root}}$
Capillary rise	$= (ET_p - (Moist + P_{pn})) * Fcap$
Comp moisture	$= P_{pn} + Moist - ET_a$
Runoff	$= P_{pn} + Moist - ET - Moist - 5$
Recharge	$= P_{pn} + Moist - ET - Moistmax - Runoff$
Moist max	$= d1 * Soilprop * 10$

3.3.4 Irrigation

In addition, since irrigation has an impact on the recharge rates the script has an option which applies a dose of irrigation to the grid cells. The irrigation option is only applied to the developed climate variability scenarios and not to the climate change scenarios. The reason of this is that the climate change scenarios are too far in the future to make an assumption about the volume of water that is irrigated. The for the climate variability applied irrigation is called the "optimum irrigation option. The script user manual describes the irrigation option as: "Whenever the available soil moisture conditions reach stress levels (normally when the rapidly available water has been depleted), then an irrigation dose of the defined amount is applied on that day. If this is still insufficient, then multiple doses may be applied". The volume of water applied by this dose is depending on the amount of water in the root zone. The volume of stored water can be between field capacity and the wilting point. Plants do not considered to suffer stress as long at 50% of the volume of accessible water depending on the root zone is available. If the water falls below this point a dose, or multiple doses of irrigation are applied.

3.3.5 iMOD

The final step is to use the generated RCH.idf files from the recharge script in iMOD (Interactive Modelling) to visualise the data and compute water balances. iMOD is an GUI developed by Deltares based on the concept of MODFLOW. In the ESCACES project iMOD is used to develop a hydrogeological model of the study area in the Cauca Valley. In this research, the model is used to compute the steady state of groundwater extraction to develop the sustainability indicator, and iMOD as a tool to convert output files of the Recharge script into ASCII files to analyse in ArcGIS. Moreover the IDF files are statistical analysed in iMOD and it is possible to generate 3D visualisations and cross-sections of groundwater and surface water systems of the study area.

3.4 Climate Scenario Development

The initial dataset is used to create new climate change and climate variability scenarios. A total of five scenarios are developed (Table 7). The difference between the climate change and climate variability scenarios is as follows:

- The climate change scenario uses a reference period (2000-2013) where three different climate forcing are projected on.
- The climate variability scenarios are new generated sequences of weather events that occurred in the past.

Table 7

Developed climate change and climate variably scenarios

Climate Change	**Climate Variability**
2000-2013 Reference Period	2000-2013 Reference period with optimal irrigation
2011-2040 Short-term Climate Forcing	2014-2020 Dry scenario with optimal irrigation
2041-2070 Mid-term Climate Forcing	2014-2020 Realistic scenario with optimal irrigation
2071-2100 Long-term Climate Forcing	

3.4.1 Climate Change Scenario

The period 2000-2013 from the initial dataset was used to develop three climate change scenarios. The daily values of this period were recalculated by projecting climate forcing on it. The climate forcing was taken from a report published early 2015 by Colombians National Weather service IDEAM. This report gives a description on regional scale of change in temperature and precipitation for the Cauca Valley Department (IDEAM, 2015). It contains absolute and percentual values how temperature and precipitation will increase or decrease for the periods 2011-2040, 2041-2070 and 2071-2100 (short, mid and long term).

The IDEAM report uses the Representative Concentration Pathways (RCP) to estimate climate change. The RCP were published in the latest IPCC AR5 report and are greenhouse gas concentration trajectories. RCP can be seen as an updated version of the AR4 report on Special Report on Emissions Scenarios (SRES) which described the climate scenarios as A1, A2, B1, and B2. There are four RCP (RCP2.6, RCP4.5, RCP6, and RCP8.5) and are named after a possible change of radiative forcing, in the year 2100 relative to pre-industrial values (+2.6, +4.5, +6.0, and +8.5 W/m2, respectively) (Weyant et al. 2009). For this research the RCP8.5 is used to project the most extreme radiative forcing (Figure 10).

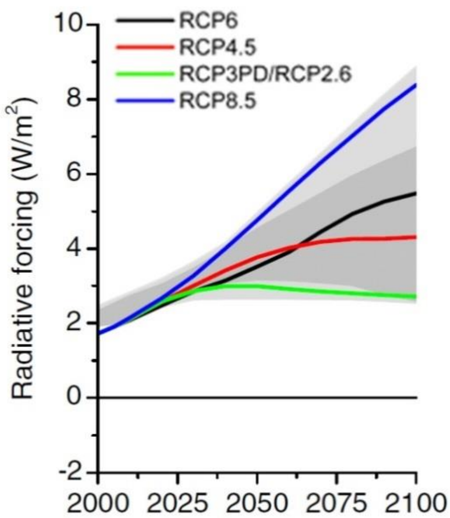


Figure 10 Representative Concentration Pathways. The blue line shows the extreme RCP8.5 scenario. Source: IPCC AR5

The results of the IDEAM report are presented in Table 8 **(chapter Results)**. These values show the change in precipitation and temperature towards the reference period 1976-2005 which was selected by IDEAM in their research. Since the period 2000-2013 is used in this thesis these values first had to be corrected before projecting on the initial data set. This is because climate change already occurred between 1976 and 2000. To correct the IDEAM values the delta change approach is used. This method is based on a change factor. This factor is the ratio between the mean value of the future and initial data set. This factor is then applied to the initial dataset to transform this series into a new dataset that is representative for the future climate (Ruiter, 2012).

$$Temperature = (X_{mean} + I) - Y_{mean}$$

And

$$Precipitation = \frac{X_{mean} + I}{Y_{mean}}$$

Where
X = 1976 2005
Y = 2000 2013
I = IDEAM values

This method was repeated for the short, mid and long-term projection for Tmaximum, Tminimum and Taverage. Precipitation shows seasonal changes divided in season 1: December, January, February (DJF), season 2: March, April, May (MAM), season 3: June, July, August (JJA) and season 4 September, October, November (SON). Therefore, the average rainfall for season 1 over the period 1976-2005 is compared to the average rainfall of season 1 2000-2013. This process is repeated for all the seasons over the three climate change scenarios.

3.4.2 Climate Variability

For climate variability two scenarios are developed starting in 2014 until 2020. The two scenarios are a realistic scenario and a dry weather scenario. The goal of the realistic scenario is to analyse the groundwater recharge with precipitation and temperature values that occurred in the past. Therefore this scenario was generated by reshuffling SPI indexes using the nearest neighbour method in order to create a new sequence for the time serie 2014-2020. The nearest neighbour method is a statistical method which is used to generate a new sequence. To do this the precipitations values were transformed into indexes by using the SPI software. The value of January 2013 was selected as a starting point. Then the nearest neighbour method identifies the 10 closest months with similar index and randomly select one of these months. The index of the randomly selected month will be used as a starting point to again select the 10 closest months (excluding the previous month) and random select one of them. In this was a synthetic sequence is created for all the years. For the nearest neighbour method, the precipitation data of weather station Alfonso Bonilla is used between 1973 and 2013. This station is used because it has enough data available to compute the SPI. Moreover, the station is situated in a flat area in the middle of the Cauca Valley and therefore it is assumed that it has less influence of the mountain ranges where it is in general wetter. The nearest neighbour method requires many calculations and, therefore, an algorithm is developed in Python to compute the scenario. To start the calculation, a starting point needs be manually selected. The script starts with the value of SPI1 January 2013 since this is the most recent year. From this month the one-dimensional Euclidean distance between all other Januaries starting from 1973 is calculated by the formula:

$$\sqrt{(x-y)^2} = |x-y|.$$

Where X is January, 2013 and Y other Januaries of the other years. After calculating the Euclidean distance for every other January, the script selects the ten lowest values. The ten lowest values indicate the ten Januaries with similar precipitation as the starting point. From these ten values, one value is randomly selected and used as a starting point for February 2014. This procedure repeats its selves until a sequence it built from 2014 to 2020.

The purpose of developing the dry scenario is to see the impact of the recharge if an extreme dry year repeats itself. The selected dry year is put in a sequence of two years right after the reference period. This means that in the simulation in 2014 and 2015 are extremely dry, the following years (2016-2020) are generated using the nearest neighbour method. The selection for the dry year was done by analysing the results of the Standardised Precipitation Index to identify a dry period, to discuss with CVC about their preferences and knowledge in which year there were problems with water shortages.

3.5 Groundwater Indicator

Indicators are a pointers or signals to show the state or the development of an object or system. With an indicator the behaviour can be directly related to changes in the state of the system (Barthel, 2011). The used indicator is developed by UNESCO's Intergovernmental scientific programme in hydrology and water resources (IHP) and is based on measurable and observable data. This indicator is developed for easy communication, especially with decision makers and, therefore, applicable in this study for communication with CVC. The indicator is calculated to compare the climate change scenarios and shows the ratio between abstraction and recharge in a percentage. According to CVC, the groundwater recharge is unsustainable if the abstraction exceeds 50% of the recharge. Abstraction and recharge are defined as following:

$$\frac{\text{Total abstraction of groundwater}}{\text{Total groundwater recharge}} \text{ x } 100$$

Where
Total abstraction is defined as all the water that leaves aquifer Unit A by groundwater pumping for agricultural, industrial or domestic purposes. The average abstraction over 2000-2009 is used and this is calculated by registrations done by CVC from water meters or taking the maximum concession for a well when data was not available. To calculate the indicator for the future scenarios the average abstraction over 2000-2009 is adjusted for the short mid and long term scenarios. To do this it is assumed that abstraction increases due to population growth according to the database of International Institute for Applied Systems Analysis (IIASA, 2015). For recharge the mean over the time serie 2000-2013 is used. This is calculated by importing the monthly RCH files of the period 2000-2013 into iMOD. In iMOD there is a tool to merge all these RCH files together into a new file which contains the average over the selected time period.

4. Results and Discussion

4.1 Climate Change

The report "Climate Change Scenarios for Precipitation and Temperature in Colombia" published by IDEAM describes for three time periods the expected climate change. The results for the Cauca Valley department are presented in Table 8. According to the report the Cauca Valley department will receive an increase in rainfall and an increase in temperature, except for the last semester of the long period which shows a reduction in precipitation. The future climate will look like as follow:

Precipitation

- The short and mid period shows an increase in precipitation for all months
- Dry season DJF becomes wetter for all the time periods
- Raining season MAM shows the biggest increase in precipitation of approximate 25%
- Raining season SON shows an increase in precipitation in the short term period, and a decrease in the long term period

The temperature will increase for all the seasons with the highest temperatures in the long term period with an increase of over 3°C.

Table 8

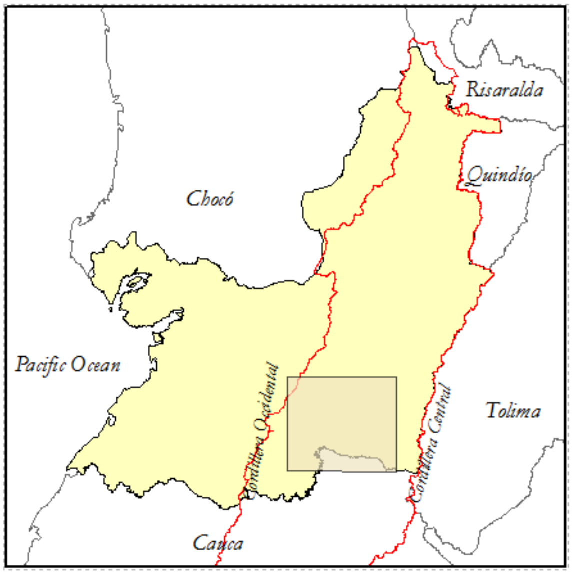
Precipitation (%) and temperature (°C) projections RCP8.5 Cauca Valley Department

	Precipitation (%)				**Temperature (°C)**		
Period	**DJF**	**MAM**	**JJA**	**SON**	**Tmax**	**Tmin**	**Tavr**
Short 2011-2040	4.9	24.2	5.4	11.7	1.1	0.8	1.1
Mid 2041-2070	5.2	25.0	1.2	0.3	2.3	2.0	2.2
Long 2071-2100	8.0	25.9	-3.7	-2.4	3.6	3.4	3.6

Note. From (IDEAM, 2015) Tables 5, 6, 7, 21, 22, 23, 37, 38, 39, 54, 55, 56
Change in precipitation and temperature according to reference period 1976-2005
The abbreviations refers to the name of the months

Scaling factors were calculated for every weather station using the delta change approach to project Table 8 on the daily precipitation and temperature values of the initial dataset (Appendix 6). In addition, the average of all scaling factors for the long scenario was calculated and applied on the initial dataset, this extra scenarios is called long average (Appendix 7). The reason for adding this scenario was because the large variation between the scaling factors. For example, the precipitation for the season SON of the weather station Silvia needs to be reduced by the factor 0.96, where the weather station Piendamo shows an increase by 1.93 for the same period. By taking the mean over all stations and apply the factors on the initial dataset the extremes have less influence. Looking at Table 8 it can be assumed that the recharge increases due to increase of precipitation. However, temperature also has an important impact on this water flux, together with other variables as explained in Figure 4. Therefore precipitation and recharge are not directly related. How these factors influence the recharge is shown in the next graphs and figures.

The recharge rates for two months are visualized in Figure 11 to see the spatial effects of recharge during a month with increase in recharge, and a month with decline in recharge. These months are selected based on their extreme values. The first period with the highest increase in recharge is April 2011, and the second period with the highest decline in recharge is June 2008.



