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Articles

Evaluation of the contraction and expansion of lentic water systems under the influence of the ENSO phenomenon (case study. Department of Córdoba, Colombia)

Evaluación de la contracción y expansión de cuerpos hídricos lénticos bajo la influencia del fenómeno ENSO (caso de estudio. Departamento de Córdoba, Colombia)

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Abstract

The sustainability of ecosystems and economic activities depend significantly on the availability of water, which can be affected by its temporal variability. Colombia is one of the countries that suffers high temporal variability of the water resource because of global, regional, and local phenomena. One of the macro-climatic events that alter the water regime is ENSO. Its impact on lotic water bodies is well known, while the effects on lentic systems are unknown. In this study, a methodology, which integrates climatic analyses with remote sensing studies, was designed to evaluate the relationship between the expansion and contraction of lotic bodies under the ENSO event, verified in four welt lands (*ciénagas*) in the department of Córdoba. The results showed that the dynamics depend up to 60 % on this macro-climatic event. The methodology developed can be considered as a tool for environmental planning of the territory around the lagoon systems, since it allows estimating buffer zones.

Keywords: Water variability, ENSO, NDWI index, Colombia, swamp.

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Resumen

La sostenibilidad de los ecosistemas y de las actividades económicas dependen de manera significativa de la disponibilidad del agua, la cual puede ser afectada por su variabilidad temporal. Colombia es uno de los países que se caracteriza por una alta variabilidad temporal del recurso hídrico, producto de fenómenos globales, regionales y locales. Uno de los eventos macro climáticos que altera el régimen hídrico es el ENSO. Es altamente conocido su impacto sobre los cuerpos hídricos lóticos, mientras que las afectaciones de los sistemas lénticos son desconocidas. En el presente estudio se diseñó una metodología que integra los análisis climáticos con los estudios de teledetección para evaluar la relación entre la expansión y contracción de los cuerpos lóticos bajo el evento ENSO, que fue comprobada en cuatro ciénagas del departamento de Córdoba. Como resultado se obtuvo que las dinámicas en hasta el 60 % dependen de este evento macro climático. La metodología desarrollada puede considerarse como una herramienta para planeación ambiental territorial de los alrededores de los sistemas lagunares, ya que permite estimar las zonas de amortiguación de estos.

Palabras clave: variabilidad hídrica, ENSO, índice NDWI, Colombia, ciénaga.

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Introduction

Climate change and its dynamics affect most of the natural cycles on earth. Among the entire range of macro-climatic events, there are proven incidences of the ENSO phenomenon (El Niño-Southern Oscillation) on the evolution of plant covers (Bothale & Katpatal, 2014), different biochemical cycles (Nergui, Evans, & Chung, 2016), rainfall regimes (Jin, Cai, & Tang, 2015) and temperatures (Murgulet, Valeriu, Tissot, & Mestas-Nuñez, 2017) and, as a consequence, on the terrestrial water balance (Ndehedehe, Awange, Kuhn, Agutu, & Fukuda, 2017), including underground (Tremblay, Larocque, Anctil, & Rivard, 2011) and shallow waters (Wang & Asefa, 2017).

Studies of the ENSO phenomenon on the water regime are justified because the water availability and variability sustain different vital processes of ecosystems (Acharya, Subedi, & Lee, 2018) and most productive activities such as the agricultural (Okonkwo & Demoz, 2014), fish farming, and hydro energetic, sectors among others.

In Colombia incidence of the ENSO phenomenon on the variation of the water supply of lotic bodies (Poveda, Álvarez, & Rueda, 2011) and the impacts that this variation generates on different economic sectors is studied.

However, it is necessary to evaluate the existence of teleconnections between the ENSO and the hydrological response of lagoon bodies to recognize these relationships as one of the variables that sustain the provision of different ecosystem services and the economic activity of different productive sectors. The impact of ENSO on lentic water bodies is expressed through a set of effects, among which are changes in lake levels (Dulanya, Reed, & Trauth, 2013), its temperatures (Mariano, Carolina, & Miranda Leandro, 2018), as well as the fluctuation of the limits of the water mirror (Dulanya *et al*., 2013) can be related. According to the latest national statistics (IDEAM, 2019), 0.8 % of the national territory is occupied by lentic bodies such as lagoons, lakes, wetlands, among others, which play an important role in balancing aquatic systems and sustaining productive systems. The largest area of these is in the Magdalena-Cauca basin which is characterized by wetlands (*ciénaga*) complexes of the Momposina Depression.

For this reason, a region of the department of Córdoba was chosen to verify the influence of the ENSO phenomenon in its cold and warm phases on the expansion and contraction of the limits of the water mirrors of four wetland systems that have information on the climatic and geospatial origin. The results of this analysis included conclusions regarding the incidence of the ENSO event on the interannual rainfall regime and conclusions on the applicability of the methodology developed in the studies of the incidence of the ENSO event on the water dynamics of lentic bodies in topographically flat areas of the country.

The methodology designed integrates the climate analysis with the multi-spectral index NDWI (Zhou, Zhao, Hao, & Wang, 2018) and its application to the study of lentic bodies in the country can complement the results of the studies by the IDEAM (Institute of Hydrology, Meteorology and Environmental Studies for its acronym in Spanish) regarding the dependence of the water regime in the country on the ENSO phenomenon.

Materials and methods

The study area is located in the Department of Córdoba and it includes the municipalities of Lorica, Momil, Chima, and Purísima. It is characterized by its flattened morphology with slopes of less than 3 %, which, in addition to the hydric variability, generate problems of flooding (Carvajal, 2009) that are reduced by the drainage works used both to manage the water regime and for agricultural purposes and extensive technical livestock farming. The swamp areas are hydraulically connected with the Magdalena River and the floods are explained by the anthropic occupation of the areas destined to the regulation of the water system (Correa & Pereira, 2019). Most of the lagoon bodies exhibit sedimentation processes (Restrepo *et al*., 2018) that generate a significant reduction in the habitat of the ichthyofauna, which leads to facilitating fishing activity by concentrating the fish population in deeper areas (Amador, 2016). Extensive uses of water pollute it, which limits its use for domestic

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purposes (Fernandez-Maestre, Johnson-Restrepo, & Olivero-Verbel, 2018). Out of everything that was mentioned it is concluded that the economic activities, as well as the sustainability of different natural processes in the region under study, depends on the provision of ecosystem services, regulations, and support associated with water (Rivillas-Ospina *et al*., 2020).

To assess whether the wetland systems contraction and expansion depend on the microclimatic ENSO phenomenon, a methodology adapted for the regions with low slopes was proposed, based on the determination of changes in the area for such bodies based on climate analysis and remote sensing tools.

To apply the designed methodology, four lentic water bodies with climatological information regarding representative rainfall record periods to carry out the teleconnection studies (Arango, Dorado, Guzmán, & Ruíz, 2021) and information from satellite images for the same period of observations of climatic variables were chosen to evaluate the effect of the ENSO phenomenon on water dynamics. Additionally, water systems that were large enough to be identified through Landsat satellite images were chosen.

