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Satellite-Based Assessment of Vegetation and Hydrological Dynamics at the Garâa of Sejnane Ramsar Wetland (Tunisia): A Multi-Temporal NDVI and NDWI Analysis

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Abstract

Wetlands are among the ecologically most vulnerable ecosystems, yet these ecosystems still lack proper monitoring in North Africa using multi-temporal remote sensing techniques. This paper aims to explore the dynamics of vegetation and hydrological processes in the Garâa of Sejnane, a Ramsar-listed wetland in northwestern Tunisia, using the Normalized Difference Vegetation Index (NDVI) and the Normalized Difference Water Index (NDWI) over a 32-year period (1992-2024). Satellite images of the region were obtained from the United States Geological Society (USGS) Earth Explorer platform using the Landsat 5 and 8 satellites with a 30-meter resolution. The images were geo-referenced in the WGS 84 / Carthage UTM Zone 32N coordinate system. The results show a gradual increase in the extent of the vegetated cover of the region accompanied by a notable reduction in the extent of the open water surface. NDVI analysis of the region reveals the ecological dependence of the heritage hydrophytic flora of the region on the flooding of the wetland in the winter season for the germination of the flora in the following spring season. NDWI mapping of the region reveals the long-term drying of the surface water availability of the region. These dynamics in the region may be attributed to the effects of the seasonality of the hydrological processes, the changing agricultural land use patterns, and the effects of climate change in the rainfall patterns, consistent with the trends observed in northwestern Tunisia.

Résumé

Les zones humides sont considérées parmi les écosystèmes les plus vulnérables. Pourtant, en Afrique du Nord, leur surveillance via les outils de la télédétection reste insuffisante. Ce travail vise à suivre la dynamique de la végétation et les processus hydrologiques dans le site Ramsar de la Garâa de Sejnane, situé au nord-ouest de la Tunisie, à l'aide de l'indice de végétation par différence normalisée (NDVI) et de l'indice d'eau par différence normalisée (NDWI) sur une période de 32 ans (1992–2024). Les images satellitaires de la région ont été obtenues auprès de l'United States Geological Survey (USGS), via la plateforme Earth Explorer, à partir des satellites Landsat 5 et 8, d'une résolution de 30 mètres. Ces images ont été géoréférencées dans le système de coordonnées WGS 84 / Carthage UTM Zone 32N. Les résultats montrent une augmentation progressive de la couverture végétale, accompagnée d'une réduction notable de la surface en eau libre. L'analyse du NDVI met en évidence la dépendance écologique de la flore hydrophyte patrimoniale vis-à-vis des inondations hivernales de la zone humide, nécessaires à la germination des plantes au printemps suivant. La cartographie du NDWI révèle un assèchement progressif des ressources en eau de surface. Ces dynamiques peuvent être attribuées à la saisonnalité des processus hydrologiques, à l'évolution des pratiques agricoles et aux effets du changement climatique sur les régimes pluviométriques, conformément aux tendances observées dans le nord-ouest de la Tunisie. Cet article présente la première analyse par télédétection à long terme de la dynamique de la végétation et des processus hydrologiques dans la zone humide de la Garâa de Sejnane, site Ramsar du nord-ouest tunisien.

Keywords: Wetland monitoring; Ramsar site; vegetation dynamics; remote sensing; NDVI; NDWI

