Universidad de Concepción

Dirección de Postgrado

Facultad de Ingeniería

EVALUACIÓN DEL IMPACTO DEL CAMBIO CLIMÁTICO EN EL COMPORTAMIENTO ESPACIAL Y TEMPORAL DE LOS EVENTOS DE SEQUÍA EN LA ZONA CENTRO SUR DE CHILE

(Evaluation of climate change impacts on the temporal and spatial behaviour of drought in South – Central Chile)

POR

ANDREA BELÉN BOBADILLA CLOUET

Tesis presentada a la Facultad de Ingeniería para optar al grado de Magíster en Ciencias de la Ingeniería con mención en Ingeniería Civil

Profesora Guía: Dr. Alejandra Patricia Stehr Gesche

abril, 2022

Concepción, Chile

Dedicado a Copito

AGRADECIMIENTOS

Este trabajo no habría sido posible sin dos importantes colaboradores. En primer lugar, agradecimientos a la profesora Alejandra Stehr, quien se sumó a este trabajo desde su conocimiento de la cuenca del Biobío no sólo como profesora guía, sino como activa participe de la ejecución de la tesis. De la misma forma, agradecer a Nicolás Toro, quien fue invitado a participar en este estudio y accedió con total compromiso, teniendo siempre voluntad para ayudar en lo que fuera necesario y a disponer de sus previos conocimientos en modelación hidrológica para este trabajo. Sin ambos, este trabajo no habría sido posible. Los más sinceros agradecimientos.

Adicionalmente agradecer a las gestiones realizadas por David Morales del Centro de Cambio Global UC por dar acceso a los datos de simulaciones climáticas escaladas utilizadas para este trabajo.

Parte de este trabajo fue gracias al aporte del Proyecto NSFC190002 “Improving water quality to sustain watershed ecosystems and socio-economic development under climate change: a China-Chile comparative study”.

Por último, dar por finalizada la etapa universitaria, agradeciendo a todos quienes fueron parte y apoyaron este desafío desde un principio.

TABLE OF CONTENTS

TABLES INDEX

FIGURES INDEX

RESUMEN

Las sequías son un fenómeno natural que se produce debido a la variabilidad natural del clima. Estos eventos poseen una baja frecuencia de ocurrencia, sin embargo, esto se ha visto modificado debido al actual cambio climático antropogénico. Chile es un país particularmente vulnerable al cambio climático debido a su geomorfología, riqueza ecológica y dependencia económica a los recursos hídricos. El objetivo de este trabajo consistió en evaluar el impacto del cambio climático en los eventos de sequía meteorológica e hidrológica en la zona centro-sur de Chile a través de la aplicación de índices estandarizados, comparando las condiciones de sequía históricas y futuras. Para esto, se evaluaron las cuencas de los ríos Maule, Itata y Biobío considerando las sequías meteorológicas e hidrológicas considerando el escenario de forzamiento radiativo RCP 8.5 según las trayectorias de concentración representativa propuestas por el Panel Intergubernamental de cambio climático (IPCC), utilizando cuatro modelos climáticos globales (GCM) escalados. Se implementó el modelo SWAT para determinar los cambios en los caudales. Los resultados se evaluaron mediante los índices SPI y SSI, comparando los eventos de sequía en dos períodos de tiempo (1993-2019 y 2034-2060). Se proyecta un aumento en la magnitud y duración de las sequías meteorológicas, especialmente en la cordillera de las cuencas de Maule y Biobío. En cuanto a la sequía hidrológica, se prevén aumentos mayores en magnitud y duración. En ambos tipos de sequías se espera un aumento en la frecuencia de los eventos futuros.

ABSTRACT

Droughts are a normal phenomenon that happens with climate natural variability. These events have a low frequency of occurrence, however, this has been modified due to the current anthropogenic climate change. Chile is a country particularly vulnerable to climate change due to its geomorphology, ecological wealth, and economic dependence to water resources. The objective of this work was to evaluate the impact of climate change on meteorological and hydrological drought events in south-central Chile through the application of standardized indices, comparing historical and future drought conditions. For this purpose, the Maule, Itata and Biobío river basins were evaluated considering meteorological and hydrological droughts considering the RCP 8.5 radiative forcing scenario according to the Representative Concentration Pathways proposed by the Intergovernmental Panel on Climate Change (IPCC) using four downscaled GCM models. The SWAT model was implemented to determine the changes in streamflow. Results were evaluated using SPI and SSI indexes comparing drought events in two periods of time (1993-2019 and 2034-2060). An increase in magnitude and duration of meteorological droughts is projected, especially in the mountain range of the Maule and Biobío River basins. Regarding hydrological drought, greater increases in magnitude and duration are anticipated. In both types of droughts, an increase in the frequency of future events is expected.

CHAPTER 1: INTRODUCTION

1.1. Motivation

Water is fundamental for human development, but unfortunately it is not evenly distributed worldwide, depending in many areas on seasonal and annual variations in precipitation (Trenberth et al., 2014; Naumann et al., 2021). The United Nations (UN) in its UN-Water program has determined that water scarcity is a problem that affects more than 40% of the world's population and is expected to increase (Guppy & Anderson, 2017). It is estimated that 2.3 billion people live in water-stressed countries, of which 733 million live in high and critically water-stressed countries (UN-Water, 2021). In Chile the scenario is no different from the rest of the world. According to the Meteorological Directorate of Chile (DMC), 2019 was the driest year in the history of the country and currently 226 communes in the country have been declared in a state of agricultural emergency by the Ministry of Agriculture, mainly affecting the regions of Coquimbo, Valparaíso, O´Higgins and Maule, between parallel 29°54′ and 35°07’. (MINAGRI, 2021).

In the face of these unfavorable conditions in recent times, climate change has become evident. The latest IPCC report (IPCC, 2021) indicates that “Human-induced climate change is already affecting many weather and climate extremes in every region across the globe. Evidence of observed changes in extremes such as heatwaves, heavy precipitation, droughts, and tropical cyclones, and their attribution to human influence, has strengthened since AR5”. Given the above mentioned, the quantification of losses and damages derived from extreme weather events, such as droughts, has become important for the implementation of policies related to climate change, the Sendai Framework for Disaster Risk

Reduction 2015-2030 and the Sustainable Development Goals (Trenberth et al., 2014; Svoboda & Fuchs, 2017; Naumann et al., 2021).

Droughts are periods of abnormally dry weather conditions with warmer temperatures and a deficit of precipitations, sufficiently prolonged to cause a serious hydrological imbalance (Trenberth et al., 2014; Huang et al., 2016; Svoboda & Fuchs, 2017). It is the natural phenomenon that affects the largest number of people in the world. According to the United Nations Development Program (UNDP) 220 million people in the world are affected by drought situations and by 2050, 52% of the world's population is projected to be exposed to severe water scarcity without significant intervention in response to global warming (Orlowsky & Seneviratne, 2013; Zhao et al., 2019; Wang et al., 2020)

There is no one classification of drought but some definitions are universal to explain the nature of these events. Wilhite & Glantz (1985) completed a thorough review of dozens of definitions of drought where they identified four categories: meteorological, hydrological, agricultural, and socioeconomic. The first two are the ones considered in this thesis. Meteorological drought is defined as a rainfall deficit, or deviation of precipitation, in respect to the long term mean while hydrological drought is defined as a period during which the flows of a basin are insufficient to satisfy the uses established under a given water management system and low water supply becomes evident in the water system.

When talking about drought, it is understood that it has a regional scope, and each region has specific climatic characteristics. Droughts can be studied and quantified using indices (WMO, 2006; Svoboda & Fuchs, 2017) where the indices are numerical representations of drought severity, determined by climatological or hydrometeorological data, such as precipitation, temperature, river flows, groundwater levels, etc. The indices provide options for determining the severity, location, duration, occurrence, and cessation of drought conditions, and have been used in many studies in different parts of the world (Vicente-Serrano, Beguería, et al., 2012; Vicente-Serrano, López-Moreno, et al., 2012; Huang et al., 2016; Yuan et al., 2016; Zhao et al., 2019; Danandeh Mehr et al., 2020; Li et al., 2021). Due to its the simplicity of calculation and easy interpretation of the results, the Standarized Precipitation Index (SPI) is used to quantify meteorological drought and the Standarized Streamflow Index (SSI) is used to quantify hydrological drought in the following study.

Considering the increasing trend in global temperatures and the impact on local climate, an intensification in the frequency and severity of extreme phenomena such as droughts is expected by the end of the 21st century (IPCC, 2021). This is reflected in the results obtained by different authors in different regions worldwide, all agreeing on an increase in the severity of drought events (Seneviratne, 2013; Huang et al., 2016; Yuan et al., 2016; Zou et al., 2018; Zhao et al., 2019; Danandeh Mehr et al., 2020; Orlowsky &; Shen et al., 2020; Li et al., 2021; Omer et al., 2020).

Given the above and considering the climate change projections for Chile (DGA, 2017; Bozkurt et al., 2018) this study aims to propose an effective framework to evaluate the historical drought conditions (1993 - 2019 as reference period) and to project the hydrological properties of drought in the future (2034 - 2060 as climate change period) in the central-southern zone of Chile, considering different global circulation models, which will act as forcing agents of a previously calibrated and validated hydrological model, in this case the Soil and Water Assessment Tool (SWAT).

1.2. Hypothesis

The research hypothesis is that climate change will strengthen meteorological and hydrological droughts with increases in the magnitude, duration and frequency of events in South-Central Chile.

1.3. General objective

The objective of this study is to evaluate the impact of climate change on meteorological and hydrological drought events in the Maule, Biobío and Ñuble river basins through the application of standardized indices, comparing historical and future drought conditions.

1.4. Specific objectives

a) Generate a fluviometric and meteorological information database for the Maule, Itata and Biobío river basins to assess the baseline situation of the area under study.
b) Estimate future flow projections through hydrological modeling using the baseline meteorological data under the effect of climate change.
c) Characterize through standardized indicators the drought events that have occurred in the past and are projected for the future in the study area based on baseline and future meteorological and hydrological situation.
d) Analyze the temporal and spatial behavior of drought events under the impact of climate change through the application of indices.

1.5. Methodology

This study was carried out in 4 stages. The first stage consisted of generating a database of the study area with climatic information to assess the baseline situation of the area and initiate the hydrological modeling of each watershed under study. The second stage consisted of ensuring the representativeness of the SWAT model through calibration and validation. In the third stage, the precipitation and temperature database were analyzed to simulate future flows. Finally, based on the estimated flows and precipitation projections, standardized indexes were calculated to analyze the effects of climate variations on droughts due to climate change.

1.6. Structure of the thesis

This work is organized in 5 main chapters. It begins with a brief introduction in which the problem is presented contextualizing it to the current situation of the country and the objectives of its realization are given. Subsequently, the state of art is shown, where the basis for the complete understanding of the work is presented. Then, the methods used to obtain the drought indexes are explained, and finally, the results of the analysis of these extreme events are presented, ending with conclusions of the results obtained.

CHAPTER 2: WATER SCARCITY AND CLIMATE CHANGE

Although climate change is a current reality, many meteorological phenomena are normal and occur with a certain frequency over time due to natural climate variability. In the case of droughts, these occur often in certain regions, however, those that escape from natural occurrence should be identified through their characterization.

2.1. Water availability and climate change projections

Water scarcity is a reality that has been known for some time, but efforts to address it as a real threat have only recently emerged (UNCC, 2019). Water use has been increasing worldwide by about 1% per year since 1980, driven by a combination of population growth, socio-economic development and changing consumption patterns putting unprecedented pressure on renewable, but finite water resources and is expected to continue increasing at a similar rate until 2050 mainly due to rising demand in the industrial and domestic sectors (WWAP UNESCO World Water Assessment Programme, 2019). The economic growth of recent years has brought with it an increase in industrialization and large amounts of water are being used in production processes and large-scale agricultural production (Boretti & Rosa, 2019). It is estimated that industrial and domestic demand for water will increase much faster than agricultural demand, although agriculture will remain the largest overall user (WWAP/UN-Water, 2018).

Water scarcity can mean insufficiency in availability due to physical lack of water to satisfy demand, or scarcity in access due to the failure of institutions to ensure a regular supply and distribution of water resources (FAO, 2012). Although climate has a natural variability over time, the current threat of anthropogenic climate change has clear evidence in being the effect of human activity, specifically, in the emissions of greenhouse gases as Carbon Dioxide (CO2) mainly caused by fossil fuel combustion and industrial processes (IPCC, 2014). In addition, water management in many parts of the world is a great challenge, where there are no water prioritizations, there is no correct legislation and there is insufficient baseline information to be able to make decisions regarding water resource management in the face of this new scenario of water scarcity due to climate change (Kumuu et al., 2010).

The effects of climate change are caused by the increase in atmospheric temperature. Global warming causes changes in several climate variables, such as precipitation, humidity, and wind speed, which lead to more frequent extreme events. (Oyounalsoud et al., 2022). These changes can produce diverse effects depending on the region, by intensifying the water cycle. This can lead to more intense rainfall and associated flooding in some places, as well as more intense droughts in other parts of the world. Globally it is proposed that precipitation will tend to increase (IPCC, 2018; Rashid et al., 2022), unlike countries like Chile, which is a particular vulnerable country where precipitation is projected to decrease considerably (The World Bank Group, 2021). In this context, the reality of each place of the globe may differ completely from another, since consequences of climate change can be different, and one basin does not behave the same as another to same conditions. Therefore, climate change projections must be worked out locally, based on a global and regional models. Current climate projections are made through Global Circulation Models (GCM) that simulate the atmosphere under conditions of high concentrations of greenhouse gases. These models themselves have uncertainties, but they are the most widely used tool for projecting future climate. The scale of these models is usually very coarse, so they must be scaled down to a regional or local scale for their use

(Siabi et al., 2021). Once a global model is downscaled to a local climate model, estimates of climate variables such as precipitation, temperature, evapotranspiration, among others, can be obtained. Finally, these outputs are used to force hydrological models to obtain predictions on rivers flows under climate change conditions.

In order to work on the same basis to estimate the conditions of the atmosphere due to climate change, in 2014 the Intergovernmental Panel on Climate Change (IPCC) in their Fifth Assessment Report, presented the Representative Concentration Pathways (RCPs). These represent future scenarios of greenhouse gas emissions under different socioeconomic, climate and climate change mitigation conditions. Their names (RCP 2.6, 4.5, 6 and 8.5) indicate the radiative forcing of each under different combinations of emissions over a time horizon up to the year 2100. The development of the RCPs considers both climate variables and changes in land use and pollution (Van Vuuren et al., 2011). In the last decade, the use of RCPs has expanded for climate change assessment. Since the most favorable scenario (RCP 2.6) assumes that emissions decrease from 2020, some recent studies do not incorporate it due to its low probability of occurrence, continuing with the following RCP 4.5 or assessing only the most pessimistic scenario RCP 8.5 where emissions do not decrease over the entire time projection (Kim et al., 2019). In 2021, in the Sixth Assessment Report, these scenarios were complemented by the Shared Socioeconomic Pathways (SSPs) that, in addition to greenhouse gas emissions, consider different climate policies that could be followed throughout the century.

2.2. Hydrologic modeling

Climate change impact studies use observed climate data in a hydrological model that has been perturbed by the climate change signal from the future climate data projected by Global Circulation Models (GCMs) (Du Plessis & Kalima, 2021). As mentioned before, to estimate flows in the face of environmental variations, it is necessary to understand the hydrological system prevailing in the basin under study. Given the complexity of these systems, it is necessary to have tools that facilitate their understanding. This is done through models that simplify the hydrological cycle. A hydrological model aims to represent the processes that make up the hydrological cycle and the interrelationship between the variables that influence it (Blade et al., 2014). There are different types, and their choice is mainly based on the availability of data and modeling purpose such as streamflow and flood forecasting, water resource management, evaluation of water quality, erosion, nutrient and pesticide circulation, etc (Siad et al., 2019).

They work at different levels of spatial discretization (lumped, distributed, semi-distributed) and their selection depends on the intended use of the results. Lumped models are useful when results are needed more than understanding the processes, as they treat the watershed as a unit, where the spatial variability of input variables, parameters and outputs are disregarded. Examples of these are the GR4J (Perrin et al., 2003) and HBV (Bergström, 1992) models. On the other hand, distributed models work at the level of the pixel or grid size in which the information is found, therefore they are more detailed, however they require greater computational capacity and calculation times can be high. Among them are the SHE (Abbott et al., 1986 a,b) and IDHM (Beven et al., 1987) models that use finite differences for their calculation.

