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CASO PRÁCTICO

Surface water extent dynamics from three periods of continuous Landsat time series; subregional differences across Argentine plains

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Abstract: The Pampean region in Argentina is an extensive plain characterized by abundant shallow lakes that fulfill many environmental, ecological, and social functions. This study aims to detect the multiannual lake area changes in this region during 2001-2009 using remote sensing, including lakes as small as ≥10,000 m^2 or 1 ha. Landsat scenes of the wet (2008-2009), normal (2006), and dry (2008-2009) seasons were obtained, and using remote sensing techniques, the number and area of shallow lakes were calculated. The spatiotemporal variation of shallow lakes was studied in different climate periods in eight singular subregions. Spatial associations between annual precipitation and lake number and area were analyzed through the development of a Geographic Information System (GIS) at a subregional scale. During the study period the total lake area in the Pampean region decreased by 5257.39 km^2 (62 %), but each subregion showed different responses to climatic events. In seven of them, the differences between climate periods prove to be statistically significant (P>0.01). The relationship between precipitation and lake number and area revealed the domain of positive association. We conclude that climate factors play a dominant role in lake changes across the Pampean plains. However, other factors such as origin, topographic and edaphic characteristics intensify or mitigate changes in surface hydrology.

Key words: Landsat, surface water dynamic, climate variability, Pampean lakes, Argentina.

Dinámica de aguas superficiales de tres períodos continuos de Landsat; diferencias subregionales en llanunas argentinas

Resumen: La Región Pampeana en Argentina es una extensa planicie caracterizada por abundantes lagunas que cumplen numerosas funciones ambientales, ecológicas y sociales. Este estudio tiene como objetivo detectar los cambios plurianuales del área lagunar en esta región durante el período 2001-2009 utilizando la teledetección, incluidos lagos tan pequeños como ≥ 10.000 m^2 o 1 ha. Se obtuvieron escenas Landsat de las estaciones húmeda (2008-2009), normal (2006) y seca (2008-2009) y, mediante técnicas de teledetección, se calculó el número y el área de las lagunas. Se estudió su variación espacio-temporal en diferentes períodos climáticos en ocho

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subregiones singulares. Se analizaron las correlaciones espaciales entre la precipitación anual y el número y el área de los lagos mediante el desarrollo de un Sistema de Información Geográfica (SIG). Durante el período de estudio el área total de lagos en la región pampeana disminuyó en 5.257,39 km^2 (62 %), pero cada subregión mostró diferentes respuestas a los eventos climáticos. En siete de ellos, las diferencias entre periodos climáticos resultan estadísticamente significativas (P>0,01). La relación entre la precipitación con el número y área de las lagunas reveló el dominio de asociaciones positivas. Si bien el clima juega un papel dominante en los cambios en las lagunas de planicie, otros factores, como el origen, las características topográficas y edáficas, intensifican o mitigan los cambios en la hidrología superficial.

Palabras clave: dinámica de aguas superficiales, variabilidad climática, lagunas Pampeanas, Argentina.

1. Introduction

Surface water dynamics have an essential role in physical, geochemical and biological processes that affect biota, water supply, transport, and energy balance (Pricope, 2013; Vincent et al., 2013). Small fluctuations in weather patterns affect the behavior of inland waters, although the specific effects vary according to their ecosystem and morphology. Hydrological processes on extensive plains differ considerably from those that characterize the mountain areas, mainly due to the low morphological energy (Zhang et al., 2017; Deng et al., 2018). In plain areas, water moves as a stratum or slightly channeled, mobilized by the local slope, rain, and wind direction. Temporary floods allow the superficial accumulation of salt and the development of swamps or puddles (Hu et al., 2017; Kumar et al., 2017).

Remote sensing is widely used for mapping surface water extent, because of data scarcity and access limitations in large regions (Jones et al., 2011; Rover et al., 2012; Roach et al., 2013). Spatial variations studies of shallow lakes are highlighted in large surfaces such as Sweden, Siberia, United States, Canada, among others; related to their resources and physical processes (Hein et al., 2012; McDonald et al., 2012; Karlsson et al., 2014, Mohsen et al., 2018). Landsat imagery is one of the most common types of data employed for mapping surface water (Tulbure et al., 2016). Spatial dynamics of shallow lakes on the Canadian plains were studied using Landsat images with different classification methods and periods. These results showed an increasing trend in their areas for 26 years (Olthof et al., 2015).

In the Tibetan plateau, Zhang et al. (2017) found new lakes and extensive lake expansion on the Tibetan Plateau during the last four decades due to increased precipitation and cryosphere contributions to water balance. This contrasts with disappearing lakes and drastic shrinkage of lake areas on the adjacent Mongolian Plateau. It showed that two adjacent plateaus have been changing in opposite directions in response to climate change, which suggests that there would be other factors affecting the dynamics of lakes. These studies show the multiple roles of regional climate and water cycles and provide useful information for planning water resources in these fragile landscapes (Zhang et al., 2017).

In the Pampean region, Argentina, shallow lakes are a prominent feature of the landscape and primary areas of the ecosystem balance. Deflation basins and eolian depression harbor permanent and temporary lakes that function as recharge or discharge points for groundwater (Gerten and Adrian, 2000, 2001; Quirós et al., 2002). This region is characterized by the occurrence of long periods of drought and floods, which affects water availability. Size distribution studies of shallow lakes considering a wide range of physical variables over large areas are not very frequent (Kling et al., 2000). Obtaining data on lake size and distribution is a necessary step for modeling regional ecosystem processes during different climate periods. Previous studies showed the influence of climate events on specific lakes, mainly explained by the annual precipitation in situ, although the response was not the same in all cases (Aliaga et al., 2016; Bohn et al., 2016; Brendel et al., 2020). In such an extensive region, the different lake responses may or may not be related to climate variability. Therefore, other factors or processes could explain the different spatiotemporal dynamics of the Pampean lakes.