The algorithm of the designed methodology is presented in Figure 1.

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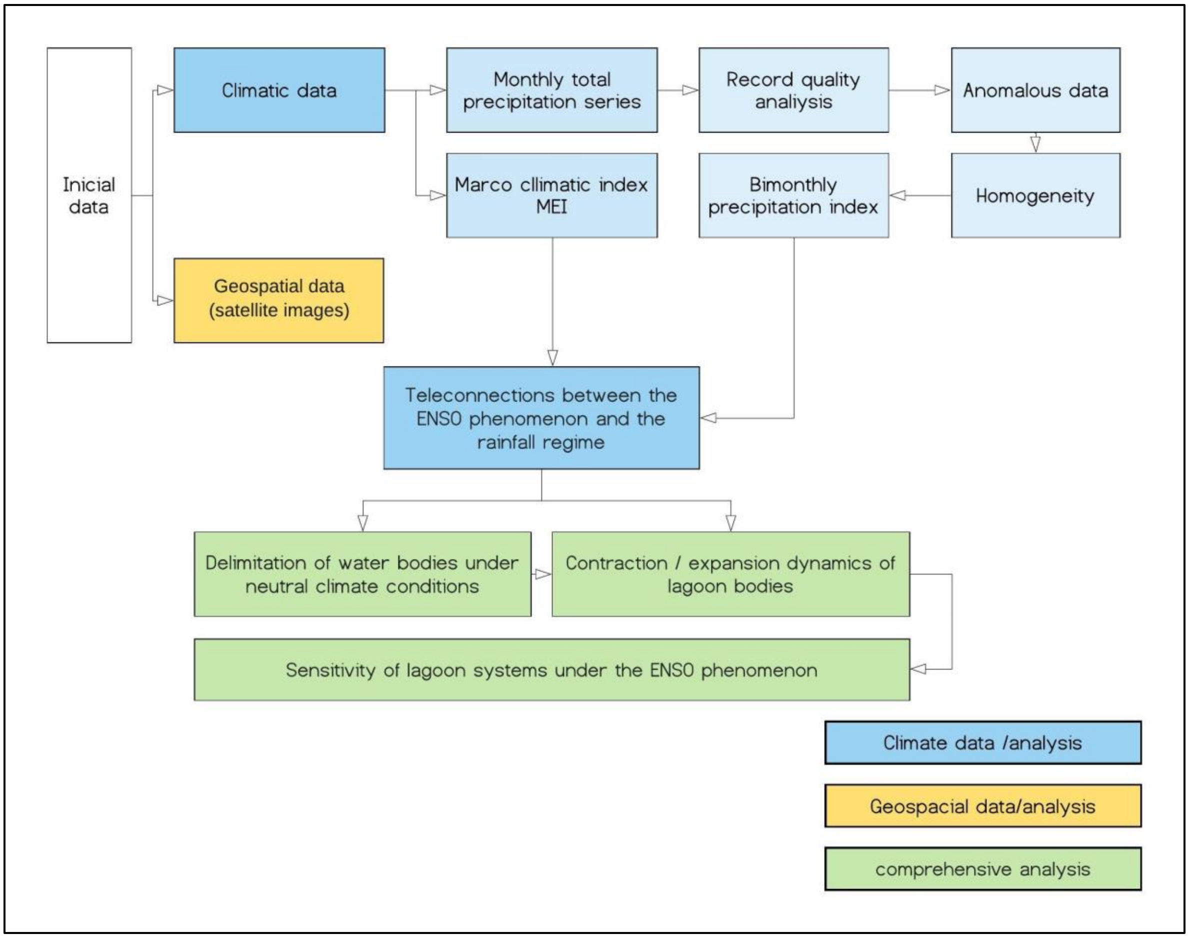

Figure 1. The algorithm of the methodology was designed to evaluate the incidence of the ENSO phenomenon on the water dynamics of lentic bodies.

The first stage involved the preparation of the climatic and geospatial information baseline, which includes its compilation and quality review. The set of hydro climatological data included the Multivariate ENSO Index (MEI) (Poveda *et al*., 2002) and the monthly series of precipitations. Figure 2 shows the location of the eight precipitation measuring stations and their general information (Table 1). All the stations chosen are considered representative of the study area according to their radius of influence recommended by the (OMM, 2011) for the stations located in the coastal areas (53.6 km influence radio and 9 000 km^2).

Table 1. General information on the weather stations in the area.

N	Code	Type	Name*
1	1307025	PM	El Trapiche
2	1308501	CP	La Doctrina
3	1307024	PM	Cerro Bahía
4	1307021	PM	Cotorra
5	1307043	PM	Venecia
6	1309023	PM	La Pastora
7	1307045	PM	Aguas Mohosas
8	1307044	PM	Villa Marcela
* PM: Pluviometric stations; CP: Main climate stations			

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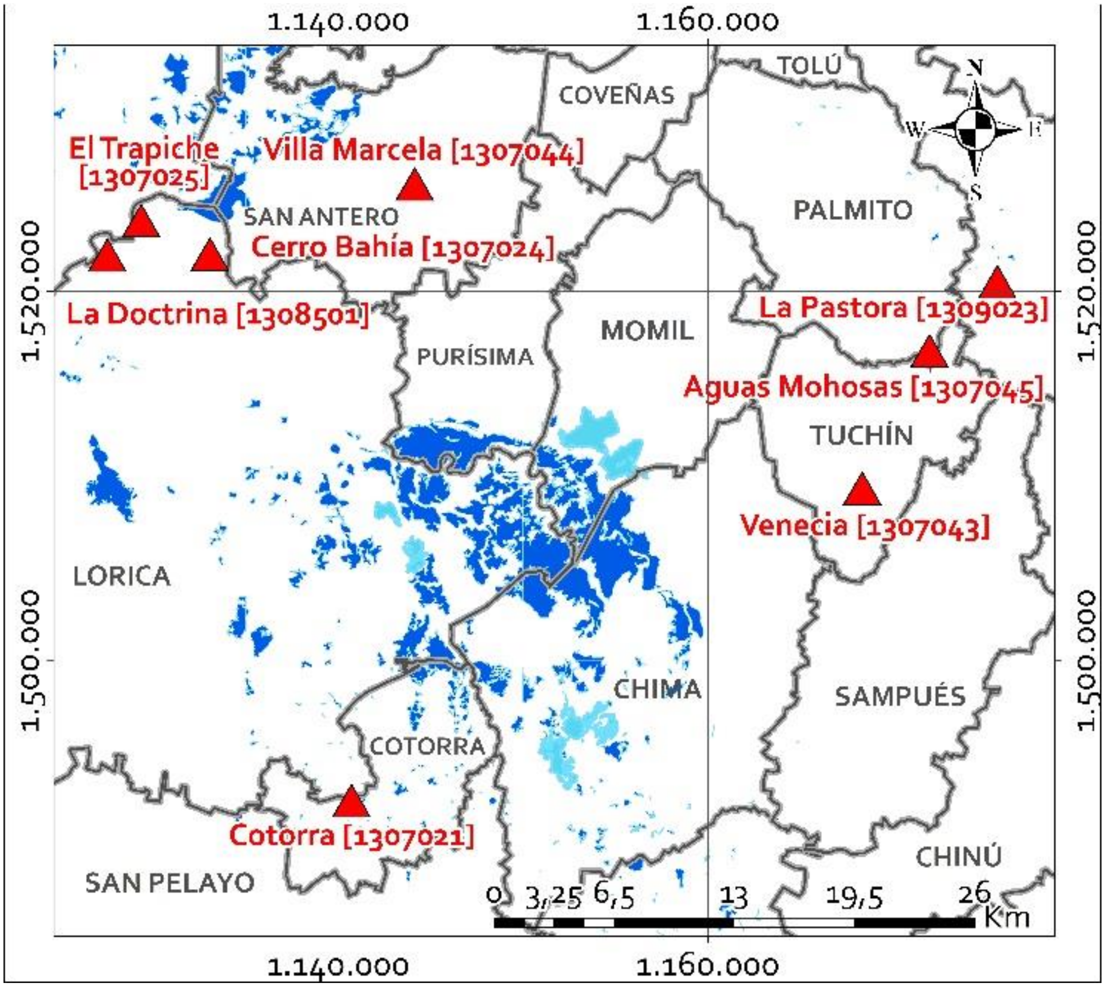