In between these two are the semi-distributed models, which divide the basin into sub-basins or smaller units where the water balance is calculated. Three recognized models of this type are the VIC model (Variable Infiltration Capacity) (Liang et al., 1994; Hamman et al., 2018), (which was used for the development of the update of the Chilean National Water Balance in 2017), the WEAP model (Water Evaluation and Planning) (Yates et al., 2005) and the SWAT model. The SWAT model (Soil and water assessment tool) (Arnold et al., 1998) is a semi-distributed model that allows obtaining flows from a water balance carried out at the level of HRU (Hydrologic Response Unit) which are homogeneous in slope, use and soil type. Once the balance is obtained in these units, it is aggregated into sub-basins generated by the same model where the results are studied. Control points, such as fluviometric stations or at a specific point of interest, can be added to the model by taking flow rates at a place of special interest. The SWAT model is widely used around the world and its uses can range from climate change studies, such as changes in flow rates (Malik et al., 2021), changes in land uses (Sharannya et al., 2021), changes in water quality (Nazari-Sharabian et al., 2019) and analysis of extreme events such as droughts (Mengistu et al., 2021) or floods , where the selection of this model allows both spatial and temporal analysis. This model has also been previously used in Chile, with good performance and results (Stehr et al., 2008; Aguayo et al., 2016; Penedo-Julien et al., 2018; Martínez-Retureta et al., 2021, 2020; Galleguillos et al., 2021).

2.3. Drought characterization

Drought is a difficult phenomenon to study since it develops over time and is evident when its consequences are inevitable. Drought propagation processes are influenced by climate but also by catchment properties and human activities such as deforestation, construction, and agriculture negatively impact the water cycle and cause droughts (Wang et al., 2021). To study this phenomenon, drought indexes are used, which work from an input variable, such as precipitation, flow, evapotranspiration, land use and see its accumulated effect in different periods of time, such as 1 month to 12 months. Among the most used to evaluate meteorological droughts is undoubtedly the Standardized precipitation Index (SPI) (Mckee et al., 1993) which despite having a long trajectory, is still the most used index for drought analysis. An advantage from the point of view of input data is that it uses only precipitation, which can also be considered a disadvantage since it omits other processes that also influence a drought. Another index used for meteorological droughts that additionally includes the effect of evapotranspiration is the SPEI (Vicente-Serrano et al., 2010).

Hydrological drought develops slowly, as the water that is generally stored in rivers, lakes, or groundwater begins to run out and the prevailing hydrological system in the area is unable to replenish it (Van Loon et al., 2010). In the case of hydrological drought, there are also indexes created exclusively for their analysis such as the Standardized Drought Index (SDI) (Nalbantis & Tsikaris, 2008), the Palmer Hydrological Drought Index (PHDI) (Palmer, 1965) and the Standardized Streamflow Index (SSI) (Vicente-Serrano et al., 2012). These three indices differ in the required input data and simplicity of calculation. The Standardized Streamflow Index uses almost the same calculations as the SPI but with streamflow instead of precipitation data. In this way they share their advantages and disadvantages. In addition to those previously mentioned, there are indices to evaluate economic and agricultural droughts.

From the calculated index values, droughts can be characterized through their duration, magnitude, and frequency of events. In this way, a quantitative analysis can be made, where each characteristic can be studied through its behavior both in time and space, being possible to analyze the behavior of droughts, estimated on the basis of precipitation and flow projections.

In general, the popular approach to study and project droughts under the climate change impact is a modeling approach including a combination of GCM simulations, downscaling techniques, hydrological models, and drought indices (Khoi et al., 2021). Results may vary depending on the projection data, the model used, and the index evaluated, but they will provide a guide to future behavior, which, although not a prediction, is a trend and serves as a basis for decision making in the face of the current threat of climate change.

2.4. Conclusions

This chapter presented a contextualization of the scenario in which this study is proposed, explaining the importance of addressing the severity of the current water situation in the context of climate change, the methods used to assess the impact of climate change on water resources, and how to perform a drought analysis for this new scenario.

CHAPTER 3: MATERIALS AND METHODS

3.1. Study area

The study area is located in South - Central Chile and comprises three important basins, Maule, Itata and Biobío River basins (from north to south), which are located between parallels 35°07’ – 38°91’. According to the territorial division of Chile, these basins are in Maule, Ñuble and Biobío regions, covering a total area of 55.803 km^2 (Figure 3.1). The Biobío basin has an area of 24.264 km^2, being the third largest watershed in Chile, followed by the Maule basin with 20.245 km^2 and the Itata basin with 11.294 km^2.

The main channel of the Maule basin, the Maule River, originates in the Andes mountains and has a length of 240 km to the outlet to the Pacific Ocean, near to the city of Constitución. The largest city in this basin is Talca, with a population of 220.357 inhabitants, which is supplied by the Claro River, an important tributary to the north of the Maule River. In the case of the Itata river basin, the Itata river is born at the confluence of the Cholguán and Huépil rivers, and then joins its main tributary, the Ñuble river, 34 km west from the city of Chillán, the most important city in the basin. When it flows into the ocean, the Itata River reaches a total length of 140 km. Finally, the Biobío River, Chile's widest and second longest river, originates from the Galletué and Icalma Lakes, and discharges in the sea next to the metropolitan area of Concepción, the largest urban core in the study area with 1.037.170 inhabitants (DGA, 2004a; DGA, 2004b; DGA, 2004c).

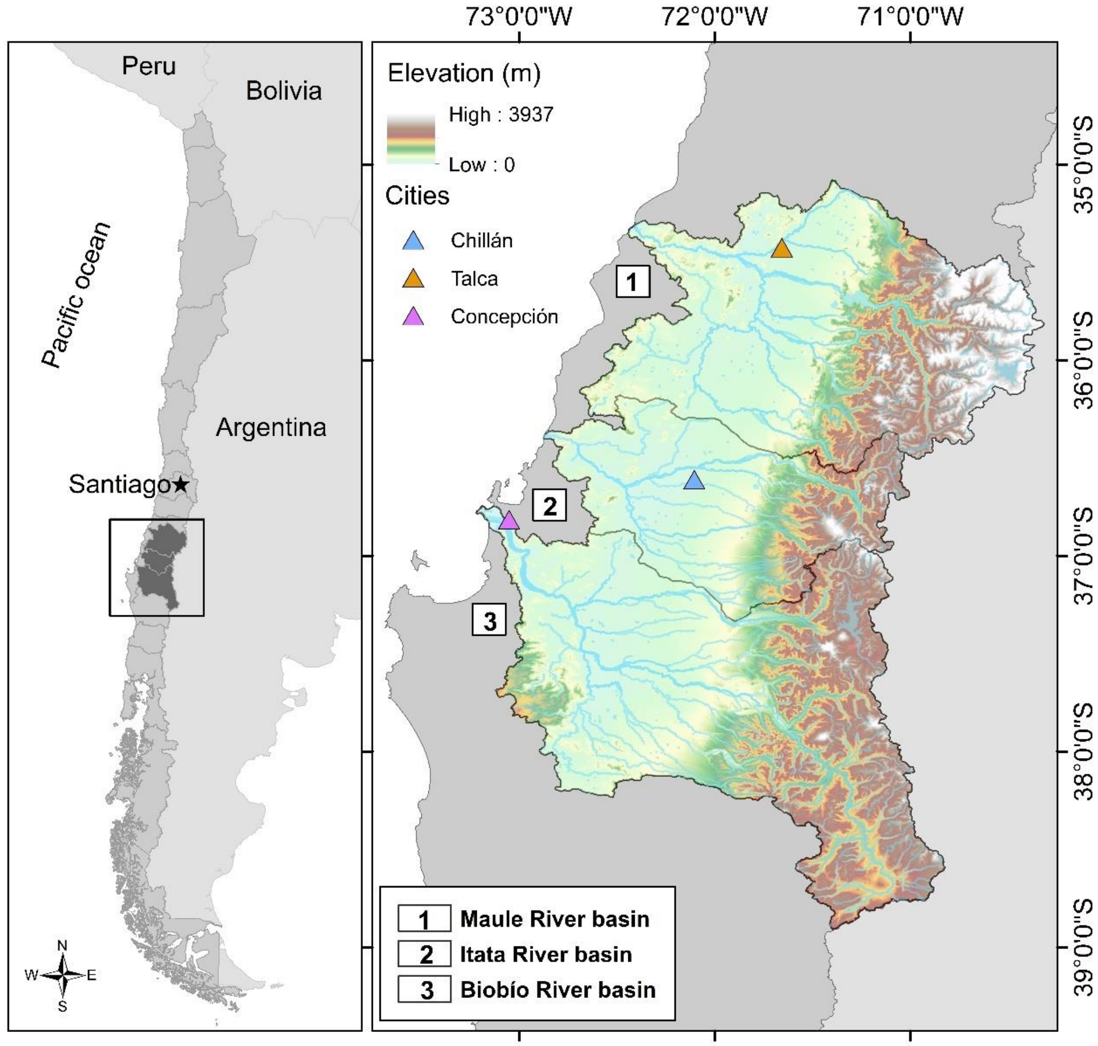

Figure 3.1: Study area

The three rivers have a similar behavior with a mixed regime due to snowmelt in the highest areas and rainfall contribution predominant in the valley and next to the sea level. The water resources in the study area are mainly used for agriculture, forestry activities and hydropower (DGA, 2016). The Colbún power plant and reservoir, located in the Maule river valley, have the largest volume capacity in the country with 1500 Mm^3 and a capacity of 400 MW (CNE, 2021). Due to its magnitude, the area of influence upstream of this reservoir was not considered in the hydrological modeling. Due to the agricultural use, interventions are present in almost all the channels of the watershed, with reservoirs and artificial channels, altering the natural regime of the rivers. According to Diaz et al. (2019), the basins with the highest number of barriers in their river systems in Chile are Maule (24) followed by Biobío (19).

The 4 main units of Chile's geomorphology are perceptible in the central-southern zone, and they are key to evaluate the spatial distribution of droughts and interpreting their behavior. The Andes Mountain range is the unit with the highest elevations found to the east in the entire study area. Along the Pacific coast and parallel to the Andes Mountains is the Chilean Coastal Range, a smaller mountain range that runs from north to south. The Chilean Central Valley is the depression between the Coastal Range and the Andes Mountains where elevations decrease significantly and where cities, economic activity and especially agriculture are concentrated. Finally, the coastal zone is called the litoral plain (Armesto et al., 2007).

The predominant climate in the zone is Mediterranean, characterized by warm and dry summers and cool, wet winters where most of the rainfall occurs. Average annual temperatures (minimum and maximum) fluctuate between 7.6°C and 21°C for the Maule River basin, between 8°C and 23°C for the Itata River basin. Average annual precipitation is 735 mm in Maule, 1025 mm in Itata and 1300 mm in Biobío (DGA, 2004a; DGA, 2004b; DGA, 2004c).

Figure 3.2 outlines the methodology used for the development of this study, showing 3 main stages 1) hydrological modeling, SWAT model and its application (Calibration and Validation); 2) Selection and analysis of climate change scenarios (precipitation and temperature) and estimation of future flows considering climate change; and 3) Calculation of current and future drought indices, and spatial analysis of changes (magnitude, duration, frequency). Each of these stages is described in detail below.

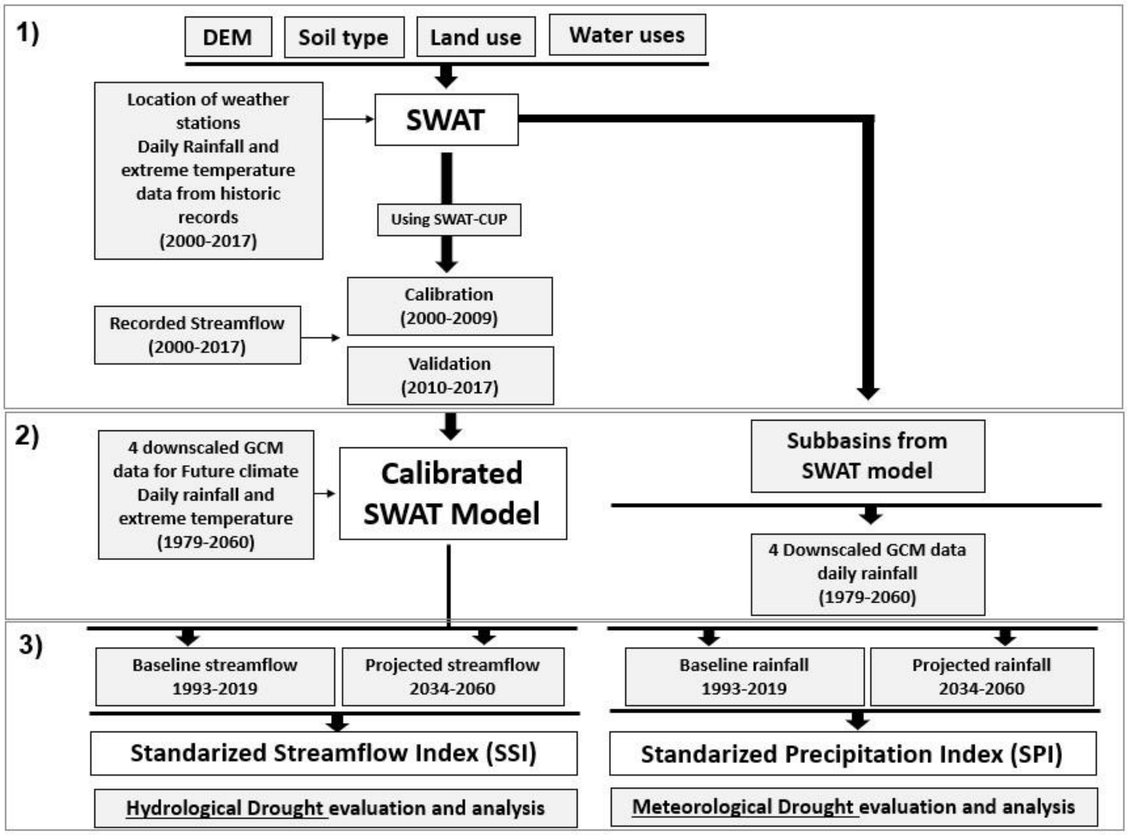

Figure 3.2: Methodology of the present study

3.2. Hydrological model

The SWAT model (Soil and Water Assessment tool) (Arnold et al., 1998) was selected for modelling the hydrological behavior of each of the three basins. SWAT is a physically based, continuous time and semi-distributed model developed by the United States Department of Agriculture. The model was developed to predict the impact of land management practices on water, sediment and agricultural chemical yields in large complex watersheds with varying soils, land use and management conditions over long periods of time (Neitsch et al., 2002). It calculates water balances by discretizing the basin according to stream network and topography into subbasins which are further divided into Hydrological Response Units (HRU) that are obtained by integrating the soil type, land use and slope from data inputs. Water balance is computed within each HRU by linking four components (snow, soil, shallow aquifer, deep aquifer) through hydrological processes such as infiltration, surface runoff, subsurface runoff, evapotranspiration, and percolation calculated in a daily time step (Grusson et al., 2021). The equation that rules the model is shown,

$$SW_t = SW_0 + \sum_{i=1}^{t} \left(R_{day} - Q_{surf} - E_a - W_{seep} - Q_{gw} \right) \tag{3.1}$$

Where, SW_t =final soil water content (mm H_2O), SW_0=initial soil water content (mm H_2O), t =time (days), R_{day}=amount of precipitation on day i (mm H_2O), Q_{surf} =amount of surface runoff on day i (mm H_2O), E_a=amount of evapotranspiration on day i (mm H_2O), W_{seep} = amount of percolation and bypass flow exiting the soil profile bottom on day i (mm H_2O), and Q_{gw}=amount of return flow on day i (mm H_2O).

SWAT model has been successfully used to assess the impact of climate change in discharge, evapotranspiration and percolation (Hao et al., 2018; Petpongpan et al., 2020; Bariamis & Baltas, 2021). Also, it has been used previously in Chile to assess climate and land use change effect (Stehr et al., 2008; Aguayo et al., 2016; Penedo-Julien et al., 2018; Martínez-Retureta et al., 2021, 2020; Galleguillos et al., 2021). In this study, three models, one for each basin, were developed to evaluate changes in drought due to climate change. The source, dataset and description of model inputs used for Maule, Itata and Biobío basins are shown in Table 3.1.