Studies regarding the spatiotemporal variability of lakes in this region were usually at the local scale in a specific lake or at basin level (Canziani et al., 2019; Maestri et al., 2019; Zunino et al., 2019; Pisano et al., 2020; Solana et al., 2021). Few works study the evolution of the physical characteristics of the lagoons concerning climate variability at the regional level. A satellite application could be useful to obtain knowledge of the spatiotemporal variations of the lakes in large and heterogeneous extensions. This study was addressed to evaluate whether the influence of the different climate periods on the spatiotemporal fluctuations of shallow lakes is similar in the entire Pampean region. Furthermore, to understand the processes that could explain the dynamics of the region, other factors such as topography and soil condition were considered, using remote sensing data and Geographical Information System (GIS) techniques.

2. Methodology

2.1. Study area

The Pampean region is a large plain in the center-east of Argentina with abundant water resources (Figure 1a). It has an extension of 613,532 km^2 and includes various provinces (Figure 1). Precipitation decreases from northeast (1500 mm/year) to southwest (400 mm/year) and determines the passage from a warm and humid climate to a semi-arid one. A marked seasonal rainfall predominates in all Pampean regions with the highest precipitation in the spring and summer months (September to March in the southern hemisphere). Annual and seasonal rainfall amplitude decreased from northeast to the southwest (Aliaga et al., 2017).

Shallow lakes with a surface between 500 and 100,000 m^2 predominate (Geraldi et al., 2011); they are highly fluctuating in salinity and water restoration time in function of the characteristic cycles of drought and flood. They consist of swamped areas with vegetation, wetlands, and the main shallow lake. Some of the lakes are connected during rainy periods forming up linear flow networks, whereas in dry periods they are disconnected from each other. The precipitation variability is qualitatively significant and can alter these ecosystems. Early works define the climate of the Pampean region as temperate humid-subhumid (Aliaga et al., 2016), but recent studies show the climatic heterogeneity in the area defining climatic subregions (Aliaga et al., 2017).

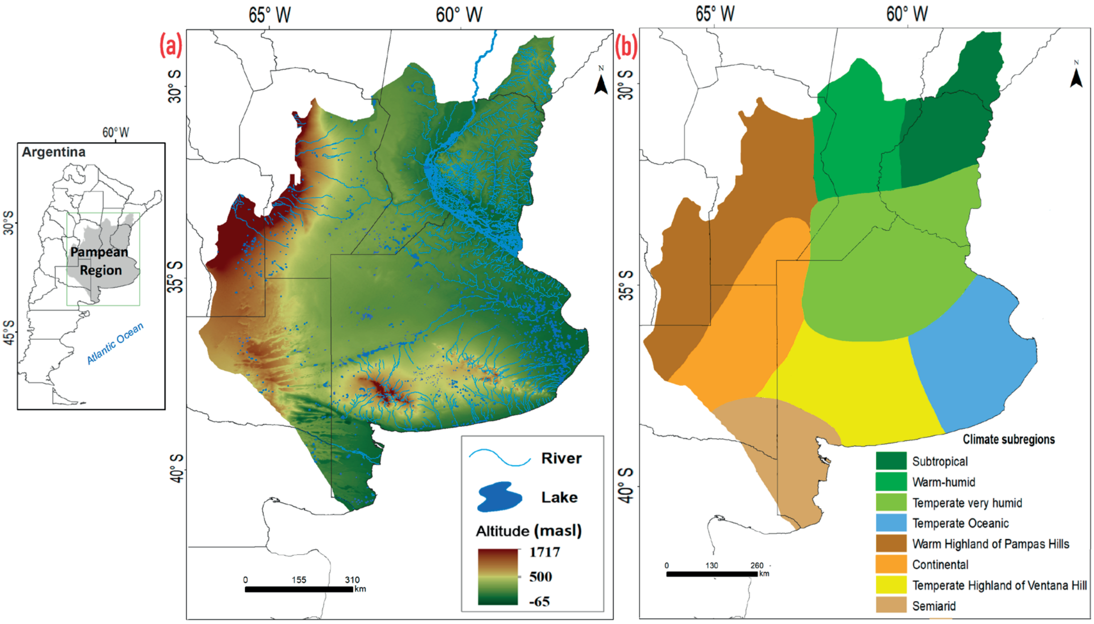

Figure 1. Location of (a) Pampean region, Argentina and (b) Pampean climatic subregions (Modified from Aliaga et al., 2017).

The Pampean region has eight climate subregions (Figure 1b) named: *Subtropical* (S), *Warm humid* (WH), *Temperate very humid* (TH), *Temperate Oceanic* (TO), *Warm Highland of Pampas Hills* (WPH), *Continental* (C), *Temperate Highland of Ventana Hill* (TVH) and *Semiarid* (SA).

In this region there are two important highland areas, the Pampean (north-east) and the Ventania (center-south) systems, which coincide with subregions WPH and TVH, respectively (Figure 1). The north, northeast and east of the Pampean region contain an abundant development of rivers, streams and coastal lakes linked to saturated and temporarily flooded areas. The south and west show the prevalence of eolian depressions (Table 1). Four taxonomic orders of great predominance were identified but Mollisols dominant with a significant presence of organic matter in temperate-humid to semi-arid climates (Geraldi et al., 2011). The amount and size of the present inorganic substances affect infiltration, soil aeration, and permeability, among others. In the Pampean region, limitations by water erosion and poor drainage have been reported in the

Table 1. Topographic and hydrographic characterization, soil taxonomy, texture, surficial drainage capacity, and main limiting factors in soils in the eight studied zones (Figure 1) in the Pampean region.

