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# The effects of extreme drought events on the morphometry of shallow lakes: Implications for sediment resuspension and littoral and pelagic zone distribution

Carina Seitz, Facundo Scordo, Alejandro J. Vitale, María I. Vélez, Gerardo M.E. Perillo

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# Title: THE EFFECTS OF EXTREME DROUGHT EVENTS ON THE MORPHOMETRY OF SHALLOW LAKES: IMPLICATIONS FOR SEDIMENT RESUSPENSION AND LITTORAL AND PELAGIC ZONE DISTRIBUTION

Authors: Carina Seitz [1,2]; Facundo Scordo [1,3,4]; Alejandro J. Vitale [1,5]; María I. Vélez [6]; Gerardo M. E. Perillo[1,2]

Affiliations:
[1] Instituto Argentino de Oceanografía (IADO), Universidad Nacional del Sur (UNS)-CONICET, Florida 8000,
Bahía Blanca B8000BFW, Argentina;

[2] Departament of Geology, Universidad Nacional del Sur, Avenida Alem 1253,
Bahía Blanca B8000CPB, Argentina;

[3] Departament of Geography and Tourism, Universidad Nacional del Sur, 12 de Octubre 1198,
Bahía Blanca B8000CTX, Argentina;

[4] Department of Biology, University of Nevada, Reno, Reno , NV

[5.] Departament of Electric Engineering and Computer Science, Universidad Nacional del Sur (UNS),
Avenida Alem 1253, Bahía Blanca B8000CPB, Argentina;

[6] Department of Geology, University of Regina, 3737 Wascana Parkway S4S 0A2, Regina Sk. Regina, Saskatchewan, Canada.

**Corresponding author :** Carina Seitz cseitz@iado-conicet.gob.ar; Florida 8000, Bahía Blanca B8000BFW, Argentina. ORCID ID: 0000-0001-7985-3724

## ABSTRACT

Shallow lakes, because of their depth, are more vulnerable to the effects of wind and changes in precipitation and evaporation that deeper lakes and thus respond more dramatically to extreme climatic events, such as drought. The morphology of shallow lakes many of their physical, chemical, biological and sedimentological processes including sediment resuspension. Sediment resuspension can trigger undesired effects such as eutrophication, increase in turbidity, cyanobacterial blooms, and also affects the distribution and extent of the littoral and pelagic zones (habitat distribution) with potentially negative consequences on biodiversity and loss of native species. These problems are an increasing concern in the face of global warming. To understand how changes in lake' morphometry, triggered by extreme drought events influence sediment resuspension and habitat distribution, we studied four shallow lakes located in the southwest of the Argentinean Pampas. Each lake was characterized by its bathymetry, morphometric parameters (including area, shore development, dynamic ratio, critical depth), the spatial distribution of the littoral and pelagic areas, and the effect of the waves on sediment resuspension. We measured the Area and Shore development again during selected extreme drought periods identified through the Standardized Precipitation-Evapotranspiration Index. Then, for the given drought period, we calculated the extent and distribution of littoral and pelagic areas and the critical depth at which sediment resuspension occurred and then estimated the percentage of the lake that would be affected by it. We found that Pampean lakes are profoundly affected by sediment resuspension triggered by wind during extreme dry events. Droughts have different effects depending on lake morphology. Dry periods caused not only a decrease in water volume, but also modified the extension of littoral and pelagic zones and increased sediment resuspension. These results have significant implications for the preservation of these rich ecosystems, especially in the context of global warming.

**Keywords**: Shallow lakes; lake morphometry; sediment resuspension; climate variability; dry events, Unmanned Surface Vessel (USV).

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## INTRODUCTION

Shallow lakes are the most common type of lakes in the global landscape (Downing et al. 2006) and important providers of ecosystem services such as flood control, groundwater recharge and nutrient regulation; also, many of them are biodiversity hotspots (Beklioğlu et al. 2016). Despite their importance and abundance, and the fact that their low depth and volume makes them very sensitive to climate change (Williamson et al. 2008; Adrian et al. 2009), they have been less studied than deep lakes (Scheffer 2001; Blottiere 2015). Their morphometry has a direct effect on their physical, chemical and biological processes (Wetzel 2001) and their shallow depths makes them particularly vulnerable to the effect of wind which can generate sediment resuspension through the generation of high, highly erosive waves (Blottiere 2015). Sediment resuspension from lake bottoms facilitates the increase of nutrients and has a significant impact on both, attenuation and temporal fluctuation of light in the water column, which altogether affect primary productivity (e.g. Hellesträm 1991). The resuspension of sediment and the bathymetry i.e. underwater slope, in turn determine habitat distribution, this is the extent of the littoral and pelagic habitats (Cozar et al. 2005). The distribution and extension of these areas are important to understand ecosystem processes such as primary productivity and biodiversity in the lake, since much of the primary productivity and species diversity is concentrated in the littoral zone (Hoverman et al. 2012).

Therefore, knowing the bathymetry of the lake is vital for understanding its ecology (Leira and Cantonati 2008). Also, the bathymetric measure and maps are necessary information for many other research areas, as well as for resource management and the development of economic activities such as tourism (Suhari et al. 2017). Most of the bathymetric studies of shallow lakes have been based on the analysis of remote sensing images. However, the current methodologies developed still have limitations, especially when studying eutrophic lakes (Yuzugullu and Aksoy 2014). That is due to the co-presence of high concentration of chlorophyll *a*, suspended particles, and colored dissolved organic matter and waves (Kishino et al. 2005; Sudheer et al. 2006) which significantly impact radiance values obtained from the remote sensing images (Swardika 2007; Yuzugullu and Aksoy 2014). The traditional equipment to survey the lake depths has some limitations to explore shallow waters. Also, this does not guarantee the on-board surveyors' safety, as well as they are time-consuming and are expensive (Suhari et al. 2017). Here we use an Unmanned Surface Vessel (USV) to carry out bathymetric studies in the Pampean shallow lakes in Argentina.

The Pampean Region is an extensive fertile plain covered by loess with more than 13,000 shallow lakes (Dangavs 2005; Geraldi et al. 2011), and is one of the most important economic regions in Argentina for its agriculture and livestock productivity (Viglizzo et al. 2001). Much of these economic activities depend on water from the lakes for irrigation and flood control. The great majority of these lakes are endorheic, have a mean depth of 4 m and are larger than 10 ha; but there are more than 200,000 between 0.5 and 10 ha (Geraldi et al. 2011). Emblematic to these waters is the native fish, the pejerrey (*Odontesthes bonariensis*), who is threated by increasing eutrophication, cyanobacterial blooms, anoxia, loss of microenvironment where they grow (Kopprio et al. 2010), and now by climate change. Changes in precipitation and evaporation produce dramatic changes in the morphology, surface area and depth of these shallow lakes, with repercussions in their physicochemical and biological characteristics (Quirós et al. 2002; Quirós 2005; Bohn et al. 2014, 2016; Pisano et al. 2020). However, despite the importance of the morphometry on the dynamic of these waterbodies, bathymetric and morphometric studies in these lakes are rare.

Our objective is to analyze how extreme climate events affect the internal lake processes and habitat distribution of four shallow water bodies located in the Argentinian Pampean Region (33-41□ S and 56-67□ W) (Fig. 1). First, we analyze how extreme dry and wet periods affect lake area and shoreline length. Second, we analyze how changes in lake' morphometry triggered by extreme dry events influence the sediment resuspension and littoral and pelagic zone distribution.

## STUDY AREA AND LAKE CHARACTERISTICS

We studied four permanent shallow lakes located in the southwest of the Pampean Region and along a precipitation gradient from lower to higher in a SW-NE direction (Fig. 1). These include, Puan (37º 33' 2.4" S / 62º 47' 24.6" W), Los Chilenos (38º 1' 43 .8" S / 62º 28' 19 .2" W), Sauce Grande (38º 56' 10.2" S / 61º 22' 34 .8" W), and La Salada (39 º 27' 0.0" S / 62 º 42 ' 0.0" W) (Fig. 1). These waterbodies are used for fishing, water sports, and recreation, while in the surroundings the main economic activities are agriculture and livestock.

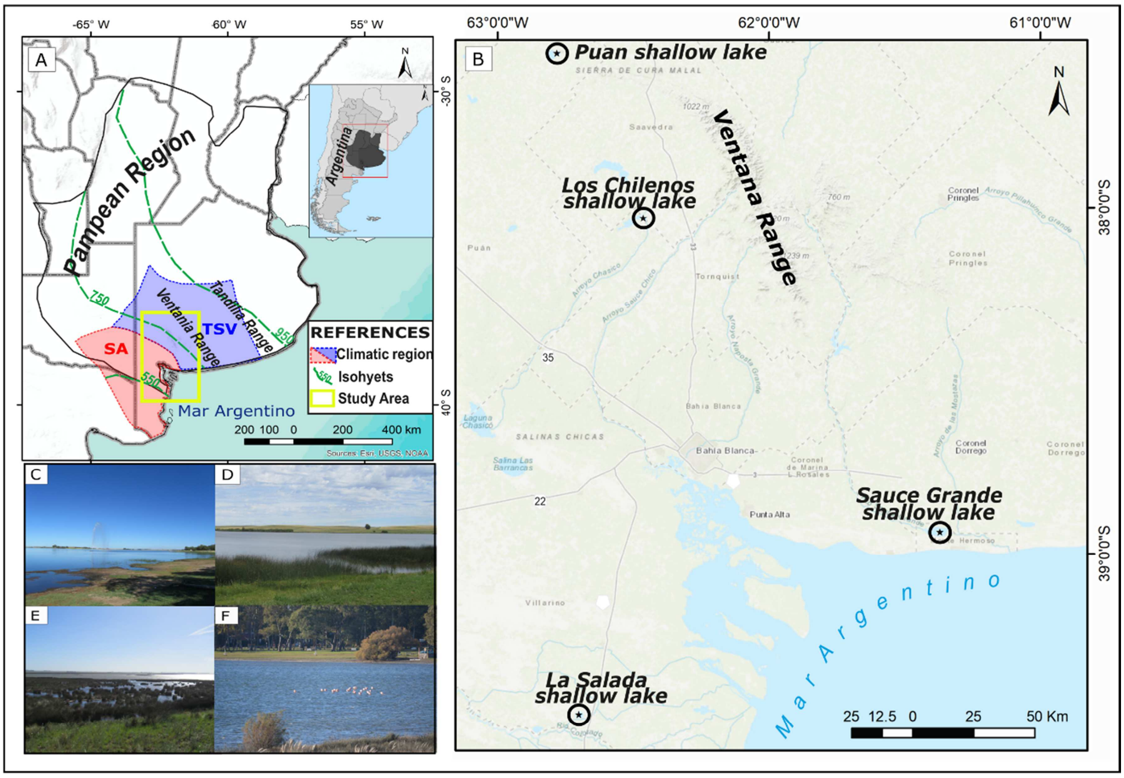


***Figure 1:*** *a) Localization of the study area in the Pampean region indicating the precipitation gradient and the climatic regions TSV (Temperate-highland of Ventania hills) and SA (Semi-Arid) involved in the study area; b) Location of the shallow lakes in the Southwest of Buenos Aires province; and pictures of the lakes: c) Puan; d) Los Chilenos; e) Sauce Grande; f) La Salada.*

