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PRESENTS:

MAYRA DANIELA PEÑA GUERRERO

CO-DIRECTOR OF THESIS PMPCA

CARLOS MUÑOZ

CO-DIRECTOR OF THESIS ITT

LARS RIBBE

ASSESSOR:

FRANCISCO MEZA

COLOGNE, GERMANY **SEPTEMBER 2017**

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Erklärung / *Declaración*

Name / *Nombre*: Mayra Daniela Peña Guerrero

Matrikel-Nr. / *N° de matricula*: 11109881 **(TH Köln),** 255970 **(UASLP)**

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ABSTRACT

In Latin America, the Andes have been identified as a key region that will be affected by climate change. It is projected that, under warmer temperatures, an increase in the severity and frequency of drought will occur, intensifying the existing stress on water availability and agricultural systems, particularly in semi-arid environments. Drought impacts on water quantity are well known, however, the consequences on water quality are not fully recognized yet. The degradation of water quality due to low water levels could trigger additional stress in irrigated agriculture. The purpose of this study was to investigate drought impacts on water quantity and quality for agriculture during drought periods in the Maipo river basin, located in the semi-arid region of central Chile. The Standardized Precipitation Index (SPI) and the Standardized Streamflow Index (SSI) were used to characterize meteorological (below-normal precipitation) and hydrological droughts (below-normal streamflow) in the period 1985-2015. Correlation coefficients between the indices were used to assess the meteorological and hydrological drought relationship. Considering that hydrological droughts can impact surface water quality, we study correlations between daily discharge and basic surface water quality parameters. The threshold level method was used to compare physicochemical parameters during hydrological drought periods with the established Chilean regulation for agricultural water uses. Meteorological (SPI) and Hydrological (SSI) drought characterization indicated a negative trend in most of the basin, with a general reduction in the river flows (SSI) more acute in the last five years (2010-2015). The highest correlation of SSI was found in the accumulation period SPI-12, indicating the dependence of the streamflow to the previous year of precipitation. A significant ($p < 0.05$) negative relationship between discharge and electrical conductivity and major ions, were found in most of the basin. Discharge stations located in the irrigation districts, exceeded the established thresholds in these parameters during hydrological drought periods, which could mean potential impacts on irrigated agriculture of the region.

Key words: Climate change; Meteorological drought; Hydrological drought; Standardized Index; Irrigated agriculture; Water quality

RESUMEN

En Latinoamérica, los Andes han sido identificados como una región clave que será afectada por el cambio climático. Se ha proyectado bajo temperaturas más calidas, un incremento en la severidad y frecuencia de las sequías, intensificando el estrés existente en la disponibilidad de agua y los sistemas agrícolas, particularmente en ambientes semi-áridos. Los efectos de la sequía en la cantidad de agua son bien conocidos, sin embargo las consecuencias sobre la calidad de agua aún no son totalmente reconocidas. La degradación de la calidad de agua debido a los bajos niveles de agua, podría provocar estrés adicional a la agrícultura de riego. El propósito de este estudio fue investigar los impactos de la sequía en la cantidad y calidad de agua para la agrícultura durante los periodos de sequía en la cuenca del río Maipo, situada en el semi-árido Chile central. El índice de precipitación estandarizada (SPI) y el índice de caudal estandarizado (SSI) se utilizaron para caracterizar sequías meteorológicas (precipitación por debajo de lo normal) e hidrológicas (caudal por debajo de lo normal) para el periodo 1985-2015. Se utilizaron coeficientes de correlación entre los índices para evaluar la relación de la sequía meteorológica e hidrológica. Considerando que las sequías hidrológicas pueden afectar la calidad de agua, estudiamos las correlaciones entre la descarga diaria y los parámetros básicos de la calidad de agua superficial. El método de nivel de umbral se utilizó para comparar los parámetros fisicoquímicos durante los periodos de sequía hidrológica con la regulación chilena establecida para agua de usos agrícolas. La caracterización de sequías meteorologícas (SPI) e hidrológicas (SSI) indicó una tendencia negativa en la mayor parte de la cuenca, con una reducción general en los caudales de los ríos (SSI), más aguda en los últimos cinco años (2010-2015). La mayor correlación de SSI se encontró con el periodo de acumulación SPI-12, lo cual denota la dependencia del caudal al año anterior de precipitación. Se encontró una relación negativa significativa (p <0.05) entre la descarga y la conductividad electrica y los iones mayores en la mayor parte de la cuenca. Las estaciones de descarga situadas en los distritos de riego superaron los umbrales establecidos en estos parámetros durante los periodos de sequía hidrológica, lo que podría significar impactos potenciales en la agrícultura de riego de la región.

Palabras clave: Cambio climático; sequía meteorológica; sequía hidrológica; Índices estandarizados; Agricultura de riego; Calidad de agua

ZUSAMMENFASSUNG

In Lateinamerika wurden die Anden als eine vom Klimawandel betroffene Schlüsselregion identifiziert. Es wird prognostiziert, dass unter wärmeren Temperaturen eine Zunahme der Schwere und Häufigkeit von Dürren auftreten wird, was die bestehende Belastung der Wasserverfügbarkeit und der landwirtschaftlichen Systeme, insbesondere in halbtrockenen Umgebungen, verstärkt. Die Auswirkungen von Dürre auf den Wasserpegel sind bekannt, aber die Folgen für die Wasserqualität sind bis jetzt noch nicht vollständig erkannt. Die Beeinflussung der Wasserqualität durch niedrige Wasserstände könnte eine zusätzliche Belastungen für die Bewässerungslandwirtschaft darstellen. Der Zweck dieser Studie war es zu untersuchen, welche Auswirkungen Dürreperioden auf den Wasserpegel und die Wasserqualität für landwirtschaftliche Anforderungen in dem Wassereinzugsgebiets des Flusses Maipo, in der semi-ariden Region von Zentral-Chile haben. Der standardisierte Niederschlagsindex (SPI) und der standardisierte Streamflow Index (SSI) wurden verwendet, um meteorologische (unterhalb der normalen Niederschlagsmenge) und hydrologische Dürren (unterhalb der normalen Durchflussmenge) im Zeitraum 1985-2015 zu charakterisieren. Korrelationskoeffizienten zwischen den Indizes wurden verwendet, um die Beziehung zwischen meteorologischer und hydrologischer Dürre zu beurteilen. In Anbetracht dessen, dass hydrologische Dürren die Wasserqualität beeinflussen können, wurden Korrelationen zwischen der täglichen Abflussmenge und den grundlegenden Oberflächenwasserqualitätsparametern beurteilt. Die Schwellenwertmethode wurde verwendet, um physikochemische Parameter während der hydrologischen Dürreperioden mit der chilenischen Regulierung für landwirtschaftliche Wasserverwendungen zu vergleichen. Meteorologische (SPI) und Hydrologische (SSI) Charakterisierungen von Dürre zeigen eine negative Tendenz in den meisten Wassereinzugsgebieten, mit einer allgemeinen Reduzierung der Flussströme (SSI), vor allem während der letzten fünf Jahre (2010-2015). Die höchste Korrelation von SSI wurde in der Akkumulationszeit SPI-12 gefunden, was die Abhängigkeit des Stromflusses zum vorherigen Niederschlagsdatum anzeigt. Eine signifikante ($p < 0,05$) negative Beziehung zwischen Entladung und elektrischer Leitfähigkeit und großen Ionen wurde in den meisten Bereichen des Wassereinzugsgebiets gefunden. Entladestationen, die

Schwellenwerte bei diesen Parametern während der hydrologischen Dürreperioden, was potenzielle Auswirkungen auf die Bewässerungslandwirtschaft der Region bedeuten könnte.

Schlüsselwörter: Klimawandel; Meteorologische Dürre; Hydrologische Dürre; Standardisierter Index; Bewässerungslandwirtschaft; Wasserqualität

1 INTRODUCTION

1.1 Background

Drought is a natural phenomenon which can occur in all climatic zones and is defined as a sustained and regionally extensive occurrence of below-normal natural water availability (Tallaksen & van Lanen 2004). In the context of climate change, it is projected an increase in global temperatures affecting evapotranspiration and atmospheric storage of water, potentially changing the magnitude, frequency, and intensity of precipitation, as well as its geographical distribution and seasonal variability (Wang et al. 2016, and references therein). As a consequence, the frequency and severity of extreme events like droughts and floods would increase, being droughts the slowest to develop, but the longest to last (Yeh et al. 2015; Bond et al. 2008).

As a natural hazard, drought can cause economic and social damages (Bond et al. 2008). Agriculture is the primary land use across the globe; it is also the major economic, social and cultural activity, and it is highly sensitive to climate variations (Howden et al. 2007). It is predicted that global food demand by 2050 will rise, indicating that crop production must double (Tilman et al. 2011). According to present trends, a major part of the supplementary food will come from irrigated agriculture (40% of the world's food supply is produced on irrigated lands (Wang et al. 2016; Döll & Siebert 2002). Currently, irrigation represents nearly 70% of freshwater withdrawals from rivers, lakes, and aquifers, and it is under the constant pressure created by drecreasing water availability and increasing water demand (Assouline et al. 2015). Climate change will intensify the existing stress on water availability and affect agricultural systems particularly in semi-arid environments (IPCC 2014). According to Iglesias & Garrote (2015) the impacts of changes in water resources for the agricultural production of these areas can include: (1) an increase in water demand due to high rates of crop evapotranspiration in response to rising temperatures; (2) intensification of water shortage, especially in the spring and summer due to increased irrigation requirements, (3) deterioration of water quality due to high temperatures and low levels of runoff in some regions, inducing additional stress to irrigated areas, among others.

During droughts, the climate water deficit that spreads through the hydrological cycle can reduce surface and ground water levels (hydrological drought) and can lead not only to reduced water availability but also to a deterioration in water quality (Mishra & Singh 2010; Mosley 2015). This condition also intensifies water shortages by lowering the amount of usable water within a region. Although drought impacts on water quantity are well known (van Vliet & Zwolsman 2008; Safavi & Malek Ahmadi 2015 and references therein), the consequences on water quality are not fully recognized yet (Zwolsman & van Bokhoven 2007). The low flows and water levels during hydrological droughts can affect water quality of freshwater systems by, for instance, increasing its residence time, reducing the flushing rate of water bodies with limited dilution of point source emissions and the interruption of sediment, organic matter and nutrient transport (Mosley 2015; Palmer & Montagna 2015; Mishra & Singh 2010; van Vliet & Zwolsman 2008). Considering that poor water quality could impact adversely agricultural crop production, water quality for irrigation plays a major role in its development (Assouline et al. 2015). Water quality characteristics such as the increase in total dissolved solids, and their constituent ions and the decrease of dissolved oxygen, could cause agronomic problems to irrigated agriculture (Sagasta & Burke 2005; Maestre-Valero & Martínez-Alvarez 2010).

1.2 Justification

In Latin America, the extra-tropical Andes have been identified as a key region affected by climate change. The accelerated retreat of glaciers may have contributed to observe negative trends in streamflow, and the drier areas are likely to suffer from salinization and desertification on agricultural lands (IPCC 2007; IPCC 2014). Chile has very diverse climatic conditions along its territory. However, it is a country that experiences multi-year droughts (Rangecroft et al. 2016). An increase in temperature across the country is projected as well as a precipitation decrease in central and south areas (CONAMA 2006).

This trend may lead to an intensification of the existing aridity in northern Chile and their advance towards the south, enhancing the risk of water scarcity in the central area (FAO 2010). This work is focused on the semi-arid central Chile, in the Metropolitan region, with extended irrigated zones where more than 90% are highly dependent on water withdrawal from surface flows (Rosegrant et al. 2000). The irrigation districts have a wide variety of annual and perennial horticultural and vineyard crops that are supplied by the channel networks from the main rivers (Meza et al. 2012). Furthermore, agriculture represents a 74% of the water use, that is shared with drinking water needs from almost 40% of the Chilean population, and significant industrial and hydroelectric development (DGA 2003; MINAGRI & CNR 2009). Chile has established in the Water Code of 1981, the economic instrument of water markets in which water-use-rights are granted permanent and transferable to individuals to reach and efficient allocation of the resource (Rosegrant et al. 2000; Donoso 2015). Initially, those rights were granted to users who had been using the water (irrigators and urban water supply companies) (Meza et al. 2012). Now, the new water rights are not conditioned to a certain use, and users can freely trade it to other individuals (Costa Cordella 2016). These water markets are more prevalent in areas of water scarcity, as the north of the country where the water-use-rights prices are greater than the South and where the demand and competition among the different users are increasing rapidly (Donoso 2015).

Considering that irrigated agriculture in drought prone arid and semiarid regions due to their biophysical characteristics are particularly vulnerable to this whole climatic, economic and human pressure. Moreover, there is a lack of case studies in Latin America related to drought impacts on water quality (Mosley 2015) and most important, its relation to irrigated agriculture; this work focuses on the following objectives:

1.3 Objectives

The general objective was to evaluate the impact of drought on water quantity and quality for agricultural requirements in the Maipo river basin.

To achieve this, the following specific objectives were designed:

1. Determine the spatiotemporal distribution of meteorological drought in the area

2. Establish the relationship between meteorological and hydrological drought events in space and time

3. Assess the impacts of hydrological drought on basic surface water quality parameters

4. Establish the potential effects of drought driven water quality deterioration on irrigated agriculture

2 CONCEPTUAL FRAMEWORK

2.1 Drought definitions

Droughts are one of the more costly natural hazards on a year-to-year basis due to their impacts are significant and widespread and can affect many economic sectors and people at any one time (WMO & GWP 2016). A simple definition of drought is a deficit in precipitation for a period of time which can cause a condition of insufficient moisture (Mckee et al. 1993), which can occur in high as well as in low rainfall areas. However, there is no consensus regarding a general drought definition. Some of the commonly used definitions are: "*Drought means a sustained, extended deficiency in precipitation*" (WMO 1986) ;"*Drought means the naturally occurring phenomenon that exists when precipitation has been significantly below normal recorded levels, causing serious hydrological imbalances that adversely affect land resource production systems*" (UN Secretariat General 1994); " *Drought is the percentage of years when crops fail from the lack of moisture*" (FAO 1983) (Mishra & Singh 2010), among others.

Drought in contrast to aridity, which is a permanent feature of climate restricted to low rainfall areas, is a temporary aberration (Wilhite 1992; Mishra & Singh 2010). Generally, drought is also confused with a heat wave. However, their differences are related to its time scale, where a heat wave last on the order of week while drought may persist for months or years (Chang & Wallace 1987). In this sense, and being aware that different definitions might lead to different conclusions regarding the drought phenomenon (Hisdal & Tallaksen 2000), Wilhite & Glantz (1985) described different drought definition and types according to its sectoral impact that are commonly accepted (Figure 1). **Meteorological drought** occurs when there is a decrease of the below-normal precipitation; if meteorological drought persists, a deficit in soil moisture can impact agricultural productions (**agricultural drought**), relating that the plant's demand for water is dependent on meteorological conditions; also if a dry spell affects surface or groundwater resources and there is no adequate water quantity to supply the habitual activities of a particular region, the **hydrological drought** takes place; finally, the **socio-economic droughts**, which incorporate features of the above-mentioned drought types, are associated with the supply and demand of some economic good.

