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A regional water balance indicator inferred from satellite images of an Andean endorheic basin in central-western Argentina

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ABSTRACT

In the Central Andes of Argentina (30–37°S), snowmelt is the main source of freshwater, an essential natural resource for ~2.2 million people in the adjacent arid lowlands. In this region, Laguna Llancanelo collects the water inputs from the Malargüe endorheic basin. Previous studies concerning the annual and intra-annual variations of this lagoon and its relationship with regional climate are rare. We obtained a monthly record for the Laguna Llancanelo area (LLA, 1984–2013) using the modified normalized difference water index derived from Landsat images. Monthly LLA ranges between 35 km^2 and 411 km^2 and is significantly related to variations of the Río Malargüe, the main snow-fed tributary to the lagoon. There is no long-term relationship between LLA and local rainfall, but rapid increases in LLA result from heavy rainfall around the lagoon. Conversely, rapid reductions in LLA encompass periods with both reduced discharge from the Río Malargüe and low local rainfall. The LLA integrates moisture of both Pacific (snowfall in the upper Andes) and Atlantic (lowland rainfall) origins; therefore, we propose using LLA as an indicator of regional water balance.

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1 Introduction

The Intergovernmental Panel on Climate Change (IPCC) has identified major changes in the hydrological cycle at global, regional and local scales. For example, an increase in the frequency and magnitude of extreme events, such as floods and droughts, has been documented for many regions of the world in association with global climate warming (IPCC 2013). In this context, the use of hydro-meteorological estimates is of great importance to assess water availability and risk at different temporal and spatial scales (Bates *et al.* 2008). Hydro-climatic indices can provide accurate information about current water conditions at regional level and therefore are useful for implementing water management plans and for making decisions when facing climatic risks. There are many hydro-meteorological indices, such as the Palmer drought severity index (PDSI, Alley 1984) or the surface water supply index (SWSI, Zargar *et al.* 2011), just to mention two of the most commonly used to assess the water balance. However, there are no uniform universal methods for monitoring and quantifying water balance (Heim 2002, Quiring 2009). In addition, many remote mountainous areas lack meteorological records to provide a clear view of climate variations at regional scale. In order to assess water balances at a regional level, it is necessary to integrate the different components of the hydrological cycle, including precipitation, evapotranspiration and changes in river flow, among others. In this context, satellite monitoring of water bodies in remote zones provides a valid alternative for estimating water conditions at regional scales (Vuille *et al.* 2008, Carilla *et al.* 2013).

Numerous studies have incorporated remote sensing as a simple, fast and low-cost tool for monitoring droughts and hydrological changes at different spatial scales (Chang *et al.* 2010, Awange *et al.* 2013, Tulbure and Broich 2013, Adams and Sada 2014). In Argentina, previous works applied remote sensing techniques to monitor changes in water conditions at regional levels. For example, Seiler *et al.* (1998) used the AVHRR sensor to infer droughts and their impacts on agricultural productivity in the Pampas region; Pagot (2003) quantified changes in the extent of the Río Dulce wetlands in Córdoba; and Chen *et al.* (2010) used satellite gravimetric data to analyse the temporal evolution of water storage in soils from the La Plata basin for the period 2002–2009. More recently, Carilla *et al.* (2013) used

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Supplementary data for this article can be accessed here.

Landsat images to determine the relationship between inter-annual variations in regional precipitation and lake size fluctuations over the period 1985–2009 in high-elevation endorheic basins in the subtropical Andes.

Laguna Llancanelo is the main water body in the Malargüe endorheic basin of south-central Mendoza Province, western Argentina. With an average depth of 30 cm over a mean area of approximately 190 km^2, the lagoon is one of the most important wetlands in South America. Situated along the extremely dry South American Arid Diagonal (Bruniard 1982), the area around the lagoon has a large biodiversity, with several species of waterfowl using the marshes and shores for nesting and feeding. Populations of up to 54 000 and 150 000 waterfowl have been reported for winter and summer, respectively (Sosa 1995). The lagoon and adjacent areas were declared a Nature Reserve by the Mendoza Government in 1980 and a Ramsar site by the Ramsar Convention in 1995. Recent archaeological studies highlight the use of the lagoon resources by humans since the early Late Holocene (Giardina *et al.* 2014).

The surface area of Laguna Llancanelo varies significantly. Previous studies reported a minimum area of 80 km^2 during dry periods and up to four times larger area during years with abundant precipitation (Isla *et al.* 2005). Major past variations in the lagoon extent during Quaternary times have also been inferred from the analysis of ostracod associations and trace elements (D'Ambrosio *et al.* 2016). The large fluctuations of the Laguna Llancanelo area (LLA) reflect, in part, the disproportionate relationship between the large surface extent and shallow depth (less than 2 m deep). The lagoon is fed by the snowmelt from the high Cordillera and local rains in the surrounding lowlands. Water losses are influenced by the large surface area exposed to evaporation and by relatively warm temperatures in the basin during summer.

Presently, the water from the lagoon is not a source for economic activities in the surrounding land. Since the lagoon and adjacent areas are a Provincial Reserve, human activities are regulated and under control. As a consequence, the influence of economic activities on middle- to long-term changes in the lagoon size is negligible. However, water availability assessment in this arid region is crucial to assess future water resource management and regional water supply demands. In this paper, we relate the surface fluctuations of Laguna Llancanelo to variations in contributing (snow *vs* rainfall) sources and their connections with large-scale climate circulation. A previous study by Isla *et al.* (2005) related annual changes in LLA to the normalized difference vegetation index (NDVI), from 1996 to 2002. In that case, inter-annual fluctuations in LLA were compared to precipitation and El Niño Southern Oscillation (ENSO) events. Here, we propose using monthly LLA fluctuations, derived from satellite images, as a regional indicator of water balance, integrating the contributions of mountain snowmelt and local rainfall around the lagoon. Therefore, we (1) use Landsat images to build a monthly-resolved record of LLA fluctuations over the past three decades; (2) determine the major water contributions to Laguna Llancanelo through analysis of the relationship between variations in lagoon size, precipitation, temperature and streamflow; and (3) propose the use of LLA as a hydro-meteorological index of regional water balance. It is expected that estimates of lagoon area will allow the monitoring of water balance at the regional scale and the establishment of comprehensive water management policies for drylands in western Argentina.

2 Materials and methods

2.1 Study area

The Llancanelo or Malargüe endorheic basin extends along the eastern margin of the Cordillera de Los Andes from 35°30′S to 36°S and from 70°30′W to 68°30′W in the southern sector of Mendoza, Argentina (Fig. 1). The Llancanelo basin covers an area of approximately 10 600 km^2 and is surrounded by mountains up to 3000 m elevation. Socio-economic activities are concentrated in Malargüe, the principal town in the basin. The major economic activities in the basin include a reduced area of intensive agriculture around the town of Malargüe, extensive rural livestock rearing and widespread oil exploitation (Chiodi 2014).