Figure 2. Location of water bodies and climate stations in the region under study.

The step before the research involved reviewing the quality of the monthly rainfall records, associated with the analysis of atypical data, to the homogeneity and complementation of the series. This procedure is used to verify that the historical series has enough values to be analyzed.

The identification of atypical data was reviewed using Grubb's criteria. (Ramírez, 2007). The analysis of the time series homogeneity is carried out to review the seasonality and to conclude whether they belong to the same statistical set (Castro & Carvajal-Escobar, 2010). Student and Fisher tests were used for this purpose (Ramírez, 2007).

Climate analysis in the methodology requires that rainfall records do not have data gaps. For this purpose, the missing precipitation data were completed based on the complete rainfall records through multiple correlation analysis as long as the series were statistically correlated.

Finally, the rainfall records were transformed to the bimonthly rainfall indexes to participate together with the MEI in the teleconnection studies that are part of the second stage in the methodology.

Teleconnection analyses are carried out to identify the degree to which monthly precipitations depend on the climatic event and the delay period it takes the ENSO to have effects on the precipitation system because the response of regional climates to macro climatic events is not immediate and it depends on a set of orographic and physiographic factors (Salas-Parra, Poveda-Jaramillo, & Mesa-Sánchez, 2020). For this purpose, the linear correlation analysis was applied using the series of the MEI and the series of the bimonthly precipitation indexes. The highest value obtained among the correlations constructed indicates the number of months the macro-climatic wave takes to reach the project location (delay period) and to what percentage it defines the interannual precipitation regime.

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For the third stage, a baseline corresponding to the delimitation of the water bodies under neutral climate conditions was prepared. For this purpose, the months with an MEI above -0.5 and below 0.5 were chosen, the delay period previously defined was applied and Landsat images were downloaded. Taking into account that the fluctuation of the limits of water bodies in neutral climate conditions depends on factors other than ENSO, it was necessary to have a statistically valid sample of images that were defined through the criterion with a confidence interval of 95 % (Corral, Corral, & Franco-Corral, 2015). In total 28 images for the 1984-2047 period were reviewed.

Initially, it was necessary to unify the reference system of the images downloaded from the North World Geodetic System (WGS84), and they were projected to the South WGS84; in addition to adjusting the work area to obtain the 1: 100 000 scales.

Subsequently, the area of each water body was calculated from an RGB composition with the Landsat image bands that allowed contrasting the land and water covers (Franco, 2017) all of this with a 1:25.000 scale. This digitization was carried out through a supervised classification based on the CORINE Land Cover, which served to confirm that the water bodies were part of the category of Water Surfaces - Inland Waters - Lagoons, lakes, and natural wetlands (*ciénagas*) (IDEAM, 2010).

Considering that according to the spectral signature of water, the highest reflectivity occurs in blue wavelengths, decreasing towards the near infrared, an RGB composition was used with the Near Infrared (NIR), Shortwave Infrared (SWIR 1), and blue bands corresponding to bands 5, 6, and 2 for Landsat 8 satellite images and bands 4, 5, and 1 for Landsat 7 and 5 satellites. This combination was used to identify water bodies in dark blue to black tones according to their depth, content of suspended materials, and surface roughness. On the other hand, the soil and vegetation cover has a higher reflectivity in the infrared, which is why they are identified in the image with green, brown, and orange colors (Figure 3) (Chuvieco, 1995).

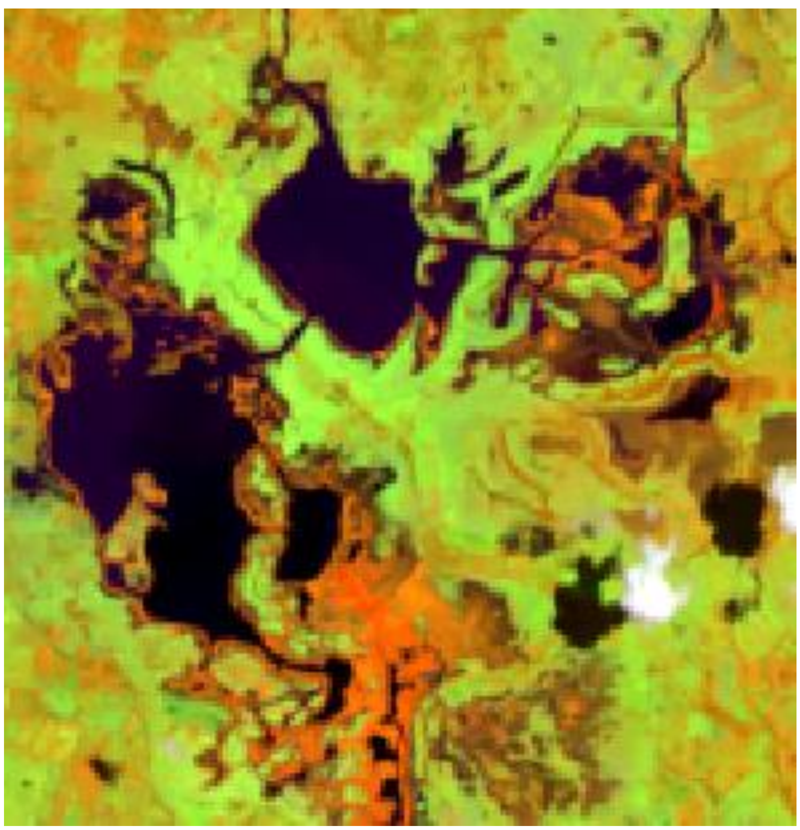

Figure 3. RGB Composition.

