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REMOTE SENSING MONITORING OF AQUATIC MACROPHYTES IN THE ALBUFERA COASTAL LAGOON (SPAIN) AND WATER MANAGEMENT IMPLICATIONS

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Abstract. The function of submerged aquatic macrophytes in wetland ecosystems, particularly in relation to nutrient cycling, has been demonstrated to be of considerable significance. These plants have a substantial impact on the biogeochemical processes occurring in the water column and sediments. Furthermore, they function as critical elements within food webs. Human activities have been demonstrated to have a detrimental effect on the conservation of macrophytes, with eutrophication being identified as one of the primary threats to their survival. The Albufera of Valencia, a Mediterranean coastal lagoon, has been in a hypertrophic state since the 1970s, causing the disappearance of these plants. However, episodes of water clarity were recorded in 2018 and 2022, which favoured the reappearance of *Myriophyllum spicatum* and *Najas marina*, respectively. Both phenomena have been monitored through the application of the Normalized Difference Vegetation Index (NDVI) to Sentinel-2 and Landsat-8 images and their correlation with the physicochemical variables of the water have been studied to determine the underlying causes. In the case of *M. spicatum*, was found that their appearance was probably favoured by increased water transparency since summer 2017. However, the high summer temperatures are hypothesised to have caused its subsequent disappearance. Its maximum coverage was 6.12 ha in June 2018. This is attributable to the fact that turbidity in the water is a determining factor in the expansion of submerged aquatic plants, as it directly affects the transparency of the water and the penetration of light, which is essential for the process of photosynthesis. Within the range of tolerances that enable plant growth and reproduction, a decline in temperature can be a critical factor in restricting growth. In the case of *N. marina*, the findings of this research demonstrate a substantial negative correlation between the surface area covered by *N. marina* and the concentration of total suspended solids. Its maximum coverage was 48.42 ha in November 2022. Conversely, an inverse correlation was observed with water transparency, as measured by Secchi disk depth. This finding suggests that the proliferation of *N. marina* in the Albufera of Valencia is also facilitated by higher water clarity and lower suspended solids. However, no relationship was found with chlorophyll-a concentration. The findings suggest that the enhancement of water quality and ecological flow through regular inflows of water from the rivers can promote the recovery of macrophytes in the Albufera. The capacity of remote sensing techniques to cover vast areas with high data acquisition frequency has been instrumental in

facilitating a comprehensive understanding of ecosystem evolution and assessing the effects of water quality. The NDVI index has been demonstrated to be a particularly effective metric for monitoring aquatic vegetation. The integration of remote sensing with geographic information systems offers a comprehensive approach to environmental management and the monitoring of macrophyte communities.
Keywords: aquatic vegetation, macrophytes, water quality, remote sensing, ecological flow and eutrophication

1. INTRODUCTION

Aquatic macrophytes, or hydrophytes, are key components of freshwater ecosystems, playing a fundamental role in ecological functions such as nutrient cycling, supporting food webs, and providing habitat and shelter for diverse aquatic fauna (Siddiqui et al., 2023; Newman, 1991; Swe et al., 2021; Germ et al., 2021; Dvořák, 1996). According to the alternative state model, the presence of submerged macrophytes can actively reduce water turbidity, fostering a clear-water phase, in contrast to a turbid phase dominated by phytoplankton (Scheffer et al., 1993; Scheffer, 1998; Scheffer & van Nes, 2007). This is achieved through various mechanisms, including preventing sediment resuspension, competing with phytoplankton for light and nutrients, inhibiting phytoplankton proliferation, and enhancing dissolved oxygen and water transparency through photosynthesis (James et al., 2004; Søndergaard & Moss, 1998; Zhou et al., 2016; Chao et al., 2021; Wang et al., 2018). Consequently, hydrophytes have been integral to numerous wetland restoration programs globally (Rodrigo, 2021).

However, aquatic environments worldwide face significant challenges from anthropogenic activities, with eutrophication being a primary human-induced disturbance (Alexander et al., 2017). Excessive nutrient loading, primarily from agricultural, industrial, and urban discharges, increases turbidity due to massive phytoplankton blooms, ultimately inhibiting submerged macrophyte growth (Cao et al., 2011; Hilton et al., 2006). In Mediterranean coastal lagoons, high summer temperatures need greater coverage of emergent macrophytes to outcompete phytoplankton and filamentous algae (Rodrigo, 2021).

The Albufera of Valencia, a shallow, oligohaline Mediterranean coastal lagoon in Spain, exemplifies these challenges. Since the 1970s, it has been in a hypertrophic and turbid state, marked by the loss of macrophyte meadows and the dominance of phytoplankton, especially cyanobacteria (Romo et al., 2008; Molner et al., 2025). Despite its average depth of approximately 1 meter, persistent turbidity, fish grazing, and toxic compounds have historically inhibited submerged macrophyte growth (Soria et al., 2024).