Table 3.1: Source of SWAT model datasets

Data	**Source**	**Description**
DEM	**DEM ALOS-PALSAR**	Elevation 12.5x12.5m (Itata and Biobío) - 30x30m (Maule)
Land Cover	**SIT-CONAF**	Land uses
Soil type	**CIREN (Chile) and FAO**	Layer and Data from each soil type in the zone.
Meteorological data (precipitation and extreme temperatures)	**DGA- DMC-CR2MET**	Daily precipitation and extremes temperatures
Water uses	**DGA**	Consumptive and non-consumptive (Maule) water users

CIREN : Natural Resources Information Center - Ministry of Agriculture, Chile
CONAF: Chilean National Forestry Corporation
DGA: Chilean General Directorate of Water

Meteorological information was obtained from two sources. In the case of the Biobío basin, it was obtained from the CR2MET gridded product (CR2, 2018), while for the Maule and Itata basins, it was obtained from stations whose details can be found in Appendix 3.1. Soil type information was obtained from the agrological studies of the VII,VIII and IX Region performed by the Natural Resources Information Center (CIREN) in 1997, 1999 and 2002 for the Biobío, Maule and Araucanía regions respectively. These studies provide information about the physical–chemical properties of soil types present in the study area. Some areas do not have smaller scale information on Chilean soils, mainly in the mountainous zone. This zone was filled with information from the World Soil Map of the Food and Agriculture Organization of the United Nations (FAO & UNESCO, 1971). All this information was included in the SWAT database. Land uses were obtained from land register for the regions of Maule and Biobío available in the territorial information system of the National Forestry Corporation of Chile. These were homologated to the land uses of the SWAT database.

In this study, surface runoff was estimated using the SCS Curve Number method (USDA-SCS, 1972), due to available data. To estimate potential evapotranspiration, Hargreaves & Samani (Hargreaves & Samani, 1985) was used in the models due to the lower data requirement for its calculation.

3.3. Model performance

Calibration and validation were performed at monthly level, using monthly mean streamflow measured at gauge stations distributed in each basin. The period 2000-2002 was used as “warm-up” period (NYSKIP), then, 7 years of calibration (8 in Biobío river basin) were used to estimate the model parameters values and 10 years for validation (Table 3.2).

Table 3.2: Calibration and validation periods

Basin	**Calibration (+ 3 years NYSKIP)**	**Validation**
Maule	2000-2009	2010-2017
Itata	2000-2009	2010-2017
Biobío	2000-2010	2011-2018

Calibration was performed using SWAT-CUP (Abbaspour, 2014) using the Sequential Uncertainty Fitting (SUFI-2) algorithm incorporated in this tool. The most sensitive parameters for modeling were identified using this software by a T - Test. Calibration and validation were performed at monthly time steps. Table 3.3 shows the hydrological parameters that were taken into account for the sensitivity analysis. These parameters and their ranges were selected based on SWAT model documentation (Arnold et al., 2012; Abbaspour et al., 2015), previous studies (Cibin et al., 2010) and the experience of the authors with the SWAT model in other watersheds in the same area (Stehr et al., 2010).

Table 3.3: Sensitive parameters used for model calibration

Parameter	Units	Description
CN2	-	Initial SCS CN II value
ALPHA_BF	-	Baseflow alpha factor
GW_DELAY	days	Groundwater delay
GWQMN	mm	Threshold depth of water in the shallow aquifer required for return flow to occur
SOL_K	mm/hr	Saturated hydraulic conductivity
SOL_AWC	mm H2O/mm soil	Available water capacity in the soil layer
GW_REVAP	-	Groundwater "revap" coefficient
RCHRG_DP	-	Deep aquifer percolation fraction
REVAPMN	mm	Threshold water depth in the shallow aquifer for revap
CANMX	mm	Maximum canopy storage
ESCO	-	Soil evaporation compensation factor
SURLAG	days	Surface runoff lag coefficient
ESCO	-	Soil evaporation compensation factor
EPCO	-	Plant uptake compensation factor
SMTMP	°C	Snow melt base temperature
SFTMP	°C	Snowfall temperature

To assess the performance of the model, four statistical indicators proposed by Moriasi et al. (2007) were used and evaluated for the calibration and validation periods. The indicators used are shown below and the performance range of goodness-of-fit indicators are shown in Table 3.4:

- Ratio of standard deviation of the mean square error of the observations (RSR): It is obtained as the ratio between the mean square error and the standard deviation of the measured observations. It varies from its optimum value 0, which indicates a perfect simulation of the model, to a high positive value. The lower the RSR, the better the model performance. It is obtained as,

$$\mathrm{RSR} = \frac{\sqrt{\sum_{i=1}^{n}(Y_{i\,obs} - Y_{i\,sim})^2}}{\sqrt{\sum_{i=1}^{n}(Y_{i\,obs} - Y_{avg})^2}} \tag{3.2}$$

- Nash-Sutcliffe efficiency (NSE): This is a statistic that represents the level of fit of the graph of observed versus simulated values to a 1:1 line. Thus, it measures the variance of the simulated data compared to the observed data. It is determined as,

$$\mathrm{NSE} = 1 - \left[\frac{\sum_{i=1}^{n}(Y_{i\,obs} - Y_{i\,sim})^2}{\sum_{i=1}^{n}(Y_{i\,obs} - Y_{avg})^2}\right] \tag{3.3}$$

- Percent Bias (PBIAS): Measures the average tendency of the simulated data to be greater or less than the observed data. Its optimum value is 0, expressed as a percentage, where positive values indicate an underestimation of the model and negative values an overestimation. It is calculated as,

$$\mathrm{PBIAS} = \left[\frac{\sum_{i=1}^{n}(Y_{i\,obs} - Y_{i\,sim}) * 100}{\sum_{i=1}^{n}(Y_{i\,obs})}\right] \tag{3.4}$$

- Coefficient of determination (R^2): Describes the proportion of collinearity of the observations that are explained by the model. It varies between 0 and 1, where a value close to unity indicates greater correlation. Generally, an R2 value greater than 0.5 is considered acceptable. It is calculated as,

$$R^2 = 1 - \frac{\sum(Y_{i\,obs} - Y_{i\,sim})^2}{\sum(Y_{i\,obs} - Y_{avg})^2} \tag{3.5}$$

Table 3.4: Performance range of goodness-of-fit indicators

Performance	RSR	NSE	PBIAS (%)
Very good	0 ≤ RSR ≤ 0.5	0.75 < NSE ≤ 1	PBIAS < ± 10
Good	0.50 < RSR ≤ 0.60	0.65 < NSE ≤ 0.75	± 10 ≤ PBIAS < ± 15
Satisfactory	0.60 < RSR ≤ 0.70	0.50 < NSE ≤ 0.65	± 15 ≤ PBIAS < ± 25
Unsatisfactory	RSR > 0.70	NSE≤ 0.50	PBIAS ≥ ± 25

Moriasi et al. (2007)

As soon as the model was calibrated and validated, the SWAT model was considered suitable to reflect the hydrological processes in each studied basin. It was then used to simulate future water balance under projected climate change conditions. Monthly streamflow outputs of the future simulations were used to evaluate hydrological drought.

3.4. Climate change projections

To evaluate future condition of weather, climate projections from Global Circulation Models (GCM) were used. A GCM is a complex mathematical representation of the major climate system components (atmosphere, land surface, ocean, and sea ice), and their interactions (Geophysical Fluid Dynamics Laboratory, n.d.). These are used to project climate data according to a specific condition of the atmosphere or in greenhouse gas concentration which is why they have been considered a suitable model for simulating climate change and predict its impact (Kim et al., 2021) .The meteorological forcing data was obtained from downscaled and bias-corrected daily climate model outputs of four GCMs (CCSM4, CSIRO-Mk3-6-0, IPSL-CM5A-LR y MIROC-ESC) produced in the framework of the Updating of the Chilean National Water Balance project (DGA, 2017). During project development these were selected and downscaled using the Quantile Delta Method (QDM) to a spatial resolution of 0.5° × 0.5° under high emission scenario RCP8.5 (IPCC, 2014) to forecast the future climate in all Chilean territory. The climate information is on a daily time scale from 1979 to 2060. For details of this methodology, the reader is directed to the Updating of the Chilean National Water Balance (DGA, 2017). For simplicity, these models will be referred in this article as CCSM4, IPLS, CSIRO and MIROC from now on.

3.5. Climate variability -Trend Analysis

To evaluate the significance of changes in precipitation and streamflow between the past and future periods, a trend analysis was performed. While trend analysis of a time series consists of the magnitude of trend and its statistical significance, statistically trend is a significant change over time which is detectable by parametric and non-parametric procedures (Hussain et al., 2015). In this study, statistical significance trend analysis was done by using Mann- Kendall test (MK) (Mann 1945, Kendall 1975) while the magnitude of trend was determined by Test-t method. The tool MAKESENS 1.0 (Salmi et al., 2002) was used to estimate Z test, significance values and sen’s slope from MK test. MK test was applied to the entire data series of mean annual precipitation and streamflow while T test was applied by comparing past and future period of projections, both with a significance level of 0.05.

3.6. Drought indexes: SPI and SSI

To identify, evaluate and contrast drought events in a large territory, its necessary to use standardized indexes that allows to compare different condition with the same scale of values. For this study, due to the information available in the area, the extension of the study area, the simplicity of calculation and easy interpretation of the results, two widely used standardized indexes were selected, the Standardized Precipitation Index (SPI) and the Standardized Streamflow Index (SSI).

3.6.1. Standarized precipitation Index (SPI)

Globally, the most used index is the Standarized Precipitation Index (SPI) (Mckee et al., 1993) because its simplicity to identify meteorological drought using only precipitation data as input. This can also be considered a disadvantage since it does not consider other variables, such as evapotranspiration, which can influence drought events. The calculation of the index consists of adjusting precipitation data to a gamma distribution, then normalize it to get an average of 0 and standard deviation of 1. Although it's been almost 30 years since its publication, it is still recommended as the standard index worldwide by the World Meteorological Organization (WMO).

The standardized precipitation index uses commonly at least 30 consecutive years of data at different points in the basin, which is analyzed according to different time periods, ranging from 1 to 24 months. By working with different time scales, it is possible to assess the impacts of droughts on different systems such as agriculture (in the short term) and water supplies, for example reservoirs and groundwater deficits (long term) (WMO, 2012). While the 3- and 6-month SPI describe droughts that affect plant life and farming, the 12- and 24-month SPI influence the way water supplies and reserves are (Caloiero et al., 2018).

According to Mckee (1993), the threshold that defines the beginning of a drought event is when the SPI value drops to -1 and it ends when it becomes greater than -1. From that definition it’s possible to characterize droughts by their duration and magnitude as the absolute sum of all SPI values during the event.

The software SPI Generator by the National Drought Mitigation Centre, University of Nebraska (NDMC, 2018) was used for SPI calculations.

3.6.2. Standardized streamflow Index (SSI)

The Standardized Streamflow Index (SSI) (Vicente-Serrano et al., 2012) is a recent way of evaluating hydrological droughts. This index, like the SPI, has the ability to compare drought events in regions with different climates, since it is a standardized index. The time scale can be set from 1 month to 24 months depending on the approach. Despite being an index that has been in use for less than 10 years, it has been implemented in several studies with good results (Lorenzo-Lacruz et al., 2013; Oertel et al., 2018; Bin Luhaim et al., 2021; Giri et al., 2021). Its calculation is similar to SPI, however it is calculated at the level of equal months and the initial distribution adjustment is extended to 6 probability distributions. In this work, the Log- Logistic, Lognormal, General Extreme Values and Weibull distributions were used to avoid values less than 0 in the probability distribution, possible error mentioned by Vicente-Serrano in the remaining distributions.

Like SPI, the SSI value represents the beginning of a drought event when it drops to -0.84 (Sutanto & Van Lanen, 2020) and lasts until it becomes greater than -0.84.

The calculation of the SSI was performed by programming the distribution fits in the R language using RStudio. The Cramér–von Mises (Cramér, 1928; Von Mises, 1931) test was used to validate the quality of fit. The calculation of the SSI-12 was performed also using R platform.

Both indexes were evaluated for a 12-month period. In this way, the long-term effects of drought, which is the reflection of longer accumulation of precipitation anomalies, can be evaluated as well as its effect on both groundwater and water supply (Giri et al., 2021). The indices were evaluated using precipitation and temperature data obtained from the 4 GCMs and in the case of the SSI, the output flows of the SWAT model previously forced with the GCM data were used.

3.7. Drought Characteristics

Once the SSI and SPI indices have been calculated for the period under study, droughts were characterized considering magnitude, duration, and frequency. An index value less than a given threshold is defined as a drought event. The number of drought events are counted as frequency in this study. The drought duration is the time between the index passing the threshold and the time of its recovery (months) and the drought magnitude is the sum of the values of the index from the time it passes until it exceeds the threshold again. The graphical form of these characteristics is shown in Figure 3.3 where D represents the duration of an event, M magnitude and 1 and 2 represent two individual events (frequency) with a threshold of -1.

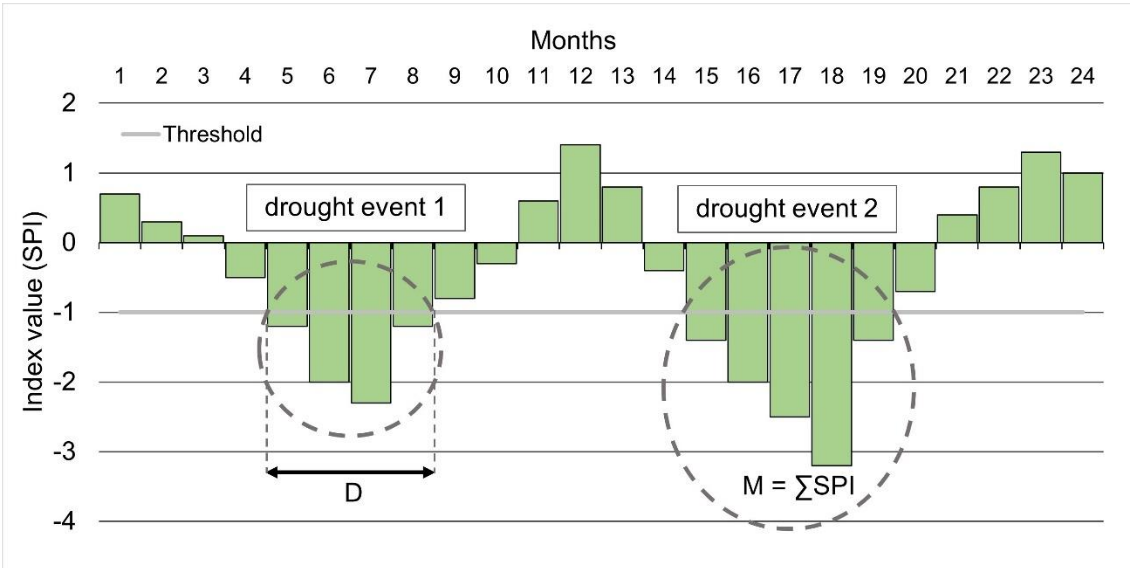

Figure 3.3: Graphical form of drought characteristics.

To quantify the effect of climate change on drought behavior, two periods were considered: the past (1993-2019) and the future (2034 - 2060). The beginning of the past period is a product of hydrological modeling, since by using 3 years of pre-warming with meteorological data since 1979, results were obtained since 1982, from which 12 cumulative years were used to calculate the SSI-12, that is, results of the index from 1993 onwards. To evaluate the same periods in both types of droughts, SPI-12 was calculated over the same period. For analysis purposes, the indices obtained for each of the GCMs were averaged over each evaluated time period and used as final result.

3.8. Conclusions

This chapter presents the methods used to create a baseline of climatic data for the area, which were used to generate hydrological models to evaluate the future situation of water resources using results from a global climate model. In addition, it was shown how drought indices were used to characterize changes in drought events due to climate change.

CHAPTER 4: RESULTS

4.1. SWAT performance, calibration, and validation

The basins were divided into 106 (Maule), 60 (Itata) and 348 (Biobío) sub – basins according to the hydrological network. The SWAT model was run to obtain water discharge in all sub-basins for the three basins. As shown in Table 4.1, the model has a good calibration performance in the 3 basins, with most of the indicators classified as very good and good according to the classification proposed by Moriasi et al. 2007 (Table 3.4). For the validation period, the model performance decreased being the most affected indicator PBIAS, showing a tendency to over- or under -estimate flow rates (Table 4.1). Although the comparative analysis by indices is essential, the graphical comparison of flow rates was also considered for calibration and validation. Graphical results from the stations closest to the outlet of each of the three basins (Figure 4.1) are shown in Figure 4.2, Figure 4.3, Figure 4.4 and Figure 4.5. As the area influenced by the Colbún reservoir was discarded from the modeling, two main sectors are considered for the Maule River basin, Claro and Loncomilla rivers. It is observed that the graphical adjustment for the station Rio Claro in Rauquén, shown in Figure 4.2 has a good performance despite having a lower performance of the indicators. The Itata River station in Coelemu, outlet of the Itata river basin, shown in Figure 4.4 maintained its behavior with a satisfactory PBIAS in both the calibration and validation periods with a good graphic adjustment. The basin with the best overall performance, in terms of validated stations and indicators values, was the Biobío river basin (Figure 4.5).

