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Evaluation of the Impact of Climate Change in Drought Events

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Abstract: Climate Change has started to affect water resources in many ways, and it is necessary to consider the effect in future hydraulic designs. This study analyzes the consequences in four Chilean sub-basins using meteorological indexes (Standardized Precipitation Index and Palmer Drought Severity Index) and a hydrological index (Low-Flow Index) based on meteorological data from four different Global Circulation Models that force WEAP hydrological model. The results of these indexes show a sustained increase of drought events and a decrease of big precipitation events in all four basins. Particularly, assuming a stationary scenario (given by data on base line period 1975-2005) for the basin “Laja Lake” results predict that, by the end of the 21st Century, severe and extreme drought events will increase in a 10% and 20%, respectively, while, in a non-stationary scenario (given by global circulation models projected data) increases of 10% and 4% for these kind of events in the same basin are projected. Using the hydrological index, the basin “Volcan en Queltehues” is the most impacted with a large increase in average and maximum amount of days considered as drought. In this case, results indicate periods higher than 500 and 130 dry days for far future in stationary and non-stationary scenarios, respectively.

Key words: impact, climate change, drought

1. Introduction

Hydraulic engineers use models based on historical data to predict future events so their consequences can be minimized or mitigated by taking this into account for structure designs and planning towards the efficient usage of water resources. Such designs assume that climate is stationary within the period when the data was collected and that its behavior will not change in the future. However, through last years a raise in the amount of natural disasters such as droughts, storms and hurricanes, has occurred. According to the International Disasters Database, in the last 15 years, there was an increase of 22% of the amount of natural disasters, compared to the 15 years before [1]. Also, a recent study [2] shows that, around a 70% of these events were due to Climate Change (CC). Climate change is defined as a statistically significant variation in the mean state of the climate or its variability, and that persists for an extended period, typically decades or longer.

In Chile, even though this topic has been studied for a while, there is no systematic evaluation of the increases of the frequency or severity of dry events. In this area, the most interesting approaches are the analysis of the effects of CC in three different basins in Chile [3], a study of the droughts in Cautin river’s basin [4], the consequences of CC on hydropower plants in Cachapoal [5], and the decrease of precipitations between Aconcagua and Biobío rivers after 1970 [6].

Therefore, given the importance of designing structures or contingency measures for this kind of events, this study analyzes, using simple indexes, the impact of CC on the frequency of hydrological and meteorological droughts. This is evaluated in four watersheds from Coquimbo Region (latitude: -71.0;

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longitude: -30.75) to Biobío Region (latitude: -72.5; longitude: -37.0) in Chile.

For achieving this goal, a variety of indexes can be used. We selected the Standardized Precipitation Index or IPE [7] and, the Palmer Drought Severity Index or PDSI [8] as meteorological indexes and the Low-Flow index [9] considered as hydrological index. As a future scenario the RCP[1] 8.5 which supposes that by the year 2100, the radiative forcing will increase by 8.5 W/m^2. Radiation and daily average flow data was taken from a previous study in the Biobio, Maule, and Maipo river's basins [3] using data from four different global circulation models (GCM): BCC-CSM1.1, CMCC-CMS, CSIRO-Mk3.6.0 and MPI-ESM-LR. In addition, we present here an analysis of meteorological indexes on Limari river's basin using future data from MRI-CGCM3 GCM [10].

In synthesis, this study aims to assess the evolution of hydrological dry events in natural regimes (i.e., not considering extractions of any kind) and meteorological droughts, both in Climate Change's RCP8.5 scenario.

2. Climate Change Review

IPCC's 2013 report group different GCMs according to greenhouse gases concentrations in near and distant future. Considering this, the models can be related to the final effect on annual average temperatures, which, on a global scale, it can be obtained for each period, for each scenario, as shown in Table 1.

Table 1 Scenarios of Climate Change and their consequences on a global scale.

Period	2046-2065		2081-2100	
Scenario	Annual average temperature variation	Most probable range	Annual average temperature variation	Most probable range
RCP2,6	1.0°C	[0.4;1.6]°C	1.0°C	[0.3;1.7]°C
RCP4,5	1.4°C	[0.9;2.0]°C	1.8°C	[1.1;2.6]°C
RCP6,0	1.3°C	[0.8;1.8]°C	2.2°C	[1.4;3.1]°C
RCP8,5	2.0°C	[1.4;2.6]°C	3.7°C	[2.6;4.8]°C

Source: IPCC (2013)

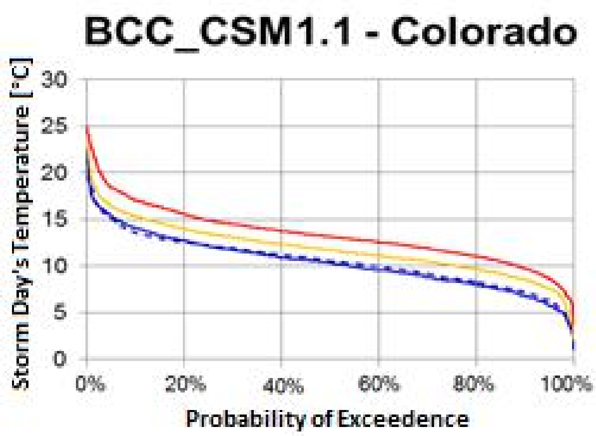
In central Chile, most GCMs show an increase in daily average temperatures during precipitation days as show in Fig. 1.