Remarkably, in spring 2018, an extraordinary emergence of *M. spicatum* was observed, developing significant density before its complete disappearance in August 2018 (Soria et al., 2024). This event was the first unique occurrence of *M. spicatum* in over 40 years, demonstrating the potential for natural recovery with improved water quality (Soria et al., 2024). Similarly, in 2022, another significant reappearance occurred, this time of N*ajas marina (N. marina)*, particularly in the western area of the lagoon (Soria et al., 2025). These events provided unique opportunities to study the factors influencing macrophyte dynamics in a highly degraded ecosystem.

Environmental monitoring is crucial for assessing the effectiveness of management and restoration strategies in aquatic ecosystems (Xue & Su, 2017). Remote sensing, a technology that offers frequent, large-area data with logistical ease, has emerged as a powerful tool for monitoring aquatic environments (Xue & Su, 2017; Hestir et al., 2015; Huang et al., 2018). It enables correlation of reflectance on different spectral bands with phytoplankton and vegetation biomass through spectral indices, capitalizing on the optical properties of various pigments (Schmidt & Skidmore, 2003; Pompêo et al., 2021). The Normalized Difference Vegetation Index (NDVI), originally adapted for terrestrial vegetation, has proven particularly successful in monitoring aquatic emergent and partially submerged macrophytes due to their similar optical properties to terrestrial plants (Malthus, 2017;

Tucker, 1979; Soria et al., 2024). This index is sensitive to aquatic vegetation up to a depth of about 50 cm, beyond which water absorption in the Near Infrared (NIR) spectrum makes detection difficult (Malthus, 2017; Soria et al., 2024).

This synthetic article aims to provide a comprehensive understanding of the ephemeral resurgence of *M. spicatum* and *N. marina* in the Albufera of Valencia. It synthesizes findings on the relationships between water quality, temporal dynamics of aquatic species, and the environmental factors influencing their density, leveraging the insights gained from remote sensing applications.

2. MATERIAL AND METHODS

2.1. Study Area

The Albufera of Valencia Natural Park, located 10 km south of Valencia city, is a shallow, hypertrophic, and oligohaline Mediterranean coastal lagoon spanning 2320 hectares, surrounded by 16,000 hectares of rice cultivation (Soria, 2006; Jégou & Sanchis-Ibor, 2019; Soria et al., 2025). Its connection to the sea was severed in the 18th century, and subsequent urban, industrial, and agricultural development in the mid-20th century led to its transformation into a hypertrophic turbid lagoon by the 1970s (Jégou & Sanchis-Ibor, 2019; Soria et al., 2021; Soria et al., 2025). Designated a Natural Park in 1986, efforts have been made to halt degradation and recover its original ecological values through infrastructure development (wastewater conveyance, treatment plants) and environmental restoration measures like green filters (Soria, 2006; Mondria, 2011; Soria et al., 2025).

Water volumes reaching the lagoon are controlled by the Jucar Basin Authority, while the Drainage Council, comprising farmers, manages the internal water level according to rice cultivation needs (Jégou & Sanchis-Ibor, 2019; Soria et al., 2025). The rice cultivation cycle involves land tillage in spring, keeping fields half-flooded in summer for crop growth, harvesting in September, and maximum flooding from January to February before emptying (Soria et al., 2024). Drained water currently passes through the central lagoon to mechanical gates connecting to the Mediterranean Sea (Soria et al., 2021).

2.2. Field Sampling and Remote Sensing Data

For the *M. spicatum* study in 2018, field sampling was conducted systematically, attempting to coincide with Sentinel-2 imaging (Soria et al., 2024). While initial observations in March did not reveal vegetation from the boat, a detailed study using imagery from May 2018 confirmed its presence, prompting weekly observation efforts and plant sampling (Soria et al., 2024). The main study area was the northern part of the lagoon, accessed by boat, where water transparency (Secchi disk depth), temperature, and conductivity were measured (Soria et al., 2024). Nine water samples were collected between March and August 2018 for laboratory analysis of total suspended solids (TSS) using the filtration method (American Public Health Association, 2017), nitrate concentration using second derivative ultraviolet absorbance (Crumpton et al., 1992), and chlorophyll-a (Chl-a) using dimethyl sulfoxide and 90% acetone extraction (Shoaf & Lium, 1976; Jeffrey & Humphrey, 1975) (Soria et al., 2024).

For the *N. marina* study in 2022–2023, in-situ exploration in mid-October 2022 confirmed the presence of emergent vegetation in the western part of the lagoon, which was atypical for the region (Soria et al., 2025).

