IIDEPROQ Scientific Journal
Vol. 3 • 2026

MULTITEMPORAL EVIDENCE OF HYDRO-VEGETATIONAL CHANGE IN HIGH-ANDEAN WETLANDS OF ANTOFAGASTA (1994–2024): IMPLICATIONS FOR CLIMATE CHANGE MANAGEMENT

Villa Gomez Gironda Sergio[1,*], Aguilera Marabolí Claudio[1], Ubaque Mozo Alejandro[1]

ABSTRACT

This study analyzes the hydro-vegetational dynamics of the Miscanti Lagoon and the Pujsa Salt Flat, two strategic high-Andean ecosystems in the Antofagasta Region of Chile, during the period 1994–2024. Landsat time series (5, 7, and 8) were processed through atmospheric correction, cloud masking, and radiometric harmonization, from which NDVI, NDWI, and NDMI indices were derived. These indices were integrated with climatic variables (precipitation, temperature, and evapotranspiration) to evaluate spatiotemporal patterns using descriptive statistics and coefficients of variation. Results reveal a progressive deterioration of vegetation cover and surface water balance, expressed in the decrease of NDVI and NDWI and the increase of NDMI, with a more sustained deterioration in the Miscanti Lagoon, while the Pujsa Salt Flat showed greater interannual variability but comparatively higher stability. The coherence between spectral signals and climatic trends confirms the vulnerability of high-Andean wetlands to climatic and environmental pressures, highlighting the usefulness of spectral indices as monitoring tools and as support for adaptive management and conservation of these socio-ecological systems.

Keywords: High-Andean wetlands, spectral indices, climate change.

1. INTRODUCTION

High-Andean wetlands of the Chilean Altiplano are strategic ecohydrological systems that fulfill essential functions in water regulation, carbon storage, and biodiversity conservation. However, they present high vulnerability to climatic and anthropogenic pressures, which makes them particularly sensitive environments to the effects of climate change and to territorial transformations induced by extractive activities (Squeo et al., 2006).

Recent regional-scale research has evidenced heterogeneity in the responses of these ecosystems to such pressures, highlighting the detection of "re-greening" processes in previously degraded bofedales, resulting from complex interactions between climate, hydrological dynamics, and vegetation regeneration (Chavez et al., 2019).

Within this framework, the Miscanti Lagoon and the Pujsa Salt Flat, located in the Antofagasta Chilean Region, constitute cases of particular interest. Both ecosystems have undergone significant hydro-vegetational transformations over the last decades (Chavez et al., 2019; Anderson et al., 2021), which have placed pressure on

[1] Faculty of History, Geography and Political Science, Pontificia Universidad Católica de Chile, Vicuña Mackenna 4860, Macul, Metropolitan Region, Chile
***Corresponding author:** svillagomezg2@estudiante.uc.cl
https://doi.org/10.53287/2026.8x1k6v9c

both water availability and the provision of ecosystem services, compromising the community and ecological sustainability of the region.

To address this challenge, multitemporal remote sensing has become established as a robust tool that allows the quantification of variations in vegetation productivity, surface moisture, and water stress through spectral indices such as NDVI, NDWI, and NDMI. The use of these indicators at annual, monthly, and even daily scales generates standardized and reproducible information, making it an indispensable input for the monitoring, strategic management, and conservation of fragile ecosystems (Alemayehu et al., 2023; Espinosa et al., 2011).

In this context, the objective of the present study is to characterize the hydro-vegetational dynamics of the Miscanti Lagoon and the Pujsa Salt Flat located in the Chilean High-Andes (Antofagasta) during the period 1994–2024 through multitemporal remote sensing using the spectral indices NDVI, NDWI, and NDMI, with the purpose of generating solid scientific evidence to support environmental planning and decision-making in the face of climate change scenarios in high-Andean wetlands.