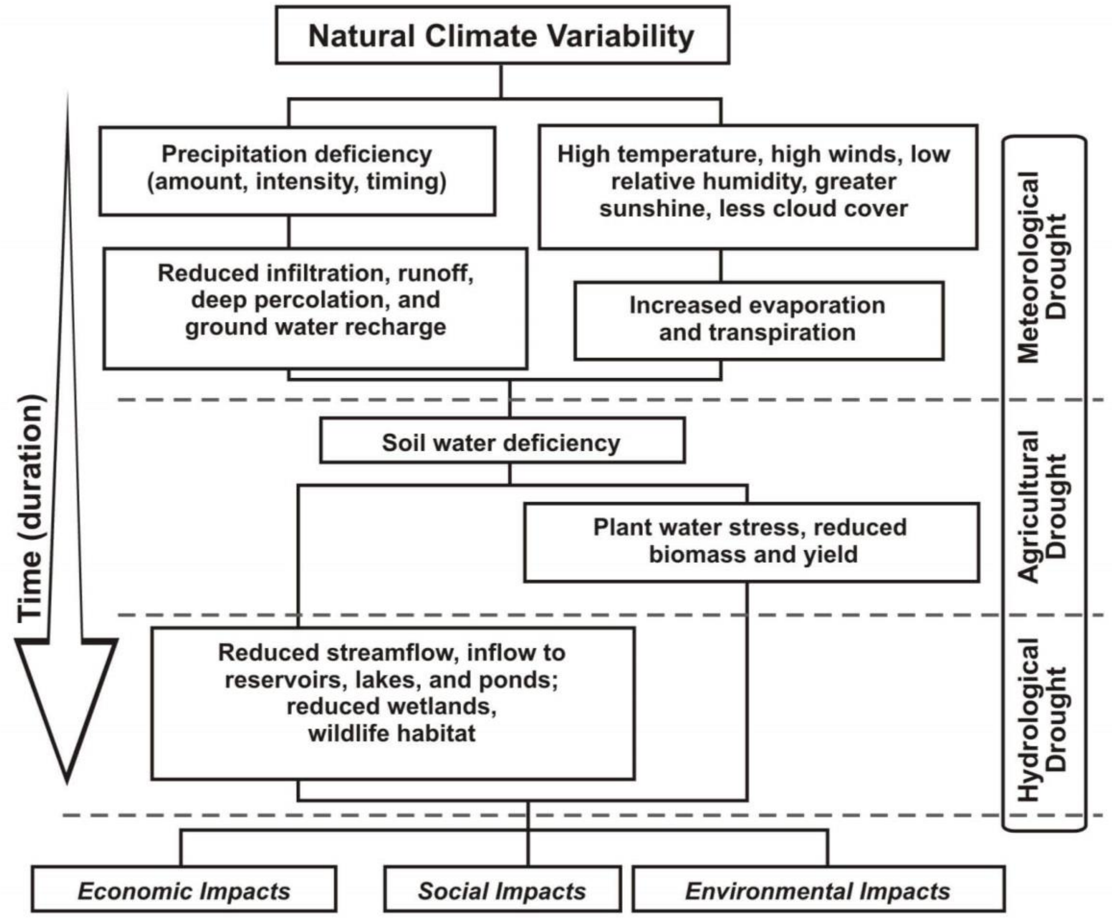


Figure 1 "Sequence of drought occurrence and impacts for commonly accepted drought types." Taken from the National Drought Mitigation Center, University of Nebraska-Lincoln, U.S.A. http://drought.unl.edu/DroughtBasics/TypesofDrought.aspx

2.2 Drought indices

Like other hazards, drought can be characterized regarding its severity, location, duration and timing (WMO & GWP 2016). To monitor drought and for an adequate management, several drought indices have been developed to characterize and quantify droughts. A variety of drought indices that can be classified as meteorological (using precipitation-rain and snow data), soil moisture, and hydrological drought indices (using streamflow, groundwater storage, and levels) (Wanders et al. 2010) are summarized in figure 2. However, it is important to highlight that there is no consensus regarding the "best" set of indices and the choice should be based on the drought characteristics associated with the impacts of concern to the stakeholders (WMO & GWP 2016; Hayes et al. 2011). Moreover, and according to Van Loon (2015), since each type of index is focused on a specific compartment of the hydrological cycle, multiple indices should be used to quantify the diversity of drought impacts.

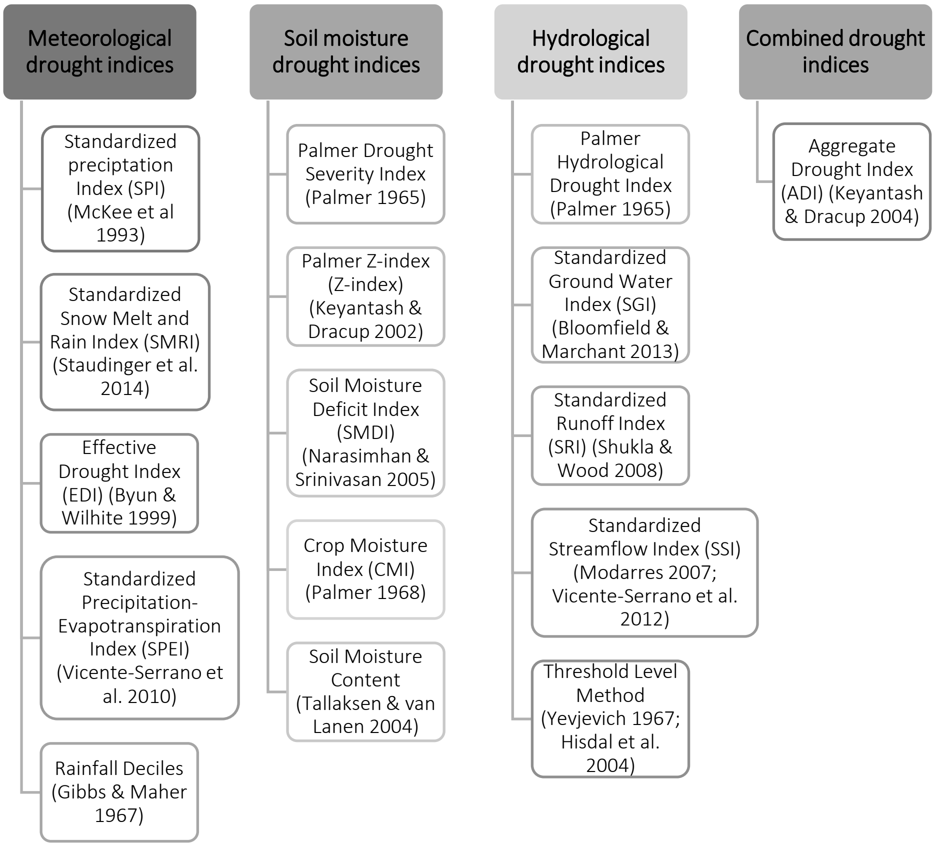


Figure 2 Some of the frequently-used drought indices. Own elaboration based on (Wanders et al. 2010 and Van Loon 2015)

The standardized drought indices have as an advantage the possibility of a regional comparison of drought values (Mishra & Singh 2010). However, since the severity of a drought event is expressed in relative terms, there is a lack of the amount of water needed regarding "normal" conditions (such as absolute values of deficit volume)(Van Loon 2015). Some of them are described below.

The Palmer Drought Severity Index (PDSI) (Palmer 1965) that can be classified under both meteorological and soil moisture indicator and is used in a standardized way (Ma et al. 2014), was developed as a tool for the USA for estimating agricultural drought damage (Van Loon 2015). The index measures the departure of moisture supply from normal conditions, calculating moisture supply from the water balance of a two-layer soil model using monthly mean precipitation and temperature data as well as the local available water content of the soil (Hisdal & Tallaksen 2000). It enables the measurement of both wetness (positive values) and dryness (negative values) due to includes the supply and demand concept of the soil water balance equation involving precipitation, moisture supply, runoff, and evaporation demand at surface level (Vicente-Serrano et al. 2010). However, the drawbacks of the index are related to its complex calculation procedure (Sheffield & Wood 2011), the fixed time scale (Mishra & Singh 2010), the re-calibration needed for application in other regions (Dai 2011), among others.

The Standardized Precipitation Index (SPI) (Mckee et al. 1993) is the most-used standardized meteorological drought index and is considered more sensitive than the PDSI (Lloyd-hughes & Saunders 2002). The SPI only requires precipitation data for its calculation, and it is based on the premise that precipitation deficits over varying periods or time scales influence streamflow, snowpack, soil moisture, reservoir storage and groundwater (Wu et al. 2005). Its calculation is based on the long term (at least 30 years) precipitation record for a desired period, where this record is fitted to a probability distribution and then transformed into a normal distribution where the mean SPI of the location and the period is zero (Tsakiris & Vangelis 2004). The advantagesof this index are that it only requires monthly precipitation and can be calculated for different time scales; moreover, SPI values can be compared among different climates (WMO & GWP 2016). Meanwhile, disadvantages are that SPI only considers precipitation, hence other meteorological drivers are not taken into account (Dai 2011). Also, the record length and fitting a probability distribution can have an impact on the SPI values (Wu et al. 2005). Therefore, since one of the main criticism of the SPI is that its calculation is based only on precipitation, the Standardized Precipitation-Evaporation Index (SPEI) (Vicente-

Serrano et al. 2010) was developed. SPEI adds to the precipitation data, the Potential Evapotranspiration (PET), that can evidence the changes in evaporation demand caused by temperature fluctuation and trends as the PDSI. Nevertheless, one of SPEI weaknesses is that the requirement for a serially complete data set for both temperature and precipitation may limit its use due to insufficient data being available (WMO & GWP 2014).

Regarding the standardized indices that originate from the SPI and are based on different hydrological variables such as: SRI (runoff) (Shukla & Wood 2008), SSI (streamflow) (Modarres 2007; Vicente-Serrano et al. 2012), SGI (Groundwater level) (Bloomfield & Marchant 2013) and SMRI (rain and snowmelt) (Staudinger et al. 2014); they also have the advantages and disadvantages of the SPI. However, since they have similar calculation procedures, they are a useful tool in drought propagation studies (ten Broek et al. 2014; Van Loon 2015).

On the other hand, non-standardized drought indices such as the threshold-based indices like the Threshold level method (Yevjevich 1967; Hisdal et al. 2004) and the Soil moisture content (Tallaksen & van Lanen 2004) have the advantage of measuring the deficit volume (water/soil moisture or another hydro meteorological variable, below of a predefined threshold). They are often used as points of action in water and agricultural management (Van Loon 2015 and references therein). A disadvantage of these methods is that in global drought studies since no standard drought classes are calculated, it is difficult to compare between different climate types (Van Loon 2015). Finally, a combined drought index like the Aggregate Drought Index (ADI) developed by Keyantash & Dracup (2004), considers all types of drought and it is composed of six different variables (Precipitation, evapotranspiration, streamflow, reservoir storage, soil moisture content and snow water content). Although it has the potential to describe different types of drought, the need for observations of all the variables it is also one of its weaknesses (Wanders et al. 2010; WMO & GWP 2016).

3 STUDY AREA AND METHODOLOGY

3.1 Study area

The Maipo river basin is located in central Chile (Figure 3), between latitudes 32°55'S and 34°15'S and between longitudes 69°55'W and 71°33'W, covering an area of 15,274 km^2. The Maipo River flows 250 km to the Pacific Ocean from the Maipo Volcano (5,623 masl) (Figure 4). It is characterized by a Mediterranean climatic regime with a long dry season and a winter period concentering more than the 75% of the annual precipitations, along with cold weather in the Andes. Mean annual total precipitation is 384 mm, and mean annual temperature is 14°C (DGA 2014). Its hydrologic regime is nivo-pluvial. The upper part of the of the basin is nival, with a significant increase of streamflow in spring months due to snow-melt from the Cordillera. The middle section is nivo-pluvial with two annual periods of higher discharge (spring and winter), and in the lower section, the regime is pluvial, with large volumes of streamflow associated with precipitation periods (Figure 5). The surface runoff it is estimated in 58 million of m^3, where 90% is generated by the winter precipitation, between April and September (DGA 2014). The Maipo river is the main source of water for the Metropolitan region, with urban and fairly large agricultural areas (16% are used for irrigated agriculture) mostly concentrated in the Central Valley (Figure 4) (DGA 2004). It is also the most populated region of Chile with almost seven millions of people including the Santiago metropolitan area, where the Maipo river supplies 70% of potable water and 90% of irrigation demands (DGA 2007).

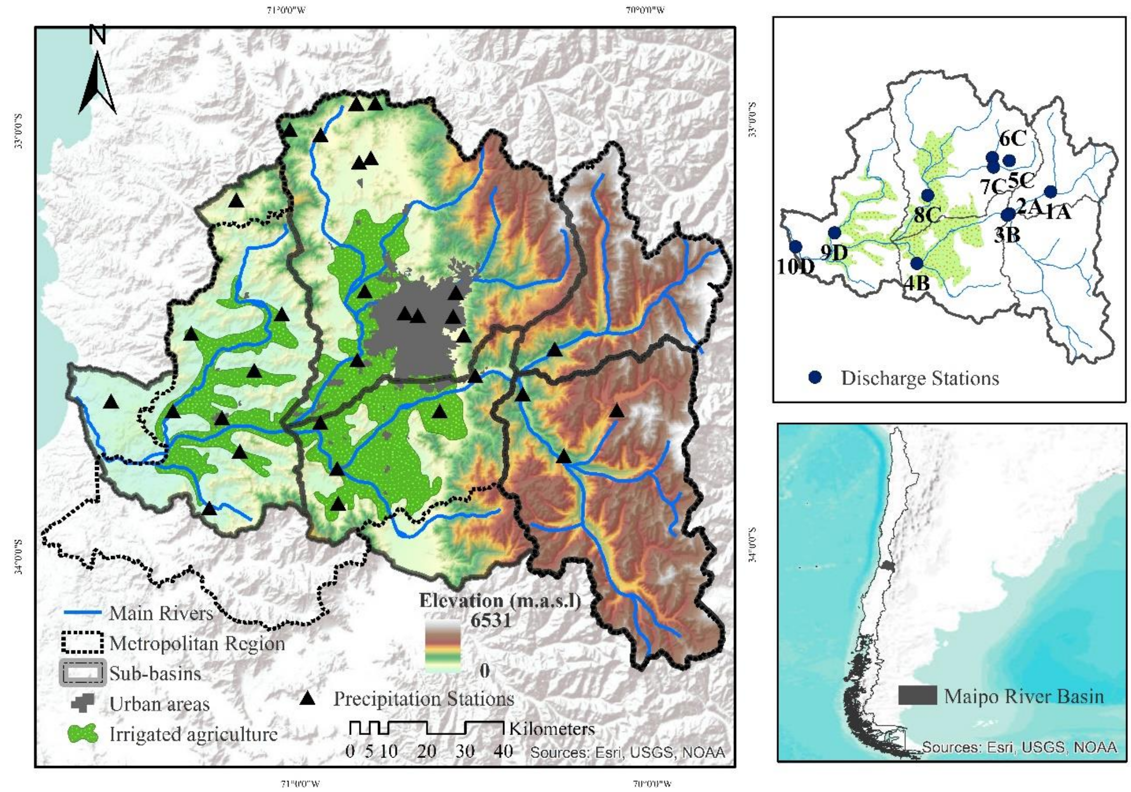


Figure 3 The Maipo river basin: general characteristics and locations of selected stations in the region under study

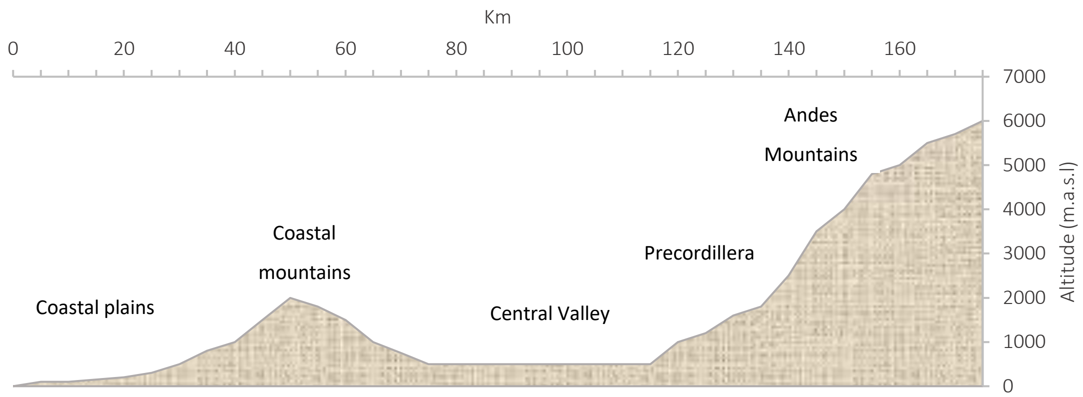


Figure 4 Topographic profile 33° South Latitude - Central Zone of Chile. Own elaboration based on Errázuriz K et al. (1998) and the Digital Elevation Model from the Maipo Basin

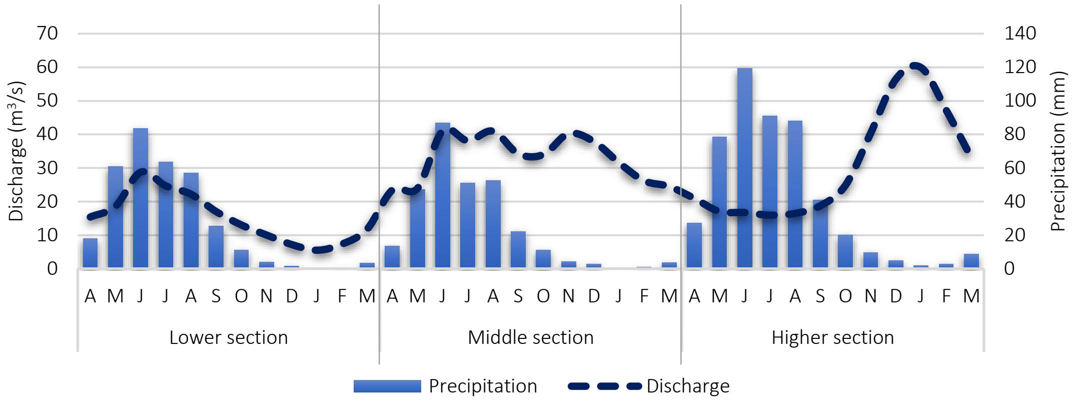


Figure 5 Mean monthly precipitation and discharge of one station per basin section (period of analysis from 1985-2015).