Remote sensing was chosen for its high temporal resolution and ability to provide large-area data (Xue & Su, 2017; Soria et al., 2024). For the *M. spicatum* study, Sentinel-2 (S2) and Landsat-8 (L8) satellite imagery coinciding with field data collection dates were used. S2 images were atmospherically corrected with Sen2Cor (Louis et al., 2016), and L8 images were atmospherically corrected using ENVI 5.0.3 software applying the QUAC procedure (Bernstein, 2012; Soria et al., 2024). All images were processed using Sentinel Applications Platform (SNAP 9.0) and resampled to 10m spatial resolution (Soria et al., 2024). For the *N. marina* study, 20 Sentinel-2A and 2B images (Level 2A) with cloud cover less than 15% were obtained between June 2022 and March 2023 from the Copernicus Browser platform (Soria et al., 2025). Sentinel-2, comprising twin satellites (S2A and S2B) with a Multispectral Sensor Instrument (MSI), measures Earth's surface reflectance in 13 spectral bands with spatial resolutions of 10, 20, and 60 meters, and a revisit time of 5 days (Drusch et al., 2012; Soria et al., 2025).

Water quality variables (Chl-a, TSS, and Secchi Disk Depth - ZSD) were estimated from Sentinel-2 imagery for both studies using previously published equations (Soria et al., 2019; Molner et al., 2023a; Molner et al., 2023b; Soria et al., 2025). For *N. marina*, a region of interest (ROI) was defined by drawing polygons over clear water zones in the western area, influenced by irrigation canals and natural groundwater upwellings ("ullals") (Soria et al., 2025).

2.3. Vegetation Indices

Vegetation indices, combinations of spectral bands, enhance vegetation cover detection (Soria et al., 2024). While water absorption in the NIR can limit their direct applicability to aquatic plants, indices designed for terrestrial vegetation often perform well for fully or partially emerged plants, or those at shallow depths less than 0.5m (Malthus, 2017; Soria et al., 2024). The Normalized Difference Vegetation Index (NDVI) was consistently chosen as the most appropriate indicator for monitoring both *M. spicatum* and *N. marina* (Soria et al., 2024; Soria et al., 2025).

The NDVI (Normalized Difference Vegetation Index) quantifies vegetation density and health using the difference in reflectance between the near-infrared (NIR) and red parts of the electromagnetic spectrum (Tucker, 1979; Soria et al., 2024). Healthy plants absorb most visible light (400–700 nm) for photosynthesis, with chlorophyll strongly absorbing blue (430–450 nm) and red (640–680 nm) light, causing healthy plants to appear green by reflecting green light (500–570 nm) (Soria et al., 2024). They also reflect strongly in the NIR region (700–1300 nm) due to leaf cellular structure (Malthus, 2017; Soria et al., 2024). Dehydration or disease deteriorates cell structure, reducing NIR reflection and increasing absorption, thus correlating with chlorophyll content and plant health (Soria et al., 2024). The NDVI formula is (Tucker, 1979; Soria et al., 2024):

$$NDVI = \frac{NIR - Red}{NIR + Red}$$

where R is reflectance in the Near Infrared and Red bands, respectively. For Sentinel-2, this corresponds to Band 8 and Band 4, and for Landsat-8, Band 5 and Band 4 (Soria et al., 2024). NDVI values range from -1 to 1; values between 0.25 and 0.7 were considered indicative of vegetation (Jiang et al., 2006; Soria et al., 2024).

Other vegetation indices like SAVI, MNDWI, LAI, FAPAR, and FCOVER were also considered for the *M. spicatum* study, but NDVI yielded the most plausible results consistent with field observations (Soria et al., 2024). For plant area extraction, the sum of pixels within the ROI with NDVI > 0.25 was used, considering a pixel size of 100 m^2 for Sentinel-2 images (Soria et al., 2025).

2.4. Data Analysis

For the *M. spicatum* study, the influence of limnological variables on plant emergence and disappearance was analyzed (Soria et al., 2024). For the *N. marina* study, the normality of *N. marina* area and hydrochemical variables was assessed using the Shapiro–Wilk test (Soria et al., 2025). Outliers (e.g., November 6, 2022, due to an annual phytoplankton bloom affecting Chl-a and TSS) were removed, and non-normal variables were standardized via base 10 logarithm transformation (Soria et al., 2025). Pearson's correlation test was then applied to identify relationships between the area of N. marina and water quality variables (Soria et al., 2025). Thematic maps of NDVI, Chl-a, TSS, and ZSD were generated to visualize spatial and temporal dynamics (Soria et al., 2025).