In the Pampean region precipitation increases from southwest (350 mm/year) to northeast (1400 mm/year), and shows a marked seasonality, with more precipitation in Autumn and Spring. Temperature increases from southwest (13.5 °C) to northeast (19.5 °C), whereas the average wind speed decrease from southwest (15 km/h) to northeast (10 km/h) (Ferrelli and Aliaga 2015). The studied area includes two different climatic subregions defined by Aliaga et al. (2017) as: Temperate-highland of Ventania hills *(TSV)* (where Puan and Los Chilenos are located) and semi-arid (SA) (where La Salada and Sauce Grande) (Fig. 1). For this study, the most important difference between these regions is that in SA wind intensity is higher and is more prone to drought than TSV. (Aliaga et al. 2017). The effects of extreme events have been reported (Zunino 2018): during a wet period, Puan's extension and volume increased significantly with the subsequent decrease in turbidity and salinity (Zunino 2018); during a dry period, Sauce Grande had an increase in turbidity, salinity, nutrients, and chlorophyll a (Fornerón 2013), and during the drought event in 2009 and 2011 Los Chilenos's volume contracted producing a massive fish mortality (Bertora et al. 2016).

Shallow lakes in the Pampas have different origins and are relatively new features in the landscape. Lakes Puan (the only lake with an island) and La Salada were originated by wind erosion during dry conditions present in the Pleistocene-early Holocene and middle-late Holocene, respectively (Seitz et al. 2019; Seitz 2019). Los Chilenos was formed by neotectonic, fluvial, and eolian processes in the late Holocene and Sauce Grande by fluvial, coastal, and eolian processes in the late Holocene (Seitz 2019). These lakes are perennial, polymictic, and have the physicochemical characteristics typical of Pampean shallow lakes (Table 1) (Baigún and Anderson 1993; Quirós et al. 2002; Alfonso et al. 2015; Cony et al. 2014; Bertora et al. 2016; Zunino 2018). La Salada is the least turbid while Sauce Grande is the more turbid with concentration of suspended sediments 30 to 100 times larger than in the other lakes.

***Table 1:*** *Summary of the main physicochemical variables of the studied lakes. Average values (minimum-maximum values in brackets) based on the studies of Cony et al. (2014), Alfonso et al. (2015), Baigún and Anderson (1993), Grosman et al. (2013); Bertora et al. (2016), Zunino (2018) and one snapshot sampling at Los Chilenos (unpublished data).*

| **Physicochemical variables** | **Puan** | **Los Chilenos** | **Sauce Grande** | **La Salada** |
|---|---|---|---|---|
| *Secchi disk depth (m)* | 0.7 (0.2-1.4) | 0.4 (0.3-0.5) | 0.1 (0.1-0.10) | 1.5 (0.6-2.9) |
| *Suspended solids (mg/l)* | 44.3 (6.4-194.0) | 14.8 | 1076.6 (896.0-1280.0) | 12 (2.4-76.9) |
| *Trophic state* | Eutrophic/ Hypertrophic | Eutrophic/ Hypertrophic | Eutrophic/ Hypertrophic | Eutrophic/ Hypertrophic |
| *Chlorophyll a (ug/l)* | 3.6 (0.0-13.5) | 31.4 (23.8- 39.0) | 486.1 (327.6-749.2) | 9.4 (1.3-18.1) |

| | | | | |
|---|---|---|---|---|
| *Conductivity (mS/cm)* | 8.1 (5.6-11.2) | 0.65 | 11.1 (9.1-10.5) | 44.7 (30.2-63.4) |
| *pH* | 9.6 (8.2-11.6) | 8.7 (7.5-9.4) | 10.0 (8.4-10.7) | 9.9 (9.3-10.5) |
| *Temperature (°C)* | 15.3 (7.4-25.1) | 14.2 (7.0-21.7) | 14.9 (5.1-26.1) | 16.7 (8.0-23.8) |

All the lakes are fed by groundwater and local rainfall (Dangavs 2005; Fornerón 2013). Puan is endorheic and receives water from the Pichincay stream (Haag 2012) (Fig. 2); Los Chilenos is feed by the Cochenleufú stream (Bertora et al. 2016) and has an outflow, the Chasicó stream, located on the southeast (Fig. 2). Sauce Grande lake is fed by the Grande River (to the west), and its outflow, also called Sauce Grande River, on the east part of the lake, drains to the Atlantic Ocean (Fig. 2). La Salada is endorheic, fed by the Don Adolfo and Fortín irrigation canals that come from the Colorado River (Fig. 2).

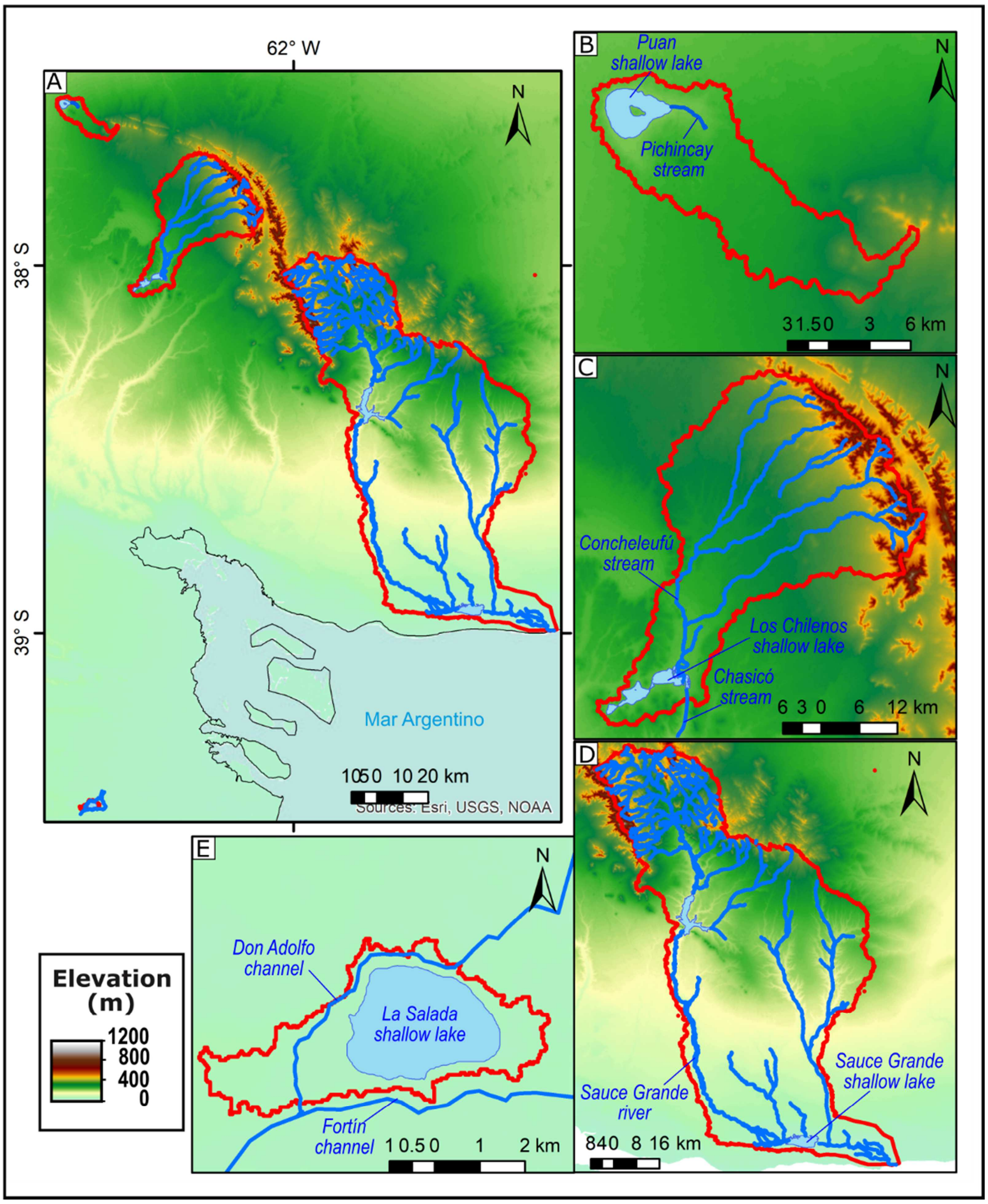



***Figure 2:*** *a) Location of watershed of the shallow lakes under study. The watershed and the main input and output rivers/streams to lakes are presented in b) for Puan; c) for Los Chilenos; d) for Sauce Grande and e) for La Salada.*

## METHODOLOGY

### MORPHOMETRIC ANALYSIS

We employed a SRTM (Shuttle Radar Topography Mission) Digital Elevation Model (DEM) to measure the lake's watershed and surface (*Aw*). The DEM has a pixel resolution of 90 x 90 m and was downloaded from the United States Geological Survey web page (http://earthexplorer.usgs.gov).