The resulting compositions facilitated direct delimitation of these bodies through the Normalized Difference Water Index (NDWI), which required developing the operation between the Green and Near Infrared (NIR) bands, Equation (1), where bands 3 and 5 correspond to Landsat 8 and bands 2 and 4 to Landsat 7 and 5 (McFeeters, 1996).

$$NDWI = \frac{V - NIR}{V + NIR} \quad (1)$$

This index is used mainly as a measure of the amount of water that the vegetation has or the level of moisture saturation the soil has (Martínez-Mena, 2017); one of its characteristics is that it suppresses vegetation and enhances bodies of water, which facilitates their identification (Figure 4).

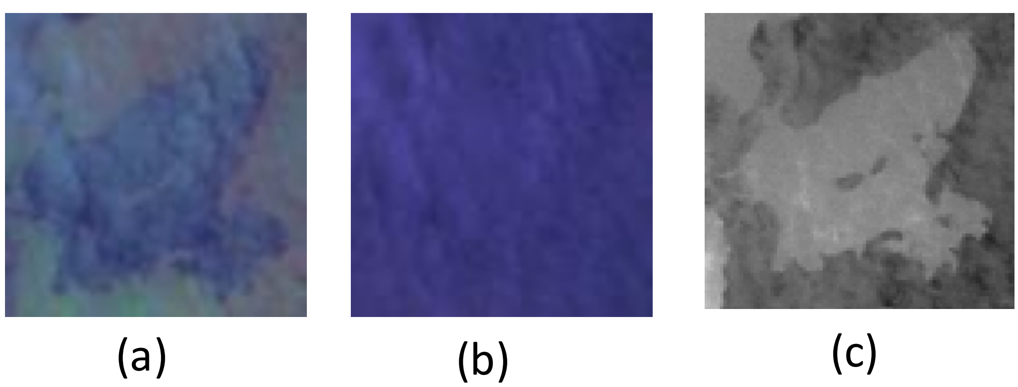

Figure 4. Landsat Compositions: a) RGB Composition; b) Natural Color; c) NDWI. Source: own made.

Thus, for each water body, 28 values of the areas were obtained and the average value corresponding to the area of each one was calculated under neutral climate conditions. To assess the accuracy in the definition of the areas, the difference between the areas of one of the Landsat images (spatial resolution of 30 m) in the baseline and a PlanetScope image (spatial resolution of 3 m) with close dates was measured. The latter was then digitized at a scale of 1: 8 000. The difference in the areas was expressed in relative terms and it was used to obtain the error in the definition of the areas and as the criterion to determine whether the change in the area affected by the ENSO phenomenon is significant; that is whenever the percentage of expansion or contraction of the area is greater than the error of the area calculation.

After the baseline was established, the analysis of the area was carried out regarding the ENSO macro climatic phenomenon to observe the contraction and expansion of the water bodies. Images corresponding to the dates that record different intensities of the phenomenon were downloaded for this purpose. They should have an MEI higher than 0.5 and come from dates between 1986 and 2016 for El Niño and La Niña an MEI index lower than -0.5 images from dates between 1985 and 2013.

Just as in the previous process, during the fourth stage, the same remote sensing procedure is repeated using a sample of 57 available images, including Landsat, RapidEye, and SPOT images, for a total of 29 images for the La Niña and 28 for El Niño.

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Next, the images were digitized based on the NDWI to obtain the area of the bodies on the different dates. Just as for the baseline, the images were digitized at 1: 25 000 scales.

Finally, the contraction and expansion of water bodies under the ENSO phenomenon were evaluated and expressed as a percentage of change in the area of water bodies versus both positive and negative MEI values. The relationship between these two variables allows us to understand to what extent the variation of the water mirror of the wetlands (*ciénagas*) responds to this macro-climatic event.

Results

As previously mentioned, there are 8 (eight) climatic stations in the area the wetlands (*ciénagas*) are located, whose records exceed 30 years, a period that is recommended in the national context to carry out climatic studies. None of the monthly precipitation series had atypical values according to Grubb's test, while the homogeneity analysis confirmed that the series is seasonal due to the average value and in most cases, they are not seasonal due to the variance.

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The latter indicates that the records show a change in the temporal variability pattern that may be associated with the global climate change effect, which can be the subject of an independent study.

Results of the teleconnection analysis —obtained through the linear correlation analysis between the precipitation series and the MEI— indicate that the macro-climatic signal of the ENSO event becomes evident in the precipitation regime in a period of three to four months. This period corresponds to the time lag between the MEI and the precipitation series, where the correlation coefficient obtained the highest value.

It should be noted that the correlation coefficient fluctuated around 0.3, which indicates that the interannual precipitation rate in the area depends 30 % on the ENSO phenomenon and 70 % on other physical-geographical factors such as The Intertropical Convergence Zone (ITCZ) (Pérez-Rendón, Ramírez-Builes, & Peña-Quiñones, 2016), on the quasi-biennial oscillation (Lubis, Matthes, Omrani, Harnik, & Wahl, 2016), on the North Atlantic Oscillation (Poveda *et al*., 2002), connection to underground waters, anthropic activities effects, among others. Six out of eight stations (75 %) confirmed that the ENSO phenomenon signal is reflected in a series of precipitations with a delay of four months, while two remaining stations —identified with the codes 13070240 and 13070250— confirmed a delay of three months. According to the results of most of the stations, four months was used as a delay time of the influence of the ENSO phenomenon on the climatic conditions in the study

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area and it was used to choose the dates of the satellite images in neutral conditions of the climate and under the cold and warm phases of the ENSO event.

As mentioned in the methodological description, to know the change in the water mirror of the wetland (*ciénaga*) complexes, it is necessary to start from the knowledge about their area without the influence of the ENSO macro climatic event (MEI variation in the range of ± 0.5). Table 2 shows the values of the areas of each water body as the average value of the interpretation results of the 28 satellite images. The same table shows the percentage relative error for each area calculated based on the areas according to the Landsat images NDWI and the areas defined according to remote sensing through the Planet Scope image of close dates.

Table 2. Values of the areas of water bodies under neutral climate conditions based on the RGB composition, NDWI index, and relative error of the areas defined by the NDWI index versus PlanetScope image.