Located at a mean elevation of 1330 m, Laguna Llancanelo is the major water body in the basin and includes, in addition to the lagoon, several adjacent ecosystems such as salt marshes, swamps and estuaries. Vegetation is dominated by reeds in the marshes. Xeric shrubs and steppe grasses cover most of the non-flooded lands near the lagoon (Cabrera 1976, Valladares 2003). Winter snow precipitation in the Upper Llancanelo basin is associated with the passage of cyclonic fronts from the Pacific Ocean in autumn and winter (Masiokas *et al.* 2006, Garreaud and Fuenzalida 2007), while summer rainfall on the piedmont and plains is related to the northern ingression of humid air masses from the Atlantic and continental subtropics (Compagnucci *et al.* 2002). Across the Llancanelo basin, total annual precipitation decreases from around 800 mm $year^{-1}$ in the main Cordillera to 300 mm $year^{-1}$ in the plains surrounding the lagoon. Mean annual temperature at the Malargüe airport station is 12.2°C (Fig. 1).

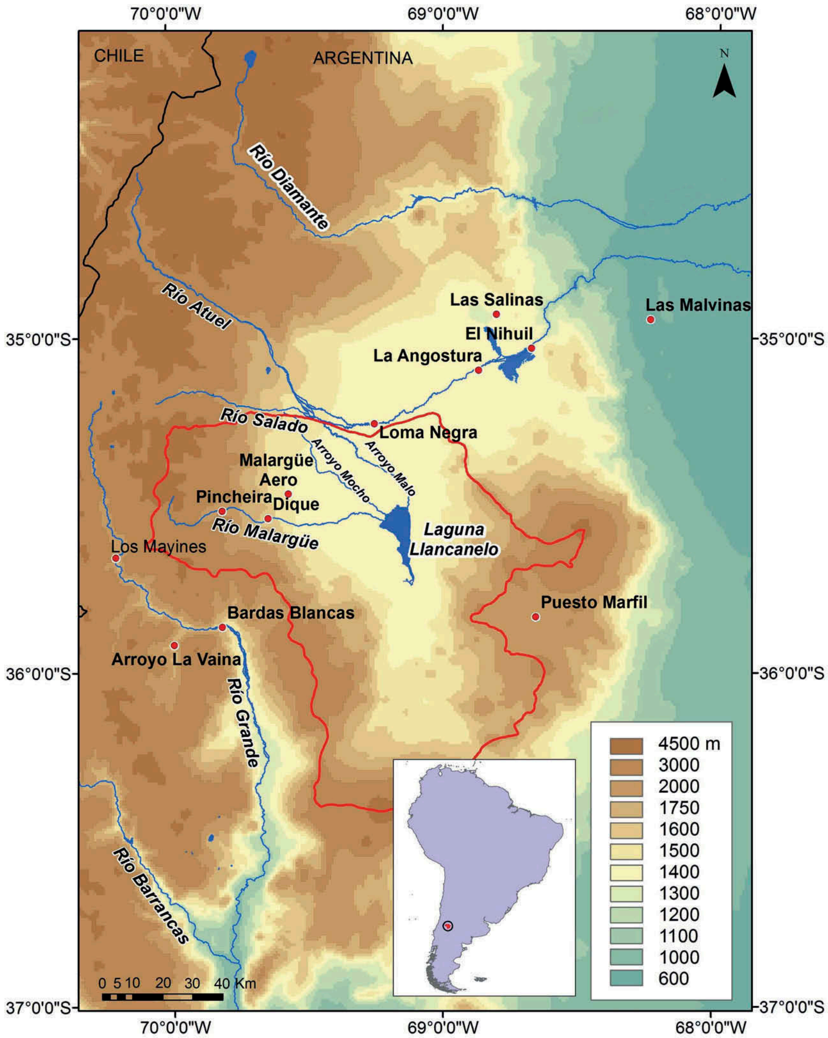

Figure 1. Geographical location of Laguna Llancanelo, Mendoza, Argentina. Temperature and precipitation records from the upper Cordillera (western sector) and from the plains (eastern sector) are indicated by small dots.

The Río Malargüe, fed mainly by snowmelt in the higher mountains, is the main tributary to the lagoon. The annual mean discharge, largely concentrated from October to December, is 9.29 $m^3 s^{-1}$ (Valladares 2003). In addition, the temporary streams, Arroyo Malo and Arroyo Mocho, which flow in a northwest–southeast direction, also contribute their waters to the lagoon (Fig. 1). The mean depth of Laguna Llancanelo is around 30 cm (Valladares 2003); therefore, its surface area is highly variable depending on changes in the contribution of the Río Malargüe and other minor tributary streams, local rainfall and evaporation rates (Martinez *et al.* 1997, Isla *et al.* 2005).

2.2 Satellite images

Landsat 5-TM, Landsat 7-ETM+ and Landsat 8-OLI-TIRS scenes (30 m spatial resolution), consisting of seven, eight and eleven bands, respectively, were obtained from the United States Geological Survey (USGS, http://glovis.usgs.gov/). Landsat images have a mean temporal resolution of 16 days. However, satellite images were available every ~8 days when two Landsat missions operated simultaneously. All available scenes in the period 1984–2013 were retrieved in an attempt to document lagoon extent on a month-to-month basis (Table 1). Due to cloud cover over the lagoon, or the absence of imagery, monthly data cover 45% of the records between the years 1984 and 1997. This record is almost complete for the period 1998–2013, with only seven missing scenes out of 192.

We tested different indices to enhance the contrast between lagoon water and nearby surfaces. These indices are calculated as arithmetic combinations of different satellite spectral bands. In the present study, three indices were tested to estimate lagoon size:

Table 1. Brief description of the satellite images used in the development of the LLA index and to test the three water indexes. Coordinate pairs is shown, K-J for the SPOT scenes and Path-Row for the Landsat scenes.

Satellite – Sensor	K-J / Path-Row	Number of images	Pixel resolution (m)
SPOT5 – HRG2	677–421	2	5
	677–422	2	10
SPOT5 – HRG1	677–421	2	5
	677–422	2	10
Landsat 5 – TM	231–085	156	30
	232–085	43	30
Landsat 7 – ETM+ 88	231–085	47	30
	232–085	41	30
Landsat 8 – OLI and TIRS 1	231–085	1	30

a. the normalized difference water index (NDWI, Gao 1996) calculated as:

$$\mathrm{NDWI} = (\mathrm{NIR} - \mathrm{MIR})/(\mathrm{NIR} + \mathrm{MIR})$$

where NIR and MIR correspond to the near infrared and the middle infrared bands;

b. the modified NDWI (MNDWI, Xu 2006) in which the green band replaces the NIR band, and therefore is calculated as:

$$\mathrm{MNDWI} = (\mathrm{G} - \mathrm{MIR})/(\mathrm{G} + \mathrm{MIR})$$

where G correspond to the green band; and

c. the automated water extraction index (AWEI, Feyisa *et al.* 2014), combining four spectral bands and calculated as:

$$\mathrm{AWEI} = 4(\mathrm{G} - \mathrm{SWIR}_1) - (0.25\mathrm{NIR} + 2.75\mathrm{SWIR}_2)$$

where SWIR_1 and SWIR_2 correspond to the short-wave infrared bands at 1.547–1.749 μm and 2.064–2.345 μm, respectively.

