Multi-parameter study of Aculeo lagoon (Chile)

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Keywords: Climate Change, Land Use, Chile, ENSO

Abstract:

The Aculeo Lagoon, located in the Santiago Metropolitan Region, was one of the main water reservoirs of central Chile. It has experienced a decline in water levels since 2009 and completely dried up in 2018. It was unable to recover until 2023 due to sustained demand for water resources associated with population growth, changes in land use, and years of drought. The objective of this study is to estimate how anthropogenic factors and climate change have influenced the drying of the lagoon. Parameters considered include population growth, housing increases, changes in land use within the Aculeo basin, local temperature and precipitation variations, and global El Niño Southern Oscillation (ENSO) phenomena. Input data included multi-year Landsat images, census data, and a systematic review of the literature on the study area. Furthermore, applying geospatial data analysis techniques such as satellite image processing, supervised classification of land cover/use, and calculation of spectral indices, it is possible to conclude that the Aculeo Lagoon dried out due to a significant precipitation deficit over nearly a decade, exacerbated by the overexploitation of land for agricultural activities.

1. Introduction

Water is a fundamental element for the development and prosperity of ecosystems and life on Earth. It covers more than 70% of the planet's surface, with the highest concentration found in the oceans, accounting for 97.5% of the world's water, though not suitable for human consumption. Only 2.5% is fresh water, of which merely 1% is accessible surface water. This limited freshwater is primarily found in lakes (52%) and wetlands (38%) (Fernández, 2012).

Chile is blessed with diverse water resources due to its geographical location (Matus et al., 2004). However, these resources have been threatened by droughts, including the mega drought from 2010 to 2020, spanning the Coquimbo to La Araucanía regions. According to the World Meteorological Organization (WMO) in 2016, droughts have been recognized as a significant climate hazard and one of the costliest natural risks annually.

Droughts in Chile occur periodically, linked to the El Niño Southern Oscillation (El Niño and La Niña), significantly impacting dryland areas and the country's agricultural production areas (Henson, 2023). Chile has been identified as vulnerable to global climate change, with projections indicating increased aridity in the north, desert expansion southward, and reduced water availability in the central zone by 2040 (Meza et al., 2010). Agriculture dominates land use, focusing on intensive annual crops like winter wheat, corn, and summer grains. Recent years have seen an expansion of water-intensive crops such as citrus fruits and avocados, alongside kiwis, cherries, plums, and grapes (CED, 2008).

The growth in Chile's population has led to urban sprawl, converting rural areas into urban zones. This urbanization trend extends to previously agricultural lands, exemplified by residential developments and condominiums cropping up on hillsides and plains, and near major cities (Soto, 2019). A notable case is the Aculeo basin in the commune of Paine, a significant tourist destination in the Santiago Metropolitan Region due to the Aculeo Lagoon.

Located in the Santiago Metropolitan Region, the Aculeo Lagoon was one of central Chile's main water reservoirs. Alongside the Maipo River, it served as a crucial water source for the commune of Paine (see Figure 1).

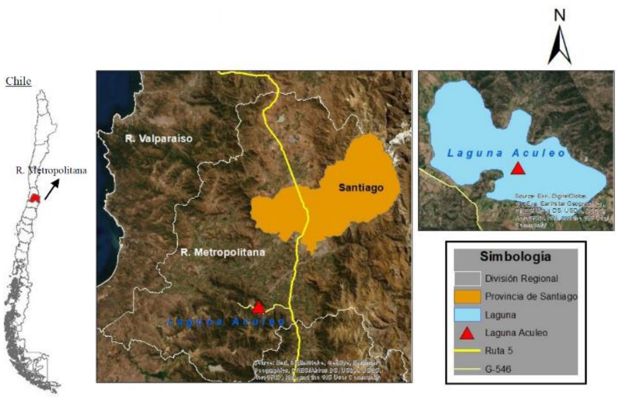

Figure 1. Location map of Aculeo Lagoon

The Aculeo Lagoon gained national and international attention when it completely dried up in mid-2018 (Figure 2). Numerous investigations, including postgraduate and undergraduate projects, have attempted to pinpoint the cause of this phenomenon and its socioeconomic and environmental impacts. Studies on the Aculeo Lagoon have yielded varied conclusions, with some attributing its disappearance to anthropogenic factors such as land use change and resource overexploitation (Boisier, 2016; Alaniz, 2019; Rivas, 2019), while others focus on climatic variables such as average temperatures and annual rainfall (Barria, 2021), and crop evapotranspiration (Cuevas, 2021).