Introduction

The conservation of biodiversity is a global issue that ensures the balance of ecosystems and their sustainability, which is very important for humans (Billé & Pirard, 2007), given the critical increase in threats, whether human-made or climate-related (Mohammadi et al., 2023). In particular, wetlands, as biodiversity hotspots, appear as ecosystems of high ecological value (Gopal, 2009). These areas, often located at the interface between terrestrial and aquatic environments, are home to specific, rare or endemic biocoenoses and benefit from unique ecological conditions characterised by high productivity (Naiman & Décamps, 1990). These environments play a multifunctional role in the ecosystem ensuring, hydrological regulation, water purification, carbon storage, and nutrient recycling (Smith et al., 2013). The sensitivity of wetlands to anthropogenic pressures and current climatic conditions is increasing significantly, which highlights the importance of implementing appropriate conservation strategies to preserve their biodiversity and functioning (Xiong et al., 2023). To protect these ecosystems, several international conventions have been established, most notably the Ramsar Convention, which links the preservation of wetlands to their rational use while recognizing their ecological, economic, scientific, and cultural importance (Finlayson et al., 2011). Globally, more than 2,500 sites in 172 countries have been designated as Ramsar sites, covering an area of nearly 2.5 million km² (Okuno et al., 2017). In Tunisia, wetlands are divided into three main categories: continental wetlands (29 sites), marine or coastal wetlands (17 sites), and artificial wetlands (15 sites) (Perennou et al., 2012). Among these, Garâa of Sejnane, was recognized as a Ramsar site in 2021, representing an ecosystem of major ecological importance within the Tunisian landscape (Mosbahi et al., 2023). This vast wetland, covering over 4,000 hectares, underwent significant transformation following drainage works in the 1950s. Actually, the site presents a mosaic of temporary wetland habitats, combining flooded farmland, marshes, and wet meadows. Its unique biodiversity includes rare species and specific plant formations, notably a remnant peat bog, which marks the eastern limit of this type of ecosystem in North Africa (Sakhraoui et al., 2024).

This fragile habitat is exposed to anthropogenic pressures, including pollution, intensive agricultural practices, aquaculture, overexploitation of biological resources, the expansion of non-agricultural urban areas, and inadequate water management (Reid et al., 2019). In addition, the increasing frequency of extreme weather events represents growing challenges, alongside alterations of natural systems. Other factors, such as the introduction of the non invasive species, further exacerbate the vulnerability of these ecosystems. This wide range of threats underscores the need for an integrated, context-specific conservation approach to ensure the long-term preservation of these critical environments (Ramsar, 2022a).

Despite its ecological importance, no study on vegetation and hydrological dynamics using multi-temporal remote sensing data has been conducted at the Garâa of Sejnane Ramsar site, and this study aims to bridge the knowledge gap on a multi-decadal time scale, thereby addressing the critical knowledge gap on vegetation and hydrological dynamics at the site.

In this context, this study aims to achieve two major objectives: (i) to understand the spatiotemporal dynamics of vegetation cover by investigating the dynamics of NDVI from 1992 to 2024, and (ii) to understand the spatiotemporal dynamics of surface water availability by investigating the dynamics of NDWI from 1992 to 2024, in order to inform effective management and conservation strategies for the protected area.

Materials and methods

Study area

The study was carried out at Garâa of Sejnane which belongs to the Bizerte governorate and the Sejnane delegation. It is situated within an intermontane depression covering approximately 12-15 km² in the Mogods region of northwestern Tunisia (37°05'N; 09°12'E) (figure 1). It is characterized by a humid climate with mild winters (INRF, 1975) and was included in the Ramsar List in 2021. Garâa of Sejnane is a privately owned wetland ecosystem covering more than 4,000 hectares. Comprising a permanent lake and marshes, it was altered by drainage works in the 1950s. It features a mosaic of temporary wetland habitats including floodplains, marshes and wet grasslands (Ramsar, 2021). It is surrounded by sandstone hills less than 300 m high, covered with degraded cork oak vegetation (Ramsar, 2021).