These indices range between −1 and +1. A threshold definition to separate water from non-water surfaces is uncertain due to the intrinsic water characteristics and land cover complexity of distinct regions; therefore, a threshold value is required in each study case (Campos *et al.* 2012). In this study, different threshold values were tested for each index. Determination of the most precise index was based on manual delimitation of LLA on two pan-sharpened SPOT-5 images (5 m spatial resolution) corresponding to summer (November) and winter (June) of 2013 (Table 1) obtained from Comisión Nacional de Actividades Espaciales, Argentina (CONAE, http://www.conae.gob.ar). The lagoon surfaces from these two images were compared with estimates from two Landsat images from the same months using different indices and thresholds. The MNDWI, with a threshold of 0.350, produced the most precise water area delimitation, showing results very similar to those developed manually (total error = 6.20%, see Supplementary material, Table S1). After that, pixels with MNDWI values equal to or higher than 0.35 were classified as water. Rivers and minor streams adjacent to the lagoon that were also classified as water were masked and excluded from the LLA estimations. When two or more Landsat scenes were available within a particular month, the size of the lagoon was computed as the mean area of the two or more selected images.

2.3 Hydro-meteorological data

Monthly precipitation and streamflow records from 27 stations in the region were retrieved from the Integrated Hydrological Database of the Subsecretaría de Recursos Hídricos de Argentina (http://www.hidricosargentina.gov.ar/acceso_bd.php). Monthly mean temperature records are from the Malargüe Airport station, Servicio Meteorológico Nacional (http://www.smn.gov.ar, Fig. 1, Table 2). Based on spatial correlation patterns, precipitation records were arranged into two groups consistent with the main topographical areas (mountains *vs* lowlands) across the basin. Mean precipitation records were estimated for each group. Precipitation variations recorded at the stations located in the Andean mountains are not significantly correlated with those from stations in the plains (r = 0.01), reflecting the different sources (Pacific or Atlantic oceans) of the air masses reaching the Llancanelo basin. These two groups of stations were identified as the Pacific (PWS) and Atlantic (AWS) weather stations (Table 2). The two groups have pronouncedly different annual precipitation cycles, with maximum precipitation in winter (PWS) or summer (AWS, Fig. 2; see also Supplementary material, Fig. S1).

2.4 Statistical analyses

Three hydro-meteorological indices were calculated to analyse the relationship between rainfall, streamflow and LLA. They are the standardized precipitation index (SPI, McKee *et al.* 1993); the standardized runoff index (SRI, Shukla and Wood 2008); and the standardized Laguna Llancanelo index (SLLI). The SPI represents the number of standard deviations that the accumulated precipitation in a given period deviates from the mean value. This index has been widely used for monitoring wet and dry climatic extremes in southern South America (Seiler *et al.* 2002, Krepper and Zucarelli 2010). The SPI is considered the best indicator of the spatial and temporal variations in drought conditions across southern South America (Penalba and Rivera 2015). The SRI is similar to the SPI but applied to river flow (Nalbantis 2008, Shukla and

Table 2. Meteorological and streamflow gauge stations used in this study.

Station name	River basin	Lat. S	Lon. W	Variable	Record period	Missing data (%)
Malargüe Aero	Malargüe	35°30′	69°35′	Temperature	1980–2013	0.00
Las Salinas	Atuel	34°55′	68°48′	Precipitation[AWS]	1983–2014	5.89
Las Malvinas	Atuel	34°56′	68°14′	Precipitation[AWS]	1980–2014	0.03
El Nihuil	Atuel	35°02′	68°36′	Precipitation[AWS]	1981–2014	<0.01
Loma Negra	Atuel	35°15′	69°14′	Precipitation[PWS]	1981–2013	<0.01
Dique	Malargüe	35°32′	69°38′	Precipitation[PWS]	1992–2014	0.02
Los Mayines	Grande	35°39′	70°12′	Precipitation[PWS]	1986–2014	2.37
Puesto Marfil	–	35°50′	68°39′	Precipitation[AWS]	2004–2014	<0.01
Bardas Blancas	Grande	35°51′	69°48′	Precipitation[PWS]	1986–2014	0.01
Arroyo La Vaina	Poti Malal	35°55′	69°36′	Precipitation[PWS]	1985–2014	<0.01
La Angostura	Atuel	35°05′	68°52′	Precipitation /Streamflow[AWS]	1984–2013	0.83
Pincheira	Malargüe	35°31′	69°48′	Precipitation /Streamflow[PWS]	1984–2013	4.44
Km 47.3	San Juan	31°30′	68°56′	Streamflow	1984–2013	3.06
Guido	Mendoza	32°54′	69°14′	Streamflow	1984–2013	<0.01
La Jaula	Diamante	34°40′	69°19′	Streamflow	1984–2013	<0.01
El Sosneado	Atuel	35°05′	69°36′	Streamflow	1984–2013	1.94
Cañada Ancha	Salado	35°11′	69°46′	Streamflow	1984–2013	3.61
La Barda	Malargüe	35°33′	69°40′	Streamflow	1987–2013	6.17
Las Loicas	Chico	35°47′	70°08′	Streamflow	1992–2013	1.52
Gendarmería	Poti Malal	35°52′	69°56′	Streamflow	1984–2013	2.22
La Gotera	Grande	35°52′	69°53′	Streamflow	1984–2013	5.28
Barrancas	Barrancas	36°48′	69°53′	Streamflow	1984–2013	11.94
Buta Ranquil	Colorado	37°05′	69°45′	Streamflow	1984–2013	2.50
Los Carrizos	Nahueve	37°07′	70°46′	Streamflow	1984–2011	14.29
Paso de Indios	Neuquén	38°31′	69°24′	Streamflow	1984–2013	2.50
Bajada del Agrio	Agrio	38°22′	70°02′	Streamflow	1984–2013	2.50
Malleo	Malleo	39°46′	71°02′	Streamflow	1984–2011	12.50
Junín de los Andes	Quilquihue	40°03′	71°01′	Streamflow	1984–2011	7.74

[AWS] and [PWS] refer to precipitation records grouped as Atlantic or Pacific Weather Stations, respectively.