Also, some studies show that annual precipitation [11-13] have a downward trend in RCP8.5 scenario, although, maximum daily values tend to increase [11].

Because of all the above, hydrological models show that daily, monthly, and annual average flows also decrease. This can be appreciated in Fig. 2 where evolution of the seasonal variation flow, for the period 2041-2070, in the upper basin of Cachapoal river using MK3.6 in RCP4.5 scenario is presented [5].

3. Studied Zone and Avaliable Information

The present study, based on the data presented by Lagos et al. (2015) [3] and Seelmann (2017) [10], analyses four sub-basins. Each one in a different drainage basin. As shown in Fig. 3, these are in Biobio, Maule, Maipo and Limari river's basins. Table 2 shows



[1] Representative Concentration Pathways.

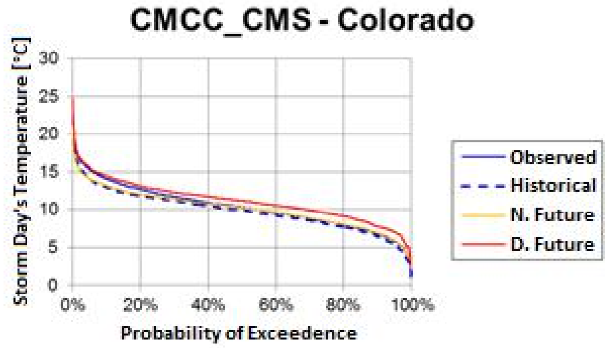


Fig. 1 Daily average temperature projections during storm days in Colorado's station [3].

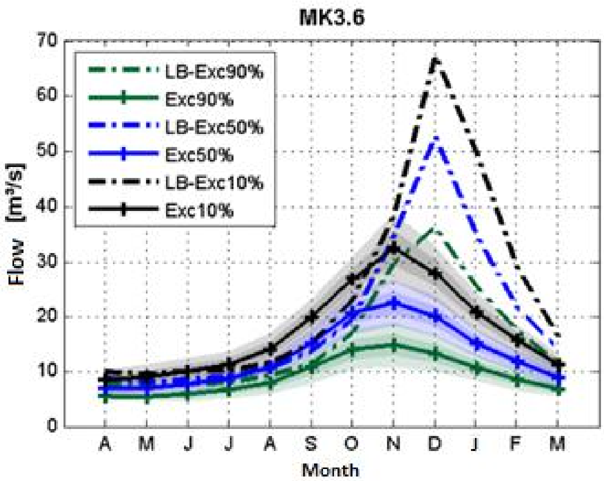


Fig. 2 Seasonal variation flow in the upper basin of Cachapoal river for period 2041-2070. LB: Base line from 1971 to 2009 [5].

the characteristics of every station used in these studies.

Given the fact that most of the meteorological and hydrological data used for this study comes from a previous downscaling done by Lagos et al. (2015) [3], relevant details of these statistics are shown below. In general, raises in annual average temperatures can be noted in all basins (Fig. 4) and a decrease in annual precipitation (Fig. 5) which would be the main reason why there is also a downward trend in annual average flows.

In Limari river's basin, the information used comes from the generated by Seelmann (2017) [10] who used MRI-CGCM3 model. Fig. 6 displays the precipitation and temperature trends for "Pichasca" and "Caren" stations, respectively. In these, it is remarkable the fact that, in opposition from the rest of the basins, the amount of annual precipitation increases almost 17% to the end of the 21st century.