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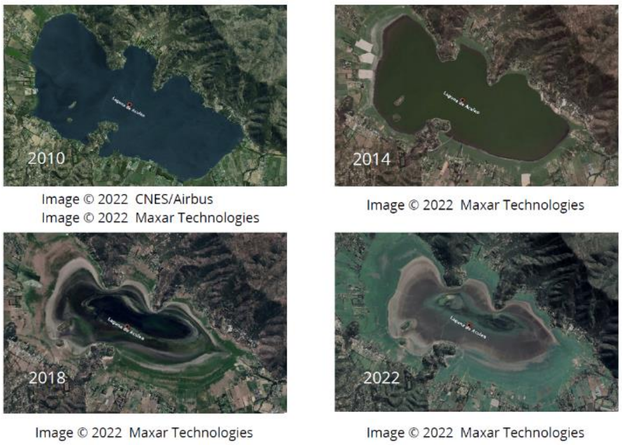

Figure 2 - Aculeo lagoon seen from space

(Valdés-Pineda et al., 2020) concluded that the water imbalance was caused by a combination of three fundamental factors: (1) the increased demand for groundwater in the areas surrounding the lagoon, which remained at 450-500 liters per second (l/s) during the three simulation periods considered in their studies between 2006 and 2018, (2) the drying of natural and artificial tributaries that fed the lagoon, contributing a combined total of at least 300-400 l/s to the body of water, and (3) the decrease in average rainfall during years of climatic "mega-drought". Subsequently, (Venegas-Quiñones, 2020) agreed that while environmental factors did affect lagoon water levels, the primary cause was anthropogenic factors.

According to Soto (2019), "most of the pleasant plots are for people who come from Santiago to spend the weekend or on vacation; they do not always live here, and very few do," referring to the residential stability of Aculeo basin inhabitants, based on interviews conducted by the author in 2018. Additionally, Valencia (2018) conducted a study in the commune of Paine, focusing on two private residential areas within the basin—Bosques de Aculeo and Piedra Molina—located in Bahía Catalina. The study revealed a demographic polarity between permanent residents and transient populations. In Bosques de Aculeo, residents constitute 40%, while the transient population makes up 60%. Conversely, Piedra Molina shows 60% permanent residents and 40% transient population.

Nevertheless, no study has yet utilized geospatial analysis techniques to estimate how anthropogenic factors and climate change have influenced the drying of the lagoon. This study aims to fill that gap by considering parameters such as population growth, housing increases, land use changes in the Aculeo basin, local temperature and precipitation variations, and the global El Niño Southern Oscillation (ENSO) phenomena.

2. Data sources

As input data, multi-year Landsat images, starting in the early 1990s, were were sourced from the TM, ETM+, and OLI/TIRS sensors of the Landsat-5, Landsat-7, and Landsat-8 missions, respectively, along with precipitation and temperature data from nearby climate observation stations and census data (1992, 2002, and 2017) from the Chilean National Statistics Institute.

Monthly average precipitation and temperature data for the period 1989-2016 were obtained from the General Directorate of Water (DGA), part of the Ministry of Public Works (MOP). The LAGUNA ACULEO station was selected for this purpose. Initially, the plan was to interpolate rainfall and average temperatures using data from four meteorological stations in the Maipo province. However, only two stations had over thirty years of records, which is required for proper completion of the Standardized Precipitation Index (SPI). Moreover, the neighboring station with adequate records had missing data for some periods. Therefore, only the LAGUNA ACULEO station was used for meteorological data acquisition. Nevertheless, the ANGOSTURA station in Valdivia de Paine provided precipitation reports to implement a linear regression for filling in missing data in some years.

Data on maximum temperatures (°C), minimum temperatures (°C), solar radiation (W/m²), wind speed (m/s), and dew point temperature (°C) were obtained for the evapotranspiration analysis dates. These data were sourced for free from the Meteorological Directorate of Chile (DMC) website, part of the General Directorate of Civil Aeronautics (DGAC), for the EL PAICO station (national code 330113), located at 33°40'23" S, 71°00'29" W, at an altitude of 275 meters above sea level.

