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HOW DOES CLIMATIC VARIABILITY AFFECT THE HIGHLAND LAGOONS OF THE VENEZUELAN ANDES?

JOEL MEJÍA BARAZARTE[1], JOSÉ GONZÁLEZ RAMÍREZ[2], ANDERSON ALBARRÁN TORRES [3]

[1] *Instituto de Geografía y Conservación de Recursos Naturales, Universidad de Los Andes, 5101 Mérida, Venezuela / Department of Integrative Environmental Geography, University of Hamburg, D-20146, Hamburg, Germany..*

[2]*Geógrafo.*

[3]*Escuela de Geografía, Universidad de Los Andes, 5101 Mérida, Venezuela.*

ABSTRACT. The influence of climate variability in the highland headwater lagoons of the Miguaguó watershed - Venezuela was evaluated from an initially defined time series of 46 years, climatologically classified by the Oceanic Niño Index (ONI). 18 climatologically different sample years were selected with the availability of Landsat imagery to evaluate the degree of surface water extent fluctuation using the Normalized Water Index (NDWI). The NDWI values were then statistically compared with the ONI and with local climate parameters, and the percentage deviations of the anomalies from the averaged neutral years were estimated. The results showed that the surface water extent of the lagoons is affected by the combination of ENSO, anti-ENSO anomalies and neutral years, although the effect is different depending on the location of the lagoons in the landscape, biophysical conditions and the intensity of the anomalies. Mapire, La Burra and Masiegal lagoons showed "severe" impact, with deviations from the surface water extent in neutral years ranging from 20 to 70%. On the other hand, the impact on the Miguaguo lagoon was mostly "slight", with deviations ranging from 0 to 10%. Positive deviations derived from anti-ENSO events and neutral conditions were generally dominant, except for La Burra lagoon, where the opposite trend was observed. Although the results were clear and conclusive, they have a limited spatial and temporal scope due to the complexity of the processes involved. Therefore, additional research is needed to complete the understanding of the climatic and atmospheric relationships in the processes governing the highlands of the tropics.

¿Cómo afecta la variabilidad climática a las lagunas altoandinas de los Andes venezolanos?

RESUMEN. Se evaluó la influencia de la variabilidad climática en las lagunas altoandinas de la microcuenca Miguaguó – Venezuela, para lo cual se definió una serie de tiempo inicial de 46 años, que fue climatológicamente tipificada a partir del Índice del Niño Oceánico (ONI). Se seleccionaron 18 años muestrales climatológicamente distintos con disponibilidad de imágenes Landsat, para evaluar el grado de fluctuación del espejo de agua de las lagunas a través del Índice Diferencial de Agua Normalizado (NDWI). Los valores de NDWI fueron estadísticamente comparados con el ONI y con indicadores climáticos locales, y se estimaron las desviaciones porcentuales de las anomalías respecto al promedio de los años neutrales. Los resultados mostraron que la extensión superficial del espejo de agua de las lagunas está influenciada por la combinación de anomalías ENOS, anti-ENOS y años neutrales, aunque la afectación es diferencial, dependiendo de la localización de las lagunas en el paisaje, de las condiciones biofísicas del entorno y de la intensidad de las anomalías. Las lagunas: Mapire, La Burra y Masiegal mostraron un impacto "severo", con desviaciones en la extensión del espejo de agua que oscilaron entre el 20 y el 70% respecto a los años neutrales. Por otro lado, el impacto en la laguna de Miguaguo fue mayoritariamente "leve", con desviaciones que oscilaron entre el 0 y el 10%. Las desviaciones positivas derivadas de eventos anti-ENOS y condiciones neutrales fueron en general dominantes, excepto en la laguna de La Burra, donde se observó la tendencia opuesta. Se concluye que, si bien los resultados fueron claros y contundentes, tienen un alcance espacial y temporal limitado, y los procesos estudiados son extremadamente complejos, por lo que se requieren investigaciones adicionales que complementen la comprensión objetiva de las relaciones climáticas y atmosféricas en los procesos hídricos de la alta montaña tropical.

Keywords: Andean lagoons, climate variability, ENSO and anti-ENSO, Normalized Difference Water Index (NDWI), headwaters watershed.

Palabras clave: lagunas andinas, variabilidad climática, ENOS y anti-ENOS, Índice Diferencial de Agua Normalizado (NDWI), cuenca de cabecera.

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***Corresponding author:** Joel Francisco Mejía Barazarte, Institut für Geographie, Universität Hamburg. Bundestrasse 55, D-20146, Hamburg. E-mail: jmejia@ula.ve: joel.francisco.mejia.barazarte@uni-hamburg.de

1. Introduction

The Andean highland wetlands are a specific type of ecosystem located above 3000 m.a.s.l. along the Andes in the bioregions of Páramo, Jalca and Puna Plateau; they form a diversity of aquatic and semi-aquatic environments that have been classified by the International Convention on RAMSAR Wetlands (2005) into the following categories: Andean high lagoons, swamps, marshes, peatlands, marshlands and wet grasses or meadows.

Both the topography and morphology of the Andean highlands above this altitude are largely dominated by the inherited glacial landforms (Franco *et al.,* 2013), creating the conditions for the formation of commonly interconnected aquatic ecosystems, usually forming a wetland complex (Ortiz, 2016) (Quintero, 2019); this complex represents the headwaters of the Andean River systems. According to Hofstede *et al.* (2014), highland ecosystems are the leading suppliers of freshwater in the northern Andes due to their capacity to regulate water, which is due to glacial and periglacial geomorphology that facilitates the accumulation of flow, the high regulatory capability of the páramo as an ecosystem, the particular soil conditions of the highlands, and favourable climatic regimes (abundant rainfall, high relative humidity, and low evapotranspiration rates).

Water regulation is the leading ecosystem service that provides value to high Andean wetlands and plays an essential role in the fluvial dynamics of river basins (Franco *et al.,* 2013; Valencia and Figueroa, 2015; Ortiz, 2016; Quesada-Román and Mora-Vega, 2017; Cáceres, 2019; Quintero, 2019; Lopez-Moreno *et al.*, 2022). Its functionality goes even further, providing humans with other environmental services that have direct and indirect use value: habitat for endemic flora and fauna, carbon storage, source of fresh water for consumption, and local traditional productive activities, mainly agriculture and livestock (Hernández, 2005). Similarly, wetlands provide other environmental services such as fisheries, aquaculture, wood production, fodder, and energy resources such as peat, as well as opportunities for tourism and recreation (Stolk *et al.,* 2006; Franco *et al.,* 2013; Valencia and Figueroa, 2015; Uribe *et al.,* 2017; Quintero, 2019).

There is no doubt about the biophysical, economic and cultural value of the high Andean wetlands to local and regional populations. Paradoxically, some anthropogenic activities have caused changes in the structure and functionality of the wetlands, increasing their vulnerability to climate variability and change, two processes that can produce various positive and negative effects and feedbacks at different scales in the Earth system.

According to Quesada-Román and Mora-Vega (2017), wetlands tend to have low ecological resilience to anthropogenic actions such as drainage, agricultural expansion, or changes in land use/land cover in their surroundings, which can lead to drastic changes in the ecosystem given the complex and intricate level of hydrological connectivity already aforementioned. In fact, Andean highland wetlands have been identified by the International Convention on RAMSAR Wetlands (2005) as fragile ecosystems, vulnerable to modification by external factors such as climate change and landscape alteration due to land use/land cover change, with negative impact on the intrinsic environmental status. They are among the most threatened ecosystems worldwide in the last 50 years (Betancur-Vargas *et al.,* 2017).

Andean highland ecosystems are highly vulnerable to climate change, especially climate variability, as argued by various authors (Franco *et al.,* 2013; De la Torre, 2014; Valencia and Figueroa, 2015; Cáceres, 2019). Wetlands are particularly sensitive to climate-induced hydrological changes: changes in precipitation significantly affect soil moisture, affecting vegetation growth and health, while increasing temperatures accelerate evaporation and ETP, affecting biodiversity and altering oxygen levels in water (Hangnan *et al.,* 2018).

The main source of climate variability in the northern Andes is the El Niño-Southern Oscillation (ENSO) phenomenon, which is characterized by the occurrence of warm (El Niño) and cold (La Niña, also referred to as anti-ENSO (Holden, 2017) phases. Both anomalies affect the temporal and spatial distribution of precipitation in South America and are the cause of extreme droughts and heavy rainfall in different geographical regions of the planet. In the northern Andes, El Niño events are associated with below-normal precipitation, while the opposite occurs during La Niña events (Herzog *et al.,* 2010).

However, the processes that dynamize the changes that occur in wetlands are usually complex, highly dynamic, stochastic, following a nonlinear path. This makes it difficult to set predictions about the transitions that can occur in wetlands after the occurrence of disturbances (Alibakhshi *et al.,* 2017). Quintero (2019) considers it very difficult to delineate the real influence of climate change in the Andean region, because it is accelerated by different anthropogenic activities, so it is difficult to separate the real influence of both processes.

The incidence of climate in any biophysical environment is limited to demonstrate and difficult to verify because it requires observations of high frequency and spatial density on the variables involved, as well as field data with high spatial and temporal resolution (Alibakhshi *et al.,* 2017). In the Andes, the scarcity of observations and monitoring add uncertainty when assessing the impact of land use change and climate change on ecosystem condition and health (Hofstede *et al.,* 2014; Uribe *et al.,* 2017).