3. RESULTS

3.1. Myriophyllum spicatum (2018 Emergence)

The emergence of *M. spicatum* in the Albufera of Valencia in 2018 was an unprecedented event after more than 40 years of absence (Soria et al., 2024). Initial signs of emergence were observed in satellite images on March 12, 2018 (Fig. 1) (Soria et al., 2024). The plant cover reached its maximum observed extent on June 20, 2018, occupying 61,200 m² in the northern study area, and a total of 106,047 m² across the entire lagoon (Soria et al., 2024; Generalitat Valenciana, 2017). The vegetation was last observed on August 19, 2018, with some plants in a senescent state by August 14, and complete disappearance by August 24 (Soria et al., 2024).

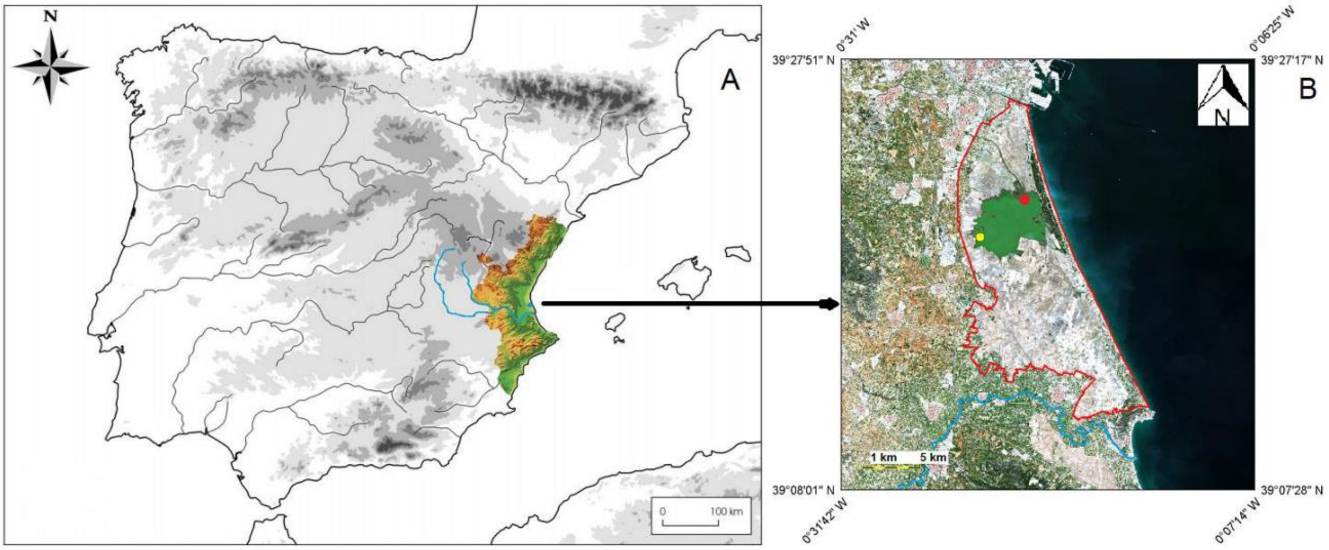

Figure 1. (**A**) Study area map, indicating the Iberian Peninsula, (**B**) geographical coordinates, the border of the Albufera Natural Park with a red line, the Albufera lagoon in green color due to its hypertrophic state, the Jucar River with a blue line, and the study area of the emerging plants with a red circle for *Myriophyllum* and yellow for *Najas*. Sentinel-2 image in natural false color dated 27 March 2018.

The Albufera lagoon in 2018 was characterized as oligohaline and hypertrophic, with an average depth of approximately 1 meter (Soria et al., 2024). Water conductivity averaged 2276 µS/cm (range: 1013–3040 µS/cm), while annual average chlorophyll-a values were 94.5 mg/m³ (range: 44.1–331.0 mg/m³) (Soria et al., 2024). Water transparency, measured by Secchi disk depth, averaged 0.37 m (range: 0.20–0.55 m) (Soria et al., 2024). Within the plant emergence area, chlorophyll-a values ranged from 46.2 mg/m³ (August 14) to 331 mg/m³ (May 21), with an average of 106.1 mg/m³ (Soria et al., 2024). Nitrate concentrations ranged from 1.64 mg/L (July 5) to 6.66 mg/L (June 15) (Soria et al., 2024). Water temperature ranged from 16.8 °C (March 27) to 30.1 °C (August 14), with an average of 25.9 °C (Soria et al., 2024).