3.2 Data: Hydro-climatic data

Monthly precipitation, daily discharge, and physicochemical data of the Maipo river basin were collected from the Chilean National Water Agency (Dirección General de Aguas, DGA) and the Chilean Meteorological Agency (Dirección Meteorológica de Chile, DMC). Data from 31 meteorological (28-DGA and 3-DMC) and ten discharge stations (DGA) were used with heterogeneity in the monitoring periods for physicochemical data (mostly one measurement per season). The period of record was from 1985 to 2015. The precipitation series with missing data were filled by multiple linear regression by using highly correlated stations (Hirsch et al. 1982; Vogel & Stedinger 1985). The discharge stations were selected with less than 5% of missing data. The official DGA code of the discharge stations that were used in this research are the following: **1A** (05706001-8), **2A** (05707002-1), **3B** (05710001-K), **4B** (05716001-2), **5C** (05721001-K), **6C** (05722001-5), **7C** (05722002-3), **8C** (05737002-5), **9D** (05746001-6), **10D** (05748001-7) (Appendix A). In appendix B, it can be found the mean monthly precipitation and discharge of the stations analyzed in this study. The Digital Elevation Model (DEM) with a resolution of 90 m was downloaded from the CGIAR Consortium for Spatial Information (http://srtm.csi.cgiar.org) (Jarvis et al. 2008). Maps corresponding to the hydro meteorological network and general characteristics of the basin were obtained from DGA official web page on (http://www.dga.cl/productosyservicios/mapas/Paginas/default.aspx). All maps were processed in ArcGIS (ArcGIS 10.4, ESRI, Redlands, CA, USA). Figure 3 shows the spatial distribution of the selected stations.

3.3 Calculation of standardized drought indices

3.3.1 The Standardized Precipitation Index (SPI)

The Standardized Precipitation Index (Mckee et al. 1993), based on the probability of rainfall on any time scale, is one of the most commonly used meteorological drought indicators. Because its relative simplicity of calculation, comparability and flexibility to assess precipitation deficits over user-defined accumulation periods (Barker et al. 2016), is recommended as the standard index worldwide by the World Meteorological Organization and the Lincoln Declaration on Drought (Hayes et al. 2011; Stagge et al. 2015; Van Loon 2015). It has also been integrated as a key index in drought monitoring and management plans of countries like the United States, Mexico, Chile and recommended for Mediterranean countries by the Mediterranean Drought Preparedness and Mitigation (MEDROPLAN) among others (Nuñez et al. 2014 and references therein).

The SPI was computed following the methodology of Mckee et al. (1993). The SPI is defined as the difference between monthly precipitation (xi) and the mean value ($\bar{x}$), divided by the standard deviation (s),

$$\mathrm{SPI} = \frac{x_i - \bar{x}}{s}$$

Considering that the precipitation data do not follow the normal distribution, the data set is first fitted to a gamma probability distribution, and then normalized to a standard normal probability distribution, where the resulting values correspond to the number of standard deviations from the historical data that is fitted as zero (Edwards & Mckee 1997). Negative values of SPI correspond to lower than the mean precipitation, and positive values indicate higher than the average rainfall. The effect of record length on the index was evaluated to use stations with data ranging from 20 to 29 years. To establish significant differences in the determination of drought periods among the different historical periods, we used data from five stations ranging from 20 to 50 years. Based on variance analysis, we obtained no differences with 5% of significance level between the paired SPI values for all time scales and drought detection (Appendix C).

For this study, the SPI for three different time scales was used: three (SPI-3), six (SPI-6) and twelve (SPI-12) months for each gauging stations from monthly historical precipitation data. As the time scales reflect the impact of drought on the availability of water resources, the short scale of SPI-3 can indicate effects on short-term water supply (soil moisture conditions) such as agricultural practices (Mckee et al. 1993). The medium and long term SPI-6 and SPI-12 can be interpreted to estimate dry periods associated with anomalous streamflow, reservoir and groundwater levels (Gocic & Trajkovic 2013; Osuch et al. 2016; WMO 2012).

The spatial and temporal distribution of meteorological drought across the river basin was represented by grouping stations within sub-basins. In the higher section the Maipo Alto-maitenes (1 station) and Maipo Alto (3 stations); in the middle section the Maipo Medio (5 stations) and Mapocho (13 stations), and in the Lower section the Maipo Bajo (9 stations). For each sub-basin and time scale, a historical series was obtained which monthly records the average SPI of the stations included in each sub-basin. Finally, drought characterization (frequency, duration, and intensity) was computed for each sub-basin.

3.3.2 The Standardized Streamflow Index (SSI)

There is a growing trend in drought research towards the standardization of other hydrological data types (e. g. soil moisture, streamflow, groundwater), due to the advantage of its consistent interpretability among the standardized indicators family (number of standard deviations from the average cumulative deficit; Stagge et al. 2015, Bachmair et al. 2016; Barker et al. 2016).

The Standardized Streamflow Index (Modarres 2007; Vicente-Serrano et al. 2012) is computed in a similar way as the Standardized Precipitation Index, which is done by considering as the only input the monthly streamflow, fitting a distribution to the data and transforming it to a normal distribution (Van Loon 2015). There is no consensus regarding the probabilistic distribution of streamflow data (Svensson et al. 2017; Vicente-Serrano et al. 2012). In this study we used the two-parameter Gamma distribution for streamflow, suggested by Mckee et al. 1993 as the procedure can be applied to other variables related to drought (Shukla & Wood 2008; Modarres 2007; Nalbantis & Tsakiris 2009). The SSI was calculated for four different time scales: one (SSI-1), three (SSI-3), six (SSI-6) and twelve (SSI-12) months in each station from monthly historical streamflow.

In this study, a drought event for the SPI is defined for values below -0.84 starting in the rainy season (April to September) and for the SSI at least consecutive three months according to the criteria from the Chilean government Water Agency DGA to determine exceptional droughts as it is shown in Table 1 (DGA and DICTUC S.A. 2009; DGA 2012).

Table 1 Classification criteria for determination of exceptional drought in Chile, modified from DGA No. 1674 (DGA 2012)

SPI/SSI VALUES	DROUGHT CATEGORY
≤ - 2.05	Extremely dry
-2.05 to -1.28	Severely dry
-0.84 to -1.28	Moderately dry
-0.84 to 0.84	Near Normal
0.84 to 1.28	Moderately wet
1.28 to 2.05	Severely wet
≥ 2.05	Extremely wet

3.3.3 Relationship between meteorological and hydrological drought

The relationship between meteorological and hydrological drought in the Maipo River Basin was assessed using the Pearson correlation coefficient from SPI and SSI of the discharge stations selected and the precipitation stations of closest proximity.

3.3.4 Trend analysis

The non-parametric Mann-Kendall (MK) test (Mann 1945; Kendall 1975) was applied to detect trends of SPI and SSI indices in the river basin. This test had been widely used and determines if a series of observations of random variables have an increasing, decreasing or no trend with time at different levels of significance (Modarres & Silva 2007; Wambua et al. 2015; Lweendo et al. 2017). The Mann-Kendall Test is based on the difference (x_j-x_i) between successive years of data for a given period, and it is calculated from the following equation:

$$S = \sum_{i=1}^{n-1} \sum_{j=i+1}^{n} sgn\ (x_j - x_i)$$

Where *n* is the number of observations, x_i and x_j are the data values in the time series *i,* and *j* (*j*>*i*), respectively and *sgn* (x_j-x_i) is the sign function as:

$$sgn\left(x_j - x_i\right) = \begin{cases} +1, \text{if } x_j - x_i > 0 \\ 0, \text{if } x_j - x_i = 0 \\ -1, \text{if } x_j - x_i < 0 \end{cases}$$

A *Z* value is then computed to estimate the significance of the trend. We defined statistically significant trends as those having *p*-values <0.05. The slope of the time series was estimated using a Sen's slope method (Sen 1968). In this method, the median of the slopes set of joined data in pairs was calculated, where a positive (negative) value of slope indicates the increasing (decreasing) trend in the time series (Li et al. 2014).

3.4 Hydrological drought and water quality

3.4.1 Threshold Level Method

The threshold level is a method that simultaneously characterizes streamflow droughts regarding duration and deficit volume, defining droughts as the periods during which the flow values fall below a predefined threshold level and continues until the threshold is exceeded again (Yevjevich 1967; Hisdal et al. 2004). The method is relevant for storage analysis and hydrological design and operation of reservoir storage systems with important areas of application such as hydropower, water management, water supply and irrigation schemes (Hisdal & Tallaksen 2000). For hydrological droughts, monthly or longer time resolutions could underestimate cases when severe droughts are shorter than one month, especially when it is analyzed for a specific activity. In these cases, streamflow deficit characteristics operating on shorter time resolutions like daily discharge series could be more appropriate to obtain a more detailed information (Fleig et al. 2006). Generally a truncation level can be fixed or varying over the year (Hisdal et al. 2004) and derived from percentiles of the flow duration curve (70th to 95th) which reflects the deficit volume of water in discharge or water levels in natural and artificial reservoirs (Tallaksen et al. 1997; Van Loon 2015). For perennial rivers, those percentiles represent the streamflow that equaled or exceeded 70-95 percent of the time respectively (Fleig et al. 2006).

In this study, daily streamflow of the selected discharge stations and its related physicochemical data were used to determine the impact of hydrological drought on water quality by the threshold level method. Due to the strong seasonal pattern of the river basin, the variable monthly threshold was selected. The 80th percentile (Q80) was calculated for drought periods (van Loon et al. 2010), and the 20th percentile (Q20) was also considered to establish the behavior of the physicochemical parameters in wet periods (extreme flows) (Hrdinka et al. 2015). The wet and dry periods were compared with the normal stages which fall between both thresholds (Q20-Q80).

3.4.2 Physicochemical Parameters and thresholds for agricultural water use

Surface water quality parameters from the period of 1985 to 2015 were evaluated for all discharge stations. Measured parameters included: Temperature (ºC), pH, dissolved oxygen (mg/L O_2), electrical conductivity/salinity (µS/cm) and related ions, nutrients and metals such as Zn, Cu and As. The database was provided with the correspondent daily discharge value. To establish the significance of possible effects of drought in water quality, the data were grouped according to the respective threshold value (Q80 and Q20) and then compared them. Correlations coefficients were used to examine, at a significant level ($P<0.05$), the associations between measured water quality parameter and daily discharge. The Chilean regulation NCh 1333/78 "*Water quality requirements for different uses*" (INN 1987) was used to established thresholds on water quality parameters for irrigation (Appendix D). This statute is aligned with international standards, such as the United States Environmental Protection Agency (US EPA) and the Food and Agriculture Organization of the United Nations (FAO).

4 RESULTS

4.1 Spatiotemporal distribution of meteorological drought

Temporal variations of meteorological drought are shown in Figure 6. It can be noted that all sub-basins depict similar patterns in severity and duration of drought events (Table 2). Common drought episodes occurred during the years 1988/1989, 1990/1991, 1996/1997, 1998/1999, 2011/2012 and 2014/2015.

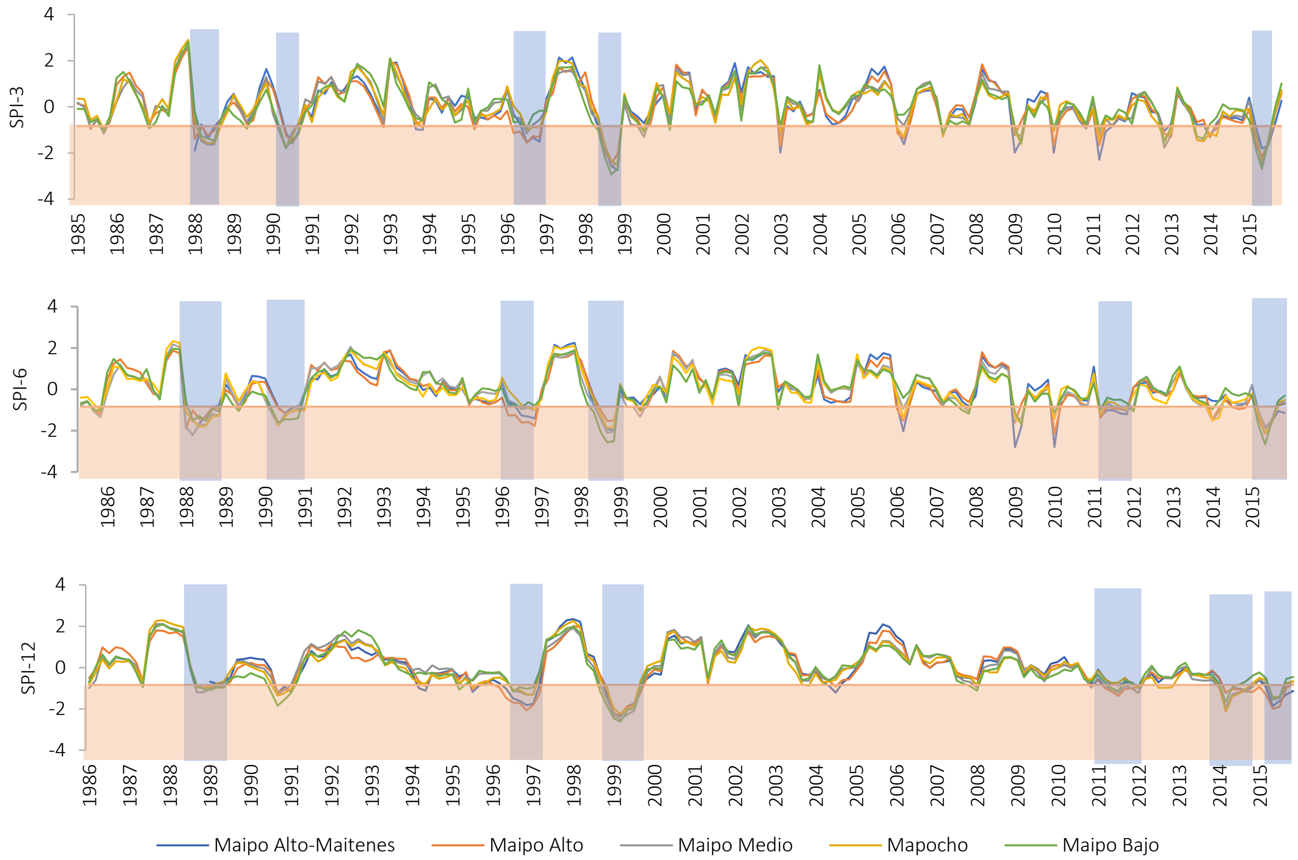


Figure 6 Temporal variation of meteorological droughts of each sub-basin based on SPI 3, 6 and 12-month aggregated for the rainy season (April to September). Blue shadings show the major drought events.

