ECONSTOR
Make Your Publications Visible.

A Service of
ZBW
Leibniz-Informationszentrum Wirtschaft
Leibniz Information Centre for Economics

Peña-Guerrero, Mayra Daniela; Nauditt, Alexandra; Muñoz-Robles, Carlos; Ribbe, Lars; Meza, Francisco

Article — Published Version

Drought impacts on water quality and potential implications for agricultural production in the Maipo River Basin, Central Chile

Hydrological Sciences Journal

Provided in Cooperation with:
Leibniz Institute of Agricultural Development in Transition Economies (IAMO), Halle (Saale)

Suggested Citation: Peña-Guerrero, Mayra Daniela; Nauditt, Alexandra; Muñoz-Robles, Carlos; Ribbe, Lars; Meza, Francisco (2020) : Drought impacts on water quality and potential implications for agricultural production in the Maipo River Basin, Central Chile, Hydrological Sciences Journal, ISSN 2150-3435, Taylor & Francis, Abingdon, Vol. 65, Iss. 6, pp. 1005-1021, https://doi.org/10.1080/02626667.2020.1711911 , https://www.tandfonline.com/doi/full/10.1080/02626667.2020.1711911

This Version is available at:
https://hdl.handle.net/10419/222269

Standard-Nutzungsbedingungen:

Die Dokumente auf EconStor dürfen zu eigenen wissenschaftlichen Zwecken und zum Privatgebrauch gespeichert und kopiert werden.

Sie dürfen die Dokumente nicht für öffentliche oder kommerzielle Zwecke vervielfältigen, öffentlich ausstellen, öffentlich zugänglich machen, vertreiben oder anderweitig nutzen.

Sofern die Verfasser die Dokumente unter Open-Content-Lizenzen (insbesondere CC-Lizenzen) zur Verfügung gestellt haben sollten, gelten abweichend von diesen Nutzungsbedingungen die in der dort genannten Lizenz gewährten Nutzungsrechte.

Terms of use:

Documents in EconStor may be saved and copied for your personal and scholarly purposes.

You are not to copy documents for public or commercial purposes, to exhibit the documents publicly, to make them publicly available on the internet, or to distribute or otherwise use the documents in public.

If the documents have been made available under an Open Content Licence (especially Creative Commons Licences), you may exercise further usage rights as specified in the indicated licence.

https://creativecommons.org/licenses/by/4.0/

WWW.ECONSTOR.EU

Mitglied der Leibniz-Gemeinschaft

HYDROLOGICAL SCIENCES JOURNAL
2020, VOL. 65, NO. 6, 1005–1021
https://doi.org/10.1080/02626667.2020.1711911

OPEN ACCESS Check for updates

Drought impacts on water quality and potential implications for agricultural production in the Maipo River Basin, Central Chile

M. D. Peña-Guerrero[a,b], A. Nauditt[a], C. Muñoz-Robles[b], L. Ribbe[a] and F. Meza[c,d]

[a]Institute for Technology and Resources Management in Tropics and Subtropics (ITT), Cologne University of Applied Sciences, Cologne, Germany; [b]Instituto de Investigación de Zonas Desérticas, Universidad Autónoma de San Luis Potosí, San Luis Potosí, Mexico; [c]Centro Interdisciplinario de Cambio Global, Pontificia Universidad Católica de Chile, Santiago, Chile; [d]Departamento de Ecosistemas y Medio Ambiente, Facultad de Agronomía e Ingeniería Forestal, Pontificia Universidad Católica de Chile, Santiago, Chile

ABSTRACT

Droughts can have serious negative impacts on the water quality needed for irrigated agriculture. The Metropolitan region of Chile is a relevant producer of high-value crops and is prone to droughts. Standardized Drought Indices were used to characterize meteorological and hydrological droughts for the period from 1985 to 2015. To understand the relationship between droughts and water quality, we evaluated the correlations between daily discharge and surface water quality observations. The threshold level method was used to compare physicochemical parameters during hydrological drought periods with the Chilean water quality thresholds for agricultural uses. A significant ($p < 0.05$) negative relationship between discharge and electrical conductivity and major ions was found in most of the basin. Hydrological stations located in irrigation districts exceeded the official thresholds for these parameters during hydrological drought periods seriously threatening irrigated agriculture of the region.

ARTICLE HISTORY
Received 8 July 2018
Accepted 13 November 2019

EDITOR
S. Archfield

ASSOCIATE EDITOR
S. Huang

KEYWORDS
Mediterranean climate; climate change; meteorological drought; hydrological drought; standardized index; irrigated agriculture; water quality

1 Introduction

Drought is a natural phenomenon that can occur in all climatic zones and is defined as a sustained and regionally extensive occurrence of below-normal natural water availability (Tallaksen and van Lanen 2004). In the context of climate change, an increase in global temperatures is projected that will impact evapotranspiration and specific humidity of the air, affecting the ability of the atmosphere to store water, with direct effects on the magnitude, frequency, intensity and spatio-temporal distribution of precipitation (Wang *et al.* 2016 and references therein). As a consequence, the frequency and severity of extreme events such as droughts and floods would increase, being droughts the slowest to develop, but the longest to last (Bond *et al.* 2008, Yeh *et al.* 2015)

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 a major economic, social and cultural activity, and it is highly sensitive to climate variations (Howden *et al.* 2007). It is predicted that, by 2050, global food demand will rise, indicating that crop production must double (Tilman *et al.* 2011). A large fraction of the supplementary food must come from irrigated agriculture (40% of the world's food supply is produced on irrigated lands) (Döll and Siebert 2002, Wang *et al.* 2016). Currently, irrigation represents nearly 70% of freshwater withdrawals from rivers, lakes, and aquifers and it is under constant pressure created by decreasing water availability and increasing water demand (Assouline *et al.* 2015). Climate change is expected to intensify the existing pressure on water availability and will affect agricultural systems particularly in semi-arid environments (IPCC 2014). According to Iglesias and Garrote (2015), the potential impacts on the agricultural production in these areas are: (a) an increase in water demand due to higher rates of crop evapotranspiration in response to rising temperatures; (b) intensification of water shortages, especially in the spring and summer due to increased irrigation requirements; and (c) deterioration of water quality due to high temperatures and low levels of runoff in some regions, inducing additional stress to irrigated areas, among others.

Meteorological drought that spreads through the hydrological cycle can reduce surface and ground water levels (triggering hydrological drought) and can lead not only to reduced water availability but also to a deterioration of water quality (Mishra and 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 and Zwolsman 2008, Safavi and Malek Ahmadi 2015 and references therein), the consequences on water quality are not fully recognized yet (Zwolsman and 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 (Van Vliet

CONTACT M. D. Peña-Guerrero Pena-Guerrero@iamo.de
Present affiliation for M. D. Peña-Guerrero is Leibniz Institute of Agricultural Development in Transition Economies (IAMO), Halle (Saale), Germany.

© 2020 The Author(s). Published by Informa UK Limited, trading as Taylor & Francis Group.
This is an Open Access article distributed under the terms of the Creative Commons Attribution License (http://creativecommons.org/licenses/by/4.0/), which permits unrestricted use, distribution, and reproduction in any medium, provided the original work is properly cited.

and Zwolsman 2008, Mishra and Singh 2010, Mosley 2015, Palmer and Montagna 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 and Burke 2005, Maestre-Valero and Martínez-Alvarez 2010). Therefore, it is an important variable to consider in the development of irrigation (Assouline *et al.* 2015).

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, 2014). Chile is a country that currently experiences multi-year droughts (Rangecroft *et al.* 2016). According to climate change projections, the country will likely see increases in drought frequency due to increases in temperature across the country as well as reductions in precipitation in the central and southern areas (Magrin *et al.* 2014). 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).

Irrigated agriculture in drought-prone arid and semi-arid regions, due to their biophysical characteristics, is 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 importantly, its relation to irrigated agriculture. Therefore, the overall objective of this research was to evaluate the impact of drought on water quality and irrigation dependent agricultural production in the Maipo River basin, Central Chile. Specific objectives were to: (1) determine the spatio-temporal distribution of meteorological drought in the basin and explore its relationship with hydrological drought; (2) assess the impacts of hydrological drought on basic surface water quality parameters; and (3) identify the potential effects of drought-driven water quality deterioration on irrigated agriculture.

2 Study area

This work was conducted in the Metropolitan region of semi-arid central Chile, where extended irrigated zones 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).

The Maipo River basin is the most populated region of Chile with almost seven million inhabitants including the Santiago metropolitan area. It supplies 70% of potable water and 90% of irrigation water demand of one of the most important producing areas of wine and cash crops in Chile, mostly concentrated in the Central Valley (DGA 2004, 2007). It is located in Central Chile (Fig. 1), between latitudes 32°55′–34°15′S and longitudes 69°55′–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 (5623 m.a.s.l.). It is characterized by a Mediterranean climatic regime with a long dry season and a winter period (April to September) concentering more than 75% of annual precipitation, along with cold weather in the Andes. Mean annual total precipitation is around 380 mm, and mean annual temperature is 14°C (DGA 2014). Its hydrological regime is nivo-pluvial. According to the Chilean Water Code of 1981 (República de Chile 1981), the Maipo River is divided into three sections (Figs. 1 and 2). The upper section of the basin is nival, with a significant increase of streamflow in spring months due to snow-melt in the Andes. 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. Surface runoff it is estimated as 58×10^6 m^3, of which 90% is generated by winter precipitation (DGA 2014). The geology in the region is characterized by rocks that range from Triassic to Tertiary in age. The statigraphic units in the Coastal Cordillera are mainly discordant Cretaceous sedimentary and volcanic rocks of continental origin, and of marine origin in intercalations towards the west. In the Andean Cordillera, the units are mainly concordant Jurassic and Cretaceous marine and continental sediments, associated with extensive evaporites (rocks formed by the evaporation of water), composed mainly of gypsum. There are also fluvio-alluvial-glacial deposits of Quaternary age in the Central Valle (Jorquera *et al.* 2015 and references therein). The geochemistry of bedrock geology in the Maipo River is dominated by outcropping evaporites that are associated with high SO_4^{2-} levels in waters. The stream water in this area has high Ca, Cl, K, SO_4^{2-} and Na concentrations, with a pH range of 7–8.5 (Jorquera 2013).

3 Data and methodology

3.1 Hydroclimatic data

Monthly precipitation data of the Maipo River basin was extracted from the Climate Hazard Group InfraRed Precipitation with Station Data (CHIRPS version 2) satellite product. CHIRPSv2 data have a 0.05° spatial resolution with the satellite data calibrated with *in situ* situation data to create gridded rainfall time-series appropriate for trend analysis and seasonal drought monitoring. CHIRPSv2 spatial coverage spans from 50°S to 50°N (over all longitudes) with a spatial data record extending from 1981 to the present (Funk *et al.* 2015). The performance of this dataset has been previously evaluated in Chile with good results (Zambrano-Bigiarini *et al.* 2017). Daily discharge and physicochemical data (in general one measurement per season) from nine hydrological stations of the river basin were collected from the Chilean National Water Agency (DGA) (Table 1). We used the period of record from 1985 to 2015. Maps corresponding to the hydro meteorological network and general characteristics of the basin were obtained from DGA official web page.[1] All

[1]http://www.dga.cl/productosyservicios/mapas/Paginas/default.aspx.