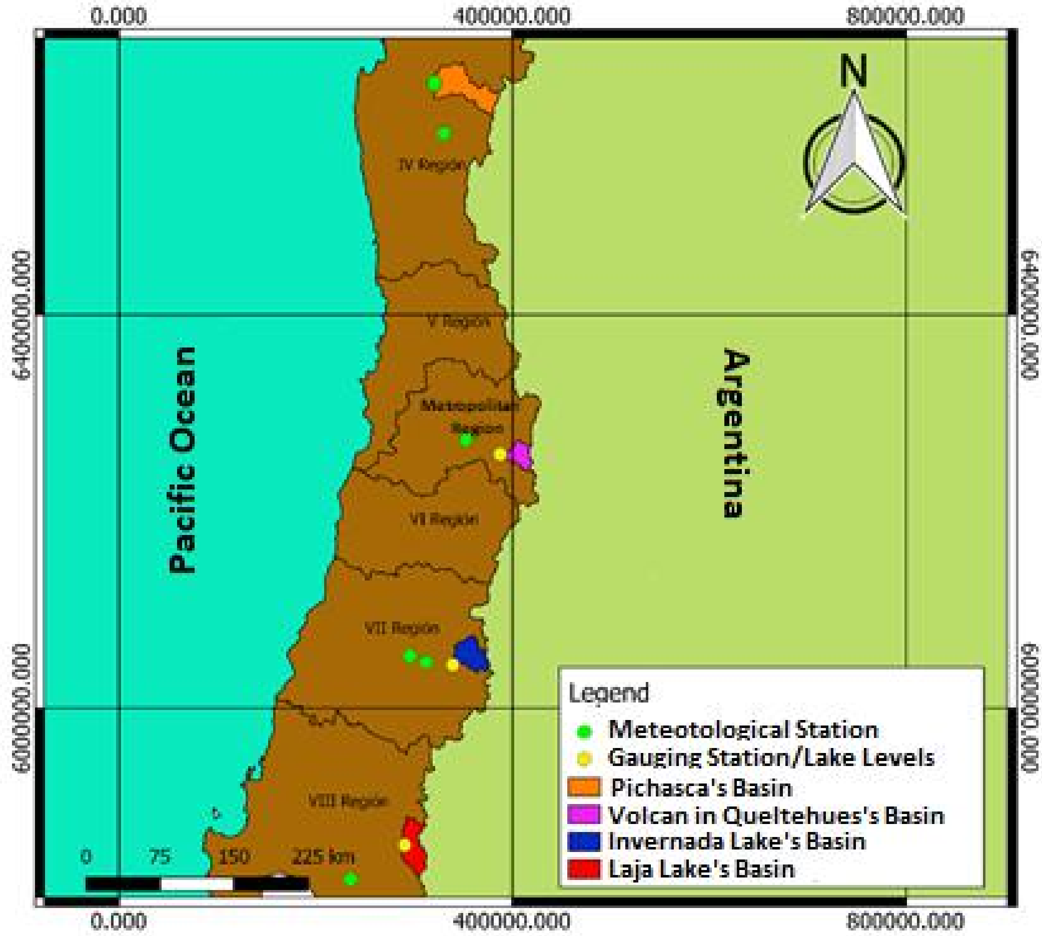


Fig. 3 Location of the studied zones.

Table 2 Characteristics of the stations used in this study.

Basin	Sub-Basin	Station	Type	Lat. [°]	Lon. [°]	Alt. [m.a.s.l]
Biobio River	Laja Lake	Quilaco	Met.	-37.68	-71.99	225
		Laguna de la Laja	Lake Levels	-37.37	-71.37	1330
Maule River	Invernada Lake	Armerillo	Met.	-35.70	-71.07	492
		Colorado	Met.	-35.64	-71.26	420
		Laguna de la Invernada	Lake Levels	-35.73	-70.78	1317
Maipo River	Volcan River in Queltehues	“Pirque”	Met.	-33.68	-70.59	659
		Rio Volcán antes junta Río Maipo	Gauging station	-33.81	-70.21	1302
Limarí River	Pichasca	Pichasca	Met.	-30.40	-70.87	725
		Carén	Met.	-30.86	-70.77	740

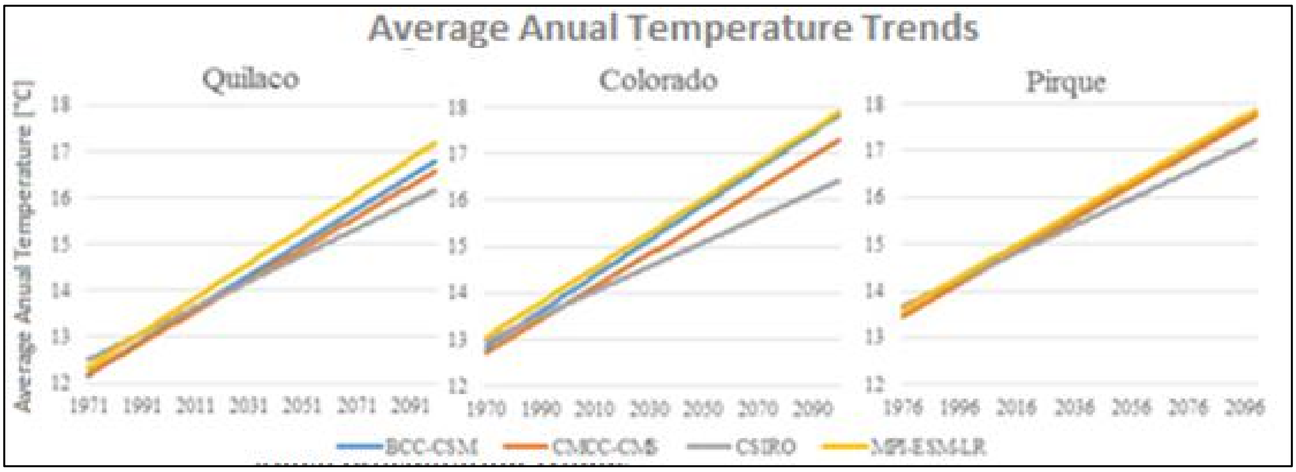


Fig. 4 Trends in annual average temperatures in "Quilaco", "Colorado", and "Pirque" stations using different models in RCP8.5 scenario [3].