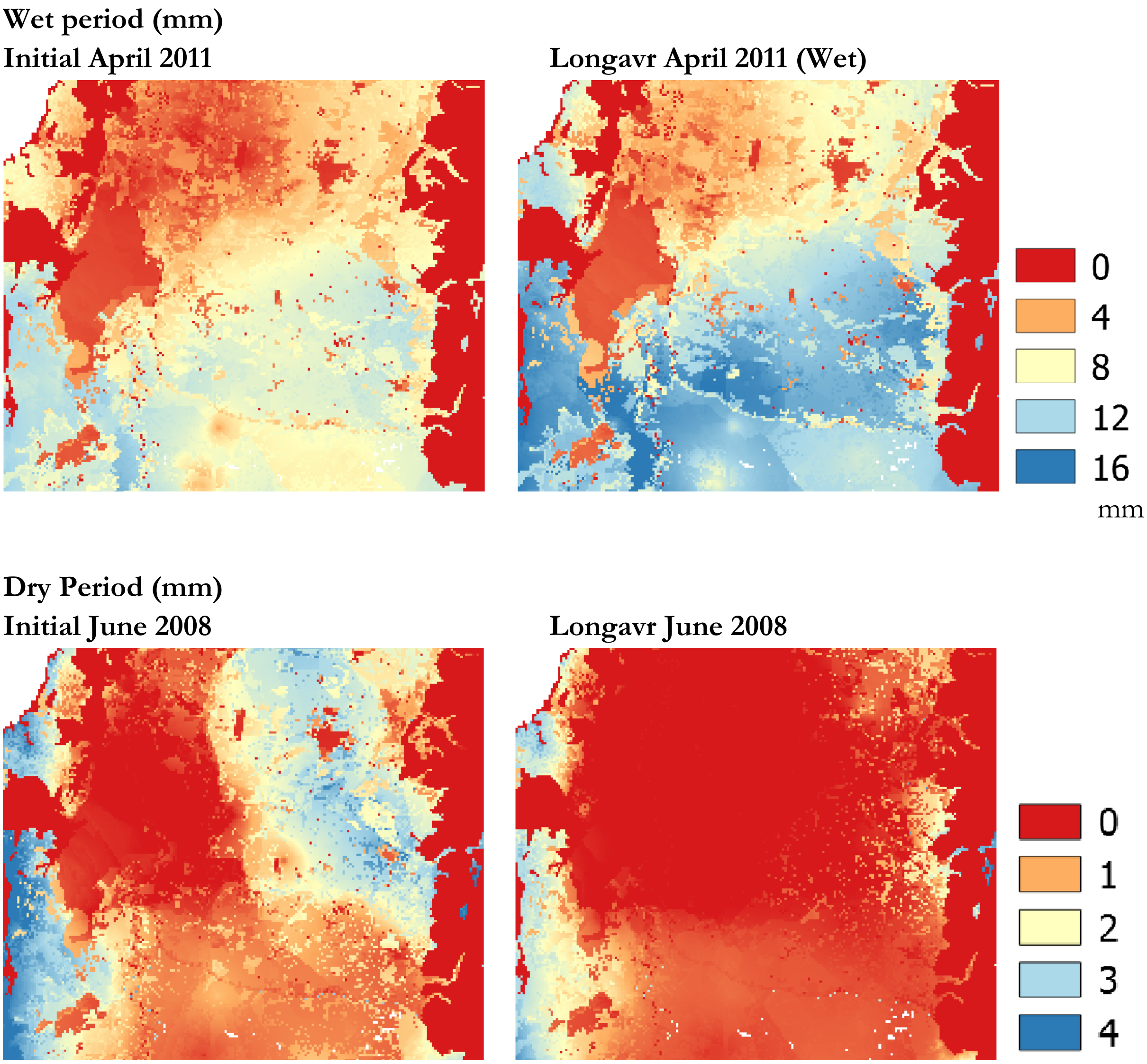


Figure 11 Spatial distribution of recharge over the study area.

The maps in Figure 11 show the result of the generated RCH.idf files and represent the recharge for one month. The generated files for every single month are plotted in Figure 12. The graph shows the recharge over the total surface of the study area at a monthly interval. This is calculated by taking the mean over all the 250 meter grid cells for a month. The graph seems to have very little difference between the initial data set and the climate change scenarios. However, the new generated long scenarios seem to have a significant increase in recharge during the wet periods MAM and SON.

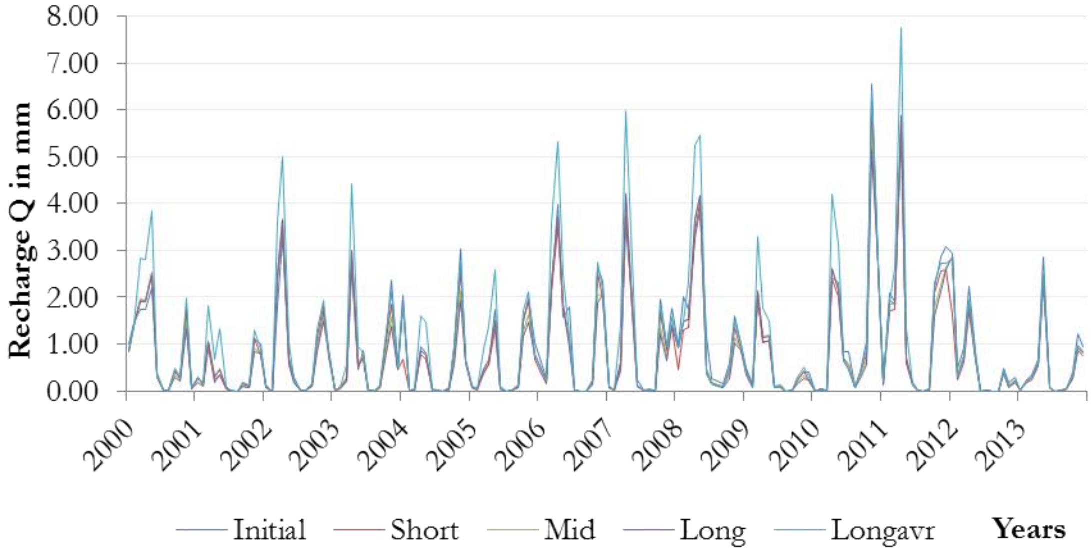


Figure 12 Average recharge over the total study area for all climate scenarios

In addition the results of the scenarios are presented in boxplots, where Figure 13 shows all the recharge values over the total period, and Figure 14 shows the recharge specified per season. The ends of the whiskers are set at 1.5*IQR above the third quartile (Q3). If the maximum values are outside this range, then they are shown as outliers. The minimum whisker is set at 0 since this indicate that no recharge occurs.

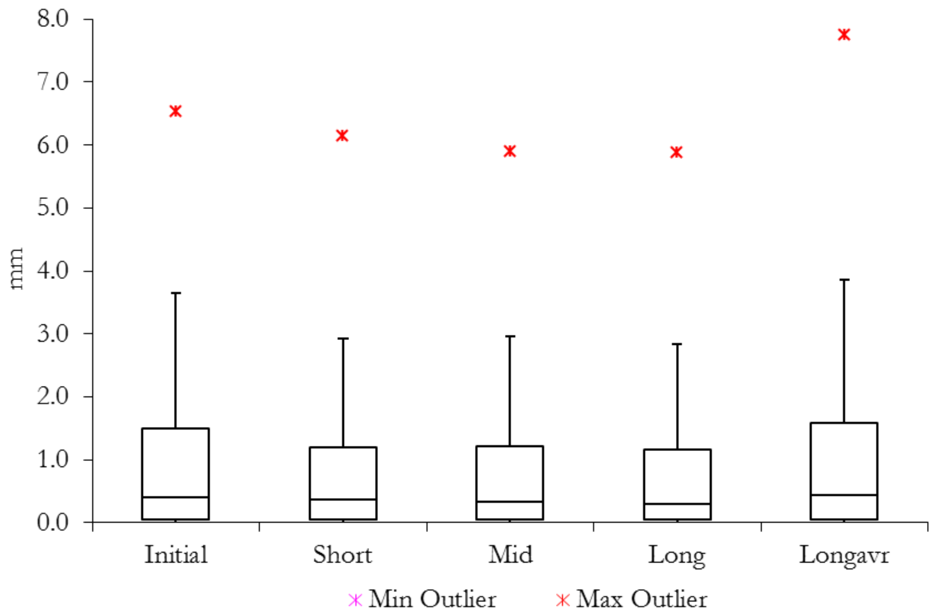


Figure 13 Recharge values in the study area calculated over the total time serie

The boxplot in Figure 13 shows that the amount of recharge for the short mid and long climate change periods are lower than the initial data set. In the third quartile the initial data set has a recharge of 1.5mm, where the three climate change scenarios, short, mid and long show a value of 1.2mm. The maximum recharge for the short, mid and long scenarios is also lower in comparison to the initial dataset with a difference ranging from 0.4mm to 0.6 mm. The long average scenario shows different results, the graph of Figure 12 and the boxplot of Figure 13 show an increase in recharge in comparison to the initial dataset.

These results are the totals over the whole time serie 2000-2013. To provide more information about the variation of the recharge the climate change scenarios are divided into seasons (Figure 14). This is done in order to see the seasonal impact on the amount of recharge in comparison to the initial dataset. The same boxplots with additional information such as outliers and values per quartile are in Appendix 8.

The first season of the rainfall calendar is the dry season DJF. This season shows a decrease in recharge for all the scenarios compared to the initial dataset. The wet season MAM shows an increase in recharge, the short, mid and long periods show little difference of 0.2 and 0.4 mm, where the long average shows the highest increase in recharge compared to the initial dataset with 2.7milimeter. The climate projections of the IDEAM report already showed a significant increase of precipitation for MAM and this also observed in the recharge of the long average scenario. The second dry season JJA shows in general a very low recharge with a maximum of 1.8 mm in the initial dataset. The climate scenarios for this season show even less recharge with a reduction of approximate 1 mm. Finally, the wet season SON shows a decrease in recharge for the mid and long scenarios where the short and long averages show similar recharge.

Looking at the extremes (Appendix 8), for the long average scenario the highest amount of recharge is observed in April 2011 with a recharge of 7.8 mm. This is an increase of 2.2 mm in comparison to the same month of the initial data set. The highest difference between the initial dataset and the longaverage period is also observed in April 2004. The highest reduction in recharge is observed in June 2008 where the recharge reduces with 0.8 mm. The rainfall during this season is in general very low under the 2.0 mm.

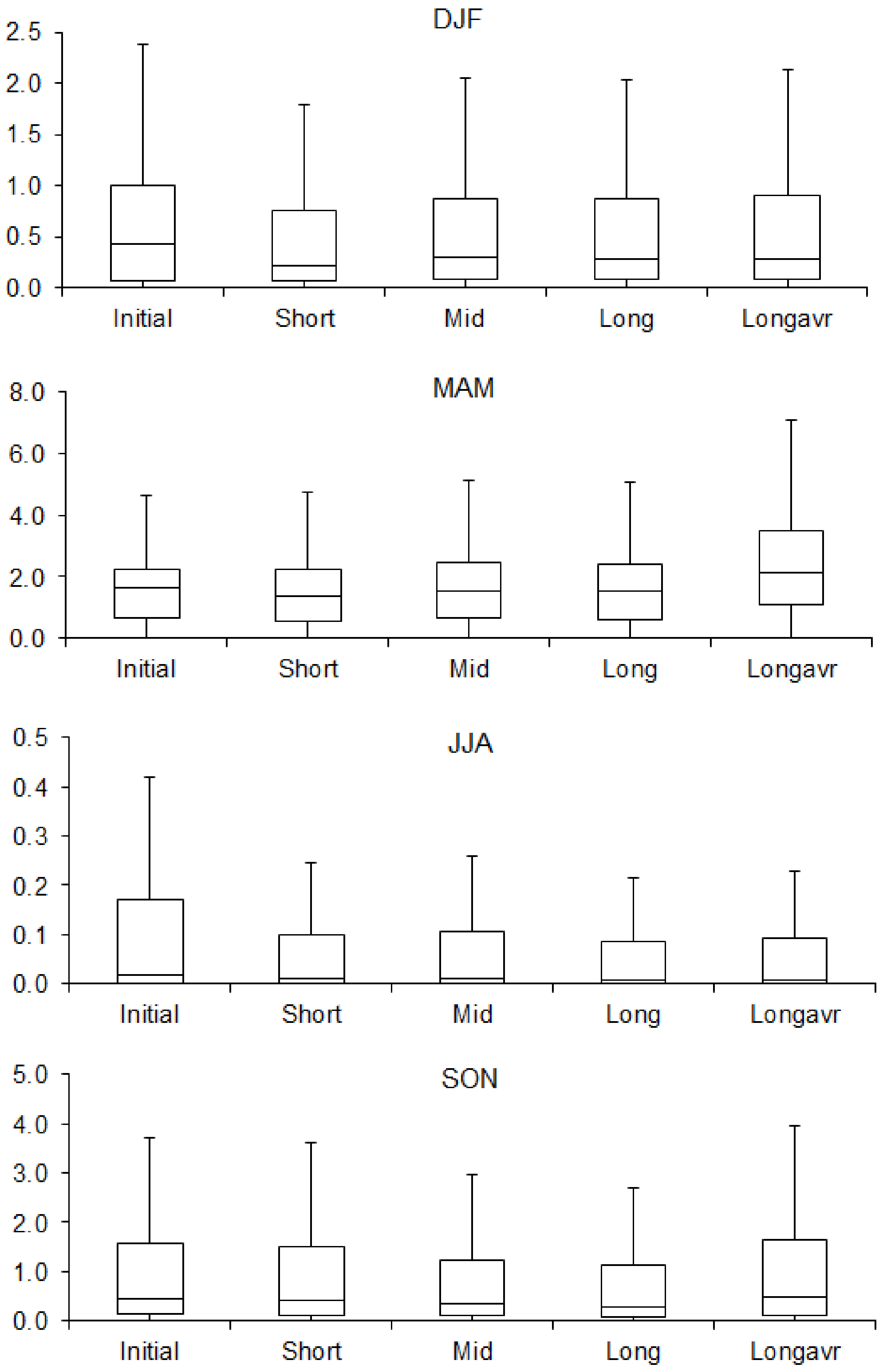


Figure 14 Recharge values in the study area calculated over the total time serie per season

4.2 Climate Variability

To analyse the impact of climate variability on groundwater recharge two scenarios were developed by generating a new sequence based on historical precipitation. The two scenarios are (1) an extreme scenario with dry weather conditions and (2) a realistic scenario. For the extreme scenario a dry year was identified as a start year to generate the scenario. This year was identified using the Standardized Precipitation Index, discussion with CVC and literature review and resulted in year 1992 for further analyses.