Zone	Climate	Topography	Hydrographic	Soil Taxonomy	Soil Texture	Surficial Drainage	Main limiting Soil
S	*Subtropical*	Great flatness and plains	Alluvial plains and dense hydrographic network	*Mollisols* *Alfisols* *Entisols*	Clayey	Moderate to poor	Water erosion, poor drainage, shallow effective depth.
WH	*Warm humid*	Plains with wavy relief	Dominance of stream dynamics	*Mollisols* *Alfisols* *Entisols*	Silty - sandy	Moderate to good	Low slope and permeability, poor drainage.
TH	*Temperate very humid*	Plains to slightly wavy topography	Arheic basin; permanent and intermittent shallow lakes	*Mollisols* *Alfisols*	Sandy - clayey	Excessive	Water erosion, poor drainage, and alkalization.
TO	*Temperate oceanic*	Wide and asymmetric eolian depression surrounded by wavy plains and hills	Deflation basin along the coast; shallow lakes on previous tidal channels	*Mollisols* *Alfisols* *Entisols*	Sandy - clayey	Good	Surface alkalization, poor drainage.
WHP	*Warm highland of the Pampas Hills*	Environment and landscape of the Pampean hills.	Fluvial valleys; permanent and intermittent shallow lakes on aeolian depressions	*Mollisols* *Alfisols* *Entisols*	Sandy - clayey.	Good to excessive	Climate, wind erosion, poor drainage.
C	*Continental*	Flat to slightly undulating relief near large rivers	Small shallow lakes over eolian depressions between dunes	*Mollisols* *Alfisols* *Entisols*	Sandy - Silty	Excessive	Climate, wind erosion.
TVH	*Temperate highland of the Ventana Hillsl*	Concave topography. Great radial depression in the east of Buenos Aires province	Tectonic, fluvial, and eolian processes originating lakes; chained and aligned distribution along structural faults	*Mollisols* *Alfisols* *Entisols*	Sandy	Excessive to moderate	Shallow effective depth, wind erosion, climate.
SA	*Semiarid*	A predominant slightly wavy plain. Tectonic faults in the east-west. Strong eolian and water modeling	Lakes and salt pans related to dunes with structural control (east-west orientation)	*Mollisols* *Aridisols* *Entisols*	Sandy	Excessive	Climate, wind erosion, alkalization.

north, northeast, and east. To the west and south, limitations are related to wind erosion and extreme climate conditions (Table 1).

2.2. Water classification and spatiotemporal variation of shallow lakes

Landsat 5 TM were used to analyze spatiotemporal fluctuations of lake surface. These images are freely available (USGS, https://glovis.usgs.gov) and have a spatial resolution of 30×30 m. Five images were digitally processed for each of the eight studied areas (Table 2). These images correspond to periods characterized pluviometrically as wet, normal, and dry, during 2001-2002, 2006, and 2008-2009, respectively (Table 2), determined from in situ data of 33 meteorological stations (period 1960-2010) by Aliaga et al. (2016). Different rainfall periods resulted using the Standardized Precipitation Index (SPI) for each station during the mentioned study period (Aliaga et al., 2016).

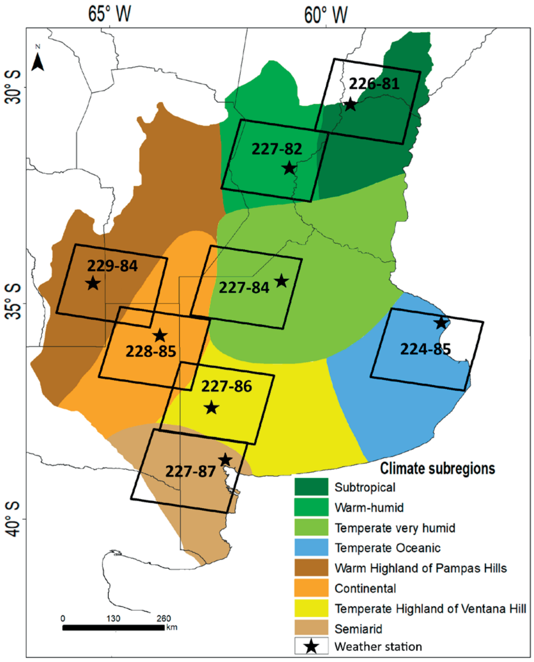

Figure 2. Landsat 5 scenes used in each subregion and reference weather stations.

Table 2. Landsat 5 TM satellite images used in this study, mean rainfall for 1960-2010, and anomalies (annual mean) compared to dry, humid and normal periods for each pampean subregion.

Subregion	Path-Row	Landsat 5 TM	Mean annual precipitation (mm) 1960-2010	Mean precipitation anomaly (mm/year)				
				2001	2002	2006	2008	2009
S	226-081	LT52260812002034COA00; LT52260812003007COA00 LT522608120060424L1TP; LT52260812008013COA02 LT52260812009013COA02	1458	408	677	-32	-547	-228
WH	227-082	LT52270822002328CUB00; LT52270822003006COA00 LT522708220060415 L1TP; LT52270822008047COA01 LT52270822009047COA01	1034	247	306	-31	-417	-236
TH	227-084	LT52270842002336XXX02; LT52270842003014COA00 LT5227084_20060821 L1TP; LT52270842008047CUB00 LT52270842009047CUB00	1012	775	309	94	-266	-166
TO	224-085	LT52240852002363XXX02; LT52240852003051CUB00 LT0522908420060819L1TP; LT52240852008036COA00 LT52240852009036COA00	951	375	320	89	-271	-150
WPH	229-084	LT52290842002002CUB00; LT52290842003007COA00 LT0522708620060311L1TP; LT52290842008024CUB00 LT52290842009024CUB00	780	503	340	52	-138	-281
C	228-085	LT52280812002002CUB00; LT52280812003024CUB00 LT0522408520060205 L1TP; LT52280812008007COA00 LT52280812009007COA00	862	336	229	-36	-276	-239
TVH	227-086	LT52270862002002CUB00; LT52270862003024CUB00 LT0522708720061211 L1TP; LT52270862008007COA00 LT52270862009007COA00	775	420	225	22	-145	-305
SA	227-087	LT52270872002002CUB00; LT52270872003024CUB00 LT0522808520061015 L1TP; LT52270872008007COA00 LT52270872009007COA00	650	210	248	-95	-322	-290

All images have low cloud cover (<5%). Geometric corrections and radiometric calibration (Carmona et al., 2011) in ENVI (ENVI-Enviromental for Visualizing Images v5.1.) were applied to Landsat 5 images to convert the stored digital values into radiance and reflectance values (Schroeder et al., 2006). In the Visible and NIR bands the radiance values are converted to reflectivity values at the top of the atmosphere without considering the effects of the atmosphere and considering a Lambertian surface under cloud-free conditions (Carmona et al., 2011). In these bands atmospheric scattering effects cannot be neglected and therefore they were estimated taking into account the equation of Schroeder et al. (2006).