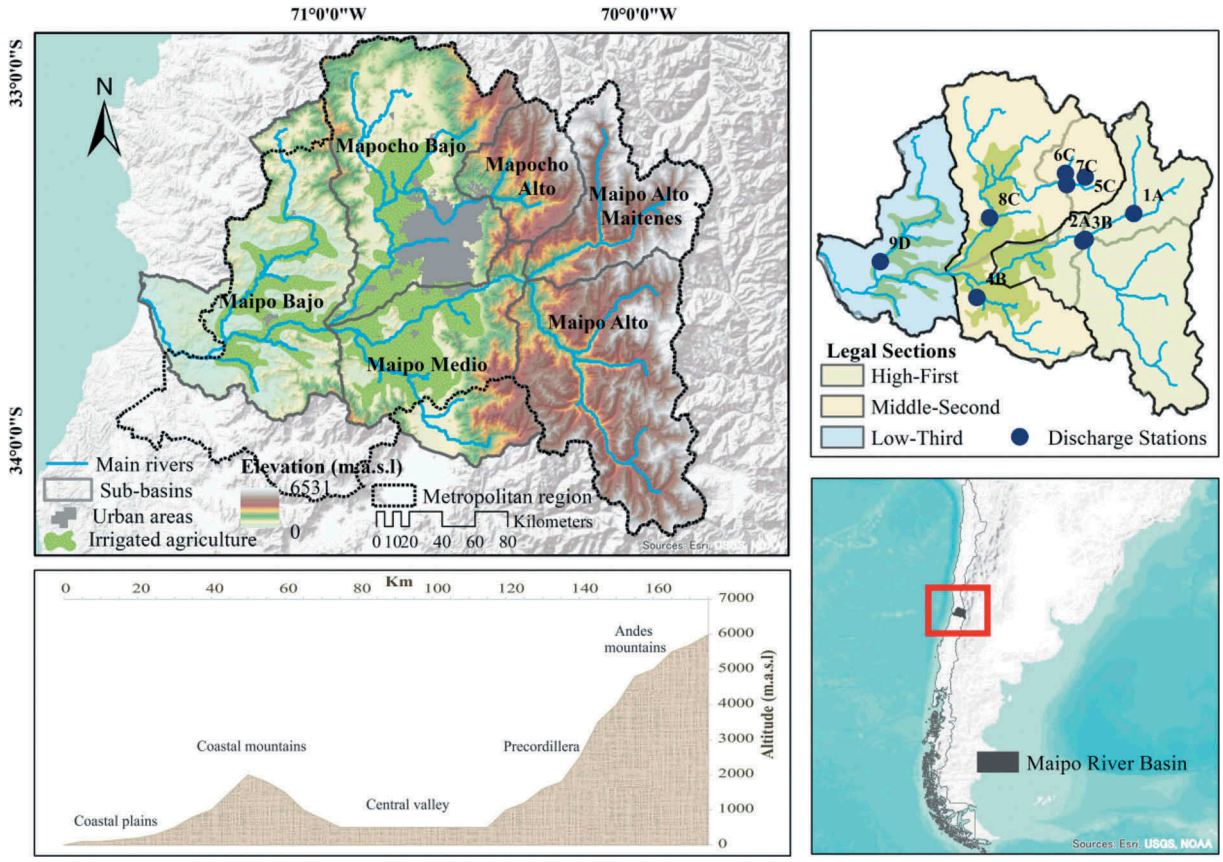

Figure 1. The Maipo River Basin: general characteristics and locations of selected stations in the region under study. Topographic profile 33°S – Central Zone of Chile. Based on Errázuriz et al. (1998) and the 90-m digital elevation model (DEM) downloaded from Consortium for Spatial Information, CGIAR (http://srtm.csi.cgiar.org) (Jarvis et al., 2008).

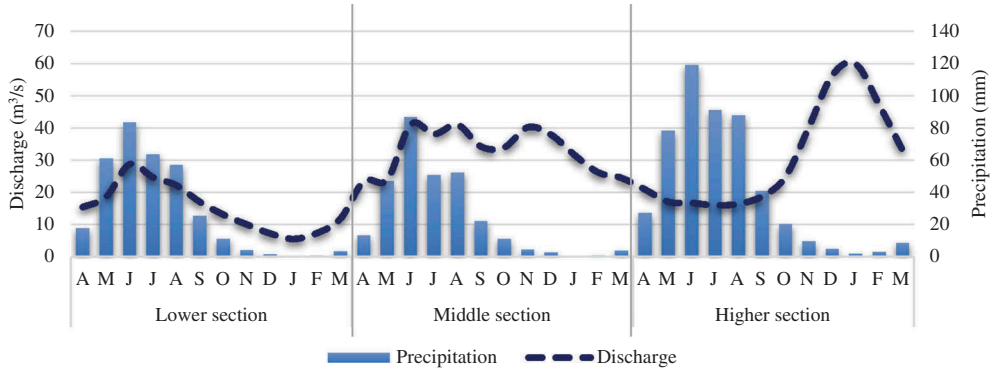

Figure 2. Mean monthly precipitation and discharge of one station per basin section (1985–2015).

Table 1. Location and identification of the discharge stations used in this study.

Altitude (m.a.s.l.)	ID	DGA-code	Station name	Latitude	Longitude
1500	1A	05706001–8	Río Olivares antes junta Río Colorado	33°29′ 16″	70°08′ 12″
890	2A	05707002–1	Río Colorado antes junta Río Maipo	33°35′ 15″	70°22′ 01″
850	3B	05710001–K	Río Maipo en el Manzano	33°35′ 38″	70° 22′ 45″
342	4B	05716001–2	Río Angostura en Valdivia de Paine	33°48′ 40″	70° 53′ 01″
1350	5C	05721001–K	Estero Yerba Loca antes junta San Francisco	33°20′ 29″	70° 21′ 49″
880	6C	05722001–5	Estero Arrayan en la Montosa	33°19′ 32″	70° 27′ 22″
966	7C	05722002–3	Río Mapocho en los Almendros	33°22′ 13″	70° 27′ 03″
440	8C	05737002–5	Río Mapocho Rinconada de Maipu	33°29′ 46″	70° 49′ 00″
93	9D	05746001–6	Estero Puangue en Ruta 78	33°39′ 41″	71°20′ 14″

maps were processed in ArcGIS (ArcGIS 10.4, ESRI, Redlands, CA, USA). Fig.1 shows the spatial distribution of the selected stations.

3.2 Calculation of standardized drought indices

3.2.1 Standardized precipitation index (SPI)

The standardized precipitation index (SPI) (Mckee *et al.* 1993) is the most commonly used drought index due to its limited data requirements and flexibility to assess precipitation deficits over user-defined accumulation periods (Barker *et al.* 2016). It was 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). The SPI was computed following the methodology of Mckee *et al.* (1993) using a gamma probability distribution. Negative values of SPI correspond to lower than the mean precipitation, and positive values indicate higher than the average rainfall.

For this study, three SPI time scales were used: 3 (SPI-3), 6 (SPI-6) and 12 (SPI-12) months. The spatial and temporal distribution of meteorological drought across the river basin was represented by sub-basins: Maipo Alto, Maipo Alto-Maitenes, Maipo Medio, Mapocho Alto, Mapocho Bajo and Maipo Bajo. Within each sub-basin, polygons of lower-order sub-basins were used and precipitation was averaged and added for all lower-order sub-basins upstream each discharge station (see Section 3.2.3); therefore, the analysis was made with matching draining areas for precipitation and discharge data. For each lower-order sub-basin and time scale, a historical series of SPI was obtained. Finally, drought characterization was undertaken for each sub-basin and drought index: frequency (number of drought events), duration (number of months with negative values below the threshold), and intensity (lowest SPI and SSI values of the drought event).

3.2.2 Standardized streamflow index (SSI)

The standardized streamflow index (SSI) (Modarres 2007, Vicente-Serrano *et al.* 2012) was computed in a similar way to the SPI: using monthly streamflow, fitting a probabilistic 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 (Vicente-Serrano *et al.* 2012, Svensson *et al.* 2017). 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 (Modarres 2007, Shukla and Wood 2008, Nalbantis and Tsakiris 2009) and it fitted well to our data. The SSI was calculated for four different time scales: 1 (SSI-1), 3 (SSI-3), 6 (SSI-6) and 12 (SSI-12) months in each station from monthly historical streamflow followed by a drought characterization.

In this study, a drought event was defined for values below − 0.84, for the SPI starting in the rainy season (April–September) and for the SSI at least three consecutive months according to the criteria from the Chilean government Water Agency, DGA, to determine exceptional droughts (Table 2) (DGA and DICTUC S.A. 2009, DGA 2012). The "SCI" package for R (Gudmundsson and Stagge 2016), was used to calculate SPI and SSI.

Table 2. Classification criteria for determination of exceptional drought in Chile, modified from DGA No. 1674 (DGA 2012).

SPI/SSI value	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

3.2.3 Relationship between meteorological and hydrological drought

The relationship between meteorological and hydrological drought in the Maipo River basin was assessed by applying the seasonal autoregressive integrated moving average (SARIMA)-based cross-correlation using the Pearson correlation coefficient from the SPI time series at different time scales of the lower-order sub-basins derived from the upstream precipitation of each discharge station and the SSI. A SARIMA model is notated as $(p,q,d)(P,D,Q)$, where p is the autoregressive (AR) order, d the differencing order, q the moving average (MA) order and P, D, and Q are the seasonal autoregressive, differencing and moving average order, respectively. The goodness-of-fit was determined based on the Akaike information criterion (AIC), the corrected Akaike information criterion (AICc) and the Bayesian information criterion (BIC). The autocorrelation function (ACF) and partial autocorrelation function (PACF) were applied to determine the AR and MA order of the time series. Prior to cross-correlation, the two time series were pre-whitened by the SARIMA model to remove autocorrelation within each individual series and make non-stationary time series stationary (Box and Jenkins 1976). All analyses were conducted in R 3.4.3 (R Core Team 2014).

3.3 Hydrological drought and water quality

3.3.1 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). For hydrological droughts, monthly or longer time resolutions could underestimate cases when severe droughts are shorter than 1 month, especially when it is analysed 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 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 dry periods with 3 days of minimum duration and inter event time, to eliminate minor droughts and pooling mutually drought events (Zelenhasić and Salvai 1987, 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).