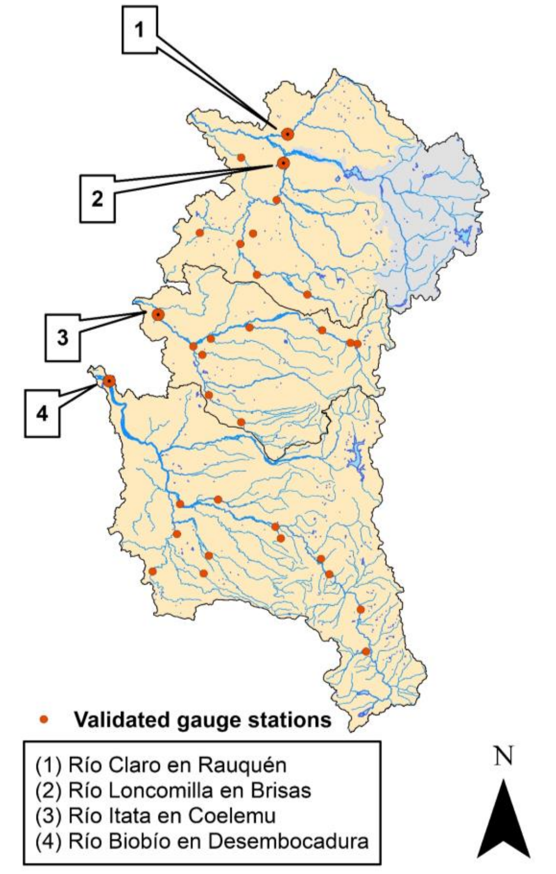

Figure 4.1: Main outlets calibration and validation periods streamflow values

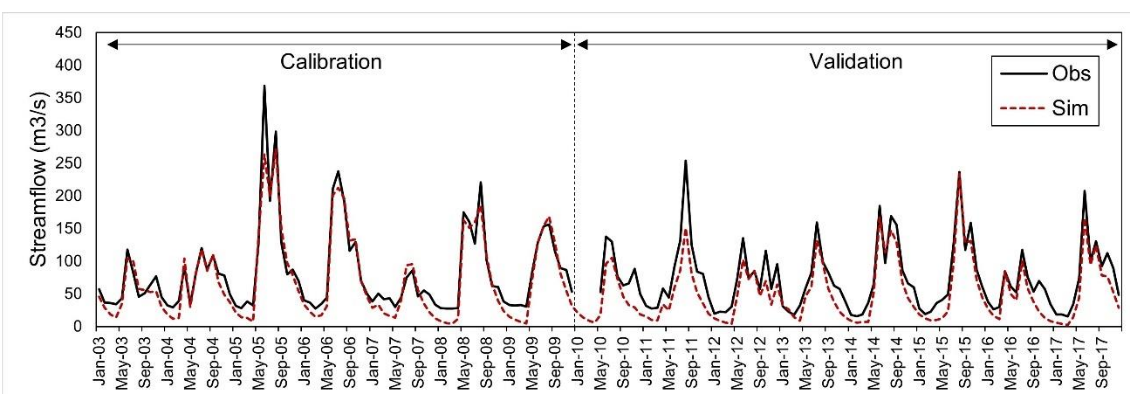

Figure 4.2: Observed and simulated streamflow from SWAT model – Río Claro in Rauquén

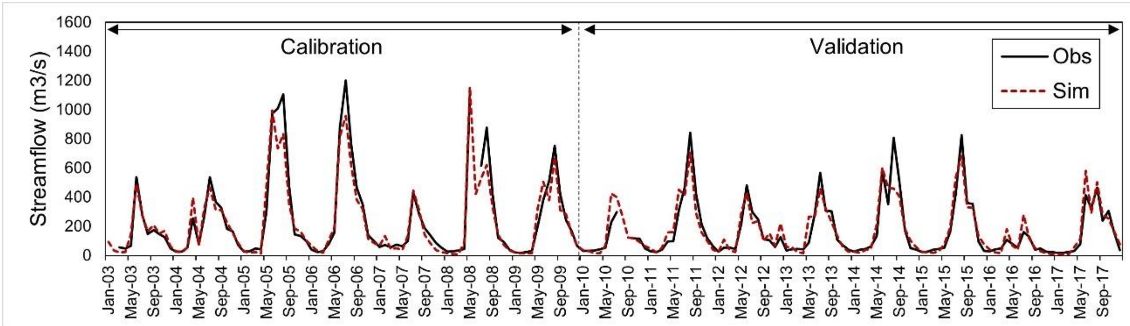

Figure 4.3: Observed and simulated streamflow from SWAT model – Río Loncomilla in Brisas

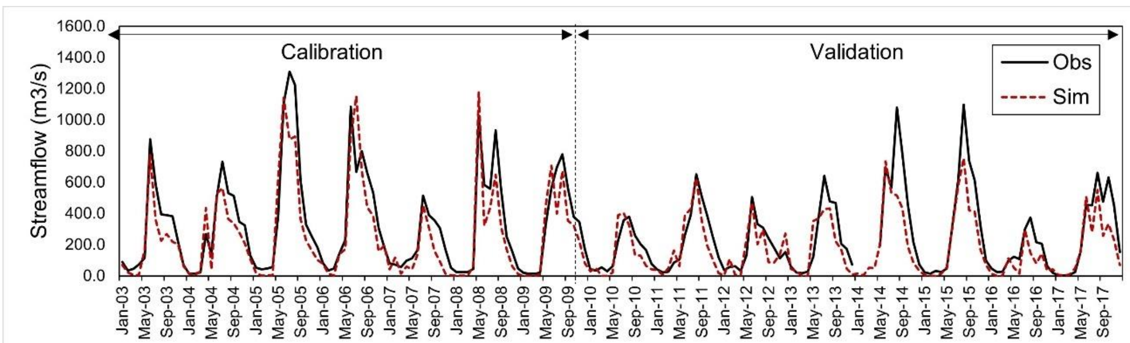

Figure 4.4: Observed and simulated streamflow from SWAT model – Río Itata in Coelemu

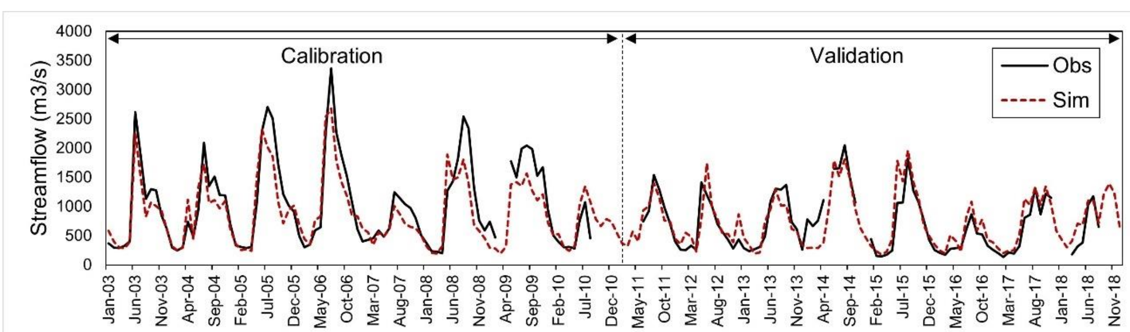

Figure 4.5: Observed and simulated streamflow from SWAT model – Río biobío in Desembocadura

Table 4.1: Model performance in main outlets of the basins (monthly flows)

	Río Claro in Rauquén		**Río Loncomilla in Brisas**	
	Calibration	Validation	Calibration	Validation
NSE	0.90	0.71	0.93	0.86
RSR	0.32	0.54	0.27	0.37
PBIAS (%)	12.38	28.92	6.47	-2.12
R^2	0.92	0.90	0.94	0.86
	Río Itata in Coelemu		**Río Biobío in Desembocadura**	
	Calibration	Validation	Calibration	Validation
NSE	0.79	0.72	0.79	0.76
RSR	0.45	0.53	0.45	0.49
PBIAS (%)	20.94	24.57	12.1	-5.4
R^2	0.84	0.78	0.84	0.77

The detail for all calibrated and validated subbasins is shown in Appendix 4.1.

4.2. Climate projections – Trend Analysis

4.2.1. Precipitation

Once the hydrological model was calibrated and validated for the three basins, it was run 4 times, for each GCM (CCSM4, CSIRO, IPSL and MIROC) precipitation and temperature dataset. A trend analysis was performed using the MK test for precipitation and flow rates for each of the basins. In the case of precipitation, the average value provided as output by SWAT (period 1982 - 2060) was used, and for the flow rates, the data from the validated outlet stations of each of the basins were analyzed.

According to the Z-test values obtained by performing the Mann Kendall test on the mean annual precipitation per basin, negative values show that there is a downward trend for the climatic data of the 4 GCMs studied which is reflected in the changes according to sen's slope values (Table 4.2). However, the CSIRO model does not show a significant downward trend. According to the Chilean National Water Balance, this can be explained by the low climatic sensitivity of the CSIRO model, i.e., it shows low modifications to minor variations in atmospheric conditions.

Table 4.2: Mann Kendall Test Z and sen's slope values and P values of Student's t-test for precipitation data.

	Test Z – Sen's slope						**Test T p values**		
Time series	**Maule**		**Itata**		**Biobío**		**Maule**	**Itata**	**Biobío**
CCSM4	-2.10	-3.89	-2.39	-3.96	-2.33	-3.35	0.04	0.04	0.04
IPLS	-5.43	-9.86	-5.55	-10.06	-5.78	-10.77	0.00	0.00	0.00
CSIRO	-1.24	-2.13	-1.06	-1.94	-1.49	-2.37	0.31	0.19	0.13
MIROC	-3.51	-5.67	-3.67	-5.78	-3.52	-4.82	0.01	0.01	0.01

4.2.2. Streamflow

In the case of the streamflow obtained from the SWAT model with each GCM data set in the same period, there is also a tendency to decrease, as a consequence of the main influence of precipitation on the flows, added to the changes in temperature. As the trends were analyzed in the validated stations from the model (Figure 4.1) the trend and its significance were analyzed at sub-basins level. In this case, according to the significance of the trend, the CSIRO model presents p-values that dismiss it, except in Biobío where, although it has better results, it does not reach a significant value ($p>0.05$). The CCSM4 model presents a value of $p>0.05$ for the Maule and Itata basins and is slightly lower in the Biobío river basin.

Regarding the magnitude of the trend, the results obtained with the Mann-Kendall test are consistent with the T-test. The CSIRO model shows a non-significant change in mean annual streamflow. For the CCSM4, IPLS and MIROC models, the magnitude of the flow reduction is significant. Z values and p-values from validated control points are shown in Appendix 4.2.

4.3. Drought evaluation

The results of the drought analysis are presented as the change in the average of each characteristic (magnitude, duration, and frequency) between the 4 GCMs evaluated for each period: Past (1993-2019) and Future (2034- 2060).

4.3.1. Meteorological Drought

Based on the SPI value, there are changes in the three characteristics analyzed across the entire study area. In the case of meteorological droughts, magnitude, duration, and frequency have an upward trend in most of the area, except for the southern zone of the Biobío basin and some areas in the Maule basin (Figure 4.6a). In terms of magnitude, there is a notable increase in the Andes mountains zone of the Maule basin of up to 50% and a slight decrease in the south, with a further increase in the Andes mountains zone of the Biobío basin, reaching increases of more than 60%. In the areas where a decrease in magnitude is observed, these changes are less than 10% in the Maule and Itata basins and raise to a 16% decrease in the south of the Biobío basin. In the case of the Maule basin, the greatest increases in magnitude are found near 2000 m of elevation, where snow precipitation is present during winter.

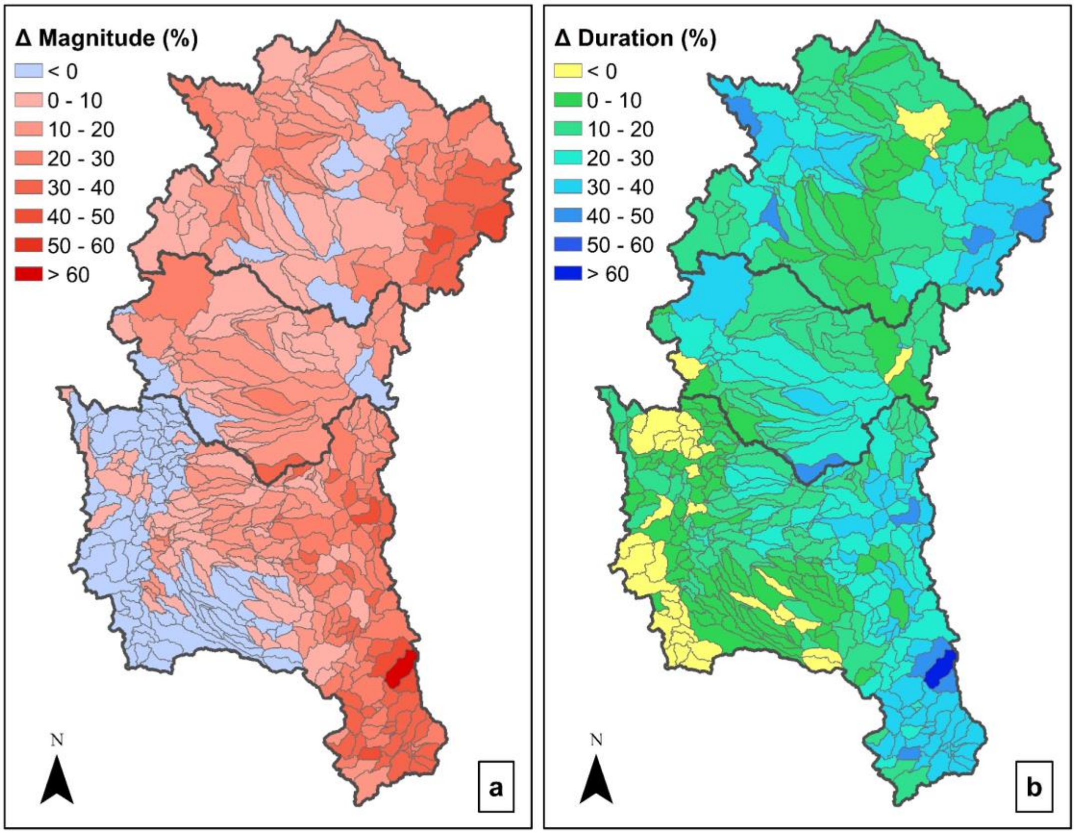

Figure 4.6: Changes in Magnitude (a) and Duration (b) of meteorological drought.

The duration of meteorological drought events also has important changes in the study area (Figure 4.6b). In most of the studied area, the duration increases, being this increase smaller in the valley areas with changes between 10-20%, which is greater in the western part of the Maule river basin and the Andes mountain range, reaching up to 60% of variation. There are areas where a decrease in the duration of droughts is projected, in particular, in the south of the Biobío basin and in certain areas of the Maule and Itata basins. The valley zone in the Maule basin shows smaller changes in duration than the west zone and the upper zone. This same pattern is repeated in the Biobío basin, where at the Andes mountain range, increases between 30% and 60% in duration can be observed. The situation in the Itata river basin is slightly different, since the valley is where there are greater increases in the duration of droughts, reaching its maximum in the southern part of the basin.

Magnitude and duration changes were also analyzed to determine their relationship with the frequency of droughts. The frequency of drought has increased in all the study area (Figure 4.7). The areas with the greatest changes are the central valley of the Maule basin, which includes the Perquilauquén, Longaví and Achibueno rivers, and the area close to the mouth of the Biobío river, where the city of Concepción is situated. In terms of the relationship between magnitude-duration and frequency, the areas that show decreases in magnitude and duration show an increase in frequency. The same happens in the opposite case in the Biobío at the Andes mountain range, where the greatest changes in magnitude and duration occur, there is less increase in the frequency of meteorological drought events, which reflects an equally serious situation. The variation in the frequency of events should not be analyzed as a future projection of the exact number of events that will occur, but as the trend of change, since they can be considered individual events of short duration, which may behave as one of longer duration if followed over a period of time.

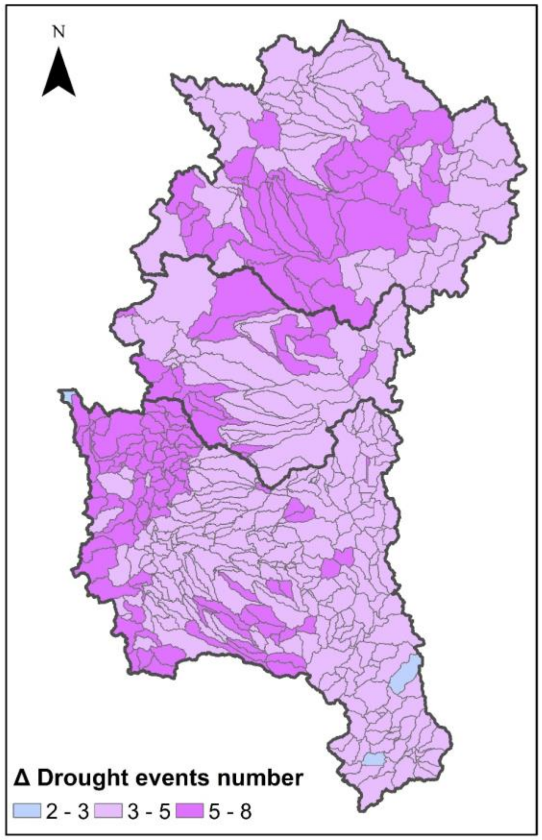

Figure 4.7: Changes in frequency of meteorological drought.