Figure 15 and Figure 16 show that in 1992 both stations have the lowest SPI values in the whole time serie. For Aeropuerto Bonilla 1992 reaches an SPI -3.47 for the month August and Univalle reaches -2.92 in October. The figures show that between 1990 and 1993 an excessive drought period occurred of three years where the SPI drops for the first time far below -2. This only happened two times earlier in 1977 and 1980.

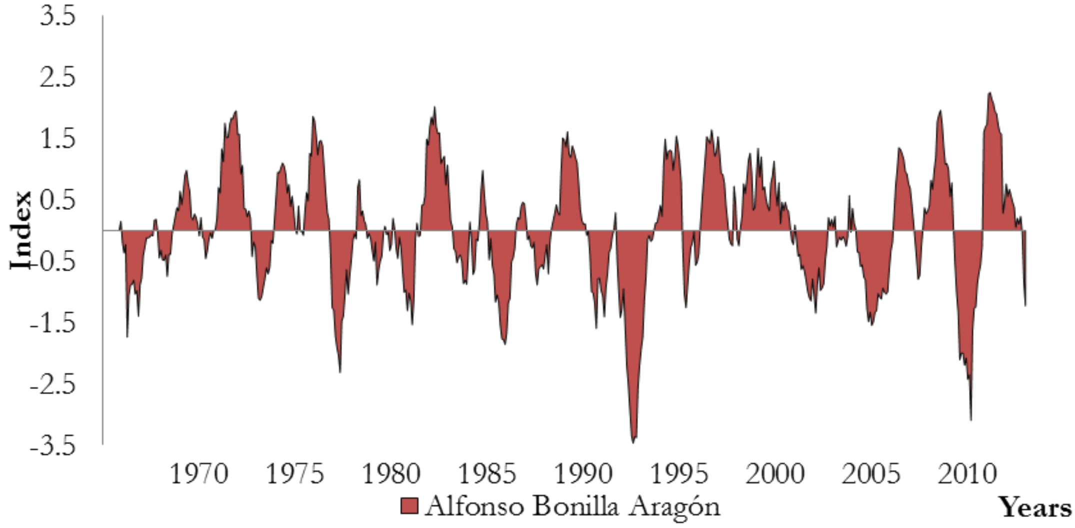


Figure 15 SPI-12 for the weather station Alfonso Bonilla Aragón, positive values indicate wet period and negative values a dry period

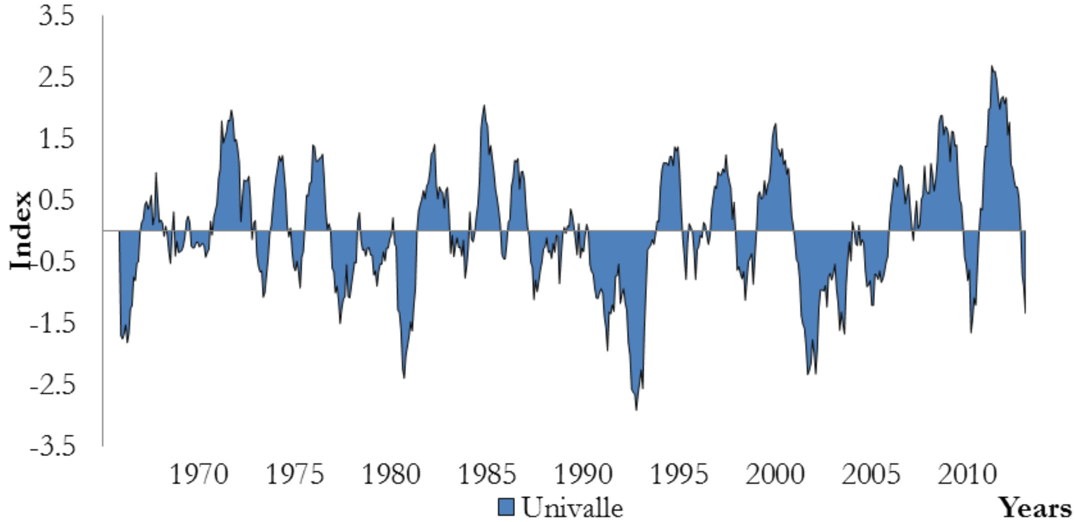


Figure 16 SPI-12 for the weather station Univalle, postive values indicate wet period and negative values a dry period

Besides the SPI index, the choice of 1992 is also based on the experience and knowledge of CVC. During conversations and discussion with experts of CVC, it became clear that they are interested to see the impact of the 1992 drought on the groundwater recharge. According to CVC, 1992 was very problematic for the agricultural sector because the farmers couldn't extract groundwater anymore because of low water levels. Moreover, currently there is not enough knowledge about the impact of 1992 on the groundwater recharge and protocols what to do if an excessive drought occurs again. Therefore CVC is interested to study the effects of 1992 on the groundwater recharge. Unfortunately, there was no data available for this period that could indicate a decline in water availability. But the demand for water is visible in Figure 17 which shows the requests for groundwater permits which CVC receives annually to construct groundwater wells. The graph shows that after the drought of 1992 the requests for permits increased. After 1993, the graph stabilises which could be related to an increase in regulation applied by CVC.

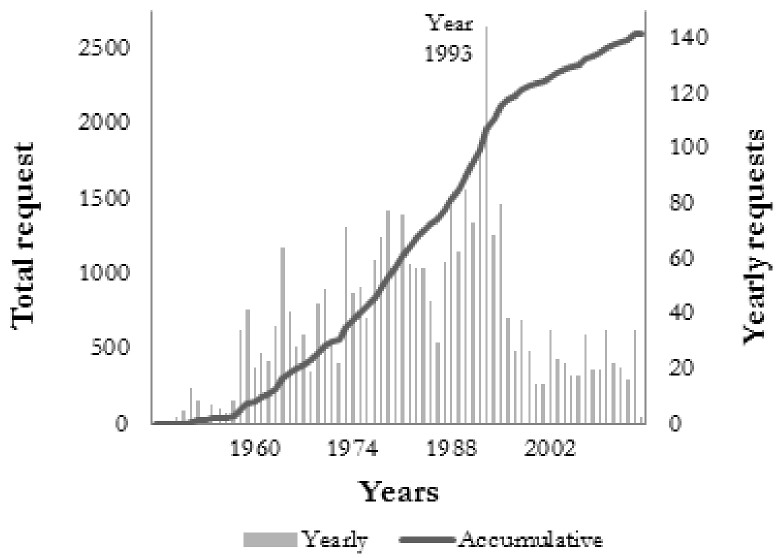


Figure 17 Amount of yearly request for groundwater drilling permits and totals for groundwater wells in the Cauca Valley. Source: CVC

Finally, in literature references were found which describe the 1992 drought as problematic. The literature described mainly socio-economic impact of the drought on several industries in the productive sectors like agriculture and energy. This resulted in less agricultural production and blackouts of electricity (Carvajal-Escobar, 2011). As a result of the SPI analyses, discussion with CVC and the literature, the period 1992 is selected to use in the extreme climate variability scenario. This year will repeat it selves for two years after the reference period and will replace 2014 and 2015 in the climate variability sequence.

Climate variability was studied in two different scenarios to analyse the groundwater recharge for the period 2014-2020 which were generated by the nearest neighbour method (Appendix 5). The two developed scenarios are presented in the graph of Figure 18.

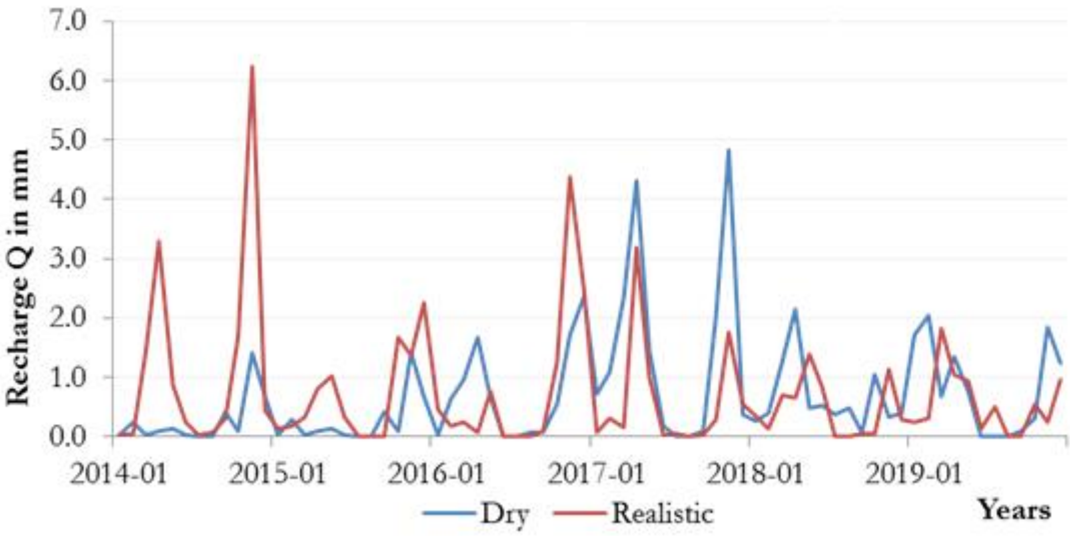


Figure 18 Recharge of the generated climate variability scenarios over the total period.

Figure 18 shows the monthly recharge in mm over the total study area between January 2014 and December 2019. The dry scenario shows a low recharge during the first two years of the time serie, which are replaced by the precipitation and temperature values of 1992. During this year there is one recharge event above 1 mm at the end of 2014. The other months of the dry years show very low recharge due to the replacement of the precipitation of 1992. Moreover, in the dry scenario the years 2014 and 2015 show exactly the same pattern because the same precipitation and temperature values of 1992 are used to replace these years.

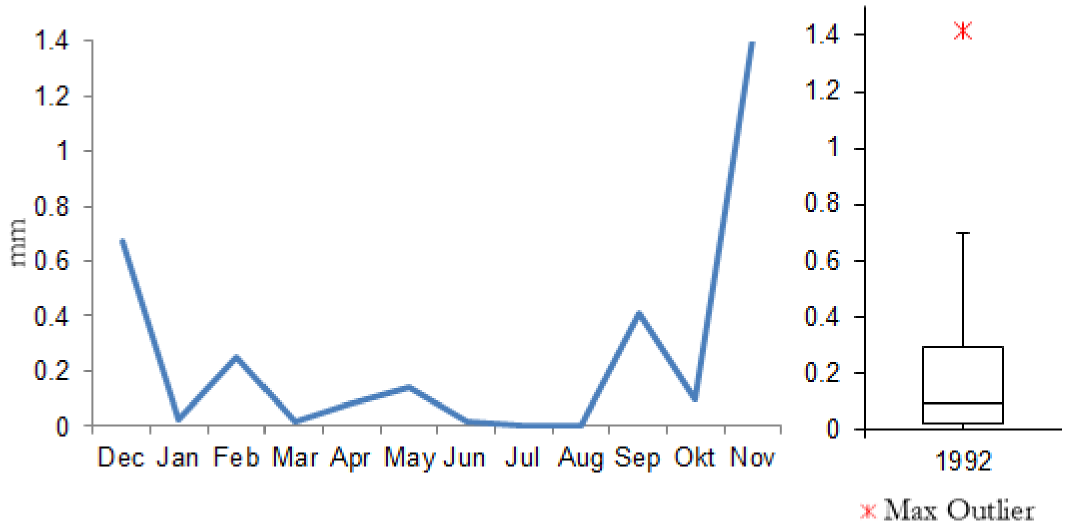


Figure 19 Recharge in millimetre over the study area for the year 1992.

4.3 Discussion on climate change scenarios

The results for the short, mid and long term climate change scenarios show a decrease in recharge. This is in contrast with the climate change projections published by IDEAM assuming that the increase in precipitation would lead to increase in recharge. The following points could give an explanation about these results.