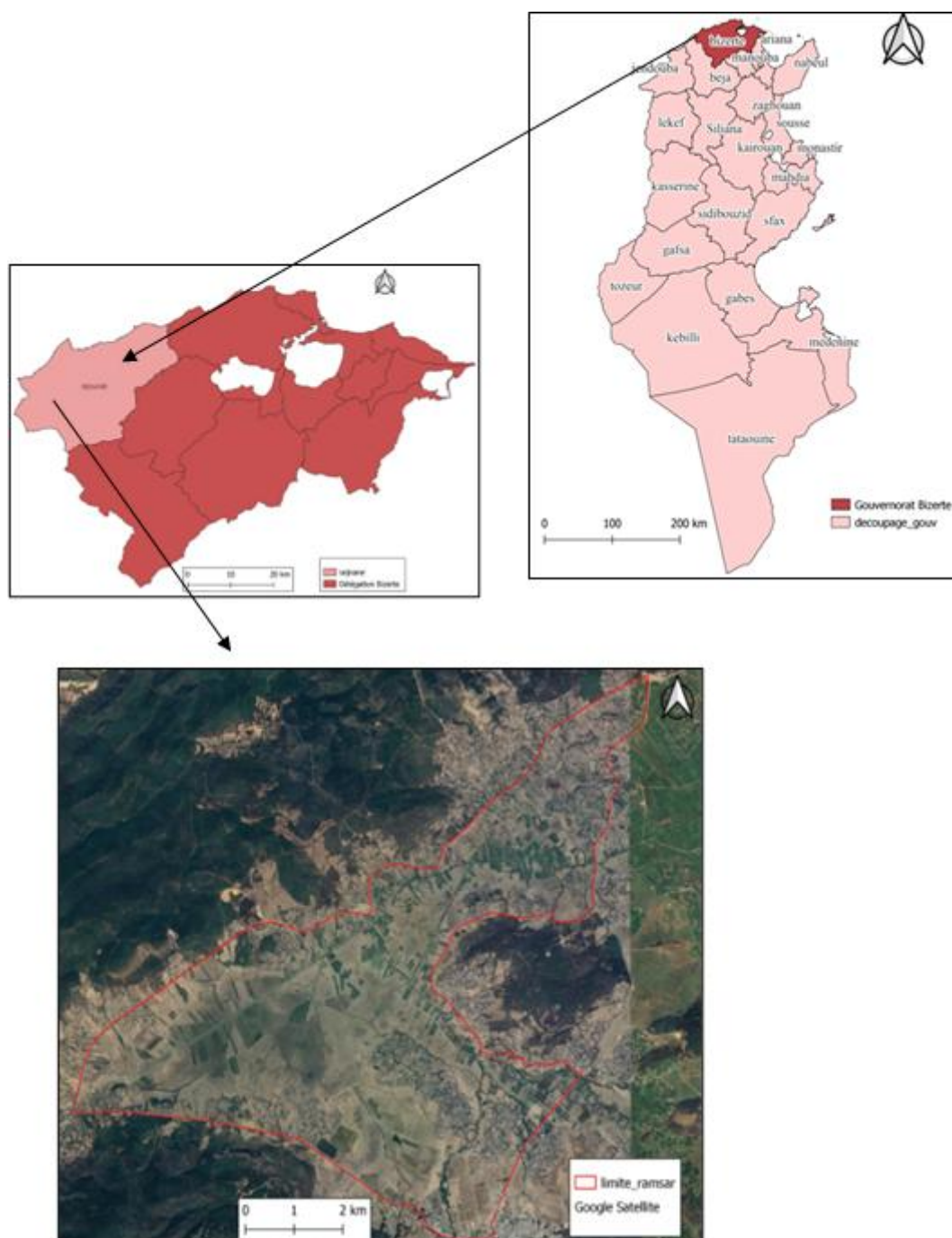


Figure 1. Location map of the Garâa of Sejnane Ramsar site, Bizerte Governorate [Google Earth].

The local flora comprises 74 plant species, representing about 58% of the total taxa recorded across the Mogods region's ponds (Rouissi et al., 2016). Notably, the site supports ecologically significant taxa, most notably the endemic plants *Rumex tunetanus* Barratte & Murb. (Le Floch et al., 2010). *Pilularia minuta* Durieu, *Crassula vaillantii* (Willd.) Roth, *Mibora minima* (L.) Desv. and *Persicaria amphibia* (Ramsar, 2021). Furthermore, the very rare plant species *Elatine macropoda* Guss is also present. According to Müller et al. (2022), these species are considered critically endangered both globally and in North Africa.

Field surveys were conducted in this location in 2023 to allow for direct observation of the current state of nature and land use. The boundaries of the area were measured using GPS (Global Positioning System).