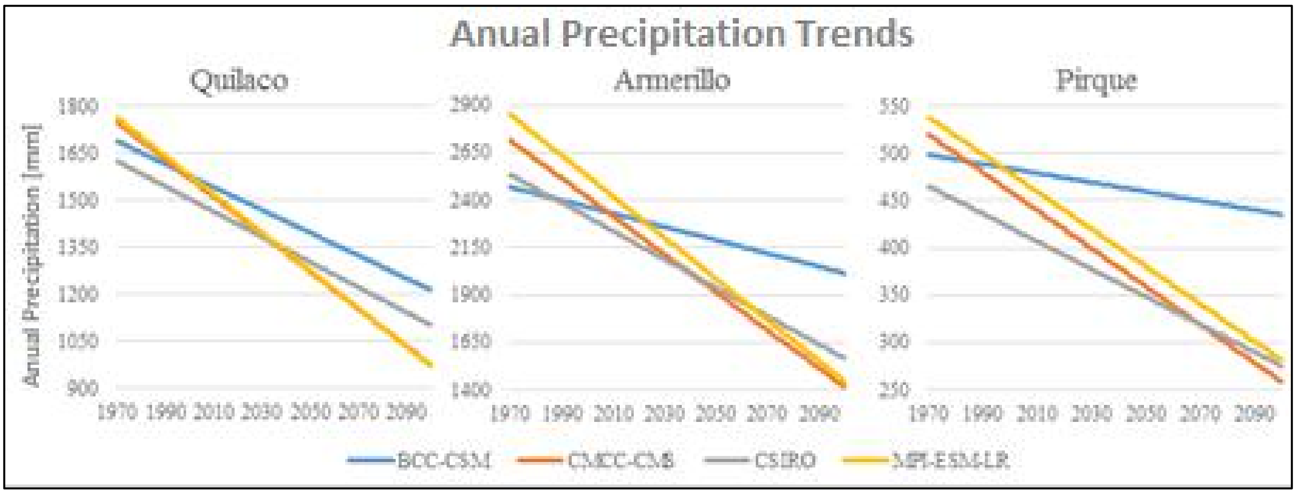


Fig. 5 Trends of annual precipitations in "Quilaco", "Armerillo", and "Pirque" using different GCMs in RCP8.5 scenario [3].

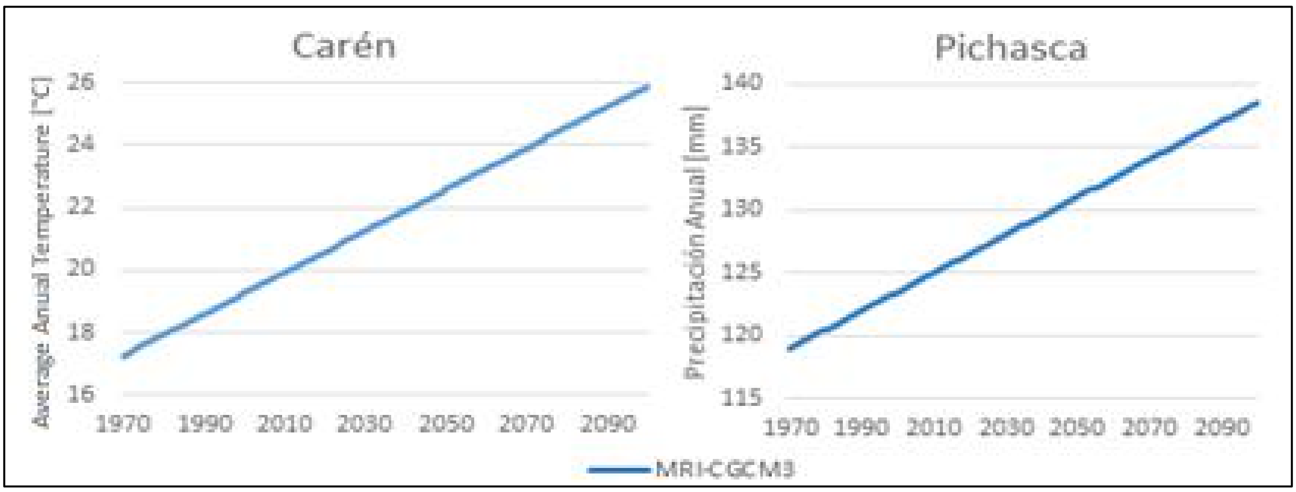


Fig. 6 Annual average temperature and annual precipitation's trends in "Caren" and "Pichasca" in a RCP8.5 scenario [10].

4. Methodology

In this study, there are two kinds of dry events analyzed: meteorological and hydrological. The first one is a downward deviation from the average amount of precipitation in the same period or, the lack of humidity in places where there is not a watercourse. On the contrary, the second term refers to those discharges that are lower than the average in the studied lapse.

It is very important to mention that every index is calculated in two different situations. The first one is called stationary scenario, where all the statistics or zone factors, of each index, are calculated using only the historical data (1970-2005). This changes in the second state, the non-stationary scenario, where these factors are updated with the modeled data.