4.3.2. Hydrological Drought

Based on the SSI values, in the case of hydrological droughts, the changes vary in spatial distribution differently compared to the variations of meteorological drought. Although precipitation is the most important factor for surface runoff, there are other processes involved in the hydrological balance that were not evaluated in this study, such as changes in evapotranspiration due to increased temperatures, or changes in soil infiltration that can produce changes in spatial distribution beyond changes in precipitation.

The most affected basin with reference to the magnitude of the changes is the Itata river basin, where increases in the magnitude of droughts are projected throughout the territory (Figure 4.8a). In particular, in the area that includes the Diguillín river, the average change in the magnitude of droughts between the past and future periods is greater than 100%, showing a possible duplication of the magnitude of the events. Another important tributary of the Itata River, the Ñuble River in the north of the basin also reaches changes close to 100%. The Biobío basin, as in the case of meteorological droughts, shows an increase in the magnitude of droughts in the central zone and part of the mountain range.

Hydrological droughts have a substantial increase in duration in almost the entire area. The Itata river basin shows an increase in duration over its entire territory, where the Diguillín river subbasin is the area with the greatest changes, following the behavior of this area with respect to changes in magnitude (Figure 4.8b). This aggravates the situation by having droughts with increases in magnitude and duration, since they will have short and long term effects. The northern zone of the Biobio river basin shows increases in duration greater than 60%.

It is shown that areas that do present an important change in the average duration of hydrological droughts present smaller changes in magnitude. The severity of this is due to the cumulative effect of the duration of a mild drought.

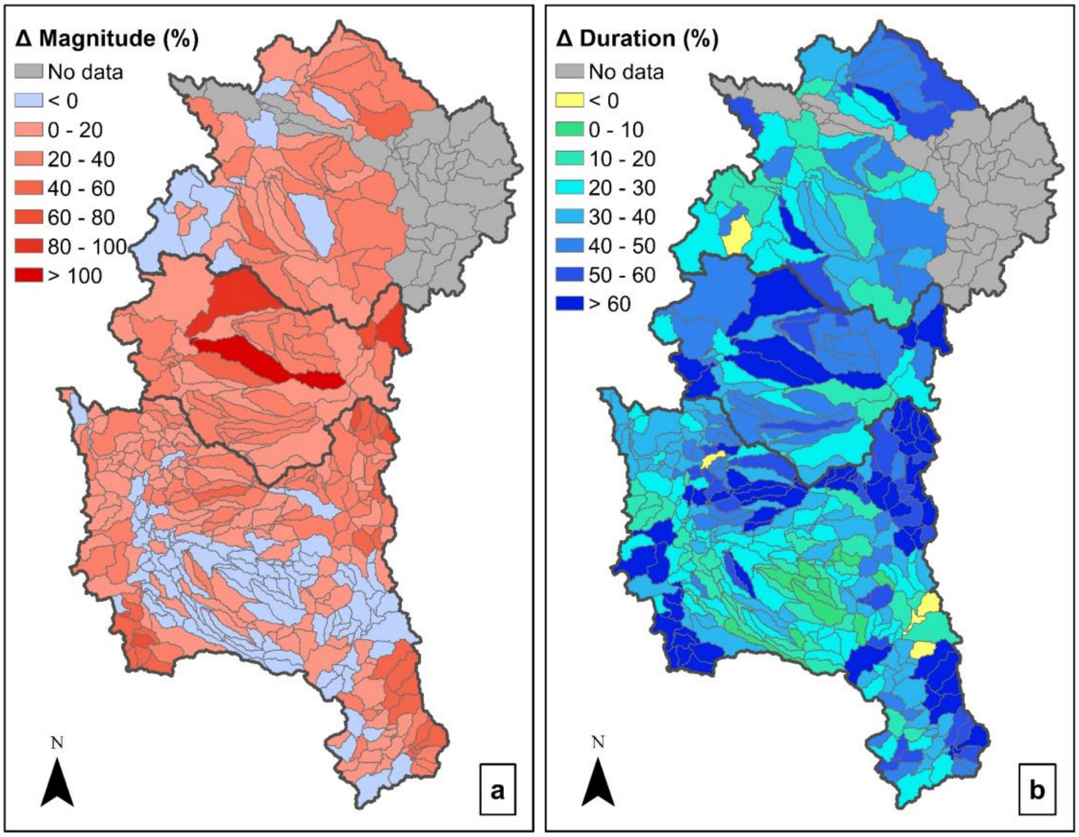

Figure 4.8: Changes in Magnitude (a) and Duration (b) of hydrological drought.

Referring to the relationship between the changes in the 3 characteristics, the frequency of events increases throughout the territory, unlike what happens with duration and magnitude (Figure 4.9). This is extremely relevant since, when working with averages, an average decrease in magnitude together with a decrease in duration and an increase in frequency, means that this decrease is at the expense of an increase in the number of short duration events in the future time period.

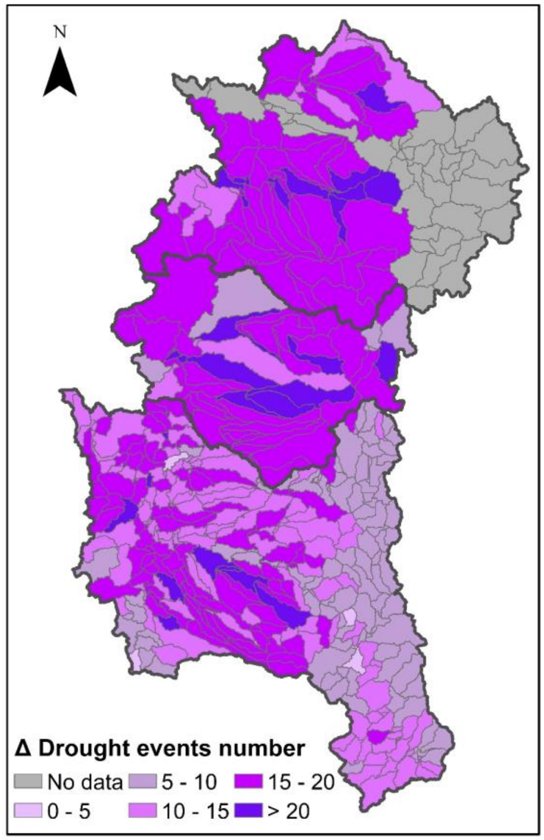

Figure 4.9: Changes in frequency of hydrological drought.

The change in the number of events per period is much greater in hydrological drought than in meteorological drought. As mentioned previously, the change in the number of events for a 27-year drought analysis may appear too high (>20 events), however it should be considered that events of short duration can be reflected as a constant dry condition. Regarding the trend of the changes, these have a marked increase in occurrence in the basin of the Maule and Itata rivers, and it is lower in the Biobío Andes mountain range.

4.4. Discussion

4.4.1. Evaluation of temporal and spatial behaviour of droughts

The previous section showed the results obtained from the comparison of drought events between a past and a future period through standardized indices. The spatial distribution of the changes was obtained, identifying the areas that will be most affected, as well as verifying that there is a variation of drought events between the past and the future.

Although it was initially expected that the 3 characteristics analyzed would be strengthened throughout the study area, the results show that the only characteristic that shows a spatially uniform behavior of increase is the frequency of drought events.

In terms of spatial evaluation, meteorological droughts have an increase in magnitude and duration in most of the area studied, except for the southern zone of Biobío and isolated areas in Itata and Maule. However, these areas do have an increase in the frequency of events, which may even be greater than areas with a marked increase in duration and magnitude. The danger in the increased frequency of drought events, both meteorological and hydrological, lies in the difficulty of the basin and its water bodies to recover between events, maintaining a dry condition over time. If the drought is of greater magnitude or of longer duration, the water stress will be greater and the dry condition will be maintained longer, aggravating the situation.

On the other hand, in the case of meteorological droughts, it is possible to observe that the areas with the greatest increases in magnitude and duration are concentrated in the mountainous zone. This is of great relevance in basins with a mixed regime, such as those of this study, where snowmelt contributions, although less than rainfall, are relevant for water supply during the first dry months.

Hydrological droughts show greater increases in magnitude, duration and frequency of events than meteorological droughts. As previously mentioned, this will be directly reflected in water availability and scarcity. The Itata river basin, where the largest percentage increases in changes in magnitude and duration are observed, is a basin whose main economic activity is agriculture, currently having a complex system of irrigation canals to supply crops.

Regarding the temporal analysis of droughts, it should be taken into account that the initial period of comparison, i.e. from 1993 to 2019, considers what is called the "mega-drought", the most severe and longest drought event in the history of Chile. This aggravates the results obtained, taking into account that the analysis was carried out with respect to porcentual changes from present to future. Current conditions represent a base dry condition, which strengthens over time in most of the territory studied, both for meteorological and hydrological droughts.

4.4.2. Climate Projections

Climate change is an issue that has been affecting Chile for some time and therefore, the need to study its effects at local scale has become a priority (Monsalves-Gavilán et al., 2013). On one hand, there is the need to generate climatological databases, such as those used in this study, on a regional scale that can better reflect the future behavior of the climate in the area (Ye et al., 2021). The use of GCMs as a basis for drought studies has expanded in the world, but the uncertainties that these incorporate to the results must be taken into account. These uncertainties can be related to uncertainty related to the forcing scenarios, the use of different GCMs or uncertainty related to sub-GCM grid scale forcing and processes (Sung et al., 2020).

In this study we worked with 4 previously downscaled GCMs that project a trend of decreasing precipitation until 2060 in the central-southern zone of Chile. As mentioned earlier, water resources have been threatened for years in Chile by changes in the climate and is currently in an extremely worrying situation with respect to water availability. As prior background, Table 4.3 shows the trend of precipitation and temperature extremes in the study area over the last 30 years, from information gridded from the CR2MET product (CR2, 2018) based on observations.

Table 4.3: Mann Kendall Test for historic data from CR2MET product (1982 – 2019)

Time series	**Basin**	**Test Z**	**Significance**
Pcp	Maule	-2.48	Less than 0.05
	Itata	-2.39	Less than 0.05
	Biobío	-2.59	Less than 0.01
Tmin	Maule	1.22	
	Itata	0.80	
	Biobío	1.00	
Tmax	Maule	1.29	
	Itata	1.72	Less than 0.1
	Biobío	0.78	

According to this information, precipitation has a negative trend in the three basins, which is more significant in the Maule and Itata basins and has less significance in the Biobío basin. In other words, the base situation used to evaluate the changes in magnitude, duration and frequency of drought was an already unfavorable scenario affected by climate change.

With respect to the projections of each selected GCM, the mean annual precipitation is overestimated in simulations. Table 4.4 shows that although meteorological droughts (which only have precipitation as input data) are projected to increase in magnitude, duration and frequency in a large part of the study area (and that this will lead to greater changes in hydrological droughts), the precipitation used has a slight overestimation in Maule and Itata basins, so the projected changes could be even more unfavorable with better quality climatic data.

Table 4.4: Relative differences in mean annual precipitation between historic data and GCM estimations (1982 – 2019)

Relative difference Mean Annual Rainfall (1982 - 2019)					
Subbasin	**CR2MET (mm)**	**CCSM4**	**IPLS**	**CSIRO**	**MIROC**
Maule	1195.09	16%	13%	17%	13%
Itata	1270.44	18%	15%	18%	16%
Biobio	1941.26	-14%	-16%	-14%	-16%

In addition, it should be taken into account that the projections do not consider anomalous events that may increase the effects of droughts such as the La Niña, which in Chile generates dry years, or ENSO, which increase extreme precipitation events and lead to other serious events such as floods. Also, this study did not include human activities or future land use changes that would also potentially affect drought characteristics. This study provides an initial point for further analysis considering that drought analysis needs to include human influences while population is constantly growing, agricultural activities are intensified, and more extreme weather events are expected.

4.4.3. Drought evaluation

In this study, the results are presented in a spatially distributed manner, making it possible to observe the distribution of changes in the characteristics of droughts over the territory covering the three basins under study. The spatial distributions of the drought indices are useful to define the territories (sub-basins, agro-climatic areas and croplands) that are more affected by drought episodes and could serve as support to better face its effects, and to focus the resources needed to cope with this type of meteorological events.(Sarricolea Espinoza & Meseguer-Ruiz, 2015)

Initially, it was predicted that the changes would follow the same trend in the 3 characteristics evaluated, increases in magnitude, duration and frequency, but it was verified that although the changes are evident, frequency is the only characteristic that has a clear increase in all the study area with the projected climate variations. This is in line with the IPCC sixth report (2021), which states that droughts will increase in frequency and magnitude due to higher temperatures and lower precipitation.

A decrease in precipitation leads to a strengthening of meteorological droughts. A meteorological drought in a basin area results in a hydrological drought, due to the cumulative negative effect over time (Wu et al., 2021; Wang et al., 2021). Basins have different responses to the lack of precipitation. For example, the Maipo basin in Central Chile, that has a nival regime, has shown a slow response where streamflow responds with a delay of four months or more to precipitation deficit. (Oertel et al., 2018). This study also found that the highest correlation of SSI with SPI-12 denotes the dependence of the streamflow on the previous year of precipitation. According to Alvarez-Garreton et al. (2021), in South-Central Chile (30 - 41°S) single-year extreme droughts induce larger absolute streamflow deficits (i.e. less water supply) and moderate but persistent deficits induce a more intensified propagation of the meteorological drought (larger streamflow deficits relative to precipitation). When a study is conducted in central Chile, its results can benefit all Mediterranean areas of the world. Due to the similarity of their climates, the expected impact of climate change is similar, making these areas warmer and drier in the future. (Peña-Guerrero et al., 2020). For example, in the Jucar River Basin in Spain, a Mediterranean basin, results have shown that the climate change scenarios lead to a general increase in the severity of both meteorological and hydrological droughts, due to the combined effects of rainfall reduction and evapotranspiration increase. (Marcos-Garcia et al., 2017)

When working with SPI - 12 and SSI - 12, the analysis shown reflects the cumulative effect of 12 months (SPI) and 12 years (SSI) in the area. When working with this time scale, the effects are not only analyzed at the level of surface water, such as the supply of reservoirs or the maintenance of ecological flows in the rivers of the area but would also have important effects on the reduction of aquifer recharge, threatening another important reserve and source of water, which is groundwater.

As mentioned above, the origin of the scaled GCMs data evaluated are from the report “Application of the national water balance updating methodology in the basins of the northern and central macrozones” (DGA, 2018) in which these data were used to make the national water balance of Chile. The variations in precipitation presented in the report show agreement with the results obtained in this drought analysis. Within the study area, the greatest net changes of precipitation occur in the mountain range, as shown in the analysis of meteorological droughts. On the other hand, in this report surface runoff was obtained from hydrological modeling with the VIC model. The changes presented in surface runoff show that the greatest decreases are found in the Andes

Mountain range and towards the valley these changes are smaller. On the coast, the decrease in runoff increases again.

4.4.4. Long-term effects of droughts

Changes in land use are an important variable not considered in this study. With the effects of climate change, it is likely that agricultural activity will shift to the south of the country, increasing the demand for water resources available in less affected areas. The number of irrigation reservoirs in the study area is significant in the valley of the Maule and Itata river basin, an area where increases are expected in all the drought characteristics analyzed. Given that the evaluation is annual, i.e., accumulated in 12 months, the reservoirs receive special attention since the possibility of having water reserves in them for the dry season in the summers is threatened.

Another risk associated with water scarcity and soil moisture is the risk of forest fires, which have already had a strengthening and changes in their behavior, with a longer season in the year. Although this study focused on changes in precipitation, it should be mentioned that with the increase in temperatures, snow reserves in the mountain range are also threatened and surface water supplies, such as reservoirs, will be more affected by evaporation.

Drought is not a sudden event and is hard to predict its occurrence, magnitude, and duration. Drought is a natural disaster which is not apparent until its final stage (Mahdavi et al., 2021). Climate projections and hydrological modeling are a good approach to evaluate droughts based on past events, but sometimes these are difficult to distinguish because drought is a cumulative event, and its effects are seen over time.