2. METHODOLOGY

The study was carried out in three interrelated phases. The first consisted of the collection and preprocessing of Landsat 5 TM, Landsat 7 ETM+, and Landsat 8 OLI satellite images corresponding to the period 1994–2024 for the Miscanti Lagoon and the Pujsa Salt Flat, processed in Google Earth Engine. The procedure included atmospheric correction, and cloud, snow, and shadow masking using the QA_PIXEL band, radiometric harmonization of Landsat 8 relative to Landsat 5/7, and spatial resampling to 30 m, ensuring consistency across the time series (Roy et al., 2016).

For the harmonization, the coefficients of Roy et al. (2016) were used (Table 1), who propose a correction for each common band of Landsat 8 OLI, (Equation 1).

$$adjusted\ value = \frac{(OLI\ value - intercept)}{slope} \qquad \textbf{Equation (1)}$$

Table 1. Intercept and slope for the radiometric harmonization of bands 3, 4, 5, and 6 of Landsat 8

Band (common name)	OLI Band	Intercept	Slope	Observation
GREEN	SR_B3	-0.0016	0.9542	Adjustment applied
RED	SR_B4	-0.0022	0.9825	Adjustment applied
NIR	SR_B5	-0.0021	1.0073	Adjustment applied
SWIR1	SR_B6	—	—	No adjustment required

In the second phase, the NDVI, NDWI, and NDMI spectral indices were calculated (combinations NIR-RED, GREEN-NIR, and NIR-SWIR1, respectively), used jointly to characterize vegetative vigor, surface moisture, and water stress (Chavez et al., 2019; Alemayehu et al., 2023).

Table 2 shows the reclassification of the spectral indices, developed from EOS Data Analytics:

Table 2. Reclassification of spectral indices to assess: vegetative vigor, surface moisture, and water stress

Spectral Index	Original values	Reclassification	Classification
NDVI	<= 0	0	No vegetation
	> 0 and < 0.2	1	Sparse vegetation
	>= 0.2 and < 0.6	2	Moderate vegetation
	>= 0.6	3	Dense vegetation
NDWI	< -0.1	0	No water presence
	>= -0.1 and < 0.2	1	Low water presence (flooding, moisture)
	>= 0.2	2	Water surface
NDMI	< -0.2	0	No water content
	>= -0.2 and < 0.2	1	High water stress
	>= 0.2 and < 0.4	2	Low water stress
	> = 0.4	3	No water stress

The indices were aggregated into monthly median composites and multi-year series for each ecosystem, ensuring spatiotemporal comparability between both sites. Statistical measures of central tendency and dispersion (mean, median, standard deviation, and coefficient of variation) were applied to these series, aimed at identifying hydro-vegetational anomalies and critical episodes linked to regional droughts.

The third phase integrated the spectral patterns with monthly climatic records of precipitation, temperature, and evapotranspiration, with the aim of evaluating coherences, divergences, and possible lags between climatic variability and ecosystem response (Anderson et al., 2021). This comparative approach, based on robust metrics (e.g., sign concordance and changes in mean and coefficient of variation), made it possible to consolidate a reference methodological framework for understanding and interpreting the hydro-vegetational dynamics of the Miscanti Lagoon and the Pujsa Salt Flat, as well as their sensitivity to climatic forcings in the Altiplano (Chavez et al., 2019; Anderson et al., 2021; Alemayehu et al., 2023; Espinosa et al., 2011; Roy et al., 2016). The climatic information used in the analysis corresponds to monthly time series of precipitation, temperature, and evapotranspiration for the period 1994–2024. These data were obtained from the Center for Climate and Resilience Science (CR2), through the CAMELS-CL platform, specifically from the Cuenca 2510001 – Río San Pedro, Cuchabrachi meteorological station.