1. Runoff and Soil Moisture

More precipitation will not automatic lead to an increase of recharge. When a grid cell receives precipitation the volume of water is divided into infiltration and runoff using the Curve Number method. If the soil moisture is already high, and an extreme wet period occurs, then this will lead to more runoff instead of infiltration. Because only vertical fluxes are studied, the runoff cannot enter a neighbouring grid cells by overland flow to infiltrate again. The reason for this approach is that due to the size, and low difference in elevation between the 250meter grid cells, it is hard to predict how much water will reach neighbouring cells. This means that runoff water is "lost" for the calculated time step. The runoff drains into the rivers and surface water where it could recharge again. This is another layer in the iMOD model but at date not calibrated yet to apply in this research.

2. Temperature

Besides an increase in precipitation the temperature is also increasing. Studies show that the correlation of groundwater recharge with precipitation is stronger than the correlation with temperature (Chen et al., 2004). However, a higher temperature can lead to an improved growth conditions and increased evapotranspiration of sugar cane (Kirshen, 2002). Since the climate scenarios show an increase in temperature the factor evapotranspiration could have greater impact on the water fluxes. And therefore less water can infiltrate beneath the root zone.

3. Spatial distribution of rainfall

The spatial distribution of rainfall according to IDEAM is shown in Appendix 9. The maps show that the biggest percentual increase in precipitation is in and close to the study area. However, the study area shows the largest sealed surface due to urbanized areas (**Error! eference source not found.**). The map of Figure 20 shows the PC raster map which is used to calculate infiltration in the Recharge script. The white area contains a fraction which lowers the infiltration, due to sealed surface. Therefore this may lead to a lower recharge for the study area.

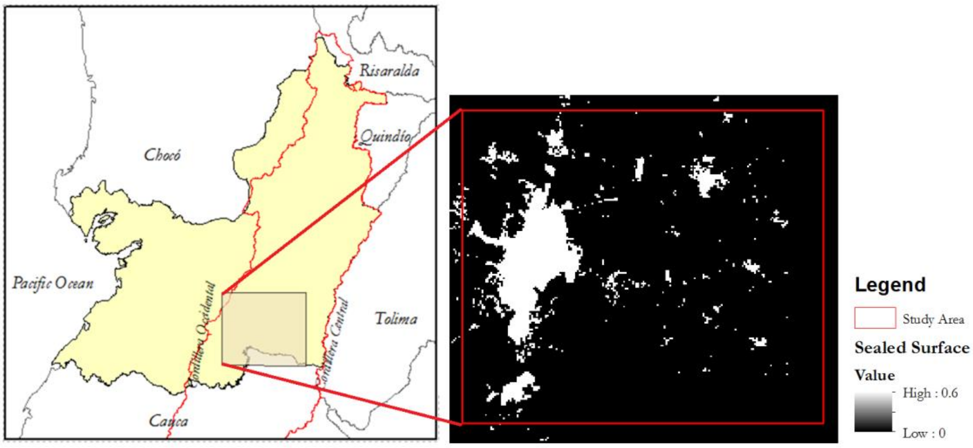


Figure 20 The white area represents sealed surface by urban area where less water can infiltrate.

4. Downscaling of IDEAM values

The values in the IDEAM report (Table 8) represent the whole Cauca Valley department and not only the study area. The values used from the IDEAM report include weather stations on the Pacific side of the Andes, where the climate is warmer and wetter. These values were projected on the period 2000-2013. Therefore the values of IDEAM were rescaled according to the difference between the average of the period 1976-2005 of the initial dataset, and the period 2000-2013 of the initial dataset. Further statistical analyses show that the time serie of the initial dataset 1976-2005 has per ratio less missing values compared to the time serie 2000-2013. The time serie 1976-2005 counts 10957 days where 7% has missing values, compared to the time serie 2000-2013 which counts 5113 days and 26% missing values. Both percentages are calculated over the total weather stations to give a quick estimation. For example, this may have resulted that for the wet seasons of period 2000-2013 less values were available to apply the climate forcing on. Therefore the data is not scaled and not visible in the results.

4.4 Discussion on climate variability

The two climate variability scenarios were developed by using the nearest neighbour script to complete the sequence from the extreme scenario, and to generate a complete new realistic scenario. During this process steps were taken which have influenced the results. The first issue is that the sequence generated 1000 scenarios, from these scenarios one time serie was selected for further analyses. But this scenarios was not compared to the other generated scenarios to see if the scenarios was statistical realistic. This was not the correct procedure. Instead, what could be done is to rerun the nearest neighbour script to generate new sequences and apply a statistical approach proposed by (Sharif and Burn, 2005). According to the paper boxplots were used for data analyses to show range variations of the simulations. This provides a straightforward method of comparing the statistics of simulations with historical data. Another approach would have been to select a low precipitation volume per month and then select one of the most severe scenarios out of the generated sequences. Second, the initial plan at the start of this research was to develop climate variability scenarios over the period 2014-2025. During the data processing phase the final five years for the realistic and the final three years for the extreme scenario showed corrupt recharge values. Running the script on different systems did not help and showed the corrupt files as well. The possible source of the error is that one of the days in the evap0000.000 or pptnn0000.000 files has a missing value which had caused the error. As a result it was decided to shorten the period from 2014-2020, which also decreases the credibility of the scenario due to few years to make reliable analyses on.

4.5 Calculation of Indicator

According to CVC the groundwater recharge is sustainable if abstraction is 50% or less than the volume of recharge. This percentage can be calculated using the indicator as explain on page 33. Table 9 shows the results of the calculated indicators for all the climate change scenarios. Both the initial and the short scenarios show a sustainable groundwater state. The other scenarios show a value of 50% or higher and can be considered as unsustainable. To calculate the results it was assumed that the abstraction will double in the long term scenario due to an increase in population. This is based on an extreme population growth scenario SSP3. This scenario is a global change scenario with slow technology development and very high population growth. Appendix 11 shows the population graph for Colombia (IIASA, 2015). However, changes in abstraction are depending on more factors than only the increase in population, like technical development, climate change, land use change, total cultivated surface and so on.

Table 9

Used factors to calculate the groundwater indicator

Scenario	Mean recharge mm	Abstraction factor	Abstraction mm	Result Indicator %
Initial	0.79	1	0.24	30
Short	0.70	1.3	0.32	46
Mid	0.72	1.6	0.40	55
Long	0.70	2	0.48	68
Longavr	0.95	2	0.48	50

Mean average: average recharge of the study area in the scenario

Abstraction factor: applied factor on abstraction due to increase in population

4.6 Adaptation Measures

The previous results show that in the study area it is expected that the recharge decreases. During extreme dry periods a decrease in recharge is observed, or there is no recharge at al. To be prepared for these situations adaptation measures are proposed which are in line with national policies for on Climate Adaptation developed by the Colombian Government for Environment (MED). These recommendations (Table 10) are a top down policy which needs to be implemented at the local scale and serve as a guideline for lower level authorities. These guidelines from MED are used together with proposed adaptation measures by the European Climate Adaptation Platform (EEA) to make a list of policy and technical measures which could be implemented by the water sector and the agricultural sector to adapt to climate change to increase groundwater and keep the groundwater state sustainable. The recommended adaptation measures are described by the EEA based on case studies and include behaviour change such as interventions to influence people's attitude towards water usage.

Table 10

Drought adaptation measures for the Water and Agricultural sector

Measure	Contribution To Groundwater Recharge
Improved water retention in urban and agricultural areas	Divert urban storm water and irrigation runoff that does not infiltrate to retention areas, including use of detention ponds and infiltration systems to increase recharge.
Rehabilitation and restoration of rivers	The development of floodplains and wetlands helps to retain and slowly release water discharge from water bodies facilitating groundwater recharge. River regulation to maintain flows over recharge beds for alluvial aquifers.
Drought and water conservation plans	Changing water users attitude and to promote efficient water use and reduction of water consumption. High water requirements required to purchase entitlement to intercept groundwater recharge or surface flow .
Establishment of early warning systems and modelling	By implementing forecasting systems such as weather forecasting, storms or dry weather can be better predicted. These predictions can be used for example for more efficient irrigation schemes.

Note. Adaptation measures based on National Plan Adaptation to Climate Change (PNACCO) and EEA Adaptation Support Tool

5. Summary, Conclusions, and Recommendations

The study was set out to analyse the effects of climate change and variability on groundwater recharge in the Cauca Valley in Colombia. This by agriculture characterized area is exposed to an increasing pressure on the water resources. This is because the most cultivated crop in the region is sugar cane which has a high demand for water whole year round, and the pressure of expanding urban areas and population. The region has approximate 4 million inhabitants and the sugar cane industry has the highest production of sugar in the country. Therefore water availability is important for the urban development and maintaining the economy. The area is characterized by a bimodal rainfall regime which has two dry and two wet seasons. During the wet seasons the farmers rely on surface water which they divert from rivers and its tributaries, but during the dry seasons when the water table declines they need to switch to groundwater abstraction for irrigation. As a result of climate change it is expected that precipitation and temperature during the seasons will change and thus will change the water supply. How climate change and variability will impact the groundwater recharge and what kind of adaptation measure could be implemented to mitigate the change were researched in this thesis. This has been done by collecting precipitation and temperature data and processing the data by several software tools to compute recharge values for the study area. Climate scenarios were developed to make a projection for the future using the latest Representative Concentration Pathways 8.5 climate scenarios as published in the IPCC Fifth Assessment Report. The scenarios were divided into a short, middle and long term time serie (2011-2040, 2041-2070, 2071-2100) to answer the following questions.

"What is the impact of climate variability on groundwater recharge in Cauca Valley, how is that affected by climate change, and how can adaptation strategies contribute to mitigating that change?"

a) What is the future climate projection for the Cauca Valley and how does this affect the groundwater recharge in the study area?
b) What is the impact of extreme dry years on the groundwater recharge in the study area?
c) Which indicators can be used to measure the sustainability of the groundwater recharge?
d) Which adaptation strategies can be adopted by the public and private sector to improve the state of the groundwater?

Conclusions

A) The future climate projection for the Cauca Valley are divided into three scenarios; a short, mid, and long term period for the years 2011-2040, 2041-2070 and 2071-2100. For these periods it is expected that the climate will change with an increase in precipitation, and increase in temperature. The main finding how this change in climate affect the groundwater recharge in the study area, is that the groundwater recharge decreases for all the time series. The recharge of the total study area for the reference period is approximate 0.9 mm and declines for the generated scenarios with approximate 10%. However there is variation in recharge among the seasons. During the wet seasons March April May there is an increase in recharge in comparison to the initial data set, while the other seasons show a decline in recharge.

B) To analyse the impact of dry years on the groundwater recharge in the study are, the year 1992 was identified as an extreme year with low precipitation and the biggest socio-economic impact in the Cauca Valley. The precipitation and temperature values were used to calculate the recharge. In conclusion the impact of extreme dry years will lead to a decline in recharge.

C) During these dry months the agricultural sector relies on groundwater abstraction for irrigation. To measure the state of the groundwater the abstraction indicator can be used.

$$\frac{\text{Total abstraction of groundwater}}{\text{Total groundwater recharge}} \text{ x } 100$$

This indicator shows the relationship between abstraction and recharge expressed in a percentage. This can help to communicate to policymaker about the problems of groundwater.

D) On national level the Colombian government has developed guidelines of adaptation strategies that can be implemented in order to mitigate the extreme weather conditions. These guidelines can be used on different scales and implemented by public and private sectors. Possible strategies to implement in the study area are improvement of water retention areas in and around urban and agricultural area. The excess of runoff could be diverted to areas where it can infiltrate to the groundwater. A similar strategy is rehabilitation and restoration of rivers where floodplains and wetlands helps to recharge the aquifer. The sugar can sector has high demand for water. Therefore water conservation strategies can help for more efficient irrigation and water consumption. This results in less abstraction and improved state of the groundwater. The idea behind these strategies is that by implementing them the groundwater availability will sustain and enough water will be available when an extreme dry year will occur.

In conclusion, the methods used in this study are mainly approaches based on calculations and deserve careful attention in relation to the uncertainty which these bring along. In particular the long-term prediction of complex climate and groundwater systems can bring a high level of uncertainty. Global climate models and the emission scenarios underlying global climatic change predictions are still highly uncertain, as evidenced by the huge differences in the assumptions and results presented in IPCC reports. When viewed in the context of a global model, regional catchments cover only a few model cells. Disaggregation of global model results to describe regional conditions is a highly challenging and uncertain task, particularly in mountainous regions like the Cauca Valley.

Recommendations

Taking these aspects into account, recommendations for further research will be as follow:

Recommendations to improve this research:

- In this research only areal recharge was studied. It can be improved by adding recharge by surface water since rivers and streams contribute to the recharge. However, this will also increase the complexity.
- The generated climate sequences for climate variability scenario are generated using the nearest neighbour method. How this method is applied in this research can be improved by more focus on statistical analyses of the results of the generated sequence.
- Increasing the length of the time serie for climate variability will give more reliable statistical results.
- Abstraction is calculated using a steady state over 2000-2009
- Besides the current climate change scenarios, also develop extra scenarios where only the change in precipitation is projected. This in order to study the influence of temperature on the recharge.
- The indicator was calculated using the abstraction which was computed by the steady state over the period 2000-2009. Therefore the research can be improved by using a transient to have more fluctuations among the months. This is more realistic because during the seasons the water demand for irrigation changes.