Widely used methods for selecting water from Landsat images include automatic water extraction (Zhang et al., 2019). In this study, the water coverage determination was obtained through an unsupervised classification of the Iterative Self-Organizing Data Analysis Technique (ISODATA) – ENVI in the NIR bands of LANDSAT 5 TM. This method allows differentiating shallow lakes from other coverage because in the NIR the water -clear and cloudy- begins to absorb radiation presenting low reflectivity. In contrast, many ground covers such as vegetation, soil, or rocks, have high reflectivity, allowing water to be easily detected.

ISODATA is an agglomerative and iterative classification method where the number of classes is defined a priori. Several iterations were performed to improve the accuracy of the determination until the classes were manually reduced to water and no water. To identify water from humid soils (both with low reflectivity), the ENVI Masking technique was used. It was carried out indicating the range of values of the pixels that belonged to water, leaving out those of humid soils. Once the mask was made, it was applied to the image. The classification allows exporting the list of identified elements and their surface. Then, they were exported in shape format and analyzed with a GIS.

Both the number and the area of shallow lakes were determined for each climate period. Because of the pixel size used by the Landsat images, the lake areas <10,000 m^2 were not considered in this study. The Friedman test for paired comparison was used to detect the statistical significance of lake area changes. A classification was performed according to the size of the water surfaces in each studied area. The size density of shallow lakes was studied applying the Pareto distribution (Winslow et al., 2015), widely used in this type of analysis (McDonald et al., 2012).

2.3. Climatic and topographic driving factors of shallow lake change

In situ precipitation data (period 2001-2009) were obtained from eight representative meteorological stations for all subregion (Figure 2), from the National Meteorological Service. The selected zones were studied to know the site conditions of each subregion, whose limits were given by the corresponding scenery. Information bases for each area were realized through the development of GIS, topographic, hydrological and edaphic characterizations, obtained from the National Geographic Institute and the National Secretariat of Water Resources, and Digital Elevation Models (USGS). The final mapping was done by applying the layer superposition techniques in the ArcMap software.

3. Results and discussion

3.1. Spatiotemporal variability of the Pampean shallow lakes

The total lake area in all subregions decreased 62 % from 8447.81±7.93 km^2 in 2001 to 3604.7±3.57 km^2 in 2009, with a significant difference based on the Friedman test (P<0.01). The lake area change in 2001-2009 (Table 3) indicated a loss in water surface area of 584.15 km^2/year. The total lake number (size ≥1 km^2) decreased 78 % from 25306 in 2001 to 5669 in 2009 (Table 3). According to the variations among the normal, dry, and wet periods, the highest number of shallow lakes responded to the periods of maximum annual precipitation (Figures 3 and 4).

In all areas, precipitation and lake number were positively associated, whereas with lake area had only a negative relationship in subregion S. This response exhibited an inverse behavior than expected, with a lake area increase of 50 % between 2001 and 2009 and the minimum lake area during rainy periods (Figure 3). As shown

Table 3. Changes in lake number and area between 2001 and 2009 in each subregion and all areas. A nonparametric analysis of variance (Friedman test) is used to detect the statistical significance of lake area changes.

	Subregion	2001	2006	2009	Change (2001-2006)	Change (%)	Change (2006-2009)	Change (%)	Change (2001-2009)	Change (%)
Lake area (km^2)	S	367.67	457.60	555.16	89.92	*24	97.55	*21	187.48	*50
		±0.62	±1.42	±1.45	±1.29		±1.67		±1.42	
	WH	510.28	562.86	479.08	52.58	10	−83.78	15	−31.19	6
		±4.23	±7.20	±5.20	±7.54		±7.57		±6.06	
	TH	2313.01	1336.28	447.56	−979.40	*42	−887.49	*66	−1865.45	*80
		±4.88	±4.85	±5.93	±6.08		±4.06		±5.23	
	TO	1111.44	578.37	653.92	−533.06	*47	−75.55	13	−457.51	*41
		±10.02	±2.05	±1.08	±8.83		±1.70		±8.91	
	WPH	441.91	100.43	84.57	−341.48	*77	−15.86	*16	−357.34	*80
		±0.52	±0.39	±0.24	±0.56		±0.20		±0.54	
	C	1838.33	399.40	46.42	−1433.33	*77	−352.97	*88	−1786.30	*97
		±1.71	±0.56	±1.36	±1.74		±0.38		±1.72	
	TVH	1502.07	1093.57	622.66	−408.50	*27	−470.90	*43	−879.40	*58
		±3.63	±6.27	±7.52	±4.78		±3.88		±4.32	
	SA	331.98	325.62	264.30	−6.36	2	−61.31	*19	−67.68	*20
		±5.51	±4.12	±7.09	±6.24		±6.02		±6.57	
	All	8447.81	5392.8	3604.7	−3559.63	*42	−1850.31	*34	−5257.39	*62
		±7.93	±4.46	±3.57	±7.20		±3.85		±7.12	
Lake number	S	2421	1452	1841	−969	40	389	27	−580	24
	WH	915	678	620	−237	26	−58	9	−295	32
	TH	3955	2172	895	−1783	45	−1277	59	−3060	77
	TO	2152	1145	761	−1007	47	−384	34	−1391	65
	WPH	2923	786	691	−3419	81	−95	12	−3514	84
	C	6293	2132	93	−4161	66	−2039	96	−6200	99
	TVH	6314	1530	600	−4784	76	−930	61	−5714	90
	SA	333	441	168	108	32	−273	62	−165	50
	All	25306	10336	5669	−14970	59	−4667	45	−19637	78

*P>0.01.

in Figure 3, there is an association between the number and the area, although they do not do it in the same proportion. This can be seen by relating them individually to in situ precipitation. Although the precipitation in both dry periods was lower than the normal period, the anomalies were notably different between the two dry periods, since in 2009 the average precipitation was higher than in 2008 (Tabla 2). In addition, this subregion is characterized by large basins with rivers and streams, poor surface drainage, and extensive underground inputs (Figure 1a, Table 1), so the dynamics of its water resources are highly conditioned by the phenomena that occur upstream.