3. RESULTS AND DISCUSSION

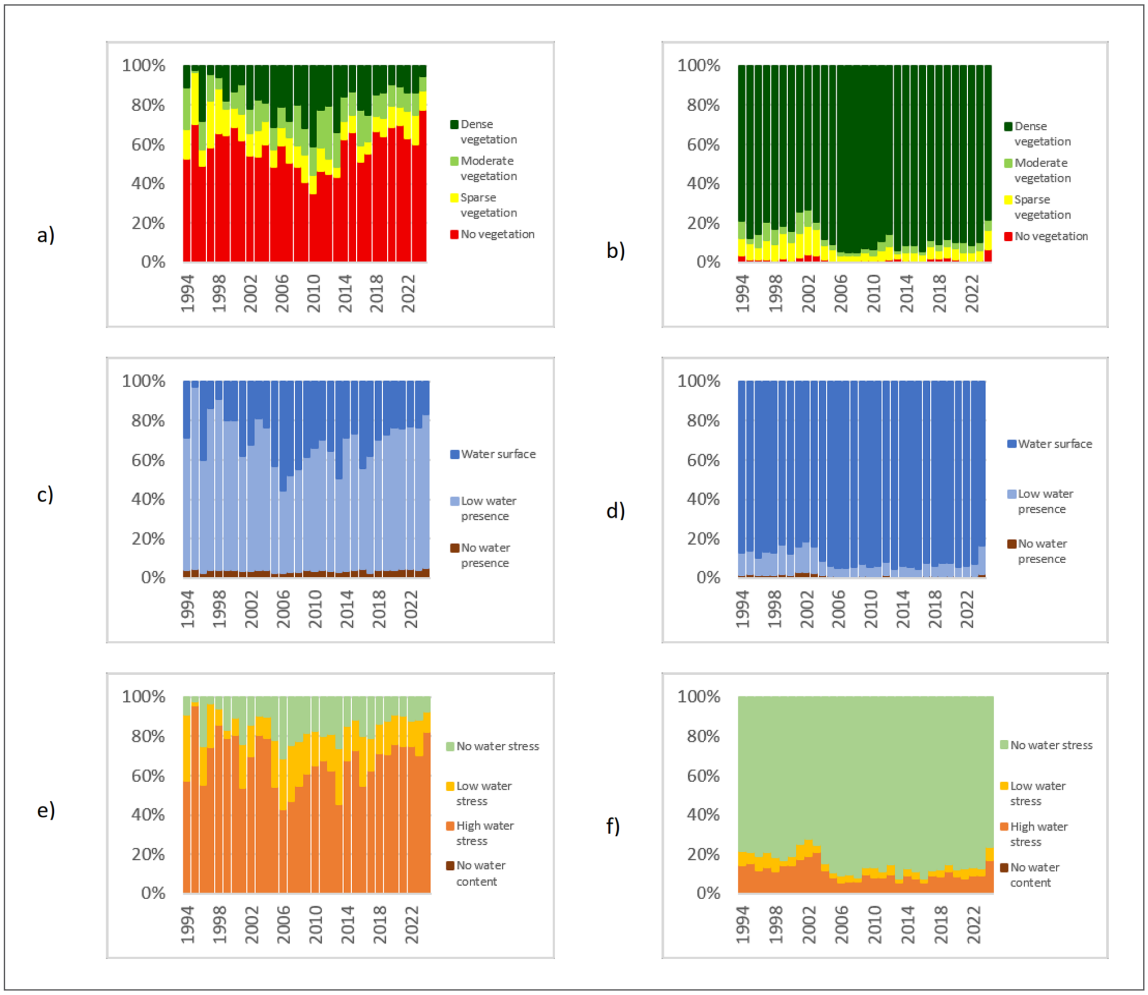
The analysis of the Landsat series (1994–2024), following preprocessing and radiometric harmonization, evidenced contrasting hydro-vegetational transformations between the Miscanti Lagoon and the Pujsa Salt Flat. The spectral indices revealed significant variations in both vegetation cover and surface moisture, reflecting differentiated trajectories of ecosystem vulnerability. NDVI showed a progressive decrease in moderate and dense vegetation sectors, particularly around the Miscanti Lagoon (Figure 1a), where the NDVI annual mean remained close to 0.0 and the maximum value only reached 0.023. The proportion of dense vegetation exhibited marked interannual fluctuations, with comparable values between the beginning and the end of the series; nevertheless, the multi-year statistical treatment (Table 3) showed a reduction in the mean and median NDVI (data not presented) together with an increase in the coefficient of variation, which indicates a net long-term deterioration of vegetative vigor, rather than a year-to-year linear decline as reported by Anderson et al., (2021). In contrast, the Pujsa Salt Flat showed greater interannual variability, with occasional episodes of increase in low-cover areas (Figure 1b), which confirms its high sensitivity to extreme climatic conditions.