4.1 Meteorological Events

The first of the used indexes is the Standardized Precipitation Index, SPI [7], which normalizes events (Eq. (1)) so they can be compared and classified according to the groups and values in Table 3.

$$\mathrm{SPI_i} = \frac{\mathrm{Pp_i} - \overline{\mathrm{Pp}}_{\mathrm{hist}}}{\sigma_{\mathrm{hist}}} \quad (1)$$

Where:

$\mathrm{Pp_i}\left[\frac{\mathrm{mm}}{\mathrm{period}}\right]$: Precipitation in period "i".

Table 3 Classification according to the event's value.

Classification (Acronym)	Lower bound	Upper bound
Extremely Humid (E.H.)	2	$+\infty$
Severely Humid (S.H.)	1.5	1.99
Moderately Humid (M.H.)	1	1.49
Normal or Almost Normal (A.N.)	-0.99	0.99
Moderately Dry (M.D).	-1.49	-1
Severely Dry (S.D.)	-1.99	-1.5
Extremely Dry (E.D.)	$-\infty$	-2

$\overline{\mathrm{Pp}}_{\mathrm{hist}}\left[\frac{\mathrm{mm}}{\mathrm{period}}\right]$: Average precipitation in the chosen time interval.

$\sigma_{\mathrm{hist}}\left[\frac{\mathrm{mm}}{\mathrm{period}}\right]$: Standard deviation in the chosen time interval.

One of the consequences of the standardization of the data is that, according to this index, probability of an extreme drought is the same everywhere. Therefore, this index is limited to areas where is mostly wet, because, in the cases where there are low to non-existent precipitations, the results are considered not reliable [7].

The second index is the Palmer Drought Severity Index, PSDI [8], which includes, in its calculations for soil's available water, a lot of coefficients based on real and theoretical factors such as evaporation, overland flow, etc. Beside this, the PSDI also integrates the results of previous months. This is especially interesting because it shows the evolution of a certain event. The classification of the results of Eq. (2) is shown on Table 4.

$$\mathrm{X_i} = \frac{\mathrm{X_{i-1}} + \mathrm{Z_i}}{3 - 0.103 * \mathrm{X_{i-1}}} \quad (2)$$

Donde:

$\mathrm{X_i}[-]$: Value of the index in the month "i".

$\mathrm{Z_i}[-]$: Factor extracted from a series of formulas [10] for month "i".

4.2 Hydrological Events

To identify and quantify hydrological droughts, the index used in this study is called Low-Flow Index which states that a drought starts when a flow (in this case, average daily flow) is under the 95th threshold level (where, the flow duration curve, is based on the historical data for the 30 days around the studied day). So, this index states the following:

$$\mathrm{Q}(\mathrm{t}=\mathrm{i}) \leq \mathrm{Q}^{\mathrm{i}}_{95\%} \quad => \quad \textit{Drought initiates} \quad (3)$$
$$\mathrm{Q}(\mathrm{t}=\mathrm{i}) > \mathrm{Q}^{\mathrm{i}}_{95\%} \quad => \quad \textit{Drought ends}$$

Because of this, it is possible to calculate the amount of days that a drought lasts and the average and maximum duration of dry events.

5. Results

Applying the methods described above, the SPI is calculated for an annual interval. In the left side of the Fig. 7, the results are shown for a stationary scenario and, on the right side, for the non-stationary. It is important to consider that this graphics do not show the

Tabla 4 Denominación por valor en el PDSI.

Value	Denomination	Value	Denomination
≥ 4.00	Extremely Humid (E.H.)	0.49 to -0.49	Almost Normal (A.N.)
3.00-3.99	Very Humid (V.H.)	-0.50 to -0.99	Incipient Drought (I.D.)
2.00-2.99	Moderately Humid (M.H.)	-1.00 to -1.99	Slightly Dry (S.D.)
1.00-1.99	Slightly Humid (S.H.)	-2.00 to -2.99	Moderately Dry (M.D.)
0.50-0.99	Incipient Humid Period (I.H.)	-3.00 to -3.99	Severely Dry (S.D.)
		≤ -4.00	Extremely Dry (E.D.)

"normal events" so the variations among the other events can be noticed. Beside this, the percentage shows an average of the results of the four GCMs for each event, scenario and period. This must be considered, also, for Fig. 8, where the results for PDSI in stationary (left side) and non-stationary (right side) are exposed. In both cases, SPI and PDSI, results are separated between historical period (1970-2005), near future (2006-2050) and distant future (2050-2100).

The results clearly state a general downward tendency, in both meteorological indexes, of humid events and an upward tendency in dry events for all basins. In terms of scenarios, the trends are much more significant in the stationary situation. In addition, its relevant to state that the results for Pichasca are dismissed for been considered not reliable.

Finally, from a hydrological point of view, the results for the Low-Flow index for Laja Lake, Invernada Lake and Volcan River in Queltehues are shown visible in Tables 5-7.

These results expose a clear trend towards longer droughts and much more frequent in both scenarios, stationary and non-stationary. Although, between these scenarios, there is a big difference. For example, for the distant future, stationary situation shows an increase of 100% more than the non-stationary one.