In this sense, remote sensing has gained relevance and usefulness in recent years as a viable long-term spatial and temporal alternative for deriving indicators that allow the detection and monitoring of the status or condition of hydro-ecosystems, allowing the analysis of remote areas (Adam *et al.,* 2010; Middleton and Souter, 2016; Dos Santos *et al.,* 2019). As vegetation stress is a primary indicator of the degree of alteration of a wetland, it can be easily estimated and monitored with a reasonable degree of accuracy through the derivation and interpretation of vegetation indices, which are dimensionless radiometric metrics that serve as indicators of the relative abundance and activity of green vegetation and moisture condition (Dos Santos *et al.,* 2019). Indices such as the Normalized Difference Water Index (NDWI) allow for efficient indirect estimation of soil and vegetation moisture available and open water features.

Such methods are potentially relevant in our region. De la Torre (2012) claimed for rigorous scientific research on the issue of water resources and climate change in south American mountain ecosystems, as a basis for making relevant decisions in land planning and management. To date, research has been carried out in the local context, analysing the impact or occurrence of climate change in high Andean ecosystems and wetlands: Colombia (Franco *et al.,* 2013; Valencia and Figueroa, 2015; Ortiz, 2016; Cáceres, 2019; and Quintero, 2019); Ecuador (Guerra, 2018); Chile (Uribe *et al.,* 2017); and in Venezuela (Moncada *et al.,* 2010; Paredes *et al.,* 2020). Research on the effects of climate variability on wetland integrity and behaviour is more recent, with few examples to date: Mexico (Castro, 2019), Costa Rica (Quesada-Román and Mora-Vega, 2017; Esquivel, 2018), Colombia (Pinilla *et al.,* 2012), Ecuador (Ramírez and Vallejo, 2018), Chile (Meza and Diaz, 2014), and Venezuela (González, 2018). However, research evaluating the effects of climate variability in the headwater systems in which the wetlands are located is remarkable scarce, and the existing experiences like: Vergara *et al.* (2010), Mejía (2012), González-Zeas *et al.* (2019) and Escanilla-Minchel *et al.* (2020), were developed on the basis of GCM (Global Circulation Models) and IPCC scenarios. Only Mejía *et al.* (2022) and Carilla *et al.* (2023) have directly included the effect of the ENSO and A-ENSO events in the hydro ecological conditions of the highlands in Venezuela and Chile, respectively. Certainly, even more research in this topic is needed.

The relevance of this issue deserves greater attention, more research and monitoring processes on the incidence of climate change and climate variability in the increasing vulnerability of high Andean ecosystems, which facilitates the design of effective strategies to guarantee its conservation.

In this context, the main goal of this paper was to analyse the occurrence of climate variability through the combination of ENSO and anti-ENSO anomalies in the degree of surface water extent fluctuation of high Andean lagoons in a watershed of the Venezuelan Andes, through the interpretation of a moisture available index derived from Landsat images, calibrated with a reliable indicator of ENSO anomalies. The results provide a first approach to the problem in the local context, which will serve as a basis for further research about this topic.

2. Methods

2.1. The study Area

A headwater watershed located in the central section of the Cordillera de Mérida was selected as a case of study. The Miguaguó watershed is located northeast of Mérida state, between the coordinates: 8º42'20.59”- 8º42'20.90” N, and 70º52'41.33”- 70º53'44.80” W. It has a surface area of 375.07 ha, with a length of 3.5 km and an average width between 0.9 and 1.5 km (Fig. 1). The watershed is located in the high Andean Mountain range, whose altitude gradient ranges from 3460 to 4060 m.a.s.l. The relief is mountainous and dissected, with a morphology dominated by periglacial and fluvioglacial dynamics during the Quaternary; therefore, periglacial landforms are the most important, representing about 90% of the surface area; this is evidenced by forms such as glacial cirques, glacial steps, muddy rocks, lateral and terminal moraines, and large rock outcrops (González, 2018).

The lithology is largely dominated by Sierra Nevada Association (Iglesias Group) materials, mainly: schists, gneisses, and highly metamorphosed feldspathic quartz (Sandoval, 2015). The gradient is highly variable (from 0% to more than 60%), with a spatial predominance of the 30-60% range in 41.2% of the area (Fig. 1).

The area is characterized by a predominantly high-mountain humid climate, with an average annual rainfall of 1170 mm and average annual temperatures ranging from 9°C in the lower part to 2°C in the upper part (Córdoba, 2014). Solar radiation is intense (1200 w m^{-2}), especially during the dry season; consequently, the contrasts between minimum night temperatures and maximum day temperatures are quite marked.

The lagoons in the Miguaguó headwaters watershed form an interconnected wetland system that is the hydrological structural source for the Miguaguó stream. Figure 2 shows an individual view of each lagoon in its local environment. La Burra Lagoon (Fig. 2a) is located in the upper part or head of the watershed, being the source and starting point of the drainage network (Fig. 1). Masiegal and Miguaguó are intra network lagoons (Fig. 2b and 2c) located in the middle sector of the watershed, completely connected by the main vector of the Miguaguó stream. On the other hand, Mapire Lagoon

(Fig. 2d) is a semi-independent entity located at the beginning of a secondary drainage in the middle part of the watershed that, after a short distance, joins the main stream vector (Fig. 1).

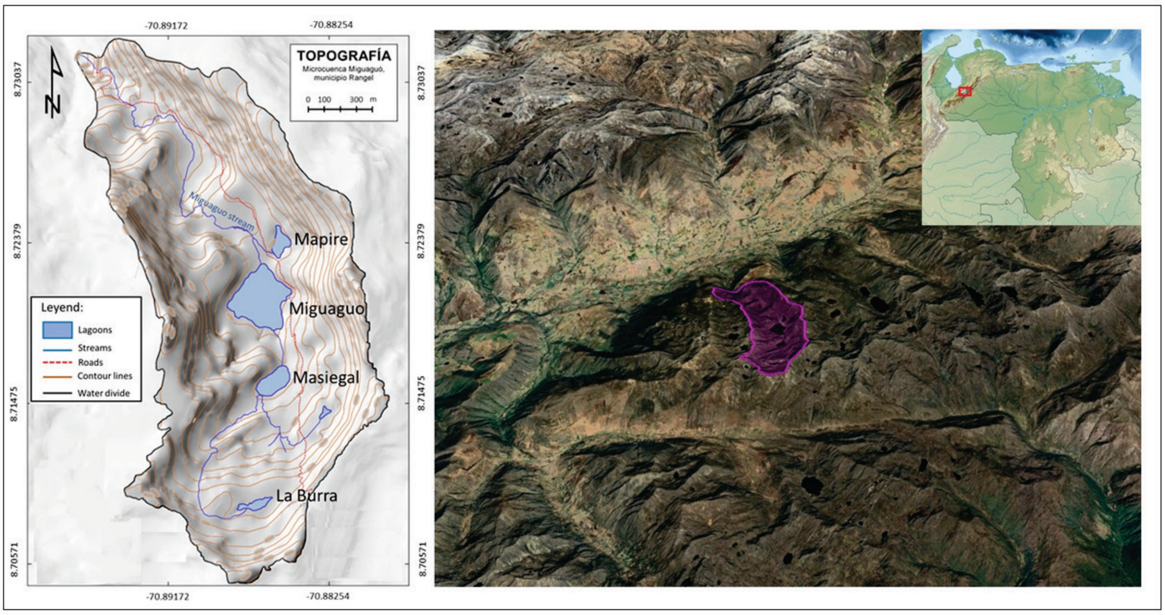

Figure 1. Location of the Miguaguo watershed. (Image: Landsat 8- Copernicus, Google Earth Pro).