Population variations in rural peripheral areas are complex to model due to generally scarce existing information. Although the census surveys conducted by the National Institute of Statistics (INE) are precise, the temporal resolution of the data does not allow for high redundancy, resulting in impoverished information that directly affects the representation of real population variability in the Aculeo basin. The population growth of the basin was estimated using data from the INE censuses conducted in 1992, 2002, and 2017. While the census reports provide a detailed analysis of population behavior over time through projections, these are carried out over more extensive spatial coverage, generating results at a community level at minimum. This factor was considered in the study because there is no precise way to determine the exact population in the Aculeo basin for the study years.

3. Data processing

Satellite images were analyzed using various image processing techniques, including the Normalized Difference Water Index (NDWI), Normalized Difference Vegetation Index (NDVI), the Surface Energy Balance Algorithm for Land (SEBAL) (Bastiaanssen et al., 1998), and supervised Land Cover Land Use (LCLU) classification.

Climate variables such as precipitation and temperature were analyzed for their impact on water surface variation using the Pearson correlation coefficient.

Estimates of urban and rural area variations in the Aculeo basin were conducted through census data analysis. Additionally, a bibliographic investigation was performed on housing occupancy in the basin, considering documents such as the Urban Regulatory Plan 2015 for the Paine commune and the Metropolitan Regional Regulatory Plan 2006.

3.1 Satellite Imagery

For the present study, the modifyed Normalized Difference Water Index (NDWI) was used, utilizing the reflectance of visible green light ($\rho GREEN$) and near-infrared (ρNIR) bands, as shown in equation 1. In this equation, ρNIR and $\rho SWIR$ represent the reflectance in the near-infrared and far-infrared bands, respectively (McFeeters, 1996).

$$NDWI = \rho GREEN - \rho NIR / \rho GREEN + \rho NIR \quad (1)$$

This optimized relationship between bands allows for maximizing the reflectance of water. By using visible green wavelengths, the method minimizes the low near-infrared reflectance caused by water characteristics and takes advantage of the high NIR reflectance due to vegetation and soil characteristics (Xu, 2006).

To determine land use variability, classifications of satellite images for the study area were performed. Several image classification methods exist, but supervised and unsupervised classification techniques are commonly used to map land use and land cover (LULC) variations (Chuvieco, 1996). For this study, the maximum likelihood algorithm was employed for image classification, as it is highly preferred for generating LULC maps (Getu & Bhat, 2021). The cover and land use samples utilized for the study are detailed in Figure 3.

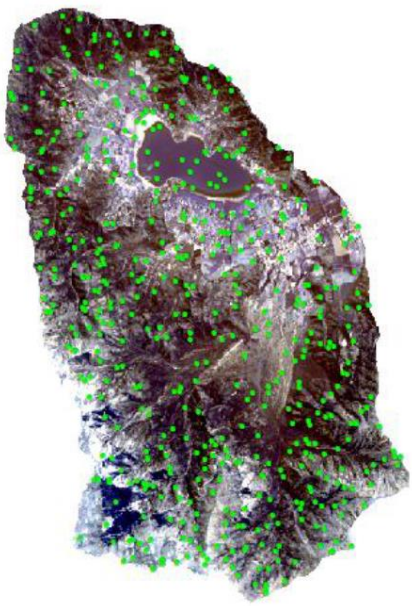

Figure 3. Samples for LULC

3.2 Climate data

To ensure a record of at least 30 years of rainfall data, linear regressions were used to fill in missing data for the years 1989, 1991, 1994, and 1999. The regression was conducted using data from the *ANGOSTURA EN VALDIVIA DE PAINE* weather station, located about 8.78 kilometers from the *LAGUNA ACULEO* weather station.