6. Conclusions

SPI results show a clear trend towards dryness, with bigger raises in the stationary scenario. This is seen, not only in the number of events, but in the evolution of the frequency and the intensity of these. It is important to add, like it was said before, that this index is not reliable in places with low precipitations. Therefore, the results for "Pichasca" station are not considered in these conclusions.

On the other hand, PDSI, which includes a lot of variables besides precipitation, does not have a significant increase of droughts with very few events in "Pichasca" and "Invernada Lake" and almost non "Extreme Dry" events. However, the humid events, in

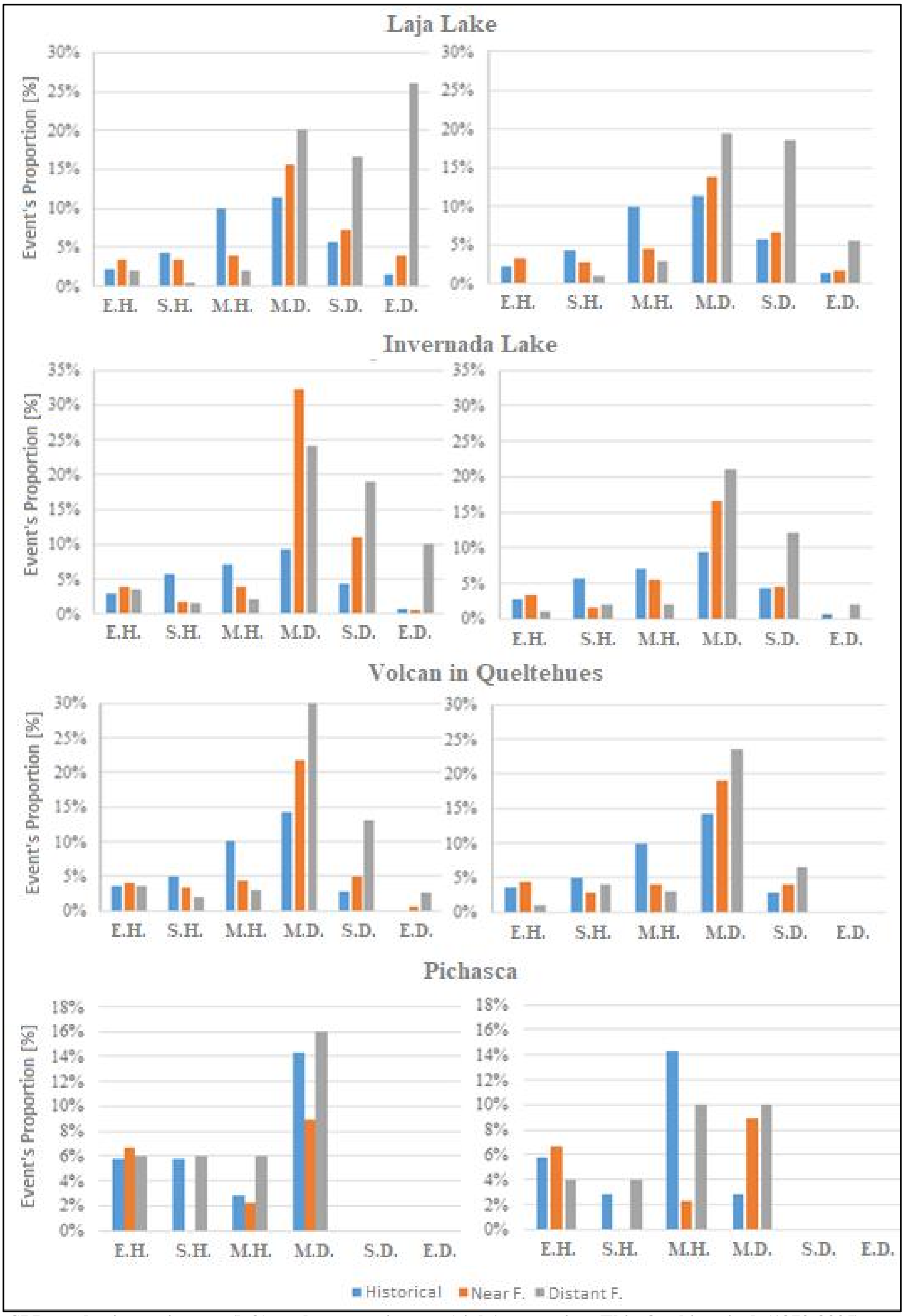


Fig. 7 SPI results in stationary (left) and non-stationary (right) scenarios. This for historical (1970-2005), near future (2006-2050), and distant future (2051-2100).