Acquired data

To analyse vegetation dynamics in Garâa of Sejnane, the Normalised Difference Vegetation Index (NDVI) was used between 1992 and 2024. The years selected for field observation were based on a preliminary assessment of remotely sensed images from SPOT, Landsat 5, and Landsat 8 sensors with a 30-meter resolution, accessible through the USGS Earth Explorer website. The selected years were intended to cover a range of wet and dry years to account for all hydrological conditions. NDVI calculation for the years 1992 and 1996 was performed using Landsat-5: $(NDVI = (B4 - B3) / (B4 + B3))$. For the years 2019 and 2024, it was performed using Landsat 8: $(NDVI = (B5 - B4) / (B5 + B4))$. Flooded areas and their variations depending on years and seasons were calculated. Furthermore, variations in water content and saturation were analyzed across years and seasons using the Normalized Difference Water Index (NDWI). The NDWI was calculated for 1992 and 1996 from Landsat-5 data: $NDWI = (B2 - B4) / (B2 + B4)$. Meanwhile, for the years 2019 – 2024, it was performed using Landsat-8 data: $NDWI = (B3 - B5) / (B3 + B5)$. All input and output data have been georeferenced in the WGS 84 global geodetic system and the EPSG:22332 projection- Carthage / UTM zone 32N.

All satellite images were selected to ensure minimal cloud cover (<10%) and were subjected to radiometric and atmospheric correction before NDVI index computation.

Results Normalised Difference Vegetation Index (NDVI)

Analysis of NDVI from 1992 to 2024 indicates considerable spatiotemporal variability in vegetation cover in the Garâa of Sejnane depression, reflecting both seasonal hydrological cycles and long-term ecological trends. In fact, on 12/15/1992, the images show (Figure 2) a dense vegetation cover as well as a remarkable presence of water in the western and central parts (Garâa). On 18/03/1992, compared to December, the water surface areas experienced a slight decline. On 10/02/1996, there was a return to a situation similar to that of 1992, confirming the long-term stability of the wetland despite seasonal cycles. On 13/03/1996, seasonal variations likely caused a slight decrease in water surface areas compared to February 1996. On 26 December 2019, high NDVI index dominance is observed over the entire area, with a significant decrease in the coverage of water bodies compared to the 1990s. This decrease in open water cover can be attributed to a combination of long-term climatic drying trends and modifications in water resource management. On 13/03/2019, a clear decrease in water zones is observed compared to the year 1992. While water levels are unchanged from December 2019, they remain lower than in 1992. On 31/01/2024, high NDVI values predominate, with only a few scattered areas showing lower values. The water masses of the Garâa wetland are decreasing, as confirmed by the further reduction of the blue zones. On

131 03/02/2024, high NDVI values are explained by the stability of the water level, although they remain at a reduced
132 threshold.