To perform this regression, records with missing data from January to December of a specific year were compared with data from the station with complete records for the same year. The data had to be correlated to apply the regression effectively, so a correlation coefficient R was used to verify the suitability of the selected station.

$$R = \Sigma(X-\bar{X})(Y-\bar{Y})/(n-1)\sigma X \sigma Y \quad (2)$$

3.3 Population

The estimation of urban and rural area variations in the Aculeo basin was conducted through the analysis of census information. Additionally, a bibliographic investigation was undertaken regarding housing occupancy in the basin, incorporating the following documents: the Regulatory Plan of the commune of Paine for the year 2015, the metropolitan regional regulatory plan, as well as spatial analysis using photointerpretation and digitization methods.

In general, modelling population variations in rural peripheral areas is complex due to the generally scarce information available. While census surveys conducted by INE are accurate, the temporal resolution of the data limits data redundancy, leading to an impoverished representation of actual population variability in the Aculeo basin.

Population growth in the basin was estimated using census data from INE Chile for the years 1992, 2002, and 2017. Although these census reports provide a detailed analysis of population trends through projections, they cover larger spatial areas, which complicates precise determination of population numbers within the Aculeo basin.

4. Results and discussions

Land use classifications from satellite images reveal variability in forest cover, agricultural land, bare land and built or residential land. After applying a confusion matrix and the Kappa index, the accuracy of these classifications was assessed (see table 1). The Kappa index has a value of 0.88, indicating that we can consider the image classifications to be good or representative.

Class	Agriculture	Forest	Soil	Construction	Σ	Ac	K
Agriculture	53	1	0	1	55	0,96	
Forest	0	184	1	1	186	0,99	
Soil	3	6	123	5	137	0,90	
Construction	9	12	5	96	122	0,79	
Total	65	203	129	103	500		
Ap	0,82	0,91	0,95	0,93		0,91	0,88

Table 1. Confusion matrix

In terms of land use, agriculture remains predominant in the study area, although crop types have varied significantly over the years. For example, evapotranspiration for a particular crop decreased from greater than 8.01 mm/day in 2016 to 2.01-4.0 mm/day in 2018 (see figure 4). While some crops, such as cherry and avocado, maintained constant evapotranspiration rates, others disappeared by 2019. The shift to less water-demanding crops, such as wheat, oats, and citrus fruits, indicates a response to the reduced water availability in the lagoon.

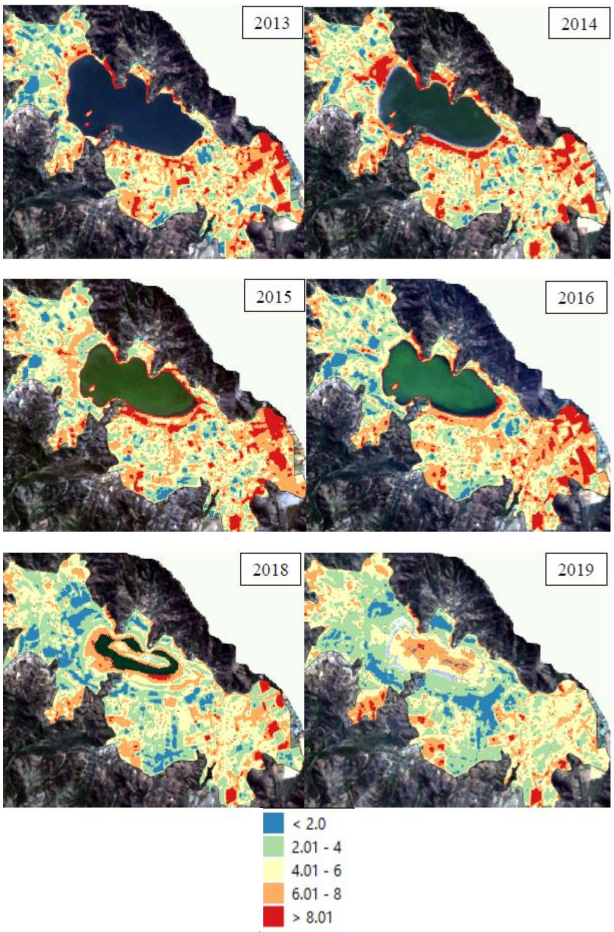

Figure 4 - Evapotranspiration (mm/d)

From the time series, we identify 1991 as the rainiest year, with an accumulated rainfall of 1208.6 mm. In contrast, the least rainy year occurred seven years later in 1998, when only 123 mm fell due to a severe drought that affected the central zone of the country (see figure 5). The average precipitation over the selected years is 543.2 mm, with 18 years below and 8 years above this average. Additionally, it was found that 93.45% of total annual precipitation occurs during the months of April to September (autumn-winter), while the remaining 6.55% falls between October and March (spring-summer).