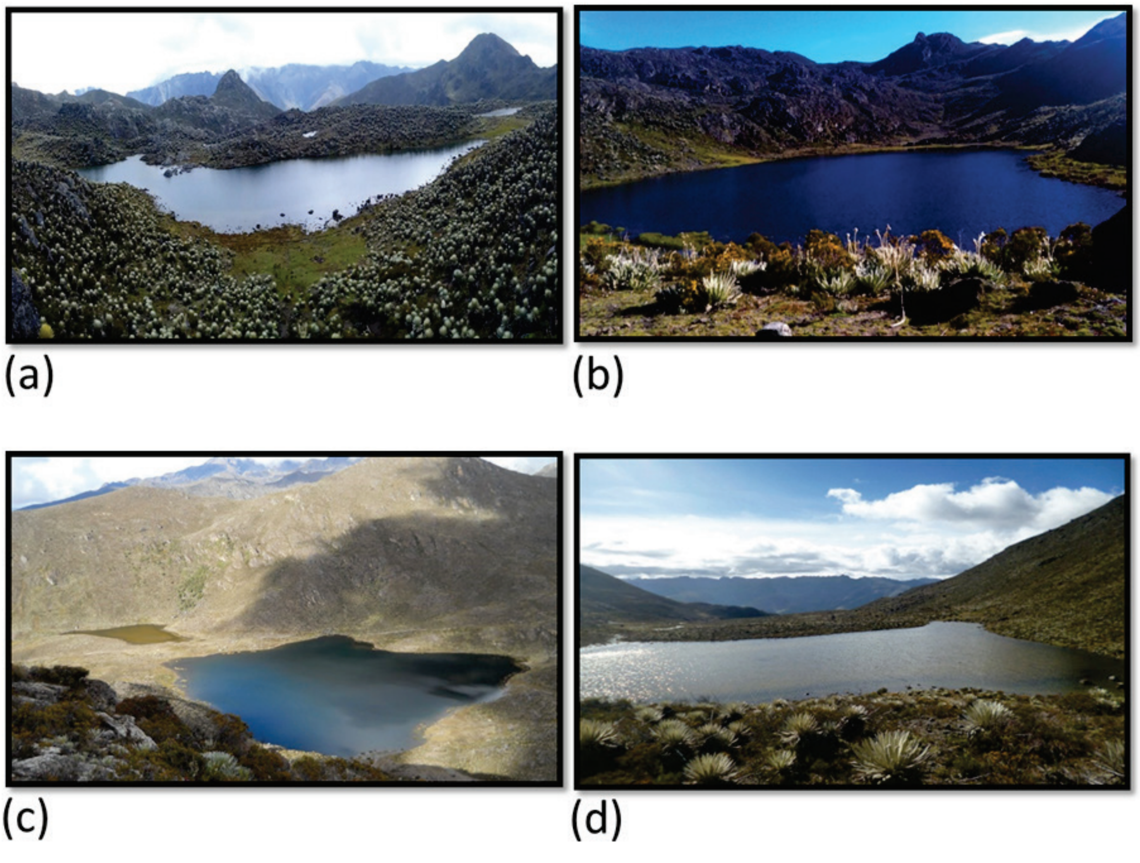

Figure 2. Watershed Lagoons: (a) La Burra; (b) Masiegal; (c) Miguaguó; (d) Mapire. (Pics. taken by Gonzalez, 2021)

2.2. Data Acquisition

The base map layer was created from a 1:25000 analog topographic map produced by Cartografía Nacional (1974), which had been previously digitized. It was rasterized using GIS software and the watershed was then delineated. The topological information was updated using aerial photographs corresponding to the flight mission 10408 (1989).

Climate data (precipitation and temperature) were collected from six rain gauges and climatic stations adjacent to the watershed, summarized in Table 1. The raw data were obtained from the Ministry of Environment and Water (MINEA) and the Institute of Agricultural Research (INIA). Since INIA-Mucuchíes has the longest and most complete historical record, it was selected as the reference station.

The data had to be preprocessed to estimate surrogate daily and monthly data (pseudo data), data distortion, and correction of anomalous records using the normal ratio and linear regression methods (Kashani and Dinpashoh, 2012; Guevara, 2013). Once the time series was completed, a common time series was defined for the comparative analysis: 1971 - 2022, considering the historical record of aerial photographs and satellite images available.

Table 1. Rain gauges and climatic stations used in the research.

Gauging station	Gauging number	Type	Coordinates		Elevation (m a.s.l.)	Distance to the watershed (km)	Serie lenght
			Latitude	Longitude			
INIA-Mucuchíes	7901	C1	084600	705400	3100	4	1971-2015
Mucubají	3072	PR	084810	704922	3560	11	1971-2003
Mucurubá	3029	C3	084222	705933	2320	12	1971-1983
Los Plantíos	3161	PR	084911	704705	3878	15	1971-2003
Páramo Pico El Águila	3112	PR	085100	704937	4126	15	1971-1998
Páramo Mucuchíes	3111	PR	085105	705019	3685	14	1971-1993

2.3. Climatological classification of the data series according to Oceanic Niño Index - ONI

The climatological classification of the years was done based on the criteria of climate variability, due to the remarkable influence of ENSO and anti-ENSO events on the convective processes and climate dynamics of Venezuela (Pulwarty *et al.,* 1998); (Andressen *et al.,* 2000). One of the most commonly used indicators for monitoring ENSO and anti-ENSO anomalies is the Oceanic Niño Index – ONI, which is defined as the three-month moving average of the sea surface temperature anomalies that occur in the Niño 3.4 region (Bedoya *et al.,* 2010). Therefore, a review of the historical behaviour of the ONI on the National Oceanic and Atmospheric Administration (NOAA) website was made to identify the years affected by the ENSO phenomenon, anti-ENSO years, and neutral or no event years. Using this index, it was possible to define the occurrence of ENSO from a 0.5 °C anomaly in surface sea temperature (SST) with respect to the historical average according to NOAA, with a positive sign indicating the occurrence of the warm phase (El Niño) and a negative sign indicating the occurrence of the cold phase (La Niña). Those years with anomalies between 0 and 0.4 °C, both negative and positive, were considered as no event or neutral years in this study.

Using this index, it was also possible to classify the anomalies according to the intensity of their occurrence: weak (between 0.5 and 0.9 °C); moderate (between 1 and 1.4 °C); strong (between 1.5 and 2°C) and very strong (greater than 2 °C), as shown in Table 2. In this sense, all the years corresponding to the selected historical series were climatologically classified.

Once the years were classified, a compilation of Landsat satellite images was performed to observe the spectral behavior of the wetlands in the study area during the historical period. Landsat images were chosen because of their higher temporal resolution compared to others, and also because of their high accessibility and availability. These images are widely used in multi-temporal studies related to vegetation and water due to their radiometric and spatial precision characteristics (Lunneta and Balogh, 1999).

Table 2. Historical ONI anomalies in the Niño 3.4 region, that occurred between August and March, during the selected historical series.

A-ENSO			ENSO			NO EVENT		
Period	ONI(°C)	Level	Period	ONI(°C)	Level	Period	ONI(°C)	Level
1971-1972	-0.8	Weak	1972-1973	1.8	Strong	1978-1979	-0.1	Neutral
1973-1974	-1.7	Strong	1976-1977	0.7	Weak	1980-1981	-0.1	
1974-1975	-0.6	Weak	1977-1978	0.7	Weak	1981-1982	-0.1	
1975-1976	-1.4	Moderate	1979-1980	0.5	Weak	1985-1986	-0.4	
1983-1984	-0.7	Weak	1982-1983	2.0	Very strong	1989-1990	-0.1	
1984-1985	-0.8	Weak	1986-1987	1.1	Moderate	1990-1991	0.4	
1988-1989	-1.6	Strong	1987-1988	1.1	Moderate	1992-1993	0.1	
1995-1996	-0.9	Weak	1991-1992	1.2	Moderate	1993-1994	0.1	
1998-1999	-1.4	Moderate	1994-1995	0.9	Weak	1996-1997	-0.4	
1999-2000	-1.5	Strong	1997-1998	2.2	Very strong	2001-2002	-0.2	
2000-2001	-0.6	Weak	2002-2003	1.0	Moderate	2003-2004	0.4	
2005-2006	-0.6	Weak	2004-2005	0.7	Weak	2012-2013	-0.1	
2007-2008	-1.4	Moderate	2006-2007	0.7	Weak	2013-2014	-0.3	
2008-2009	-0.6	Weak	2009-2010	1.2	Moderate			
2010-2011	-1.5	Strong	2014-2015	0.5	Weak			
2011-2012	-0.9	Weak	2015-2016	2.4	Very strong			
2016-2017	-0.5	Weak	2018-2019	0.68	Weak			
2017-2018	-0.79	Weak						
2019-2020	0.20	Neutral						
2020-2021	-0.91	Weak						
2021-2022	-0.89	Weak						

Source: web: http://www.cpc.ncep.noaa.gov/products/analysis_monitoring/ensostuff/ensoyears.shtml del National Climate Prediction Center-NOAA.

Images were extracted from the EarthExplorer server of the United States Geological Survey (USGS) being selected according to the following criteria: (1) homogeneous spatial resolution with bands corresponding to the visible, near-infrared, and mid-infrared spectral ranges to ensure comparability; (2) date of scene acquisition corresponding to the dry season in Venezuela (December-March), a period when the wetlands could be more affected climatologically and hydrologically; and (3) minimal cloud cover in the useful area of interpretation. From a total of 50 initially preselected Landsat scenes, 18 images identified in Table 3 were finally selected for analysis. These images correspond to climatologically different years, hereafter referred to as "sample years".

Table 3. Images selected to monitor the dry period for the sample years.

Satélite / Sensor	Scene identifier	Date	Event	Level of intensity
LANDSAT 5 TM	LT50060541985051AAA06	20/02/1985	A-ENSO	Weak
LANDSAT 5TM	LT50060541986054XXX03	23/02/1986	S/E	Neutral
LANDSAT 4 TM	LT40060541988084XXX01	24/02/1988	ENSO	Moderate
Aerial Photo	M-10408	04/02/1989	A-ENSO	Strong
LANDSAT 5 TM	LT50060541991036AAA02	05/02/1991	S/E	Neutral
LANDSAT 5 TM	LT50060541998055CPE00	24/02/1998	ENSO	Very strong
LANDSAT 5 TM	LT50060541999090CPE01	31/03/1999	A-ENSO	Moderate
LANDSAT 7 ETM+	LE70060542000037AGS01	06/02/2000	A-ENSO	Strong
LANDSAT 7 ETM+	LE70060542001055EDC01	24/02/2001	A-ENSO	Weak
LANDSAT 7 ETM+	LE70060542003045AGS00	14/02/2003	ENSO	Moderate
LANDSAT 5 TM	LT50060542011091CHM00	01/04/2011	A-ENSO	Strong
LANDSAT 8 OLI	LC80060542014051LGN00	20/02/2014	S/E	Neutral
LANDSAT 8 OLI	LC80060542015054LGN00	23/02/2015	ENSO	Weak
LANDSAT 8 OLI	LC80060542016041LGN00	10/02/2016	ENSO	Very strong
LANDSAT 8 OLI	LC80060542017075LGN00	16/03/2017	A-ENSO	Weak
LANDSAT 8 OLI	LC80060542019033LGN00	02/02/2019	ENSO	Weak
LANDSAT 8 OLI	LC80060542020132LGN00	05/05/2020	S/E	Neutral
LANDSAT 8 OLI	LC80060542021134LGN00	14/05/2021	A-ENSO	Weak
LANDSAT 8 OLI	LC80060542022025LGN00	25/01/2022	A-ENSO	Weak

Source: EarthExplorer website (https://earthexplorer.usgs.gov/). Colors: ENSO (red), A-ENSO (blue), Neutral (green).