4.5. Conclusions

In this chapter, the changes obtained in the 3 characteristics analyzed in the drought events in the central-southern zone of Chile were presented. The results were presented graphically and in terms of percentage changes between the base situation and the future. Additionally, the quality of the input data, the baseline situation and the effect of these results in the study area were discussed.

CHAPTER 5: CONCLUSIONS

In this study, Standardized Precipitation Index (SPI) and Standardized Streamflow Index (SSI) were used to assess relative changes in future meteorological and hydrological drought due to climate change in 3 important basins in South central Chile. Climate projections from 4 downscaled GCMs (CCSM4, IPLS, CSIRO, MIROC) for the future IPCC scenario RCP 8.5 were used to estimate SPI values for meteorological drought. For hydrological drought, SWAT model was the selected tool to obtain future streamflow from GCMs climate projections to calculate SSI and evaluate drought characteristics. A model was calibrated and validated for each basin. Trend analysis was performed to precipitation and streamflow projections showing a significant downward trend in both for the three studied basins.

As a result, there was an increase in the frequency of meteorological and hydrological drought events throughout the territory. The magnitude of meteorological droughts will be greater in the highlands and with smaller changes in the southern part of the Biobío river basin. The magnitude of hydrological droughts will be greater in the Itata river basin, where it will increase the most. The duration of meteorological droughts has a similar behaviour to the magnitude but with greater increases on the Maule coast. The increases in the duration of hydrological drought events are greater, with less impact in the Biobío river basin and the greatest in the Itata river basin.

Although the results show an alarming and dangerous situation for a country that is already under water stress, it is important to note that the impact of climate change goes alongside the increase in demand from different productive sectors due to the explosive economic growth. In this way, it is important to highlight that although this study presents a projection of the relative changes of droughts in the future, at this point prevention and actions should be reflected in an improvement in the management of the resources that will be available in the future.

CHAPTER 6: REFERENCES

Abbaspour, K. C. (2014). *Swat-Cup 2012: SWAT Calibration and Uncertainty Program—A User Manual.* Swiss Federal Institute of Aquatic Science and Technology.

Abbaspour, K. C., Rouholahnejad, E., Vaghefi, S., Srinivasan, R., Yang, H., & Kløve, B. (2015). A continental-scale hydrology and water quality model for Europe: Calibration and uncertainty of a high-resolution large-scale SWAT model. *Journal of Hydrology, 524,* 733–752. https://doi.org/10.1016/j.jhydrol.2015.03.027

Abbott, M.B., Bathurst, J.C., Cunge, J.A., O'Connell, P.E., & Rasmussen, J. (1986a). An introduction to the European Hydrological 'SHE' 1. History and philosophy of a physically-based, distributed modeling system. *Journal of Hydrology, 87*, 45–59. https://doi.org/10.1016/0022-1694(86)90114-9

Abbott, M.B., Bathurst, J.C., Cunge, J.A., O'Connell, P.E., & Rasmussen, J. (1986b). An introduction to the European Hydrological System, 'SHE' 2. Structure of physically-based, distributed modeling system. *Journal of Hydrology, 87,* 61–77. https://doi.org/10.1016/0022-1694(86)90115-0

Aguayo, M., Stehr, A., & Link, O. (2016). Respuesta hidrológica de una cuenca de meso escala frente a futuros escenarios de expansión forestal. *Revista de Geografía Norte Grande, 65*, 197–214. https://doi.org/10.4067/s0718-34022016000300010

Alvarez-Garreton, C., Pablo Boisier, J., Garreaud, R., Seibert, J., & Vis, M. (2021). Progressive water deficits during multiyear droughts in basins with long hydrological memory in Chile. *Hydrology and Earth System Sciences*, *25*(1), 429–446. https://doi.org/10.5194/hess-25-429-2021

Arnold, J. G., Srinivasan, R., Muttiah, R. S., & Williams, J. R. (1998). Large area hydrologic modeling and assessment part I: model development. *Journal of the American Water Resources association, 34*(1), 73–89.

Arnold, J. G., Kiniry, J. R., Srinivasan, R., Williams, J. R., Haney, E. B., & Neitsch, S. L. (2012). *SWAT 2012 Input/output documentation.* Texas Water Resources Institute.

Armesto, J., Arroyo, M. y Hinojosa Opazo, L. (2007).*The mediterranean environment of Central Chile*. https://repositorio.uchile.cl/handle/2250/120061

Bariamis, G., & Baltas, E. (2021). Hydrological modeling in agricultural intensive watershed: The case of upper east fork white river, USA. *Hydrology*, *8*(3). https://doi.org/10.3390/hydrology8030137

Beven, K.J., Alver, A.C., & Morris, E.M. (1987). *The Institute of Hydrology Distributed Model (HDM).* Institute of Hydrology, United Kingdom.

Bergström, S. (1992). *The HBV-Model—Its Structure and Applications*. SMHI Reports RH No. 4, Norrköping, Sweden.

Bin Luhaim, Z., Tan, M. L., Tangang, F., Zulkafli, Z., Chun, K. P., Yusop, Z., & Yaseen, Z. M. (2021). Drought variability and characteristics in the muda river basin of malaysia from 1985 to 2019. *Atmosphere, 12*(9), 1–19. https://doi.org/10.3390/atmos12091210

Blade, E., Sánchez, H., Dolz, J., Sanchez, M., Dominguez, R., Arganis, M., Carrizosa, E., Esquivel, G., & Juárez, J. (2014). *Estimación del hidrograma de salida en una cuenca usando un modelo hidrológico distribuido y un modelo hidráulico bidimensional en volúmenes finitos.* Instituto Flumen - Instituto de Ingeniería de la UNAM.

Boisier, J. P., Alvarez-Garretón, C., Cepeda, J., Osses, A., Vásquez, N., & Rondanelli, R. (2018). CR2MET: A high-resolution precipitation and temperature dataset for hydroclimatic research in Chile. *Geophysical Research Abstracts, 20,* 19739.

Boretti, A., & Rosa, L. (2019). Reassessing the projections of the World Water Development Report. *Npj Clean Water, 2*(1). https://doi.org/10.1038/s41545-019-0039-9

Bozkurt, D., Rojas, M., Boisier, J. P., & Valdivieso, J. (2018). Projected hydroclimate changes over Andean basins in central Chile from downscaled CMIP5 models under the low and high emission scenarios. *Climatic Change*, *150*(3–4), 131–147. https://doi.org/10.1007/s10584-018-2246-7

Caloiero, T., Veltri, S., Caloiero, P., & Frustaci, F. (2018). Drought analysis in Europe and in the Mediterranean basin using the standardized precipitation index. *Water*, *10*(8), 1–13. https://doi.org/10.3390/w10081043

Cibin, R., Sudheer, K. P., & Chaubey, I., (2010). Sensitivity and identifiability of stream flow generation parameters of the SWAT model. *Hydrological Processes*, *24*(9), 1133–1148. https://doi.org/10.1002/hyp.7568

CIREN (1997). *Estudio agrológico VIII Región*. Natural Resources Information Center. Chile.

CIREN (1999). *Estudio agrológico VII Región*. Natural Resources Information Center. Chile.

CIREN (2002). *Estudio agrológico IX Región*. Natural Resources Information Center. Chile.

CNE (2021) GEO portal. Comisión Nacional de Energía. Chile. http://energiamaps.cne.cl/

Danandeh Mehr, A., Sorman, A. U., Kahya, E., & Hesami Afshar, M. (2020). Climate change impacts on meteorological drought using SPI and SPEI: case study of Ankara, Turkey. *Hydrological Sciences Journal, 65*(2), 254–268. https://doi.org/10.1080/02626667.2019.1691218

Diaz, G., Arriagada, P., Górski, K., Link, O., Karelovic, B., Gonzalez, J., & Habit, E. (2019). Fragmentation of Chilean Andean rivers: Expected effects of hydropower development. *Revista Chilena de Historia Natural, 92*(1), 1–13. https://doi.org/10.1186/s40693-019-0081-5

DGA. (2004a). *Cuenca del río Itata. Diagnóstico y clasificación de los cursos y cuerpos de agua según objetivos de calidad*. General Directorate of Water. Santiago, Chile.

DGA. (2004b). *Cuenca del río Maule. Diagnóstico y clasificación de los cursos y cuerpos de agua según objetivos de calidad*. General Directorate of Water. Santiago, Chile.

DGA. (2004c). Evaluación de los recursos hídricos superficiales en la cuenca del rio Bio bío. General Directorate of Water. Santiago, Chile.

DGA. (2016). *Atlas del Agua Chile 2016*. General Directorate of Water. Santiago, Chile.

DGA. (2017). *Actualización del Balance Hídrico Nacional. SIT N° 417*. Ministry of Public Works, General Directorate of Water, Studies and Planning Division, Universidad de Chile & Pontificia Universidad Católica de Chile. Santiago, Chile. https://snia.mop.gob.cl/sad/REH5796v1.pdf

DGA. (2018). *Aplicación de la metodología de actualización del balance hídrico nacional en las cuencas de las macrozonas norte y centro. SIT N° 435*. Ministry of Public Works, General Directorate of Water, Planning Studies Division, Foundation for Technological for Technology Transfer and Pontificia Universidad Católica de Chile. Santiago, Chile.

Du Plessis, J. A., & Kalima, S. G. (2021). Modelling the impact of climate change on the flow of the Eerste River in South Africa. *Physics and Chemistry of the Earth*, *124*(P1), 103025. https://doi.org/10.1016/j.pce.2021.103025

FAO. (2012). Coping with water scarcity: An action framework for agriculture and food security. *Soil Science, 153(3)*. https://doi.org/10.1097/00010694-199203000-00010

FAO & UNESCO. (1971). *Soil Map of the World 1: 5.000.000.* Agriculture Organization of the United Nations and United Nations Educational. Paris, France.

Galleguillos, M., Gimeno, F., Puelma, C., Zambrano-Bigiarini, M., Lara, A., & Rojas, M. (2021). Disentangling the effect of future land use strategies and climate change on streamflow in a Mediterranean catchment dominated by tree plantations. *Journal of Hydrology*, *595*. https://doi.org/10.1016/j.jhydrol.2021.126047

Geophysical Fluid Dynamics Laboratory. (n.d.). *Climate modeling*. Princeton University Forrestal Campus. https://www.gfdl.noaa.gov/wp-content/uploads/files/model_development/climate_modeling.pdf

Giri, S., Mishra, A., Zhang, Z., Lathrop, R. G., & Alnahit, A. O. (2021). Meteorological and hydrological drought analysis and its impact on water quality and stream integrity. *Sustainability, 13*(15), 1–24. https://doi.org/10.3390/su13158175

Grusson, Y., Wesström, I., Svedberg, E., & Joel, A. (2021). Influence of climate change on water partitioning in agricultural watersheds: Examples from Sweden. *Agricultural Water Management*, *249*. https://doi.org/10.1016/j.agwat.2021.106766

Guppy, L., & Anderson, K. (2017). *Water crisis report*. United Nations University Institute for Water, Environment and Health. Hamilton, Canada.

Hamman, J. J., Nijssen, B., Bohn, T. J., Gergel, D. R., & Mao, Y. (2018) The Variable Infiltration Capacity model version 5 (VIC-5): infrastructure improvements for new applications and reproducibility. *Geoscientific Model Development*., *11*, 3481-3496, https://doi.org/10.5194/gmd-11-3481-2018

Hao, Y., Ma, J., Chen, J., Wang, D., Wang, Y., & Xu, H. (2018). Assessment of changes in water balance components under 1.5 °C and 2.0 °C global warming in transitional climate basin by multi-RCPs and multi-GCMs approach. *Water, 10*(12). https://doi.org/10.3390/w10121863

Cramér, H. (1928). On the composition of elementary errors. *Scandinavian Actuarial Journal, 1928*(1), 13-74. https://doi.org/10.1080/03461238.1928.10416862

Hargreaves, G., & Samani, Z. A. (1985). Reference Crop Evapotranspiration from Temperature. *Applied Engineering in Agriculture*, *1*(2), 96–99. https://doi.org/10.13031/2013.26773

Huang, Y. F., Ang, J. T., Tiong, Y. J., Mirzaei, M., & Amin, M. Z. M. (2016). Drought Forecasting using SPI and EDI under RCP-8.5 Climate Change Scenarios for Langat River Basin, Malaysia. *Procedia Engineering*, *154*, 710–717. https://doi.org/10.1016/j.proeng.2016.07.573

Hussain, F., Nabi, G., & Waseem Boota, M. (2015). Rainfall trend analysis by using the Mann-Kendall Test & Sen'S Slope estimates: a case study of District Chakwal Rain Gauge, Barani Area, Northern Punjab Province, Pakistan. *Science International-Lahore*, *27*,3159–3165.

IPCC. (2014). *Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. Intergovernmental Panel on Climate Change. Geneva, Switzerland.

IPCC. (2018). *Global warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global* *response to the threat of climate change.* Intergovernmental Panel on Climate Change.

IPCC. (2021). *Climate Change 2021 Working Group I contribution to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change.* Intergovernmental Panel on Climate Change. Geneva, Switzerland.

Kendall, M. G. (1975). *Rank Correlation Methods*. Griffin, London, UK.

Khoi, D. N., Sam, T. T., Loi, P. T., Hung, B. V., & Nguyen, V. T. (2021). Impact of climate change on hydro-meteorological drought over the Be River Basin, Vietnam. *Journal of Water and Climate Change*, *12*(7), 3159–3169. https://doi.org/10.2166/wcc.2021.137

Kim, W., Lee, J., Kim, J., & Kim, S. (2019). Assessment of Water Supply Stability for Drought-Vulnerable Boryeong Multipurpose Dam in South Korea Using Future Dry Climate Change Scenarios. *Water, 11*(11), 2403. https://doi.org/10.3390/w11112403

Kim, J. H., Sung, J. H., Chung, E. S., Kim, S. U., Son, M., & Shiru, M. S. (2021). Comparison of projection in meteorological and hydrological droughts in the cheongmicheon watershed for rcp4.5 and ssp2-4.5. *Sustainability*, *13*(4), 1–22. https://doi.org/10.3390/su13042066

Kummu, M., Ward, P. J., De Moel, H., & Varis, O. (2010). Is physical water scarcity a new phenomenon? Global assessment of water shortage over the last two millennia. *Environmental Research Letters*, *5*(3). https://doi.org/10.1088/1748-9326/5/3/034006

Li, Y., Lu, H., Yang, K., Wang, W., Tang, Q., Khem, S., Yang, F., & Huang, Y. (2021). Meteorological and hydrological droughts in Mekong River Basin and surrounding areas under climate change. *Journal of Hydrology: Regional Studies*, *36*, 100873. https://doi.org/10.1016/j.ejrh.2021.100873

Liang, X., Lettenmaier, D. P., Wood, E. F., & Burges, S. J. (1994), A simple hydrologically based model of land surface water and energy fluxes for general circulation models, *Journal of Geophysical Research*, ***99***(D7), 14415–14428, https://doi.org/10.1029/94JD00483.

Lorenzo-Lacruz, J., Mo ́ran-Tejeda, E., Vicente-Serrano, S. M., & ́Lopez-Moreno, J. I. (2013). Streamflow droughts in the Iberian Peninsula between 1945 and 2005: Spatial and temporal patterns. *Hydrology and Earth System Sciences*, *17*(1), 119–134. https://doi.org/10.5194/hess-17-119-2013

Mahdavi, P., Kharazi, H. G., Eslami, H., Zohrabi, N., & Razaz, M. (2021). Drought occurrence under future climate change scenarios in the Zard River basin, Iran. *Water Supply*, *21*(2), 899–917. https://doi.org/10.2166/ws.2020.367

Malik, M. A., Dar, A. Q., & Jain, M. K. (2021). Modelling streamflow using the SWAT model and multi-site calibration utilizing SUFI-2 of SWAT-CUP model for high altitude catchments, NW Himalaya's. *Modeling Earth Systems and Environment*. https://doi.org/10.1007/s40808-021-01145-0

Mann, H. B. (1945) Nonparametric tests against trend. *Econometrica,13*, 245–259

Marcos-Garcia, P., Lopez-Nicolas, A., & Pulido-Velazquez, M. (2017). Combined use of relative drought indices to analyze climate change impact on meteorological and hydrological droughts in a Mediterranean basin. *Journal of Hydrology*, *554*, 292–305. https://doi.org/10.1016/j.jhydrol.2017.09.028

Martínez-Retureta, R., Aguayo, M., Stehr, A., Sauvage, S., Echeverría, C., & Sánchez-Pérez, J. M. (2020). Effect of land use/cover change on the hydrological response of a southern center basin of Chile. *Water*, *12*(1), 1–21. https://doi.org/10.3390/w12010302

Martínez-Retureta, R., Aguayo, M., Abreu, N. J., Stehr, A., Duran-Llacer, I., Rodríguez-López, L., Sauvage, S., & Sánchez-Pérez, J. M. (2021). Estimation of the climate change impact on the hydrological balance in basins of south-central Chile. *Water ,13*(6). https://doi.org/10.3390/w13060794

Mckee, T., Doesken, N., & Kleist, J. (1993). The relationship of drought frequency and duration to time scales. *Eight Conference of Applied Climatology*, 17–22.