Recommendations for further research

- Currently only vertical moment of water if studied, by also including horizontal moment the system would be represented more realistic. However the complexity of the models would increase as well.
- The implementation of adaptation measures is a top down approach as developed in the Conceptual Framework of the Ministry of the Environment. Research how the local sugar cane sector would implement these measures and how they perceive them would make it easier for authorities such as CVC to develop legislation.
- For further research it would be interesting to see where a similar research can be conducted. In which other regions can this research be implemented, what are the boundary conditions for stakeholders to participate, and which data is available to conduct the research.
- Other scenarios can be generated by changing variables such as crop type. These variables are relatively easy to adjust and give new insights how the groundwater situation looks like if, for example other crop types are cultivated.

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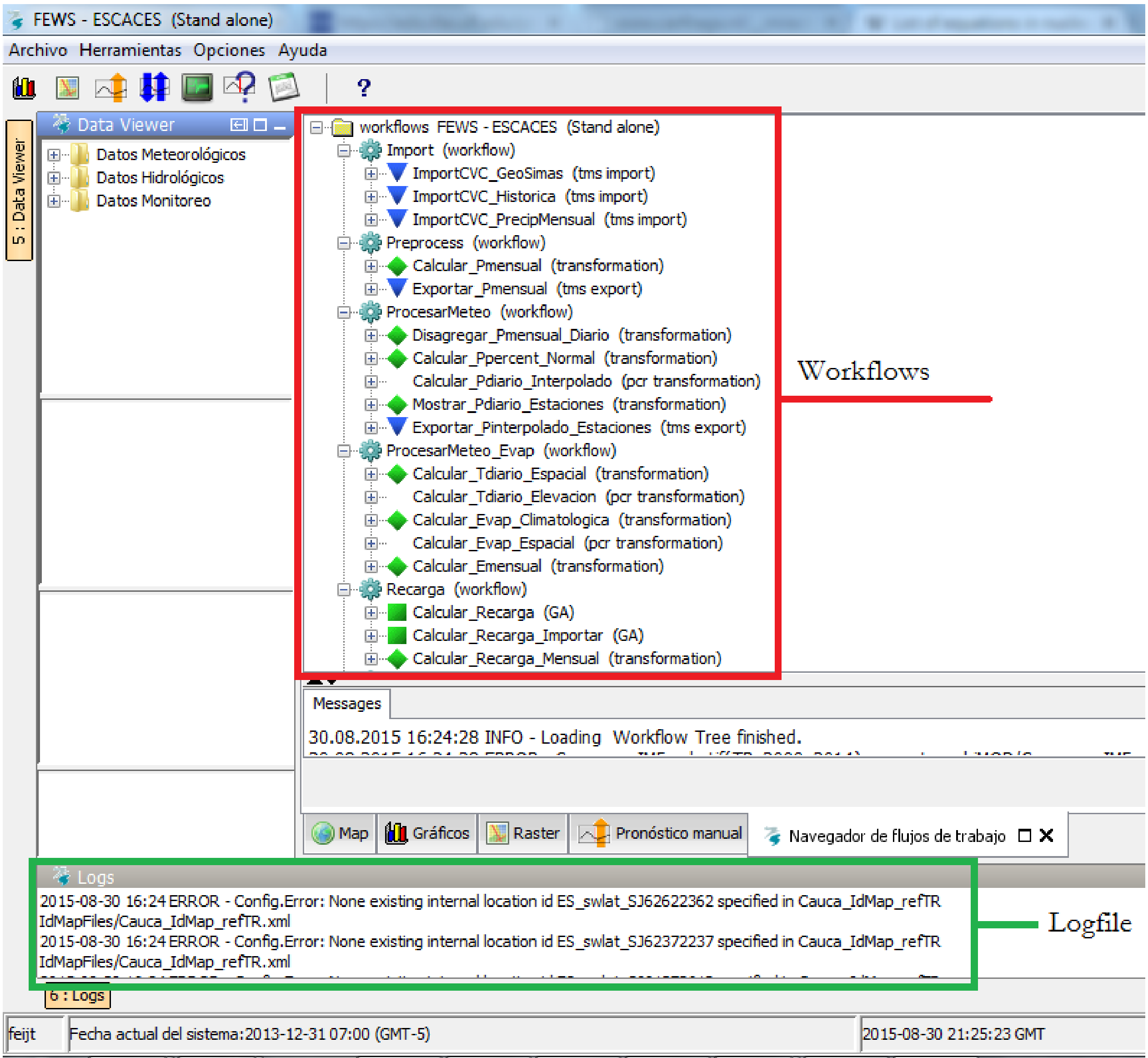
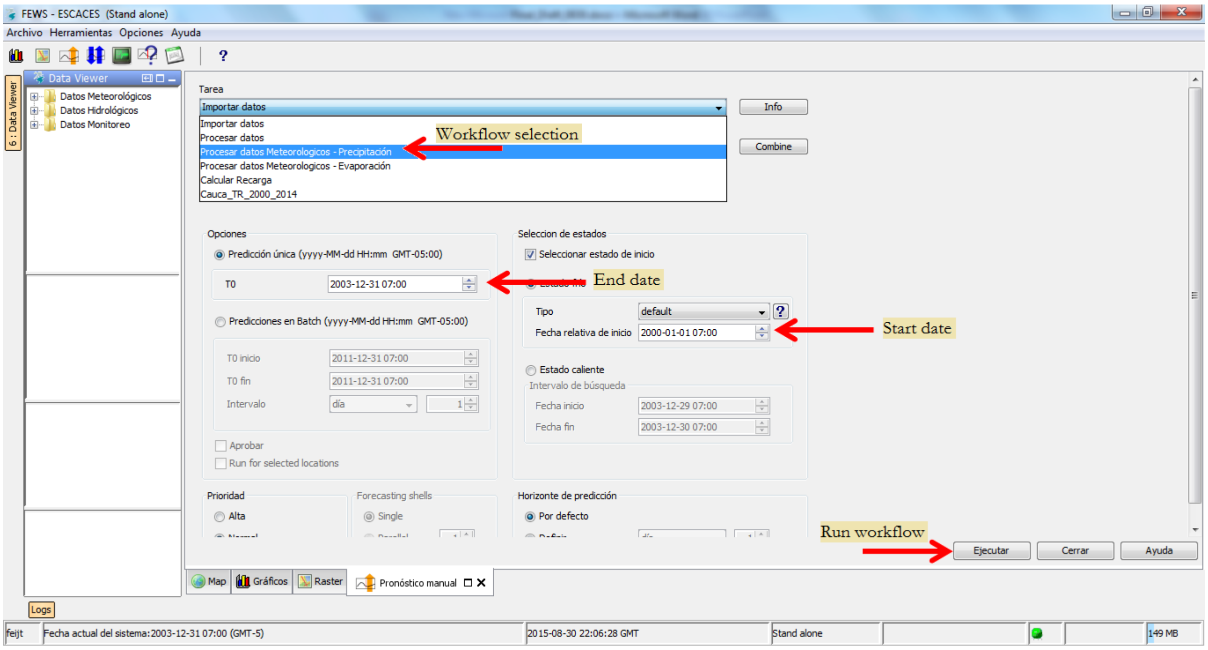
7. Appendix

Appendix 1



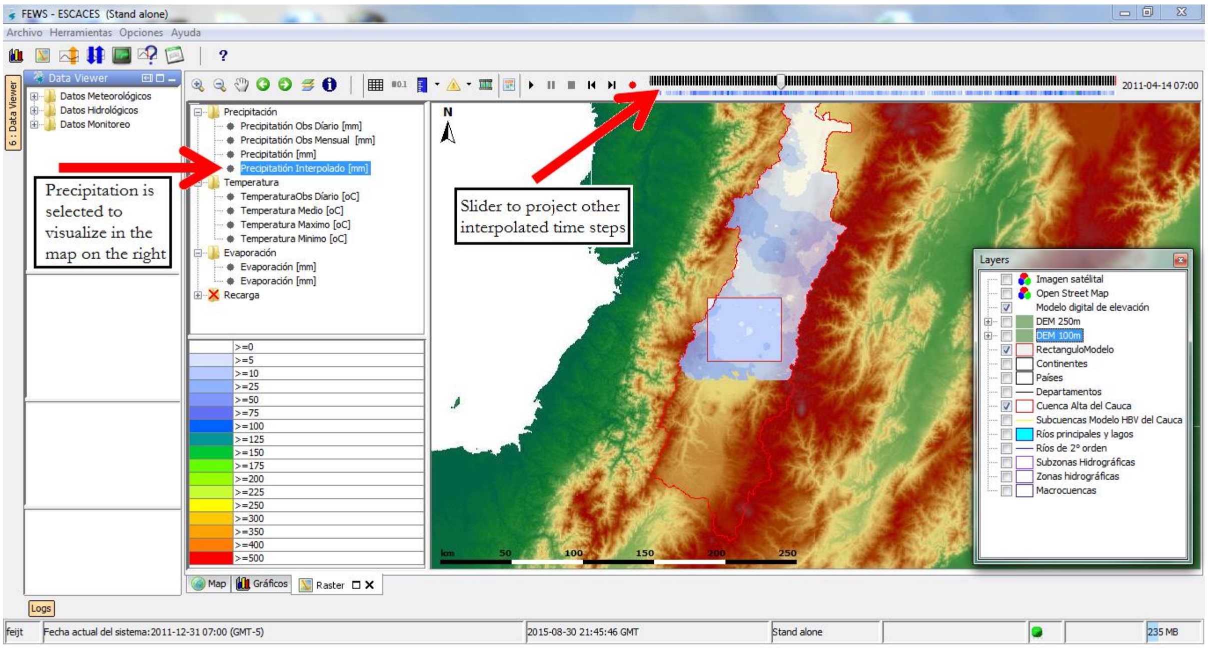
The initial climate data is processed in Delft-FEWS taking five different steps which are designated as “workflows”. This stand-alone version is part of the ESCACES project and therefore written in Spanish.

Appendix 2



Workflows are manually selected in the dropdown menu. The workflow can be run after the time serie is entered.

Appendix 3



Visualization of an interpolated time serie

Appendix 4


```xml
<?xml version="1.0" encoding="UTF-8"?>

<Run xmlns:xsi="http://www.w3.org/2001/XMLSchema-instance" xmlns="http://www.wldelft.nl/fews/PI"
xsi:schemaLocation="http://www.wldelft.nl/fews/PI http://fews.wldelft.nl/schemas/version1.0/pi-
schemas/pi_run.xsd" version="1.8">

	<logLevel>info</logLevel>

	<timeZone>0.0</timeZone>

	<startDateTime date="2012-01-01" time="12:00:00"/>

		<endDateTime date="2013-12-31" time="12:00:00"/>

	<time0 date="2012-01-01" time="12:00:00"/>

		<lastObservationDateTime date="2013-12-31" time="12:00:00"/>

	<workDir>D:\feijt\Desktop\FEWS_ESCACES\FewsESCACES\Modelos\Recarga\work</workDir>

	<inputMapStackFile>D:\feijt\Desktop\inputTimeSeries\pptn_mapstack.xml</inputMapStackFile>

	<inputMapStackFile>D:\feijt\Desktop\inputTimeSeries\evap_mapstack.xml</inputMapStackFile>

	<outputDiagnosticFile>D:\feijt\Desktop\FEWS_ESCACES\FewsESCACES\Modelos\Recarga\work\
recarga_diagnostic.xml</outputDiagnosticFile>

	<outputMapStackFile>D:\feijt\Desktop\outputTimeSeries\rchrg_mapstack.xml</outputMapStackFile>

	<properties>

		<string key="outputDir" value="D:\feijt\Desktop/outputTimeSeries"/>

		<string key="inputDir" value="D:\feijt\Desktop/inputTimeSeries"/>

		<string key="staticDir"
value="D:\feijt\Desktop\FEWS_ESCACES\FewsESCACES\Modelos\Recarga/static"/>

		<string key="outputDirIDF" value="D:\feijt\Desktop/OutputIDF"/>

		<string key="IrrigationOption" value="0"/>

		<string key="IrrigationAmount" value="15"/>

		<string key="createMaps" value="0"/>

		<string key="RunoffOption" value="1"/>

	</properties>
</Run>
```

Appendix 5

Sequence Realistic Scenario

Year	2014	2015	2016	2017	2018	2019	2020
Jan	2013	1981	1978	1975	1989	1993	1996
Feb	1991	1998	1994	1976	2009	1976	1985
March	2009	2005	1988	1988	1998	2006	2007
April	1986	1973	1992	1978	2009	2000	1985
May	1991	2007	2005	1988	2000	1995	1975
June	2011	2001	1978	1978	1980	1987	1974
July	1991	1999	1993	1985	2006	2010	1999
Aug	2010	2001	1999	2003	1989	2011	1981
Sep	1991	2004	1996	1986	2003	2009	1973
Oct	2005	1975	1973	1997	1991	1989	1997
Nov	2010	1986	1988	2004	1998	2009	1996
Dec	1981	1978	1975	1989	1993	1996	1986

Note. The table shows which months from which year are taken to build the realistic scenario.