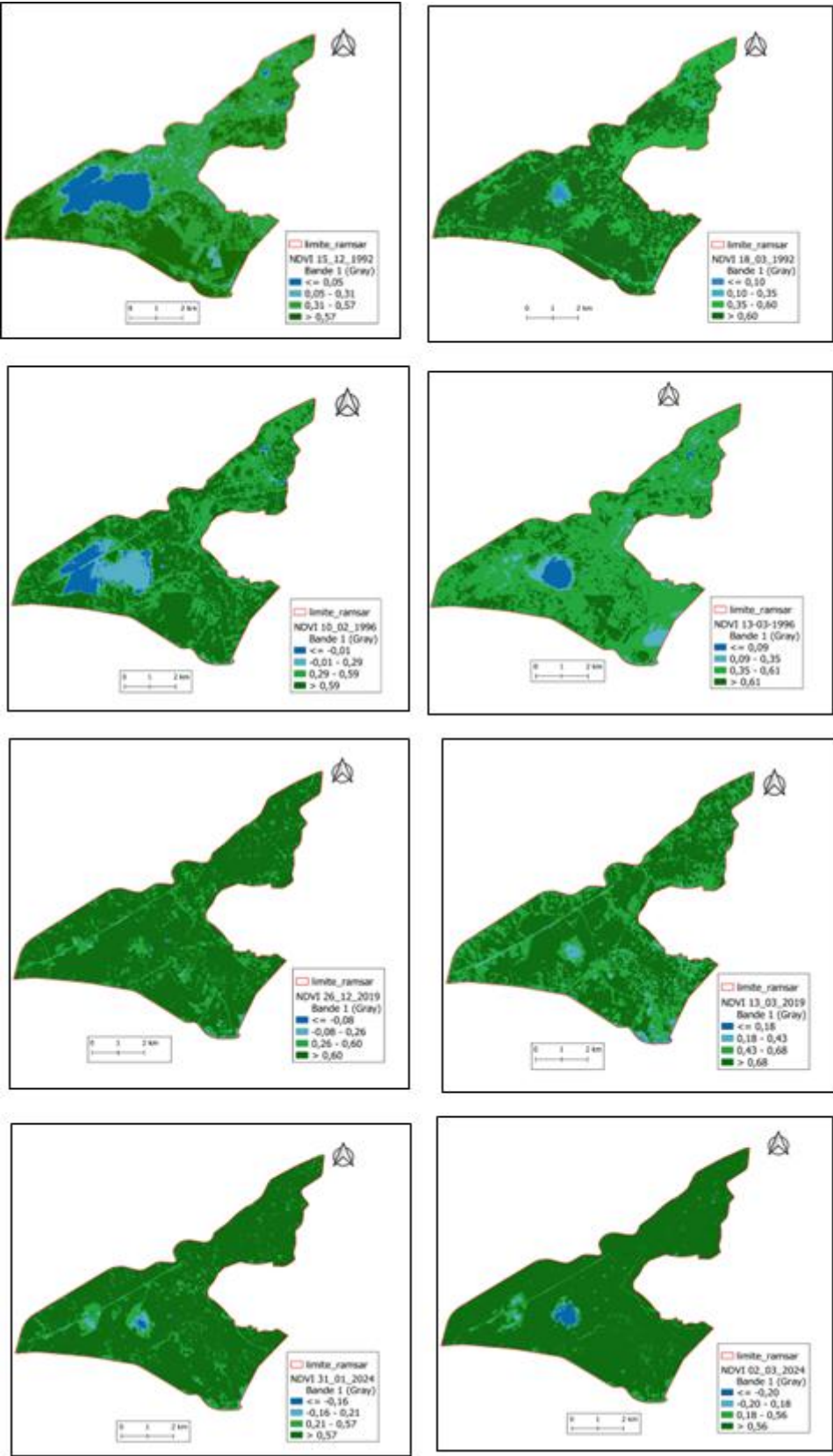


Figure 2. Spatiotemporal distribution of the Normalized Difference Vegetation Index (NDVI) at the Garâa of Sejnane wetland for selected dates between 1992 and 2024. Images derived from Landsat-5 (1992, 1996) and Landsat-8 (2019, 2024) at 30 m spatial resolution (USGS Earth Explorer). Higher NDVI values (green tones) indicate denser vegetation cover; lower values (blue/white tones) correspond to open water or bare soil.

Overall, the NDVI analysis indicates a progressive increase in vegetated surface area from 1992 to 2024, concurrent with a reduction in open water and bare soil coverage, suggesting a long-term shift in the wetland's hydro-ecological equilibrium.

Normalized Difference Water Index (NDWI)

The analysis of the Normalized Difference Water Index (NDWI) over the study period (1992–2024) revealed a degradation of colors from dark blue to white (Figure 3). The highest values of NDWI are indicated in dark blue, which corresponds to areas with a high presence of water, indicating flooded areas. The light blue color represents intermediate NDWI values, indicating less water or areas with high soil moisture. The very pale blue color indicates the presence of abundant vegetation. The white areas represent the lowest NDWI values, indicating dry areas or areas with sparse vegetation cover.