3.3.2 Physicochemical parameters and thresholds for agricultural water use

Surface water quality data from the period 1985–2015 of differing temporal resolution (in general one measurement per season) were evaluated for all discharge stations. The Chilean regulation NCh 1333/78 "*Water quality requirements for different uses*" (INN 1987) was used as a reference to select the physicochemical parameters and to compare their values to the established thresholds of water quality for irrigation. These parameters were also chosen according to previous drought and water quality studies and having at least 20 years of data. Measured parameters included: temperature (ºC), pH, dissolved oxygen (O_2; mg/L), electrical conductivity/salinity (µS/cm) and related ions, nutrients and metals, such as Zn, Cu and As. The DGA follows the sampling and analytical procedures described in the "*Standard Methods for the Examination of Water and Wasterwater*" (APHA AWWA WEF 1995), details associated with these analysis are described in (Oyarzun *et al.* 2006). The database was provided with the correspondent daily discharge value. To establish a significant data set showing potential effects of drought on water quality, the data were grouped according to the respective threshold value (Q80 and Q20) and then compared. To examine, at a significant level ($P < 0.05$), the degree of association between measured water quality parameter and daily discharge, we used Spearman's correlation coefficient.

4 Results

4.1 Spatio-temporal distribution of meteorological and hydrological drought

Table 3 shows the characterization of meteorological and hydrological droughts. Temporal variations of meteorological drought are shown in Fig. 3. It can be noted that all sub-basins depicted similar patterns in the frequency and duration of meteorological drought events. Common drought episodes occurred during the years 1988/89, 1990/91, 1996/97, 1998/99, 2011/12 and 2014/15.

All the sub-basins reached the extremely dry category, whereas the lowest SPI-3 and SPI-6 (<–2.05) values were obtained for the period 2009–2015 in five of the six sub-basins. The lowest value in Maipo Alto Maitenes was observed in 1989. None of the sub-basins showed the extremely dry category in the SPI-12 accumulation period. Also, most of the sub-basins experienced the longest drought event in the period 1988–1999 and 2010–2014. During 16–18% of the study period the basin experienced meteorological drought. The frequency of drought events ranged between 8 and 22 times during the period of record.

Although the hydrological droughts were less frequent (3–12 events) compared to meteorological droughts (8–22 events), these were longer, obtaining periods up to 64 months under hydrological drought. This pattern was also observed in the percentage of time in which most of the basin experienced hydrological drought (20–23%, with the exception of station 9D, 10%), being higher than meteorological drought (16–18%). Also, the longest drought periods in most of the basin occurred in recent years (2010–2015), while in meteorological droughts, the longest and most intense droughts were in the period of 2010–2013 and also 1988–1999. All stations, except 1A, reached the most extreme drought class. As is also shown in Table 3 for both SPI and SSI, the frequency of drought events was higher at shorter accumulation periods. Hydrological drought characteristics based on SSI exhibited more spatial variability than the meteorological drought. The stations located in Maipo Alto Maitenes (1A) and Maipo Bajo (9D) showed the shortest hydrological drought duration from the basin. Stations 3B, 5C, 7C and 9D had most of the lowest values in the period 1994–1997. In contrast, stations 1A, 2A, 4B and 6C showed the lowest values in the period 2009–2015. Station 8C presented its lowest value (–2.62) in both periods.

4.2 Relationship between meteorological and hydrological droughts

Figure 4 shows the correlation coefficients for SPI and SSI at all temporal scales. Positive relationships were obtained for most of the stations and the highest correlation of SSI in all temporal scales was identified with the highest accumulation period SPI-12 (Fig. 4). Also, correlation values tend to increase from the upper to the lower part of the basin. This pattern might show the significant high dependence of the streamflow on snowfall during the previous hydrological year. Fig. 5 provides an illustrative overview of the analysis. It shows the temporal variation of the SSI-1 and the SPI at 12-monthly scale in the station 4B, which are the time scales with one of the highest correlations ($R = 0.77$) and the station 1A with one of the lowest correlations ($R = 0.43$). Also, the figure shows the dominance of dry hydrological events during the last 10 years.

4.3 Hydrological drought and water quality

Spearman correlation coefficients between daily discharge volumes and the related physicochemical parameter from the period of record 1985–2015 are shown in Table 4. Mixed responses were observed for temperature and dissolved oxygen, and between 30% and 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 located in the lower part of the basin 8C and 9D for temperature (–0.24 and – 0.72; $p < 0.05$), which have mixed and pluvial regime. On the other hand, stations

Table 3. Characteristics of meteorological and hydrological drought events (1985–2015). * Drainage area considered as the representative SPI for each sub-basin.

Sub-basin	Meteorological drought						Hydrological drought				
	Discharge station	Temporal scale	Maximum drought duration		% Time in drought	Frequency	Temporal scale	Maximum drought duration		% Time in drought	Frequency
			Months	Years				Months	Years		
MAIPO ALTO		SPI-3	5	1988, 1996, 2013	17	19					
		SPI-6	15	1988-1989		15					
		SPI-12	21	1988-1990		11					
MAIPO ALTO-MAITENES		SPI-3	6	1988, 1996, 2013	18	17	SSI-1	6	1999, 2004, 2010-2011	21	8
		SPI-6	9	1988,1990-1991		16	SSI-3	13	2014-2015		12
	1A	SPI-12	22	1988-1990		13	SSI-6	14	2014-2015		10
							SSI-12	23	2013-2015		6
		SPI-3	5-6	1988, 1996, 2013		17	SSI-1	19	2014-2015		12
		SPI-6	9	1988,1990-1991		16	SSI-3	22	2014-2015		10
	2A*	SPI-12	13-14	1988-1989, 2013-2014		13	SSI-6	24	2014-2015		9
							SSI-12	40	2012-2015		8
MAIPO MEDIO		SPI-3	5	1988, 1996, 2013	17	19	SSI-1	18	2010-2012	20	7
		SPI-6	7-8	1988, 1996-1997, 2013-2014		16	SSI-3	25	2010-2012		7
	3B	SPI-12	21	1988-1990		11	SSI-6	26	2010-2013		5
							SSI-12	34	2011-2013		5
		SPI-3	7	1996-1997		22	SSI-1	30	2013-2015		7
		SPI-6	8-9	1988, 1996-1997		19	SSI-3	36	2012-2015		6
	4B*	SPI-12	19	1988-1990		12	SSI-6	64	2010-2015		4
							SSI-12	64	2010-2015		3
MAPOCHO ALTO		SPI-3	5-6	1988, 1996, 2013	16	19	SSI-1	15	2014-2015	20	10
		SPI-6	8	1988, 1996-1997		17	SSI-3	17	2014-2015		9
	5C	SPI-12	12-13	1988-1989, 2011-2012, 2013-2014		13	SSI-6	18	2010-2012		6
							SSI-12	25	2010-2012		6
		SPI-3	5-6	1988, 1996, 2013		18	SSI-1	16	2014-2015		9
		SPI-6	9	1988		17	SSI-3	28	2013-2015		7
	6C	SPI-12	12-13	1988-1989, 2011-2012		12	SSI-6	28	2013-2015		5
							SSI-12	30	2013-2015		6
		SPI-3	7	1996-1997		19	SSI-1	16	1996-1997		9
		SPI-6	9	1988		17	SSI-3	16	1996-1997, 2013-2015		6
	7C*	SPI-12	12-13	1988-1989, 2011-2012		12	SSI-6	34	2012-2015		6
							SSI-12	54	2011-2015		5
MAPOCHO BAJO					17		SSI-1	22	2010-2012	23	9
		SPI-3	5-6	1988, 1996, 2013-2014		17	SSI-3	27	2010-2012		10
	8C*	SPI-6	9	1988		18	SSI-6	29	2010-2012		8
		SPI-12	23	1988-1990		8	SSI-12	40	2010-2014		6
MAIPO BAJO					16		SSI-1	8	1996-1997	10	4
		SPI-3	5-6	1988, 1996		19	SSI-3	8	1996-1997		5
	9D*	SPI-6	7-8	1988, 1996-1999		15	SSI-6	12	2010-2012		5
		SPI-12	20-21	1988-1990, 2010-2012		9	SSI-12	18	2010-2012		6

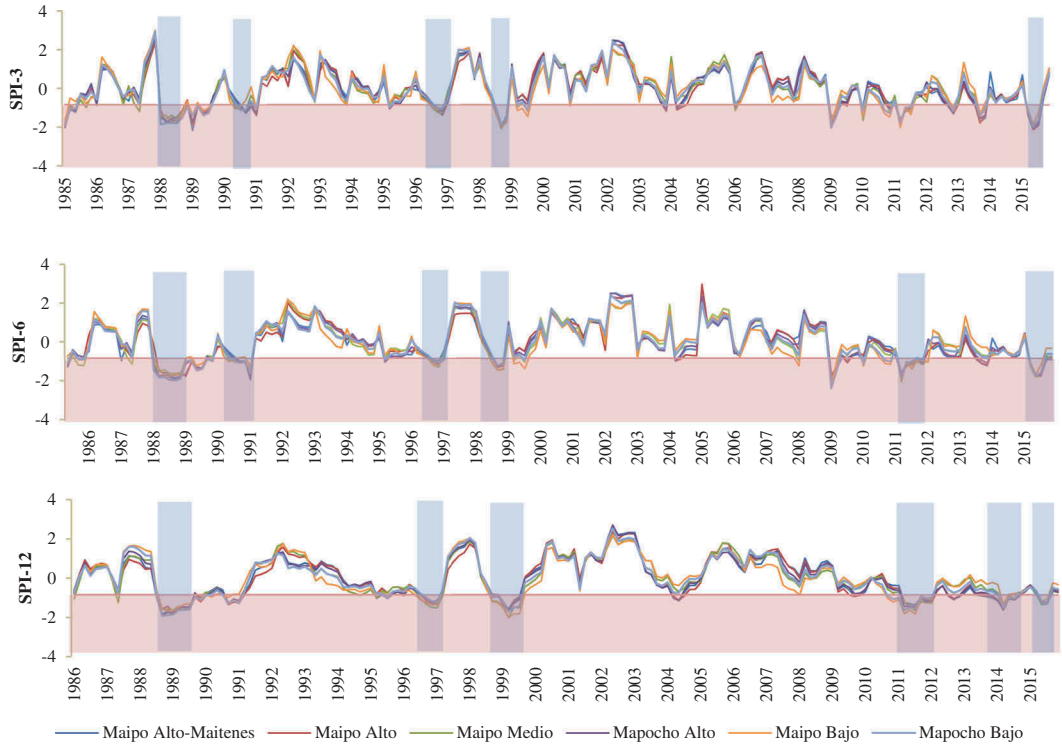

Figure 3. Temporal variation of meteorological droughts of each sub-basin based on the SPI of 3-, 6- and 12-month aggregated for the rainy season (April–September). The SPI of each sub-basin is represented by the largest drainage area of the related discharge stations (Table 3). Pink shading indicates the – 0.84 threshold value defined for drought events. Blue shading shows the major drought events (longer than 3 months).

with a nival regime such as 1A, 2A, 3B, and 5C showed positive relationships (0.42, 0.46, 0.61 and 0.60; $p < 0.05$) with temperature. In the stations showing positive relations with temperature, significant negative relationships were found for dissolved oxygen in two of them (3B and 5C) ($p < 0.05$). Nonetheless, this parameter showed one of the lowest range of significant correlations within the whole set of physicochemical parameter data.