Water bodies	**Area (km^2)**		**Relative error (%)**
	RGB Composition Mean	**NDWI**	
Ciénaga El Caracolí	0.56	0.65	0.88
Charco el Baradero	0.48	0.45	0.05
Ciénaga Zapal	2.39	2.76	0.05
Ciénaga de Momil	3.21	3.48	0.08

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Water bodies	**Area (km^2)**		**Relative error (%)**
	RGB Composition Mean	**NDWI**	
Cienaga set	4.1	3.91	0.41

As observed from the results obtained, the values of the areas of the water mirrors of the water bodies in neutral climate conditions defined both using the RGB composition and through the NDWI index are close. The relative error between the areas (mean NDWI) of the Landsat images and the PlanetScope image for all wetland (*ciénaga* bodies) does not exceed 0.88 %. This value indicates that from the change of 0.88 %, both positive and negative, in the areas of wetland (*ciénaga*) bodies they are considered significant to evaluate the hydrological response to the ENSO event.

Subsequently, the areas of the water mirrors of the water bodies under the influence of El Niño and La Niña phenomena of different intensities were obtained. 57 images were used in this interpretation using the NDWI. These values, in turn, were transformed to the percentage change of the area in relation to the area of the water body under neutral climate conditions and were constructed against the corresponding values of the MEI. It should be noted that in none of the cases said changes were less than the definition error of the areas, which indicates that all the changes obtained can be considered significant.

Figure 5, Figure 6, Figure 7, Figure 8 and Figure 9 are graphic representations of the results obtained, they include a graph of sensitivity of water bodies to the ENSO event and three consecutive diagrams where the dynamics of contraction and expansion of the wetland (*ciénaga*) bodies can be visually appreciated under the effects of the ENSO phenomenon with the highest intensities registered according to the satellite images consulted. The values of the correlation coefficients with their respective regression equations are presented in Table 3. Significance of the correlation coefficient values was demonstrated through the Fischer criterion with a significance level of 5 %.

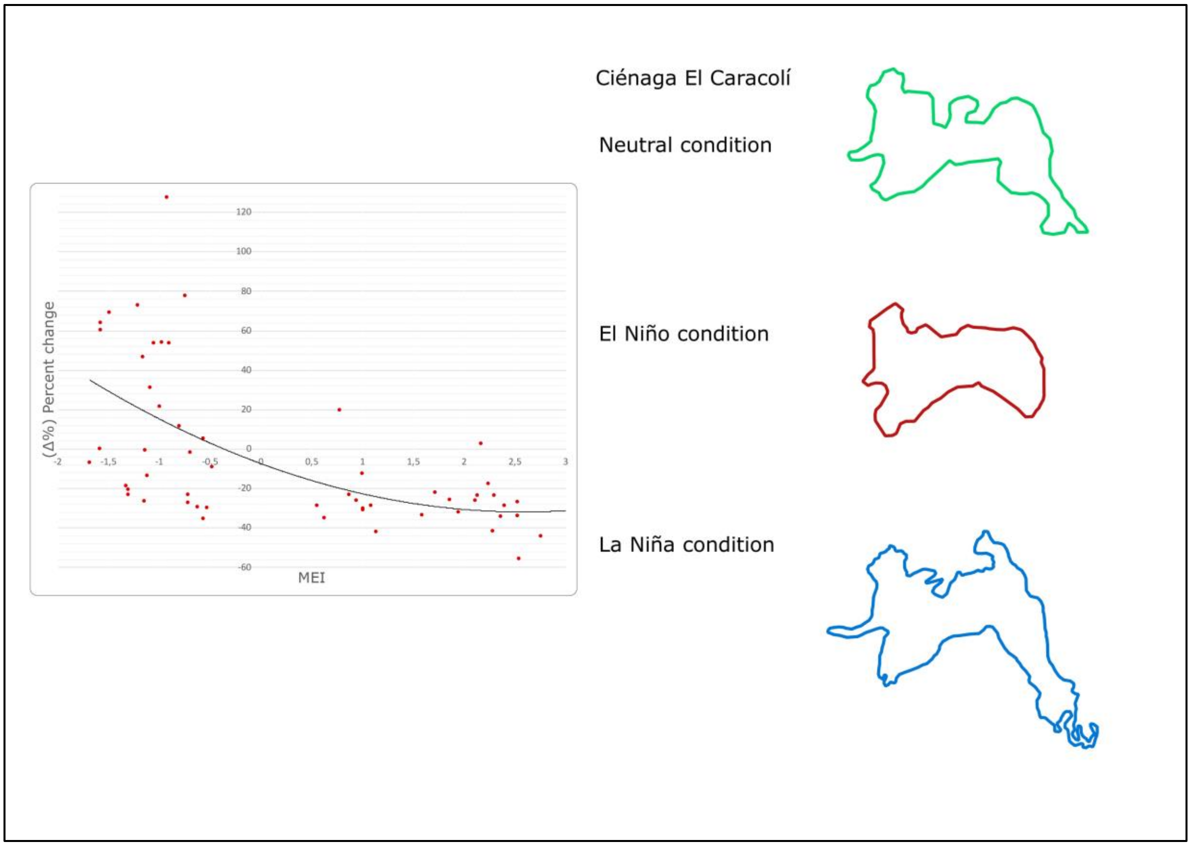

Figure 5. Ciénaga Caracolí sensitivity chart for the ENSO event and ENSO contraction and expansion and contraction graphs under ENSO with the highest intensities recorded according to the satellite images consulted.