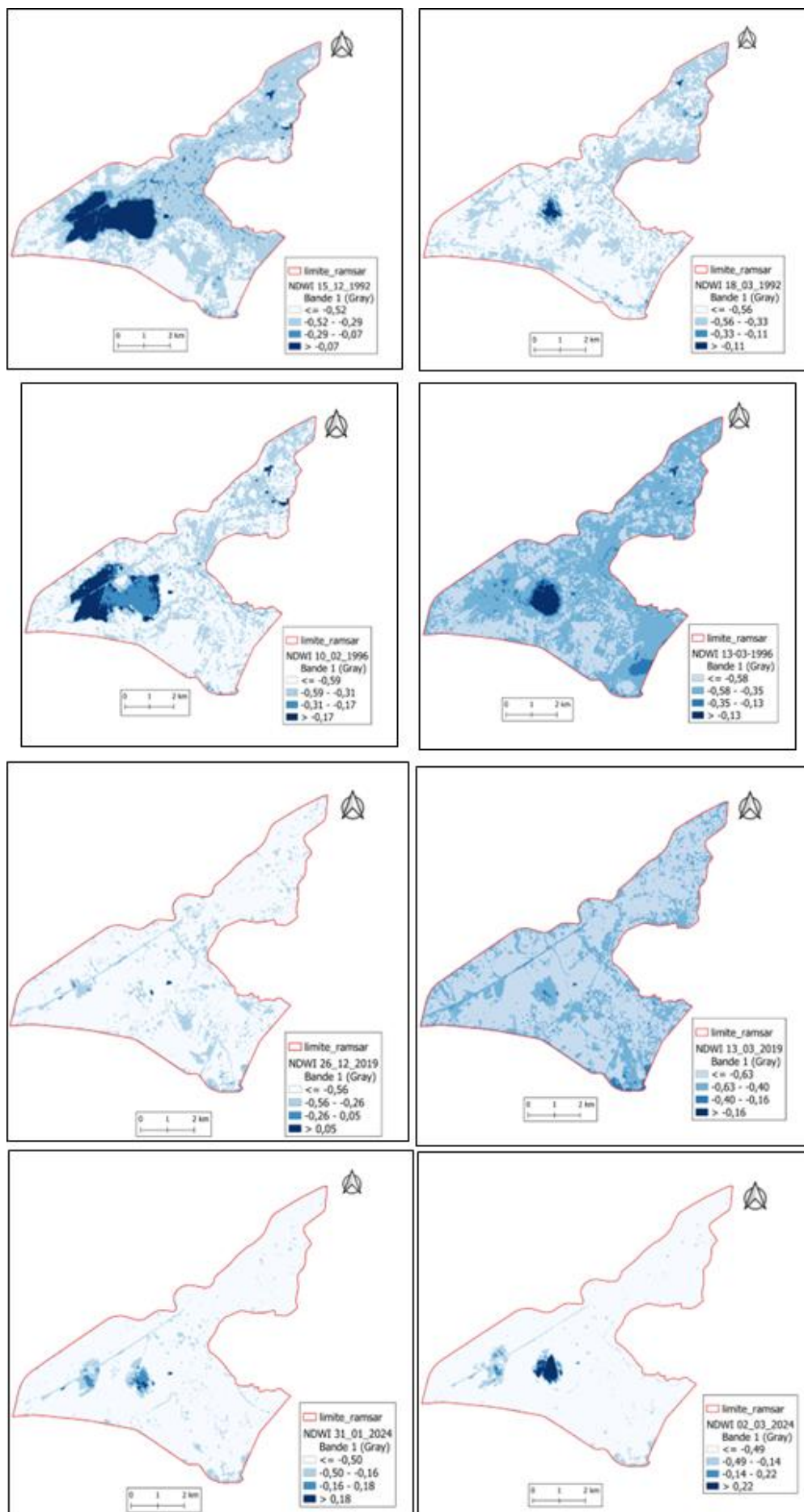


Figure 3. Spatiotemporal distribution of the Normalized Difference Water Index (NDWI) at the Garâa of Sejnane wetland for selected dates between 1992 and 2024. Images derived from Landsat-5 (1992, 1996) and Landsat-8 (2019, 2024) at 30 m spatial resolution. Dark blue indicates high water presence (flooded areas); light blue corresponds to areas with high soil moisture; pale blue reflects abundant vegetation; white indicates dry areas or sparse vegetation cover.

Discussion

Since the 1960s, the Garâa of Sejnane has been used for agricultural activities, including market gardening and breeding livestock for forage crops (Muller et al., 2014). These activities, combined with fluctuations in water availability, drive the spatiotemporal variations observed in the vegetation cover.