Significant negative relationships were observed for pH, electrical conductivity, Na, Mg, Ca, SO_4, Cl, K, NO_3 and PO_4. For these parameters, most of the highest concentrations were found in drought periods. The percentage of response to this characteristic is variable in the basin ranging from 100% to 20% of the stations (Mg and NO_3, respectively). Nitrate was the parameter showing the lowest correlation, supported by the fact that it did not show strong variations in its concentration due to periods of variable streamflow. The station 7C was the only site displaying a significant positive relationship of PO_4 (0.26; $p < 0.05$). For electrical conductivity, only the stations 5C and 9D from Mapocho Alto and Maipo Bajo sub-basins did not show a significant relationship with discharge, finding relatively constant values of this parameter in dry, regular and wet periods. The highest significant negative correlations ($p < 0.05$) for electrical conductivity ($r_s = -0.94$) and related ions such as Na ($r_s = -0.92$) and Cl ($r_s = -0.94$) were found for the same station (3B); this behavior was a continuous pattern at most of the 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 60% of the stations showing this pattern (Fe and Mn, respectively). Most of the highest concentrations of these parameters were observed in wet periods. The station 6C was the only site with a significant negative relationship of As and Zn.

4.4 Drought driven water quality impacts on irrigated agriculture

Table 5 shows the water quality threshold values (NCh 1333/78) compared to maximum, mean and minimum water quality values for three key station within the three subareas of the Maipo located in irrigation districts: 4B, 8C, and 9D (Fig. 1) and selected crops tolerance to salinity (FAO 1985) and chloride. At these stations, the parameters were compared with thresholds from official regulation for irrigation water uses.

Physicochemical data were grouped according to the corresponding thresholds levels (Q80, Q20–Q80 and Q20) and the threshold for each parameter according to the Chilean regulation for irrigation water uses (dashed lines). Related curves represent its relationship with daily discharge (solid black line) of the station 4B, as shown in Fig. 6. Stations 4B and 8C showed significant positive relationships with dissolved oxygen, which tends to decrease during low flows (Fig. 6, station 8C not shown). 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 could increase with high streamflow (Table 4), during drought periods their concentrations were not surpass-

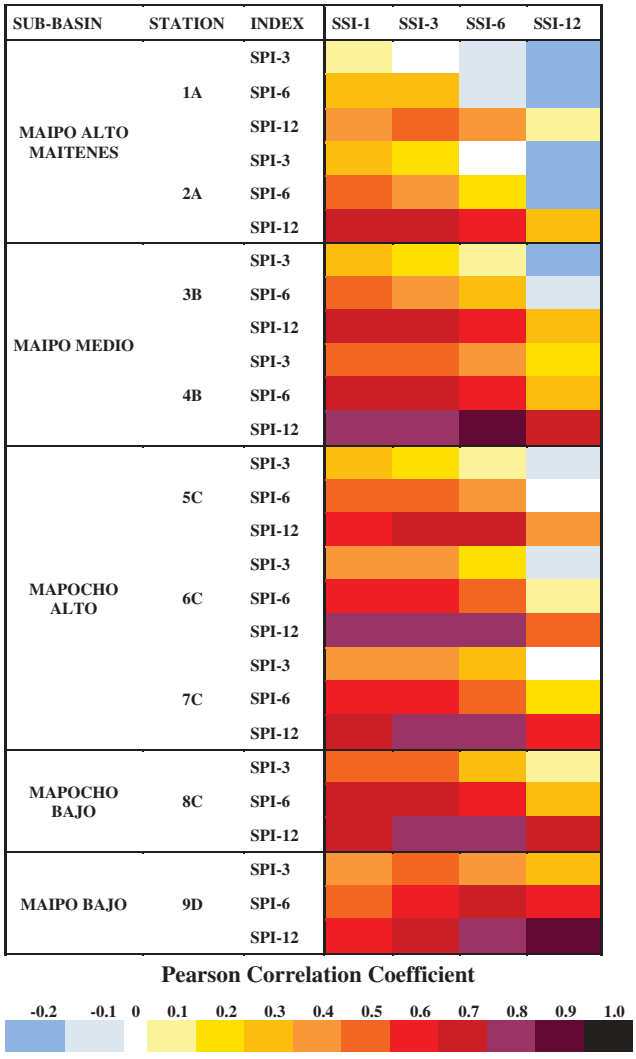

Figure 4. Heat map showing the Pearson correlation coefficient between upstream SPI and SSI of the selected stations within the sub-basins.

ing the established limit. However, variables such as electrical conductivity, SO_4, and Cl showed an exponential behavior while the streamflow decreased (station 4B and 8C), and reached their maximum mean concentration during hydrological drought periods, markedly exceeding its relative threshold (Fig. 6; Table 5). 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).

5 Discussion

5.1 Spatio-temporal drought characterization

The drought events identified in the scope of this study coincide with those described in previous publications (Garreaud *et al.* 2017, Oertel *et al.* 2018). 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), similar meteorological drought frequency, duration and intensity values were found for all the sub-basins. This result could be mostly related to the shared Mediterranean climate of the central Chilean region, in which the differences in altitude related to temperature and precipitation are not strongly influencing the meteorological drought pattern. Furthermore, the basin can be considered as a homogeneus region in terms of the underlain precipitation probability distribution, regardless of the mean annual precipitation at any place across the basin (Núñez *et al.* 2011). The same applies to other arid regions in Latin America like Mexico (Núñez *et al.* 2016). Similar results were reported by Van Loon and 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.

The monthly streamflow deficit (SSI-1) in the basin ranged from 6 to 30 months; from which the longest corresponds to the station 4B located in the central valley, reflecting the anthropic intervention. Longer drought events were observed for recent years (2010–2015), indicating that the rainfall following droughts was unable to generate the surpluses needed to restore hydrological conditions that were present prior to the drought and to compensate the increasing demand from the activities within the basin (agriculture, industrial and urban supply) (Lorenzo-Lacruz *et al.* 2013a). 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. The decrease in the annual streamflows since 2010 in the region was also reported by the Center for Climate and Resilience Research (CR)[2] (2015).

In contrast to meteorological drought characteristics, hydrological droughts detected by SSI show differences among the sub-basins. The station located at the higher sub-basin (1A) shows a lower drought duration compared to the middle zones of the basin. The hydrological drought periods in the basin were not restricted to the rainy season (winter-autumn) but also to the snowmelt months (spring-summer). This pattern can be explained by the relationship between precipitation and snowpack accumulation, and the impacts 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.

According to Van Loon *et al.* (2010) the combined effect of higher temperatures in winter with lower precipitations determines the development of hydrological droughts in snow affected regions: 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.

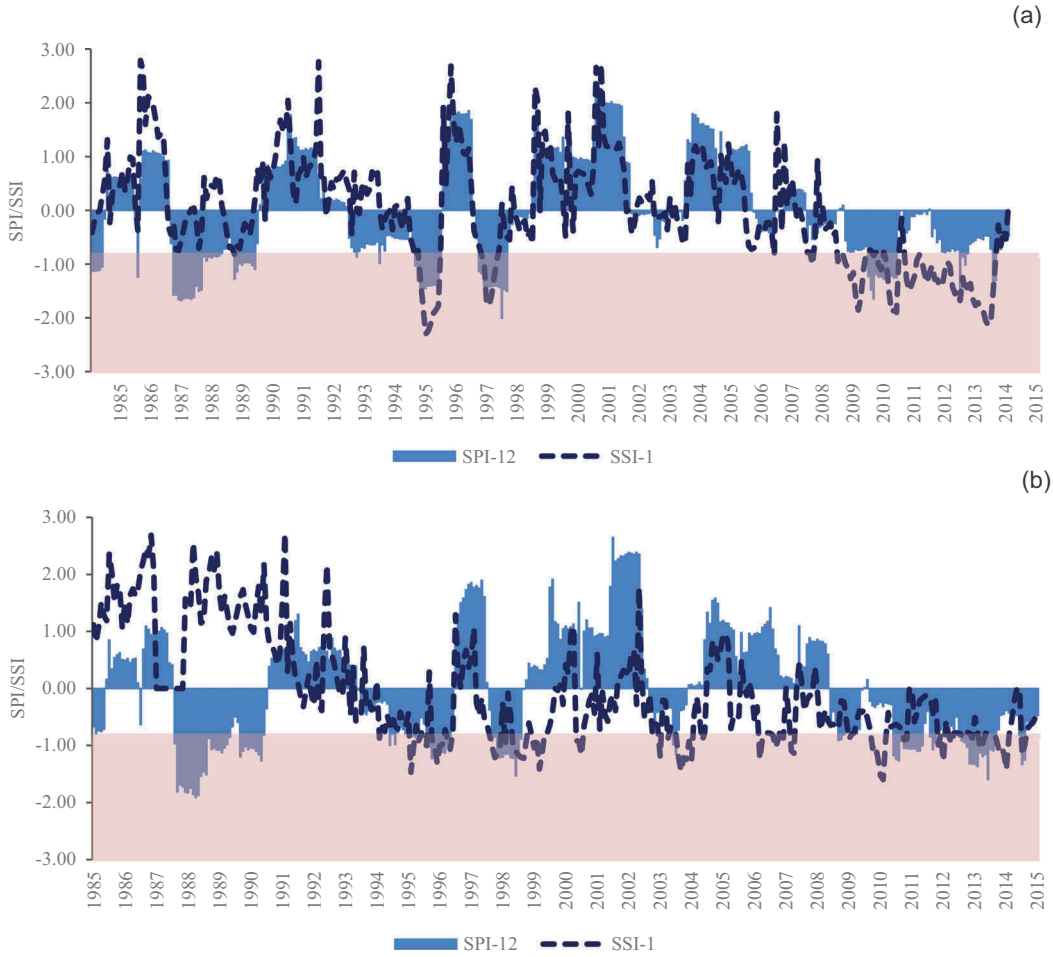

Figure 5. Temporal variation of SPI and SSI at: (a) Station 4B in Mapocho sub-basin (R = 0.77) and (b) Station 1A in Maipo Alto-Maitenes sub-basin (R = 0.43). Pink shading indicates the − 0.84 threshold-value defined for drought events.