Sequence Dry Scenario

Year	2014	2015	2016	2017	2018	2019	2020
Jan	1992	1992	1996	2006	1974	2012	1995
Feb	1992	1992	1980	1986	1994	2008	1990
March	1992	1992	2008	1994	1982	2012	2006
April	1992	1992	2012	1982	1979	1990	2000
May	1992	1992	1973	1978	1997	2001	1989
June	1992	1992	1978	1976	1989	1978	1991
July	1992	1992	2004	2007	1995	2005	2001
Aug	1992	1992	2007	1998	1975	1989	1994
Sep	1992	1992	2008	2002	1981	2010	1974
Oct	1992	1992	2012	2007	1982	1997	1992
Nov	1992	1992	1982	1988	1996	2011	2001
Dec	1992	1992	2006	1974	2012	1995	1995

Note. The table shows which months from which year are taken to build the dry scenario.

Appendix 6

Factors applied to the precipitation data to project the precipitation values according to the IDEAM Climate forcing.

Code	2620000107	2610000119	2610000116	2623500101	2610000104	2610300102	2611000102	2611200101	2611400101	2611400102	2612000112	2612000110
Station	Pan d. Azu	La Balsa	Juanchito	Mediacanoa	La Victoria	La Rafael	Dinde	Silvia	Piendamo	Mondomo	Jambalo	Tacueyo
2011-2040												
DJF	0.86	0.89	1.68	1.38	1.37	0.74	0.80	1.08	2.05	0.90	1.16	1.27
MAM	1.10	1.09	1.67	1.44	1.42	0.91	1.13	1.52	2.72	1.32	1.44	1.41
JJA	0.95	0.91	1.52	1.06	1.45	1.12	0.90	1.28	2.23	0.90	1.02	1.17
SON	1.16	1.20	1.54	1.74	1.47	0.96	1.12	1.07	2.15	1.12	1.34	1.26
2041-2070												
DJF	0.86	0.90	1.69	1.39	1.38	0.74	0.80	1.08	2.06	0.90	1.16	1.27
MAM	1.10	1.10	1.68	1.45	1.43	0.92	1.13	1.53	2.74	1.33	1.45	1.42
JJA	0.91	0.88	1.46	1.02	1.39	1.08	0.86	1.22	2.14	0.87	0.98	1.12
SON	1.05	1.08	1.38	1.56	1.32	0.86	1.00	0.96	1.93	1.01	1.20	1.13
2071-2100												
DJF	0.89	0.92	1.73	1.42	1.41	0.76	0.82	1.11	2.11	0.93	1.19	1.30
MAM	1.11	1.11	1.70	1.46	1.44	0.92	1.14	1.54	2.76	1.34	1.46	1.43
JJA	0.87	0.83	1.39	0.97	1.33	1.03	0.82	1.17	2.04	0.82	0.93	1.07
SON	1.02	1.05	1.35	1.52	1.29	0.84	0.98	0.94	1.88	0.98	1.17	1.10

Code	2612000113	2612000114	2612000111	2612000107	2610000111	2612200105	2612200103	2612710104	2612710105	2612710103	2612720103	2612710101
Station	Bocatoma	P. Tejada	Corinto	El Trapiche	Villarrica	Cajones	Los Alpes	Los Andes	La Soledad	I La Quinta	Bolo Blanco	Florida
2011-2040												
DJF	1.11	1.30	1.11	1.09	1.00	1.09	0.98	N/A	1.08	0.86	0.95	0.91
MAM	1.56	1.69	1.30	1.25	1.23	1.34	1.13	N/A	1.30	1.17	0.91	1.10
JJA	0.99	1.34	0.82	1.34	1.13	1.45	0.79	N/A	0.84	1.02	0.76	0.84
SON	1.27	1.14	1.28	1.12	1.25	1.18	0.95	N/A	1.02	1.34	0.88	1.08
2041-2070												
DJF	1.11	1.30	1.12	1.10	1.00	1.10	0.99	N/A	1.08	0.86	0.95	0.92
MAM	1.57	1.70	1.31	1.26	1.24	1.35	1.14	N/A	1.31	1.18	0.91	1.11
JJA	0.95	1.29	0.79	1.28	1.08	1.39	0.76	N/A	0.81	0.98	0.73	0.81
SON	1.14	1.02	1.15	1.01	1.12	1.06	0.86	N/A	0.91	1.20	0.79	0.97
2071-2100												
DJF	1.14	1.34	1.15	1.13	1.03	1.13	1.01	N/A	1.11	0.89	0.97	0.94
MAM	1.58	1.72	1.32	1.26	1.25	1.36	1.14	N/A	1.32	1.19	0.92	1.12
JJA	0.90	1.23	0.75	1.22	1.03	1.32	0.72	N/A	0.77	0.94	0.69	0.77
SON	1.11	1.00	1.12	0.98	1.09	1.03	0.83	N/A	0.89	1.17	0.77	0.94

Code	2612710301	2612700201	2612810118	2612700202	2612810112	2612800106	2612810102	2612810201	2612800202	2613000103	2613000102	2613100103
Station	La Diana	I Manuelita	Caseteja	Granja Exp	Austria	La Ceja	Santa Teresa	S Emigdio	Tenerife	El Castillo	El Paraiso	La Selva
2011-2040												
DJF	1.02	0.89	0.76	0.70	1.02	0.98	0.92	0.92	0.93	0.94	0.91	0.88
MAM	1.34	1.20	1.55	1.34	1.49	1.12	1.55	1.37	1.22	1.35	1.04	1.28
JJA	0.95	0.87	1.69	0.85	1.09	0.79	1.18	0.94	0.92	0.85	0.91	0.95
SON	1.05	1.29	1.49	0.84	1.30	1.09	1.16	1.20	1.13	1.11	1.02	1.09
2041-2070												
DJF	1.02	0.89	0.76	0.70	1.02	0.99	0.93	0.92	0.93	0.95	0.92	0.89
MAM	1.35	1.21	1.56	1.35	1.50	1.13	1.56	1.38	1.23	1.36	1.05	1.29
JJA	0.92	0.83	1.63	0.81	1.05	0.76	1.14	0.90	0.88	0.81	0.87	0.91
SON	0.95	1.16	1.33	0.75	1.17	0.98	1.04	1.08	1.01	1.00	0.92	0.98
2071-2100												
DJF	1.05	0.91	0.78	0.72	1.05	1.01	0.95	0.95	0.95	0.97	0.94	0.91
MAM	1.36	1.22	1.57	1.36	1.51	1.14	1.57	1.39	1.24	1.37	1.06	1.30
JJA	0.87	0.79	1.55	0.77	1.00	0.73	1.08	0.86	0.84	0.77	0.83	0.87
SON	0.92	1.13	1.30	0.73	1.14	0.96	1.01	1.05	0.99	0.97	0.90	0.95

Code	2613100106	2613100107	2613100104	2613200101	2613600104	2613600102	2613600103	2613600101	2613600301	2613800101	2614100103	2614100202
Station	Las Juntas	Costa Rica	Guacari	Ing Pichichi	El Janeiro	El Diluvio	Primavera	Dosquebradas	Magdalena	Angosturas	La Gitana	Tulua
2011-2040												
DJF	1.13	0.83	1.23	1.10	N/A	1.05	1.03	0.77	0.88	1.04	0.71	0.88
MAM	1.50	1.10	1.39	1.58	N/A	1.17	1.25	1.03	1.08	1.32	0.67	1.13
JJA	1.08	0.81	1.28	1.21	N/A	0.94	1.03	0.76	0.86	0.96	0.61	0.88
SON	1.42	1.03	1.34	1.27	N/A	1.05	1.32	0.96	0.99	1.11	0.65	1.12
2041-2070												
DJF	1.13	0.84	1.23	1.10	N/A	1.06	1.03	0.77	0.88	1.05	0.71	0.89
MAM	1.51	1.11	1.40	1.59	N/A	1.18	1.26	1.04	1.09	1.33	0.68	1.13
JJA	1.04	0.78	1.22	1.16	N/A	0.90	0.99	0.73	0.82	0.92	0.59	0.85
SON	1.27	0.93	1.21	1.14	N/A	0.94	1.18	0.86	0.88	1.00	0.58	1.01
2071-2100												
DJF	1.16	0.86	1.27	1.13	N/A	1.09	1.06	0.79	0.90	1.08	0.73	0.91
MAM	1.52	1.11	1.41	1.60	N/A	1.19	1.27	1.04	1.10	1.33	0.68	1.14
JJA	0.99	0.74	1.17	1.10	N/A	0.85	0.94	0.70	0.78	0.88	0.56	0.80
SON	1.24	0.90	1.17	1.11	N/A	0.92	1.15	0.84	0.86	0.97	0.56	0.98

Code	2614100102	2614100203	2614200101	2614400103	2614400105	2614400104	2614400102	2614400201	2614500104	2614500102	2614500201	2614900201
Station	El Placer	Monteloro	Venus	Puerto Frazadas	Pardo	Irlanda	Bugalagrande	Barragan	Galicia	El Alcazar	Hda San Marcos	Miravalles
2011-2040												
DJF	1.00	0.96	0.91	1.31	1.08	1.04	0.99	0.90	0.99	0.89	0.89	0.95
MAM	1.26	1.31	1.30	1.53	1.17	1.16	1.18	1.27	1.26	1.40	1.18	1.16
JJA	0.98	1.01	0.85	1.21	1.20	0.95	0.88	0.65	0.93	0.94	1.05	0.89
SON	1.13	1.18	1.01	1.37	1.11	1.07	1.07	0.96	1.11	0.95	1.16	1.09
2041-2070												
DJF	1.01	0.96	0.92	1.31	1.09	1.04	0.99	0.91	0.99	0.89	0.89	0.95
MAM	1.27	1.31	1.31	1.54	1.18	1.16	1.19	1.28	1.27	1.41	1.19	1.17
JJA	0.94	0.97	0.81	1.16	1.15	0.91	0.85	0.62	0.89	0.90	1.01	0.85
SON	1.02	1.06	0.91	1.23	0.99	0.96	0.96	0.86	1.00	0.85	1.04	0.98
2071-2100												
DJF	1.03	0.98	0.94	1.35	1.11	1.07	1.02	0.93	1.02	0.91	0.92	0.98
MAM	1.28	1.32	1.32	1.55	1.19	1.17	1.20	1.29	1.28	1.42	1.20	1.18
JJA	0.89	0.92	0.77	1.11	1.09	0.87	0.81	0.59	0.85	0.85	0.96	0.81
SON	0.99	1.03	0.88	1.19	0.97	0.93	0.93	0.84	0.97	0.83	1.02	0.95

Code	2615400202	2615400104	2615400110	2615400106	2615400105	2615400111	2610000202	2615400112	2620000203	2620000101	2620500201	2620610102
Station	Cumbarco	La Camelia	El Alambrado	Corozal	Alcala	Pied. D Moler	Zaragoza	Heraclio Uribe	Paletara	Coconuco	A Machangara	El Tambo
2011-2040												
DJF	0.94	1.04	1.30	1.21	1.10	0.88	0.79	0.90	0.92	1.16	0.98	1.12
MAM	1.14	1.19	1.24	1.15	1.42	1.12	1.12	1.16	1.41	1.29	1.54	1.53
JJA	0.86	1.19	1.02	1.04	1.15	0.94	0.87	0.96	0.98	0.88	1.13	0.86
SON	1.06	1.13	1.37	1.29	1.13	0.97	1.05	1.15	1.42	1.18	1.24	1.10
2041-2070												
DJF	0.94	1.04	1.30	1.21	1.10	0.89	0.79	0.91	0.92	1.16	0.99	1.13
MAM	1.15	1.19	1.25	1.15	1.43	1.13	1.13	1.17	1.42	1.30	1.55	1.54
JJA	0.83	1.14	0.98	1.00	1.10	0.90	0.84	0.92	0.94	0.84	1.08	0.83
SON	0.95	1.01	1.23	1.15	1.01	0.87	0.94	1.03	1.28	1.06	1.12	0.99
2071-2100												
DJF	0.97	1.07	1.33	1.24	1.13	0.91	0.81	0.93	0.95	1.20	1.01	1.16
MAM	1.16	1.20	1.26	1.16	1.44	1.13	1.14	1.18	1.43	1.31	1.56	1.55
JJA	0.79	1.09	0.94	0.95	1.05	0.86	0.80	0.88	0.89	0.80	1.03	0.79
SON	0.92	0.98	1.20	1.12	0.98	0.85	0.92	1.01	1.24	1.03	1.09	0.96