The emergence of *M. spicatum* coincided with an episode of water clarity in the lagoon during March (Soria et al., 2024). However, the period of maximum plant expansion coincided with the highest water turbidity, attributed to a late spring algal bloom (Soria et al., 2024). Despite initial indications of a correlation between decreasing *M. spicatum* cover and increasing water transparency through linear regression, the low coefficient of determination (R^2 = 0.2248) suggested a weak relationship or the influence of other factors (Soria et al., 2024). This contradicted expected relationships from literature (Soria et al., 2024).

Correlation analysis revealed a modest positive correlation between *M. spicatum* cover and nitrate levels ($R^2 \approx 0.2$), indicating that an increase in nitrate was associated with an increase in cover (Soria et al., 2024). In contrast, a significant decrease in *M. spicatum* cover was observed with increasing temperature, with a higher R^2 of approximately 0.35, suggesting temperature had a more pronounced effect on the macrophyte dynamics during summer compared to nitrate levels (Soria et al., 2024). High summer temperatures, sometimes reaching or exceeding 30 °C, along with high nitrate concentrations from rice fields, were concluded to limit the presence of *M. spicatum* (Soria et al., 2024).

The Normalized Difference Vegetation Index (NDVI) proved to be the most appropriate radiometric index for monitoring *M. spicatum*, providing plausible results consistent with field observations (Fig. 2) (Soria et al., 2024).

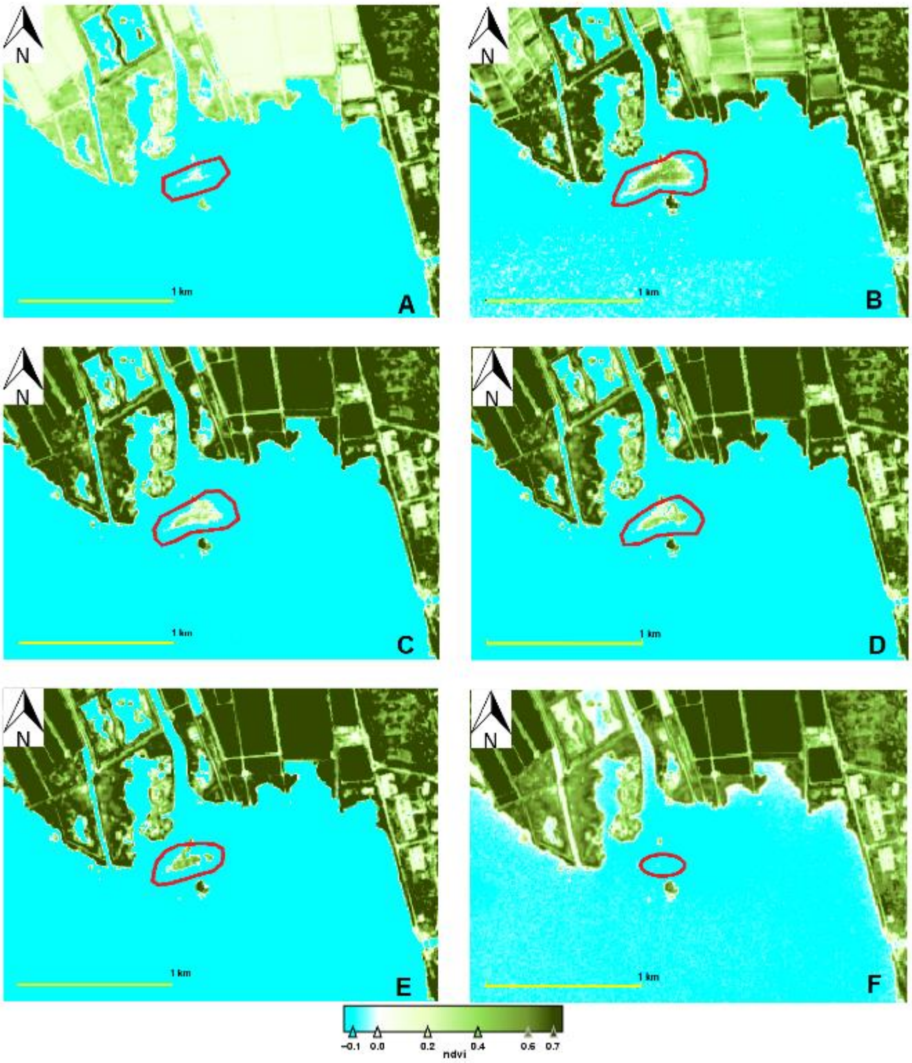

Figure 2. Comparison of NDVI values in low coverage and high coverage images to disappearance. (**A**) 27 March 2018. (**B**) 20 June 2018. (**C**) 10 July 2018. (**D**) 30 July 2018. (**E**) 4 August 2018. (**F**) 9 August 2018. In each image, a red polygon indicates the emerging plants, and the yellow bar equals 1 km.