5.2 Relationship between meteorological and hydrological drought

Positive correlation coefficients were found in most of the basin between SPI and SSI in which as SPI accumulated period increases, the correlations with SSI increase. The highest correlation of SSI at all temporal scales was found with the SPI-12 accumulation period. This pattern increases from the upper to the lower part of the basin, denoting the dependence of the streamflow on snowmelt and the previous year of precipitation especially downstream. 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.* (2013b) found similar results, attaching the response to the high-permeable geologies of the catchments characterized by limestone lithology in the South of the Iberian Peninsula which results in groundwater recharge delaying the streamflow response to meteorological variability. In the Maipo River basin, the regions close to the Andes mountains present an extremely low 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 analysed 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 (data not shown) of this station revealed that it continues to increase its correlation up to SPI-24 and then starts to decrease. López-Moreno *et al.* (2013) 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 cited 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 and López-Moreno 2005, Lorenzo-Lacruz *et al.* 2010, López-Moreno *et al.* 2013, Vicente-Serrano *et al.* 2017). In our study, the surface water resources from the Maipo River are partially regulated through damming in the Laguna Negra and El Yeso dam (DGA 2008).

Table 4. Discharge stations and physicochemical parameters. Bold figures indicate significant correlation with daily discharge, with Spearman correlation coefficient $p < 0.05$. *Stations located in irrigation districts. °C: temperature; 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); PO_4: orthophosphate (mg/L); Zn: zinc (mg/L).

Sub-basin	Discharge station	Altitude (m.a.s.l.)	Hydrological 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	**0.42**	**−0.27**	−0.23	**0.73**	**0.40**	**0.40**	**−0.89**	**−0.92**	**−0.64**	**0.61**	**−0.44**	**−0.55**	**−0.89**	**−0.68**	**−0.34**	**0.64**	−0.21	**0.56**
	2A	890	Nival	**0.46**	**−0.28**	−0.13	**0.73**	**0.54**	**0.49**	**−0.84**	**−0.85**	**−0.67**	**0.66**	**−0.51**	−0.04	**−0.91**	**−0.42**	−0.23	**0.69**	−0.04	**0.63**
Maipo Medio	3B	850	Nival	**0.61**	**−0.27**	**−0.29**	**0.74**	**0.25**	**0.51**	**−0.94**	**−0.92**	**−0.65**	**0.52**	**−0.52**	**−0.57**	**−0.94**	**−0.41**	−0.18	**0.57**	0.01	**0.42**
	4B*	342	Pluvial	−0.10	**−0.22**	**0.35**	**0.52**	**0.23**	**0.39**	**−0.69**	**−0.71**	**−0.65**	**0.25**	**−0.58**	**−0.64**	**−0.76**	**−0.47**	−0.13	**0.37**	**−0.30**	**0.28**
Mapocho Alto	5C	1350	Nival	**0.60**	**−0.43**	**−0.38**	**0.39**	**0.39**	0.16	−0.06	**−0.69**	**−0.26**	0.17	0.08	0.09	**−0.67**	−0.06	**−0.29**	**0.63**	0.11	0.13
	6C	880	Nival	−0.01	−0.11	0.15	0.13	**−0.51**	−0.18	**−0.73**	**−0.43**	**−0.64**	−0.18	**−0.57**	**−0.77**	−0.15	**−0.25**	−0.05	0.18	0.06	**−0.31**
	7C	966	Nival	0.14	**−0.29**	−0.07	**0.45**	**0.23**	−0.01	**−0.62**	**−0.58**	**−0.41**	0.02	**−0.47**	**−0.43**	**−0.58**	0.02	−0.04	**0.32**	**0.26**	−0.07
Mapocho Bajo	8C*	440	Nivo-Pluvial	**−0.24**	−0.04	**0.24**	**0.45**	**0.23**	**0.26**	**−0.76**	**−0.64**	**−0.52**	0.20	**−0.63**	**−0.62**	**−0.67**	**−0.63**	−0.02	**0.39**	**−0.56**	**0.27**
Maipo Bajo	9D*	93	Pluvial	**−0.72**	−0.19	−0.16	0.17	0.14	**0.31**	−0.17	−0.01	**−0.48**	**0.36**	**−0.47**	**−0.32**	−0.04	**−0.25**	0.16	**0.28**	0.14	**0.32**

Table 5. Minimum, maximum and mean concentrations of physicochemical parameters during drought periods. Related threshold levels according to the Chilean regulation NCh 1333/78 for stations located in irrigation districts and selected crop tolerance to salinity (FAO, 1985) and chloride. Bold figures indicate significant relationships with discharge ($p < 0.05$).

Sub-basin	Station	Cond (µS/cm)				SO_4 (mg/L)				Cl (mg/L)				Selected crops	Cl (mg/L)$^{+}$	Cond (µS/cm)$^{++}$
		Min	Max	Mean	NCh1333	Min	Max	Mean	NCh1333	Min	Max	Mean	NCh1333	Avocado (*Persea americana*)	116.8 – 177	<750 (*)
Maipo Medio	4B	**831**	**1507**	**1267**	750–1500*/1500–3000**/>3000***	**84.0**	**382.3**	**296.1**	250	**85.4**	**202.3**	**137.4**	200	Citrus (*Citrus* spp.)	237.2–354	2200
Mapocho	8C	**1146**	**2213**	**1656**		**221.0**	**404.4**	**312.4**		**101.0**	**323.9**	**210.8**		Grape (*Vitis* spp.)	237.2–470.8	2700
Maipo Bajo	9D	1307	2183	1713		**309.8**	**450.5**	**369.6**		143.0	291.8	203.9		Strawberries (*Fragraria* spp)	116.8 – 177	1200

* 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.
$^{+}$Chloride tolerance of some fruit crop cultivars and rootstocks; Maximum Permissible Range of Cl^{-} without Leaf Injury in irrigation water
$^{++}$Crop tolerance of selected crops as influenced by irrigation water salinity with a yield potential of 75%. (*) (INDAP 2007).

5.3 Drought impacts on water quality

In the following sections, surface water quality and its relation to discharge and especially low flows are discussed. However, it is important to highlight that the seasonality of the low flows (which was not restricted to summer droughts), the mixed regime of the basin, and the anthropogenic activities, strongly influence the behavior of the parameters.

5.3.1 Surface water temperature

Surface water temperature at stations located in irrigation districts and with a mixed or pluvial regime, showed a significant negative correlation with discharge. This behavior can be attributed to the inverse relationship between water temperature and river discharge with higher warming rates under low-flow conditions (Caruso 2002, Van Vliet and 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). Positive relationships were observed mostly at stations located in higher zones with a nival regime which can be explained by the fact that higher flows at these elevations correspond to colder melting water from the Andes Mountains.

5.3.2 Electrical conductivity/salinity

Salinity expressed by electrical conductivity and major ions (Cl, Na, SO_4, Mg, Ca, K) had significant negative correlations with discharge and increased in almost all the stations analyzed during low-flow conditions. Similar results have been reported by Nosrati (2011); Dezfuli *et al.* (2013); Momblanch *et al.* (2015), Flores *et al.* (2017) among others. The major ion geochemistry of the streams waters in Central Chile is dominated by their interaction with evaporites, carbonates in marine sediments, andesites and granodiorites which explains their high concentrations (Jorquera *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). 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). In the case of the station 5C, that does not show a significant relationship with electrical conductivity, suggest that the natural conditions of the station (river of glacial origin, rich in ionic compounds) prevailed against the variable streamflow (DGA 2004). Also, the station 9D located in Maipo Bajo which showed a similar behavior could be mostly related to the dominance of groundwater outcrops and irrigation returns from the areas served by the channels in the irrigation districts (DGA 2003; DGA 2004).

5.3.3 Dissolved oxygen (DO)

The responses related to DO are variable but with lower significant relationships than the other parameters. We would expect decreased DO values under low flows 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 (Prathumratana *et al.* 2008, Van Vliet and Zwolsman 2008, Palmer and Montagna 2015). However, this positive correlation was only observed at two stations located in irrigation districts. Increases in DO during drought periods, have been reported by Zwolsman and van Bokhoven (2007) due to an increase in primary production in the river water and by Attrill and Power (2000) as a result of the reduction in the number of storm events that lead to a less untreated sewage inputs or/and improved effluent quality from the wastewater treatment.

5.3.4 pH

Six stations showed significant negative correlations with pH. In those cases where pH increased, it is likely that lower water volumes favored stagnant conditions for algae growth which along with plants use all the carbon dioxide dissolved (Van Vliet and Zwolsman 2008, Gołdyn *et al.* 2015 and references therein). In other cases, and depending on the water body and its location, increases in pH during low-flow conditions could be due to marine intrusion (Senhorst and Zwolsman 2005, Prathumratana *et al.* 2008).

5.3.5 Nutrients

We found significant negative relationships for nitrate at two stations (1A and 5C), significant negative correlations of phosphate at two stations located in irrigation districts (4B and 8C), and one significant positive correlation at station 7C. This erratic behaviour can be related to the constant nutrient input from the different human activities with anomalously high concentrations mainly downstream in the Central Valley and the Coastal Cordillera in agricultural areas (Jorquera *et al.* 2015). It is expected that a higher nutrient content during droughts could have a connection with a reducing dilution capacity of the water body (Zwolsman and van Bokhoven 2007, Prathumratana *et al.* 2008, Van Vliet and Zwolsman 2008). On the contrary, deficient levels of dissolved nutrient concentrations in rivers could lead to rapid assimilation by algae where differences between nitrogen and phosphorus concentration could be linked to nutrient limitations and increasing denitrification process with higher water residence time (Cook cited Mosley *et al.* 2012). Also, low nutrient levels can be due to a reduced non-point source runoff inputs (Caruso 2002).

5.3.6 Metals

Significant positive relationships with discharge were found at most of the stations for essential (Zn, Cu, Fe and Mn) and nonessential (Al, As) metals (DGA 2004), as most of the concentrations of those variables increased during wet periods. Only the station 6C showed a significant negative relationship with discharge. Similar positive correlations between Fe and discharge have been observed by Flores *et al.* (2017) in the Elqui river basin in North Central Chile, but with a more erratic behaviour for Cu and As. It is expected that several elements from regular anthropogenic activities can concentrate due to limited dilution (Zwolsman and van Bokhoven 2007, Van Vliet and Zwolsman 2008). However, for inorganic