We used an USV to measure the bathymetry, analyze the underwater morphology, and estimate morphometric parameters of size, form and critical depth. The equipment is based on the Arduino open electronic platform build by Alejandro J. Vitale (2014) at the Instituto Argentino de Oceanografía (IADO) (Fig. 3.a.) (See the complete technical specification at Genchi et al. (2020)). The vehicle is equipped with an autopilot system, and it has a Garmin Echo 100 echosounder working at 200 kHz. Also, the battery capacity allowed approximately 6 hs of continuous navigation at cruise navigation speed (1.1-1.5 m/s). The Table 2 summarized the travelled distance at each lake and the time employed to the bathymetric survey. All data is stored on a memory card on board at 5 Hz and also sent by telemetry to the Mission Planner 1.3.44 software (ArduPilot.org, 2017). We programmed the navigation route with the Mission Planner 1.3.44 software (ArduPilot.org, 2017). For planning the navigation route, we combined the triangulation method and a regular grid. We processed the stored data (GPS, echo sounder profile) with a Matlab script that transforms the sound speed to depth and corrects for pitch and roll resulting in the XYZ location data in the WGS1984 datum geographic coordinates system.

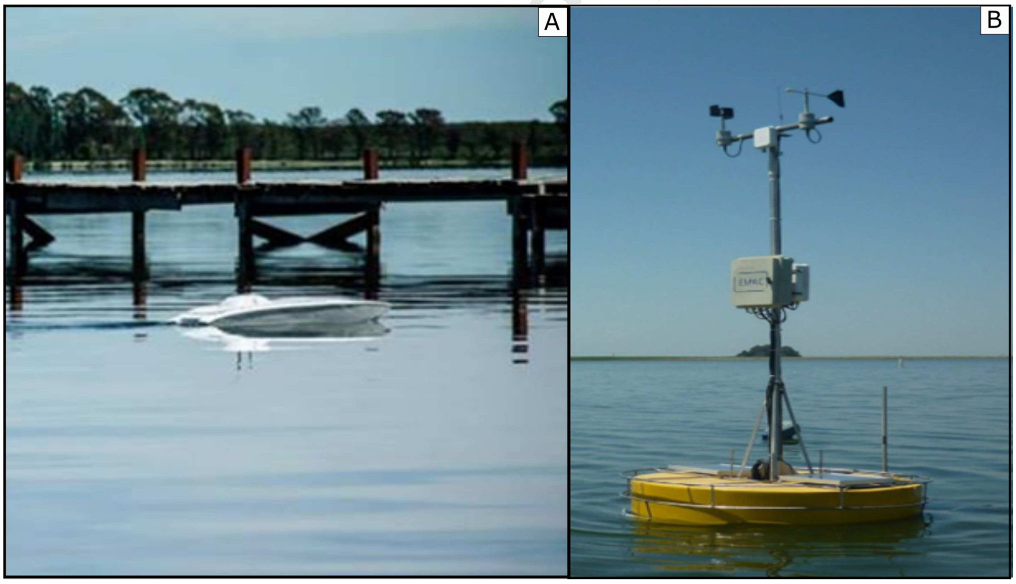



***Figure 3:*** *a) Bathymetric drone; b) Environmental monitoring Buoy EMAC designed and built at IADO (http://emac.iado-conicet.gob.ar).*

***Table 2:*** *Travel distance and hour employed in the bathymetric survey at each lake*

| | **Puan** | **Los Chilenos** | **Sauce Grande** | **La Salada** | **Total** |
|---|---|---|---|---|---|
| *Traveled distance (km)* | 29.23 | 22.47 | 38.22 | 20.82 | 110.74 |
| *Hours of work (h)* | 5.42 | 4.16 | 7.07 | 3.85 | 20.5 |

We determine the shoreline length ($L_o$) and the lake area (*A*) using the closest Landsat satellite images 5 Thematic Mapper (TM; bands 4, 5 and 3) and Landsat 8 Operational Land imager (OLI; bands 5, 6 and 4) to the bathymetric survey date (Table 3). For Puan we used Landsat 8 OLI from 21/01/2016 Los Chilenos we use the Landsat 8 OLI from 23/01/17; Sauce Grande Landsat 8 OLI from 22/04/17 and La Salada we use Landsat 5 TM from 20/12/2015. All these dates correspond with regular flood condition of the lakes, as according to the Standardized Precipitation-Evapotranspiration Index (SPEI; Vicente-Serrano and Beguería 2016) the twelve previous months' present normal or slightly humid moisture conditions (see at section "Lake's response to climate variability" full explanation of the Standardized Precipitation-Evapotranspiration Index). The Landsat images have a temporal resolution of 16 days and a spatial resolution of 30 x 30 m; downloaded from the website of the United States Geological Survey (http://earthexplorer.usgs.gov). We used Landsat Collection 1 - Level 2 product (Path 227 and Row 86 used for Puan and Los Chilenos; Path 226 and Row 87 for La Salada and Sauce Grande). This collection of Landsat images provides surface reflectance data ensuring consistent quality through time and across the different Landsat sensors. These images include calibration processes between the different sensors, and geographic, radiometric and atmospheric corrections (further information on the calibration and corrections processes can be found in https://www.usgs.gov/land-resources/nli/landsat/landsat-collection-1-surface-reflectance).

First, we projected the images to the Universal Transversal Mercator (UTM) projection, zone 20S. Then, to differentiate between water bodies and other land cover, we applied a RGB band stack (near-infrared; far-infrared; red) to the images (Landsat 5 TM: bands 4-5-3; Landsat 8 OLI: bands 5-6-4) since this false color composition is best suited to differentiate water bodies from other land covers (NASA 1999; Horning 2004). Finally, we obtained the area of the shallow lake applying an unsupervised classification method (IsoData) to the RGB combination of each image, and the subsequent vectorization of the defined layers. We performed the image and DEM processing in the softwares ENVI 4.1 and ArcGIS® 10.2.2. Subsequently, we transformed the coastline polygon into points that were assigned a zero-depth value. Then we imported the depth values obtained from the bathymetric measurements, along with the coastline points in the Global Mapper software. Finally, we interpolated the data using the triangulation method to generate bathymetric contour lines. The bathymetric map produced was used to measure the different features associated with size (Table 3) and the hypsographic curves of each lake (Table 2). For the determination of form and specific morphometric parameters, we use the formulas summarized in Table 2 according to Ryding and Rast, (1992), Quirós et al. (2002) and Håkanson (2004). Also, we analyzed the Aw/A ratio to see the influence of the basin over lake (Håkanson 2004).

***Table 3:*** *Estimated morphometric parameters based on Håkanson (2004) [1], Ryding and Rast, (1992) [2], Quirós et al. 2002 [3], Carper and Bachmann (1984) and Scheffer (2004) [4].*

| | | | |
|---|---|---|---|
| Facts | **Area (*A*)** | $km^2$ | - |
| | **Volume (*V*)** | $km^3$ | - |

| | | | |
|---|---|---|---|
| | **Watershed Area ($A_w$)** | $km^2$ | - |
| | **Maximum length ($L_{max}$)** | km | - |
| | **Maximum Width ($W_{máx}$)** | m | - |
| | **Maximum Depth ($Z_{max}$)** | m | - |
| **Form Factors** | **Mean Depth ($Z_{mv}$)** | m | $Zmv = \frac{V}{A}$[1] |
| | **Relative Depth ($Z_r$)** | Adim. | $Zr = \frac{Zmax*\sqrt{\pi}}{20*\sqrt{A}}$ [1] |
| | **Shoreline length ($L_o$)** | km | |
| | **Shore development ($L_d$)** | Adim. | $Ld = Lo/(2*\sqrt{\pi A})$ [1] |
| | **Mean Slope (*S*)** | Adim. | $S = \left\{[Lo + (2*Lcot)] * \left[\frac{Zmax}{20*n*A}\right]\right\}$ *Lcot: Total length of all contour lines excluding the coastline in km, n = number of contour lines. [1]* |
| | **Dynamic ratio (*DR*)** | Adim. | $DR = \sqrt{A}/Zmv$ [1] |
| | **Erosion and Transportation areas (*ET-área*)** | **%** | $ET = 0.25 * DR * 41^{(0.061/DR)}$ [1] |
| | **Anual mean depth of euphotic zone ($Z_{eu}$)** | m | $Zeu = 2.5 * Secchidiskdepth$[2] |
| | ***$Z_{mv}$/$Z_{eu}$ ratio*** | Adim. | <1 clear water<br>>1 turbid water [3] |
| | **Wavelength *($L_w$)*** | *m* | $Lw = 1{,}56\left[0{,}77 * W * tanh\left[0{,}077\left[\frac{9.8*F}{W^2}\right]^{0.25}\right]\right]^2$<br>[4] Where:<br>*W*: wind speed (m/s)<br>*F*: Fetch (m) |
| | **Critical Depth *($Z_{wc}$)*** | *m* | $Z_{wc} \le \frac{Lw}{2}$[4] |

APPROXIMATION TO SEDIMENT RESUSPENSION AND DISTRIBUTION OF LITTORAL AND PELAGIC AREAS

Since we do not have wave measurements we approximated the surface of the lake affected by sediment resuspension using the relationship between the hypsographic curve and the *critical depth* ($Z_{wc}$) (Table 3). We followed Carper and Bachmann (1984) (modified by Scheffer (2004)) to estimate the *wavelength* of the waves ($L_w$) and calculate the *critical depth* ($Z_{wc}$) at which the sediment resuspension occurs. $L_w$ was calculated for the maximum and mean wind speed (Table 3).

We calculated predominant wind direction and their maximum and average speed using high frequency data (5-minute sample rate) from weather stations located in the EMAC buoys stationed in lakes Puan, Sauce Grande, and La Salada (Fig. 2.b.). We obtained the mean and maximum daily wind speeds in Los Chilenos from a close meteorological station (52 km at northwest) which data was provided by INTA Bordenave (period January 1961- September 2016).

We identified the main prevailing process of sediment erosion and resuspension, using the *Dynamic ratio* (*DR*) (Table 3). This ratio allows the differentiation between erosion and transportation caused by wind from those driven by slope processes (gravitational forces). *DR* values between 0.05 and 4 indicate the predominance of sediment erosion and transportation caused by wind and values less than 0.05 indicate the predominance of slope processes. We also used the *DR* to determine the percentage of the lake area subject to *erosion and transport* (*ET-areas*) (Håkanson 2004).