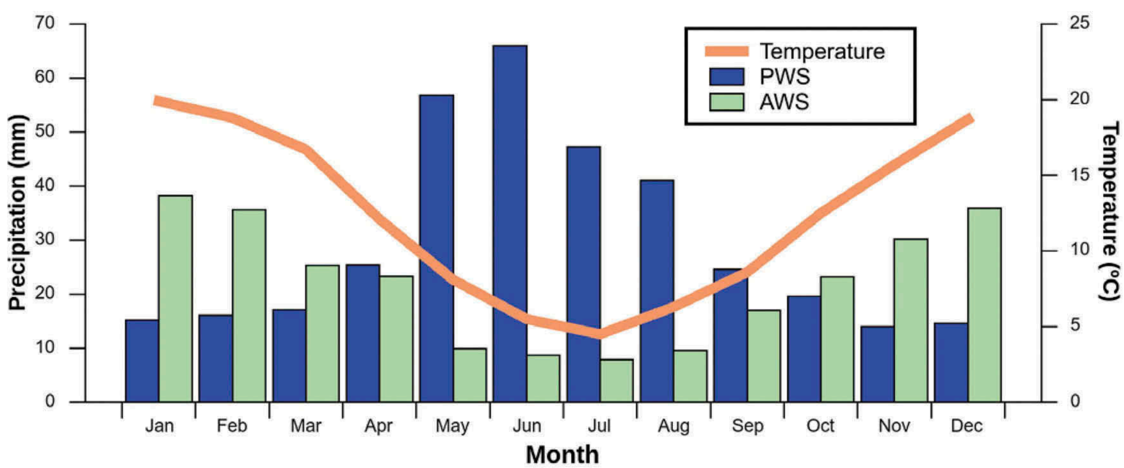

Figure 2. Mean total monthly precipitations for the PWS and AWS (bars) records. The solid line represents the monthly mean temperature at the Malargüe Airport station.

Wood 2008); whereas the SRI is a measure of hydrological droughts, the SPI is a measure of meteorological droughts (Amor *et al.* 2009). The SPI and SRI can be estimated at multiple temporal scales (i.e. cumulative rainfall and streamflow over a different number of months). Positive SPI (SRI) values indicate greater than median rainfall (streamflow) and negative values indicate less than median rainfall (streamflow). Since both indices are standardized rainfall and streamflow records, they have zero mean and standard deviation of 1, with unbounded values typically lying between −3 and +3. In this study, both indices were estimated for 1, 3, 6 and 12 consecutive months. Methods analogous to those employed to compute SPI and SRI were used to calculate the standardized LLA (hereafter, standardized Llancanelo Lagoon index, SLLI). In the present study, SLLI was used for comparison with the standardized indices from SPI, SRI and temperature; otherwise the LLA record was used.

The relationship between lagoon size and hydro-meteorological variations was determined by computing the Pearson product moment correlation coefficient between SLLI and (a) SPI, (b) SRI and (c) temperature on monthly and seasonal (3, 6 and 12 months) bases. In addition, lagged correlations between SLLI and standardized indexes were estimated to account for processes that delay the hydro-climatic signal of variations of streamflow or rainfall into the lagoon. For these analyses, only data from years with more than 10 months of records (1998–2013) were used.

To evaluate the regional representativeness of lagoon surface variations, SLLI was compared to streamflow from most of the rivers in the Central Andes and northern Patagonia in Argentina (Table 2) over the common period 1984–2013. First, correlations between SLLI and SRI from each river were estimated. Those river records showing statistically significant correlations with SLLI were merged into a regional streamflow record. Finally, the correlation between this regional SRI and SLLI was calculated.

3 Results

3.1 Temporal variations in LLA

We built a monthly resolution record of LLA fluctuations over the period 1984–2013 based on the classification of 288 Landsat scenes (Fig. 3).

Periods of extended lagoon area (more than 200 km^2) occurred in 1984–1988, 2001–2003 and 2006–2009, whereas reduced areas (less than 150 km^2) were recorded in the period 1989–1999 and after 2010. Indeed, the period 2010–2013 represents the longest period of continuous small lagoon size. Over the period 1984–2013, the largest and smallest areas of 411 and 35 km^2 were recorded in November 2001 and January 2012, respectively (Fig. 3). Increases in the lagoon surface occur from late winter to spring, whereas reductions occur from late summer to autumn (Fig. 4). Inter-annual LLA variations for seasonal large (August–October) and small (March–June) lagoon sizes show similar trends over the 1998–2013 period. However, the intra-annual range of fluctuations between the largest and smallest sizes along the annual cycle is greater during the years with large lake sizes (Fig. 3).

3.2 Relationship between lagoon size and hydro-meteorological variations

Fluctuations in the area of Laguna Llancanelo (SLLI) follow variations in Río Malargüe streamflow (SRI; $r = 0.66$, $p < 0.001$, $n = 257$). Periods of low streamflow (SRI ≤ −1.0) are associated with small lagoon extensions, whereas abundant river flows (SRI ≥ 1.0) are concurrent with large lagoon sizes (Fig. 5). This relationship becomes stronger when the Río Malargüe