3.2. *Najas marina (2022–2023 Resurgence)*

N. marina exhibited a substantial resurgence in the western part of the Albufera of Valencia in 2022 (Fig. 3) (Soria et al., 2025). Initial emergence was observed in satellite images on July 9, 2022, concentrated in the western region, and expanded northward by August 18 (Soria et al., 2025). The maximum cover was reached in November 2022, at 48.42 hectares, followed by a decline until March 2023, when the vegetation completely disappeared (Soria et al., 2025). Field observations confirmed the presence of the plants in October 2022 (Soria et al., 2025).

Figure 3. The image captured by Sentinel-2 on 30 May 2022 provides a comprehensive overview of the Albufera de Valencia, including the area surrounding the lagoon. Rice fields were depicted as dry, with the purple polygon delineating the region of occurrence of *N. marina*. Red star indicates the sampling point.

Water quality variables during the *N. marina* study period (June 2022 to March 2023) showed fluctuations (Soria et al., 2025). Chlorophyll-a (Chl-a) concentrations ranged from 26.91 mg/m³ (September 7, 2022) to 363.50 mg/m³ (November 6, 2022) (Soria et al., 2025). Total Suspended Solids (TSS) varied from 14.41 mg/L (October 2, 2022) to 145.30 mg/L (November 6, 2022) (Soria et al., 2025). Secchi Disk Depth (ZSD) ranged from 0.21 m (November 6, 2022) to 0.49 m (September 7 and October 2, 2022) (Soria et al., 2025). A significant outlier in the data was identified on November 6, 2022, corresponding to an annual phytoplankton bloom, characterized by elevated Chl-a and TSS, and a significant decline in transparency (Soria et al., 2025).

After removing the outlier data from November 6, 2022, and normalizing the suspended solids variable (which was initially non-normal), all variables became statistically normal, allowing for Pearson's correlation analysis (Soria et al., 2025). The analysis revealed a significant negative correlation between the area covered by *N. marina* and the concentration of total suspended solids (TSS) ($r = -0.774$, $p < 0.001$) (Soria et al., 2025). Conversely, a significant positive correlation was observed with water transparency, measured by Secchi depth ($r = 0.723$, $p < 0.05$) (Soria et al., 2025). No significant correlation was found with chlorophyll-a concentration, suggesting phytoplankton biomass might not be a primary limiting factor for *N. marina* growth within the observed conditions (Soria et al., 2025).

The initial growth of *N. marina* was predominantly in the southwestern part of the lagoon, characterized by clearer waters and reduced suspended solids and chlorophyll-a concentrations (Soria et al., 2025). Clearings within the vegetation mass were observed, coinciding with water upwelling points ("ullals"), suggesting a relationship between these water flows and the plant's distribution (Soria et al., 2025). The senescence phase of *N. marina* was associated with a continuous worsening of water conditions, evidenced by decreasing transparency and increasing chlorophyll and solids concentrations, which coincided with the winter flooding of rice fields (Soria et al., 2025). The NDVI again proved to be an effective tool for tracking the colonization and senescence process of *N. marina* (Fig. 4) (Soria et al., 2025).

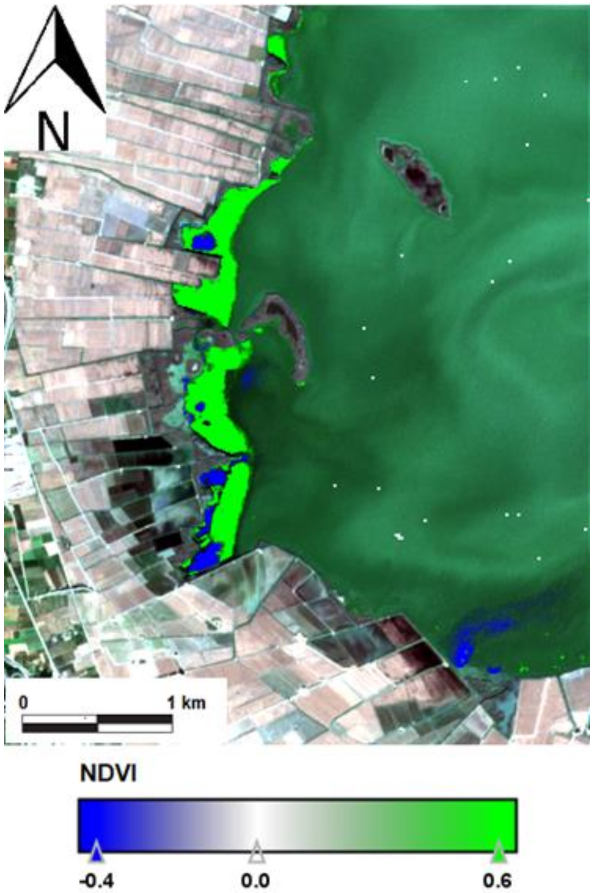

Figure 4. NDVI Thematic Map of 6 November 2022. Blue areas indicate clearer waters. Green indicates the area covered by *N. marina*.