All the sub-basins reached the extremely dry category, where the lowest values detected by SPI-3, SPI-6 and SPI-12 were in the years 1998-1999. This period was also the longest drought event for all sub-basins (Table 2). During 12 to 16 percent of the study period the basin has experienced meteorological drought. The frequency ranged between 10 to 19 times during the period of record.

4.2 Trend analysis

According to Mann-Kendall Test in SPI and SSI, we can state that no positive trends were found for any station of the basin for any time scale. In the case of SPI, most of the stations located closest to the coast in accumulation periods of 3, 6 and 12 months (Figure 7), do not show significant trends (p <0.05). In contrast, negative trends (p <0.05) were detected in the middle zone in all temporal scales. However, mixed results were observed in higher stations due to SPI-3, and SPI-6 did not show significant trends (p <0.05) but in longer periods such as the SPI-12 significant negative (p <0.05) trends are shown. The result of the analysis also indicated that the accumulation periods may change the magnitude of the trend but not its direction. Drier conditions were more pronounced in the higher, middle and starting the lower zones of the basin for longer accumulation periods, such as the SPI-12 than shorter periods such as SPI-3. Regarding SSI trend analysis, for all discharge stations and time scales, negative trends were obtained as it is shown in Figure 8 (Linear SSI).

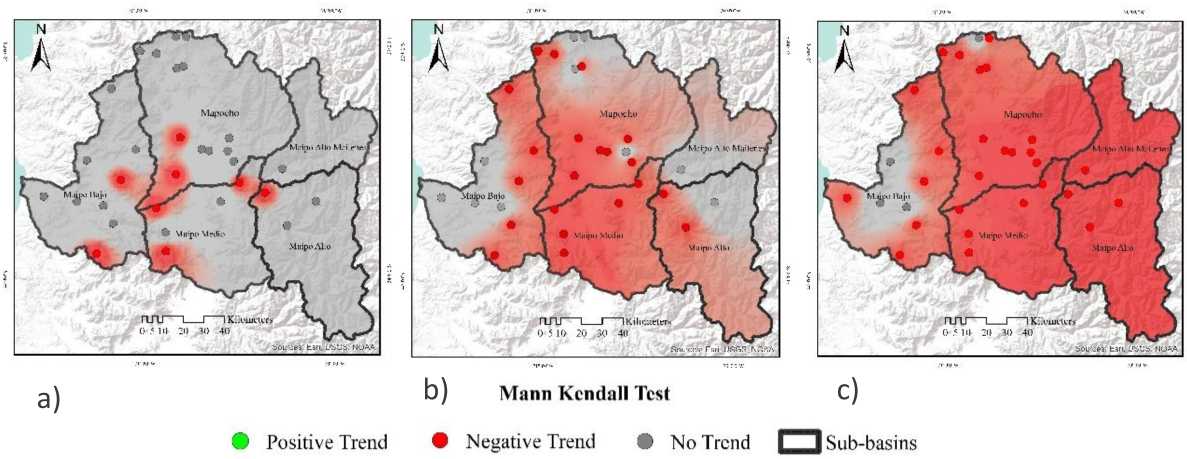


Figure 7 Spatial representation of the Mann Kendall Test trends for a) SPI-3, b) SPI-6 and c) SPI-12 monthly aggregates for the period 1985 -2015

Table 2 Characteristics of meteorological and hydrological drought events (1985 to 2015) and the correlation between SPI and SSI values

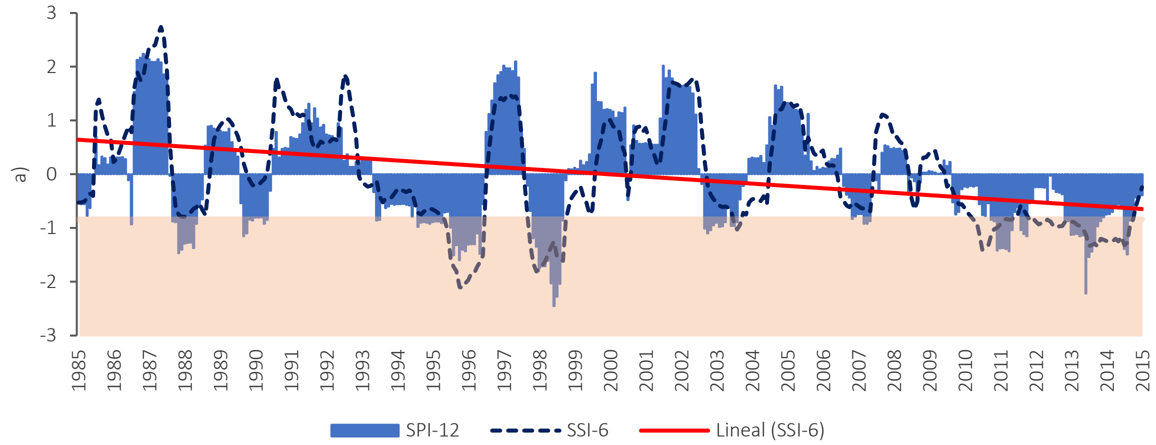
METEOROLOGICAL DROUGHT						HYDROLOGICAL DROUGHT						
SUB-BASIN	**TEMPORAL SCALE**	**MAXIMUM DROUGHT DURATION (MONTHS)/YEAR**		**% TIME IN DROUGHT**	**FREQUENCY**	**DISCHARGE STATION**	**TEMPORAL SCALE**	**MAXIMUM DROUGHT DURATION (MONTHS)/YEAR**		**% TIME IN DROUGHT**	**FREQUENCY**	**HIGHEST CORRELATION VALUE / CLOSEST PRECIPITATION STATION (SPI-12)**
MAIPO ALTO	SPI-3	7	1998	16	19							
	SPI-6	10	1998		12							
	SPI-12	16	1998-1999		10							
MAIPO ALTO-MAITENES						1A	SSI-1	11	1987-1988		8	0.34
	SPI-3	5	1998		14		SSI-3	11	1988		10	0.36
							SSI-6	11	1988		6	0.36
	SPI-6	9	1998	12	11		SSI-12	12	2008 / 2011-2012	20	6	0.31
						2A	SSI-1	19	2014-2015		12	0.77
	SPI-12	12	1998-1999		11		SSI-3	23	2014-2015		10	0.79
							SSI-6	24	2014-2015		7	0.72
							SSI-12	38	2012-2015		7	0.52
MAIPO-MEDIO						3B	SSI-1	18	2010-2012		6	0.79
	SPI-3	6	1998		17		SSI-3	25	2010-2012		7	0.80
							SSI-6	26	2010-2013		5	0.75
	SPI-6	7	1998	14	13		SSI-12	58	2011-2015	22	3	0.52
						4B	SSI-1	30	2013-2015		5	0.69
	SPI-12	13	1998-1999		10		SSI-3	36	2012-2015		5	0.74
							SSI-6	64	2010-2015		3	0.76
							SSI-12	64	2010-2015		3	0.69
MAPOCHO						5C	SSI-1	15	2014-2015		10	0.70
							SSI-3	17	2014-2015		9	0.75
							SSI-6	18	2010-2012		6	0.74
	SPI-3	6	1998		15		SSI-12	25	2010-2012		6	0.52
						6C	SSI-1	16	2014-2015		9	0.80
							SSI-3	28	2013-2015		7	0.84
							SSI-6	28	2013-2015		5	0.84
	SPI-6	8	1998	12	12		SSI-12	30	2013-2015	22	6	0.64
						7C	SSI-1	16	2013-2015		7	0.76
							SSI-3	16	2013-2015		6	0.81
							SSI-6	34	2012-2015		5	0.85
							SSI-12	54	2010-2015		4	0.69
	SPI-12	11	1998-1999		10	8C	SSI-1	22	2010-2012		9	0.78
							SSI-3	27	2010-2012		10	0.82
							SSI-6	29	2010-2012		8	0.83
							SSI-12	40	2010-2014		6	0.71
MAIPO-BAJO						9D	SSI-1	8	1996-1997		4	0.44
	SPI-3	4	1998		17		SSI-3	8	1996-1997		5	0.51
							SSI-6	11	2011		5	0.57
	SPI-6	8	1998	13	16		SSI-12	18	2010-2012	22	6	0.58
						10D	SSI-1	13	2014-2015		10	0.74
	SPI-12	13	1998-1999		11		SSI-3	20	2014-2015		10	0.79
							SSI-6	32	2013-2015		6	0.79
							SSI-12	60	2011-2015		4	0.63

4.3 Hydrological droughts

Table 2 shows the characterization of hydrological and meteorological droughts. Although the hydrological droughts (between 3 and 12 times from the period of record) are less frequent compared to meteorological droughts (between 10 and 19 times from the period of record), these are longer, obtaining periods up to 64 months under hydrological drought. This pattern is also observed in the percentage of time when the basin experienced hydrological drought (20-22%), being higher than meteorological drought (12-16%). Also, the longest drought periods in most of the basin have occurred in recent years (2010-2015), while in meteorological droughts the longest and more severe drought was in the year of 1998-1999. All stations, except 1A (showing severe drought as the maximum drought category in November 2011), reached the most extreme drought class. As it is also shown in table 2 for both SPI and SSI, more drought events were identified at shorter accumulation periods. Hydrological drought characteristics based on SSI show more spatial variability than meteorological drought characteristics. The stations located in Maipo Alto Maitenes (1-A) and Maipo Bajo (9D) showed the shortest hydrological drought duration from the basin. However, this last station (9D) reached the lowest value from the whole basin and time scales (-4.69) for SSI-1 in January 1997. Station 3B, 4B,5C, 7C 8C,9D, and 10D had the lowest values for this time scale in the period 1994 to 1997. Also, as it is seen in Figure 8, the last ten years are dominated by dry hydrological events.

4.4 Relationships between meteorological and hydrological droughts

The Pearson correlation coefficient (R) values between SSI and SPI at multiple time scales are also shown in Table 2. Positive relationships were obtained in all stations, where the highest correlation of SSI in all temporal scales was identified with the highest accumulation period SPI-12. This pattern might show the significant dependence of the streamflow of snowfall during the previous hydrological year. Figure 8 provides an illustrative overview of the analysis. It shows the temporal variation of the SSI-6 and the SPI at 12-monthly scale in the station 7C which are the time scales with the highest correlations (R=0.85) and the temporal variation of SSI-1 and SPI-12 in the station 1A with the lowest correlation (R=0.34) from Table 2.



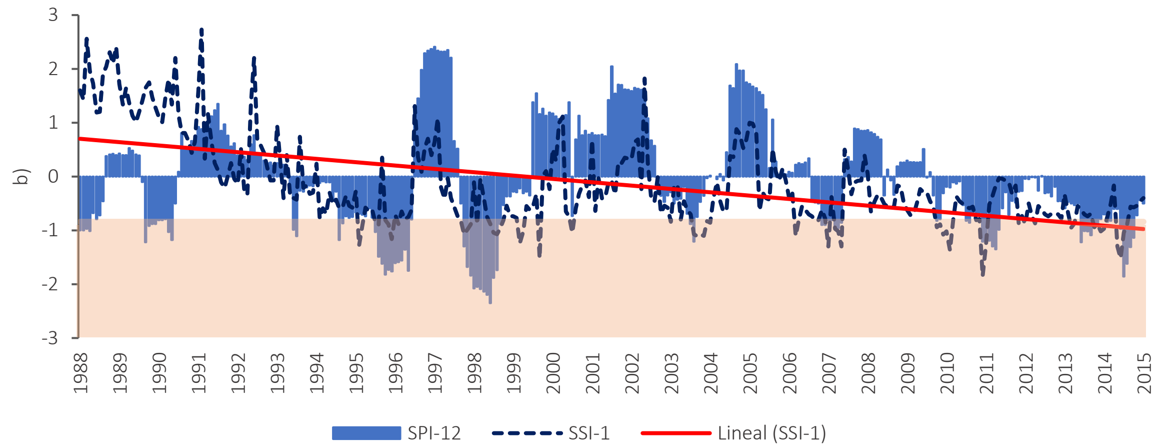


Figure 8 Example of temporal variation of SPI and SSI on selected stations with different correlation coefficients. a) Station 7C in Mapocho sub-basin (R= 0.85) and b) Station 1A in Maipo Alto-Maitenes sub-basin (R= 0.34).

4.5 Hydrological drought and water quality

Correlation coefficients between daily discharge volume and the related physicochemical parameter from the period of record 1985 to 2015 are shown in Table 3. Physicochemical data grouped according to the corresponding thresholds levels of the station 4B are shown in Figure 9.

Mixed responses were observed for temperature and dissolved oxygen, and at least 50% of the stations did not show significant correlations with discharge in both parameters (p <0.05). On the one hand, significant negative relationships are found in the stations 4B, 8C, and 9D for temperature (-0.26, -0.27 and -0.54; $p < 0.05$), which have a pluvial and mixed regime. In these same stations, significant positive relationships were found for dissolved oxygen in two of them ($p < 0.05$). Nonetheless, this parameter showed the lowest range of significant correlations within the whole set of physicochemical parameters data. On the other hand, stations with a nival regime such as 2A, 3B, and 5C (0.40, 0.51 and 0.45) showed positive relationships with temperature.

Significant negative relationships were observed for pH, electrical conductivity, Na, Mg, Ca, SO_4, Cl, K, and PO_4. In these parameters, maximum concentrations were found in drought periods. The percentage of response to this characteristic is variable in the basin ranging from 100 to 10% of the stations (Na and PO_4 respectively). The station 8C was the only site displaying significant negative relationship of PO_4. For electrical conductivity, only the station 5C from Mapocho sub-basin does not show a significative relationship with discharge, finding the maximum values of this parameter (560-570 µS/cm) in both dry and regular periods. The highest significant correlation coefficients for electrical conductivity (R= -0.78) and related ions such as Na^+ (R= -0.84) and Cl^- (R= -0.81) were found in the same station (3B); this behavior was a continuing pattern in most of the basin locations. In contrast, significant positive relationships ($p < 0.05$) were found for Al, As, Cu, Mn, Fe, and Zn within a range of 90 to 50% of the stations showed this pattern (Al and Cu respectively). The maximum concentrations of these parameters were observed in wet periods (Appendix E). Also, no relationship was found for nitrate in any station of the basin, supported by the fact that it did not show strong variations in its concentration due to periods of variable streamflow.

Table 3 Discharge stations and Physicochemical Parameters. Correlation coefficient with daily discharge, significant correlations ($p < 0.05$) are presented in bold character. * Stations located in irrigation districts. °C: Temperature; pH: pH units; O_2: Dissolved oxygen (mg/L); As: Arsenic (mg/L); Cu: Copper (mg/L); Cond: Electrical conductivity (µS/cm); Na: Sodium (mg/L); Mg: Magnesium (mg/L); Mn: Manganese (mg/L); Ca: Calcium (mg/L); SO_4: Sulphate (mg/L); Cl: Chloride (mg/L); K: Potassium (mg/l); NO_3: Nitrogen nitrate (mg/L); Fe: Iron (mg/l); PO4: Orthophosphate (mg/l); Zn: Zinc (mg/L).