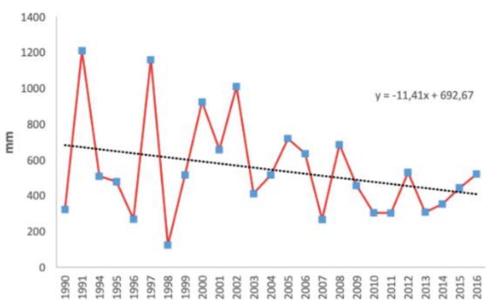

Figure 5 - Mean precipitation

Temperatures exhibit a cyclical pattern with a slight negative trend close to zero. The highest average temperature occurred in January 2017, reaching 21.9°C, while the lowest was recorded in July 2010 at 7.0°C. An analysis of each month (see Annexes, Figures 56-67) reveals that January, February, and March show a positive trend with greater data dispersion. In contrast, April, May, June, and July exhibit a trend that is slightly negative, particularly noticeable in June. August, September, October, November, and December display a consistent behavior with a cyclical pattern over the years, showing trends close to zero; only October and December show a slight negative trend.

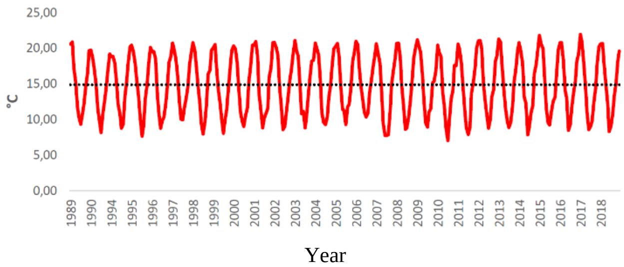

Figure 6 - Mean temperature

The Pearson coefficient indicates a moderate positive correlation, signifying a moderate linear relationship between the surface variations of the Aculeo lagoon and the annual accumulated precipitation.

A further analysis confirms the linear relationship between variables. Time series correlation and Student's t-test, with a 95% confidence level, indicate that years 2006, 2007, 2010, 2015, and 2018 had a significant impact on the lagoon's surface variations. The period from 2011 to 2014 showed low to moderate correlation, potentially due to missing water surface data. The direct impact is thus confirmed for 2006, 2007, 2010, 2015, and 2018.

The correlation results show a negative relationship between lagoon surface variations and average monthly temperatures for 12 of the 13 study years, except for 2011, which had a very low positive correlation. In contrast, 2008 showed a high negative correlation, indicating that higher values in one variable correspond to lower values in the other. Years such as 2006, 2007, 2009, 2010, 2012, and 2016 exhibited a moderate negative relationship, while 2014, 2015, 2017, and 2018 showed low negative correlations. The year 2013 had a very low negative correlation (see table 2).

Year	R_P	R_T
2006	0.89	-0.65
2007	0.76	-0.51
2008	0.61	-0.79
2009	0.60	-0.56
2010.	0.91	-0.64
2011	0.23	0.03
2012	0.51	-0.66
2013	0.30	-0.17
2014	0.22	-0.21
2015	0.70	0.22
2016	0.15	-0.66
2017	0.17	-0.35
2018	0.78	-0.29

Table 2. Correlation coefficients precipitation R_P and temperature R_T

The economically active population (EAP) consists of individuals willing to contribute their labor to the production of economic goods and services. It is noteworthy that the EAP percentage is similar in both rural and urban areas relative to the total communal population. The EPA socioeconomic index for the Aculeo basin recorded 936 individuals in 2017, whereas the

2017 census reported a total population of 3,161 people. Notably, Bahía Catalina, one of the largest residential areas in the basin, with over a hundred homes, has only 17 economically active people (see table 3).