We calculated the average annual depth of the *euphotic zone* ($Z_{eu}$) by applying the formula proposed by Ryding and Rast (1992) (Table 3). $Z_{eu}$ estimates the depth at which the intensity of the light that penetrates the water column is reduced to 1%, and below which there is not enough light for photosynthesis (Wetzel 2001). To calculate and map the extent of the littoral and pelagic areas, we used the hypsographic curve and $Z_{eu}$ (littoral > $Z_{eu}$ > pelagic) and to map the lake's slope we used the *Slope* tool of the *Spatial Analyst* package ArcGIS® 10.2.2. Finally, we determined the form of the lake and its possible origin after determining $L_d$ (shore development; Table 2) using the classification proposed by Timms (1992) (Table 4).

***Table 4:*** *Classification of the origin of the lakes based on their forms (Timms 1992).*

| **Lakes form** | $L_d$ | **Origin** |
|---|---|---|
| **Circular** | $1 < L_d \leq 1.25$ | volcanic cones, perfect dolines, small blowouts |
| **Subcircular** | $1.25 < L_d < 1.5$ | Glacial cirque, kettle holes, volcanic calderas, dolines, and blowouts lakes |
| **Elliptical** | Slightly superior to the circular and subcircular | Lakes connected by deflation, or lakes that are between coastal parabolic dunes |
| **Elongated subrectangular** | >2.0 can exceed 5.0 | Grabens, fjords, deep valley lakes that appear as widened rivers |
| **Dendritic** | >3.0 | Shallow river valleys blocked by dams |
| **Semilunar** | - | Abandoned meanders, maars |
| **Triangular** | 1.5 – 2.0 | Flood in not dissected valleys |
| **Irregular** | can exceed 20 | Complex morphologies by basin fusion |

LAKE'S RESPONSE TO EXTREME DRY AND WET EVENTS

To understand the effect climate on the studied lakes, we selected one extreme drought event and a flood period occurred in the last 29 years to measure the contraction and expansion of lake's area produced by them. To identify the wet and dry periods we used the Standardized Precipitation-Evapotranspiration Index (SPEI; Vicente-Serrano and Beguería 2016). We downloaded the SPEI data at a 12-month time scale (SPEI 12M), with a spatial resolution of 0.5° for the period 1951-2017 from SPEI Global Drought Monitor global model (https://sac.csic.es/spei/home.html) (Vicente-Serrano and Beguería 2016). We choose a 12-month time scale (SPEI 12M) since it would reflect the complete annual cycles of precipitation affecting the final hydrologic budget, i.e. river input, and the volume of water in the water body (Mc Kee et al. 1995; Vicente-Serrano et al. 2010). Also, this SPEI time scale has been successfully applied in similar studies in the region (Bohn et al. 2016). SPEI > 0.5 corresponds to wet periods; values < -0.5 to dry periods and values between -0.5 and 0.5 are considered normal years (Wang et al. 2015).

We analyzed the time series of the SPEI for three stations: one located at 37.25° S- 62.25° W close to Puan and Los Chilenos, another one at 38.75° S - 61.25° W close to Sauce Grande, and a third one at 39.25° S – 62.25° W close to La Salada. We selected one extremely dry or humid period for each station considering the longest period under dry or humid condition including extreme events. The area and shoreline length of the lake after extreme wet and dry periods, were calculated using Landsat Collection 1 - Level 2 product containing surface reflectance data (Path 227 and Row 86 used for Puan and Los Chilenos; Path 226 and Row 87 for La Salada and Sauce Grande) temporally near to the end of each extremely dry or humid period. For Puan and Los Chilenos, we consider the drought period April 2008 to February 2010 (selected date image 20/01/10) and wet period December 1990 to December 1993 (selected date image 07/12/93). For Sauce Grande we considered the drought period February 2008 to January 2010 (selected date image 12/12/2009) and the wet period January 1997 to September 1998 (selected date image 09/09/1998). Finally, for La Salada we considered the dry period December 2007 to January 2010 (selected date image 29/01/2010) and the wet period June 2014 to December 2015 (selected date image 20/12/2015). After processing the images for the dry period all morphometric parameters were calculated, and the resulting pelagic, littoral zones and depth were estimated using the hypsographic curve. To estimate the new areas prone to sediment resuspension, the $Z_{wc}$ (critical depth) was used along with the hypsographic curve. For the wet period we calculated lake area and shoreline length. However, we did not analyze the other parameters during the wet period due to that the area of the lakes was higher than the area obtained for the bathymetric maps, and we did not have trustworthy high resolution topographic information to estimate the depth of lake under this condition.

## RESULTS

## BATHYMETRY AND MORPHOMETRY OF SHALLOW LAKES UNDER REGULAR FLOOD CONDITIONS

The bathymetric map of each lake is presented in Figure 4, and the morphometric parameters in Table 5. Figure 5 presents the hypsographic curves for the four shallow lakes. We carried out the bathymetric survey under the regular flood conditions of the lakes. Following the SPEI data, the twelve previous months' present normal or slightly humid moisture conditions (see below in section "Variation in morphometric parameters and resuspension processes during dry periods").

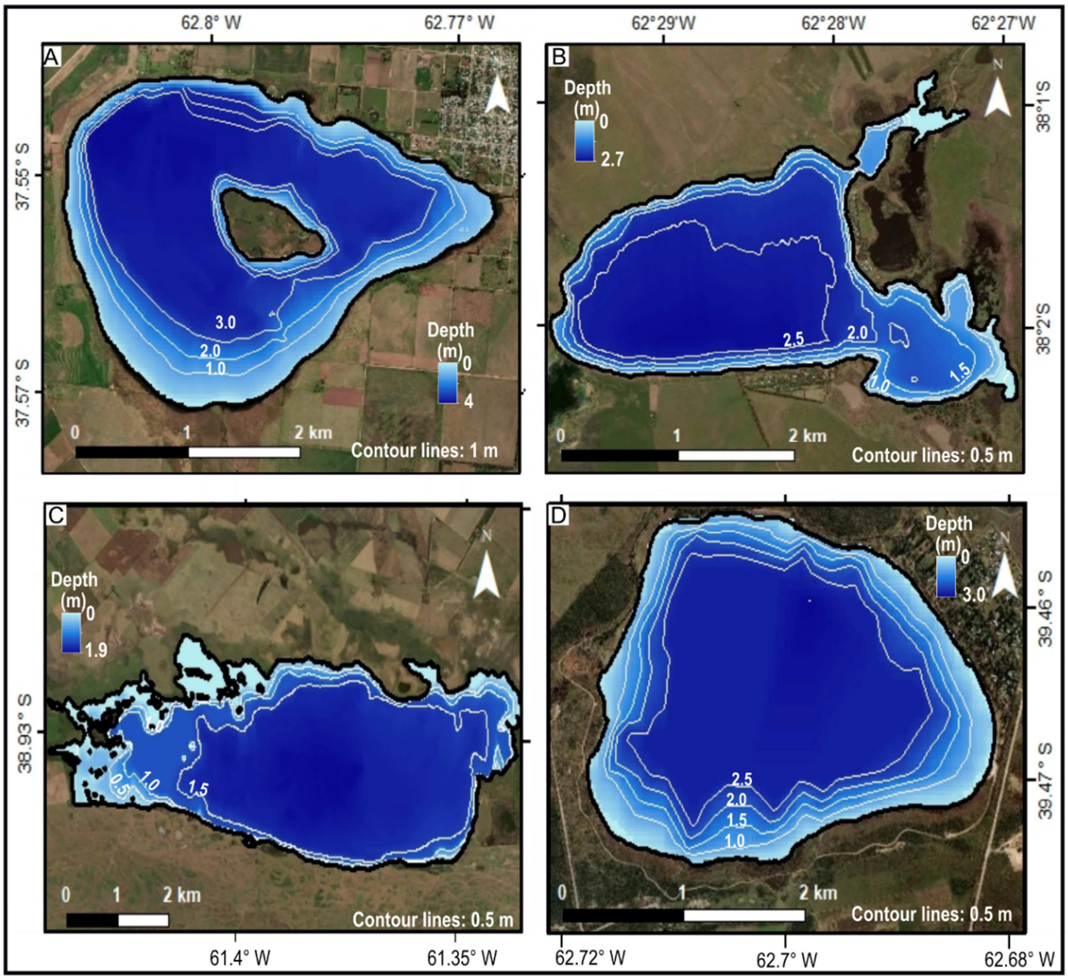



***Figure 4:*** *Bathymetry of the studied lakes a) Puan; b) Los Chilenos; c) Sauce Grande and d) La Salada (Source: Own elaboration). The background satellite images are from the world imagery basemap of ArcMap (Sources: Esri, DigitalGlobe, GeoEye, Earthstar Geographics, CNES/Airbus DS, USDA, USGS, AeroGRID, IGN, and the GIS User Community, 2009).*

***Table 5:** Results of morphometric parameters related to size and form during regular flood conditions of the bathymetric map.*

| | | | **PUAN** | **LOS CHILENOS** | **SAUCE GRANDE** | **LA SALADA** |
|---|---|---|---|---|---|---|
| **Size Factors** | **Area (*A*)** | $km^2$ | 6.70 | 4.90 | 20.39 | 3.53 |
| | **Volume (*V*)** | $km^3$ | $8.0x10^{-3}$ | $3.5x10^{-3}$ | $1.2x10^{-2}$ | $3.2x10\text{-}^{3}$ |
| | **Watershed Area (Aw)** | $km^2$ | 95.2 | 794.9 | 4576.1 | 9.1 |
| | **Maximum length ($L_{max}$)** | km | 3.86 | 3.9 | 9.3 | 3.41 |
| | **Maximum Width ($W_{máx}$)** | km | 2.84 | 1.8 | 3.3 | 2.56 |
| | **Maximum Depth ($Z_{max}$)** | m | 4.00 | 2.79 | 1.97 | 3.06 |
| | **Mean Depth ($Z_{mv}$)** | m | 1.19 | 0.72 | 0.59 | 0.91 |
| **Form Factors** | **Relative Depth ($Z_r$)** | % | 0.32 | 0.23 | 0.15 | 0.25 |
| | **Shoreline length ($L_o$)** | km | 13.14 | 16.26 | 45.41 | 7.52 |
| | **Shore development ($L_d$)** | Adim. | 1.43 | 2.07 | 2.84 | 1.13 |
| | **Mean Slope (*S*)** | Adim. | 0.66 | 0.29 | 0.09 | 1.29 |
| | **Dynamic ratio (*DR*)** | Adim. | 2.17 | 3.09 | 7.62 | 2.06 |
| | **Erosion and Transportation areas (*ET-área*)** | % | 60 | 83 | 100 | 57 |
| | **Anual mean depth of euphotic zone ($Z_{eu}$)** | m | 1.16 | 1.07 | 0.41 | 2.10 |
| | ***$Z_{mv}/Z_{eu}$ ratio*** | Adim. | 1.03 | 0.67 | 1.45 | 0.43 |
| | **Wavelength ($L_w$)** | m | 2.30 | 2.50 | 4.10 | 5.10 |
| | **Critical Depth ($Z_{wc}$)** | m | 1.20 | 1.30 | 2.10 | 2.60 |