Code	2621500301	2621500101	2622100301	2622100104	2622100102	2622110101	2622110201	2622330106	2622330102	2622330105	2622320101	2622320201
Station	Samarkanda	Villacolombia	San Antonio	Pena Mona	El Palacio	La Argentina	El Topacio	Las Brisas	Canaveralejo	Los Cristales	La Fonda	Univalle
2011-2040												
DJF	0.95	0.98	0.99	1.00	1.01	0.83	0.93	0.96	0.81	0.91	0.95	0.90
MAM	1.19	1.21	1.25	1.31	1.29	1.05	1.16	1.21	1.07	1.30	1.36	1.16
JJA	1.03	0.97	0.99	1.00	0.92	0.86	1.04	0.83	0.76	0.81	1.05	0.84
SON	1.19	1.16	1.22	1.37	1.22	1.08	1.20	1.25	1.00	1.18	1.34	1.18
2041-2070												
DJF	0.96	0.98	0.99	1.00	1.01	0.83	0.94	0.96	0.81	0.91	0.95	0.90
MAM	1.20	1.22	1.26	1.32	1.30	1.06	1.17	1.22	1.07	1.31	1.37	1.17
JJA	0.99	0.93	0.95	0.96	0.88	0.82	1.00	0.79	0.73	0.78	1.00	0.80
SON	1.07	1.04	1.10	1.23	1.09	0.97	1.08	1.12	0.90	1.06	1.20	1.06
2071-2100												
DJF	0.98	1.01	1.02	1.03	1.04	0.85	0.96	0.98	0.83	0.94	0.98	0.92
MAM	1.21	1.23	1.27	1.33	1.31	1.07	1.17	1.23	1.08	1.32	1.38	1.18
JJA	0.94	0.88	0.91	0.91	0.84	0.78	0.95	0.76	0.70	0.74	0.96	0.76
SON	1.04	1.01	1.07	1.20	1.06	0.94	1.05	1.09	0.87	1.03	1.17	1.03

Code	2622400103	2622400104	2622420102	2622400201	2622500101	2622500102	2622600101	2622600201	2622900101	2622900102	2622900301	2623300101
Station	Planta Rio Cali	Brasilia	San Pablo	La Teresita	Dapa	Lloredas	Santa Ines	La Buitrera	Villa Maria	Ocache	Vijes	Buenos Aires
2011-2040												
DJF	0.82	0.99	0.91	1.04	1.03	1.08	1.37	0.92	1.03	1.18	1.02	0.98
MAM	1.14	1.14	1.25	1.24	1.27	1.60	1.62	1.19	1.33	1.40	1.47	1.12
JJA	0.79	0.94	1.05	1.04	0.94	1.25	1.30	0.89	1.20	1.28	1.05	1.03
SON	1.14	1.11	1.18	1.30	1.14	1.51	1.77	1.08	1.31	1.36	1.28	1.01
2041-2070												
DJF	0.82	0.99	0.91	1.05	1.03	1.09	1.38	0.93	1.04	1.18	1.02	0.98
MAM	1.15	1.15	1.26	1.24	1.28	1.62	1.63	1.20	1.34	1.41	1.48	1.13
JJA	0.76	0.90	1.01	1.00	0.91	1.20	1.24	0.86	1.15	1.23	1.01	0.99
SON	1.03	1.00	1.06	1.17	1.02	1.36	1.59	0.97	1.17	1.22	1.15	0.91
2071-2100												
DJF	0.84	1.02	0.94	1.07	1.06	1.12	1.41	0.95	1.06	1.21	1.05	1.01
MAM	1.16	1.15	1.27	1.25	1.29	1.63	1.64	1.21	1.34	1.42	1.49	1.14
JJA	0.73	0.86	0.96	0.95	0.86	1.14	1.18	0.82	1.09	1.17	0.96	0.94
SON	1.00	0.97	1.03	1.14	0.99	1.32	1.55	0.94	1.14	1.19	1.12	0.89

Factors applied to the precipitation data to project the precipitation values according to the IDEAM Climate forcing.

Code	2620000202	2623500101	2624000101	2624600103	2624600102	2624700114	2624700112	2624700108	2624700103	2624700202	2624700301	2610000105
Station	Garzonero	El Caney	Venecia	La Herradura	El Retiro	Buenavista	El Bohio	Las Penas	El Vesubio	C. La Union	Sabanazo	Puerto Molina
2011-2040												
DJF	0.94	0.88	0.84	1.00	0.99	1.03	N/A	0.97	0.83	0.99	1.06	0.69
MAM	1.34	1.09	1.20	1.14	1.12	1.22	N/A	1.14	0.88	1.28	1.00	0.85
JJA	0.98	0.92	0.91	0.99	0.98	0.95	N/A	0.98	0.66	0.86	0.90	0.67
SON	1.21	0.99	1.10	1.07	1.08	1.16	N/A	1.12	0.89	1.15	1.09	0.89
2041-2070												
DJF	0.94	0.88	0.84	1.00	0.99	1.04	N/A	0.97	0.83	0.99	1.07	0.69
MAM	1.35	1.10	1.21	1.15	1.12	1.23	N/A	1.15	0.88	1.29	1.01	0.85
JJA	0.94	0.88	0.87	0.95	0.94	0.91	N/A	0.94	0.63	0.83	0.87	0.64
SON	1.08	0.89	0.99	0.96	0.97	1.04	N/A	1.01	0.80	1.03	0.97	0.80
2071-2100												
DJF	0.97	0.90	0.86	1.03	1.02	1.07	N/A	1.00	0.85	1.02	1.10	0.71
MAM	1.36	1.11	1.22	1.16	1.13	1.24	N/A	1.16	0.89	1.30	1.02	0.86
JJA	0.89	0.84	0.83	0.91	0.89	0.87	N/A	0.89	0.60	0.79	0.83	0.61
SON	1.06	0.87	0.96	0.94	0.94	1.02	N/A	0.98	0.78	1.00	0.95	0.78

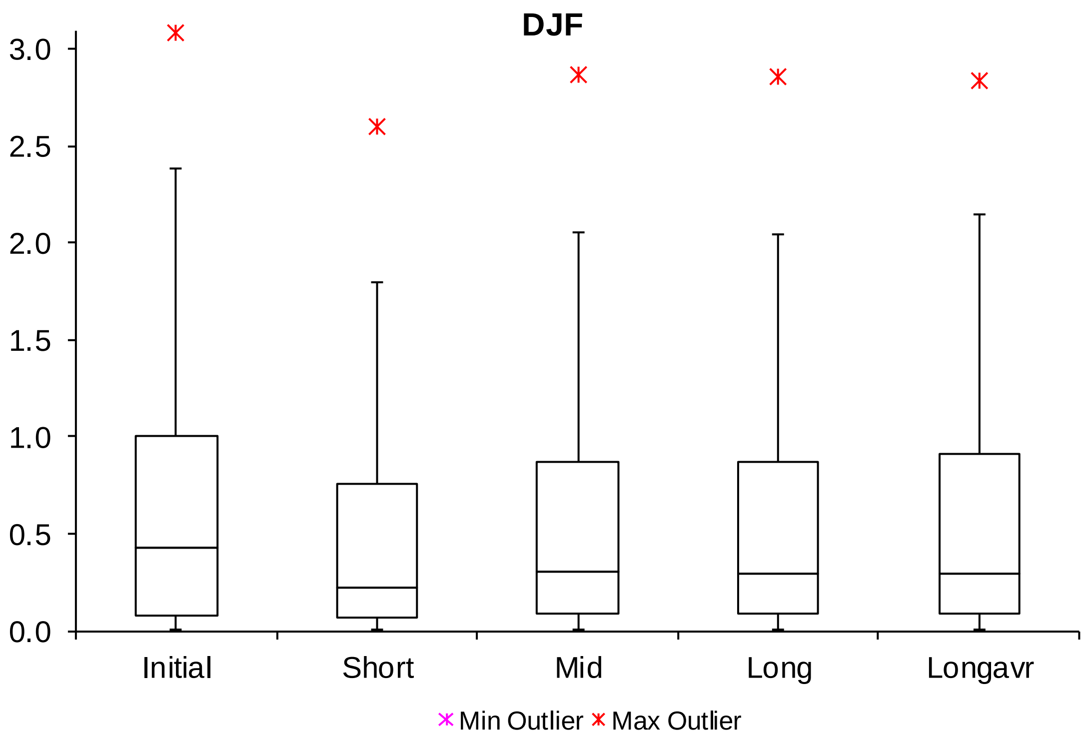
Notes

Appendix 7

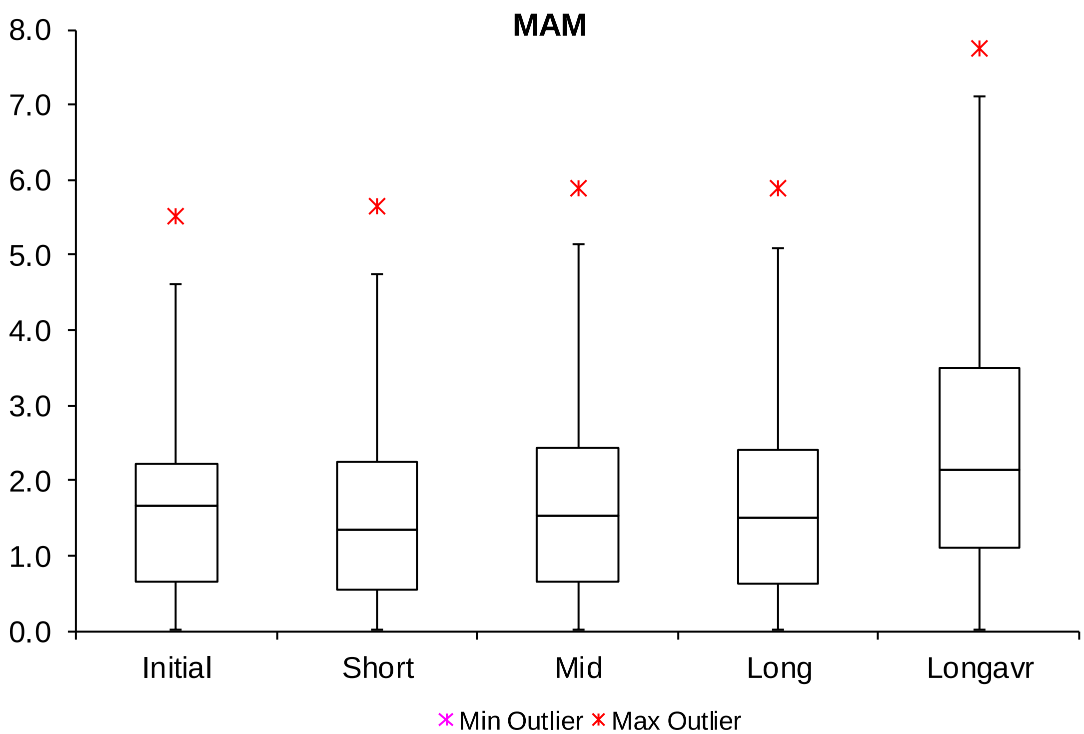
Average of the change factors over all the stations for the long scenario