Table 3. Coefficient of variation by index and by season

Site	Season	NDVI	NDMI	NDWI
Miscanti Lagoon	Wet	0.285	0.131	0.116
	Dry	0.326	0.510	0.456
Pujsa Salt Flat	Wet	0.284	0.107	0.525
	Dry	0.187	0.255	1.717

Convergently, the NDWI showed a differentiated dynamic between the two wetlands (Figure 1c–d). In Miscanti, the area with water increased until 2007, and then steadily declined until the end of the period. In Pujsa, on the other hand, this proportion remained stable and high, with a decrease only around 2022–2024, when the NDWI reached values below 0.01. In turn, NDMI showed a progressive increase in values associated with water stress (Figure 1e–f), with a more marked trend of ecohydrological degradation in the Miscanti Lagoon, where "high water stress" categories predominated (70% of the surface; see Figure 1e). The joint interpretation of the three indices showed an oscillatory pattern, associated with recurrent drought episodes (2007, 2013, 2019, and 2023), embedded within a net multi-year trend of reduced vegetation productivity and greater exposure to water deficit, which reinforces the hypothesis of increasing vulnerability in these high-Andean ecosystems.

Figure 1. Multitemporal evolution (1994–2024) of the spectral indices: a) NDVI in the Miscanti Lagoon, b) NDVI in the Pujsa Salt Flat, c) NDWI in the Miscanti Lagoon, d) NDWI in the Pujsa Salt Flat, e) NDMI in the Miscanti Lagoon, f) NDMI in the Pujsa Salt Flat



The statistical treatment of the time series corroborated these trends. The mean and median of NDVI, NDMI, and NDWI decreased over the last fifteen years, while the standard deviation and coefficient of variation increased, reflecting growing instability in vegetation response and hydrological dynamics. In Miscanti, NDMI showed intra-seasonal hydrological instability during dry periods (CV = 0.510), while in Pujsa, NDWI recorded the greatest variability (CV = 1.717), reflecting strong surface water fluctuations. These fluctuations correspond to anomalies detected in critical drought years (2007, 2013, 2019, and 2023), confirming the capacity of spectral indices to capture the incidence of regional climatic events (Squeo et al., 2006).

Integration with climatic records reinforced these interpretations. The decrease in NDVI and NDWI coincided with sustained reductions in precipitation and increases in mean temperature, in parallel with an intensification of potential evapotranspiration. In Miscanti, vegetation dynamics showed greater dependence on thermal factors, evidenced by the positive correlation of NDVI with temperature ($r = 0.69$) and accumulated evapotranspiration ($r = 0.60$), while the relationship with precipitation was weak ($r = 0.16$). In Pujsa, by contrast, vegetation responded mainly to water availability, with NDVI significantly correlated with accumulated precipitation ($r = 0.60$).

This coherence between spectral patterns and climatic forcings suggests that the observed degradation responds mainly to large-scale climatic variability, with a marginal influence of internal ecosystem processes. However, in the Pujsa Salt Flat, exceptions were identified, where occasional NDVI increases in seasonal intervals did not correspond to climatic improvements, suggesting the presence of differentiated resilience mechanisms associated with halophytic vegetation and specific ecohydrological dynamics.

4. CONCLUSIONS

- Satellite processing and the combined application of the NDVI, NDWI, and NDMI indices allowed for the precise characterization of the net decline in vegetative vigor, the decrease in surface moisture, and the increase in water stress in both wetlands, within the context of marked interannual variability. Miscanti Lagoon exhibited the most sustained decline, while the Pujsa Salt Flat showed greater interannual variability along with relative stability.

- The statistical analysis, integrated with climatic variables, evidenced the high sensitivity of these ecosystems to decreased precipitation and increased temperature, corroborating consistent patterns of hydrological and ecological deterioration throughout the study period.