SUB-BASIN	Discharge Station	Altitude (m.a.s.l)	Hydrologic regime	°C	pH	O_2	Al	As	Cu	Cond	Na	Mg	Mn	Ca	SO_4	Cl	K	NO_3	Fe	PO_4	Zn
Maipo Alto - Maitenes	1A	1500	Nival	0.13	-0.18	-0.14	**0.63**	**0.38**	**0.55**	**-0.58**	**-0.65**	**-0.30**	**0.45**	-0.15	-0.11	**-0.55**	-0.08	-0.25	**0.62**	-0.10	**0.49**
	2A	890	Nival	**0.40**	**-0.28**	**0.24**	**0.53**	**0.34**	-0.00	**-0.69**	**-0.84**	**-0.26**	**0.35**	-0.09	**-0.53**	**-0.79**	**-0.26**	-0.15	**0.50**	-0.08	**0.46**
Maipo Medio	3B	850	Nival	**0.51**	-0.18	-0.12	**0.36**	**0.23**	**0.27**	**-0.78**	**-0.84**	-0.20	0.21	-0.22	**-0.40**	**-0.81**	-0.12	0.06	**0.28**	-0.05	**0.29**
	4B*	342	Pluvial	**-0.26**	**-0.25**	**0.29**	**0.65**	**0.26**	**0.27**	**-0.72**	**-0.72**	**-0.67**	**0.27**	**-0.66**	**-0.69**	**-0.70**	-0.18	-0.05	**0.54**	0.09	**0.44**
Mapocho	5C	1350	Nival	**0.45**	**-0.43**	**-0.23**	**0.28**	0.18	0.13	-0.07	**-0.24**	**-0.28**	0.10	0.06	0.06	**-0.28**	-0.13	0.02	**0.47**	0.12	0.07
	6C	880	Nival	-0.05	-0.19	**0.23**	0.10	-0.07	-0.09	**-0.69**	**-0.25**	-0.06	**0.33**	**-0.26**	**-0.61**	-0.13	-0.09	0.13	**0.30**	0.09	-0.13
	7C	966	Nival	-0.04	**-0.22**	0.09	**0.34**	-0.06	-0.03	**-0.43**	**-0.29**	-0.19	0.17	-0.10	**-0.41**	**-0.25**	0.02	0.18	0.08	0.09	0.12
	8C*	440	Nivo-Pluvial	**-0.27**	0.03	**0.26**	**0.40**	**0.23**	**0.20**	**-0.66**	**-0.55**	**-0.41**	0.21	**-0.53**	**-0.61**	**-0.56**	**-0.35**	-0.12	**0.50**	**-0.34**	**0.45**
Maipo Bajo	9D*	93	Pluvial	**-0.54**	-0.17	-0.10	**0.43**	0.15	0.21	**-0.48**	**-0.36**	**-0.52**	**0.30**	**-0.57**	**-0.59**	-0.18	**-0.36**	-0.07	**0.47**	-0.07	0.25
	10D	35	Pluvial	-0.19	**-0.23**	0.05	**0.53**	**0.41**	**0.31**	**-0.68**	**-0.34**	**-0.43**	0.11	**-0.29**	**-0.52**	**-0.60**	-0.16	-0.11	0.17	-0.00	**0.40**

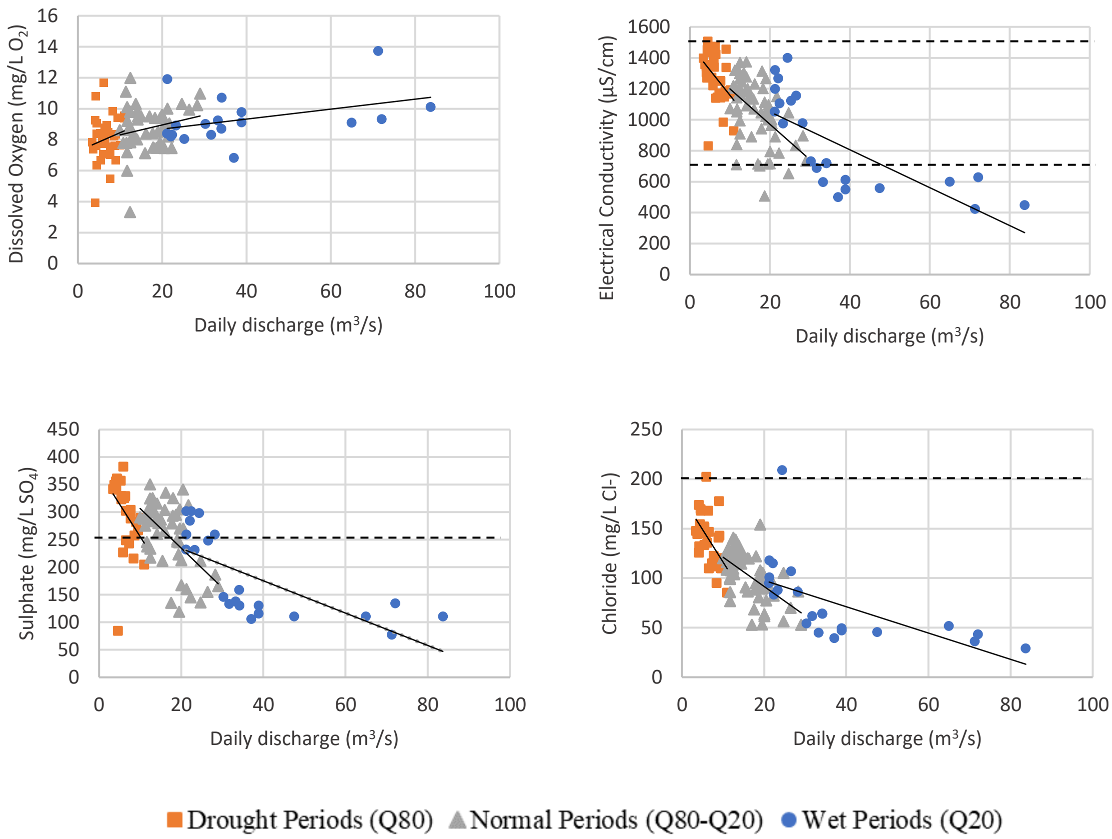


Figure 9 Daily discharge and physicochemical parameters from station 4B grouped by the related threshold level. Dashed lines represent the threshold for each parameter according to the Chilean regulation for irrigation water uses

4.6 Drought driven water quality impacts on irrigated agriculture

Table 4 shows the water quality threshold values (NCH) compared to maximum, mean and minimum water quality values for three key station within the three subareas of the Maipo and located in irrigation districts: 4B, 8C, and 9D (Table 3 and Figure 3). At these stations, the parameters were compared with thresholds from official regulation for irrigation water uses.

Although pH had a negative relationship with discharge for station 4B, its values remained in the allowable range for agricultural water use (5,5-9). As heavy metals like As and Cu increased with streamflow (Table 3), during drought periods their concentrations were not surpassing the established limit. However, parameters such as electrical conductivity, SO_4, and Cl^- reached their maximum mean concentration during hydrological drought periods, markedly exceeding its relative threshold (Figure 9; Table 4). Electrical conductivity and related ions that are associated with salinity and sodicity irrigation problems also had highest values during drought periods. Parameters without an official threshold but with possible impacts on agriculture such as dissolved oxygen found its lowest concentration on dry periods. Most of these maximum and minimum values related to water quality for agricultural water use were reached in recent periods of extreme low flows (2010-2015).

Table 4 Minimum, maximum and mean concentrations of physicochemical parameters during drought periods and related threshold levels according to the Chilean regulation NCh 1333/78 for stations located in irrigation districts.

		Cond (µS/cm)				SO_4 (mg/L)				Cl (mg/L)			
SUB-BASIN	**Dicharge Station**	**Min**	**Max**	**Mean**	**NCh1333**	**Min**	**Max**	**Mean**	**NCh1333**	**Min**	**Max**	**Mean**	**NCh1333**
Maipo Medio	4B	831	1507	1267	750-1500*	84.0	382.3	296.1		85.4	202.3	137.4	
Mapocho	8C	1146	2213	1656	1500-3000**	221.0	404.4	312.4	250	101.0	323.9	210.8	200
Maipo Bajo	9D	1307	2183	1713	>3000***	309.8	450.5	369.6		143.0	291.8	203.9	

* Possible detrimental effects on sensitive crops, ** Possible adverse effects on sensitive crops and requires careful handling methods *** Water can be used for tolerant plants in permeable soils with conservative management practices.

5 Discussion

In particularly dry years (Figure 10), the whole water cycle is affected due to the reduced reservoir recharge and snow storage that will extend to the zones of the basin that depend of them. The important input from the precipitations months of the previous hydrological year(s), could also represent the retreating in the snow cover for the thaw months affecting the recovery of the low flows from the rainy season. Summer and spring months in particularly dry years could be warmer (Carrasco et al. 2005) and this result in a higher demand from the different activities (e.g. higher rates of evapotranspiration which means more irrigation demands). The over-extraction of an already scarce resource, can lead to impact even more the streamflow. This continue low flows conditions along the inputs from the economic activities, deteriorates the water quality of the main rivers from which the water will be distributed through channels to the irrigation districts, causing a major risk for agriculture. These impacts are discussed below.

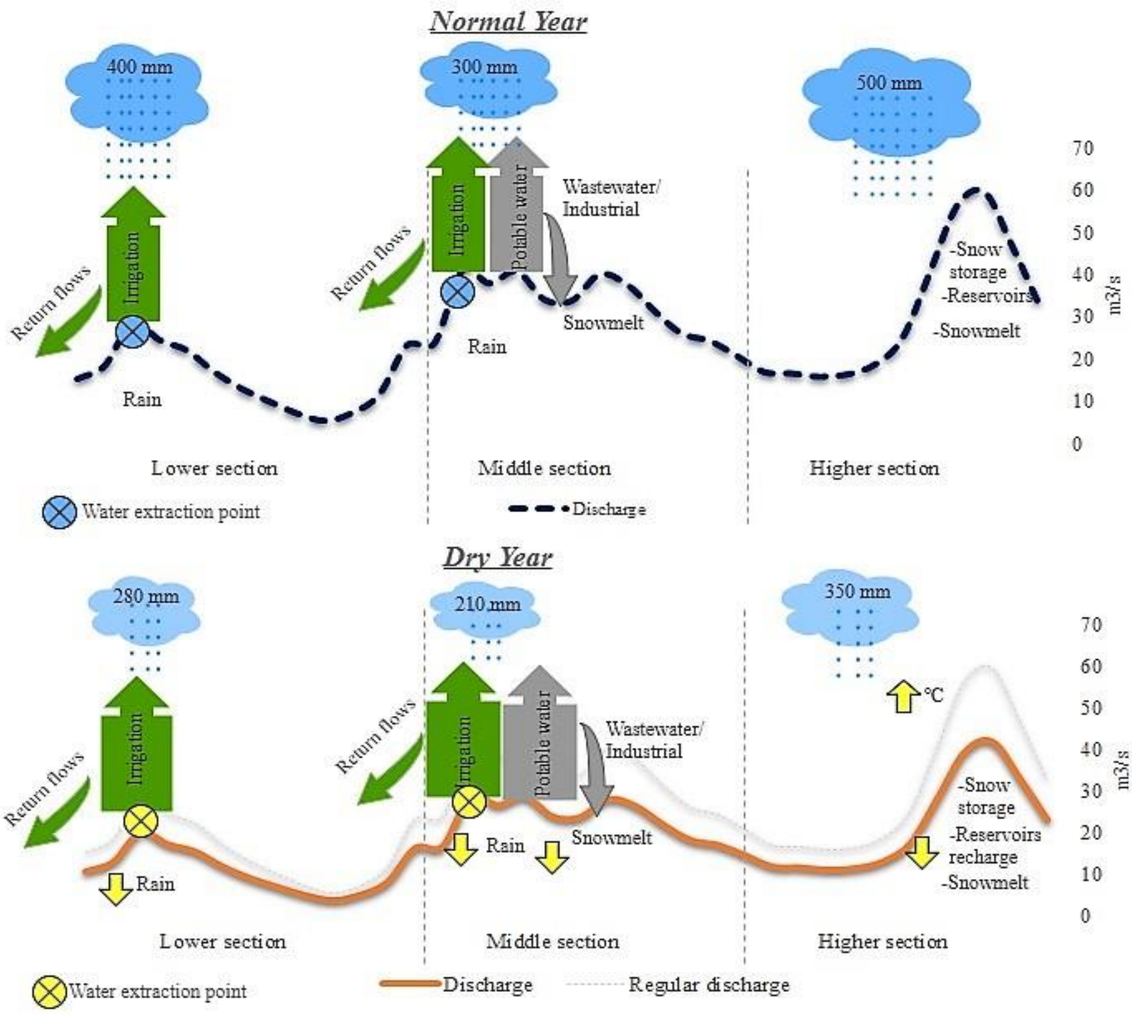


Figure 10 Drought impacts on streamflow in the Maipo River Basin. Diagram by Author

5.1 Drought impacts on water quantity

5.1.1 Meteorological drought

Regarding meteorological drought analysis, although the basin has a precipitation gradient from the east (Andes mountains), decreasing in the central valley and rising again to the west (Pacific Ocean coast), the results show that there is a similar behavior between the sub-basins. This result could be mostly related to the shared Mediterranean climate of the central Chilean region in which the difference in altitude related to temperature and precipitation changes are not highly influencing the meteorological drought pattern. Similar results were reported by Van Loon & Laaha (2015), where comparable meteorological drought conditions were found in catchments from Austria mainly governed by a continental climate type. Also, Barker et al. (2016) found comparatively little differences for shorter accumulation periods in SPI for different catchment types in the UK. Between 1985 and 2015, there was a general negative trend in SPI in most of the stations of the basin, this pattern is consistent with previous analysis undertaken at national and regional scales (CONAMA) 2006; Universidad de Chile 2016), where there is a continuous trend in a general reduction of precipitation in central and northern Chile. According to the Center for Climate and Resilience Research (CR)^2 (2015), in this zone of the country, a quarter of the period between 1940 and 2010 have presented a precipitation deficit higher than 30%. This trend of decreasing precipitation has also been reported with the gradual increase of temperatures in the Andes by several authors (Haylock et al. 2006; Falvey & Garreaud 2009; Magrin et al. 2014). Falvey & Garreaud (2009) address that in central and northern Chile (17°- 37° S) for 1979-2006, there is a strong contrast between surface cooling at coastal stations (-0.2°C/decade) and warming in only 100-200 km further inland and the Andes (+0.25°C/decade). This finding can be related to our results of no significative trends in SPI in most of the coastal stations in the Maipo river basin, due to the strong relationship between precipitation and temperature trends. Studies from Trenberth & Shea (2005) found negative correlations of the stratus decks in the Pacific off the Coast of California and South America for the period 1979-2002, suggesting that cold surface conditions can produce stratocumulus and precipitation, while warm sea surface temperatures are accompanied by dry air. Also, according to Masiokas et al. (2006) and references therein, the warm (cold) phases of ENSO, usually associated with El Niño (La Niña) events in the tropical Pacific, have been related to wet (dry) years in Central Chile. It is important to highlight that in our study in higher zones of the basin (Maipo Alto and Maipo Alto Maitenes), the station density is not so representative due to the low number of stations with a significant number of years for drought analysis. However, in this sense, more station above 1500 m.a.s.l were placed recently by the Chilean National Water Agency with periods of record starting on 2013 approximately.

5.1.2 Hydrological drought

The hydrological drought characterization at different time scales indicates a continuous negative trend in the whole basin and a general reduction in the rivers flows, more acute in the last five years (2010-2015). The monthly streamflow deficit (SSI-1) in the basin ranged from 8 to 30 months; this latter corresponds to the station 4B located in the central valley, which reflects the great anthropic intervention. The apparent long droughts (from 3 to 12 months accumulation period), are the result of strong long-term decreasing temporal trends in streamflow (Barker et al. 2016), being the SSI-12 the measure of the annual drought severity. These events have been longer in recent years (2010-2015), indicating that the rainfall following droughts has been unable to generate the surpluses needed to a full restore of the hydrological conditions that were present prior the drought and the increasing demand from the activities within the basin (agriculture, industrial and urban supply)(J. Lorenzo-Lacruz et al. 2013). This decrease in the annual streamflows since 2010 in the region has also been reported by the (CR)^2 2015.

In contrast to meteorological drought characteristics, hydrological drought displays some differences between the sub-basins. The station located in the higher zone (1A) showed, the lower drought duration in comparison with the middle and lower zones of the basin. Furthermore, the decrease in streamflow is more pronounced in the middle and lower areas with the high demand of water for agriculture, urban and industrial uses in the basin that could accentuate the hydrological droughts. Only the station 9D, located in Maipo Bajo, showed a similar behavior of the station 1A. This could be mostly related to its location closer to the cost, where did not show significative trends in SPI analysis and also because is dominated by groundwater outcrops and irrigation returns from the areas served by the channels in the irrigation districts (DGA 2004; DGA 2003).