Area	Locality	EAP	EAP (%)
Rural	Aculeo	139	14,85
	Bahia Catalina	17	1,81
	Rangue	525	56,09
Urban	Pintué	255	27,24
TOTAL		936	

Table 3. EAPs for different locations in the study area

Between 1992 and 1997, the area of residential or built land in the basin doubled from 1.9 hectares to 4.0 hectares. By 2002, residential areas had doubled again compared to 1997. This increase in residential development is attributed to the influence of outdated legislation (Law No. 3,516, 1980), land subdivision by local farmers, and rising real estate projects, which, combined with the high demand for housing and acute water deficit, led to a significant decline in agricultural activities in the basin.

The real estate market in the Aculeo basin has grown, promoting development in the Paine commune and the Aculeo area. In 1992, the basin was entirely rural. It consisted of four residential areas: Aculeo, Peralillo, Pintué, and Rangue. By the 2002 census, the Aculeo basin had expanded to include six populated localities, including Bahía Catalina and Los Hornos. Although most plots in the basin are legally subdivided (greater than 0.5 hectares), many irregular subdivisions (less than 0.25 hectares) exist. These irregular plots may exacerbate the water demand on the Aculeo lagoon, compounded by illegal water extraction practices for irrigation and filling pools.

Graphical analysis (see figure 7) of agricultural and residential land use shows a trend of anti-correlation with the lagoon’s surface area since 2012. This trend is more clearly visible in Figures 26 and 27, which illustrate 2012 as a turning point in the lagoon's water levels. Correlation data in Table 12 indicate a strong negative correlation between residential land use (-0.65) and agricultural land use (-0.87) with the lagoon’s surface area.

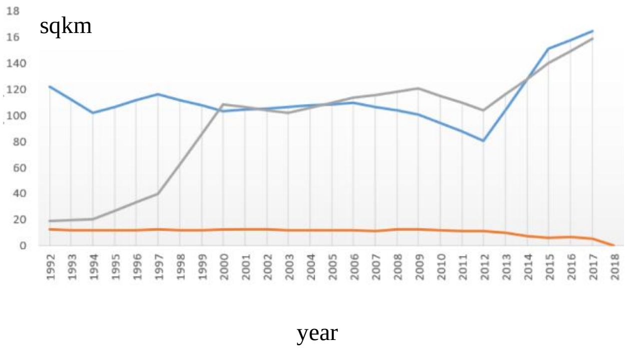

Figure 7. Evolution of Aculeo lagoon surface extension (orange), built area (gray) and area used for agriculture (blue)

5. Conclusions

Crops like corn, grapevines, citrus fruits, cherry trees, and avocado trees, are the most prevalent in the Aculeo sector. Correlation between the lagoon's water loss and decreased precipitation, especially in 2015 and 2018 can be observed. However, average temperatures did not show a direct relationship with lagoon drying. Despite increasing reference evapotranspiration from extreme temperatures, solar radiation, wind speed, and dew point temperature, the lagoon's water level has been adversely affected by agricultural demands.

The lagoon's water level changes are attributed to extensive cropping around it. High evapotranspiration orchards, which demand significant irrigation, have led to lagoon water level decreases. Changing to less water-intensive crops was a necessary adaptation due to the reduced lagoon supply.

The statistical correlations of precipitation, temperature, and land use variables, alongside spatial classifications, reveal significant relationships and anti-correlations with lagoon water levels. While linear trends between variables do not imply causation, they suggest that increasing residential and agricultural areas are correlated with decreased lagoon water levels. However, the primary driver of lagoon drying appears to be a significant precipitation deficit starting in 2006. Evidence of partial recovery in winter 2023 (figure 8), due to heavy rainfall and ENSO events, underscores the impact of climatic factors.

Figure 8 - Acuelo lagoon March 2023 (left) and December 2023 (right); Image © Maxar Technologies

Overall, the Aculeo lagoon has undergone significant alterations, resulting in severe socioeconomic, cultural, and environmental repercussions.

References

Fernández Cirelli, A., 2012. El agua: un recurso esencial. *Química Viva*, 11 (3), 147- 170.