Mengistu, A. G., Woyessa, Y. E., van Rensburg, L. D., & Tesfuhuney, W. A. (2021). Analysis of the spatio-temporal variability of soil water dynamics in an arid catchment in South Africa. *Geoderma Regional, 25.* https://doi.org/10.1016/j.geodrs.2021.e00395

MINAGRI. (2021). *Coyuntura agroclimática*. Institutional Management Department-Chilean Ministry of Agriculture. Chile.

Monsalves-Gavilán, P., Pincheira-Ulbrich, J., & Rojo Mendoza, F. (2013). Climate change and its effects on urban spaces in Chile: A summary of research carried out in the period 2000-2012. *Atmosfera, 26*(4), 547–566. https://doi.org/10.1016/S0187-6236(13)71095-6

Moriasi, D. N., Arnold, J. G., Van Liew, M. W., Bingner, R. L., Harmel, R. D., & Veith, T. L. (2007). Model evaluation guidelines for systematic quantification of accuracy in watershed simulations. *Transactions of the ASABE*, *50*(3), 885–900. https://doi.org/10.13031/2013.23153

Nalbantis, I. & Tsakiris, G. (2008) Assessment of hydrological drought revisited. *Water Resources Management*, *23*(5),881–897.

Naumann, G., Cammalleri, C., Mentaschi, L., & Feyen, L. (2021). Increased economic drought impacts in Europe with anthropogenic warming. *Nature Climate Change, 11*(6), 485–491. https://doi.org/10.1038/s41558-021-01044-3

Nazari-Sharabian, M., Taheriyoun, M., Ahmad, S., Karakouzian, M., & Ahmadi, A. (2019). Water quality modeling of Mahabad Dam watershed-reservoir system under climate change conditions, using SWAT and system dynamics. *Water*, *11*(2), 1–16. https://doi.org/10.3390/w11020394

NDMC. (2018). *SPI Generator* [Software] National Drought Mitigation Center, University of Nebraska. https://drought.unl.edu/Monitoring/SPI/SPIProgram.aspx

Neitsch, S. L., Arnold, J. G., Kiniry, J. R., Williams, J. R., & King, K. W. (2002). *Soil and Water Assesssment Tool Theoretical Documentation - Version 2000*. Texas Water Resources Institute. Texas. https://doi.org/10.1055/s-0029-1192096

Oertel, M., Meza, F. J., Gironás, J., Scott, C. A., Rojas, F., & Pineda-Pablos, N. (2018). Drought propagation in semi-arid river basins in Latin America: Lessons from Mexico to the Southern Cone. *Water*, *10*(11), 1–21. https://doi.org/10.3390/w10111564

Omer, A., Elagib, N. A., Zhuguo, M., Saleem, F., & Mohammed, A., (2020). Water scarcity in the Yellow River Basin under future climate change and human activities. *Science of the Total Environment, 749*, 141446. https://doi.org/10.1016/j.scitotenv.2020.141446

Orlowsky, B., & Seneviratne, S. I. (2013). Elusive drought: Uncertainty in observed trends and short-and long-term CMIP5 projections. *Hydrology and Earth System Sciences, 17*(5), 1765–1781. https://doi.org/10.5194/hess-17-1765-2013

Oyounalsoud, M. S., Najah, A., Yilmaz, A. G., Abdallah, M., & Siddique, M. (2022). Meteorological Drought Assessment in Sharjah, UAE Using Drought Indices. *International Journal of Environmental Science and Development*, *13*(1), 16–20. https://doi.org/10.18178/ijesd.2022.13.1.1366

Palmer, W.C. (1965) *Meteorological Drought. Research Paper No. 45.* US Weather Bureau, Washington, DC

Penedo-Julien, S., Nauditt, A., Künne, A., Souvignet, M., & Krause, P. (2018). Hydrological Modeling to Assess Runoff in a Semi-arid Andean Headwater Catchment for Water Management in Central Chile. *Andean Hydrology*, 231–253. https://doi.org/10.1201/9781315155982-10

Peña-Guerrero, M. D., Nauditt, A., Muñoz-Robles, C., Ribbe, L., & Meza, F. (2020). Drought impacts on water quality and potential implications for agricultural production in the Maipo River Basin, Central Chile. *Hydrological Sciences Journal*, *65*(6), 1005–1021. https://doi.org/10.1080/02626667.2020.1711911

Perrin, C., Michel, C., & Andréassian, V. (2003). Improvement of a parsimonious model for streamflow simulation. *Journal of Hydrology*, *279*, 275–289. https://doi.org/10.1016/S0022-1694(03)00225-7.

Petpongpan, C., Ekkawatpanit, C., & Kositgittiwong, D. (2020). Climate change impact on surface water and groundwater recharge in northern Thailand. *Water, 12*(4). https://doi.org/10.3390/W12041029

Rashid, H., Yang, K., Zeng, A., Ju, S., Rashid, A., & Guo, F. (2022). Predicting the Hydrological Impacts of Future Climate Change in a Humid-Subtropical Watershed. *Atmosphere, 13*(1), 12. https://doi.org/10.3390/atmos13010012

Salmi, T., Määttä, A., Anttila, P., Ruoho-Airola, T., & Amnell, T. (2002). *Detecting Trends of Annual Values of Atmospheric Pollutants by the Mann-Kendall Test and Sen's Slope Estimates: The Excel Template Application MAKESENS*. Publications on Air Quality, 31.

Sarricolea Espinoza, P. A., & Meseguer-Ruiz, O. (2015). Sequías en Chile central a partir de diferentes índices en el período 1981-2010. *Investigaciones Geográficas*, *32*(50), 19. https://doi.org/10.5354/0719-5370.2015.41178

Sharannya, T. M., Venkatesh, K., Mudbhatkal, A., Dineshkumar, M., & Mahesha, A. (2021). Effects of land use and climate change on water scarcity in rivers of the Western Ghats of India. *Environmental Monitoring and Assessment*, *193*(12). https://doi.org/10.1007/s10661-021-09598-7

Shen, S., Song, C., Cheng, C., & Ye, S. (2020). The coupling impact of climate change on streamflow complexity in the headwater area of the northeastern Tibetan Plateau across multiple timescales. *Journal of Hydrology*, *588*, 124996. https://doi.org/10.1016/j.jhydrol.2020.124996

Siabi, E. K., Kabobah, A. T., Akpoti, K., Anornu, G. K., Amo-Boateng, M., & Nyantakyi, E. K. (2021). Statistical downscaling of global circulation models to assess future climate changes in the Black Volta basin of Ghana. *Environmental Challenges*, *5*, 100299. https://doi.org/10.1016/j.envc.2021.100299

Siad, S. M., Iacobellis, V., Zdruli, P., Gioia, A., Stavi, I., & Hoogenboom, G. (2019). A review of coupled hydrologic and crop growth models. *Agricultural Water Management*, 224, 105746. https://doi.org/10.1016/j.agwat.2019.105746

Stehr, A., Debels, P., Romero, F., & Alcayaga, H. (2008). Hydrological modelling with SWAT under conditions of limited data availability: Evaluation of results from a Chilean case study. *Hydrological Sciences Journal*, *53*(3), 588–601. https://doi.org/10.1623/hysj.53.3.588

Stehr, A., Aguayo, M., Link, O., Parra, O., Romero, F., & Alcayaga, H. (2010). Modelling the hydrologic response of a mesoscale Andean watershed to changes in land use patterns for environmental planning. *Hydrology and Earth System Sciences*, *14*(10), 1963–1977. https://doi.org/10.5194/hess-14-1963-2010

Sung, J. H., Park, J., Jeon, J. J., & Seo, S. B. (2020). Assessment of Inter-Model Variability in Meteorological Drought Characteristics Using CMIP5 GCMs over South Korea. *KSCE Journal of Civil Engineering*, *24*(9), 2824–2834. https://doi.org/10.1007/s12205-020-0494-3

Sutanto, S., & Van Lanen, H. (2020). Streamflow drought: implication of drought definitions and its application for drought forecasting. *Hydrology and Earth System Sciences Discussions*, 1–29. https://doi.org/10.5194/hess-2020-458

Svoboda, M., & Fuchs, B. (2017). *Handbook of Drought Indicators and Indices.* Drought Mitigation Center Faculty Publications. 117. http://digitalcommons.unl.edu/droughtfacpub/117

The World Bank Group. (2021). *Climate Risk Profile: Chile*.

Trenberth, K. E., Dai, A., van der Schrier, G., Jones, P. D., Barichivich, J., Briffa, K. R., & Sheffield, J. (2014). Global warming and changes in drought. *Nature Climate Change*, *4,* 17-22. https://doi.org/10.1038/nclimate2067

USDA-SCS. (1972). *National Engineering Handbook*. *NEH Notice, 4,*4-102.

UNCC. (2019). *Climate action and support trends*. United Nations Climate Change Secretariat. Bonn, Germany.

UN-Water (2021). *Summary Progress Update 2021 : SDG 6 — water and sanitation for all. In UN-Water integrated monitoring initiative*. Geneva, Switzerland.

Van Loon, A. F., Van Lanen, H. A. J., Hisdal, H., Tallaksen, L. M., Fendeková, M., Oosterwijk, J., Horvát, O., & Machlica, A. (2010). Understanding hydrological winter drought in Europe. *IAHS-AISH Publication*, *340*, 189–197.

Van Vuuren, D.P., Edmonds, J., Kainuma, J., Riahi, M. K., Thomson, A., Hibbard, K., Hurtt, G., Kram, T., Krey, V., Lamarque, J.F.,Meinhausen, M., Smith, S., &

Rose, K. (2011). The representative concentration pathways: an overview. *Climatic Change, 109,* 5–31. https://doi.org/10.1007/s10584-011-0148-z

Vicente-Serrano, S. M., Beguería, S., & López-Moreno, J. I. (2010). A multiscalar drought index sensitive to global warming: The standardized precipitation evapotranspiration index. *Journal of Climate*, *23*(7), 1696–1718. https://doi.org/10.1175/2009JCLI2909.1

Vicente-Serrano, S. M., López-Moreno, J. I., Beguería, S., Lorenzo-Lacruz, J., Azorin-Molina, C., & Morán-Tejeda, E. (2012). Accurate Computation of a Streamflow Drought Index. *Journal of Hydrologic Engineering*, *17*(2), 318–332. https://doi.org/10.1061/(ASCE)HE.1943-5584.0000433

Vicente-Serrano, S. M., Beguería, S., Lorenzo-Lacruz, J., Camarero, J. J., López-Moreno, J. I., Azorin-Molina, C., Revuelto, J., Morán-Tejeda, E., & Sanchez-Lorenzo, A., (2012). Performance of drought indices for ecological, agricultural, and hydrological applications. *Earth Interactions*, *16*(10), 1- 27. https://doi.org/10.1175/2012EI000434.1

Von Mises, R. (1931). *Vorlesungen aus dem Gebiete der Angewandten Mathematik: Wahrscheinlichkeitsrechnung und ihre Anwendung in der Statistik und Theoretischen Physik*. Vienna, Austria.

Wang, H., Stephenson, S. R., & Qu, S. (2020). Quantifying the relationship between streamflow and climate change in a small basin under future scenarios. *Ecological Indicators, 113,* 106251. https://doi.org/10.1016/j.ecolind.2020.106251

Wang, J., Wang, W., Cheng, H., Wang, H., & Zhu, Y. (2021). Propagation from meteorological to hydrological drought and its influencing factors in the Huaihe river basin. *Water*, *13*(14). https://doi.org/10.3390/w13141985

Wilhite, D. A., & Glantz, M. H. (1985). Understanding: The drought phenomenon: The role of definitions. *Water International*, *10*(3), 111–120. https://doi.org/10.1080/02508068508686328

WMO (2006). *Drought monitoring and early warning: concepts, progress and future challenges*. World Meteorological Organization. 1006.

WMO (2012). *Standardized Precipitation Index User Guide*. World Meteorological Organization. 1090. Geneva, Switzerland.

WWAP/UN-Water. (2018). *The United Nations world water development report 2018: Nature-Based Solutions for Water*. UNESCO World Water Assessment Programme

WWAP. (2019). The United Nations World Water Development Report 2019: Leaving no one behind. In *Energy Access and Forced Migration*. UNESCO World Water Assessment Programme. https://doi.org/10.4324/9781351006941-3

Wu, J., Chen, X., Yao, H., & Zhang, D. (2021). Multi-timescale assessment of propagation thresholds from meteorological to hydrological drought. *Science of the Total Environment, 765,* 144232. https://doi.org/10.1016/j.scitotenv.2020.144232

Ye, B., Jiang, J., Liu, J., Zheng, Y., & Zhou, N. (2021). Research on quantitative assessment of climate change risk at an urban scale: Review of recent progress and outlook of future direction. *Renewable and Sustainable Energy Reviews*, *135,* 110415. https://doi.org/10.1016/j.rser.2020.110415

Yates D., Sieber, J., Purkey, D.R & Huber-Lee, A. (2005) WEAP21--A Demand-, Priority-, and Preference-Driven Water Planning Model: Part 1, Model Characteristics, *Water International*, *30*(4), 487-500, https://doi.org/10.1080/02508060508691893

Yuan, F., Ma, M., Ren, L., Shen, H., Li, Y., Jiang, S., Yang, X., Zhao, C., & Kong, H. (2016). Possible future climate change impacts on the hydrological drought events in the weihe river basin, China. *Advances in Meteorology*, 905198. https://doi.org/10.1155/2016/2905198

Zhao, P., Lü, H., Yang, H., Wang, W., & Fu, G. (2019). Impacts of climate change on hydrological droughts at basin scale: A case study of the Weihe River Basin, China. *Quaternary International, 513,* 37–46. https://doi.org/10.1016/j.quaint.2019.02.022

Zou, L., Xia, J., Ning, L., She, D., & Zhan, C. (2018). Identification of hydrological drought in Eastern China using a time-dependent drought index. *Water, 10*(3), 315. https://doi.org/10.3390/w10030315

CHAPTER 7: APPENDICES

Appendix 3.1

Table A.1 Meteorological stations used for precipitation data – Maule River basin

Code	Station	Latitude	Longitude
7371002	Agua Fría	-35.31	-71.10
7384002	Constitución	-35.32	-72.41
7381003	Pencahue	-35.37	-71.83
7383001	Rio Maule En Forel	-35.41	-72.21
7370001	Fundo El Radal	-35.42	-71.04
7378002	Talca U.C.	-35.44	-71.62
7379002	Rio Claro En Rauquen	-35.45	-71.73
7374005	Huapi	-35.49	-71.29
7376002	El Durazno	-35.49	-71.32
7341002	Nirivilo	-35.54	-72.09
7374004	Vilches Alto	-35.59	-71.09
7359005	San Javier	-35.60	-71.66
7359001	Rio Loncomilla En Las Brisas	-35.62	-71.77
7358008	Colbún (Maule Sur)	-35.62	-71.40
7378003	Colorado	-35.64	-71.26
7342002	Huerta Del Maule	-35.66	-71.95
7320002	Armerillo	-35.70	-71.08
7321002	Rio Maule En Armerillo	-35.71	-71.11
7357003	Melozal	-35.79	-71.77
7358007	Linares	-35.84	-71.60
7355006	Hornillo	-35.87	-71.12
7337002	Tutuvén Embalse	-35.90	-72.37
7355002	Rio Ancoa En El Morro	-35.91	-71.30
7355007	Ancoa Embalse	-35.91	-71.30
7352003	Liguay	-35.95	-71.68
7373003	El Guindo	-35.26	-71.32
7373004	San Rafael	-35.31	-71.52
7340003	Los Huinganes En Curipeumo	-35.98	-71.91
7335004	Quella	-36.06	-72.09
7353001	Juan Amigo	-36.08	-71.39
7352002	La Sexta De Longaví	-36.11	-71.62
7336003	El Álamo	-36.11	-72.42
7345001	Parral	-36.19	-71.83
7350001	Rio Longaví En La Quiriquina	-36.23	-71.46
7331002	Digua Embalse	-36.26	-71.55
7350006	Bullileo Embalse	-36.29	-71.41
7332003	San Manuel En Perquilauquén	-36.36	-71.65

Table A.2 Meteorological stations used for precipitation data – Itata River basin