- Taken together, the results obtained highlight the relevance of combining spectral metrics with climatic information to interpret ecosystem responses and anticipate vulnerability scenarios. This approach constitutes a solid scientific basis for strengthening management, conservation, and sustainable planning strategies for high-Andean wetlands in the face of increasing anthropogenic pressure and the impacts of climate change.

5. ACKNOWLEDGMENTS

To the Pontificia Universidad Católica de Chile, for the institutional support provided for carrying out this research.

6. REFERENCES

Alemayehu, B., Suarez-Minguez, J., Rosette, J., & Khan, S. A. (2023). Vegetation trend detection using time series satellite data as ecosystem condition indicators for analysis in the northwestern highlands of Ethiopia. *Remote Sensing*, 15(20), 5032. https://doi.org/10.3390/rs15205032

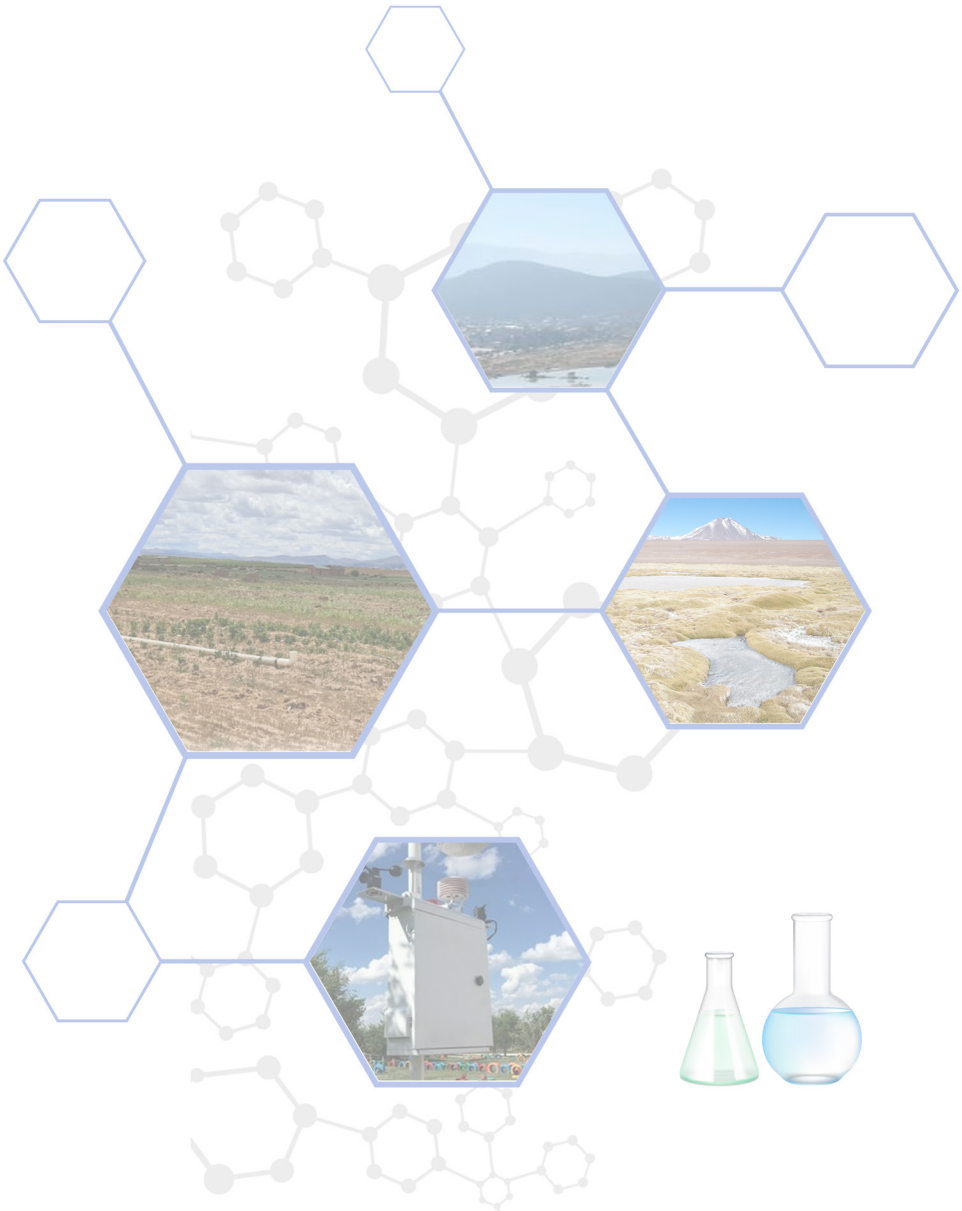
Anderson, T. G., Christie, D. A., Chávez, R. O., Olea, M., & Anchukaitis, K. J. (2021). Spatiotemporal peatland productivity and climate relationships across the western South American Altiplano. *Journal of Geophysical Research: Biogeosciences*, 126(6), e2020JG005994. https://doi.org/10.1029/2020JG005994