During the study period, subregions TH, WPH, C, and TVH were the ones with the most significant number variability, from 3000 to 6200 lakes (Figures 3 and 4). The variation between wet and normal periods was 59 %, whereas the one between normal and dry periods was 45 %. For example, in subregions C and TVH the number of shallow lakes varied in 4000 lakes between wet and normal periods, but the number oscillated between 2000 and 900 lakes between regular and dry events, respectively (Figures 3 and 4).

The variation in water coverage did not respond directly to the increase or decrease in lake number. Different responses of the total area covered by water were recorded (Table 3; Figures 3 and 4). The relationship between annual precipitation and the total area covered by water was direct in subregions WH to TVH, but opposite trends were observed in the other two subregions. In subregion S, there

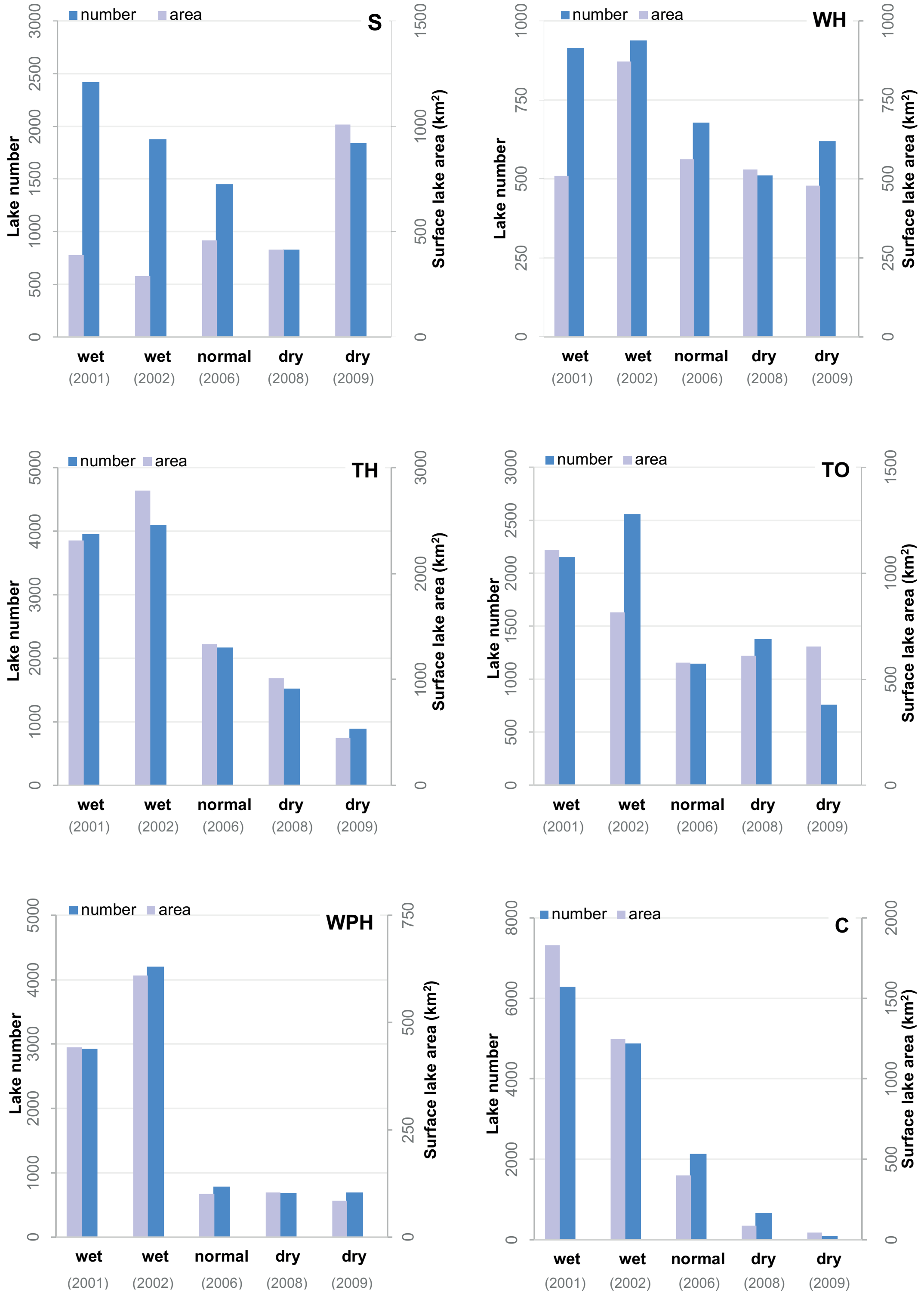

Figure 3. Total number and surface lake area in subregions S, WH, TH, TO, WPH, and C for a wet (2001-2002), dry (2008-2009) and normal (2006) pluviometric period.