The images had to be preprocessed to make radiometric and atmospheric adjustments using the semi-automatic classification plug-in (SCP) method and geometrically using both the nearest neighbor and root mean square (RMS) methods (Olaya, 2016).

2.4. Image processing and NDWI estimation

The wetlands were identified and delineated from the interpretation of the Landsat 8 OLI image of February 20, 2014, with RGB combination to false color 542 (Fig. 3a), combining the mid-infrared, near-infrared, and green bands to identify the lagoons with sufficient accuracy. Since Landsat imagery have a middle resolution, the delineation process was calibrated using an aerial photograph of the area (flight mission 10408, 1989) to achieve greater accuracy (Fig. 3b). In post-processing, the results of the interpretation were verified and validated *in situ*. Eight (8) wetlands were identified: (4) swamps and (4) high Andean lagoons located in the valley bottom of the watershed.

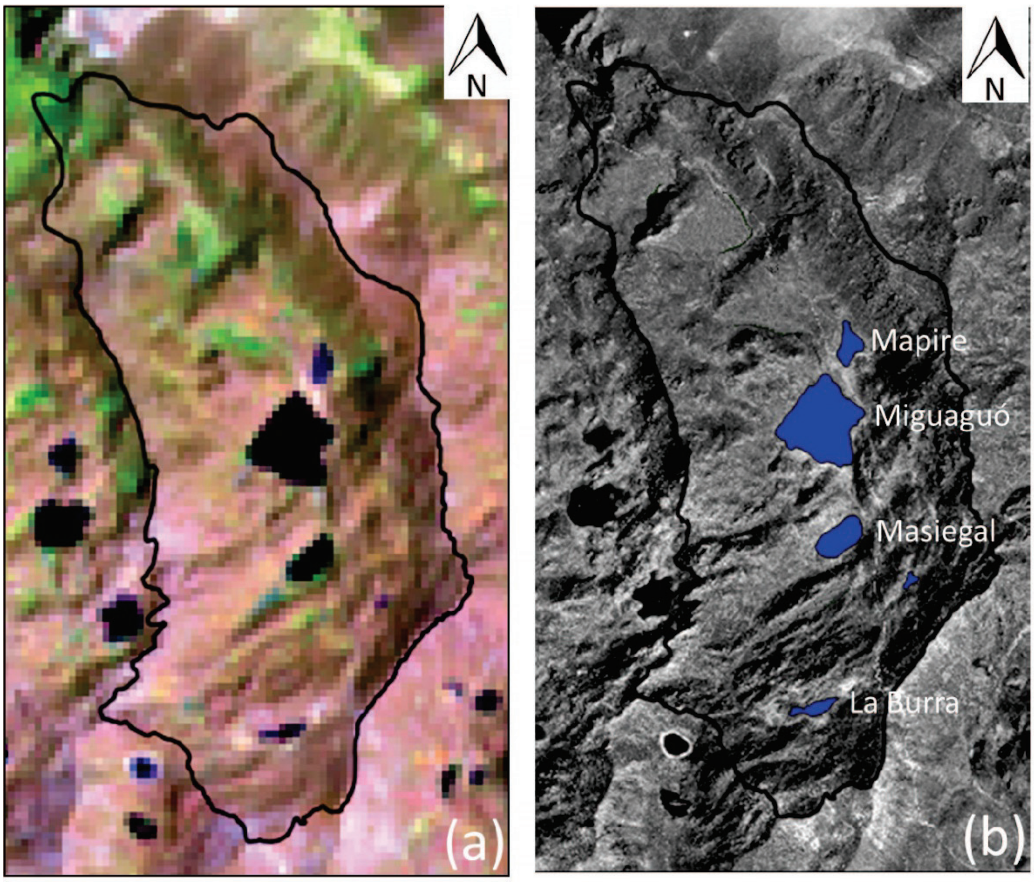

Figure 3. Identification of highland Andean lagoons in the Miguaguó watershed: (a): LANDSAT image in false color (542) of 02/20/2014, (b): lagoons delineated from aerial photo (Flight Mission 10408, 1989).

We considered the Normalized Difference Water Index (NDWI) as an indicator to evaluate perimetral water level fluctuation for the lagoons during the sample years. The degree of water extent fluctuation is considered one of the core indicators in the assessment of wetlands conditions (Fennessy *et al.,* 2004). The NDWI was developed to delineate open water features and enhance their presence in remotely sensed digital imagery. The index uses reflected near-infrared radiation and visible green light to enhance the presence of such features while eliminating the presence of soil and terrestrial vegetation features (McFeeters, 1996). For a good performance in its use, a validation process of the thresholds used to delineate water table is always required. NDWI has been widely used to identify wetlands and water bodies, and also to delineate the surface characteristics of water (Ji *et al.,* 2009) and glaciers (López-Moreno *et al.,* 2020, 2022). It is derived from the difference between the green and near-infrared bands divided by the sum of these bands by equation (1):

$$NDWI = \frac{(\rho_{GREEN} - \rho_{NIR})}{(\rho_{GREEN} + \rho_{NIR})} \quad [1]$$

where:

ρ_{GREEN} y ρ_{NIR} correspond to the visible (green) and near-infrared reflectivity, respectively, of each NDWI image in the historical series.

NDWI values range from -1 to 1, with zero being the threshold. The cover category is water if NDWI >0 and non-water if NDWI ≤ 0.

To compare the water level oscillation for each lagoon, a vector layer was used to delineate the reference area (using aerial photographs from 1989) to identify the pixels that the NDWI counts as "WATER", and thus observe the changes in the water surface area of the lagoons from one year to another. The NDWI was derived in each selected image and the metrics and zonal statistics corresponding to the spectral index were estimated.

2.5. Statistical relationship between NDWI and ONI index

Since the SST anomalies indicate the occurrence of the ENSO phenomenon through the ONI index, the Pearson linear correlation coefficient between these anomalies and the NDWI indices was calculated for each sample year. The average NDWI values extracted from the vector polygons of the four lagoons were used to study the relationship between the oscillation of the wetlands and the possible influence of the ENSO phenomenon in the hydroperiod.

From the average NDWI values, the change or anomaly in the state of the lagoons was calculated by comparing the water surface extent in a sample year with the averaged neutral years, using equation (2):

$$\Delta NDWI\ (\%) = \left(\left(\frac{NDWI_{year\ n}}{NDWI_{referencial}}\right) * 100\right) - 100 \quad [2]$$

Where:

ΔNDWI (%): anomalies in percentage values

Reference NDWI: value corresponding to the NDWI for the averaged neutral years

NDWI year n: NDWI value for year n

According to Jiménez (2010), the percentage of variation (ΔNDWI) expresses the degree of anomaly (impact or recovery) experienced by each of the lagoons (water surface extent) quantified with respect to a reference value, and the variations are categorized as follows:

- Recovery or improvement: the value has increased compared to the averaged neutral years.
- Slight impact: the anomaly is greater than 0 and less than 10%.
- Moderate impact: the anomaly is between 10-20%.
- Severe impact: the anomaly is greater than 20%.

Thus, positive anomalies indicate an excess of rainfall resulting in a very humid rainy season, while negative anomalies indicate a deficit or low rainfall regimes with a dry season longer or more intense than usual. The purpose of calculating these anomalies was to observe the behavioral deviation of the hydroperiod respect to the neutral years, which can indicate the level of elasticity and resilience of the lentic systems due the influence of the inter annual Pacific Oscillation.

The statistical relationship between the fluctuations of the lagoons and the influence of ENSO and anti-ENSO was also evaluated by the Pearson linear correlation coefficient, comparing the average values of the NDWI of each lentic system with the values of the sea surface temperature anomalies in the Niño region 3.4.

2.6. Relationship between NDWI and local climatology

Considering the spatial dynamics of the occurrence of ENSO anomalies and the notable scarcity of climatic data recorded in the region, the degree of influence or correspondence between the surface water extent fluctuation of the lagoons and the local climatology was analyzed by comparing the normalized NDWI values observed in the sample years with the historical precipitation recorded at the INIA-Mucuchíes station (the reference station). In this case, the accumulated precipitation during the period between August - March of each year (the second half period of the rainy season plus the dry season) recorded in the reference station (1971-2015) was considered, because this period showed the best statistical performance between the surface water extent area of the lagoons and the rainfall regime.