4. DISCUSSION

The reappearance of submerged macrophytes, *M. spicatum* in 2018 and *N. marina* in 2022, in the Albufera of Valencia, after decades of hypertrophic conditions and macrophyte absence, presents a compelling case study on the interplay between environmental factors and ecological restoration (Soria et al., 2024; Soria et al., 2025). Both events underscore the critical role of water quality, particularly light availability and water clarity, as fundamental drivers for macrophyte abundance, composition, and distribution (Bini et al., 1999; Lougheed et al., 2001; Pandit, 2002; Harvey et al., 1987; Chambers et al., 2007; Lacoul & Freedman, 2006; Wetzel, 2001; Feldmann, 2012).

The Albufera has been in a turbid state since the 1970s due to extensive anthropogenic pollution from urban, industrial, and agricultural sources, leading to the loss of macrophyte meadows (Romo et al., 2008; Soria et al., 2024; Soria et al., 2025). The singular reappearance of *M. spicatum* in 2018 was attributed to a period of increased water transparency starting in summer 2017, likely due to clean water inputs from the Jucar River during the winter of 2017–2018 (Soria et al., 2024; Soria et al., 2021). Similarly, the 2022 resurgence of *N. marina* was linked to a reduction in discharges and an exceptional influx of high-quality water from the Jucar River, managed by the Jucar Basin Authority, which significantly improved water transparency (Confederación Hidrográfica del Júcar, 2022; Soria et al., 2025). These findings strongly support the hypothesis that improving water quality and maintaining adequate ecological flow can facilitate the recovery of macrophyte meadows (Soria et al., 2024; Soria et al., 2025; Soria et al., 2025).

However, the dynamics of disappearance highlight distinct influences. For *M. spicatum*, despite its onset coinciding with water clarity, its maximum expansion occurred during a turbid period due to late spring algal blooms (Soria et al., 2024). The subsequent decline and complete disappearance of *M. spicatum* by late summer 2018 were strongly correlated with high summer temperatures, often exceeding 30 °C (Soria et al., 2024; Carpenter & Adams, 1979). While nitrate concentrations also showed a modest positive correlation with *M. spicatum* cover, temperature emerged as the more dominant factor in its disappearance (Soria et al., 2024).

For *N. marina*, its senescence phase was linked to a continuous worsening of water conditions, including decreasing transparency and increasing chlorophyll-a and suspended solids concentrations (Soria et al., 2025). This period coincided with the winter flooding of rice fields, a seasonal phenomenon that can significantly influence nutrient dynamics and water quality (Soria et al., 2025). Unlike *M. spicatum*, the study on *N. marina f*ound a significant negative correlation between its cover and total suspended solids, and a positive correlation with water transparency, while chlorophyll-a concentration showed no significant correlation (Soria et al., 2025). This suggests that for *N. marina*, light penetration, affected by TSS, was a more direct limiting factor than phytoplankton biomass (Soria et al., 2025). Temperature is also a key factor for *N. marina*, with optimal germination at 20-25 °C and plant death below 15 °C (Hoffmann et al., 2013; Proctor, 1967; Triest, 1989; Handley & Davy, 2002; Agami & Waisel, 1983). The Albufera's water temperature can reach 32 °C in summer but drops to around 15 °C in autumn and 10 °C in winter, potentially causing *N. marina* death (Molner et al., 2025; Soria et al., 2025).

The general principles governing aquatic macrophyte growth are affected by multiple factors, including light, temperature, turbidity, sediment composition, and nutrient availability (Sastroutomo, 1980; Robledo & Freile-Pelegrin, 2005; Barko & Smart, 1986; Kaul et al., 1978; Pandit, 2008; Drew et al., 1980; Barko et al., 1991; Boedeltje et al., 2001; Toivonen & Huttunen, 1995; Alahuhta, 2011; Dennison, 1987; Sfriso et al., 2003; Moore & Wetzel, 2000; Zharova et al., 2001; Christian & Sheng, 2003). While *M. spicatum* density is known to decrease with increasing nitrate concentration and high temperatures (Carpenter & Adams, 1979; GVA, 2021), the complex interplay of these variables makes direct correlations challenging. The "hysteresis effect" – where vegetation absence for extended periods requires greater enhancements than historical conditions for reestablishment – might also play a role (Soria et al., 2024).