The hydrological drought periods in the basin were not restricted to the rainy season (winter-autumn) but also to the thaw months (spring-summer). This pattern can be explained by the direct relationship between precipitation and snowpack accumulation, and the impacts of rainfall reduction on spring and summer discharge in rivers with a nival regime in the Central Andes (Masiokas et al. 2006). Carrasco et al. (2005) reported for central Chile that the number of days with precipitation have decreased after the 1970s, suggesting that glaciers are exposed to more days with atmospheric conditions appropriate for melting. Also, the same study showed an increase in elevation of the 0°C isotherm in winter and summer for the period 1974-2001, and that warming has concentrated during periods with no precipitation, enhancing melting of glaciers that lead to its recession. The increased glacier recession may result in higher runoff in the short term, however the observed and predicted climate tendencies for the central Andes (warmer temperature/decrease in precipitation) could indicate that ultimately the glacier melt contribution to streamflow will diminish, with substantial and widespread socioeconomic impacts especially during extreme dry years (Masiokas et al. 2006).

According to van Loon et al. (2010) a type of drought that has not been mostly studied, but is probably more widespread in snow affected regions such as the Maipo river basin can apply, in consonance with the trends above mentioned: The combined effect of higher temperatures in winter with lower precipitations determines the development of hydrological droughts. It happens when the recharge from snowmelt is often too low to end the drought, and it continues into summer having an adverse impact on water resources. Also, when winter temperatures are above 0°C, the snow accumulation is limited, and a continuous snow cover does not develop. Although is possible to suggest this behavior for the region, a deeper analysis should be developed to assure and understand this pattern.

5.1.3 Meteorological and hydrological drought relationship

The highest correlation of SSI in all temporal scales was found with SPI-12 accumulation period, a pattern that distributes along the basin denoting the dependence of the streamflow to the previous year(s) of precipitation. Some authors have evaluated the propagation of meteorological drought through the hydrological cycle, linking different time scales of SPI to SSI-1, which represents the streamflow deficits. Lorenzo-Lacruz et al. (2013) found similar results, attaching the response to the high permeable geologies of the catchments characterized by limestone lithology in southern of the Iberian Peninsula which results in groundwater recharge delaying the streamflow response to meteorological variability. Besides in the study of Barker et al. (2016), they found that the highest correlation of SSI-1 with longer SPI time scales (south and east in the UK) were located in regions underlain by major aquifers. In the case of the Maipo river basin, the regions close to the Andes mountains present a practically null permeability due to the presence of granitic rocks. However, the central depression corresponding to a tectonic pit and the region closest to the cost, with a large influence of the presence of Cretaceous volcanic and sedimentary rocks, present a permeability from medium-high and medium-low respectively (DGA 2004). The low correlation in the station 1A (1500 m.a.s.l), the highest altitude analyzed in this study for discharge, could be linked to its relationship with snow, which is a key factor explaining the variability of the hydrological response. Further analysis (Appendix F) of this station revealed that it continues to increase its correlation up to SPI-24 and then start to decrease. In the study of López-Moreno et al. (2013) was found a progressive increase in the correlation of SSI at longer time scales during winter and particularly during spring. This increase effect could be a consequence of the storage of winter precipitation as snow and its subsequent contribution to streamflow during the snowmelt period (Adam et al. 2010 cited in López-Moreno et al. 2013).

Furthermore, this pattern could also be a characteristic of regions where damming can modify the timescales of the response of hydrological droughts to climate variability (Vicente-Serrano & López-Moreno 2005; Lorenzo-Lacruz et al. 2010; López-Moreno et al. 2013; Vicente-Serrano et al. 2017). The response of SSI to a longer accumulations periods was observed in Vicente-Serrano et al. (2017) with the climatological index SPEI in the lower areas of a highly regulated river basin from northeastern Spain because of the high-water storage capacity in the upstream. In our study, the surface water resources from the Maipo river are partially regulated through damming in the Negra Lagoon and El Yeso dam (DGA 2008). Whereby the permeable lithology of the medium and lower zones of the basin and the multi-year regulation of the dams could cause temporary delays in the rate of streamflow deficits related to the absence of precipitation (Lorenzo-Lacruz et al. 2010; J. Lorenzo-Lacruz et al. 2013).

However, to establish the time scale at which hydrological droughts responds to meteorological droughts, more factors have to be involved: the physical attributes of the catchments (geology, topography, soils and vegetation), climatic conditions (evapotranspiration rates, snow cover, rainfall intensity) and water management strategies (Lorenzo-Lacruz et al. 2013 and references therein). Also, the anthropogenic factor manifested through the use of water and the extraction from the different activities, and the several land use and land cover modifications during centuries can have a strong influence on the meteorological-hydrological relationships (García-Ruiz et al. 2011; Ljubenkov & Cindric 2016)

It is possible to highlight that as we obtained the highest correlation with SPI-12 (Table 2) in all stations of the basin, this suggests the high potential to predict streamflow droughts from meteorological records (Vicente-Serrano & López-Moreno 2005). As it is possible to have more meteorological gauging stations than discharge stations, the use of precipitation to identify future potential streamflow deficits will be useful as a monitoring and early warning indicator to prevent or mitigate the impact of a hydrological drought (Barker et al. 2016). Since the surface waters in Maipo basin are the major available water sources, the SPI-12 becomes central since irrigation, and the urban water supply depends greatly on annual reservoir storage.

5.1.4 Drought impacts on water quantity for agricultural requirements

In an overall drought perspective, the water resources of the basin in the period of record studied in this work are diminishing. Although our period of analysis covered from 1985 to 2015, according to NASA & NOAA 2017, 2016 has been the third consecutive year with record-high surface temperature registered since 1880, which could mean a continuing trend in the conditions above mentioned. This context can address the following question: Will be enough water to sustain irrigation requirements? According to Fiebig-Wittmaack et al. (2012), who studied the Norte Chico in Chile, it is difficult to have a clear answer to how understand the streamflow behavior in the Andes due to the sparse precipitation data on the high mountain and the lack of knowledge concerning cryosphere. However, the positive (negative) trends of temperature (precipitation) suggest an increase in the frequency and severity of droughts impacting water resources. Moreover, affecting not only only rainfall but the resources stored in the form of snow, permafrost, and glacier, questioning the possibility to sustain adequate irrigation requirements.

In agriculture, the water shortage is determined not only by the decrease in precipitation under normal conditions but also by the intensity with which water is being demanded (evapotranspiration) and the amount of moisture that is available in soils for the growing season, being the available soil moisture, the most important variable for the satisfaction of plant water demand (Meza 2013). For this reason, although the highest water agricultural requirements in the region are from October to March (Spring-Summer) the farmers continue irrigating in winter and autumn to avoid salinity and maintain soil moisture for the growing season (Personal communication, Carlos Castillo González-Manager of the United Channel Association of Buin, May 2017). Therefore, since it is difficult for a farmer to define if there is a water deficit or not, they tend to "play safe" increasing irrigation amount especially when associated costs are low (Chartzoulakis & Bertaki 2015). In this sense, farmers (and other users) acquire additional water rights to minimize the risk of water scarcity and secure the operation of their irrigation systems (Meza et al. 2012). This over-irrigation can cause temporal water shortage to other farmers, particularly in dry years. For instance, in the study of the Chilean National Water Agency (DGA) (2003) was reported that it was not possible to establish more eventual and permanent consumptive rights in the basin due to in the dry years the channel partnerships can not receive the whole of their water rights.

Furthermore, according to the Chilean National Water Agency (DGA) (2008) and the World Bank (2011), in the Metropolitan region the water demand overcome the surface water resources available, suggesting that the future satisfaction of the growing demand should be made: (1) at the expense of more efficient use of water, (2) greater use of groundwater resources or (3) the incorporation of the use of new surface resources during the low flows by means of regulation works. Regarding water use efficiency in agriculture, 16% of the Maipo river basin (virtually the entire Maipo Valley) is destined to agricultural land with significant part of the land, currently occupied by meadows and bushes, susceptible to be incorporated into irrigation (MOP 2007). Of these areas, 88.4% are gravitationally irrigated, 7.5% with micro-irrigation and only 4.1% with greater mechanical irrigation. Given the irrigation efficiency of each system: gravitational:35%, macro-mechanized irrigation: 70% and micro-irrigation 85%, the irrigation efficiency of the basin ranged between 38 and 45% (CNR et al. 2003). Also concerning water allocation, the channels in the region are mostly old, and some of them are in bad conditions, which would result in high water losses in the delivery process (DGA 2008). Meanwhile, the increase in the use of groundwater, given the economic growth of the region which presents a sustained growth of water demands mainly intended for potable and irrigation uses, can put at risk the sustainability of the groundwater resources in some reservoirs due to the water rights already exceed its exploitation capacity (World Bank 2011).

Therefore, the situation could be more acute under climate change conditions. In the study of Meza et al. (2012) to determine the availability of water resources and water rights for irrigated agriculture, using the historical streamflow data of the station 3B, determined that the discharge from the Maipo river under climate change sceneries will be in approximately 40 to 50 % of the current discharge. This context will difficult the viability of irrigated agriculture (water allocation) at its current level of intensity, cropping patterns, and water use efficiency. In that study, they also highlighted that water rights may be oversubscribed for highly stressed basins under future climate change, and adaptation will be imperative. In this context Nuñez et al. (2014) and references therein, also address the relevance of persistent drought events could indicate the presence of dryness conditions, which will require the re-evaluation of what is normal and the time scale of water management and political decision-making. In this sense and according to Núñez et al. (2013), the north-central Chile region is experiencing a significant water deficit associated with multidecadal climate variability consistent with the Pacific Decadal Oscillation, which suggests that the precision of the decadal time scale is more appropriate for this purpose.

5.2 Drought impacts on water quality

The analysis of hydrological drought it is necessary not only for the determination of minimal downstream flow requirements of the different regional economic activities but it is also crucial for the water quality management to supply those activities such as the irrigation systems (Nosrati 2011). Surface water withdrawal can be severely affected by water quality degradation since it is also the first water source to be impacted by hydrological droughts (Delpla et al. 2009). However, it is important to highlight that the seasonality of the low flows (which were not restricted to summer droughts), the mixed regime of the basin, and the anthropogenic activities, highly influence the behavior of the parameters. In our study, the results related to surface water quality changes due to the variable discharge and especially low flows will be discussed below.

5.2.1 Temperature

The responses of this parameter to discharge were mixed. On the one hand, the stations with significant (p <0.05) negative relationship with discharge (stations located in irrigation districts and with a mixed or pluvial regime), it is observed an increase in temperature during drought periods. This behavior is mostly due to the inverse relationship between water temperature and river discharge which reflects higher warming rates under low-flow conditions (Caruso 2002; van Vliet & Zwolsman 2008). Low flows could cause longer water residence times and reduced water volumes allowing higher water temperatures as a result of reduced thermal capacity and higher sensitivity to atmospheric and other heat inputs (Mosley et al. 2012 and references therein). Similar results were found in rivers of the Otago region in New Zealand, the Pinois river basin in Greece, rivers and lakes of Beijing China, among others (Mimikou et al. 2000; Caruso 2002; Huang et al. 2015). On the other hand, significant positive relationships were observed mostly in stations located in higher zones and with a nival regime. This behavior of the temperature could be mostly related to the seasonality of the region, where higher volumes of streamflow are related to thawing months from the Andes mountains (Summer-Spring). Although the station 10D has a pluvial regime, also has a drainage network of 15040 km^2 considering practically the total network of the basin. This condition reflects the seasonal variation, the human interference and the irrigation influence from the irrigation networks (DGA 2004). In those stations were not found significant changes related to discharge, could be related to not significant variations in the air temperature in the station's area. Similar results were seen in the Murray River and Lower Lakes Albert and Alexandrina in Australia (Mosley et al. 2012), where no changes in water temperature during drought periods were found, regardless a general regional warming across the river basin.

5.2.2 Electrical conductivity/salinity

As a general behavior, electrical conductivity/salinity and major ions (Cl^-, Na^+, SO_4^{-2}, Mg^+, Ca^+, K^+) had significant negative correlations with discharge and increased in almost all the station analyzed during low flow conditions. Similar results have been reported in for Karoon river and streams from the Mazandaran province of Iran, Llobregat river in Spain among others (Nosrati 2011; Dezfuli et al. 2013; Momblanch et al. 2015). Droughts cause substantial rises in salinity, and it has been reported an inverse relationship between low-inflow and high salinity periods, where a change in discharge flows can increase the conductivity concentrating the present dissolved contaminants (Prathumratana et al. 2008). In rivers and lakes, the decreased dilution of saline groundwater inputs and high evaporation rates along to longer water residence times benefits salt accumulation (Caruso 2002; Mosley et al. 2012). Nevertheless, depending on the water body, different concentrations and sources of salinity could cause this change. In estuaries, as its coastal nature, higher chlorinity (influx of saline water) levels were strongly linked with reduced freshwater flows into the estuary during drought, changing its salinity distribution (Attrill & Power 2000). In the case of the station 5C, that does not show significant relationship with electrical conductivity, it could suggest that the natural conditions of the station (river of glacial origin, rich in ionic compounds) prevailed against the variable streamflow (DGA 2004).

5.2.3 Dissolved oxygen (DO)

The responses related to dissolved oxygen are variable but with lower significant relationships than the other parameters. The expected result of drought and low flow conditions is a decreased dissolved oxygen due to a lower oxygen saturation concentration under higher water temperatures (summer droughts), higher rates of organic matter decomposition by microorganisms, and lower re-aeration rates (van Vliet & Zwolsman 2008; Palmer & Montagna 2015; Prathumratana et al. 2008). This pattern (significant positive correlation) is slightly observed in just four stations of the basin regardless its hydrologic regime. In those cases where dissolved oxygen increases (Station 5C) could have specific conditions. For instance, in the Rhine, the increase in dissolved oxygen was mainly due to an increase in primary production in the river water (Zwolsman & van Bokhoven 2007). At the same time, for the Thames estuary, higher DO than normal during drought periods was linked to the reduction in the number of storm events leading to a less untreated sewage inputs or/and improved effluent quality from the wastewater treatment (Attrill & Power 2000). Also, an increase in DO in the kettle holes located in Wielkopolska Province in Poland were related to a result of photosynthesis process by submerged vegetation (Gołdyn et al. 2015).

5.2.4 pH

In our study, five stations of the basin showed significant negative correlations. In those cases where pH increase, could be as a result of lower water volumes favor stagnant conditions for algae growth and along with plants, they use all the carbon dioxide dissolved (van Vliet & Zwolsman 2008; Gołdyn et al. 2015 and references therein). Also, and depending on the water body, different sources can explain this increase. For instance, in the studies of Senhorst & Zwolsman 2005 and Prathumratana et al. 2008, for the Rhine, Meuse, and Mekong rivers have been reported increases in pH during low flow conditions that could be possible due to marine intrusion. In other cases, like in the Thames estuary in Great Britain, this change was related to the low inputs of freshwater during low flows, which tend to have lower pH than estuarine waters (Attrill & Power 2000).

5.2.5 Nutrients

Nutrients (NO_3 and PO_4) concentration can have different responses. In our study, no significant relationships were found for nitrogen in any discharge station and just one significant negative correlation of phosphate in one station located in an irrigation district (Station 8C). This pattern can be related to the high anthropic intervention in the region, where it is not possible to link a general behavior of this components with discharge due to the constant input from the different activities. However, it is expected that higher nutrient content during droughts could have a connection with a reducing dilution capacity of the water body (van Vliet & Zwolsman 2008; Zwolsman & van Bokhoven 2007; Prathumratana et al. 2008). On the contrary, deficient levels of dissolved nutrient concentrations in rivers can be related to rapid assimilation by algae where differences between nitrogen and phosphorus concentration could be linked to P or N limitations and increasing denitrification process with higher water residence time (Cook cited in Mosley et al. 2012). Also, low nutrient levels can be due to a reduced non-point source runoff inputs (Caruso 2002).