3. Results

3.1. Chronological relationship of ENSO/anti-ENSO episodes during the time series and sample years

During the period initially considered, the temporal relationship between ENSO and anti-ENSO anomalies was heterogeneous, showing variable sequences between them according to their own episodic dynamics (Fig. 4a). In this sequential dynamic, the frequency of anti-ENSO episodes (21) was slightly higher than ENSO episodes (17), while the number of years classified as no event occurrence or neutral was lower (13). Regarding the intensity of the anomalies, a relative dominance of “weak” and “moderate” intensity events was observed, while the episodes of "strong" and "very strong" intensity seem to show a certain temporal recurrence, oscillating between 10 and 18 years for ENSO episodes and between 10 and 14 years for anti-ENSO episodes. Another trend can also be observed between the two anomalies in terms of the dynamics of their occurrence in Figure 4a, since the anti-ENSO anomalies tend to manifest themselves sequentially or successively in two (2) or three (3) years, which seems to be less frequent for the ENSO anomalies.

The sample years series chosen for the subsequent analysis (Fig. 4b) appears to adequately reproduce the temporal trend of the general period. In the sample years series were included: 9 events classified as anti-ENSO, 6 events classified as ENSO and 4 years classified as no event or neutral years.

Of the 9 anti-ENSO episodes, those of 1989, 2000 and 2011 were classified as "strong", with ONI values equal to or less than -1.5 ºC. In the remaining years: 1985, 2001, 2017, 2021 and 2022, the anomalies were of "weak" intensity (between -0.5 and -1). Meanwhile, all the intensity levels are represented for ENSO episodes, since in 1998 and 2016 there were anomalies of "very strong" intensity with a positive temperature deviation > 2 ºC; the episodes of 1988 and 2003 were of "moderate" intensity, while in 2015 and 2019 there were events of "weak" intensity. Finally, the neutral or no event years were temporally dispersed (Fig. 4b).

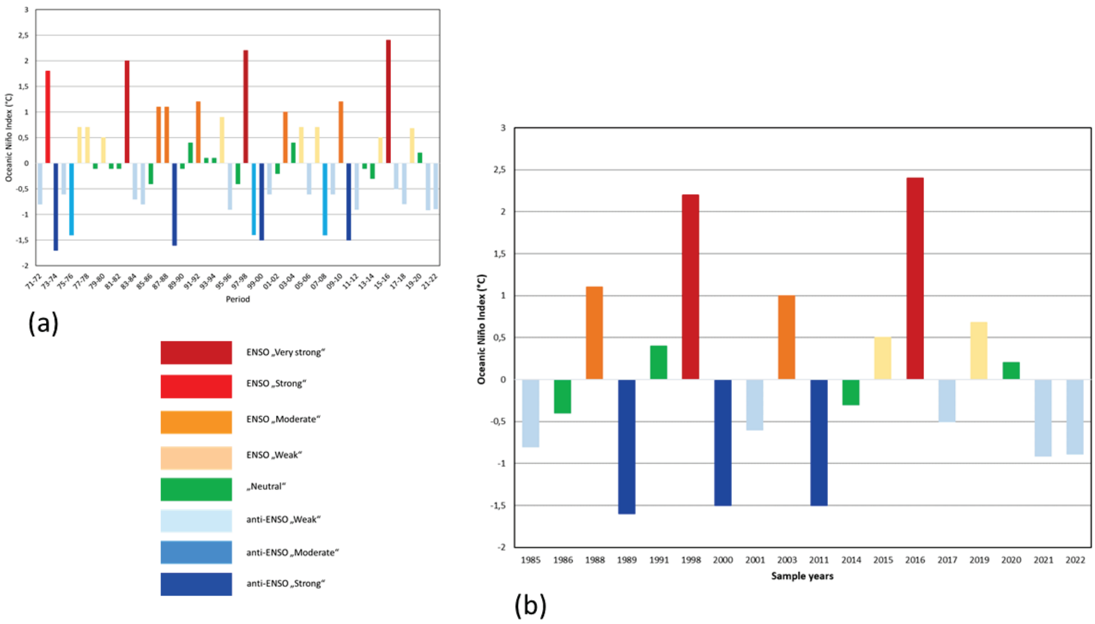

Figure 4. Chronological relationship of the occurrence of ENSO and anti-ENSO anomalies according to the Oceanic Niño Index - ONI during the initial period (a), and during the selected sample years (b).

Figure 5 shows the interannual variability of precipitation at the reference station. In the period 1971-2015, precipitation showed a high variability in occurrence (CV = 29.4%), with wet periods alternating with relatively dry periods. Between 1976 and 1990, precipitation was above the historical average, while the first decade of the 21st century was characterized by a dry period in which precipitation was significantly below the historical average (except in 2003) (Fig. 5). A maximum peak of pp occurred in 2011, coinciding with a "strong" anti-ENSO episode (Fig. 4b). On the other hand, 1992 was the driest year recorded, coinciding with an ENSO episode of "moderate" intensity (Fig. 4a).

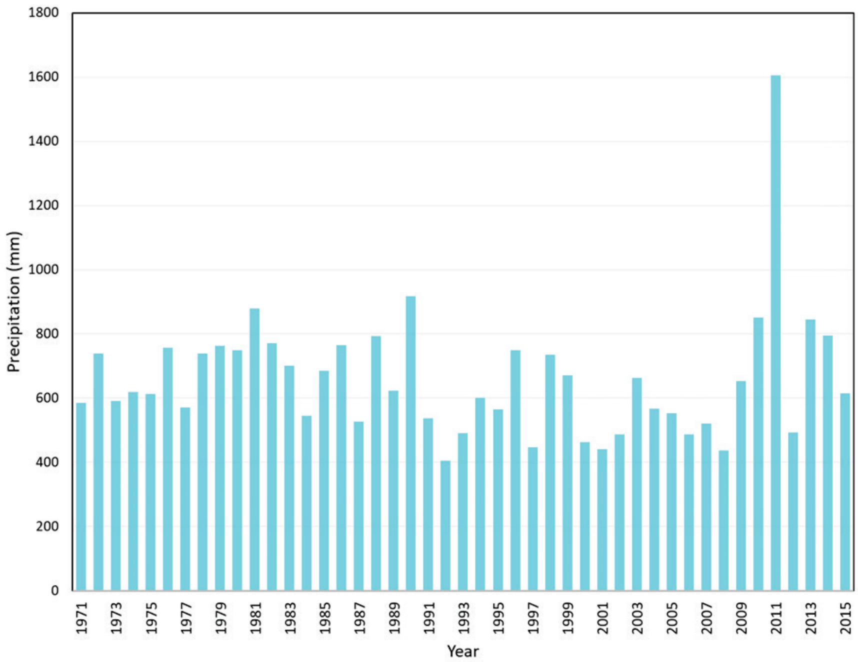

Figure 5. Total annual precipitation for the INIA-Mucuchíes weather station.

A further comparison showed, that for the 20 years with precipitation below the historical average, 8 coincided with anti-ENSO events, 2 coincided with ENSO events, while the remaining 8 were classified as no event or typologically neutral years. Meanwhile, 25 years showed precipitation values above the historical average, of which 10 coincided with ENSO events, 11 occurred during anti-ENSO events, and 4 were no event or neutral years.

3.2. Lagoon water surface extent dynamics according to NDWI results.

Figure 6 show the degree of water level fluctuation for the lagoons during the sample years classified according to ONI. The Miguaguó Lagoon has the largest surface area with 8.24 ha, followed by Masiegal Lagoon with 1.75 ha; Mapire Lagoon with 0.82 ha, meanwhile La Burra Lagoon is the smallest with only 0.57 ha.

As shown in Figure 6, the water surface extent for the four lagoons reflect a differential elastic hydrological behavior during the sample years, whose surface oscillations seemed to follow the oscillation of the climate through the relationship or combination between ENSO, anti-ENSO episodes and neutral years.

The hydrological oscillation of the water surface extent was highly dynamic among the sample years, with noticeable differences between the lagoons (Fig. 6). The CV of La Burra (45%) and Mapire (33%) lagoons clearly showed that both lentic systems had a substantial variability in their water surface extent and, therefore, the most elastic hydrological behaviour.