From a methodological standpoint, remote sensing proved highly effective for monitoring both macrophyte species (Soria et al., 2024; Soria et al., 2025). The Normalized Difference Vegetation Index (NDVI) was consistently found to be a valuable tool for tracking the density, growth, and health of submerged macrophytes, particularly those with subsurface characteristics (Soria et al., 2024; Soria et al., 2025; Malthus, 2017; Tucker, 1979). Its successful application highlights its potential for assessing the dynamics of aquatic ecosystems, especially given its sensitivity to aquatic vegetation at shallow depths (Malthus, 2017; Soria et al., 2024).

The use of Sentinel-2 and Landsat-8 imagery allowed for frequent, large-area data collection, crucial for comprehensive monitoring (Soria et al., 2024; Soria et al., 2025; Drusch et al., 2012; Xue & Su, 2017). Combining remote sensing data with Geographic Information Systems (GIS) provides a holistic view of the relationship between vegetation presence and spatial factors, aiding management decisions (Soria et al., 2024). While NDVI has known limitations, such as not fully accounting for differential transmissions at red and NIR wavelengths or non-linear spectral mixing (Jiang et al., 2006), its utility in eutrophic waters like the Albufera, even under conditions where the spectral response of turbid waters might resemble bare soil, was affirmed (Soria et al., 2024; Soria et al., 2025). Other specialized aquatic vegetation indices exist (Xu, 2006; Hu, 2009; Gao, 1996; Villa et al., 2015), but the adaptability and proven success of NDVI in this context make it a practical choice (Soria et al., 2024).

Comparisons with other studies on *Najas* species indicate varying controlling factors across different lake systems (Ma et al., 2008; Song, 2024; Liu et al., 2023; Bresciani et al., 2011; Sotgia, 2010; Silva et al., 2020; Cao et al., 2012). For example, *N. marina* proliferation in Lake Velenjsko Jezero was linked to warm water and unstable sediments (Mazej & Epšek, 2005), while in Lake Myall, it was related to low biomass of other species and limited by mechanical disturbances (Sanderson et al., 2008). Some studies show enhanced macrophyte growth with moderate to low water levels due to increased light availability (Silva et al., 2020; Cao et al., 2012), which aligns with *N.*

marina's development on the Albufera's shoreline (Soria et al., 2025). This highlights the system-specific nature of macrophyte dynamics, emphasizing the importance of localized studies.

The ecological events observed in the Albufera underscore the strong coupling between hydrological management and aquatic vegetation dynamics. Extraordinary water inflows, such as those from the Jucar River, increase the lake's renewal rate and temporarily enhance water quality, reducing chlorophyll and conductivity levels (Soria et al., 2025; Soria et al., 2025). However, seasonal hydrological management practices, like the closure of floodgates and winter rice field flooding, can lead to nutrient accumulation and increased turbidity, negatively impacting water quality and potentially hindering long-term macrophyte recovery (Soria et al., 2025).

5. CONCLUSIONS

The extraordinary, ephemeral reappearance of *Myriophyllum spicatum* in 2018 and *Najas marina* in 2022–2023 in the Albufera of Valencia provides crucial insights into the potential for ecological recovery in highly degraded coastal lagoons. Both events strongly suggest that improved water quality, particularly increased water transparency resulting from episodic clean water inputs, is a primary catalyst for the initial recolonization of submerged macrophyte meadows. This aligns with the understanding that light availability is a fundamental limiting factor for aquatic plant growth.

However, the factors contributing to their subsequent disappearance differed. For *M. spicatum*, high summer temperatures emerged as the most significant environmental variable contributing to its decline. For *N. marina*, the decline was correlated with a worsening of water conditions characterized by decreasing transparency and increasing suspended solids, exacerbated by seasonal agricultural practices such as winter rice field flooding. While other factors like nutrient concentrations (nitrates for *M. spicatum*) and chlorophyll-a were also studied, their direct correlations were less pronounced or absent compared to temperature and suspended solids.

The studies definitively demonstrated the immense value of remote sensing techniques, specifically the Normalized Difference Vegetation Index (NDVI) derived from Sentinel-2 and Landsat-8 satellite imagery, as an effective and efficient tool for monitoring aquatic vegetation dynamics. This methodology allowed for the early detection of macrophyte proliferation, quantification of occupied areas, and comprehensive understanding of species-environment relationships over large spatial and temporal scales, overcoming limitations of conventional fieldwork.

In conclusion, while sporadic clean water inputs can trigger temporary macrophyte resurgence, sustained recovery in the Albufera of Valencia requires long-term improvements in water quality and adaptive hydrological management. These findings underscore the imperative for ongoing remote sensing-based monitoring strategies, integrated with in situ data collection, to assess the impact of future water inputs and guide comprehensive restoration efforts for this vital wetland ecosystem.

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