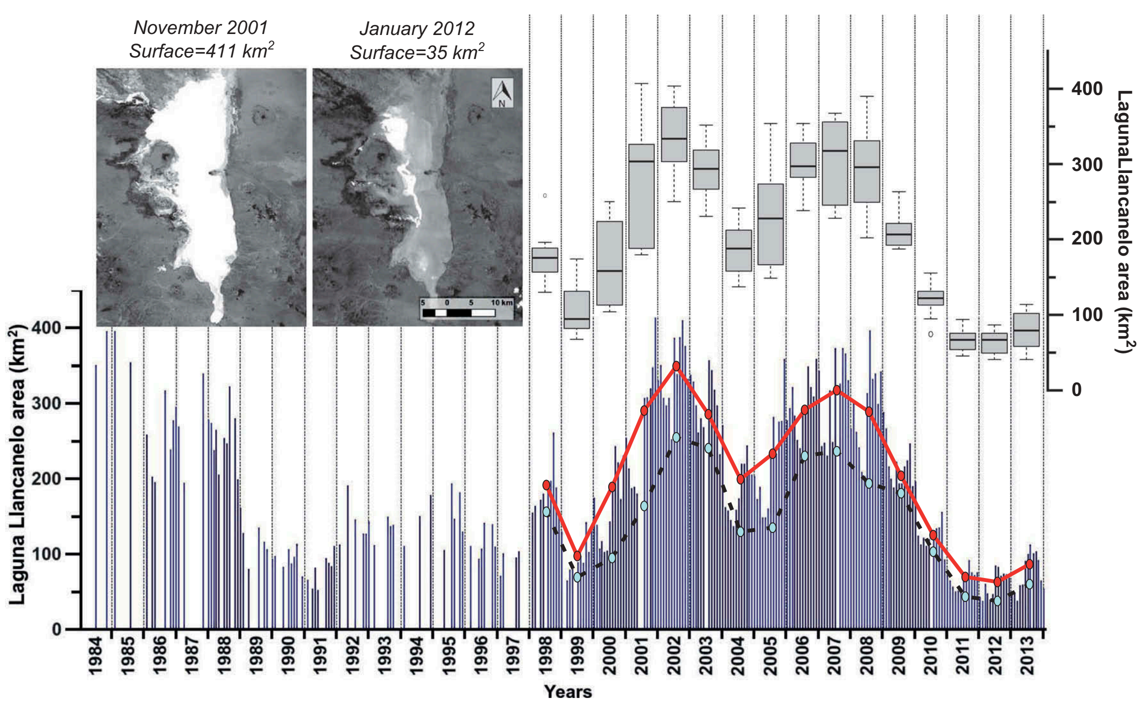

Figure 3. Monthly variations in LLA (bars), lagoon mean size for the periods of highest (August–October, solid line) and lowest (March–June, dotted line) surface area of the lagoon within each year (1998–2013). Upper left, Landsat images related to the extremes of November 2001 and January 2012, white areas represent the water area delimited from MNDWI. Upper right, box plots showing the median and deviations of lagoon size for each year (1998–2013).

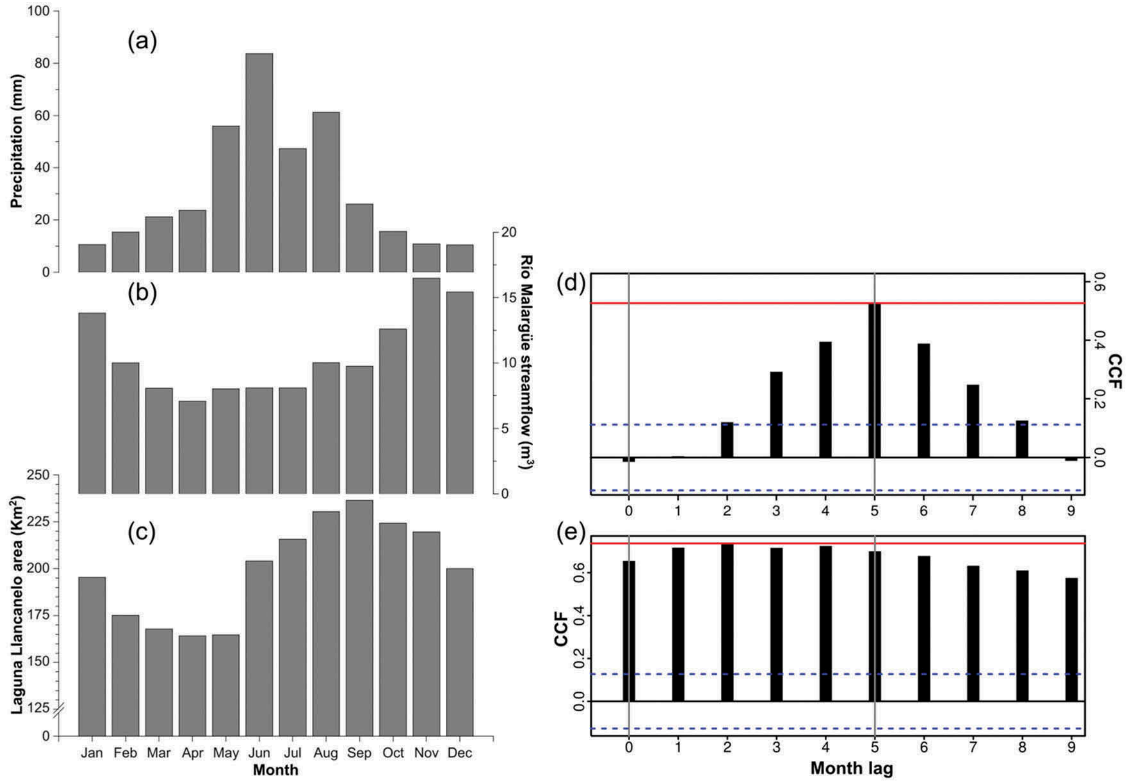

Figure 4. Monthly mean variations (1998–2013) of (a) precipitation at PWS, (b) Río Malargüe streamflow and (c) Laguna Llancanelo area monthly average. Cross-correlation functions between LLA and (d) precipitation at PWS and (e) Río Malargüe streamflow. The dashed line represents the 95% confidence intervals.

streamflow is composed of seasonal (3 and 6 months) to annual means (Table 3). The cross-correlation between the standardized indices of Río Malargüe streamflow and LLA show the strongest relationship, with a lag of 2 months ($r = 0.74$, Fig. 4).

Monthly fluctuations of LLA are not significantly related to rainfall in the lowlands, which is mostly associated with Atlantic (AWS) air masses in summer. In contrast, correlations between LLA and precipitation in the upper basin (PWS) are significant when considering accumulated time lapses of 6 and 12 months (Table 3).

Correlation coefficients between SLLI and streamflow from the most important rivers east of the central and northern Patagonian Andes of Argentina decrease with distance from the lagoon (Fig. 6 and Table 2). However, significant relationships between SLLI and streamflow departures are documented for several rivers during the period 1984–2013, some of them located more than 300 km from Laguna Llancanelo (Fig. 6). Indeed, correlation coefficients between SLLI and Río San Juan (Km 47.3 gauge station), and Rio Neuquén (Paso de Indios gauge station), situated 459 km to the north and 323 km to the south of the lagoon, respectively, are significant at the 95% confidence level ($r = 0.58$ and $r = 0.43$, respectively). We combined, in a regional streamflow record, the 16 rivers significantly correlated with the LLA fluctuations. This regional SRI is statistically significant in relation to changes in lagoon surface area ($r = 0.55$, $p < 0.01$) over the period 1984–2013. Furthermore, the correlation notably increases when northern Patagonian rivers (Fig. 6) are excluded from this regional composite ($r = 0.69$, $p < 0.001$). It is noteworthy that there is no significant correlation between SLLI and long-term temperature variations over the basin ($r = 0.002$; see Supplementary material, Fig. S2).