Puan has an overall sub-circular shape with a slight east-west elongation (Table 5). This shape is characteristic of lakes generated by deflation with additional alteration of the coastline by coastal and wind processes (Timms 1992). This waterbody has an $A_w/A$ of 14.2 (Fig. 2.b). Los Chilenos is elliptical to elongated subrectangular with an east-west elongation (Table 5, Fig.4.b). Its morphology is usually associated with lakes developed between longitudinal dunes or generated in widening river valleys (Timms 1992). The lake has an *Aw/A* ratio of 162.2 (Table 5, Fig. 2.c). Sauce Grande Lake is elongated subrectangular in east-west orientation (Table 5, Fig. 4.c). Its morphology is associated with lakes originated in grabens, fjords and deep valley lakes (Timms 1992). It has an $A_w/A$ ratio of 224.4 (Table 5, Figs. 5.d, 2.d). La Salada is almost circular with an east-west elongation (Table 5, Fig. 4.d), a form is associated with deflation processes (Timms 1992). It has an $A_w/A$ ratio of 2.57 (Table 5, Fig. 2.e).

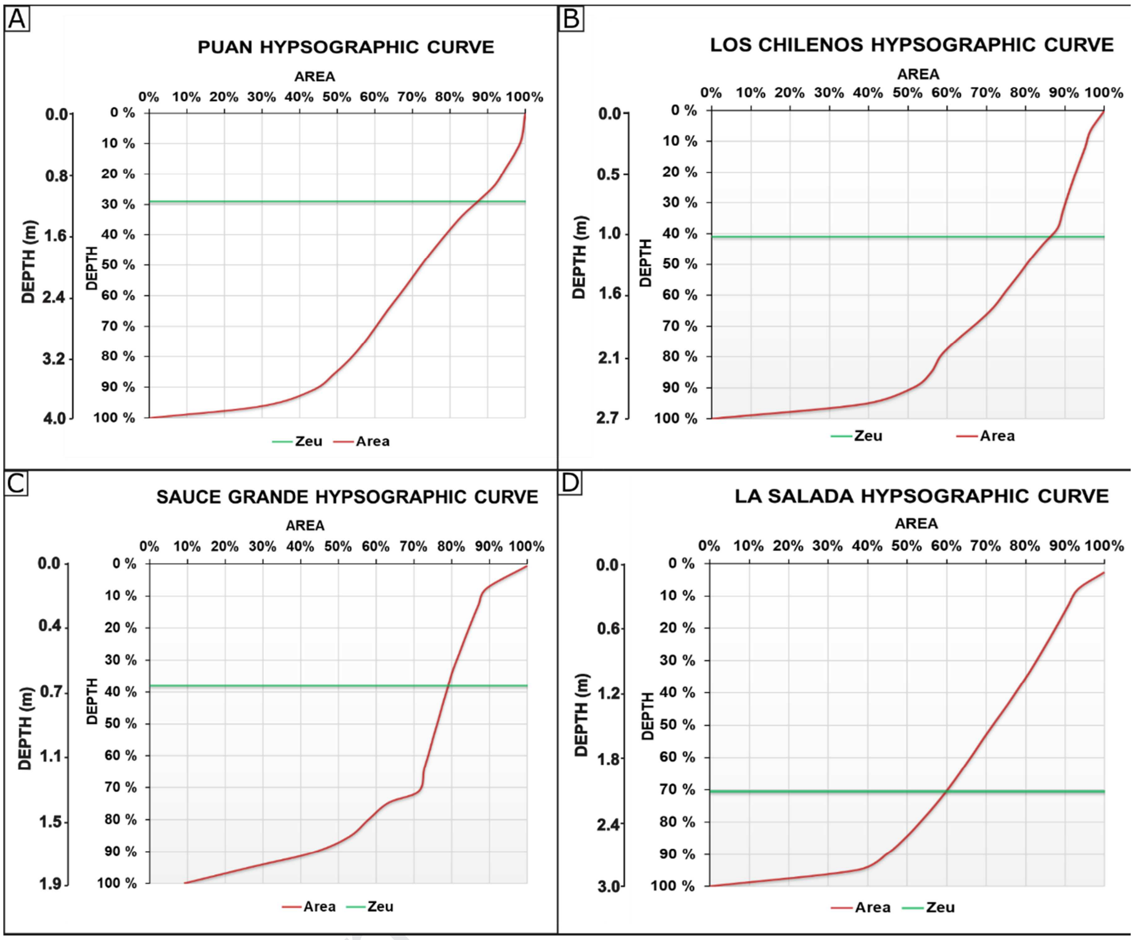



***Figure 5:*** *Hypsographic curves for the four shallow lakes: a) Puan; b) Los Chilenos; c) Sauce Grande and d) La Salada.*

APPROXIMATION OF SEDIMENT RESUSPENSION AND DELIMITATION OF THE LITTORAL AND PELAGIC AREAS UNDER REGULAR FLOOD CONDITIONS

The hypsographic curve and the slope map of Puan (Fig. 6a) show that the higher slopes are restricted to the coastal zone. Predominant slopes are between 0.4 to 2% but they can reach up to 4%. The deepest area is relatively flat (0.4%), and represents approximately 50% of *A* (Fig. 6.a). The $Z_{eu}$ is 1.16 m, thus the littoral zone is of 1 km$^2$ (15.7% of *A*), distributed homogeneously along the coast, and the pelagic area is of 5.6 km$^2$ (84.3% of *A*) (Fig. 7.a). The $Z_{wc}$ is 1.2 m which means that with the average wind speed, sediment resuspension would affect only 10% of the lake (Fig. 8.a), but it can rise to 6.7 m during times of maximum wind speed (15 m/s), which would indicate that under this conditions sediment resuspension occurs in the entire lake. The *DR* and *ET-area* show that wind erosion and transport processes affect 60% of the lake area and predominate over the slope processes. The $Z_{mv}/Z_{eu}$ ratio of 1.03 indicates that the lake is slightly turbid.

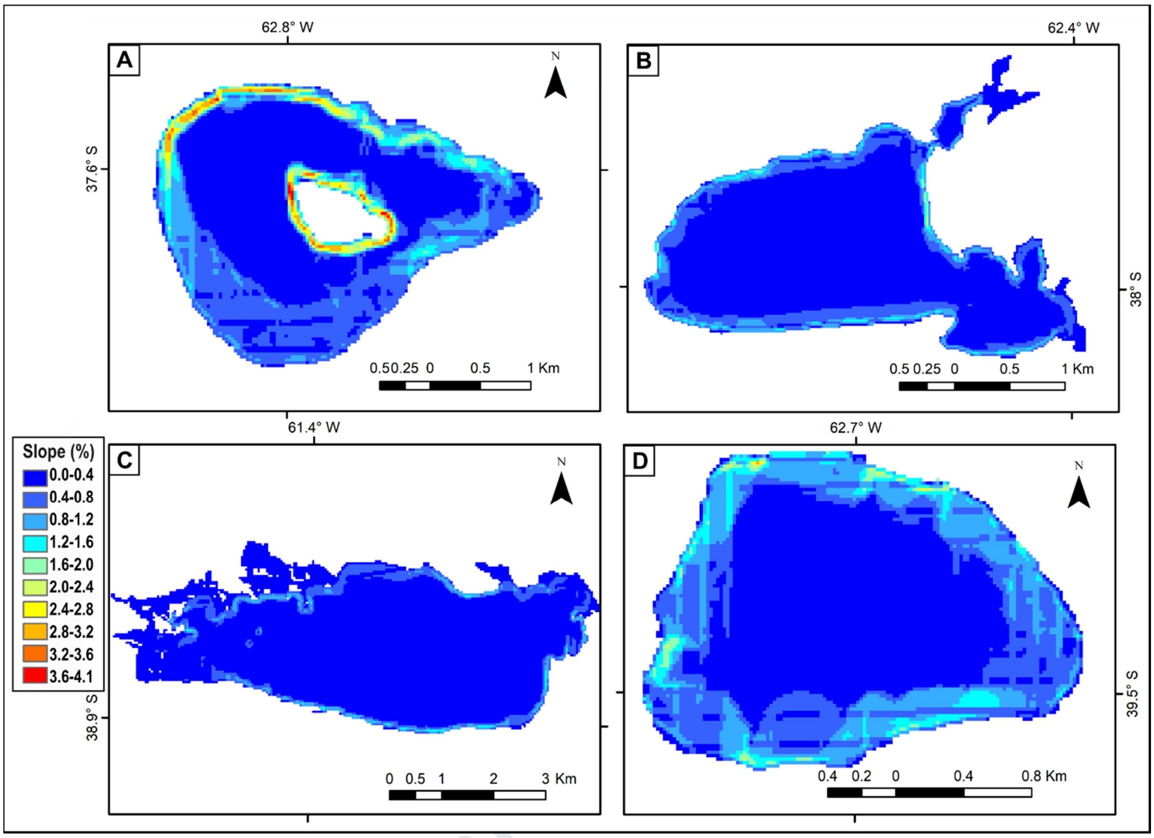



***Figure 6:*** *Delimitation of the slope in the studied lakes a) Puan; b) Los Chilenos; c) Sauce Grande and d) La Salada (Source: Own elaboration based on bathymetric information).*



The highest slopes of Los Chilenos is 1.2% (10-15% of *A*) and most of its bottom is relatively flat (55%) (Fig. 6.b). The $Z_{eu}$ is 1.07 m; the littoral zone is 0.8 km$^2$ (15% of *A*), and the pelagic zone is 4.28 km$^2$ (84% of *A*) (Fig. 7.b). The littoral area is larger near the entrance of the Cochenleufú stream and at the headwater of the Chasicó stream (Fig. 7.b). The $Z_{wc}$ is 1.3 m based on the average wind speed (Fig. 8.c) indicating that sediment resuspension occurs approximately in 20% of the lake (Fig. 8.c). Considering the maximum wind speed (16 m/s) $Z_{wc}$ rise to 7.9 m, under these conditions sediment resuspension would occur in the entire lake. *DR* and *ET-areas* show that wind erosion and transportation affect 83% of the lake area and predominate over slope processes. The $Z_{mv}/Z_{eu}$ ratio of 0.67 indicates that it is a clear water lake.