Our study, which focused on monitoring the vegetation dynamics between 1992 and 2024, revealed an overall increase in vegetation cover and a decrease in non-vegetated areas (e.g. water or bare soil). The variation in NDVI also depends on the ecology of the plants present at the site, which germinate in spring after benefiting from sufficient flooding during winter (Gademer, 2010). Accounting for these ecological requirements, the maps from 2019 and 2024 show greater vegetation density compared to the early 1990s. This progression may reflect natural ecological succession, reduced flooding frequency due to climatic shifts, and/or changes in land use and grazing pressure, though further quantitative analysis is needed to disentangle these drivers. While large bodies of water were visible on maps of the Garâa area in 1992, their extent notably decreased by 2019 and 2024. This trend suggests a possible reduction in the number of water bodies, an increase in vegetation around existing ones, as well as the influence of anthropogenic activity and the changes in water management.

These findings are consistent with the climate trend analysis conducted by Abidi et al. (2025) in the Medjerda High Valley, which identified significant shifts in rainfall regimes and temperature patterns in northwestern Tunisia, likely contributing to the reduction in surface water extent and the modification of seasonal vegetation dynamics observed at the Garâa of Sejnane.

Analysis of SPOT imagery also revealed that a major flood event comparable to those recorded in 1992 and 1996 occurred in 2012, providing additional confirmation of the recurrent hydrological dynamics at this site and reinforcing the robustness of our findings. These results corroborate those of Jamaa & Davranche (2008), Djoufack (2011), and Rapinel (2012) in several wetlands in the Mediterranean (Camargue), tropical (Cameroon), and temperate (France) regions.

During periods of heavy rainfall, the lowest-lying areas become waterlogged, while during dry periods, the area becomes dehydrated. This wetland harbours rich biodiversity, including heritage hydrophytic species (Jamaa et al., 2010; JAZIRI, 2018). These plants are adapted to humid conditions and germinate in spring after winter flooding, remaining dormant during dry seasons (Jamaa et al., 2014). Therefore, to ensure good germination in spring, these species must have sufficient water in winter. However, in recent years, changes in rainfall and seasonal shifts have endangered this heritage flora (PARME, 2011). In the absence of water, the local population exploits these conditions for land use and grazing, thereby putting further stress on this fragile ecosystem.

This study has several limitations worth acknowledging: the 30 m spatial resolution of Landsat imagery may obscure fine-scale vegetation heterogeneity; reliance on single-date imagery per year introduces potential seasonal

bias; and the absence of systematic ground-truth validation across all study years limits the precision of index interpretation.

Conclusion

Our study of the Garâa of Sejnane wetland revealed the complexity and the ecological richness of this ecosystem, which currently faces increasing challenges due to human pressures and climate change. Through multi-temporal analysis of NDVI and NDWI derived from Landsat imagery spanning 1992 to 2024, we documented a progressive increase in vegetation cover and a concurrent decline in open water surface extent, driven by a combination of seasonal hydrological variability, dam infrastructure effects, and evolving land use practices. Fluctuations in rainfall directly influence water availability, which is essential for the germination and growth of hydrophytic species. Climate change can exacerbate drought conditions through alterations in water withdrawal patterns and temperatures, threatening the biodiversity of Garâa of Sejnane and highlighting the need for appropriate management of this ecosystem. Future studies should integrate higher-resolution satellite data, long-term rainfall records, and species-level biodiversity surveys to better resolve the ecological drivers of vegetation change at this site. Strengthened monitoring protocols and adaptive management plans are urgently needed to safeguard the heritage flora and hydrological integrity of the Garâa of Sejnane Ramsar site under accelerating climate change.

Author Contributions

Imen Khemiri contributed to the drafting of the manuscript, supervised the implementation of the protocol, monitored the results, and participated in conducting the study. Alaeddine Rouissi contributed to the conceptualization of the paper and reviewed the manuscript. Chahida Chemingui conducted the experimental work, carried out the fieldwork, prepared the maps, and contributed to the drafting of the first version of the manuscript. Sahar Abidi supervised the entire study.

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Statements & Declarations

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Competing Interests

The authors declare that they have no competing interests.

Data Availability

The data supporting the findings of this study are available from the corresponding author upon reasonable request.

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