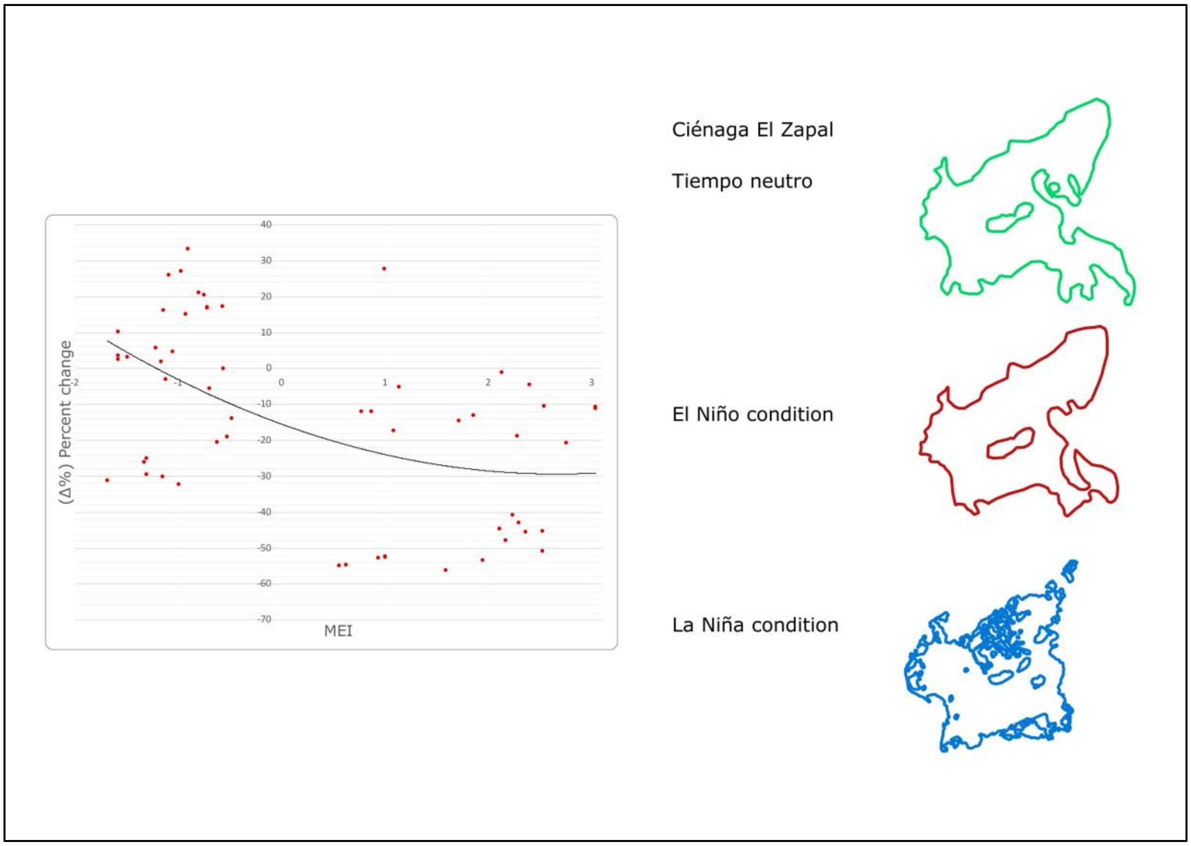

Figure 6. Ciénaga El Zapal ENSO sensitivity charts and expansion and contraction graphs under ENSO with the highest intensities recorded according to the satellite images consulted.

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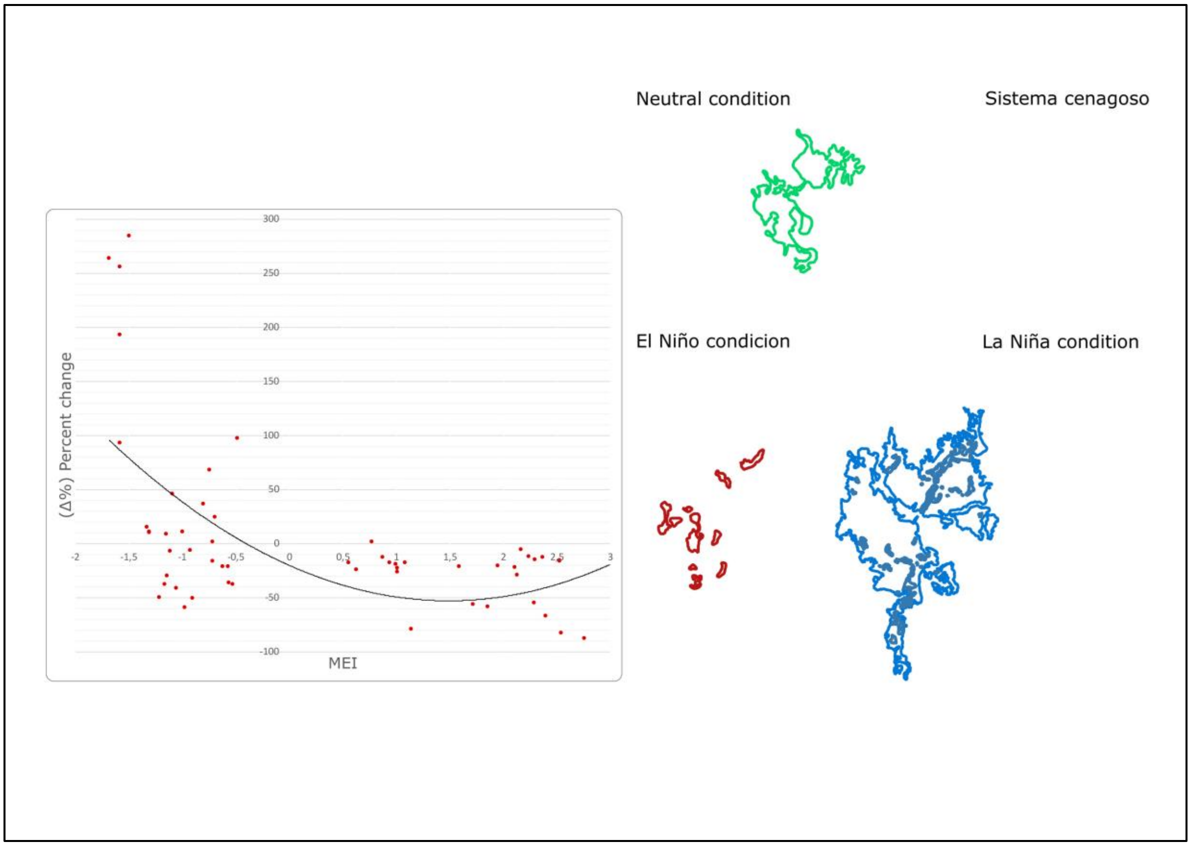

Figure 7. Water bodies ENSO sensitivity charts and expansion and contraction graphs under ENSO with the highest intensities recorded according to the satellite images consulted.

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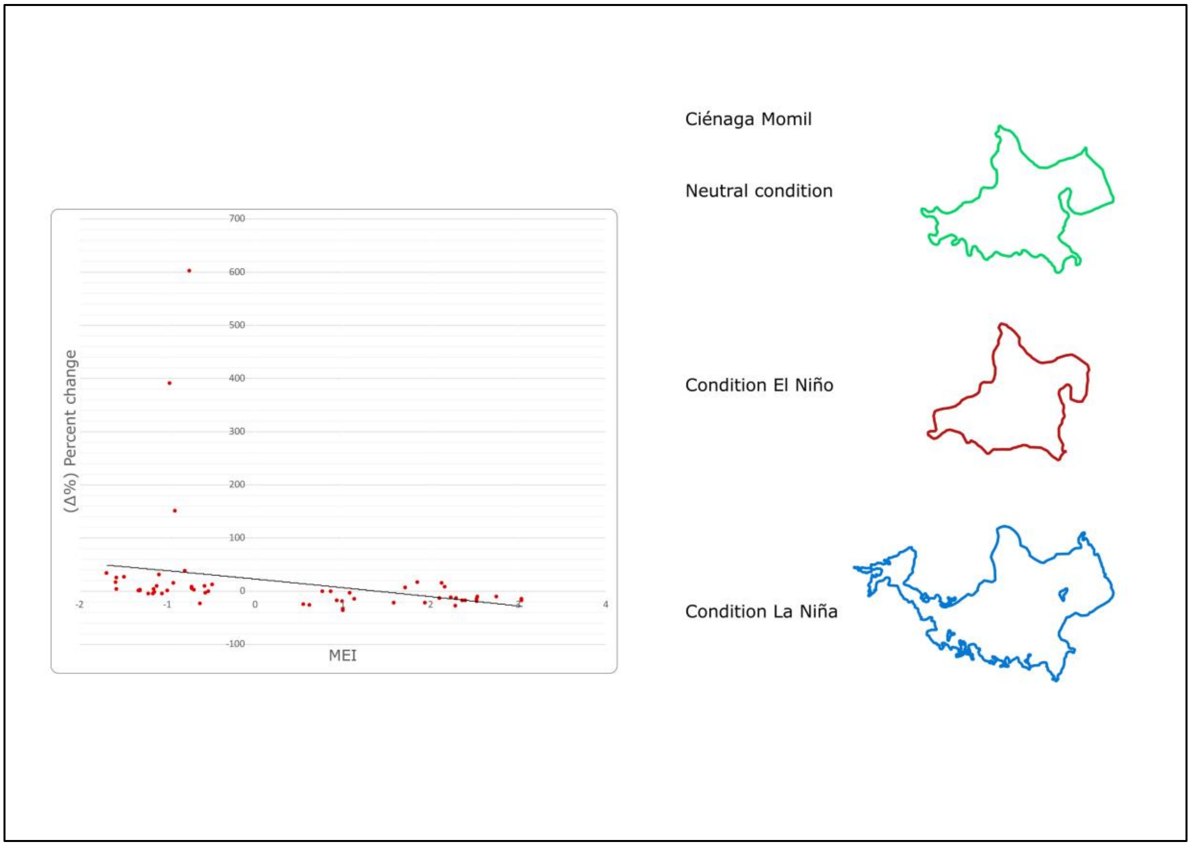