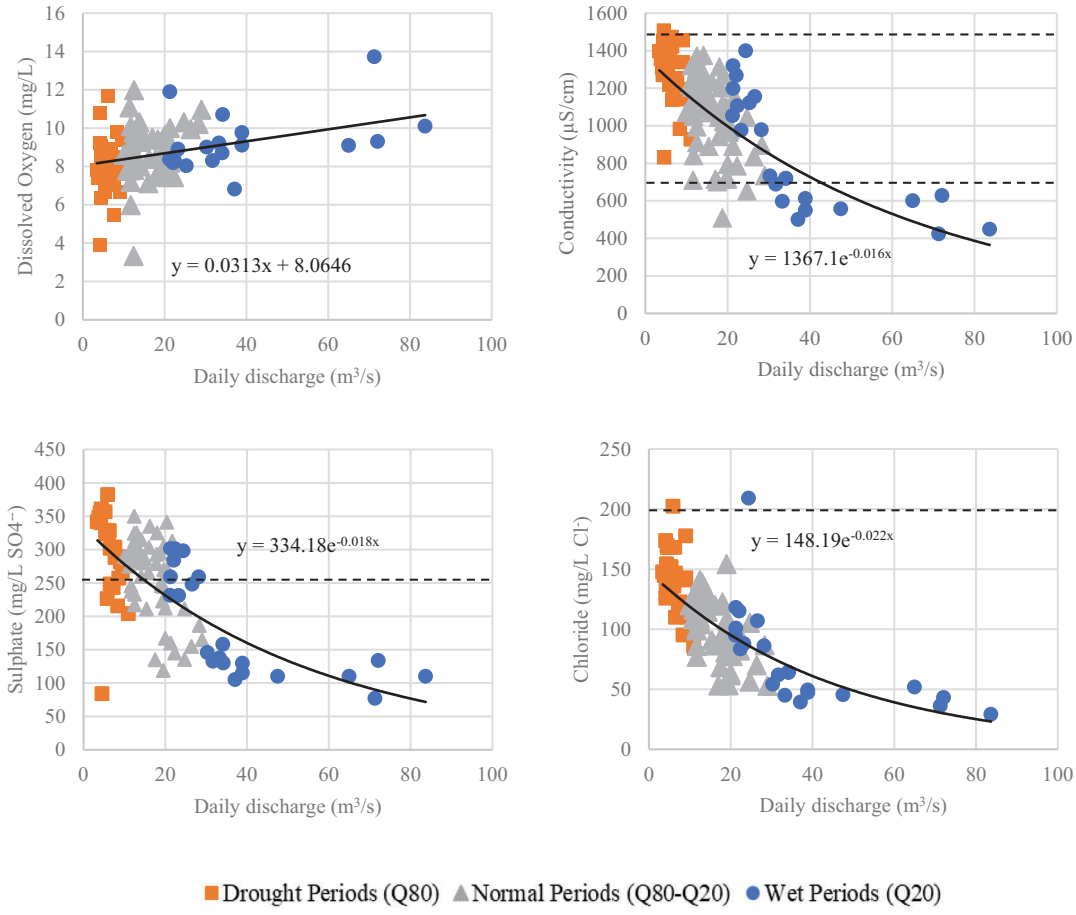

Figure 6. Daily discharge and physicochemical parameters from station 4B grouped by the related threshold level. Dashed lines represent the threshold for each parameter according to the Chilean regulation for irrigation water uses.

pollutants, an indirect relation could be assumed. 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 high flows (thaw streamflow) after a drought period, enhancing their concentration in the river. Flores *et al.* (2017) suggested that turbulent flows associated with higher discharges could favour the transport of particulate forms of Fe in the Elqui basin. Furthermore, 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.

5.3.7 Overall perspective of hydrological drought impacts on water quality

Impacts on water quality and their magnitude depend on the specific characteristics of the water body: 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 and Zwolsman 2008, Delpla *et al.* 2009, Li *et al.* 2016). In addition, according to Zwolsman and van Bokhoven (2007) the impact of droughts on water quality would be greater when the water quality 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 and van Bokhoven 2007). 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). Fertilizers are the principal source of nitrate in tributaries of the Maipo River in the central valley and high values of K, Mg, NO_3 and P are also related to the presence of septic waste and detergent in sewage (Jorquera *et al.* 2015). According to DGA (2004), liquid industrial waste has been a significant source of deterioration in the basin, turning it in the most contaminated basin in the country.

An additional effect is that during a 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). Therefore, water quality problems can not be limited only 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 Delpla *et al.* 2009, Huang *et al.* 2015). 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 Verweij *et al.* 2010).

In general terms, across the stations, electrical conductivity/salinity has been one of the most direct drought-related quality parameters and can be suggested as a characteristic variable for decision-making. Palmer and 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 have been also proposed for monitoring impacts (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 this aspect. Also, be aware of its implications to develop drought mitigation and adaptation measures for water quality impacts.

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

The production of fruit trees has great importance at the national level, especially grapes and avocado plantations mainly destined to exportation (MOP 2007). According to INE (2007), the local agricultural land is cultivated according to the order of importance of crops and fruit plantations, annual and permanent forage, vegetables, and vineyards which concentrate mostly in the central Maipo Valley. The most important and extensive agricultural areas according to crop type are located in Melipilla, Maipo and Cordillera provinces, where two of the evaluated stations are located. The exceedance of the Chilean thresholds at these stations during hydrological drought periods could be linked to potential effects on irrigated agriculture as described in the following section:

Commonly, relevant water quality parameters 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, 2016). 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 at two stations of the irrigation districts had a 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. The values of electrical conductivity vs. discharge had an exponential relationship with streamflow at stations 4B and 8C, reaching values of 2213 μS/cm (station 8C) water that can only be used by salinity-tolerant plants. Avocado 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 obtaining better yields, this concentration could affect its productivity greatly (INDAP 2007). Also, the use of saline water in the land can cause, from the evaporation process, the salinization of the soil (Sagasta and 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 and Burke 2005). The worst panorama in 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 to Ca and magnesium Mg ions, can degrade the soil structure resulting in a more erodible and impermeable soil that could reduce plant growth (Sagasta and Burke 2005). In the Maipo River and under normal conditions, chloride concentration decreases, from the mountain range to the ocean; whereas in the Mapocho sub-basin chloride concentration registers an increase due to the great anthropic influence (DGA 2004). Higher chloride concentration can burn plant leaves during irrigation (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 only 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 River 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). Sulphate and Cu concentrations exceeding water irrigation thresholds in the basin have been also reported by Pizarro *et al.* (2010) with an increasing trend over time. This increase is probably a response to dynamic processes resulting from the interaction between mining pollution, erosion, and natural processes such as weathering or flooding.

Although dissolved oxygen is not included in the regulation, according to Bhattarai and Chérif cited Maestre-Valero and Martínez-Alvarez (2010), dissolved oxygen 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 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 could be at risk during low-flow conditions.

Nonetheless, essential and nonessential metals parameters had a significant positive relationship with discharge, thus, 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. Higher Mn concentration can cause phytotoxicity which is mostly related to the reduction of biomass and photosynthesis inhibition (Al-Isawi *et al.* 2016). Also, an 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 summary, the results suggest that in dry years the whole water cycle is affected by the reduced reservoir recharge and snow storage that will extend to the zones of the basin that depend on them. The important precipitation input from the 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 results in a higher demand from the different activities (e.g. higher rates of evapotranspiration which means more irrigation demands). Low flow conditions combined with inputs from 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.

6 Conclusion

We used standardized indices to analyse drought in different sections of the Maipo River basin and assessed their relationships with water quality variables. The longest hydrological drought periods in most of the basin occurred in recent years (2010–2015). The highest correlation of SSI with SPI-12 denotes the dependence of the streamflow on the previous year of precipitation. In general terms, across the stations, electrical conductivity/salinity has been one of the most direct drought-related water quality parameters and can be suggested as a characteristic variable for decision-making. 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 can affect sensible crops produced in the basin such as avocado plantations. For inorganic pollutants, a more deep analysis should be carried out to determine if there is a relationship between drought re-wetting cycles and the increase of its concentration in wet periods. It is important to highlight that this basin is highly influenced by human activities that could impact the behavior of the physicochemical parameters being difficult to attribute it to a unique source. Therefore, this study stands out the importance of tracking the anthropogenic contribution to water quality under drought conditions within the framework of climate variability and change. Deeper and more frequent monitoring is needed to differentiate and detail the changes during the different seasonal droughts and the role of natural conditions. Although the present study focuses on central Chile, its results can be of benefit to all Mediterranean areas of the world. Because of their similar climates, these regions have much in common: cash crops, major wine industries, urban development pressure, facing water-shortage through months of summer drought in the present, and the forecasted climate change impact to make them hotter and drier in the future. To conclude, this study gives a valuable overview of drought-driven water quality deterioration and its potential impacts on irrigated agriculture, indicating that further water management strategies should consider monitoring water quality during drought periods.

Acknowledgements

The authors would like to thank the Chilean National Water Agency (Dirección General de Aguas-DGA) for providing the daily time series of the discharge stations in the Maipo River Basin, and also an anonymous reviewer and the editor Dr. Shaochun Huang, for their constructive comments that helped to improve the paper.

Disclosure statement

No potential conflict of interest was reported by the authors.

Funding

Funding for field research was provided by the BMZ/DAAD (German Federal Ministry for International Cooperation and Development) in the scope of the project "Education and Research related to the Water Energy and Food Nexus at River Basin Scale (EDUNEXUS)". A Master scholarship from the Mexican Council of Science and Technology (CONACYT) was granted to M.D Peña-Guerrero.

ORCID

A. Nauditt http://orcid.org/0000-0002-9780-5280

References

Al-Isawi, R.H.K., Almuktar, S.A.A.A.N., and Scholz, M., 2016. Monitoring and assessment of treated river, rain, gully pot and grey waters for irrigation of Capsicum annuum. *Environmental Monitoring and Assessment*, 188 (5). doi:10.1007/s10661-016-5285-4

APHA AWWA WEF, 1995. *Standard methods for the examination of water and wastewater*. 19th ed. Washington, DC: American Public Health Association.

Assouline, S., *et al.*, 2015. Balancing water scarcity and quality for sustainable irrigated agriculture. *Water Resources Research*, 51 (5), 3419–3436. doi:10.1002/2015WR017071

Attrill, M.J. and Power, M., 2000. Modelling the effect of drought on estuarine water quality. *Water Research*, 34 (5), 1584–1594. doi:10.1016/S0043-1354(99)00305-X

Barker, L.J., *et al.*, 2016. From meteorological to hydrological drought using standardised indicators. *Hydrology and Earth System Sciences*, 20 (6), 2483–2505. doi:10.5194/hess-20-2483-2016

Bauder, J.W., *et al.*, 2008. Assessing the suitability of water (quality) for irrigation – salinity and sodium. *In*: *Western fertilizer handbook*. Sacramento, CA: Western Plant Health Association, 1–5.

Bauder, T.A., *et al.*, 2016. *Irrigation water quality criteria*[online]. Colorado State University, Extension-Agriculture 0.506. Available from: https://extension.colostate.edu/docs/pubs/crops/00506.pdf [Accessed 15 Dec 2016].

Bond, N.R., Lake, P.S., and Arthington, A.H., 2008. The impacts of drought on freshwater ecosystems: an Australian perspective. *Hydrobiologia*, 1–14. doi:10.1007/s10750-008-9326-z

Box, G.E.P. and Jenkins, G., 1976. *Time series analysis forecasting and control. Revised* ed. San Francisco, CA: Holden-Day. doi:10.1111/j.1467-9892.2009.00643.x

Carrasco, J.F., Casassa, G., and Quintana, J., 2005. Changes of the 0°C isotherm and the equilibrium line altitude in central Chile during the

last quarter of the 20th century. *Hydrological Sciences Journal*, 50 (6), 933–948. doi:10.1623/hysj.2005.50.6.933

Caruso, B.S., 2002. Temporal and spatial patterns of extreme low flows and effects on stream ecosystems in Otago, New Zealand. *Journal of Hydrology*, 257 (1–4), 115–133. doi:10.1016/S0022-1694(01)00546-7

Centro de Ciencia del Clima y la Resilencia (CR)2, 2015. *Informe a la Nación La megasequía 2010–2015: Una lección para el futuro*[online]. Available from: www.cr2.cl/megasequia [Accessed 13 April 2017].