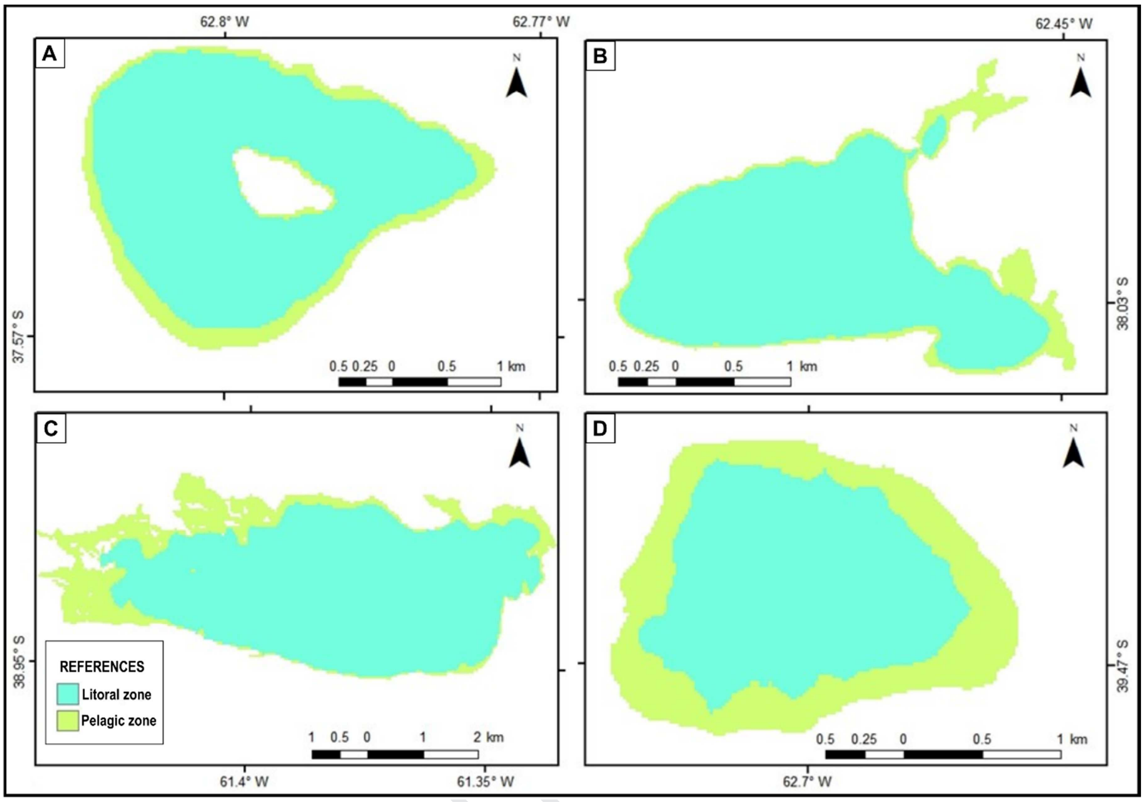
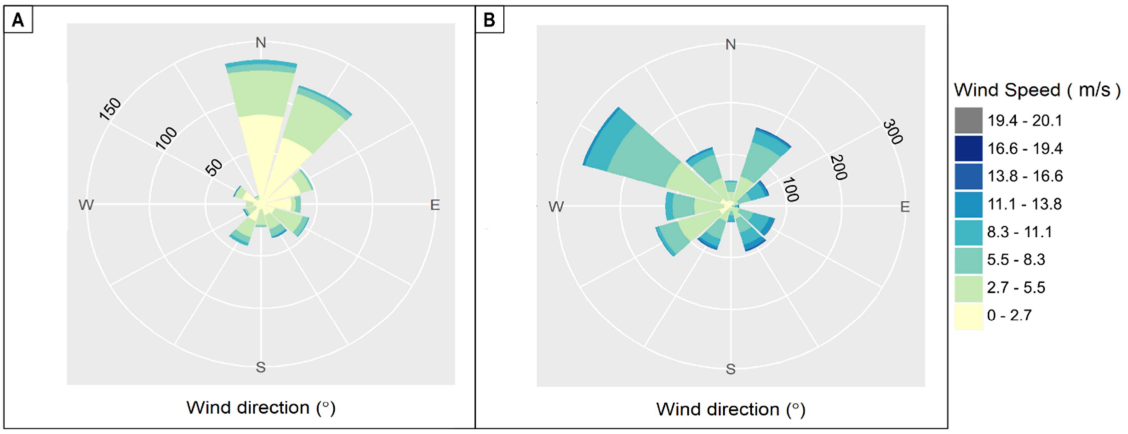



***Figure 7:*** *Distribution of the littoral and pelagic areas of the lakes a) Puan; b) The Chilenos; c) Sauce Grande and d) La Salada (Source: Own elaboration based on bathymetric information and* $Z_{eu}$*).*

Sauce Grande has slopes lower than 1.2% in the littoral and the deeper zone is overall flat (> 0.4%) (70% of *A*) (Fig. 6.c). The $Z_{eu}$ is 0.4 m thus the littoral zone is of 4.6 km$^2$ (21% of *A*) mostly developed in the inflow and outflow of the streams, and the pelagic area is of 16.7 km$^2$ (78% of *A*) (Fig. 7.c). Based on average and maximum wind speed (4.63 and 19 m/s, respectively), $Z_{wc}$ is 2.1 m and 9.5 m respectively (Fig 8.c) and thus include the entire water column of the lake (Fig 8.c). The *DR* and *ET-area* parameters show that erosion and transport processes affect 100% of the lake. The values of *DR* and *ET-areas* are outliers (DR> 4) (Håkanson 2012), and are due to the large area compared to the low average depth of the lake (Table 5). The $Z_{mv}/Z_{eu}$ ratio of 1.45 indicates it is a turbid lake.




C

| | Mean wind direction | Mean wind speed (m/s) | Maximum speed (m/s) | Maximum Fetch (m) | Wavelength (m) | Critical depth (m) |
|---|---|---|---|---|---|---|
| Puan | N , NE | 3.09 | 15 | 2800 | 2.3 | 1.2 |
| Los Chilenos | NNW | 3.05 | 16 | 3500 | 2.5 | 1.3 |
| Sauce Grande | NNW, SSW, SE | 4.63 | 19 | 3500 | 4.1 | 2.1 |
| La Salada | WNW, NNW, NNE | 6.90 | 30 | 2500 | 5.1 | 2.6 |

***Figure 8:*** *a) Wind rose from weather station close to Puan and b) Wind rose from La Salada buoy; c) Table indicating the direction and average wind speed prevailing in each lake, maximum fetch associated with the most frequent wind direction, the corresponding wavelength and critical depth for the average wind speed (see supplementary material).*

La Salada has slopes between 0.4 - 3.2% in the littoral area whereas, the deeper zone is flat (> 0.4%) (40% of *A*) (Fig. 6.d). The $Z_{eu}$ is 2.1 m and the littoral area of 1.44 km$^2$ (39.8% of *A*), which develops homogeneously around the nearshore; the pelagic area is 2.8 km$^2$ (60.2% of *A*) (Fig. 7.d). The $Z_{wc}$ is 2.6 m based on the average wind speed (6.9 m/s) indicating that the waves affect 80%of the lake (Fig. 8.c). The $Z_{wc}$ increases to 13.1 m when considering the maximum wind speed (30 m/s), which means that the entire lake is affected by waves. The *DR* and *ET-area* parameters indicate that sediment erosion and transport occur in 57% of the lake area (Table 5). The $Z_{mv}/Z_{eu}$ ratio is 0.43, which indicates it is a clear water lake.

Winds analysis shows that in Puan and Los Chilenos, the wind intensity below 5 m/s are frequent while wind speed higher than 10 m/s occurs rarely and corresponds to isolated and short duration gusts (see supplementary material). On the contrary, at La Salada and Sauce Grande low wind speed < 10 m/s occurs frequently and winds speed between 10-20 m/s are less common (14%). These facts are significant considering that with a wind speed of 5 m/s in Puan, and Los Chilenos, the area affected by resuspension will be 50% and 80%, respectively. Wind speed of 5 m/s influence 65% of La Salada and the entire area in Sauce Grande, while wind speeds of 10 m/s generate resuspension in the entire lake in La Salada and Sauce Grande.

VARIATION IN MORPHOMETRIC PARAMETERS AND RESUSPENSION PROCESSES DURING DRY PERIODS

The selected extreme climatic events for each lake are presented in Fig. 9. The *A* of each lake during the wet and dry periods, and the difference in *A* are summarized in the Table 6 and presented in Fig. 10. We estimated the *ET-areas*, $Z_{wc}$, area under erosion and littoral and pelagic area considering the morphometric parameters during drought. Then we compared the results with those obtained from normal flood conditions as reference (Table 5). The dry event produced a decrease in the *ET-areas* and the $Z_{wc}$ in Puan (Table 6). Despite less $Z_{wc}$ the area affected by wave erosion increase. In addition, the littoral area increase. In Los Chilenos the *ET-areas* increased. Although the $Z_{wc}$ is lower the area under erosion increases and the littoral area decreases (Table 6). In Sauce Grande the *ET-areas* and the $Z_{wc}$ showed that resuspension process affects the whole lake and there was a decrease in the littoral area (Table 6). This analysis could not be carried out in La Salada since a significant variation in its surface was not observed.