Figure 8. Ciénaga de Momil ENSO sensitivity charts and expansion and contraction graphs under ENSO with the highest intensities recorded according to the satellite images consulted.

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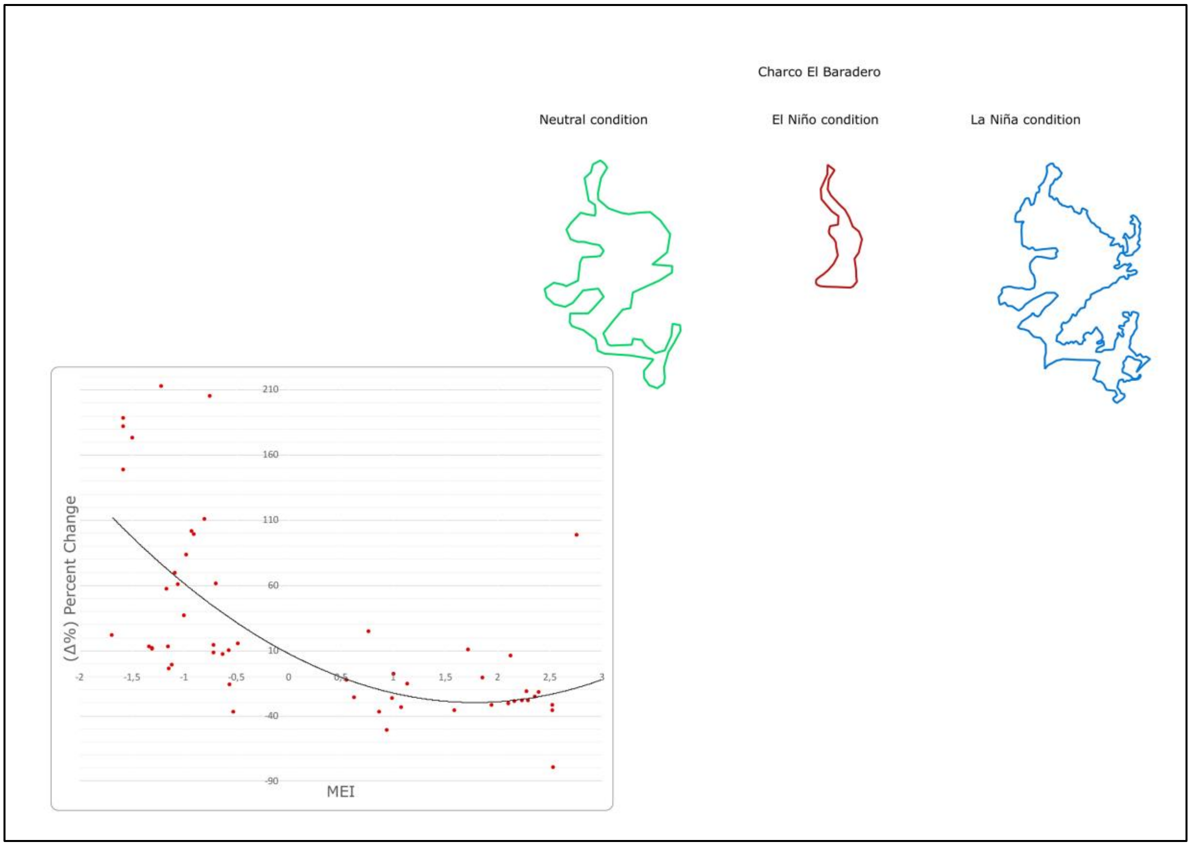

Figure 9. Sensitivity graph of the Charco Baradero to the ENSO event, and diagrams of the dynamics of contraction and expansion of the boggy bodies under the effects of the ENSO phenomenon with the highest recorded intensities according to the satellite images consulted.

Table 3. Values of the correlation coefficients of the contraction and expansion response of water bodies versus the MEI.

Lentic Body	Correlation Coefficients	Regression equation
Ciénaga El Caracolí	R=0.61	$\Delta_{\%} = 3.672 \times MEI^2 - 18.965 \times MEI - 7.3706$
Ciénaga Zapal	R=0.51	$\Delta_{\%} = 1.9612 \times MEI^2 - 10.445 \times MEI - 15.457$
Cienaga complex	R=0.61	$\Delta_{\%} = 14.779 \times MEI^2 - 43.972 \times MEI - 20.301$
Ciénaga Momil	R=0.26	$\Delta_{\%} = -0.2995 \times MEI^2 - 15.981 \times MEI + 22.392$
Charco el Baradero	R=0.68	$\Delta_{\%} = 11.785 \times MEI^2 - 42.023 \times MEI + 7.7886$

Discussion

Wetlands of the Cordoba department turn out to be sensitive to the ENSO phenomenon and the inter-annual hydrological regime. These areas change by an average of 32 % for the La Niña phenomenon and 25.5 % for El Niño. In the study area, the presence of the warm phase of the ENSO (El Niño) phenomenon is reflected in a decrease in precipitations, and, therefore, in the concentration of wetlands, while the ENSO (La Niña) cold phenomenon is reflected in an increase in precipitation and an extension of the limits of the water bodies.