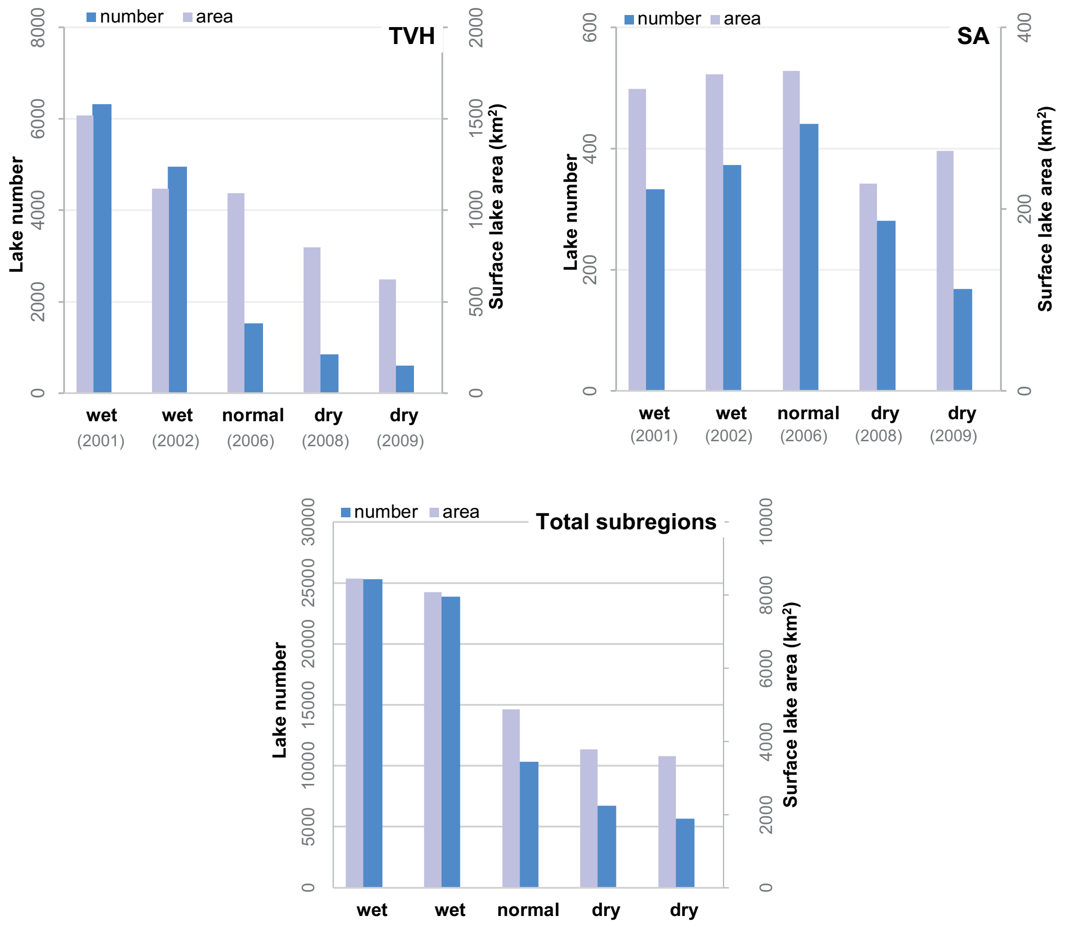

Figure 4. Total number and surface lake area in subregions TVH, SA and all of them for a wet (2001-2002), dry (2008-2009) and normal (2006) pluviometric period.

was an opposite relationship between water area and rainfall, whereas in subregion SA there was no response from shallow lakes regarding an increase in their surface area in the wet period. The variation of the total water area between normal and wet periods (42%) was not as high as the number of shallow lakes (59%). These results indicate that a smaller lake number did not imply a decrease in lake area in the same proportion during the study period (Table 3; Figures 3 and 4).

Subregions TH, WPH, and C revealed the most significant water losses, 80%, 80%, and 97%, respectively (Table 3). In the WH, TH, C and TVH subregions, a direct association is observed between precipitation and the number and area of shallow lakes. The lowest relationships were found in subregions S, TO, and SA during the same period (Table 3; Figures 3 and 4). Subregions C and SA were highlighted as those with the greatest and least spatiotemporal variation of water bodies, respectively (Figure 5). The variation exceeded 5000 shallow lakes in the first case and 400 lakes in the second case (Figures 3 and 4).

3.2. Analysis of the lake areas

According to the range of values in the areas studied and described by various authors, the following lake sizes were established: *Very small* from 1 ha to 10 ha; *Small* from 10 ha to 1 km^2; *Medium* from 1 km^2 to 10 km^2; *Large* from 10 km^2 to 100 km^2 and V*ery large*, greater than 100 km^2. The Pampean lakes have an average size of 1.72 km^2. Our results show that the distribution of the surface area of