Delpla, I., *et al*., 2009. Impacts of climate change on surface water quality in relation to drinking water production. *Environment International* Elsevier Ltd, 35 (8), 1225–1233. doi:10.1016/j.envint.2009.07.001.

Dezfuli, A.T., Kashkuli, H.A., and Heidarnejad, M., 2013. Drought and the impact of natural saline river on the quality of surface water resources in Karoon River (IRAN). *Albanian Journal of Agricultural Sciences*, 12 (June), 455–463.

DGA (Dirección General de Aguas), 2003. *Evaluación de los recursos hídricos superficiales en la cuenca del rio Maipo*. Santiago, Chile: Ministerio de Obras Públicas. Gobierno de Chile.

DGA (Dirección General de Aguas), 2004. *Diagnóstico y Clasificación de los cursos y cuerpos de agua segun objetivos de calidad.Cuenca del Río Maipo*. Santiago, Chile: Ministerio de Obras Públicas. Gobierno de Chile, 195.

DGA (Dirección General de Aguas), 2007. *Estimaciones de la demanda de agua y proyeciones futuras. Zona II. Regiones V a XII y Región Metropolitana*. Santiago, Chile: Ministerio de Obras Públicas. Gobierno de Chile.

DGA (Dirección General de Aguas), 2008. *Plan director para la Gestión de los Recursos Hídricos Cuenca del Río Maipo – Fase II Actualización del modelo de Operación del Sistema y Formulación del Plan*. Santiago, Chile: Ministerio de Obras Públicas. Gobierno de Chile.

DGA (Dirección General de Aguas), 2012. DGA No. 1674. *Deja sin efecto resolución D.G.A. No. 39, de 9 de Febrero de 1984 y establece nuevos criterios para calificar épocas de extraordinaria sequía*. Santiago, Chile: Ministerio de Obras Públicas. Gobierno de Chile.

DGA (Dirección General de Aguas), 2014. *Propuesta programa de vigilancia ambiental cuenca río Maipo*. Santiago, Chile: Ministerio de Obras Públicas. Gobierno de Chile.

DGA (Dirección General de Aguas). *DICTUS S.A*. 2009. *Propuesta de modificación de la Resolución (DGA) No.39 de 1984, Criterios para calificar épocas de sequía que revistan el carácter de extraordinarias, Art. 314 del código de aguas*. Santiago, Chile: Ministerio de Obras Públicas. Gobierno de Chile, S.I.T No. 203, 286.

Döll, P. and Siebert, S., 2002. Global modeling of irrigation water requirements. *Water Resources Research*, 38 (4), 8–10. doi:10.1029/2001WR000355.

Errázuriz, K.A.M., *et al*., 1998. *Manual de Geografía de Chile*. Santiago, Chile: Andrés Bello.

FAO (Food and Agriculture Organization), 1985. Water quality for agriculture. *In*: R.S. Ayers and D.W. Westcot, eds. *FAO IRRIGATION AND DRAINAGE PAPER*. 29th. Rome, Italy: Food and Agriculture Organization of the United Nations. Available from: http://www.fao.org/docrep/003/T0234E/T0234E00.htm#TOC

FAO (Food and Agriculture Organization), 2010. *Gestión del riesgo de sequía y otros eventos climáticos extremos en Chile: estudio piloto sobre la vulnerabilidad y la gestión local del riesgo*. Santiago, Chile: Oficina de Estudios y Políticas Agrarias (ODEPA)/Food and Agriculture Organization (FAO).

Fleig, A.K., *et al*., 2006. A global evaluation of streamflow drought characteristics. *Hydrology and Earth System Sciences*, 10, 535–552. doi:10.5194/hess-10-535-2006

Flores, M., *et al*., 2017. Surface water quality in a sulfide mineral-rich arid zone in North-Central Chile: learning from a complex past, addressing an uncertain future. *Hydrological Processes*, 31 (3), 498–513. doi:10.1002/hyp.11086

Funk, C.C., *et al*., 2015. The climate hazards infrared precipitation with stations – a new environmental record for monitoring extremes. *Scientific Data*, 2, 150066. doi:10.1038/sdata.2015.66

Garreaud, R.D., *et al*., 2017. The 2010–2015 megadrought in central Chile: impacts on regional hydroclimate and vegetation. *Hydrology and Earth System Sciences*, 21 (12), 6307–6327. doi:10.5194/hess-21-6307-2017

Ghassemi, F., Jakeman, A., and Nix, H., 1995. *Salinization of land and water resources. Human causes, extent, management and case studies*. Canberra: Australian National University.

Gołdyn, B., Kowalczewska-Madura, K., and Celewicz-Gołdyn, S., 2015. Drought and deluge: influence of environmental factors on water quality of kettle holes in two subsequent years with different precipitation. *Limnologica - Ecology and Management of Inland Waters* Elsevier GmbH., 54, 14–22. doi:10.1016/j.limno.2015.07.002

Gudmundsson, L. and Stagge, J.H., 2016. SCI: standardized Climate Indices such as SPI, SRI, or SPEI. R package version 1.0.2. doi:10.1002/joc.4267.Stagee.

Hayes, M., Wall, N., and Widhalm, M., 2011. The Lincoln declaration on drought indices: universal meteorological drought index recommended. *American Meteorological Society*, 92, 485–488. doi:10.1175/2010BAMS3103.1

Heikens, A., 2006. *Arsenic contamination of irrigation water, soil and crops in Bangladesh: risk implications for sustainable agriculture and food safety in Asia*. Bangkok, Thailand: Food and Agriculture Organization (FAO).

Hisdal, H., 2004. Hydrological drought charateristics. *In*: L. Tallaksen, *et al*., eds. *Hydrological drought- processes and estimation methods for streamflow and groundwater. Developments in water science*. 48th. Amsterdam: Elsevier B.V., 139–198.

Howden, S.M., *et al*., 2007. Adapting agriculture to climate change. *Proceedings of the National Academy of Sciences of the United States of America*, 104 (50), 19691–19696. doi:10.1073/pnas.0701890104

Hrdinka, T., *et al*., 2015. Possible impacts of climate change on water quality in streams of the Czech Republic. *Hydrological Sciences Journal*, 60 (2), 192–201. doi:10.1080/02626667.2014.889830

Huang, B.B., *et al*., 2015. Effects of water quality of the basin caused by nitrogen loss from soil in drought. *Natural Hazards*, 2357–2368. doi:10.1007/s11069-014–1433-8

Iglesias, A. and Garrote, L., 2015. Adaptation strategies for agricultural water management under climate change in Europe. *Agricultural Water Management* Elsevier B.V., 155, 113–124. doi:10.1016/j.agwat.2015.03.014

INDAP (Instituto de Desarrollo Agropecuario), 2007. Producción y Mercado. Estrategias Regionales de Competitividad por Rubro.

INE (Instituto Nacional de Estadística), 2007. *Censo Agropecuario y Forestal 2007*. Santiago, Chile: Ministerio de Agrícultura. Gobierno de Chile.

INN (Instituto Nacional de Normalización), 1987. *Norma Chilena Oficial NCh 1333/78. Modificada en 1987. Requisitos de calidad del agua para diferentes usos*. Santiago, Chile: Gobierno de Chile.

IPCC (Intergovernmental Panel on Climate Change), 2007. In: M. Parry, *et al*., eds. *Climate change 2007: impacts, adaptation and vulnerability. Contribution of working group II to the fourth assessment report of the intergovernmental panel on climate change*. Cambridge, UK: Cambridge University Press.

IPCC (Intergovernmental Panel on Climate Change), 2014. *Climate change 2014: impacts, adaptation, and vulnerability, contribution of working groups ii to the fifth assessment report of the intergovernmental panel on climate change*. Geneva, Switzerland: IPCC.

Jarvis, A. *et al*., 2008. *Hole-filled STRM for the globe Version 4, available from the CGIAR-CSI STRM 90m Database*. Available from: http://srtm.csi.cgiar.org [Accessed 26 July 2017].

Jorquera, C.O., *et al*., 2015. Regional hydrogeochemical mapping in Central Chile : natural and anthropogenic sources of elements and compounds. *Geochemistry: Exploration, Environment, Analysis*, 15, 72–96. doi:10.1144/geochem2013-220

Jorquera, O.C., 2013. *Geochemical baselines based on stream waters : applications to environmental studies, Central Chile as a case study*. London, UK: Imperial College London.

Li, S., *et al*., 2016. Extreme drought causes distinct water acidification and eutrophication in the Lower Lakes (Lakes Alexandrina and Albert), Australia. *Journal of Hydrology* Elsevier B.V., 544. doi:10.1016/j.jhydrol.2016.11.015

López-Moreno, J.I., *et al.*, 2013. Hydrological response to climate variability at different time scales: A study in the Ebro basin. *Journal of Hydrology*, 477, 175–188. doi:10.1016/j.jhydrol.2012.11.028

Lorenzo-Lacruz, J., *et al.*, 2010. The impact of droughts and water management on various hydrological systems in the headwaters of the Tagus River (central Spain). *Journal of Hydrology* Elsevier B.V., 386 (1–4), 13–26. doi:10.1016/j.jhydrol.2010.01.001.

Lorenzo-Lacruz, J., *et al.*, 2013a. Streamflow droughts in the Iberian Peninsula between 1945 and 2005: spatial and temporal patterns. *Hydrology and Earth System Sciences*, 17, 119–134. doi:10.5194/hessd-9-8063-2012

Lorenzo-Lacruz, J., *et al.*, 2013b. Hydrological drought response to meteorological drought in the Iberian Peninsula. *Climate Research*, 58 (2), 117–131. doi:10.3354/cr01177

Maestre-Valero, J.F. and Martínez-Alvarez, V., 2010. Effects of drip irrigation systems on the recovery of dissolved oxygen from hypoxic water. *Agricultural Water Management* Elsevier B.V., 97(11), 1806–1812. doi:10.1016/j.agwat.2010.06.018.

Magrin, G.O., *et al.*, 2014. Central and South America. *In*: V. Barros, *et al.*, ed. *Climate change 2014: impacts, adaptation, and vulnerability. Part B: regional Aspects. Contribution of working group II to the fifth assessment report of the intergovernmental panel on climate change*. Cambridge, Uk: Cambridge University Press, 1499–1566. doi:10.1017/CBO9781107415386.007

Masiokas, M.H., *et al.*, 2006. Snowpack variations in the Central Andes of Argentina and Chile, 1951 – 2005 : large-scale atmospheric influences and implications for water resources in the region. *Journal of Climate*, 19, 6334–6352. doi:10.1175/JCLI3969.1

Mckee, T.B., Doesken, N.J., and Kleist, J., 1993. The relationship of drought frequency and duration to time scales. *In*: *8th conference on applied climatology*. Anaheim, CA, 179–183.