Henson, B., 2023. "NOAA makes it official: El Niño is here » Yale Climate Connections". Yale Climate Connections. Available at https://yaleclimateconnections.org/2023/06/noaa-makes-it-official-el-nino-is-here/

Matus, N., Fernández, B., Aedo, M. P., & Larraín, S., 2004. Recursos Hídricos en Chile: Desafíos para la sustentabilidad. Water Resources in Chile: Challenges for Sustainability. Available at: https://www.researchgate.net/publication/327212218_Recursos_hidricos_en_Chile_Desafios_para_la_Sustentabilidad

Meza, L., Corso, S., Soza, S., Hammarskjöld, A. D., de Estudios, O., & Agrarias-ODEPA, P., 2010. Gestión del riesgo de sequía y otros eventos climáticos extremos en Chile. Organización de las Naciones Unidas para la Agricultura y la Alimentación (FAO).

CED, 2008. Centro de Estudios para el Desarrollo. Diseño y Ejecución de un Programa de Gestión Ambiental Participativo para la cuenca de Aculeo, Región Metropolitana de Santiago, Chile.

Soto, C, 2019. Ni tan campo ni tan ciudad: Transformaciones socio-espaciales al interior de la comuna de Paine, en las primeras décadas del siglo XXI. Master thesis. Available at https://estudiosurbanos.uc.cl/wp-content/uploads/2019/01/TESIS-CBS.pdf

Boisier, J. P., Rondanelli, R., Garreaud, R. D., & Muñoz, F. et al., 2016. Anthropogenic and natural contributions to the Southeast Pacific precipitation decline and recent megadrought in central Chile. *Geophysical Research Letters*, 43(1), 413-421.

Alaniz, A. J., Carvajal, M. A., Núñez-Hidalgo, I., & Vergara, P. M. et al., 2019. Chronicle of an environmental disaster: Aculeo Lake, the collapse of the largest natural freshwater ecosystem in central Chile. *Environmental Conservation*, 46(3), 201-204.

Rivas, C., 2019. Analisis multicriterio para la recuperación de la laguna Aculeo. (Proyecto de grado). Universidad de Chile, Santiago de Chile.

Barría, P., Chadwick, C., Ocampo-Melgar, A. et al., 2021. Water management or megadrought: what caused the Chilean Aculeo Lake drying?. *Regional Environmental Change* 21, 19.

Cuevas, M., 2021. Análisis espacio temporal de uso de suelos en la Cuenca de Aculeo y su impacto en el secado de la Laguna Available at http://repositorio.udec.cl/xmlui/bitstream/handle/11594/7941/An%C3%A1lisis%20espacio%20temporal%20de%20uso%20de%20suelos%20en%20la%20cuenca.pdf?sequence=1

Valdés-Pineda, R., García-Chevesich, P., Valdés, J. B., & Pizarro-Tapia, R., 2020. The first drying Lake in Chile: causes and recovery options. *Water*, 12(1), 290. https://doi.org/10.3390/w12010290

Venegas-Quiñones H.L., T., 2020.Water scarcity or drought? The cause and solution for the lack of water in Laguna de Aculeo. Available at https://repositorio.uchile.cl/handle/2250/190889

Valencia García, C., 2018. Transformaciones socio-territoriales derivadas de la urbanización del suelo, Laguna de Aculeo, Paine. Región Metropolitana, Chile (Doctoral dissertation, Universidad Academia de Humanismo Cristiano).

Bastiaanssen, W., Menenti, M., Feddes, R., Holtslag, A., 1998. A remote sensing surface energy balance algorithm for land (SEBAL). 1. Formulation, *Journal of Hydrology*, 212–213, pp. 198-212, ISSN 0022-1694, https://doi.org/10.1016/S0022-1694(98)00253-4.

McFeeters, S., 2013. Using the normalized difference water index (NDWI) within a geographic information system to detect swimming pools for mosquito abatement: A practical approach. *Remote Sensing*, 5(7), 3544-3561.

Xu, H., 2006. Modification of normalised difference water index (NDWI) to enhance open water f eatures in remotely sensed imagery. *International journal of remote sensing*, 27(14), 3025-3033.

Chuvieco, E., 1996. Fundamentos de teledetección espacial. Ediciones Rialp.

Getu, K., & Bhat, H., 2021. Analysis of spatio-temporal dynamics of urban sprawl and growth pattern using geospatial technologies and landscape metrics in Bahir Dar, Northwest Ethiopia. *Land Use Policy*, 109. https://doi.org/10.1016/j.landusepol.2021.105676.