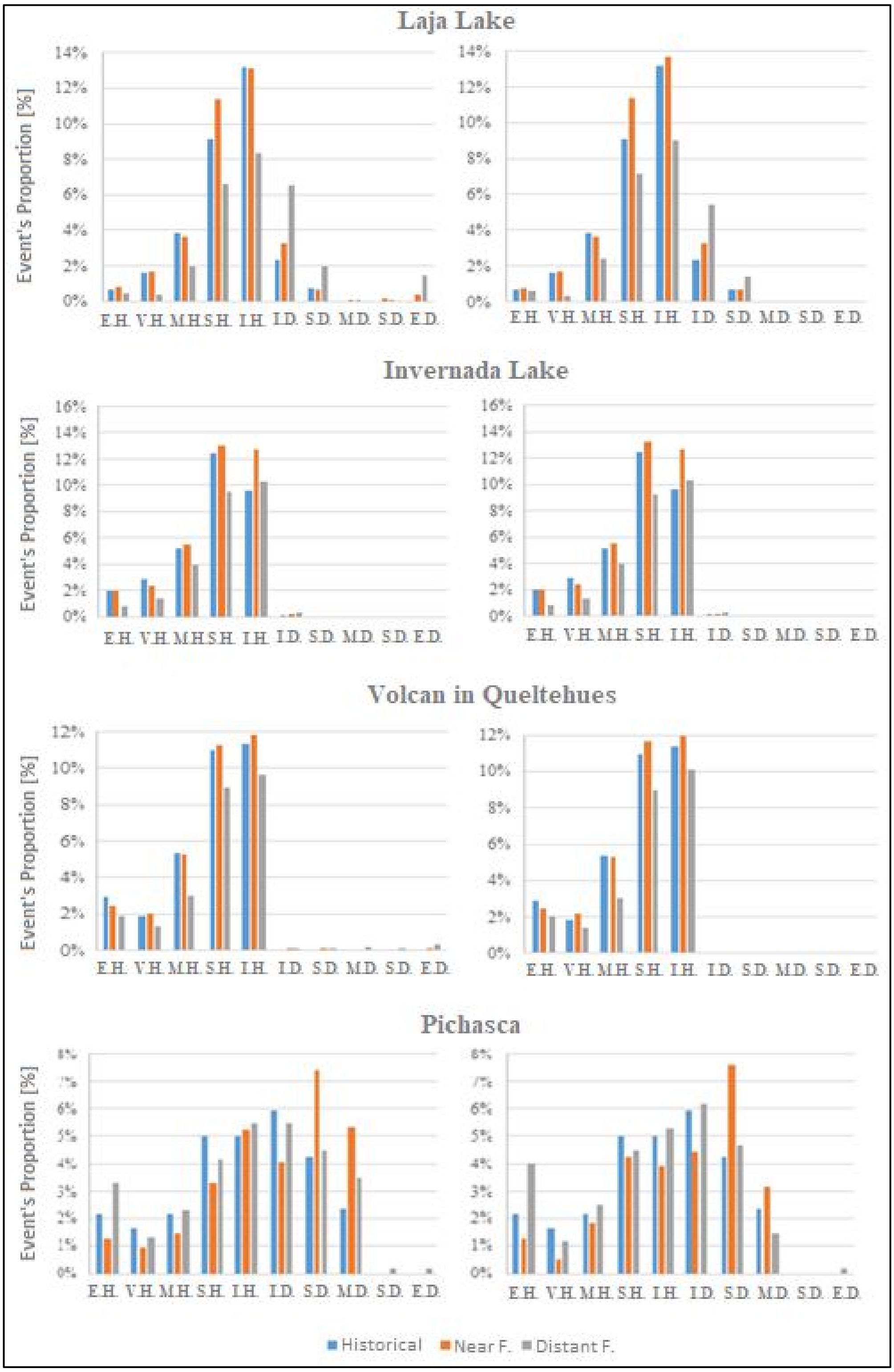


Fig. 8 PDSI results in stationary (left) and non-stationary (right) scenarios. This for historical (1970-2005), near future (2006-2050), and distant future (2051-2100).

Table 5 Low-Flow Index's results for Laja Lake.

Laja Lake	Stationary			Non-stationary		
	Historical	Near F.	Distant F.	Historical	Near F.	Distant F.
Drought Duration [days]	565.5	1705.3	2457.8	565.5	969.0	1017.5
Drought Duration [%]	4.3%	10.4%	26.9%	4.3%	5.9%	11.2%
Average Duration [days]	8.3	14.0	20.4	8.3	10.6	13.1
Maximum Duration [days]	65.5	162.8	179.8	65.5	125.5	91.0

Table 6 Low-Flow Index's results for Invernada Lake.

Invernada Lake	Stationary			Non-stationary		
	Historical	Near F.	Historical	Near F.	Historical	Near F.
Drought Duration [days]	570.5	1653.0	2912.3	570.5	798.0	1354.8
Drought Duration [%]	4.4%	10.1%	31.9%	4.4%	4.9%	14.8%
Average Duration [days]	13.4	23.3	40.1	13.4	14.3	23.8
Maximum Duration [days]	234.8	218.3	498.8	234.8	170.0	313.0

Table 7 Low-Flow Index results for Volcan river in Queltehues.