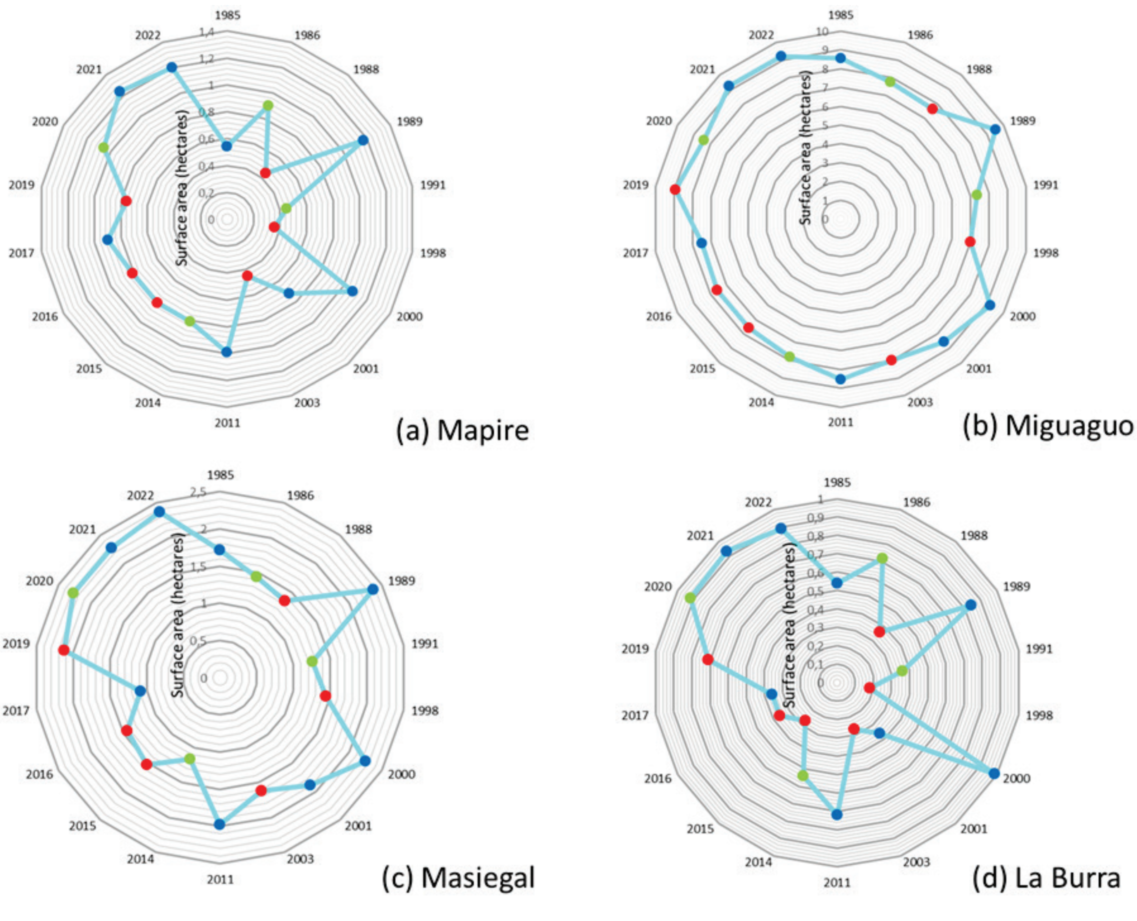

Figure 6. Water surface fluctuation during the sample years classified according to ONI index. Colors indicates: ENSO (red), A-ENSO (blue), Neutral (green) episodes.

Both lagoons are perimeter headwaters entities located downslope of a small concave "zero-order area" (see Fig. 1), so that atmospheric water reaching the rocky surface is easily concentrated there. Thus, both lagoons are highly dependent on atmospheric discharges as the primary water input, since the surface draining area is remarkably narrow and the bedrock is found at a very shallow depth, thus inhibiting subsurface inflow.

The Masiegal (CV= 24%) and Miguaguó (CV= 9%) lagoons showed a less variable and elastic statistical behavior, suggesting a lower or less evident dependence on atmospheric processes. These intra network lagoons are connected to the main channel vector of the stream, and their location in the geomorphic landscape guarantees water confinement with constant lateral subsurface flux.

As shown in Figure 6, the oscillations of the lagoons showed sensitivity to the historical alternation of the episodes of climate variability, since during the ENSO years: 1988, 1998, 2003, 2015 and 2019, the water surface level retreated and showed values below the observed mean. The greatest reduction occurred in 1998, coinciding with a "very strong" ENSO episode (see Table 2, Fig. 4b), which, according to *Corporación Andina de Fomento* [CAF] (2000), caused a rainfall deficit throughout the country. The episodes of 1988 and 2003 were of "moderate" intensity and the intra network lagoons (Masiegal and Miguaguó) did not show a significant oscillation (Fig. 6); meanwhile, the 2015 and 2019 episodes were of "weak" intensity (see Table 2, Fig. 4a and 4b).

The opposite trend occurred during the anti-ENSO years: 1989, 2000, 2011, 2021 y 2022, when the lagoons showed a significant increase in the water surface level, particularly in 2000, when a "strong" Niña event was recorded, preceded by a "moderate" one (see Table 2, Fig. 4a). During this anti-ENSO event, exceptional seasonal rainfall occurred, causing the most devastating natural disaster of the 20th century in Venezuela (Jiménez, 2007) (Córdova and López, 2015). In line with this, Artigas and Vicuña (2011) argued that the extreme rainfall that occurred in the last months of 1999 and early 2000 was a consequence of the cold phase of ENSO (La Niña), which dumped heavy rainfall on the country above the observed average. The anomalies that occurred in 1989 and 2011 were also classified as "strong" intensity events; meanwhile, “weak” anomalies occurred in 2017, 2021 and 2022 (Table 2, Fig. 4a and 4b).

For the "neutral" years, the behavioral trend of the surface water extent was less predictable, particularly for both La Burra and Mapire lagoons, which are the base of the hydrological system, showing an erratic oscillation during the sample years. On the other hand, Masiegal and Miguaguó lagoons showed a slightly decreasing trend in surface water extent (Fig. 6).

The results clearly indicate that these lagoon systems seem to be sensitive and at the same time dependent on the input of atmospheric water within the watershed, necessary to stimulate the processes of hydrological partitioning and conduction at surface and subsurface levels in the high Andean hydrological landscapes.

3.3. Statistical relationship between NDWI and ONI index

Fluctuations in water surface area and ONI are statistically inversely proportional, as can be seen from the scatter plots in Figure 7. Although the data show an adequate linear fit, the strength of this relationship is not essentially homogeneous between the lagoons. Miguaguó lagoon is the one that shows the best fit and relationship between the variables, suggesting that 50% of the variation in lagoon area can be explained by the oscillation in the occurrence of ENSO/anti-ENSO episodes. In La Burra and Mapire lagoons, the level of agreement decreases slightly to 46 and 43% respectively; finally, Masiegal lagoon is the one that shows the lowest level of fit between the variables (25%).

The statistical relationship between the two variables is more clearly reflected by the results of the Pearson correlation coefficient. The results of the "r" considering all the sample years evaluated showed a "high" negative correlation for Miguaguó Lagoon, Mapire and La Burra lagoons and a “moderate” correlation for Masiegal lagoon, indicating that the episodes of ENSO anti-ENSO can affect the lagoons differently (Table 4).

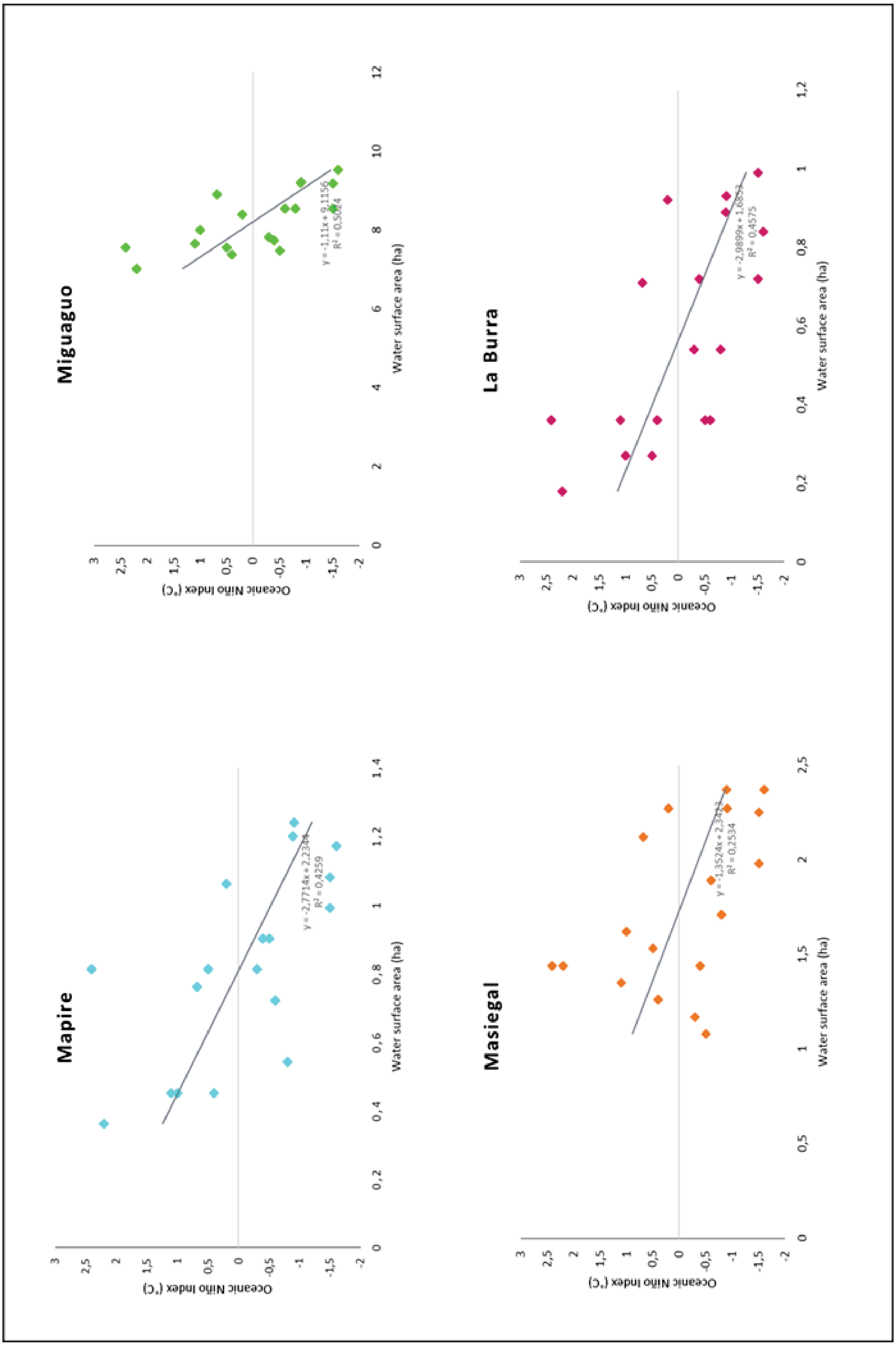

Figure 7. Statistical relationship between NDWI and ONI.