Chávez, R. O., Christie, D. A., Olea, M., & Anderson, T. G. (2019). A multiscale productivity assessment of high Andean peatlands across the Chilean Altiplano using 31 years of Landsat imagery. *Remote Sensing*, 11(24), 2955. https://doi.org/10.3390/rs11242955

Espinosa, C., Correa, C., Villarroel, D., & Pinto, R. (2011). Caracterización y análisis de humedales altoandinos mediante sensores remotos: experiencia en el norte de Chile. *Revista Geográfica de Valparaíso*, 46, 1–20.

Roy, D. P., Li, J., Zhang, H. K., & Irons, J. R. (2016). Harmonization of Landsat-8 and Landsat-7 reflectance measurements to enable consistent time series analysis. *Remote Sensing of Environment*, 185, 57–70. https://doi.org/10.1016/j.rse.2015.12.024

Squeo, F. A., Warner, B. G., Aravena, R., & Espinoza, D. (2006). Bofedales: High altitude peatlands of the central Andes. *Revista Chilena de Historia Natural*, 79(2), 245–255. https://doi.org/10.4067/S0716-078X2006000200010



CORE VALUES OF IIDEPROQ

- ✓ *Respect. For individual ideas, people, and the environment.*
- ✓ *Integrity. In personal conduct inside and outside of IIDEPROQ.*
- ✓ *Loyalty. To the activities and members of IIDEPROQ.*
- ✓ *Quality. In the research conducted, in the services provided, and in the training and updating of professionals.*
- ✓ *Excellence. In all areas of our work.*



IIDEPROQ

ININSTITUTE OF RESEARCH AND DEVELOPMENT OF CHEMICAL PROCESSES

SERVICES

- ✓ Quality analysis of water, soil, air, and food.
- ✓ Physico-chemical analysis of general samples using GC, HPLC, TOC, and AA. (*)
- ✓ Determination of Higher and Lower Calorific Value of solid and liquid samples.
- ✓ Monitoring of air quality, ambient, and indoor environments.
- ✓ Noise measurement.
- ✓ Modeling and simulation of water and atmospheric pollution.
- ✓ Research and development of chemical, environmental, and food processes.
- ✓ Environmental bioremediation.
- ✓ Training and instruction in environmental engineering and biotechnology.

(*)
GC: Gas Chromatography
HPLC: High-Performance Liquid Chromatography
TOC: Total Organic Carbon
AA: Atomic Absorption

FIELDS AND LINES OF RESEARCH

CATALYSIS AND PETROCHEMICALS
AIR QUALITY
ENERGY EFFICIENCY
ENVIRONMENTAL QUALITY AND WATER
NUMERICAL MODELING AND SIMULATION
CLIMATE AND SOIL MANAGEMENT
ANAEROBIC DIGESTION
BIOENGINEERING AND BIOREFINERY
EVAPORITE RESOURCES AND SALT TECHNOLOGY
FOOD TECHNOLOGY
CIRCULAR ECONOMY

30TH STREET AT COTA COTA UNIVERSITY CAMPUS
FACULTY OF ENGINEERING COMPLEX – UMSA
PHONE – FAX: (591 – 2) 2774412
E MAIL: SERVICIOS.IIDEPROQ@GMAIL.COM
WEB: WWW.IIDEPROQ.UMSA.BO

LA PAZ – BOLIVIA