3.3 Changes in LLA related to local rainfall events

The relationship between Lower Llancanelo basin rainfall (AWS) and LLA is not statistically significant, suggesting a poor contribution of local precipitation to changes in lagoon size at seasonal to annual scales (Table 3). However, rapid increases in the lagoon area do occur in response to local heavy rainfall, mostly in summer. Note that these heavier precipitation events are limited to the lower-basin sector (AWS, Fig. 7). Figure 7 illustrates an increase of 66.2% in lagoon area between 14 January and 15 February 2012. During this short period, the Río Malargüe discharge was substantially

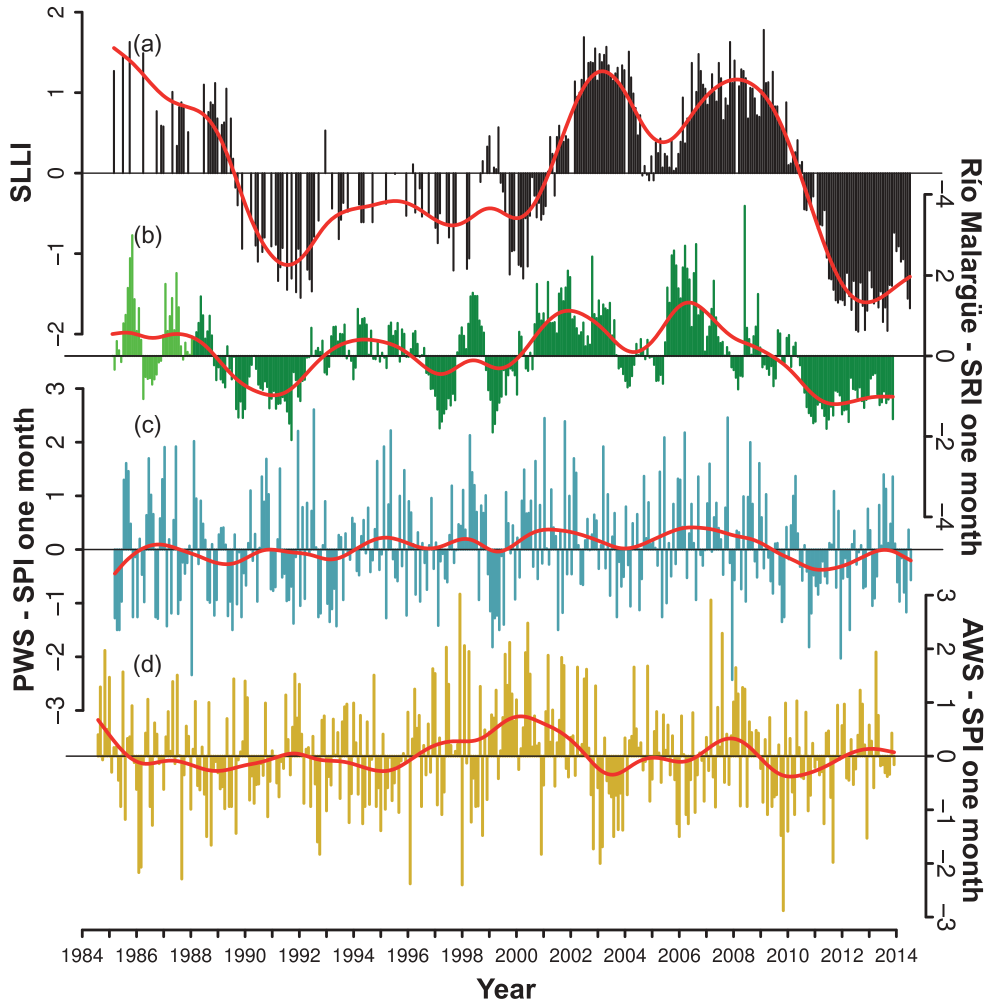

Figure 5. Monthly variations of (a) standardized LLA fluctuations (SLLI), (b) SRI from Río Malargüe (data from Pincheira gauge station are light shaded and data from La Barda gauge station are dark shaded), and SPI annual variations for (c) PWS and (d) AWS. All series were smoothed using a 48-month spline.

Table 3. Pearson correlation coefficients (r) between fluctuations in Laguna Llancanelo size (SLLI, n = 257) and (a) Río Malargüe standardized runoff index (SRI, n = 238), (b) PWS and AWS standardized precipitation index (SPI, n = 256) at different time scales (from 1 to 12 months). Bold values represent correlation coefficients significant at $p < 0.01$.

Accumulated months	SRI Malargüe	SPI PWS	SPI AWS
1	**0.66**	0.06	−0.03
3	**0.78**	0.19	0.02
6	**0.82**	**0.35**	0.09
12	**0.86**	**0.63**	0.16

below the long-term mean and showed no relationship with the recorded increase in LLA. Before 14 January 2012, rainfall was scarce in the Llancanelo basin. However, at least six events with daily rainfall higher than 10 mm were recorded at the lowland stations between 15 January and 12 February 2012, some of them with totals of up to 30 mm. Summer episodes of heavy precipitation are therefore able to increase LLA by more than 50% in a short period of less than 24 days.

Rapid reductions in the lagoon surface were also recorded. For example, between 31 October and 23 November 2010, the LLA decreased by 41.60% (Fig. 8). This period was characterized by few rainfall events and a comparatively reduced Río Malargüe discharge in relation to the long-term mean. Also, precipitation was extremely low in both the upper- and the lower-basin sectors over this time interval (Fig. 8).

4 Discussion

Landsat images were used to estimate month-to-month variations in the size of Laguna Llancanelo over 30 years. Laguna Llancanelo, the main water body in the Malargüe or Llancanelo endorheic basin, has a mean depth of 30 cm, a comparatively large surface

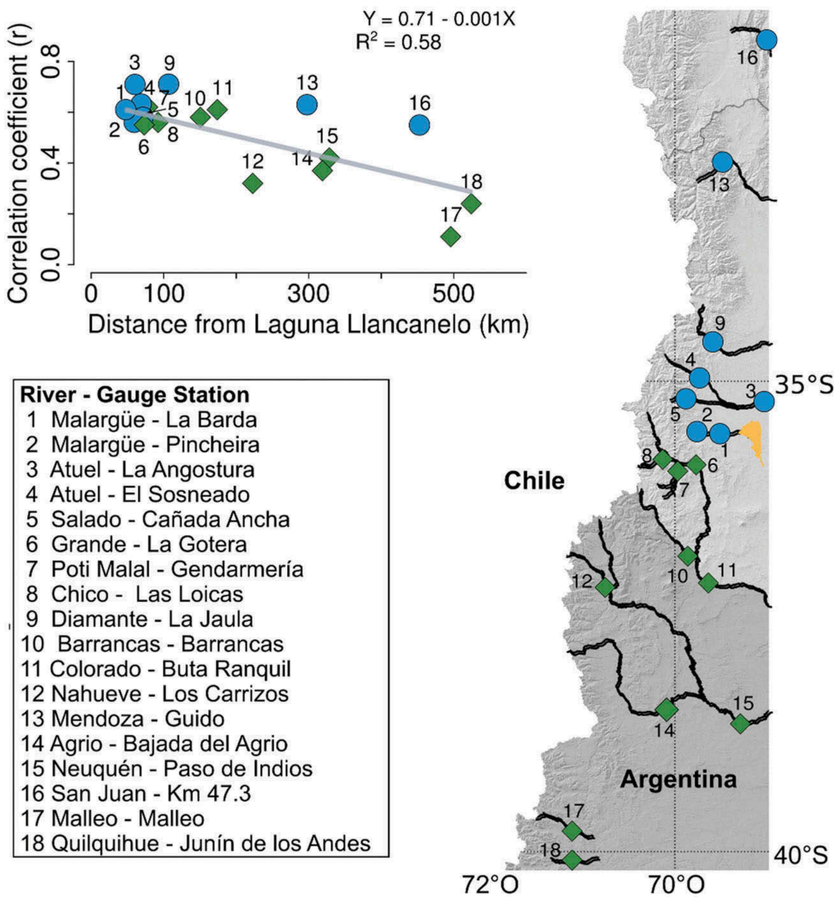

Figure 6. Correlation coefficients between SLLI and 18 SRI streamflow records (1984–2013). Locations are shown as distance to the north (circles) and south (diamonds) from Laguna Llancanelo. Northern Patagonia is represented by the shaded area in the map. Except for Malleo (17) and Quilquihue (18) records, all correlations are statistically significant ($p < 0.001$).