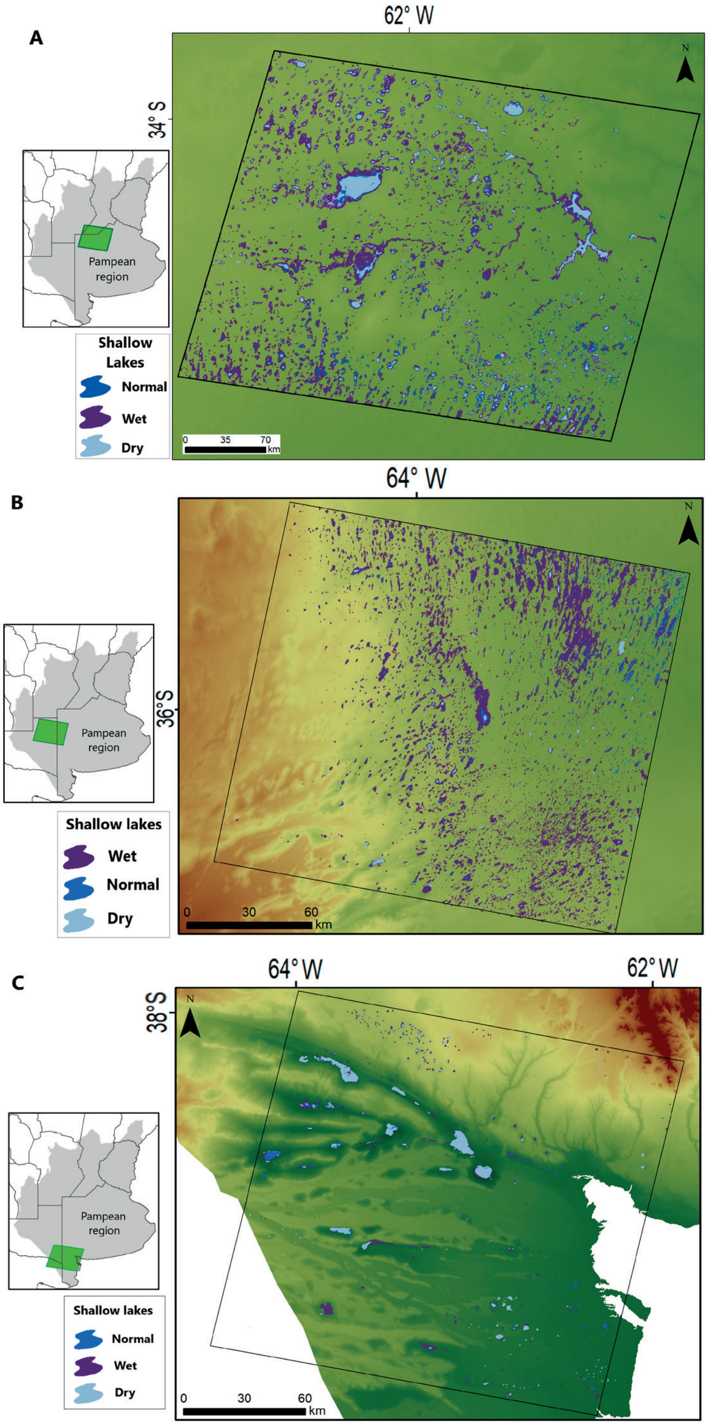

Figure 5. Shallow lakes in subregions A) TH, B) C, and C) SA during normal, dry, and wet periods.

shallow lakes responded to a balance between a decrease in the area represented by large shallow lakes in dry periods and an increase in the abundance of smaller lakes in wet periods.

Considering the Pareto statement, the two smallest categories (from 1 ha to 1 km^2) exceeded 80 % of the total number of shallow lakes in each studied area (Figure 6). In all subregions, *Very*

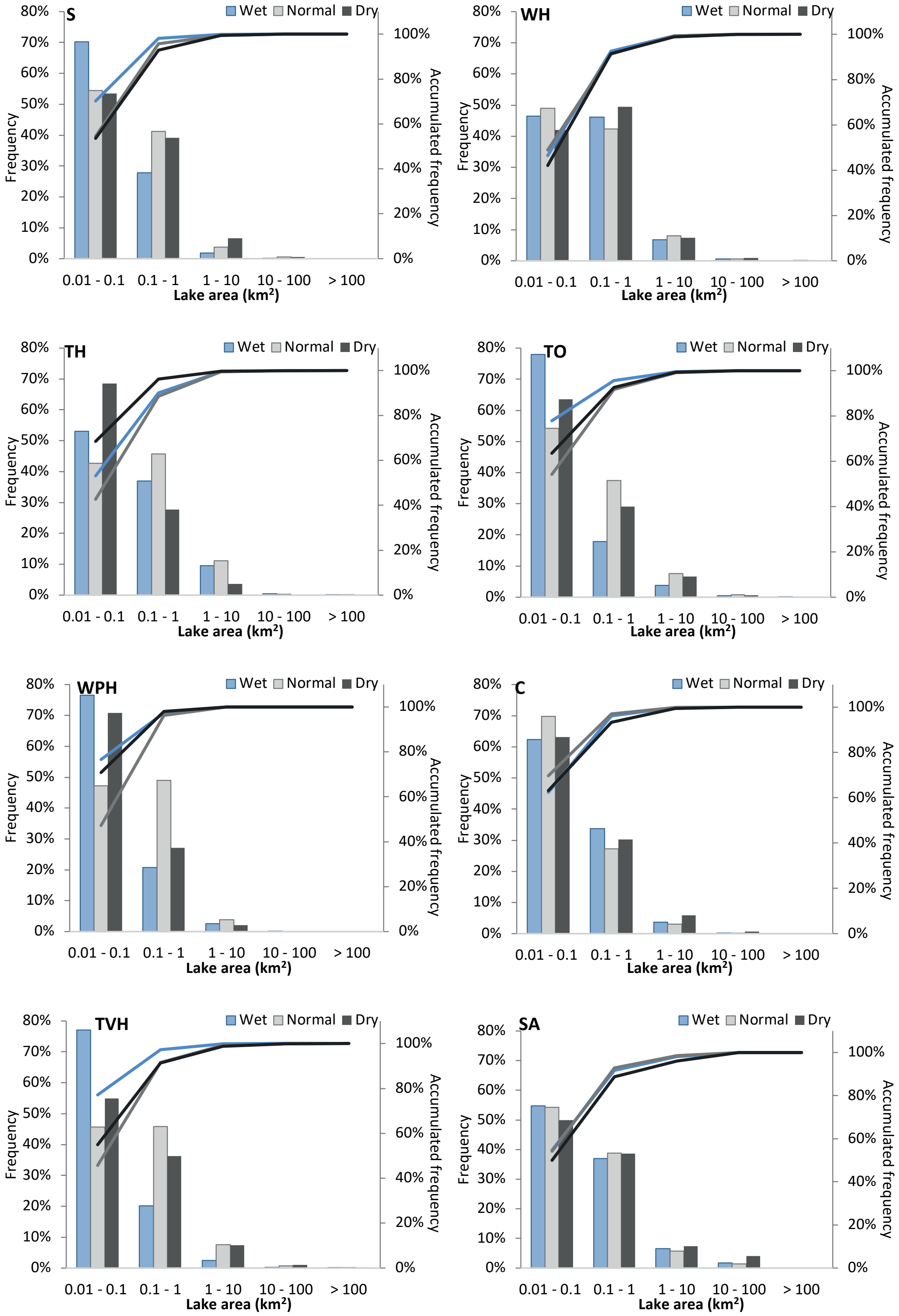

Figure 6. Shallow lake size-abundance ratio according to the Pareto distribution in different climate periods for each subregion. The accumulated frequency (right axis) is represented by solid lines.

Small shallow lakes were dominant, although this dominance was more noticeable in subregions TO, C, and SA. The composition also highlighted that *Small* shallow lakes were more significant in subregions S, WH, and TH in the northern center of the Pampean region. *Medium* lakes reached their maximum presence in subregions WH and TH (Figure 6). Finally, *Large* shallow lakes occupied the lowest surface percentage, mainly in subregions TO and SA. In subregions S and TH to C, there was an increase in the presence of *Very small* shallow lakes during wet periods. There were only *Very large* shallow lakes of more than 100 km^2 in subregions WH, TH, TO, and TVH, but with minimum values (less than 1 % of the total set of shallow lakes). On the other hand, a greater contribution of larger shallow lakes was observed in subregions TVH and SA during the dry period, which could be in detriment of the smaller shallow lakes during the period of scarce rains (Figure 6).