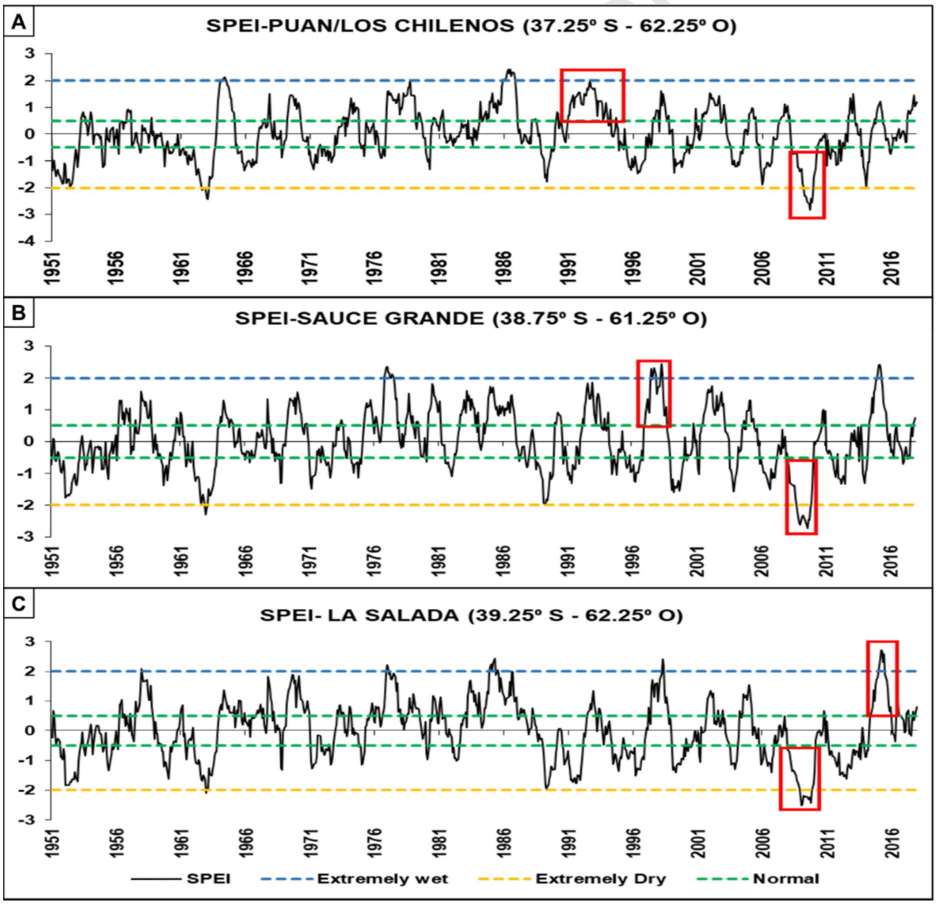



***Figure 9:*** *SPEI index between 1951-2017 at 12M scale for a) Puan / Los Chilenos b) Sauce Grande and c) La Salada; in red are the selected wet and dry periods.*

***Table 6**: Variations in lake's area during the selected wet and dry periods. In bracket, for comparison, are indicated the values obtained from the bathymetry.*

| | ***A*** **during the wet period (km²)** | ***A*** **during the dry period (km²)** | **Difference in *A* between dry and wet periods (%)** | **ET-areas during dry period (%)** | **Zwc (m)** | **Area affected by waves during dry periods (%)** | **Littoral area dry period** |
|---|---|---|---|---|---|---|---|
| **Púan** | 7.9 | 6.4 | 19.0 | 52 (60) | 1.1(1.2) | 15 (10) | 23.8 (15.7) |
| **Los Chilenos** | 6.6 | 4.7 | 28.8 | 96 (83) | 1.2 (1.3) | 27 (20) | 13 (15) |
| **Sauce Grande** | 20.7 | 17.8 | 14.0 | 100 (100) | 2 (2.1) | 100 (100) | 5.9 (21) |
| **La Salada** | 3.7 | 3.6 | 2.7 | - | - | - | - |

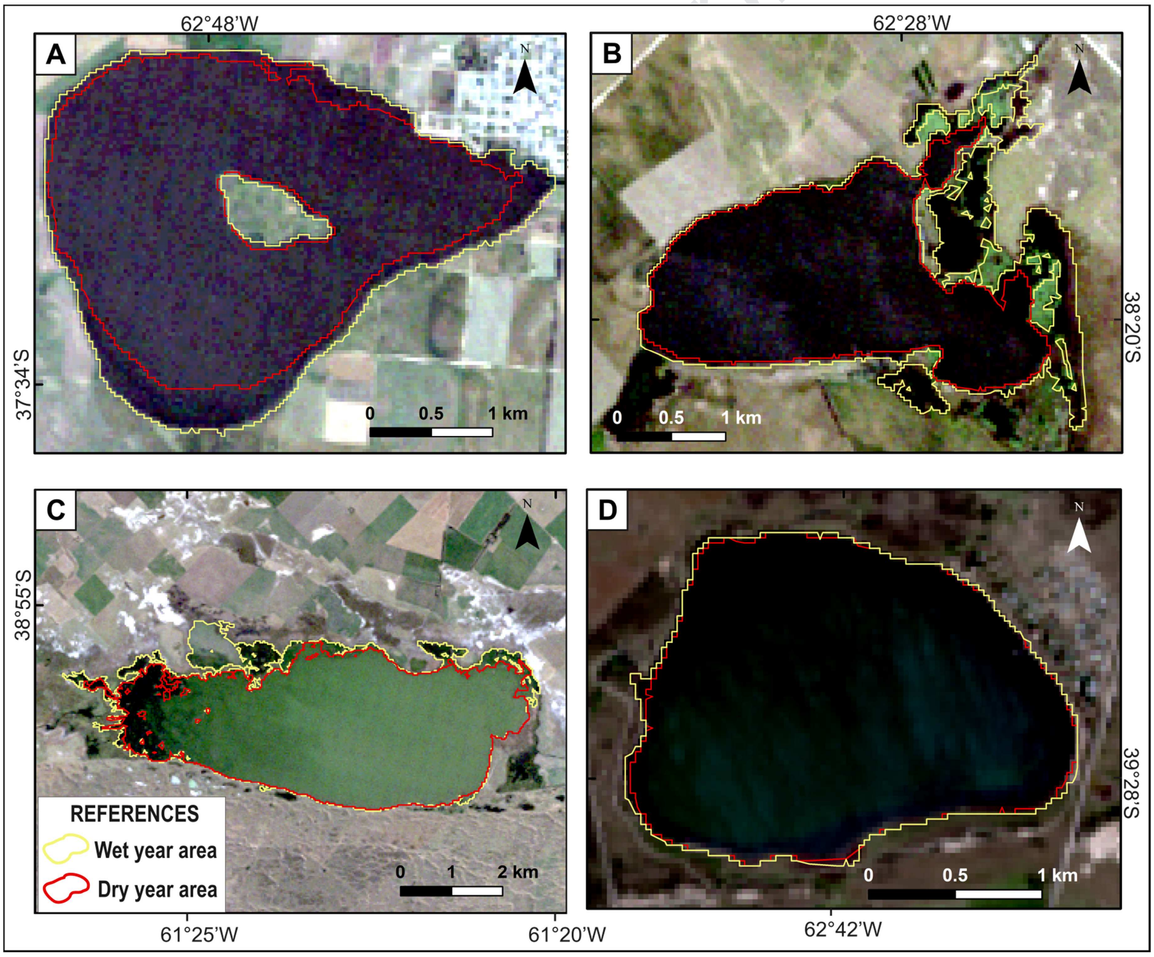



***Figure 10:** Variations in lake A during extreme wet (yellow line) and dry periods (red line) (Determined in this work). a) Puan; b) Los Chilenos c) Sauce Grande; and d) La Salada. The background*

*satellite images correspond to the Landsat image used to the determination of the lake area during humid periods (see detailed information in methodology).*

## DISCUSSION

The USV used here demonstrated autonomy to survey large surface as great as Sauce Grande shallow lake (20.4 $km^2$) and without need wireless radio connectivity. In addition, the equipment cost (U$S 800-100) (Genchi et al. 2020) is very affordable compared to the traditional equipment needed to survey shallow lakes. Also the USV have almost no maintenance cost and the relationship between cost and benefit is very high, as was demonstrated by the results of this work. In that sense, the USV motor and electronic system worked without issues a total distance of 111 km (20.5 h of work) and was not needed exchange the batteries in most of the cases, which allow determining their efficiency and operability. Also, the device was operated by one person from the shore of the lake, which reduced the risk of people being in the water and also reduced the cost compare to the traditional bathymetric methodology which generally includes a boat with two persons (one for driving the boat and the second one for taking care of the echosounder). In addition, the shallow draft of the USV (0.15 m) used in this study made possible to explore very shallow (0.3 m) in high accuracy. The capacity to explore the very shallow depths is very important in shallow lakes that have extended and very shallow littoral zones.

The four waterbodies studied shared a similar basin morphology with gentle slopes and flat bottom; $Z_{mv}$ is 70% of their maximum depth, which is typical of Pampean lakes (Quirós 2005). $Z_r$ was extremely low in all lakes, which is explained by their large extent and shallow depth. The $A_w/A$ ratio was small in Puan and La Salada and high in Los Chilenos and Sauce Grande which indicates that Sauce Grande and Los Chilenos are highly influenced by erosion and transportation processes on the watershed, thus explaining their higher turbidity, suspended particulate matter, and hypereutrophic conditions reported by Cony et al. (2014) and Bertora et al. (2016). Also, a high proportion of the watershed of Los Chilenos and Sauce Grande is used for agricultural activities and thus their soils are poorly vegetated. Under these land use/land cover conditions sediment and nutrients may be easily eroded by runoff.