Table 4. Pearson linear correlation coefficient (r)between NDWI and ONI index for the sample years.

r considering all sample years (ENSO, anti-ENSO, Neutral)		**r considering ENSO and anti-ENSO years only**	
NDWI / ONI		NDWI / ONI	
Mapire	-0.65	Mapire	-0.69
Miguaguó	-0.71	Miguaguó	-0.77
Masiegal	-0.50	Masiegal	-0.63
La Burra	-0.68	La Burra	-0.73

Source: calculations based on the ONI index provided by the NOAA Climate Agency and water surface area as a result of the NDWI for the temporal items under study.

The resulting "r" values considering only ENSO and anti-ENSO years showed a better performance in the correlation, as a high negative correlation between the ONI and the surface water extent exist in all lagoons. This suggest that the oscillations occurred during neutral years are stochastic, introducing uncertainty to the strong relationship between the two processes.

3.4. Level of deviation of the surface water extent during ENSO / anti-ENSO episodes

Figure 8 shows the temporal variation of the percentage deviation of the NDWI (ΔNDWI) with respect to the mean accounted for the neutral years. It is clearly observed that the surface water extent of lagoons experienced a highly dynamic behaviour during the sample years, with different trends among them. La Burra and Mapire lagoons had the most elastic behaviour and higher amplitude in their surface water extent fluctuations, defining a similar temporal trend in which both lagoons show positive and negative deviations on their surfaces due to the alternation of ENSO and anti-ENSO episodes. La Burra showed the most extreme percentage of deviation, ranging from 56% for positive anomalies (anti-ENSO) to -72% for negative anomalies (ENSO). For Mapire lagoon the magnitude of the deviation is slightly lower, ranging from 54% to -55% (See Fig. 8).

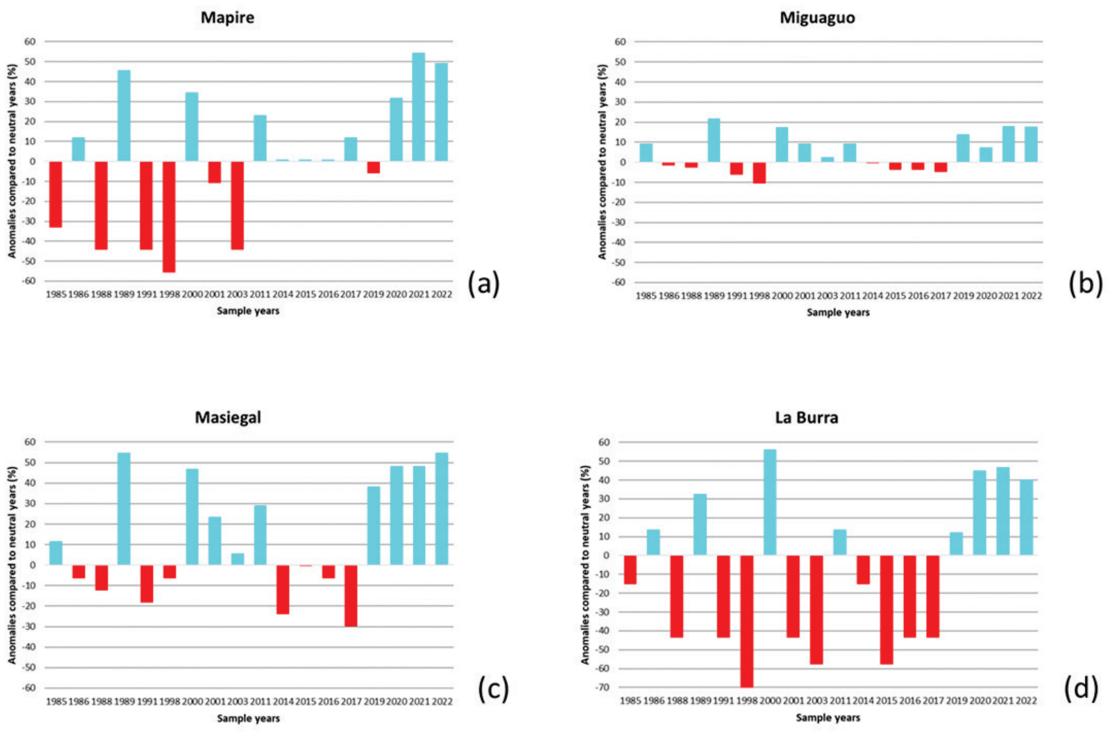

Figure 8. Percentage of variation-anomalies ΔNDWI being compared with the averaged neutral years.

The Miguaguó Lagoon showed a less elastic and more resilient behaviour during the period, with mostly positive deviations, suggesting that its surface water extent experienced relative stability during the sample period. The amplitude of the deviations with respect to the neutral years is remarkably small (between 21% and -10%), with an apparent dominance of positive deviations in its surface water extent. For the Masiegal Lagoon, the amplitude of the deviations is greater than the previous one, with values ranging between 54% and -30%.

Thus, la Burra and Mapire lagoons have the highest level of severity in anomalies related with the occurrence of ENSO and anti-ENSO events, followed by Masiegal Lagoon, meanwhile in Miguaguó Lagoon predominate the slight intensity anomalies. For La Burra Lagoon, the dominance of "severe impact" for anomalies occurred during the sample period is evident, since in 13 of the 18 sample years the surface water extent had a severe level of deviation respect to the averaged neutral years; 8 anomalies were negative, which suggests that the lagoon tends to be more prone to negative anomalies produced by ENSO. The Mapire Lagoon showed anomalies of "severe impact" intensity in 11 sample years, meanwhile Masiegal Lagoon showed this condition in 10 sample years. In Miguaguó Lagoon, a dominance of anomalies of "slight impact" intensity level was observed, thus being the lentic system that denotes high stability against the disturbances generated by the El Niño South Pacific Oscillation.

3.5. Relationship between the surface water extent and the local climatology

Figure 9 shows the relationship between the interannual precipitation recorded at the reference gauging station (INIA Mucuchíes) and the surface water extent (normalized values) of the four lagoons. Previous statistical analysis suggested that the rainfall occurring at the end of the rainy season have an important impact on the water level fluctuation of the lagoons during the dry season.

The relationship shown in Figure 9 clearly suggests that the variation in the surface water extent of the four lagoons is virtually conditioned by the direct input of atmospheric water, with La Burra and Mapire lagoons being the entities that show a more sensitive reaction to the interannual rainfall variability. The relative location of both lagoons within the hydrological landscape system, as already mentioned, seems to play an important role in this level of sensitivity.

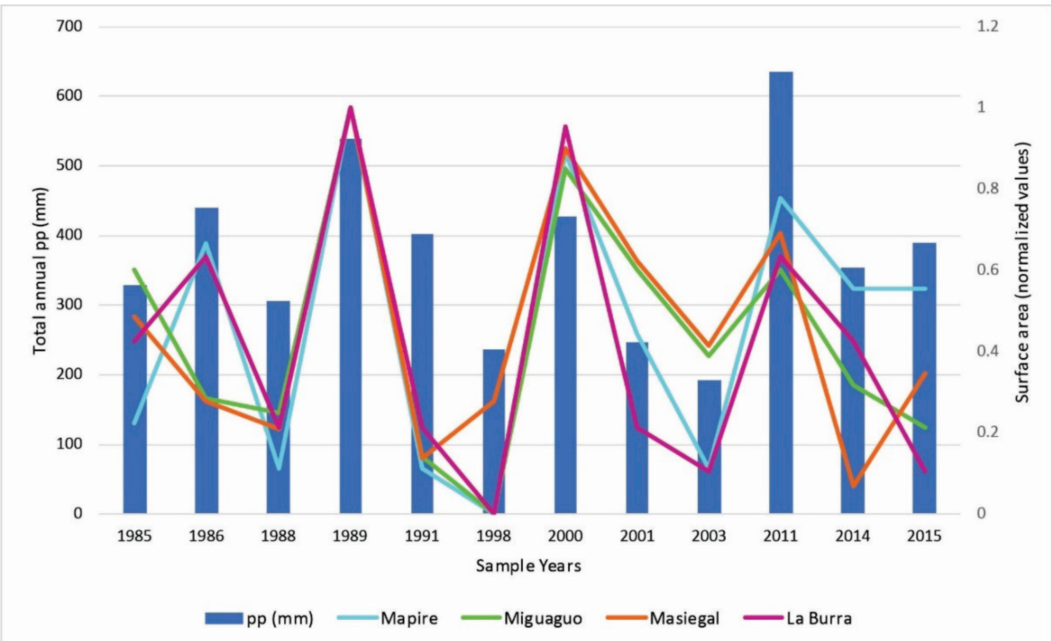

Figure 9. Ratio of accumulated precipitation between the months of August to March in the INIA-Mucuchíes reference gauge station and the surface water extent of the lagoons, according to the NDWI.