3.3. Subregional assessment of determining factors in lake spatiotemporal variation

The spatiotemporal response of lakes in the Pampean subregions allowed their possible relationship with the climate periods. In most of the subregions, this relationship was clear, although in some cases the low direct incidence could be explained by their topographic and edaphic characteristics. In the north, subregions S and WH had a robust fluvial control, where shallow lakes were concentrated along rivers, responding not only to local rainfall but also to the contributions upstream of their basins. These contributions could explain why there were no decreases in the number of shallow lakes during the periods considered as dry in S subregion (Figure 3). In addition, the surface hydrological system was conditioned by the predominance of clay soils in both zones, which led to water retention and the development of flooded areas with low slopes and poor drainage (Table 1).

In WH the relationship is positive between the number and area of lagoons (Figure 3), responding to the behavior of the anomalies for that subregion (Table 2). As the S subregion, the landscape is mainly low relief where soil degradation processes such as water erosion are potentially important (Table 1). In this subregion, the main limitations of the soil are related to the scarce slopes, poor drainage, and low permeability. Some lakes are considered artificial (Tricart, 1973) under anthropic control. In most cases, they constitute reservoirs located at the headwaters of the rivers.

Subregion TH is one of the few zones in which significant variations were observed in the number of *Very small* shallow lakes but also in *Medium* and *Large* shallow lakes. In the wet period, the effect of the maximum precipitations kept increasing; this increase could be related to the predominance of an arheic drain, a low slope, and the permeability of soils (Table 1). This subregion represented the maximum water coverage of 2800 km^2 although it did not contain the maximum number of shallow lakes. This area has been mainly studied because of the frequent and extensive floods during wet periods, which have been reported as the most prolonged and intense ones of the Pampean region (Aliaga et al., 2017). Therefore, the effect of rainfall on lake dynamics is intensified, favored by the low slope and permeability of soils (Table 1). In subregion TO, the number and area of shallow lakes responded to the development of wet and dry periods. In this area, the hydrological system is conditioned by its structural and geomorphologic characteristics and the proximity to the coast (Table 1). The eolian depressions explain the considerable presence of areas covered by wetlands. The shallow depth of the groundwater level of the drainage could be the driving force of the system, so that precipitation acts as a determining factor (Bohn et al., 2016).

Subregions WPH, C, and TV, located in the center-west of the Pampean region, presented the maximum number of lakes during wet periods, with 4200, 6200 and 6300 lakes, respectively. However, the predominance of the *Very small* category did not indicate the greatest water coverage in surface. These maximums in the number of lakes decreased considerably during the dry periods to 690, 93, and 600 lakes, respectively, which represented an important proportion of ephemeral water coverage in the Pampean region. Subregion WPH has a landscape of hills and the lakes are in valleys and deflation basins or depressions. The dominance of sandy loam to silty textures indicates that the soils do not flood easily and, although there were abundant lakes in wet periods, no significant floods took place. In subregion C, the formation of *Very small* ephemeral shallow lakes was considerable, although it was the second least rainy area (Aliaga et al., 2017); they were mainly located in eolian depressions with sandy soils that are saturated with little water (Table 1).

In subregion TVH, the spatiotemporal dynamics of the shallow lakes responded to wet and dry periods. The wet period affected them more than the dry events since this area behaves hydrologically as an accumulation zone (Geraldi et al., 2011). This subregion is located between the *Ventana Hills* to the southwest and a zone of dunes to the northwest. Several authors have addressed the risk of flooding and the reception of most of the local contributions of groundwater in this system. The main lakes are connected to each other according to the direction of the structural faults of the area. To the south, subregion SA showed its condition of extreme aridity in some periods. The presence of Aridisol textures and the scarce rainfall allowed the formation of large saltpeter. This subregion is the least affected by wet periods concerning the number of water bodies. According to Bohn et al. (2016), the hydrological balance of previous years contributes to regulate the effects of the dry event, which is very relevant in a semiarid environment.

Understanding the changes in lake number and extent as well as lake abundance and size distribution is essential for the evaluation of water resources at regional and subregional levels, biogeochemical cycles, and climatic changes (Zhang et al., 2014). Our results highlight the importance of using multi-temporal remote sensing data to reveal complex temporal space variations, in the face of climate variability in these fragile landscapes. The impact of climate variability on lake water balance is complex and can be sharply different across regions. This impact, together with the diverse lake ecosystem properties, calls for management strategies that explicitly identify environmental changes and potential risks associated with region-specific hydrological and ecosystem dynamical processes (Zhang et al., 2017). However, it is necessary to highlight that these results are limited by the small number of samples for each subregion. The discussion and conclusion regarding the subject represent an approximation to the spatiotemporal behavior of the lakes in this region. These results could be improved by increasing the temporal frequency in each subregion, thus these implications should be considered in the scope of the conclusions presented.

4. Conclusions

The spatiotemporal variation of shallow lakes in the Pampean region is affected by climate variability, although it does not fully explain this variation. Their extensions and temporary space arrangements are linked to the origin of the shallow lakes, their current topography, hydrology, and geomorphology (i.e., their environmental conditions). The temporary space transitions of the Pampean shallow lakes in the face of the distinct climate periods are remarkable, and they can be explained by the amplitude in the number of shallow lakes and the total water coverage. These variations fluctuate between 6200 shallow lakes in subregion C and up to 270 in subregion SA between the wet and dry periods studied. These fluctuations show the heterogeneity of the Pampean region in many aspects that should be considered in regional studies. Our study shows a simple and effective way to use remote sensing and GIS for monitoring water resource dynamics and studying these ecosystems to mitigate the effects of floods and droughts in regions that appear to be relatively homogeneous. This new lake evolution dataset provides foundations to support evidence-based decisions for water resource management and environmental protection in different Pampean subregions.

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