The fact that the values of the correlation coefficient between ENSO and the percentage change in the areas of water bodies defer from one indicates that other climatic forcing factors may influence the inter-annual regime of the lagoon systems. These may include the passage of the Intertropical Convergence Zone (ITCZ), the Quasi-biennial Oscillation phenomenon, and the North Atlantic Oscillation. Likewise, some specific characteristics of the lagoon systems modify the hydrological response of water bodies to climate events. These characteristics include the hydraulic connectivity of lagoon systems which serves as a regulating element of the surface runoff; the irrigation canals and the Urrá dam, located downstream of the study area, which modify the natural flow regime; connection with groundwater; evaporation process from the water surface that depends on the area of mirror of water directly and the temperature regime, among others.

Because of this complex interaction between different variables, most of the relationships constructed between the ENSO phenomenon and

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the dynamic of contraction and expansion of water bodies are not linear (cases like Caracolí swamp, swamp complex, and charco Baradero) and where the correlation coefficient between MEI index and the percentage change of the area of wetlands varies in the range of 0.61 to 0.68. This indicates that the fluctuations of these swamp complexes depend 61 to 68 % on the positive or negative phases of the ENSO event. The non-linear relationship indicates that a change in the MEI value will correspond to a quadratic, non-proportional change in the contraction and expansion of lagoon systems.

Other two water bodies (*ciénagas* Momil y Zapal) present linear correlations with the MEI of 0.26 to 0.51, respectively. The graphics presented in Figures 6 and 8 show some points that are significantly different from the other data, indicating that in some periods some factors will have a more significant weight than the ENSO in the dynamics of hydric contraction and expansion. Although these points can be considered as statistically anomalous, it was considered not to eliminate them because the inter-annual hydrological variability is due to a range of factors other than ENSO which interfere with the correlation between the hydrological dynamics and the micro-climatic phenomenon studied. Instead, the results demonstrate the complexity and non-linearity of the interrelationships of natural and anthropogenic processes in the studied area.

Wetland systems can change their area by more than 80 % at the highest intensities (above 1.5 of the MEI value) of the La Niña phenomenon and around 26 % for the El Niño phenomenon. The percentages presented indicate that a water body can present a very important fluctuation in its linear size, fulfilling the ecological function of regulating the surface runoff and other natural cycles, but, in the same way, conditioning human activities that depend on the availability of water in swamp systems.

Wetland systems can change their area by more than 80 % at the highest intensities (above 1.5 of the MEI value) of the La Niña phenomenon and around 26 % for the El Niño phenomenon. The percentages presented indicate that a water body can go through a very important fluctuation in its linear size, fulfilling the ecological function of regulating the surface runoff and other natural cycles, but, in the same way, conditioning human activities that depend on the availability of water in swamp systems.

To define the baselines of water bodies, 28 satellite pictures were used with dates when MEI indicated the absence of the ENSO event. The percentage difference obtained between the areas in all cases does not exceed 9 % compared to their average value. This fact demonstrates the importance of the influence of ENSO on the dynamics of contraction and expansion of the water systems of the Colombian Momposina depression.

Results of expansion and contraction of wetlands obtained in this study provide guidance on the elements that should be taken into account to define the water buffer and the conservation zone that support ecological (Smith *et al*., 2010) and environmental functions (Salazar, 2008), preventing the process of land salinization by human intervention in the area (Restrepo *et al*., 2018) and achieving ecosystem balance. Likewise, they allow evaluating zones of conflict between human activities and the ecological functions of swamp systems in regulating the surface runoff of the Magdalena River (Jaramillo *et al*., 2018).

Considering the developed methodology allows evaluating the contraction and expansion of the water mirrors of swamp systems under the ENSO phenomenon, which defines the inter-annual hydrological variability of swamp systems by around 60 %, it can serve as an instrument for environmental zoning (Tengberg, Gustafsson, Samuelson, & Weyler, 2021) of the territory under hydrological variables that can be used for land planning projects in regions where socio-economic activities are based on the availability and variability of lentic water systems. It is proposed that water be considered as the transversal axis of environmental sustainability and economic development, articulating issues of food security, climate action, conservation and restoration of ecosystem services, as well as sustainable consumption and production of products derived from the use of water resource. This sustainable water management is achieved not only by integrating the technical part of monitoring through remote sensing tools (Vargas, Willemen, & Hein, 2019), but through multi-parameter sustainable water management models that include different environmental, technological, political, and citizen participation (Cansino-Loeza & Ponce-Ortega, 2021). In this regard, this study contributes to the technical dimension of water resource management projects.

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The methodology was developed for zones with flat slopes where the effect of swamp systems on the ENSO phenomenon is reflected in the changes in these areas and should be corroborated in other areas of the country with similar topographic characteristics (for example, the Orinoquía region) (for example, the Orinoquía region) (Hamilton, Sippel, & Melack, 2004). These studies can provide an answer to the current uncertainty in Colombia regarding the effect ENSO has on lentic ecosystems because the impact of the said phenomenon on lotic water bodies is widely known.

Following the research logic, there is a need to develop a methodology that can evaluate the sensitivity to ENSO of lentic water bodies located in topographically complex zones because its impact should be reflected in the change of water depth. This is where the integration of climate studies and remote sensing tools plays a fundamental role (Condom *et al*., 2020).

This study showed that the integration of climate studies with remote sensing tools makes it possible to understand the relationships between the climate events and the water dynamics of lentic bodies that have not been known so far and to integrate these results into environmental planning models of territory.

Conclusions

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The following conclusions can be drawn from the results obtained:

- The water body's contraction and expansion dynamics respond to ENSO.
- There is a pattern in the response when the warm phase of the event corresponds to contraction and the cold phase expansion of the hydrographic boundary. On average, in the cold episode of the event (La Niña), the water bodies expand their linear size by 32 %, while in the warm episodes of ENSO (El Niño), the bodies contract by 25.5 %.
- In some great intensity episodes of the La Niña event (the MEI value is below -1.5) the boundaries of charco el Baradero and the swamp, complex expands by more than 80 %, demonstrating a high sensitivity of water regime to this climatic phenomenon.
- The response to the El Niño phenomenon is more damped and the manifestation of the event with MEI values above 1.5 corresponds to the maximum area expansion of 56 % in the Zapal swamp. The other water bodies analyzed decreased their area by an average of 26 %.
- In the ENSO neutral periods variation of water, mirrors do not exceed 9 %, which indicates the importance of the macro climatic event on water dynamics in the studied area.
- The graphical outputs of the correlative analysis between the contraction and expansion of water bodies indicate that there are other factors that

influence and condition water dynamics and that should be the subject of an independent study.

- It was shown that the methodology developed can be applied to studies of contraction and expansion of wetlands/swamps under the effect of the ENSO phenomenon in topographically flat areas where the response of the lagoon systems to the macro climatic event is reflected in the change of the water mirror areas.
- The study showed that there is an environmental conflict in the region due to the anthropic occupation of the Magdalena River's high water buffer zone by the swamp systems, causing deterioration in water quality and salinization, as well as affecting the ecosystem services of water provision and regulation.

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