5.2.6 Metals

Significant positive relationship with discharge was found in most of the stations for essential (Zn, Cu, Fe and Mn) and nonessential (Al, As) metals (DGA 2004), meaning that the concentrations of those components increase in wet periods (Appendix E). As a general result of low flows, it is expected that several elements from regular anthropogenic activities can concentrate due to limited dilution (van Vliet & Zwolsman 2008; Zwolsman & van Bokhoven 2007). However, for inorganic pollutants, an indirect relation could be detected. The low flows along with elevated temperatures, could modify the rates of respiration, reaeration and retain water quality constituents which may be released during wet conditions (Mosley 2015). This condition means that components sediment can be delivered with the highest flows that come with the next rain (thaw streamflow) after a drought period, enhancing their concentration in the river flow due to were accumulated in the bottom of the river. Meanwhile, and according to Mosley et al. 2014, in the acidification process resulted from sediment exposure to air during lower water levels, it can release high and potentially toxic concentrations of dissolved metals. In the same study, it was possible to identify that dissolved metals as Zn and Ni (nickel) increase concentration at higher pH and others like Al, Fe and As at lower pH values. Furthermore, some metals as Pb (lead), Cr (chrome), Hg(mercury) and Cd (cadmium) could have high adsorption capacities to suspended soils which usually decreased in lower flow conditions (van Vliet & Zwolsman 2008).

5.2.7 Overall perspective of hydrological drought impacts on water quality

Water quality impacts and its magnitude depend on the specific characteristics of the water body as: water body type (for instance river, lake, estuarine) size, depth, shape, water regime, water residence time, the human activities in the catchment among others (van Vliet & Zwolsman 2008; Li et al. 2016; Delpla et al. 2009). Besides, according to Zwolsman & van Bokhoven (2007) in their comparison between the water quality during the different summer drought periods showed that the impact of droughts on water quality would be bigger when the water is already poor. Although the reductions in nonpoint source pollution during drought periods can improve the quality of the receiving water body (Caruso 2002), the decreased dilution of point source pollution during low flow conditions can increase its concentration (Zwolsman & van Bokhoven 2007). On the one hand, the sources of diffuse pollution in the Maipo river basin are pesticides (mainly applied during summer), solid household waste or minor wastes from agriculture, clandestine landfills along rivers and canals and infiltration from black wells, especially in rural areas (DGA 2008). According to DGA (2004), the liquid industrial waste has been a significant source of deterioration in the basin, turning it in the most contaminated basin in the country. On the other hand, the pollution from point sources are discharges of liquid industrial waste and from sewage treatment plants. In the Metropolitan Region the Mapocho River, the main water-receiving channel served by the city of Santiago, receives more than 60% of the total wastewater directly, and subsequently, these waters join the Maipo River (Matus et al. 2004).

Mostly, water quality impacts can be related to higher temperatures and low flows conditions, being more pronounced in summer droughts (van Vliet & Zwolsman 2008; Zwolsman & van Bokhoven 2007). However, water quality problems can be not just limited to the drought period itself. Drought-rewetting cycles may impact water quality for a long-term, as it enhances decomposition and flushing of organic matter into streams (Evans cited in Delpla et al. 2009; Huang et al. 2015). During drought, higher temperatures will increase mineralization and releases of nitrogen, phosphorus, and carbon from soil organic matter which will be discharged during runoff and erosion from intense precipitations after a drought period transporting the contaminants to the water bodies (Delpla et al. 2009). This wet and dry cycles also can increase the bioavailability of heavy metals due to less stable forms of metal deposits (Claessens and van der Wal cited in Verweij 2010).

Despite the importance of the quality parameters studied in this research, other components could have impacts on water quality during drought periods. Algae development is directly related to nutrient concentration (van Vliet & Zwolsman 2008; Mosley et al. 2012; Palmer & Montagna 2015; Zwolsman & van Bokhoven 2007). Decreases in algae biomass can coincide with decreases in nitrogen and phosphate concentrations or variable inflow that can produce algae flushing out the water body (Palmer & Montagna 2015). Another variable linked to algae concentration is turbidity, were a reduction in suspended solids load (lower turbidity) during drought conditions increase light penetration resulting higher primary production (Attrill & Power 2000). In general, the turbidity is expected to decrease due to the input of suspended solids decline from riverine sources and storms outfalls with low flows causing the settlement of suspended material in the water bodies (Attrill & Power 2000; van Vliet & Zwolsman 2008; Palmer & Montagna 2015). However, increased turbidity was found in the Lower Lakes in Australia, mainly due to the dominance of suspended colloidal fraction in the Murray system (Mosley et al. 2012). Additionally, total and fecal coliforms have increased during low flow drought conditions in the Otago Region, New Zealand, and the Turia River in Spain (Paredes-Arquiola et al. 2016; Caruso 2002). Furthermore, according to Delpla et al. 2009 and references therein, other components and process such as Phototransformation (UV transformation) of products from organic micro pollutants like pharmaceuticals should be taken into account, due to they are considered in some studies to be photoreactive substances.

In general terms across the stations, electrical conductivity/salinity has been one of the most direct drought-related quality parameters. This parameter has been suggested as a characteristic variable for decision-making methods but, more investigation has to be assessed to validate the results obtained (Safavi & Malek Ahmadi 2015). Palmer & Montagna (2015) recommend salinity-based predictions to dry regions, which can have more drought-like inflows more frequently than natural droughts due to its water demand. In addition to electrical conductivity/salinity, total suspended solids and alkalinity were proposed for monitoring impacts for the lower Mekong River (Prathumratana et al. 2008). Under continuous climatic variations driven by global warming and the developing research in its impacts on water quality, it is important to involve comprehensive and efficient governmental measures respecting to this aspect. Laws of generation, transfer, and diffusion of river basin pollutants could be one of them (Huang et al. 2015). Also, be aware of its implications to develop drought mitigation and adaptation measures for water quality impacts.

5.3 Potential effects of drought driven water quality deterioration on irrigated agriculture

Irrigation represents nearly 70% of surface water withdrawals in the basin, and it is actually under the constant pressure of lower water availability and increasing water demand. Although agricultural activity is not the major contributor to regional GDP, the production of fruit trees has great significance at the national level, especially grapes and avocado plantations mainly destined to exports (MOP 2007). In fact, according to INE (2007), the local agricultural land is dedicated in order of importance to crops and fruit plantations, annual and permanent forage, vegetables, and vineyards, mostly concentrated in the central Maipo Valley. The most important and extensive agricultural sector according to crop type is located in Melipilla, Maipo and Cordillera provinces, where are two of the station evaluated in this work. According to DGA (2004), the Angostura river (4B) has an irrigation area of 2672 ha, the Puangue estuary (9D) irrigates a surface of 3657 ha and the Mapocho river (8C), irrigates 33954 ha. Considering that hydrological droughts can impact the surface water quality and that water quality for irrigation plays a major role in the agricultural development (Assouline et al. 2015), the results of the three discharge stations located in the irrigation districts during hydrological drought periods (Q80) were compared with the established Chilean thresholds on water quality parameters for agricultural water uses. Further research was done on the agricultural impacts of parameters analyzed in this study but not included in the regulation. The exceedance of the thresholds could be linked to potential effects on irrigated agriculture, as follows:

Commonly, water quality parameters important for agriculture include salt content, sodium concentration, presence or quantity of macro and micro nutrients and trace elements, alkalinity, acidity and hardness of water (Bauder et al. 2008; Bauder et al. 2000). Nonetheless, according to its priority, salinity is the most important factor for assessing irrigation water quality (Ghassemi et al. 1995). The electrical conductivity and major ions analyzed in the irrigation districts had significant negative correlation with discharge (Table 4). According to DGA (2004), the values of electrical conductivity in the Maipo river surpass the regulation under normal conditions due to the presence of salts in natural conditions from leachates, groundwater outcrops in the lower parts of the basin and by the effect of the wastewater discharge. However, the periods of low flows can alter to a large extent the concentration of salts harming the water quality for irrigation purposes. In fact, in further analysis, the values of electrical conductivity vs. discharge had a better adjustment to an exponential behavior while the streamflow decrease (Appendix G), reaching values of 2213 µS/cm (station 8C) where only can be used in tolerant plants (Table 4). Among the crops produced in the basin, the avocado it is highly sensitive to the salts in irrigation waters (<750 µS/cm) and although in the metropolitan region it is common the use of rootstocks more resistant to the salinity for better yields, this concentration could affect its productivity greatly (INDAP 2007). Also, the use of saline water in the land can cause, from evaporation process, the salinization of the soil (Sagasta & Burke 2005; Multsch et al. 2017). Soil salinization can reduce soil productivity in early stages; it also has a lethal effect on vegetation in advanced stages, and high salt concentrations inhibit the uptake of water by plants (Sagasta & Burke

2005). The worst panorama to this case could be a salt crust on the soil surface, making agriculture impossible (Multsch et al. 2017).

Regarding the major ions impacts, the high proportion of Na^+, sodicity, in relation with Ca^{2+} and magnesium Mg^{2+} ions, can degrade the soil structure resulting in a more erodible and impermeable soil that could reduce plant growth (Sagasta & Burke 2005). In the Maipo river, under normal conditions chloride concentration decreases, from the mountain range to the sea; whereas in the Mapocho sub-basin chloride concentration registeres an increase due to the greater anthropic influence (DGA 2004). The direct contact of plant leaves with higher chlorine concentration during irrigation can burn them (Dezfuli et al. 2013). In the case of strawberry crops, they are highly sensitive to salts especially sodium and chloride, and saline soils up to max 2500 µS/cm, although it is suggested a maximum of total salt of 400 ppm (INDAP 2007). However, in drought periods just chloride have reached at least the half of the concentration limit for this crop, obtaining the same values for sodium (from 145 to 350 mg/L as maximum values) in the three stations. The same behavior is observed for sulphate, where is surpassed the threshold in the three stations. The presence of sulphate in the sub-basins of the Maipo basin is attributable to the exploitation of plaster in the area, with an increasing tendency downstream, which could be explained by the evapotranspiration associated with the intensive use of water in irrigation (DGA 2004).

Considering the values of dissolved oxygen, although it is not included in the regulation, it has a downward trend in normal conditions within the Mapocho sub-basin observing lowest values ranging between 3 and 6 mg/L and is constant in the rest of the basin (9-10 mg/L) (DGA 2004). According to Bhattarai and Chérif cited in Maestre-Valero & Martínez-Alvarez (2010), oxygen dissolved concentration is an important irrigation water quality parameter, due to low values can cause oxygen deficiency in the root zone of plants inducing poor root and plant performance, making them prone to disease, with slow growth and low yields. Therefore, the significant positive relationship found in two of the three stations, although is low, could suggest an increased risk during low flow conditions for the irrigation areas. Regarding pH, plants irrigated with great changes in water pH can affect rhizosphere pH, impacting plant growth, photosynthesis and nutrient absorption (Zhao et al. 2013). The station 4B was the only one having a significant negative relationship with discharge, although it did not surpass the range of the threshold. The crops that are sensitive to more basic pH may be could be at risk during low flow conditions.

Finally, although essential and nonessential metals parameters had a significant positive relationship with discharge (Table 3), the high flows after droughts should be studied more carefully to determine if the increase in the concentration of pollutants are due to settlement in the river bottom during low flow conditions. Regarding toxicity aspects, the increase in their concentration is also harmful to the irrigated agriculture. Higher Mn concentration can cause phytotoxicity which is mostly related to the reduction of biomass and photosynthesis inhibition (Al-Isawi et al. 2016). Also, arsenic concentration above the threshold may result in land degradation regarding crop production and food safety due to it is absorbed by crops adding it to the dietary intake and in a long-term reduce yields because of toxic accumulation (Heikens 2006). In the extension of the basin Al, Fe, Mn, and Mo (molybdenum) have exceeded the NCh 1333 with more frequency in normal conditions (DGA 2004). According to DGA (2004), these components are found in the basin due to the following causes: sediment runoff composed mainly of silicate aluminates; high levels of iron are due to the leaching and weathering of the rocks, in addition to the mining processes developed in the upper part of the basin and the downstream of the river by the discharge of liquid industrial waste; manganese in the water is due to the leaching of the rocks of the high mountain range, the mining activities developed in the basin and the outcropping of underground water in the lowest section of Maipo (4B), Mapocho (8C) and Puangue estuary (9D); Copper in the basin is due to the existence of metallogenic zones, which by processes of leaching of the mineralized veins and melting of acid snows add it to the watercourses of the Andes along with the anthropogenic pollution from the disposal of materials from copper mining. Although bacterial contamination was not included in this analysis, its effects on agriculture are directly related to food security and have been reported to increase during drought periods. Total and fecal coliforms are water pollution indicators, which pathogens as *Escherichia coli, Salmonella* and enterococci can cause gastrointestinal infections being a potential risk for public health (Fonseca-Salazar et al.

2016; Shrestha et al. 2016; Palacios et al. 2017). Fecal coliforms are found at high levels throughout the basin, limiting creeping crops by microbiological contamination and its direct use as potable water (DGA 2004). This condition is because rivers receive sewage from different populated centers and liquid industrial waste with organic loads. In the study of the CNR et al. (2003) for the Maipo, it has been reported that in normal conditions fecal coliforms were above the threshold. In this sense, the strawberries, and other low plants of direct consumption are considered high-risk crops due to they fructify very close to the soil, making them susceptible to contamination by waters of poor quality (INDAP 2007).

6 CONCLUDING REMARKS

Meteorological drought shows a similar behavior in all the basin. However, negative trends for SPI were observed across the basin but not in the coast, relating to this pattern the cooling effect reported in the Pacific, the increasing trend in the temperatures in the inland and the Andes along with decreased precipitation. Also, negative trends were found in all the stations analyzed in this study for SSI, showing a general reduction of river flows more acute in the last five years (2010-2015) in agreement with the present trends of glacier retreat and warmer temperatures in the Andes. Regarding meteorological and hydrological drought relationship, the highest correlation of SSI with SPI-12 denotes the dependence of the streamflow to the previous year(s) of precipitation, also suggesting that this temporal scale in SPI has a high potential to predict streamflow droughts from meteorological records. In general terms across the stations, electrical conductivity/salinity has been one of the most direct drought-related quality parameters and could also be suggested as a characteristic variable for decision-making methods but, more investigation should be assessed. The electrical conductivity and major ions analyzed in the irrigation districts increase during drought periods, reaching values that had surpassed the Chilean regulation for agricultural water uses. This increase means that can affect sensible crops produced in the basin such as avocado plantations. For inorganic pollutants, more deep analysis should be carried out to determine if exists a relationship between drought re-wetting cycles and the increase of its concentration in wet periods. Finally, it is important to highlight that this basin is highly influenced by artificial components that could impact the behavior of the physicochemical parameters, being difficult to award it to a unique source. Deeper and more frequent monitoring is needed to differentiate and detail the changes during the different seasonal droughts. However, this study, as a first approach, gives a general overview of drought driven water quality impacts and its potenttial impact on a high water demanding and major economic activity like agriculture, for further water management strategies that involve water quality during drought periods. Further research could be done in a water scarcity assessment for the basin that includes and give values to water quality characteristics as poor quality of water intensifies the water shortage and reduces the usable water for the different economic sectors.