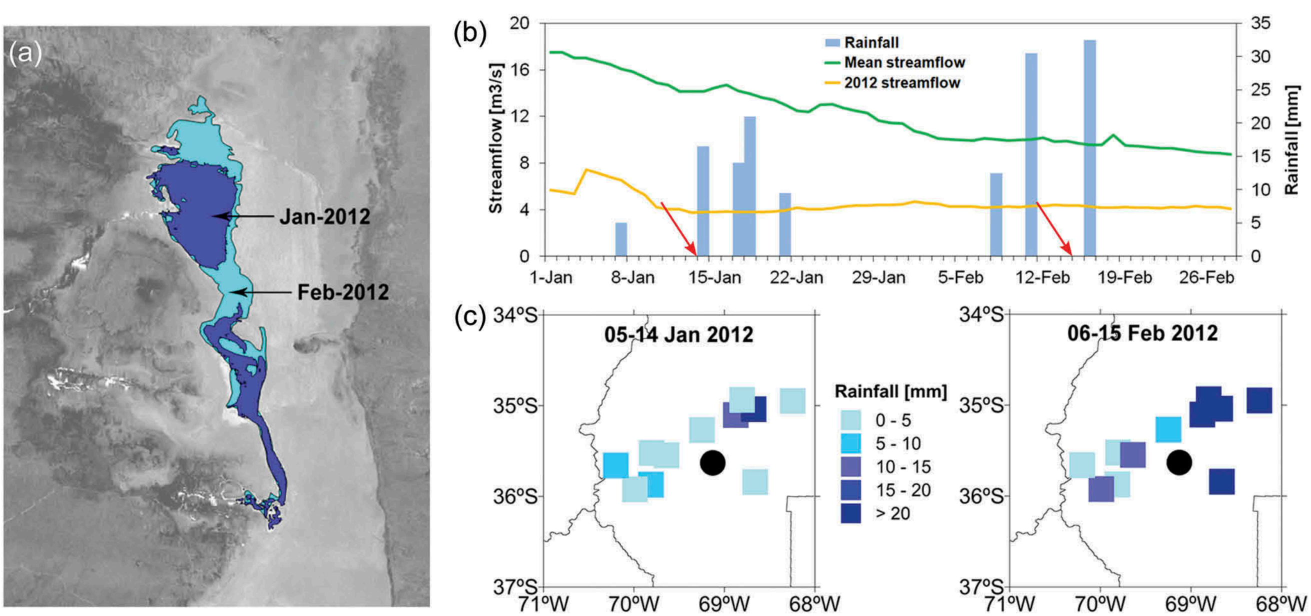

Figure 7. Influence of heavy summer rainfall on the area variations of Laguna Llancanelo. (a) Lagoon surface area on 14 January (dark blue) and 15 February (light blue) 2012. (b) Precipitation and streamflow in January and February 2012. Daily rainfall is indicated by blue bars. Río Malargüe streamflow from 1 January to 28 February 2012 (yellow line) and long-term (1987–2013) mean record (green line). Red arrows indicate the dates of the satellite images used in (a). (c) Accumulated rainfall for adjacent weather stations beginning 10 days prior to the two satellite image dates, location of the lagoon represented by the black dot.

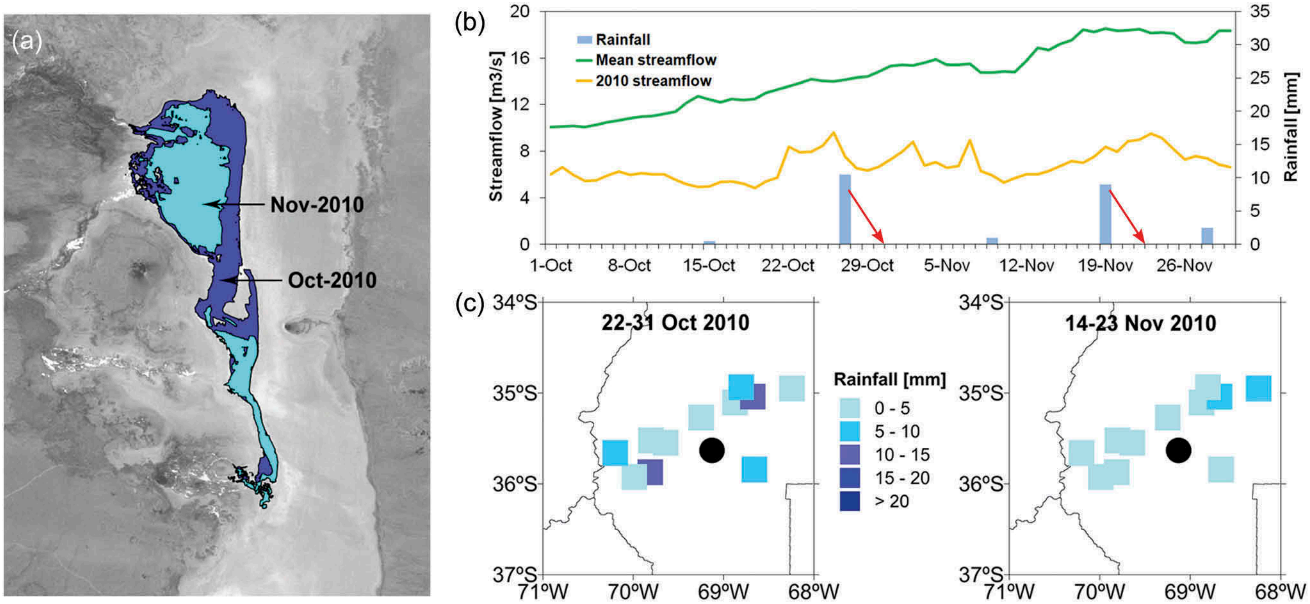

Figure 8. Rapid reduction in lagoon surface area during dry periods. (a) Lagoon surface area on 31 October (dark blue) and 23 November (light blue) 2010. (b) Precipitation and streamflow in October and November 2010. Daily rainfall is indicated by blue bars. Río Malargüe streamflow from 1 October to 30 November 2010 (yellow line) and long-term (1987–2013) mean (green line). Red arrows indicate the dates of the satellite images used in (a). (c) Accumulated rainfall for adjacent weather stations beginning 10 days prior to the two satellite image dates, location of the lagoon represented by the black dot.