Season	Change Factor
DJF	1.03
MAM	1.29
JJA	0.92
SON	1.03

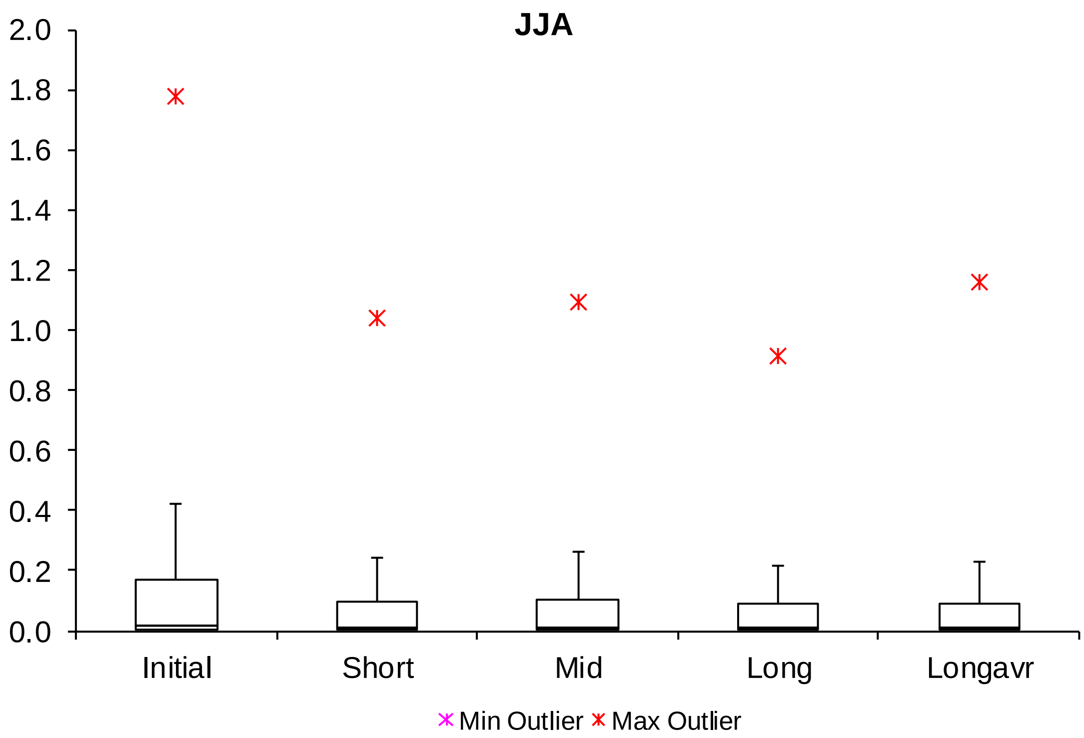
Appendix 8



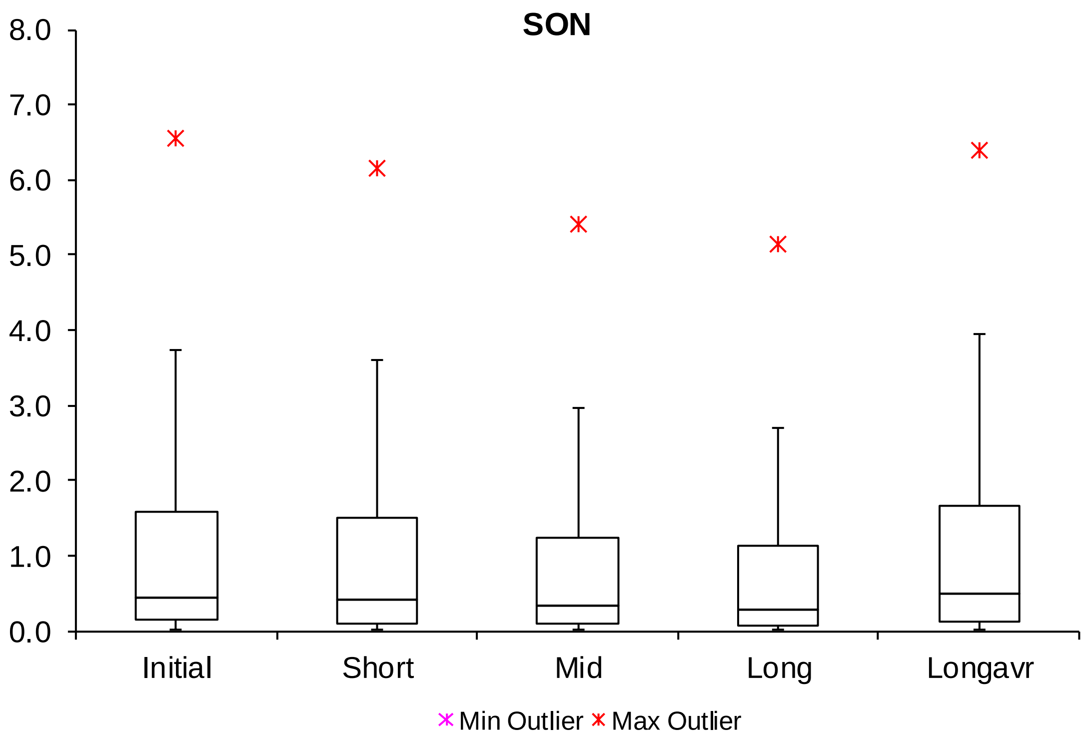
Labels	Initial	Short	Mid	Long	Longavr
Min	0.0	0.0	0.0	0.0	0.0
Q_1	0.1	0.1	0.1	0.1	0.1
Median	0.4	0.2	0.3	0.3	0.3
Q_3	1.0	0.8	0.9	0.9	0.9
Max	3.1	2.6	2.9	2.9	2.8
IQR	0.9	0.7	0.8	0.8	0.8
Upper Outliers	3.0	3.0	3.0	4.0	3.0
Lower Outliers	0.0	0.0	0.0	0.0	0.0



Labels	Initial	Short	Mid	Long	Longavr
Min	0.0	0.0	0.0	0.0	0.0
Q_1	0.6	0.6	0.6	0.6	1.1
Median	1.7	1.3	1.5	1.5	2.1
Q_3	2.2	2.2	2.4	2.4	3.5
Max	5.5	5.6	5.9	5.9	7.8
IQR	1.6	1.7	1.8	1.8	2.4
Upper Outliers	1.0	1.0	1.0	1.0	1.0
Lower Outliers	0.0	0.0	0.0	0.0	0.0



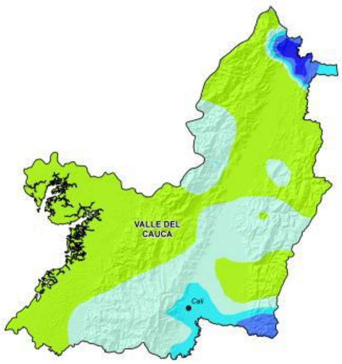
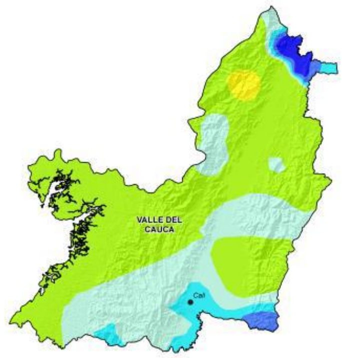
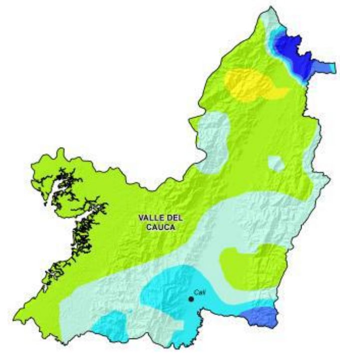
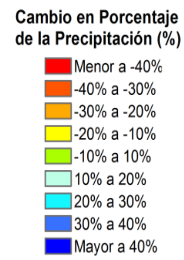
Labels	Initial	Short	Mid	Long	Longavr
Min	0.0	0.0	0.0	0.0	0.0
Q_1	0.0	0.0	0.0	0.0	0.0
Median	0.0	0.0	0.0	0.0	0.0
Q_3	0.2	0.1	0.1	0.1	0.1
Max	1.8	1.0	1.1	0.9	1.2
IQR	0.2	0.1	0.1	0.1	0.1
Upper Outliers	5.0	6.0	6.0	6.0	6.0
Lower Outliers	0.0	0.0	0.0	0.0	0.0



Labels	Initial	Short	Mid	Long	Longavr
Min	0.0	0.0	0.0	0.0	0.0
Q_1	0.1	0.1	0.1	0.1	0.1
Median	0.4	0.4	0.3	0.3	0.5
Q_3	1.6	1.5	1.2	1.1	1.6
Max	6.5	6.1	5.4	5.2	6.4
IQR	1.4	1.4	1.2	1.1	1.5
Upper Outliers	1.0	1.0	1.0	1.0	1.0
Lower Outliers	0.0	0.0	0.0	0.0	0.0

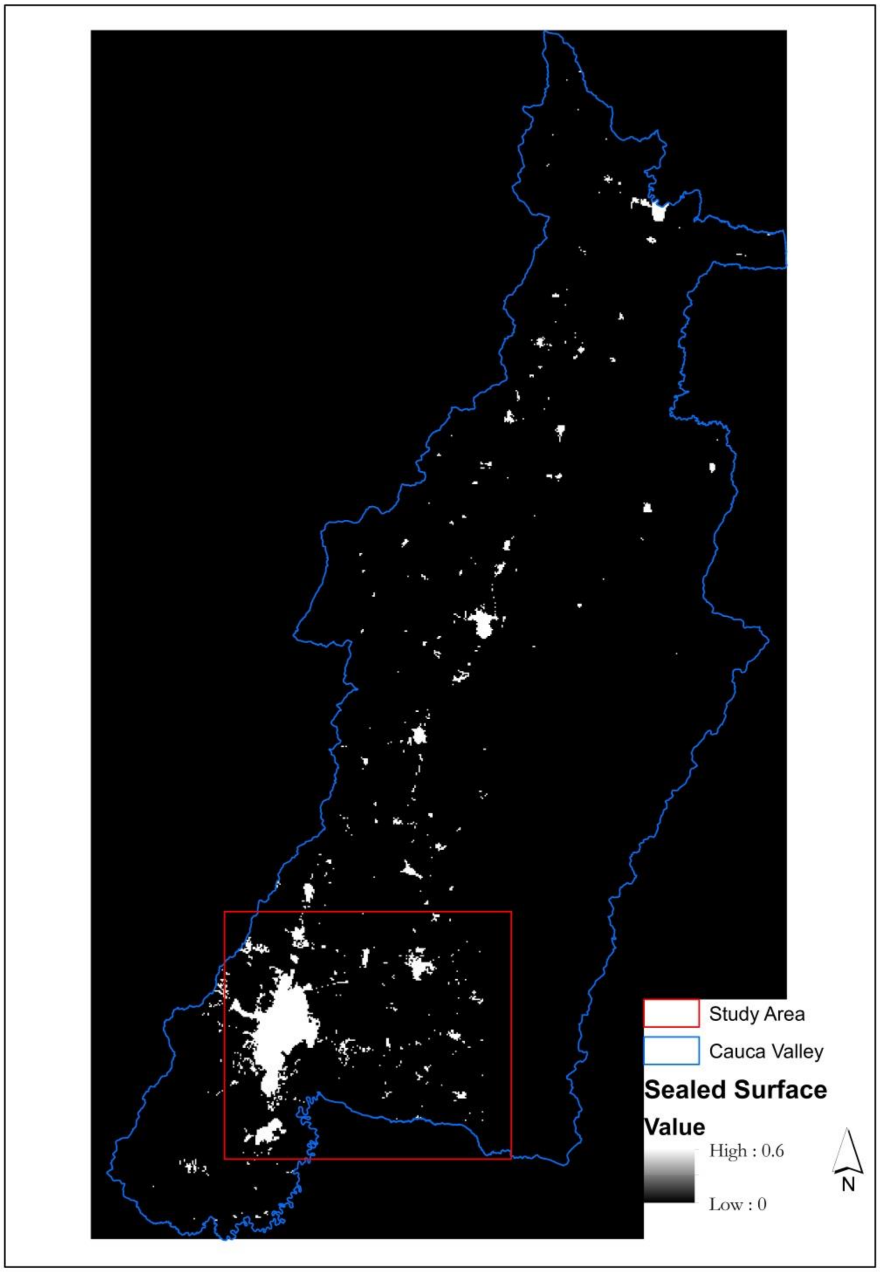
Appendix 9

Rainfall Distribution over the Cauca Valley Department

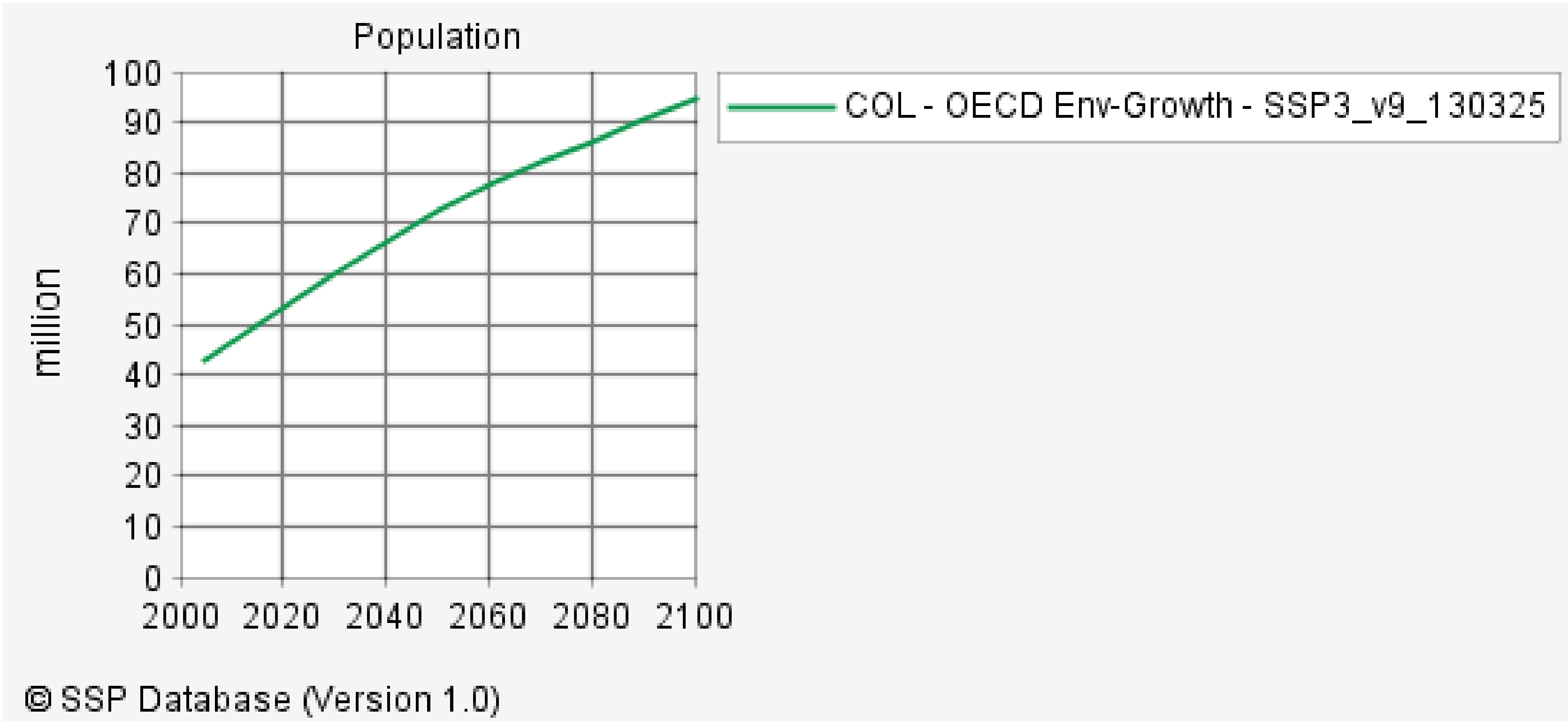
Short	Mid	Long	Legend
			

Source: (IDEAM, 2015) Page 276

Appendix 10



Appendix 11



Population
million
100
90
80
70
60
50
40
30
20
10
0
2000
2020
2040
2060
2080
2100
COL - OECD Env-Growth - SSP3_v9_130325
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