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APPENDIX A

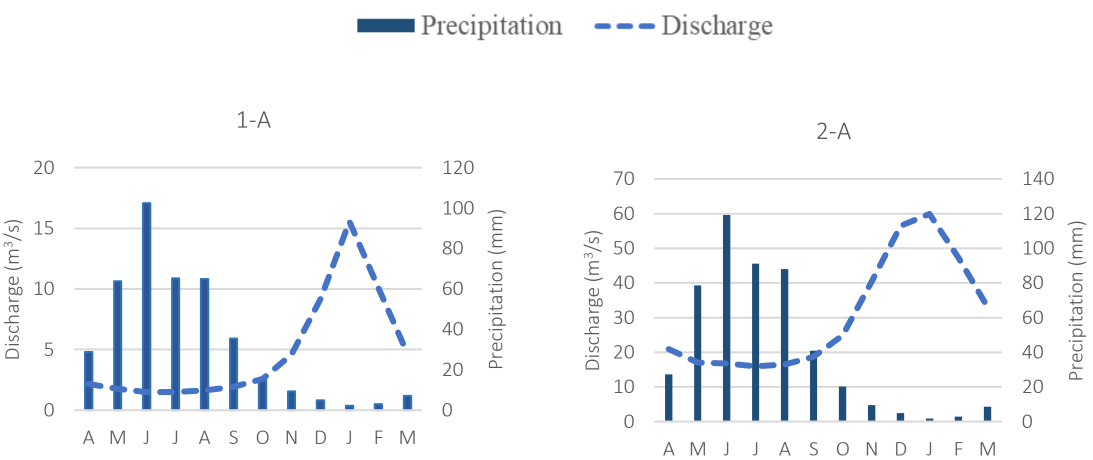
Table 1. Precipitation and discharge stations used for drought analysis and impact on water quality

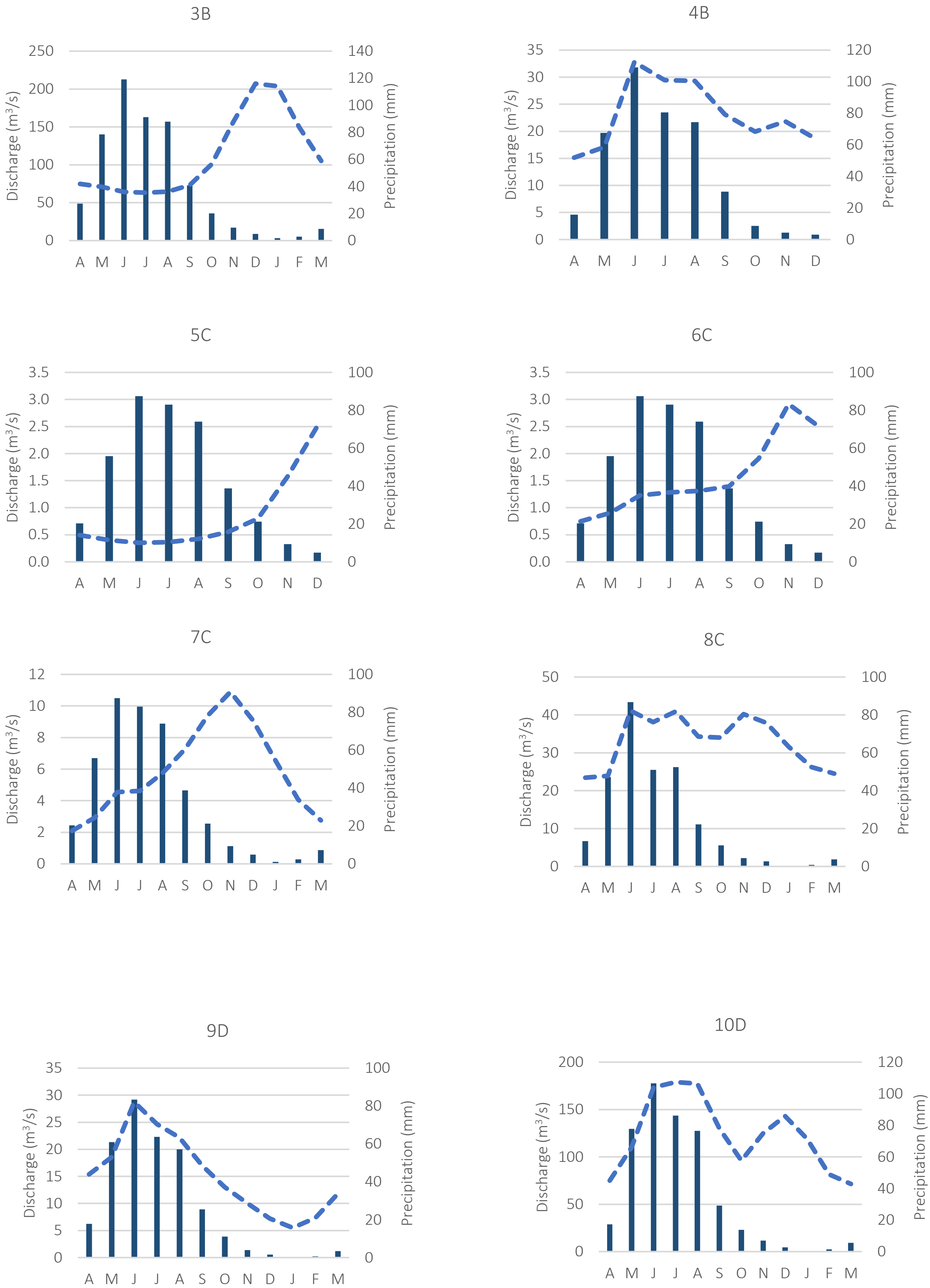
PRECIPITATION STATIONS				DISCHARGE STATIONS					
DGA-CODE	**ALTITUDE**	**STATION NAME**	**DATA SERIES**	**ALTITUDE**	**THESIS ID**	**DGA-CODE**	**STATION NAME**	**DATA SERIES DISCHARGE**	**DATA SERIES PHYSICHO-CHEMICAL PARAMETERS**
05703008-9	2475	El yeso Embalse	1985 - 2015	1500	1A	05706001-8	Río Olivares antes junta Rio Colorado	1985-2015	1995-2015
05704004-1	1266	San Gabriel	1985 - 2015	890	2A	05707002-1	Río Colorado antes junta Rio Maipo	1985-2015	1985-2015
05704006-8	943	San José de Maipo en el Reten	1985 - 2015	850	3B	05710001-k	Río Maipo en el Manzano	1985-2015	1986-2015
05707003-k	1143	Maitenes Bocatoma	1988 - 2015	342	4B	05716001-2	Río Angostura en Valdivia de Paine	1985-2015	1986-2015
05710007-9	796	La Obra Recinto Emos	1995 - 2015	1350	5C	05721001-k	Estero Yerba Loca antes junta San Francisco	1986-2015	1986-2015
05711003-1	659	Pirque	1985 - 2015	880	6C	05722001-5	Estero Arrayan en la Montosa	1985-2015	1986-2015
05716005-5	360	Laguna Aculeo	1989 - 2015	966	7C	05722002-3	Río Mapocho en los Almendros	1985-2015	1985-2015
05717008-5	340	El Vergel	1988-2015	440	8C	05737002-5	Río Mapocho Rinconada de Maipu	1985-2015	1985-2015
05730012-4	848	Cerro Calan	1985 - 2015	93	9D	05746001-6	Estero Puangue en Ruta 78	1986-2015	1985-2015
05730013-2	904	Antupiren	1985 - 2015	35	10D	05748001-7	Río Maipo en Cabimbao	1939-2015	1986-2015
05730016-7	560	Terraza Oficinas Centrales DGA	1985 - 2015						
05732001-k	556	Huechun Embalse	1988 - 2015						
05732002-8	590	Huechun Andina	1994 - 2015						
05733006-6	955	Rincón de los Valles	1985 - 2015						
05733007-4	1120	Caleu	1985 - 2015						
05733008-2	700	Rungue Embalse	1985 - 2015						
05733010-4	810	Fundo las Bateas	1986 - 2015						
05737008-4	430	Fundo Marruecos	1989 - 2015						

PRECIPITATION STATIONS			
DGA-CODE	**ALTITUDE**	**STATION NAME**	**DATA SERIES**
05740004-8	165	Carmen de las Rosas	1985 - 2015
05740005-6	168	Melipilla	1985 - 2015
05741002-7	490	Colliguay	1985 - 2015
05744002-3	190	Los Panguiles	1985 - 2015
05744003-1	169	Ibacache Alto	1988 - 2015
05745001-0	176	Mallarauco	1992 - 2015
05746001-6	93	Estero Puangue en Ruta 78	1989 - 2015
05747001-1	125	Los Guindos	1989 - 2015
05748003-3	182	Cerrillos de Leyda	1985 - 2015
05716004-7	350	Angostura en Valdivia de Paine	1988- 2015
DIRECCIÓN METEOROLÓGICA DE CHILE (DMC)			
330020-DMC	527	Quinta Normal Santiago	1985 - 2015
330019-DMC	650	Eulogio Sanchez Tobalaba ad.	1985 - 2015
330021-DMC	482	Pudahuel Santiago	1985 - 2015

APPENDIX B

Figure 1. Mean monthly precipitation and discharge of the discharge stations used in this research




3B
Discharge (m³/s)
Precipitation (mm)
A M J J A S O N D J F M
4B
Discharge (m³/s)
Precipitation (mm)
A M J J A S O N D
5C
Discharge (m³/s)
Precipitation (mm)
A M J J A S O N D
6C
Discharge (m³/s)
Precipitation (mm)
A M J J A S O N D
7C
Discharge (m³/s)
Precipitation (mm)
A M J J A S O N D J F M
8C
Discharge (m³/s)
Precipitation (mm)
A M J J A S O N D J F M
9D
Discharge (m³/s)
Precipitation (mm)
A M J J A S O N D J F M
10D
Discharge (m³/s)
Precipitation (mm)
A M J J A S O N D J F M

APPENDIX C

Analysis of Variance (ANOVA) of SPI calculations at different time scales from five precipitation stations with different record length, obtaining no significant ($p < 0.05$) differences between the groups of data for all the stations evaluated:

$$H_0 = \mu 1 = \mu 2 = \mu 3$$

H_a= At least one inequality

p <0.05 = At least one difference between the groups

Table 2 *p* Value Analysis of variance (ANOVA)

SPI-Time scale	El Yeso Embalse (40, 30 and 20 years)	Pirque (47, 30, 20)	Terraza Oficinas Centrales DGA (55, 30 and 20 years)	Rungue Embalse (58, 30 and 20 years)	Cerrillos de Leyda (40, 30 and 20 years)
SPI-3	0.9988	0.8454	0.8454	0.9258	0.8073
SPI-6	0.9993	0.9072	0.9940	0.7266	0.7492
SPI-12	0.9712	0.6593	0.9731	0.5566	0.6280

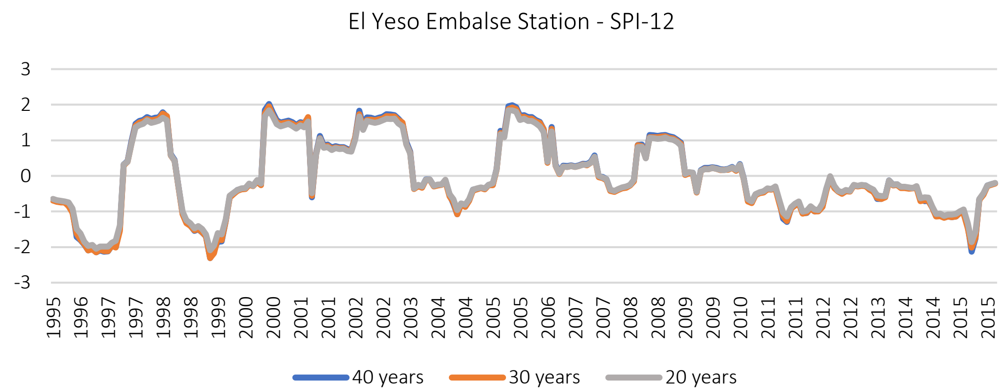


Figure 2. Example of temporal variation of SPI-12 calculations for El Yeso Embalse station at different record lengths.

APPENDIX D

Table 3 Chilean regulation NCh 1333/78 "*Water quality requirements for different uses*" (INN 1987)

Chemical Elements

	mg/L		mg/L
Aluminium	5.00	Lithium	2.50
Arsenic	0.10	Lithium citrate	0.08
Barium	4.00	Manganese	0.20
Beryllium	0.10	Mercury	0.00
Boro	0.75	Molybdenum	0.01
Cadmium	0.01	Nickel	0.20
Cyanide	0.20	Silver	0.20
Chloride	200	Lead	5.00
Cobalt	0.05	Selenium	0.02
Copper	0.20	Sodium (%)	35
Chrome	0.10	Sulphate	250
Fluoride	1.00	Vanadium	0.10
Iron	5.00	Zinc	2.00

Electrical conductivity

Classification	Electrical conductivity µS/cm at 25 °C
No adverse effects are observed	≤ 750
Possible detrimental effects on sensitive crops	750 - 1500
Possible adverse effects on sensitive crops and requires careful handling methods	1500 - 3000
Water can be used for tolerant plants in permeable soils with conservative management practices	> 3000

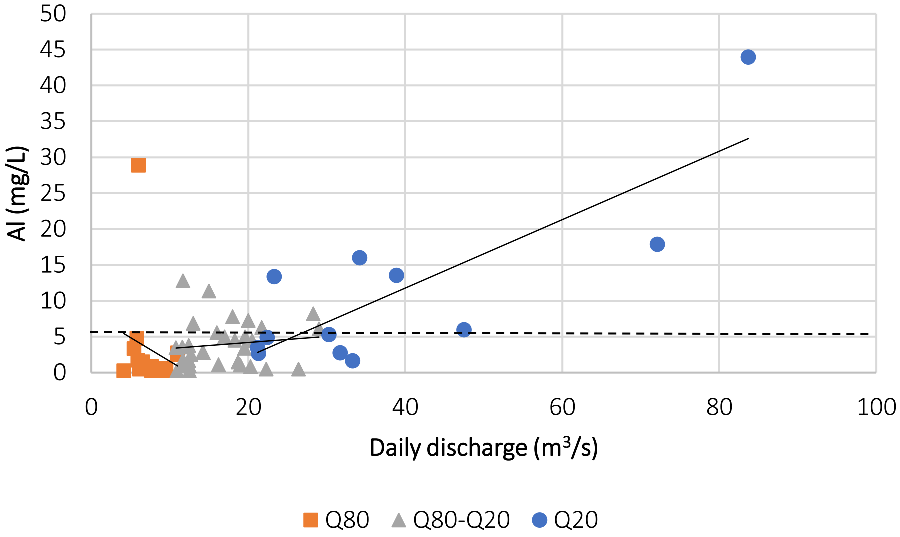
pH 5,5 - 9,0

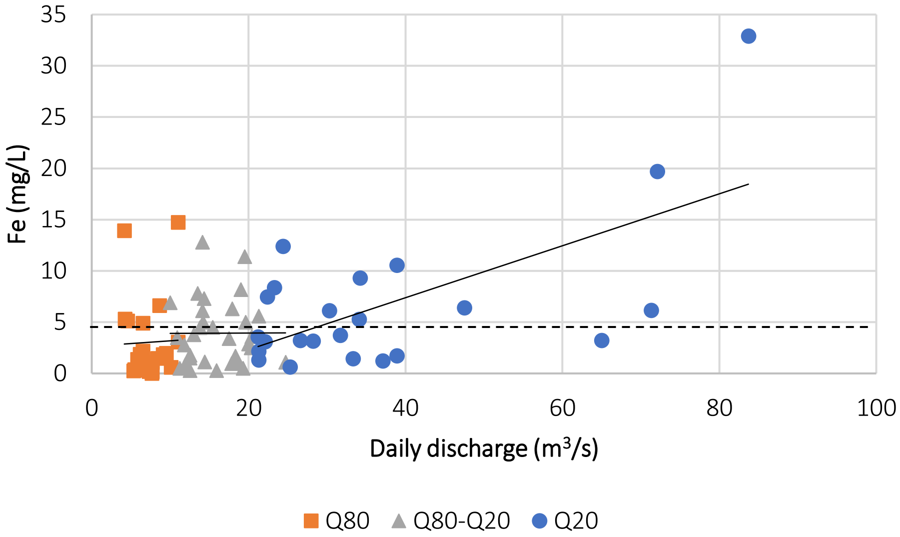
Microbiological requirements

Water for irrigation of vegetables and fruits that develop at ground level and will be consumed raw should have a fecal coliform (FC) content of: ≤ 1000 FC/100 mL

APPENDIX E

Figure 3 Daily discharge vs. some metals (Al and Fe) from station 4B grouped by the related threshold level. Dashed lines represent the threshold for each parameter according to the Chilean regulation for irrigation water uses.





APPENDIX F

Table 4 Pearson Correlation coefficient of station **1A** between SPI and SSI at different time scales. Grey shadings show the highest correlation coefficients.

	SSI-1	SSI-3	SSI-6	SSI-12
SPI-1	0.20	0.13	0.08	0.02
SPI-3	0.21	0.19	0.11	0.05
SPI-6	0.31	0.31	0.23	0.15
SPI-12	0.34	0.36	0.36	0.31
SPI-18	0.43	0.48	0.52	0.53
SPI-24	0.40	0.45	0.49	0.53
SPI-30	0.32	0.39	0.45	0.52
SPI-36	0.23	0.26	0.31	0.39

APPENDIX G

Figure 4 Exponential and linear trend line of electrical conductivity vs. daily discharge of station 8C and 4B.