Meza, F.J., *et al.*, 2012. Impacts of climate change on irrigated agriculture in the Maipo Basin, Chile : reliability of water rights and changes in the demand for irrigation. *Journal of Water Resources Planning and Management*, 138 (5), 421–430. doi:10.1061/(ASCE)WR.1943-5452

Ministerio de Agrícultura (MINAGRI) and Comisión Nacional de Riego (CNR), 2009. *Diagnóstico de las organizaciones de ususarios del agua de la región Metropolitana, Etapa I*. 273. Santiago, Chile: Ministerio de Agrícultura. Gobierno de Chile.

Ministerio de Obras Públicas (MOP), 2007. *Infraestructura para la competitividad 2007–2012 Sector Agrícola*. Santiago, Chile: Gobierno de Chile.

Mishra, A.K. and Singh, V.P., 2010. A review of drought concepts. *Journal of Hydrology* Elsevier B.V., 391(1–2), 202–216. doi:10.1016/j.jhydrol.2010.07.012.

Modarres, R., 2007. Streamflow drought time series forecasting. *Stochastic Environmental Research and Risk Assessment*, 21 (3), 223–233. doi:10.1007/s00477-006-0058-1

Momblanch, A., *et al.*, 2015. Managing water quality under drought conditions in the Llobregat River Basin. *Science of the Total Environment* Elsevier B.V., 503–504, 300–318. doi:10.1016/j.scitotenv.2014.06.069

Mosley, L.M., *et al.*, 2012. The impact of extreme low flows on the water quality of the lower Murray River and Lakes (South Australia). *Water Resources Management*, 26 (13), 3923–3946. doi:10.1007/s11269-012-0113-2

Mosley, L.M., *et al.*, 2014. Acidification of lake water due to drought. *Journal of Hydrology* Elsevier B.V., 511, 484–493. doi:10.1016/j.jhydrol.2014.02.001

Mosley, L.M., 2015. Drought impacts on the water quality of freshwater systems; review and integration. *Earth-Science Reviews*, 140, 203–214. doi:10.1016/j.earscirev.2014.11.010

Multsch, S., *et al.*, 2017. A practical planning software program for desalination in agriculture - SPARE:wATERopt. *Desalination* Elsevier B.V., 404, 121–131. doi:10.1016/j.desal.2016.11.012

Nalbantis, I. and Tsakiris, G., 2009. Assessment of hydrological drought revisited. *Water Resources Management*, 23 (5), 881–897. doi:10.1007/s11269-008-9305-1

Nosrati, K., 2011. The effects of hydrological drought on water quality. *In*: *Water quality: current trends and expected climate change impacts (Proceedings of symposium)*, Melbourne, Australia, 4.

Núñez, J., Hallack-Alegría, M., and Cadena, M., 2016. Resolving regional frequency analysis of precipitation at large and complex scales using a bottom-up approach: the Latin America and the Caribbean Drought Atlas. *Journal of Hydrology*, 538, 515–538. doi:10.1016/j.jhydrol.2016.04.025

Núñez, J.H., *et al.*, 2011. Regional frequency analysis for mapping drought events in north-central Chile. *Journal of Hydrology*, 405 (3–4), 352–366. doi:10.1016/j.jhydrol.2011.05.035

Oertel, M., *et al.*, 2018. Drought propagation in semi-arid river basins in Latin America: lessons from Mexico to the Southern Cone. *Water*, 10, 11. doi:10.3390/w10111564

Oyarzun, R., *et al.*, 2006. The As-contaminated Elqui river Basin: A long lasting perspective (1975–1995) covering the initiation and development of Au-Cu-As mining in the high Andes of northern Chile. *Environmental Geochemistry and Health*, 28 (5), 431–443. doi:10.1007/s10653-006-9045-1

Palmer, T.A. and Montagna, P.A., 2015. Impacts of droughts and low flows on estuarine water quality and benthic fauna. *Hydrobiologia*, 753 (1), 111–129. doi:10.1007/s10750-015-2200-x

Pizarro, J., *et al.*, 2010. Heavy metals in northern Chilean rivers: spatial variation and temporal trends. *Journal of Hazardous Materials* Elsevier B.V., 181 (1–3), 747–754. doi:10.1016/j.jhazmat.2010.05.076.

Prathumratana, L., Sthiannopkao, S., and Kim, K.W., 2008. The relationship of climatic and hydrological parameters to surface water quality in the lower Mekong River. *Environment International*, 34 (6), 860–866. doi:10.1016/j.envint.2007.10.011

R Core Team, 2014. *R: A language and environment for statistical computing*. Vienna, Austria: R Foundation for Statistical Computing.

Rangecroft, S., *et al.*, 2016. Multi-method assessment of reservoir effects on hydrological droughts in an arid region. *Earth System Dynamics*, 1–32. doi:10.5194/esd-2016-57

República de Chile, 1981. *Código de aguas*. Santiago, Chile: Ministerio de Justicia. Gobierno de Chile.

Rosegrant, M.W., *et al.*, 2000. Integrated economic-hydrologic water modeling at the basin scale : the Maipo river basin. *Agricultural Economics*, 24 (1), 33–46. doi: PII: S0169-S150(00)001 13-4.

Safavi, H.R. and Malek Ahmadi, K., 2015. Prediction and assessment of drought effects on surface water quality using artificial neural networks: case study of Zayandehrud River, Iran. *Journal of Environmental Health Science and Engineering*, 13 (1), 68. doi:10.1186/s40201-015-0227-6

Sagasta, J.M. and Burke, J., 2005. *Agriculture and water quality interactions: a global overview*. Rome, Italy: Food and Agriculture Organization of the United Nations (FAO).

Senhorst, H.A.J. and Zwolsman, J.J.G., 2005. Climate change and effects on water quality a first impression. *Water Science and Technology*, 51 (5), 53–59. doi:10.2166/wst.2005.0107

Shukla, S. and Wood, A.W., 2008. Use of a standardized runoff index for characterizing hydrologic drought. *Geophysical Research Letters*, 35, 1–7. doi:10.1029/2007GL032487

Stagge, J.H., *et al.*, 2015. Candidate distributions for climatological drought indices (SPI and SPEI). *International Journal of Climatology*, 35 (13), 4027–4040. doi:10.1002/joc.4267

Svensson, C., Hannaford, J., and Prosdocimi, I., 2017. Statistical distributions for monthly aggregations of precipitation and streamflow in drought indicator applications. *Water Resources Research*, 52 (2), 999–1018. doi:10.1002/2016WR019276.Received

Tallaksen, L.M. and van Lanen, H.A.J., 2004. Hydrological drought - Processes and estimation methods for streamflow and groundwater. *In*: L.M. Tallaksen and H.A.J. van Lanen, eds.. *Developments in water sciences*. 48th ed. Amsterdam: Elsevier B.V., 4.

Tallaksen, L.M., Madsen, H., and Clausen, B., 1997. On the definition and modelling of streamflow drought duration and deficit volume. *Hydrological Sciences Journal*, 42 (1), 15–33. doi:10.1080/02626669709492003

Tilman, D., *et al*., 2011. Global food demand and the sustainable intensification of agriculture. *Proceedings of the National Academy of Sciences*, 108 (50), 20260–20264. doi:10.1073/pnas.1116437108

Van Loon, A. *et al*. 2010. Understanding hydrological winter drought in Europe. *In*: *Global change: facing risks and threats to water resources (Proceedings of the sixth world friend conference)*. Fez, Morocco, 189–197.

Van Loon, A.F., 2015. Hydrological drought explained. *Wiley Interdisciplinary Reviews: Water*, 2 (4), 359–392. doi:10.1002/wat2.1085

Van Loon, A.F. and Laaha, G., 2015. Hydrological drought severity explained by climate and catchment characteristics. *Journal of Hydrology* Elsevier B.V., 526, 3–14. doi:10.1016/j.jhydrol.2014.10.059

Van Vliet, M.T.H. and Zwolsman, J.J.G., 2008. Impact of summer droughts on the water quality of the Meuse river. *Journal of Hydrology*, 353 (1–2), 1–17. doi:10.1016/j.jhydrol.2008.01.001

Verweij, W., *et al*., 2010. *Impact of climate change on water quality in the Netherlands*. Bilthoven: National Institute for Public Health and the Environment, 1–63 .

Vicente-Serrano, S. and López-Moreno, J.I., 2005. Hydrological response to different time scales of climatological drought: an evaluation of the standardized precipitation index in a mountainous mediterranean basin. *Hydrology and Earth System Sciences Discussions*, 9 (5), 523–533. doi:10.5194/hessd-2-1221-2005

Vicente-Serrano, S.M., *et al*., 2012. Accurate Computation of a Streamflow Drought Index. *Journal of Hydrologic Engineering*, 17 (2), 318–332. doi:10.1061/(asce)he.1943-5584.0000433

Vicente-Serrano, S.M., *et al*., 2017. Extreme hydrological events and the influence of reservoirs in a highly regulated river basin of northeastern Spain. *Journal of Hydrology: Regional Studies*, 12, 13–32. doi:10.1016/j.ejrh.2017.01.004

Wang, X., *et al*., 2016. Adaptation to climate change impacts on water demand. *Mitigation and Adaptation Strategies for Global Change*, 21 (1), 81–99. doi:10.1007/s11027-014-9571-6

Yeh, C.-F., *et al*., 2015. SDI and Markov chains for regional drought characteristics. *Sustainability*, 7 (8), 10789–10808. doi:10.3390/su70810789

Yevjevich, V., 1967. *An objective approach to definition and investigations of continental hydrologic droughts*. Hydrology papers. Fort Collins, CO: Colorado State University.

Zambrano-Bigiarini, M., *et al*., 2017. Temporal and spatial evaluation of satellite- based rainfall estimates across the complex topographical and climatic gradients of Chile. *Hydrology and Earth System Sciences*, 21 (March), 1295–1320. doi:10.5194/hess-21-1295-2017

Zelenhasić, E. and Salvai, A., 1987. A method of streamflow drought analysis. *Water Resources Research*, 23 (1). doi:10.1029/WR023i001p00156

Zhao, D., *et al*., 2013. Effects of pH in irrigation water on plant growth and flower quality in herbaceous peony (Paeonia lactiflora Pall.). *Scientia Horticulturae* Elsevier B.V., 154, 45–53. doi:10.1016/j.scienta.2013.02.023

Zwolsman, J.J.G. and van Bokhoven, A.J., 2007. Impact of summer droughts on water quality of the Rhine River – a preview of climate change? *Water Science and Technology*, 56 (4), 45–55. doi:10.2166/wst.2007.535