Code	Station	Latitude	Longitude
360011	Bernardo O'Higgins Chillán Ad.	-36.59	-72.04
8105005	Camán	-36.67	-71.30
8135004	Cancha Los Litres	-36.71	-72.58
8105004	Caracol	-36.65	-71.40
8117002	Chillán Viejo	-36.63	-72.13
8133003	Chillancito	-36.76	-72.42
8123004	Cholguán	-37.15	-72.07
8141002	Coelemu	-36.48	-72.69
8113001	Coihueco Embalse	-36.64	-71.80
8130006	Diguillín	-36.87	-71.64
8130003	Fundo Atacalco	-36.92	-71.58
8124004	Las Cruces	-37.11	-71.77
8142001	Mangarral	-36.24	-72.34
8124005	Mayulermo	-36.82	-71.89
8118003	Millauquén	-36.32	-72.04
8135003	Nueva Aldea	-36.65	-72.46
8132002	Pemuco	-36.98	-72.10
8106002	Río Ñuble En San Fabián N 2	-36.59	-71.53
8118004	San Agustín De Puñal	-36.42	-72.39
8106003	San Fabián	-36.58	-71.52
8130007	San Lorenzo	-36.92	-71.58
8122002	Trupán	-37.28	-71.82
8122003	Tucapel	-37.29	-71.95

Table A.3 Meteorological stations used for extremes temperature data – Maule River basin

Code	Station	Latitude	Longitude
7381003	Pencahue	-35.37	-71.83
7378002	Talca U.C.	-35.44	-71.62
7378003	Colorado	-35.64	-71.26
7355007	Ancoa Embalse	-35.91	-72.30
7345001	Parral	-36.19	-71.83
7331002	Digua Embalse	-36.26	-71.55

Table A.4 Meteorological stations used for extremes temperature data – Itata River basin

Code	**Station**	**Latitude**	**Longitude**
360011	Bernardo Ohiggins Chillán Ad.	-36.59	-72.04
8105004	Caracol	-36.65	-71.40
8113001	Coihueco Embalse	-36.64	-71.80
8130006	Diguillín	-36.87	-71.64

Appendix 4.1

Table A.5: Calibration and Validation results - Maule River Basin

Code	Station	Calibration				Validation			
		NS	RSR	PBIAS	R2	NS	RSR	PBIAS	R2
7372001	Rio Claro En Camarico	0.9	0.32	-8.37	0.91	0.33	0.82	17.62	0.48
7379002	Rio Claro En Rauquen	0.9	0.32	12.38	0.92	0.71	0.54	28.92	0.9
7374001	Rio Lircay En Puente Las Rastras	0.86	0.38	10.73	0.87	0.12	0.94	31.91	0.26
7341001	Rio Purapel En Nirivilo	0.66	0.58	11.89	0.67	0.5	0.71	3.21	0.53
7359001	Rio Loncomilla En Las Brisas	0.93	0.27	6.47	0.94	0.86	0.37	-2.12	0.86
7343001	Rio Purapel En Sauzal	0.81	0.43	-6.07	0.82	-0.27	1.13	-75.07	0.62
7357002	Rio Loncomilla En Bodega	0.66	0.59	-7.24	0.67	0.86	0.37	-22.53	0.89
7339001	Rio Cauquenes En Desembocadura	0.77	0.48	-7.53	0.78	0.09	0.96	-82.88	0.46
7335002	Estero Curipeumo en lo Hernández	0.92	0.28	6.3	0.93	0.65	0.59	6.35	0.67
7335001	Rio Perquilauquén En Quella	0.87	0.35	3.16	0.89	0.8	0.45	1.24	0.81
7336001	Rio Cauquenes En El Arrayan	0.74	0.51	13.31	0.79	0.75	0.5	-2.4	0.78
7332001	Rio Perquilauquén En Ñiquén	0.84	0.41	-16.66	0.85	0.8	0.44	-2.53	0.81
7330001	Rio Perquilauquén En San Manuel	0.81	0.44	14.17	0.84	0.57	0.65	9.73	0.66

Table A.6: Calibration and Validation results - Itata River Basin

Code	Station	Calibration				Validation			
		NS	RSR	PBIAS	R2	NS	RSR	PBIAS	R2
8135002	Río Itata en Balsa Nueva Aldea	0.75	0.48	-5.77	0.81	0.77	0.5	0.06	0.75
8114001	Río Cato en Puente Cato	0.7	0.52	8.36	0.72	0.73	0.55	19.38	0.79
8117005	Río Chillán en Camino a Confluencia	0.81	0.47	4.55	0.82	0.78	0.44	-24.34	0.85
8123001	Río Itata en Cholguán	0.68	0.76	21.06	0.78	0.43	0.57	30.41	0.7
8141001	Río Itata en Coelemu	0.79	0.53	20.94	0.84	0.72	0.45	24.57	0.78
8132001	Río Diguillín en Longitudinal	0.75	0.61	-4.6	0.79	0.63	0.5	-37.94	0.66
8130002	Río Diguillín en San Lorenzo	0.2	0.89	32.94	0.37	0.21	0.9	39.96	0.47
8124001	Río Itata en General Cruz	0.75	0.49	-10.57	0.81	0.76	0.5	-3.1	0.78
8134003	Río Larqui en Santa Cruz	0.72	0.62	9.26	0.72	0.62	0.53	-23.02	0.66
8105001	Río Ñuble en la Punilla	0.75	0.65	3.14	0.76	0.58	0.5	5.83	0.46
8106002	Río Ñuble en San Fabián N°2	0.83	0.63	7.73	0.84	0.61	0.42	13.37	0.58
8104001	Río Sauces Antes Junta con Ñuble	0.92	0.58	-5.65	0.85	0.66	0.28	9.43	0.68
8124002	Río Itata en Trilaleo	0.79	0.5	-7.03	0.81	0.75	0.46	-4.78	0.76

Table A.7: Calibration and Validation results - Biobío River Basin

Code	Station	Calibration				Validation			
		NS	RSR	PBIAS	R2	NS	RSR	PBIAS	R2
8304001	Rio Lonquimay Antes Junta Rio Biobío	0.75	0.5	3.8	0.75	0.52	0.69	14.9	0.57
8307002	Rio Bio-Bio En Llanquén	0.82	0.42	4.3	0.82	0.79	0.45	-4	0.8
8323002	Rio Duqueco En Villucura	0.59	0.64	10.1	0.63	0.48	0.72	1	0.52
8323001	Rio Duqueco En Cerrillos	0.75	0.5	-10.5	0.76	0.7	0.54	-11.8	0.73
8362001	Rio Nicodahue En Pichun	0.92	0.28	-2.2	0.93	-0.69	1.3	-13.9	0.13
8313000	Rio Pangue En Captación	0.76	0.48	10.6	0.8	0.52	0.69	1.2	0.74
8383001	Rio Laja En Puente Perales	0.76	0.49	0.1	0.77	0.34	0.81	-51.4	0.79
8351001	Rio Malleco En Collipulli	0.69	0.55	13.1	0.77	0.7	0.54	6.4	0.77
8343001	Rio Mininco En Longitudinal	0.82	0.43	-3.5	0.85	0.81	0.44	-10.9	0.82
8342001	Rio Renaico En Longitudinal	0.88	0.35	9.4	0.9	0.86	0.38	13.1	0.91
8356001	Rio Rahue En Quebrada Culen	0.9	0.31	-8.2	0.92	0.76	0.49	-17.7	0.78
8358001	Rio Vergara En Tijeral	0.95	0.22	-5.8	0.96	0.91	0.3	-3.4	0.92
8317002	Rio Lirquen En Cerro El Padre	0.85	0.38	10.6	0.91	0.77	0.48	-3.5	0.79
8312001	Rio Biobío Ante Junta Huiri Huiri	0.73	0.52	9.5	0.76	0.74	0.51	9.1	0.77
8317001	Rio Biobío En Rucalhue	0.71	0.53	12.7	0.82	0.79	0.46	4.9	0.81
8334001	Rio Biobío En Coihue	0.81	0.43	10	0.87	0.83	0.41	6.2	0.86
8394001	Rio Biobío En Desembocadura	0.79	0.45	12.1	0.84	0.76	0.49	-5.4	0.77

Appendix 4.2

Table A.8: Streamflow Test T results - Maule River Basin

Test T p values					
CCSM4	p1	0.021	**CSIRO**	p1	0.222
	p2	0.019		p2	0.330
	p3	0.012		p3	0.215
	p4	0.011		p4	0.218
	p5	0.011		p5	0.260
	p6	0.015		p6	0.212
	p7	0.003		p7	0.161
	p8	0.021		p8	0.228
	p9	0.065		p9	0.331
IPLS	p1	0.000	**MIROC**	p1	0.000
	p2	0.000		p2	0.001
	p3	0.000		p3	0.000
	p4	0.000		p4	0.000
	p5	0.000		p5	0.000
	p6	0.000		p6	0.000
	p7	0.000		p7	0.000
	p8	0.000		p8	0.001
	p9	0.000		p9	0.006

Table A.9: Streamflow Test T results - Itata River Basin

Test T p values					
CCSM4	p1	0.003	CSIRO	p1	0.066
	p2	0.010		p2	0.172
	p3	0.003		p3	0.050
	p4	0.001		p4	0.044
	p5	0.001		p5	0.024
	p6	0.001		p6	0.035
	p7	0.018		p7	0.079
	p8	0.004		p8	0.106
	p9	0.008		p9	0.086
	p10	0.010		p10	0.095
IPLS	p1	0.000	MIROC	p1	0.000
	p2	0.000		p2	0.000
	p3	0.000		p3	0.000
	p4	0.000		p4	0.000
	p5	0.000		p5	0.000
	p6	0.000		p6	0.000
	p7	0.000		p7	0.001
	p8	0.000		p8	0.000
	p9	0.000		p9	0.000
	p10	0.000		p10	0.000

Table A.10: Streamflow Test T results - Biobío River Basin

Test T p values					
CCSM4	p1	0.002	**CSIRO**	p1	0.036
	p2	0.028		p2	0.157
	p3	0.001		p3	0.016
	p4	0.001		p4	0.007
	p5	0.017		p5	0.141
	p6	0.018		p6	0.127
	p7	0.000		p7	0.002
	p8	0.009		p8	0.069
	p9	0.001		p9	0.005
	p10	0.010		p10	0.074
	p11	0.013		p11	0.297
	p12	0.011		p12	0.086
	p13	0.012		p13	0.026
	p14	0.014		p14	0.049
IPLS	p1	0.000	**MIROC**	p1	0.000
	p2	0.000		p2	0.001
	p3	0.000		p3	0.000
	p4	0.000		p4	0.000
	p5	0.000		p5	0.000
	p6	0.000		p6	0.000
	p7	0.000		p7	0.000
	p8	0.000		p8	0.000
	p9	0.000		p9	0.000
	p10	0.000		p10	0.000
	p11	0.000		p11	0.000
	p12	0.000		p12	0.000
	p13	0.000		p13	0.000
	p14	0.000		p14	0.000

Table A.11: Streamflow Mann Kendall test results – Maule River Basin

MODEL		Test Z	Signific.	Sen's slope	MODEL		Test Z	Signific.	Sen's slope
CCSM4	p1	-2.06	0.05	-0.33	CSIRO	p1	-1.21		-0.19
	p2	-2.39	0.05	-0.02		p2	-1.16		-0.01
	p3	-2.13	0.05	-1.10		p3	-1.03		-0.51
	p4	-2.16	0.05	-0.72		p4	-1.02		-0.32
	p5	-2.29	0.05	-0.02		p5	-0.83		-0.01
	p6	-2.23	0.05	-0.24		p6	-1.06		-0.11
	p7	-2.40	0.05	-0.06		p7	-1.07		-0.02
	p8	-2.29	0.05	-0.18		p8	-1.05		-0.08
	p9	-2.14	0.05	-0.08		p9	-1.13		-0.04
IPLS	p1	-5.27	0.001	-0.76	MIROC	p1	-3.62	0.05	-0.46
	p2	-6.14	0.001	-0.05		p2	-3.86	0.001	-0.03
	p3	-5.59	0.001	-2.69		p3	-3.60	0.001	-1.46
	p4	-5.60	0.001	-1.82		p4	-3.42	0.001	-0.97
	p5	-5.36	0.001	-0.04		p5	-3.28	0.05	-0.02
	p6	-5.52	0.001	-0.58		p6	-3.55	0.001	-0.32
	p7	-5.89	0.001	-0.15		p7	-3.79	0.001	-0.08
	p8	-5.44	0.001	-0.46		p8	-3.62	0.001	-0.25
	p9	-5.36	0.001	-0.21		p9	-3.60	0.001	-0.12

Table A.12: Streamflow Mann Kendall test results – Itata River Basin

MODEL		Test Z	Signific.	Sen's slope	MODEL		Test Z	Signific.	Sen's slope
CCSM4	p1	-2.37	0.05	-1.21	CSIRO	p1	-1.30		-0.68
	p2	-2.48	0.05	-0.13		p2	-1.23		-0.06
	p3	-2.40	0.05	-0.50		p3	-1.36		-0.27
	p4	-2.47	0.05	-0.32		p4	-1.39		-0.16
	p5	-2.55	0.05	-0.12		p5	-1.33		-0.06
	p6	-2.49	0.05	-0.24		p6	-1.36		-0.12
	p7	-2.46	0.05	-0.06		p7	-1.98	0.05	-0.04
	p8	-2.16	0.05	-0.09		p8	-1.11		-0.05
	p9	-2.50	0.05	-0.24		p9	-1.35		-0.13
	p10	-2.45	0.05	-0.17		p10	-1.25		-0.09
IPLS	p1	-5.67	0.001	-3.03	MIROC	p1	-3.42	0.001	-1.56
	p2	-5.61	0.001	-0.30		p2	-3.52	0.001	-0.15
	p3	-5.77	0.001	-1.30		p3	-3.60	0.001	-0.69
	p4	-5.73	0.001	-0.76		p4	-3.87	0.001	-0.44
	p5	-5.77	0.001	-0.27		p5	-4.02	0.001	-0.16
	p6	-5.79	0.001	-0.58		p6	-3.94	0.001	-0.34
	p7	-5.67	0.001	-0.13		p7	-3.26	0.01	-0.07
	p8	-5.06	0.001	-0.24		p8	-2.78	0.01	-0.10
	p9	-5.76	0.001	-0.64		p9	-3.48	0.001	-0.30
	p10	-5.68	0.001	-0.46		p10	-3.41	0.001	-0.22

Table A.13: Streamflow Mann Kendall test results – Biobío River Basin

MODEL		Test Z	Signific.	Sen's slope	MODEL		Test Z	Signific.	Sen's slope
CCSM4	p1	-2.80	0.01	-2.76	CSIRO	p1	-1.85	0.1	-1.67
	p2	-2.31	0.05	-0.16		p2	-1.34		-0.09
	p3	-2.95	0.01	-1.43		p3	-1.83	0.1	-0.98
	p4	-3.12	0.01	-1.00		p4	-1.95	0.1	-0.69
	p5	-2.51	0.05	-0.21		p5	-1.31		-0.11
	p6	-2.51	0.05	-0.01		p6	-1.40		-0.01
	p7	-3.28	0.01	-0.02		p7	-1.78	0.1	-0.01
	p8	-2.63	0.01	-0.04		p8	-1.45		-0.02
	p9	-3.06	0.01	-0.69		p9	-2.00	0.05	-0.52
	p10	-2.83	0.01	-0.09		p10	-1.67	0.1	-0.06
	p11	-2.18	0.05	-0.03		p11	-0.33		-0.01
	p12	-2.83	0.01	-0.06		p12	-1.55		-0.04
	p13	-2.89	0.01	-0.41		p13	-2.02	0.05	-0.35
	p14	-2.97	0.01	-0.06		p14	-1.84	0.1	-0.05
IPLS	p1	-6.21	0.001	-7.33	MIROC	p1	-3.59	0.001	-3.42
	p2	-5.35	0.001	-0.44		p2	-3.48	0.001	-0.20
	p3	-5.88	0.001	-3.70		p3	-3.67	0.001	-1.81
	p4	-5.88	0.001	-2.48		p4	-3.64	0.001	-1.21
	p5	-6.00	0.001	-0.64		p5	-3.06	0.01	-0.24
	p6	-5.74	0.001	-0.04		p6	-3.73	0.001	-0.02
	p7	-6.19	0.001	-0.06		p7	-4.50	0.001	-0.03
	p8	-5.96	0.001	-0.13		p8	-3.07	0.01	-0.05
	p9	-5.72	0.001	-1.71		p9	-3.44	0.001	-0.79
	p10	-5.85	0.001	-0.26		p10	-3.74	0.001	-0.12
	p11	-6.03	0.001	-0.12		p11	-2.58	0.01	-0.04
	p12	-5.68	0.001	-0.17		p12	-3.49	0.001	-0.08
	p13	-5.49	0.001	-1.09		p13	-3.38	0.001	-0.48
	p14	-5.58	0.001	-0.17		p14	-3.44	0.001	-0.07