area and, consequently, remarkable sensitivity to variations in water supply at the regional level. Over the period 1984–2013, our satellite estimates indicate an area ranging from 35 to 411 km^2 with a mean of 189 km^2. A previous study, based on seven satellite images, reported minimum and maximum sizes of approximately 80 and 300 km^2 (Isla *et al.* 2005). Differences in lagoon size estimations respond to the shorter period analysed by these authors (1996–2002) and the use of a single image per year. Similar studies estimating the area of water bodies from satellite images have recently been conducted elsewhere (Hui *et al.* 2008, El-Asmar *et al.* 2013, Adams and Sada 2014, and references therein). Our results are consistent with studies from arid regions, indicating that MNDWI is the most efficient procedure to discriminate water bodies from adjacent terrestrial environments (Zhang *et al.* 2011, Campos *et al.* 2012, and references therein). We were unable to fill many gaps in coverage of Landsat images during the early 1984–1997 period due to the paucity of satellite images or the dense cloud cover over the lagoon. This is a common difficulty reported by other studies tracking long-term temporal variations in the size of water bodies (Adams and Sada 2014). In contrast, we were able to collect satellite images for most months during the recent period 1998–2013.

Fluctuations of LLA are strongly related to discharge of the Río Malargüe, which is fed largely by spring and summer snowmelt in the mountainous upper basin. Maximum correlations indicate a 5-month lag between snow precipitation and runoff. Similar relationships have been reported by Masiokas *et al.* (2006), who described high correlation values (~0.8) between regional April–October snowfall in the Andes and subsequent December–February streamflow of six rivers in the adjacent lowlands. However, despite the significant relationship between Río Malargüe streamflow and LLA, the annual cycle of LLA peaks 2 months earlier than Río Malargüe streamflow (Fig. 4). We speculate that contributions from winter precipitation as rainfall close to the lagoon might contribute to an early increase in lagoon size.

There is no significant relationship between rainfall in the lower Llancanelo basin (AWS) and changes in LLA. However, heavy local precipitation, particularly during the spring–ummer season can induce rapid changes in LLA (Fig. 7). However, the relationships between satellite-inferred LLA and accumulated precipitation in the upper cordillera (PWS) are statistically significant after integrating precipitation on composite means of 6 months or longer (Table 3). This delay in precipitation–discharge response could be related to subsurface runoff processes and later melting of the accumulated snow in the upper basin with the advance of warmer temperatures in spring and summer. Although an increase in the relationship is expected when increasing the autocorrelation in the long-term means from climate and streamflow, the strongest relationship on intervals of 6 or more months reflects the lag between snow precipitation in winter at the upper basin and the subsequent melting in late spring and summer (Masiokas *et al.* 2006). The delay in the snow contribution to rivers in combination with subsurface infiltration may also contribute to the stronger relationship recorded at seasonal or longer time scales. Comparable results have been reported in previous studies in southeastern South America, which have documented a 2–5 month lag between rainfall and fluctuations in soil moisture (Spennemann *et al.* 2015) and runoff (Rivera 2014). Lags from 6 to 24 months have also been documented between changes in precipitation and levels of groundwater and reservoirs (Vicente-Serrano and López-Moreno 2005, Díaz *et al.* 2013). However, the lack of a statistically significant correlation between SLLI and monthly temperature (see Supplementary material, Fig. S2) suggests a negligible effect of local temperature modulating middle- to long-term changes in LLA. In this sense, long-term variations in Laguna Llancanelo size are mainly driven by changes in Rio Malargüe discharges. Heavy precipitation events, particularly in summer, contribute to rapid, but not lasting changes in LLA.

Correlation coefficients between LLA and river flow were significant for most rivers located in the central and northern Patagonian Andes of Argentina, even for those located more than 400 km from the lagoon. The relationship between lagoon size and river discharge decreases with increasing distance of the river basins from the lagoon. However, based on the significant correlation coefficients between variations in LLA and both individual and regional composite streamflow, the lagoon surface can be considered representative of the water balance at the regional scale. The comparatively stronger relationships between LLA and river discharge north of the Río Colorado (Fig. 6, Table 2) reflect the homogeneous patterns of runoff variations in the Central Andes of Argentina and Chile documented by Compagnucci and Araneo (2005) and Masiokas *et al.* (2006). Differences in climatic conditions further south are consistent with the lower, although significant, relationship between LLA and streamflow over the transition to hydrological regimes of the northern Patagonian Andes (Fig. 6). In contrast to rivers in the Central Andes, the contribution to runoff in northern Patagonia from both winter snowmelt and autumn rainfall introduces two peaks in the annual streamflow cycle (Compagnucci and Araneo 2005). These changes in hydrological regimes may explain the lower correlation coefficients between LLA and the Patagonian streamflow.

The estimated variability in LLA is also consistent with regional snowpack fluctuations in the Central Andes reported by Masiokas *et al.* (2012) for the period 1980–2010. More recently, Masiokas *et al.* (2014) noted that winter precipitation during the 2010–2014 period represents the driest pentad since at least 1951, the initial year for the snow accumulation records in the region. Consistently, the years 2010–2013 are the longest period of sustained small lagoon size in our 30-year record.

5 Conclusions

Variations in area of Laguna Llancanelo have been estimated over a 30-year period using a simple, fast and low-cost technique based on satellite images. Good estimates of lake area were obtained using AWEI and MNDWI indices; however, the latter provides a more precise water area delimitation. In the closed basin of the Río Malargüe, Laguna Llancanelo collects regional runoff composed of water transported by air masses ultimately originating in the Pacific and Atlantic oceans. Upper-elevation snowpacks are fed by precipitation in the Upper Malargüe basin from Pacific air masses that collide with the Andean Cordillera in autumn and winter. Rainfall in the lower basin is brought by Atlantic subtropical air masses in summer. Changes in the area of Laguna Llancanelo reflect the water contributions to the basin from both Pacific and Atlantic air masses. By integrating these different components across the basin, LLA data provide a better indication of regional water balance than estimates derived from records based only on the upper- or lower-basin precipitation. Moreover, fluctuations in the lagoon area are significantly correlated with river streamflow at the regional scale, mainly in central-western Argentina, east of the Andes. Based on these observations, we propose using the LLA fluctuations as an indicator of water balance for this region. Presently, we are developing rapid and efficient methodologies to derive, in a systematic way, an index of LLA variations. In addition to Landsat images, we are considering other remote sensing products with daily resolution, such as the images from the Terra and Aqua satellites (Moderate Resolution Imaging Spectroradiometer, MODIS).

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Disclosure statement

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