On the other hand, the Miguaguó and Masiegal lagoons showed a less evident variability of the surface water extent with respect to precipitation, which suggests that in both lentic systems the incoming runoff may be more complex and heterogeneous than in the other two lagoons, so that the hydroperiod is conditioned by the strategies of partitioning and transfer of water within the hydrological landscape.

4. Discussion

Our results clearly show that the high Andean lagoons and the headwaters of the Venezuelan Andes have a spatial and temporal dynamic that is strongly influenced by processes derived from the interannual variability of precipitation, in which the El Niño Southern Oscillation plays an important role. The results also show that climatic variability has a direct impact on the oscillation of water level of lagoons, which depends on the magnitude of the anomaly, the temporal sequence of the lagoons and the location of the lagoons in the landscape. From the results it can be concluded that the lagoons have different levels of atmospheric dependence.

4.1. El Niño Southern Oscillation and Climate Variability in the High Andes of Venezuela

The influence of ENSO/anti-ENSO on the climate of northern South America is well known, although the region is also climatically influenced by the Pacific Decadal Oscillation (PDO) on a decadal or interdecadal scale (Schoolmeester *et al.,* 2016), and there are even links or feedbacks between the two processes, as pointed out by Martínez *et al.* (2011). However, the impact of the PDO on the climate of the region has been poorly studied. On the other hand, other factors seem to modulate the climate of the region and act in close relation with ENSO (especially in its warm phase), such as changes in atmospheric pressure in the Caribbean and tropical Atlantic (Aceituno, 1988), and even the North Atlantic Oscillation exhibits an interesting coupling with the hydrometeorology of tropical South America (Poveda and Mesa, 1997).

These factors could help to explain the historical variations in precipitation observed at the reference station, which are inconsistent with the ENSO/anti-ENSO alternation. Due to the size and complexity of the Andean Mountain range, climatic processes exhibit important latitudinal differences, so that even the influence of ENSO/anti-ENSO on local climatology often shows different patterns and intensities.

4.2. Climate variability and its impact on high Andean lagoons

The relationship between ENSO/anti-ENSO events and their alternation with neutral years has a direct impact on the hydroperiod of the high Andean lagoons, which is directly reflected in the oscillations observed in their surface water extent. The location of these wetlands at the altitudinal base of the regional hydrological cycle makes them highly dependent on atmospheric dynamics, so that the hydrological response and the hydroperiod are directly related. Similar results have been obtained by Dangles *et al.* (2017) in the Cordillera Real of Bolivia, by De la Fuente *et al.* (2021) in the Chilean Andes, and recently by Carilla *et al.* (2023) in the Argentine Andes. In all these cases, the direct impact of climate variability on the wetlands studied was clearly evident, although with temporal variations imposed by latitude and climate regime.

The type of anomaly, as well as its magnitude, intensity and sequential relationship, also have an effect on the magnitude of the surface water extent in the high Andean lagoons. It is well known that anti-ENSO anomalies have more pronounced effects on the climate and hydrology of the continent than the opposite anomaly, and authors such as Poveda and Mesa (1997), Mejía (2012), Dangles *et al.* (2017), De la Fuente *et al.* (2021), Mejía *et al.* (2022) and Carilla *et al.* (2023), confirmed this. On the other hand, the frequency of episodes is usually variable in temporal scale, and the biophysical conditions of the environment, as well as the location of lagoons in the landscape and the configuration of the drainage network, influence their hydrological response to atmospheric processes. De la Fuente *et al.* (2021) found differences in the hydroperiod of lagoons depending on the size of the wetland. Similarly, the authors previously studied the Miguaguó swamps and found differential behaviors among them respect to the climate variability, probably explained by their location in the hydrological landscape.

4.3. Influence of the hydrological landscape

Due to its topographic and hydrological position in the high Andes, the Miguaguó watershed consists of a system of wetlands (lagoons and swamps) which are directly and permanently connected to the drainage network that forms the Miguaguó stream. Conceptually, and according to Rains *et al.* (2016), it is a hydrologic landscape in which the wetlands act as nodes that receive, store, and release water to the main transmission vector of drainage flow. For Winter (2001), the hydrologic landscape with glacial landforms is perhaps the most complex to describe, since the complex topography, in addition to the type and distribution of unconsolidated geologic material in glacial terrain, can result in a wide scalar typology of hydrologic landscapes, from micro-depressions to entire moraine complexes.

These landscapes have complex surface and subsurface water flow systems, in which drainages can have very different interactions with groundwater depending on whether they cross moraine till, till plains, or pure alluvial plains. In the case of the Miguaguó watershed, the soils are basically moraine and fluvioglacial deposits, so the transmissivity of the subsurface water is probably high due to the glacial morphology.

The differences in trends observed between the lagoons may be due to their location at the landscape level and, more specifically, to their relative position in the local hydrological network. As can be seen in Figure 1, La Burra Lagoon is located in the upper zone of the watershed and channel network, specifically in the so-called transition zone between the zero-order and first-order channels (Benda *et al.,* 2005). The lagoon has a very small draining area, with very shallow soils and bedrock very close to the surface; this means that its water regulation capacity is likely limited -as suggested by Franco *et al.* (2013)- so that the hydroperiod of the lagoon is essentially controlled by atmospheric water input, rather than surface runoff.

The Masiegal and Miguaguó are intra network lagoons located in the central part of the watershed, just in the middle section of the channel network, being nodal points of surface flow convergence, thus having a higher level of hydrological connectivity and perennial inflow. The presence of glacial cirques in this sector has resulted in a predominantly concave topography, facilitating the concentration of flow at the bottom of the valley. The two well-developed lateral moraine channels on either side of the stream, surrounded by moraine and fluvioglacial deposits, suggest a complex dynamic of diffuse, laminar, and especially lateral subsurface flow towards the two lagoons. This greatly diversifies the water input, thus favoring the hydroperiod of both lentic systems, which is additionally favored by a local morphology containing coarse-textured soils with high organic matter content that facilitates hydric confinement. According to Hofstede *et al.* (2014), the soils of the paramo usually have low bulk density, high porosity and high organic matter content, making them highly suitable to retain water for long periods and to release it slowly and constantly. In addition, the shallow bedrock inhibits the vertical transmissivity of water, thus guaranteeing its persistence at the surface.

The conditions described above also apply to the Mapire Lagoon, located in the middle part of the watershed, although it is a headwater lentic system that functions as a spring being connected to the network by a single low-volume stream. Its relative location in the lower part of the watershed, very close to the abstraction of water for consumption, irrigation and extensive cattle grazing, suggests that this lagoon could be under anthropogenic pressure that could be affecting its hydroperiod. Both topography and land use variables has been remarked by Vanderhoof *et al.* (2017) as determining the surface-water connectivity across the landscape.

For Franco *et al.* (2013), the diversity of inputs sources of water leads to greater opportunities to maintain the quantity and quality of water, thus favoring the hydroperiod of the lentic systems; this can explain the distinctive behavior of the lagoons based on the NDWI for the sample years considered.

4.4. Scope of the results in the context of the region

As mentioned above, the size and complexity of the Andes, its large latitudinal gradient and its complex climatic and biogeographical structure mean that the processes and factors that control and modulate climate at regional and local scales often vary from one region to another; similarly, ENSO/anti-ENSO episodes have different effects at spatial and temporal scales within the whole Andes range. Therefore, the results obtained may have a reduced spatial scope in their potential for spatial correlation at the regional scale. In addition, the notable scarcity of climatic records in much of the Andes and the limited access to the recorded data may in many cases affect the predictive reliability of the results. These considerations must be taken into account when studying the links between climatic variability and local hydrological or ecological processes in the Andes.

5. Conclusions

The results showed that there is a clear influence of climatic variability, specifically on the anomalies derived from ENSO and anti-ENSO events in the local climate, and on the dynamics and behaviour of the lagoons of the Miguaguó headwater watershed. The spatio-temporal behavior of the NDWI during the sample years, the statistical relationship with the Oceanic Niño Index (ONI), and its agreement with the local climatological records have helped to demonstrate this fact.

The climate variability has a different level of incidence in the surface water extent fluctuation of the lagoons. Differences are explained by: the spatial hydrological configuration, the relative position of each lagoon in the hydrological landscape, the topographic conditions, the morphology of the landforms and the soil characteristics of the environment. Similarly, the level of intensity and temporal frequency of each event also condition the dynamics of the hydroperiod of the lagoons.

The headwater lagoons showed greater hydrological elasticity and greater sensitivity to climatic anomalies, suggesting that their hydroperiod is highly dependent on atmospheric processes; the intra network lagoons appear to have greater resilience and stability to ENSO and anti-ENSO events, suggesting that their hydroperiod is structurally more complex and heterogeneous, presumably dependent on elements of the hydrological landscape.

The research demonstrated the advantage and remarkable potential usefulness of remote sensing tools and their derived indicators, such as the NDWI, in understanding the dynamics of lentic systems at different scales: spatial, temporal and climatic. Similarly, the Oceanic Niño Index seems to be a very useful indicator to be able to quantitatively and accurately delimit ENSO and anti-ENSO events, having comparability and relationship with other climatological and hydrological indicators.

Although the results of this research are clear and convincing, they are also spatially and temporally scale limited because the processes involved are inherently complex. For these reasons, additional research is needed to facilitate and complement the understanding of the climatic and atmospheric relationships in water processes typical of mountainous areas in the tropics.

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