Volcan River in Queltehues	Stationary			Non-stationary		
	Historical	Near F.	Historical	Near F.	Historical	Near F.
Drought Duration [days]	719.5	3710.8	4083.8	719.5	1232.8	1261.5
Drought Duration [%]	5.5%	22.6%	44.8%	5.5%	7.5%	13.8%
Average Duration [days]	9.1	19.4	46.3	9.1	10.5	15.4
Maximum Duration [days]	78.0	198.8	504.3	78.0	89.8	138.0

general, tend to decrease towards the distant future. It is very interesting to notice that, in three of the four studied zones (Maipo, Maule, and Biobio), there are increases in these events towards the near future. This could be an effect of Climate Change on maximum precipitations, combined with a different distribution of temperatures around the year, considering that this index takes in account the latest month's value.

Finally, the hydrological index presented in this study shows very consistent results between the different sub-basins, where the trend is clear towards a raise in the quantity of days considered as drought and the duration of these, as much in the average as in the maximum cases. In this index, the most interesting analysis comes from comparing the stationary and non-stationary scenarios. For example, in the three studied sub-basins, the percentage of drought days is doubled in the stationary situation (and quadruple in Volcan River) from historical to near future. On the contrary, in the non-stationary scenario, the values between these two periods are very similar. However, the relations in variation are the same between near and distant future, for both scenarios. For instance, in Invernada Lake, the percentage of drought days for near future in a stationary situation is 10.1% to raise to 31.9% for distant future. In the non-stationary, this increases from a 4.9% to a 14.9%. Just like in the stationary scenario, the percentage is tripled. This states that the raise in drought days is bigger between near and distant future than from historical to near future.

In general, the driest meteorological results are found in the most southern basin, Laja Lake. In hydrological terms, Volcan river is the most affected one among the three studied.

References

[1] D. Guha-sapir, P. Hoyois and R. Below, Annual disaster statistical review 2013: The numbers and trends, *Review Literature and Arts of the Americas* (2014) 1-50, http://doi.org/10.1093/rof/rfs003.

[2] S. Herring, M. Hoerling, T. Peterson and P. Stott, Explaining extreme events of 2013 events of 2013,

Bulletin of the American Meteorological Society 95 (2014) (9) 1-96.

[3] M. Lagos, M. P. Bobadilla, X. Vargas, J. Cepeda, V. Silva, F. Uribe and N. Vásquez, *Proyecciones de Crecidas de cuencas andinas bajo distintos modelos de circulación general. XXII Congreso Chileno de Ingeniería Hidráulica*, Sociedad Chilena de Ingeniería Hidráulica, Santiago, Chile, 2015.

[4] J. C. Richard, Respuesta hidrológica del río Cautín en la IX Región de La Araucanía, Chile, ante escenarios de cambio global. Memoria para optar al título de ingeniero civil, Universidad de Chile, 2014, available online at: http://repositorio.uchile.cl/handle/2250/117073.

[5] T. Gómez, Análisis del Impacto del cambio climático en la generación hidroeléctrica de centrales de la cuenca del Alto Cachapoal, Memoria para optar al título de ingeniero civil, Universidad de Chile, 2013).

[6] J. P. Boisier, R. Rondanelli, R. D. Garreaud and F. Muñoz, Anthropogenic and natural contributions to the Southeast Pacific precipitation decline and recent megadrought in central Chile, *Geophys. Res. Lett.* 43 (2016) 413-421, doi: 10.1002/2015GL067265.

[7] Organización Meteorológica Mundial, Indice Normalizado de Precipitación, Guía del Usuario, OMM-N°1090, 2012.

[8] W. M. Alley, The palmer drought severity index: Limitations and assumptions, *Journal of Climate and Applied Meteorology* 23 (1984) (7): 1100-1109, doi: http://doi.org/10.1175/1520-0450(1984)023<1100:TPDSIL>2.0.CO;2.

[9] C. Cammalleri, J. Vogt and P. Salamon, Development of an operational low-flow index for hydrological drought monitoring over Europe, *Hydrological Sciences Journal* (2016), doi: 10.1080/02626667.2016.1240869.

[10] D. Seelmann, Evaluación del impacto del cambio climático en eventos extremos. Análisis de riesgo de sequías e inundaciones usando métodos simples. Memoria para optar al título de ingeniero civil, Universidad de Chile, 2017.

[11] M. Díaz, Modelación de hidrogramas de crecidas usando proyecciones de precipitaciones diris del modelo climático MK3.6. Aplicación en la cuenca Butamalal en Butamalal, VIII Región, Chile. Memoria para optar al título de ingeniero civil, Universidad de Chile, 2015.

[12] V. Silva, Impacto de las proyecciones meteorológicas del modelo de circulación global MK en los recursos hídricos de cuencas pluviales de la región del Bío-Bío para mediados del siglo XXI. Memoria para optar al título de ingeniero civil, Universidad de Chile, 2015.

[13] X. Vargas, T. Gómez, F. Ahumada, E. Rubio, M. Cartes and M. Gibbs, Water availability in a mountainous Andean watershed under CMIP5 climate change scenarios, *Cold and Mountain Region Hydrological Systems Under Climate Change: Towards Improved Projections Proceedings of H02*, IAHS-IAPSO-IASPEI Assembly, Gothenburg, Sweden, IAHS Publ. 360, 2013, 2013.