The existence of slopes less than 4% and *DR* greater than or close to 4 (and > 0.05) in all lakes suggests that the areas of sediment erosion and transportation are caused by waves (Håkanson 2004). The approximation of sediment resuspension using $Z_{wc}$ indicated that under mean wind intensity sediment resuspension occurs in 10 to 100% of the lakes' bottom area. Sauce Grande and La Salada were the lakes most affected by sediment resuspension under mean wind conditions (4.63 and 6.09 m/s, respectively), and this is explained by their location in a windy climatic region. Puan was the lake least affected by sediment resuspension under those wind conditions. It should be noted that these percentages are overestimated since they reflect the surface of the entire lake whose depth is less than $Z_{wc}$; resuspension processes, on the other hand, would only take place in the area where the distance from where wind blow (fetch) produces waves capable of reaching the bottom of the lake ($Z_{wc}$). Sediment resuspension is evident in Sauce Grande. This lake is hypereutrophic and has high turbidity associated with bottom particulate material and nutrients present in the water column. Cony et al. (2014) found that despite the high phytoplankton abundance in Sauce Grande, its turbidity is mostly of inorganic matter due to low depth and resuspension of sediments by wind.

The turbidity of the lakes (indicated by secchi disk) was closely related with their morphometry (lake area, depth, fetch) and watershed area. La Salada has low turbidity, and the suspended solids are mostly organic (70 %) (Zunino 2018), despite being subjected to the same wind conditions as Sauce Grande. This is probably due to the presence of charophytes rooted in its bottom, which reduce or nullify the influence of the waves, even under maximum wind conditions (Alfonso 2018; Seitz 2019). Charophytes play a significant role as they take available nutrients and prevent sediment resuspension inhibiting phytoplankton development and increasing water clarity (Blindow 1992; Osmon 2008). According to the $Z_{mv}/Z_{eu}$ ratio, Puan and Sauce Grande are turbid, while Los Chilenos and La Salada are clear lakes. Lakes that have a Zmv/Zeu ratio low or close to 1 and low slopes (< 5.33 %) make them adequate for the development of aquatic plants (Duarte and Kalff 1986; Quirós et al. 2002). Despite the favorable for the development of aquatic plants in all the studied lakes (except for La Salada), are turbid without vegetation. Scheffer et al. (1993) proposed that the lake can experience stable ecosystem states between one dominated by phytoplankton (turbid water) and other dominated by macrophytes (clear water), between these extremes can exist other less evident (Scheffer and van Nes 2007). Changes in lake size, depth, and climate affect the critical nutrient level and thus can push the ecosystem into a regime shift (Scheffer and van Nes 2007). Water level changes can cause regime shift depending on the lake morphology, the physical-chemical and biological characteristic associated with water level change (e.g salinity and turbidity) and the relationship between water level change and aquatic plant germination (Coops et al. 2003; Casco et al. 2009). Also, there is evidence that small shallow lakes are more prone to keep a clear vegetated state due to their higher critical nutrient for becoming turbid and low fish biomass (Scheffer and van Nes 2007); this is true for La Salada. On the other hand, lakes with large area and fetch, as Los Chilenos and Sauce Grande, are prone to develop stronger waves, preventing the growth of macrophytes (Wallsten and Forsgren 1989) and favoring the incorporation of nutrient in the water column, and thus causing turbid lake conditions.

In this study, we found that lakes that have a different origin have different morphology and consequently, different dynamics of their internal processes (e.g. sediment resuspension). Compared with lakes that have a polygenetic origin, eolian lakes have small basins and watersheds, larger littoral areas, and their morphological characteristics ($A$, $Z_{max}$, $Z_{mv}$, etc.) make them less vulnerable to sediment resuspension and drought events. Also, under similar wind conditions, lakes from eolian origin are less affected by sediment resuspension because of their small lake area, thus small wind fetch, and higher depth, which reduce the chance of sediment resuspension. Besides the lake's origin, we argue that wind-induced sediment resuspension is another important factor determining the physical processes that affect the lakes. The SPEI analysis showed that $A$ in Puan, Los Chilenos and Sauce Grande changed significantly under extreme climatic conditions. The small changes recorded in La Salada contradict observed changes in fieldwork recorded by the authors; this is explained possibly by the combination of a low spatial resolution of the Landsat images and the lake basin morphology. Also, La Salada receives water from an irrigation channel from 1 August to 1 May (Alfonso et al. 2018) when there is an excess of water after the crop irrigation. This fact also could have masked the effect of the drought period on the lake.

Changes in the *A* of the lakes must be evaluated considering other morphological and limnological parameters. That is because similar changes in the *A* of water bodies with different morphometry may have different effects on the functioning and internal structure of the lakes. During a drought period in Puan and Los Chilenos (located in the same climatic sub-region) there was a decrease in *A* of 4.4 and 4%, respectively compared with the bathymetric maps produced in this study. These variations represented a drop in the water level of 70 cm in Puan and 55 cm in Los Chilenos. However, although the drop in the water level was higher in Puan, the decrease in Los Chilenos represented a higher percentage (20%) of its total depth. This fact seems to have had severe implications in the functioning of Los Chilenos since during this period massive fish mortality was documented and there was an important decrease in fish population in the following year after the dry period (Bertora et al. 2016, Berasain et al. 2017) while in Puan a large and healthy fish community was reported during the same drought (Argemi et al. 2009). The drought could have led to a decrease in the littoral area which may have affected the fish population. The littoral habitat provides refuge for adult fish reproduction and for juveniles to feed (Kopprio et al. 2010). The drought could have led to eutrophication in the lake due to the increase of resuspension and concentration in nutrients. If the algae community composition was dominated by toxic cyanobacteria, which are non-palatable for zooplankton, this may have reduced fish food. Also an algae bloom, or an increased in water temperature due to a reduction in lake water volume could have caused anoxic conditions with deadly consequences for fishes (Kroppio et al. 2010). In Puan, the littoral increased at the expense of pelagic area during the dry period, while the opposite occurred in Los Chilenos and Sauce Grande. This different response is associated with the lake's basin morphology: Puan, has gentler and larger slopes, especially in its southern coast, while in Los Chilenos and Sauce Grande slopes are steeper.

Regarding the influence of drought events on sediment resuspension, we observed that in Puan and Los Chilenos, there was an increase of the erodible area of around 5 and 7% respectively as water depth lowered. In Sauce Grande, the whole lake continued to be subjected to resuspension processes during dry conditions despite the decrease in the fetch, most likely due to its shallow depth, large extension and its location in a windy climatic sub-region.

These results are important in the context of future scenarios of climate changes. Prediction suggests an increase in the frequency of extreme El Niño–Southern Oscillation (ENSO) events over the next 50 years (Cai et al. 2015) which will favor the regional evaporation and decrease in area. Our results show that a reduction in the lake area favors sediment resuspension and modifies the distribution of the littoral and pelagic areas. Other studies have shown that shallow eutrophic lakes with the intensification of ENSO events could result in synergistic adverse effects with nutrient pollution, higher internal loading, more toxic cyanobacteria communities, and an altered assemblage of zooplankton (Havens and Jeppesen 2018). While regular water mixing prevents cyanobacterial blooms of buoyant species (as *Microcystis aeruginosa*) even in a high trophic level lake, sediment resuspension by storm events can favor their blooming by nutrient resuspension. Therefore, the interactions between eutrophication, warming, and wind regimes can have unexpected effects on cyanobacterial dynamics in shallow lakes (Blottiere 2015). Also, increasing turbidity or prolonged turbid periods may affect the predation pressure from planktivorous fish, and consequently, the composition of the zooplankton community (Zehrer et al. 2015). In this work we saw that drought events not only reduce the volume of water, but also modified the littoral and pelagic zones and increase sediment resuspension. These potential threats could have a significant impact on the ecosystem services provided by the Pampean lakes, in particular, the preservation of the native species as the pejerrey *Odontesthes bonariensis* (Kopprio et al. 2010). Therefore, more integrated studies considering the morphometric changes, physical-chemical and biological characteristic of the lake and the meteorological and hydrological variations are needed to understand the complexity of the Pampean shallow lakes and forecast the effect of global warming and define the adequate management strategies to reduce their risk.

## CONCLUSION

Our results indicate that even small changes in the depth of shallow lakes could increase sediment resuspension and therefore possibly increase in water turbidity, nutrient resuspension, and pollutants with consequences in the lake productivity. We carried out our study using an Unmanned Surface Vessel (USV) developed by a member of the research group, which demonstrated to be an accurate and inexpensive tool to study the bathymetry of shallow lakes. The results obtained here show that future studies should consider changes in depth related to dry and wet periods as one of the principals responsible for changes in the shallow lake ecology.

In the Pampean region, lakes of polygenetic origin have bigger watersheds and their morphological characteristics are relatively more influenced by the processes that occur in their catchment. Under the same wind conditions, and due to their morphologic characteristics, polygenetic lakes are more affected by sediment resuspension processes and have smaller littoral areas than eolian lakes. In that sense, we found that sediment resuspension induced by wind generated waves is one of the main factors affecting the ecosystem of the Pampean lakes. That is particularly important in the windy, semiarid sub-regions.

All the studied lakes respond to extreme climate conditions. Their sediment resuspended by wind increases during drought events, despite a reduction in fetch. This phenomenon is particularly important in those lakes that are very shallow and with a great area under high wind intensity. During dry periods eolian lakes presented an increase in the littoral area whereas in the polygenic lakes, the pelagic zones increased. This difference is because in the former the slopes of the lake basin are less steep.

Future studies in the Pampean shallow lakes should involve the modeling of sediment resuspension induced by wind in the analysis of physical-chemical and biological parameters, in particular, if it is intended to preserve or recover ecosystems that are located in regions with high wind influence. This is especially important in the context of global warming, since there is numerous evidence of the influence of this process on these ecosystems.

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**HIGHLIGHTS**

- Drought events have differentiated effects depending on lake morphology.
- Dry periods caused a decrease in lake' volume and increased sediment resuspension
- Dry periods modified the distribution of littoral and pelagic zones
- The USV is an accurate and low-cost tool to study the bathymetry of shallow lakes

Author statement

Seitz: Conceptualization; Data curation; Formal analysis; Roles/Writing - original draft; Visualization; Methodology; Visualization; Writing - review & editing; Project administration.

Scordo: Conceptualization; Roles/Writing - original draft; Investigation; Methodology; Visualization; Writing - review & editing.

Vitale: Conceptualization; Funding acquisition; Resources; Software; Methodology; Investigation; Writing - review & editing.

Vélez: Conceptualization; Funding acquisition; Supervision; Writing - review & editing.

Perillo: Conceptualization; Funding acquisition; Supervision; Writing - review & editing.

**Declaration of interests**

☒ The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

☐The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

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