

SPATIAL PATTERNS OF AQUATIC VEGETATION AND FLOATING REED BEDS (*PLAURI*) IN RELATION TO HYDROLOGICAL CONNECTIVITY: A CASE STUDY OF THE MATIȚA-MERHEI LACUSTRINE NETWORK, DANUBE DELTA

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Abstract. Deltaic landscapes undergo successional cycles driven by hydro-geomorphological and ecological processes. This study analyzes the spatial distribution and community ecology of aquatic vegetation across 11 lakes within the Matița-Merhei depression (Danube Delta). Macrophyte structures were mapped using differential GPS, total stations, Landsat 8 imagery, and orthophoto maps in May and September 2023. The investigation identified 11 native taxa, dominated by *Stratiotes aloides*, *Trapa natans*, *Salvinia natans*, and *Nuphar lutea*, including the invasive *Elodea canadensis*. Cartographic analyses revealed distinct ecological gradients governed by fluvial connectivity. *Stratiotes aloides* acts as an ecosystem engineer in isolated lakes, whereas active canal inflows favor anchored *Trapa natans* rosettes, which facilitate free-floating *Salvinia natans* populations. Notably, benthic *Chara* sp. mats in Miazăzi Lake indicate a well-preserved, clear-water stable state. Intense fragmentation of floating reed beds (*Phragmites australis*) into smaller or larger isolated patches was recorded in the northern lacustrine subsystem (*i.e.*, Babina, Corciuvatele, Ciorticut) and the central subsystem (*i.e.*, Lungu Lake), where 40 distinct mats of wetland vegetation covered over 35 ha. This phenomenon may rapidly reduce water purification capacity, compromise shoreline stability, and drive severe biodiversity loss among habitat species. Biogeographically, *Elodea canadensis* was strictly confined to Bogdaproste Lake, driven by nutrient pulses and influxes of vegetative fragments from the Old Danube channel. Conversely, isolated lakes protected by reed barriers resisted biological invasion. These findings demonstrate that hydrological connectivity regimes dictate local successional trajectories and biological vulnerability, providing a critical baseline for wetland conservation.

Key words: Danube Delta; emergent macrophytes; floating reed beds (*plauri*); mapping; plant communities; satellite imagery

1. INTRODUCTION

Biodiversity changes in deltaic landscapes, driven by both natural processes and anthropogenic activities, represent global-scale phenomena. Natural pressures permanently alter deltaic biodiversity by continuously shifting the balance between land and water. Deltaic environments, such as the Danube Delta, are among the most dynamic ecosystems on Earth, where biodiversity adapts to an ongoing evolutionary timeline driven by fluctuating water flows, changing salinity gradients, and sediment deposition (Bănăduc *et al.*, 2023).

Within these systems, siltation and clogging function as primary natural drivers of landscape transformation. They form the ecological foundation of wetland plant succession, a multi-century process that gradually converts open-water bodies into terrestrial habitats (Donohue & Garcia Molinos, 2009; Tătar *et al.*, 2017).

However, recent research indicates that climate change, accelerating eutrophication, and water level fluctuations have significantly compressed these evolutionary timelines. These factors have transformed the Danube Delta into

a highly favorable environment for the emergence of alien invasive species and the aggressive, quasi-invasive expansion of certain tolerant native macrophytes (Coops *et al.*, 1999; Török *et al.*, 2017). In open waters and slow-flowing channels, organic pollution and nutrient enrichment have lowered taxonomic diversity, leading to the dominance of opportunistic species. For instance, submerged and floating-leaved macrophytes such as *Ceratophyllum demersum*, *Trapa natans*, and *Potamogeton natans* form dense vegetation mats that block sunlight, deplete dissolved oxygen, and outcompete sensitive protected species, including *Marsilea quadrifolia* (Janauer *et al.*, 2021; Chirilă *et al.*, 2024). This structural shift is further exacerbated by recent bioinvasions of species of concern, such as *Ludwigia peploides*, or highly competitive thermophilic plants like *Azolla filiculoides* and *Lemna minuta*, which reproduce aggressively during summer heatwaves (WWF-România, 2014; Doroftei *et al.*, 2026; Chirilă *et al.*, 2026).

While these floating and submerged communities alter local hydrodynamic and chemical properties, emergent aquatic vegetation drives the final and most critical stage of lake infilling. Supported by massive nutrient accumulation, emergent macrophytes - most notably the giant reed (*Phragmites australis*) - expand aggressively onto newly deposited sediments, progressively blocking secondary channels and consolidating land-building processes (Gâstescu, 2009; Gâstescu, 2021; Oteman *et al.*, 2021). The expansion of these emergent stands acts as a physical barrier that alters water circulation, traps terrestrial sediments, and accelerates the ecological succession from open lakes toward marshes and dry land, a well-known process of deltaic evolution (Gâstescu, 1993; Wetzel, 2001).

Given its designation as a UNESCO World Heritage Site, a Biosphere Reserve, and a Ramsar Site (Ramsar, 1987), understanding macrophyte dynamics is essential for wetland conservation. However, the spatial manifestation of this emergent vegetation is not uniform across the deltaic biome, as it depends heavily on local hydrological connectivity and lake morphometry.

The Danube Delta ecosystem supports rich biodiversity, with over 5,500 flora and fauna species, including diverse freshwater fish and colonial and non-colonial water birds (Coops *et al.*, 1999; Oosterberg *et al.*, 2000). Extensive research has examined how environmental variables affect this aquatic vegetation (Coops *et al.*, 1999; Covaliov *et al.*, 2003; Niculescu *et al.*, 2020; Gâstescu, 2021; Moza *et al.*, 2021).

Both natural dynamics and human-induced activities have significantly altered vegetation patterns across numerous deltaic lakes. Local factors such as water movement, climate, bathymetry, topography, and geomorphology dictate the specific drivers, diversity, and abundance of organisms in each lake.

Within this vast network, hydrological connectivity between the main freshwater source, the Danube River,

and the shallow deltaic lakes is a primary driver of lake functioning, regulating water movement through a system of dikes, channels, canals, and dense reed formations (Covaliov *et al.*, 2003). Most lakes are physically outlined by common reed (*Phragmites australis*) beds, within which aquatic vegetation plays a vital ecological role by filtering nutrients and trapping sediments.

Gradients of hydrology, water chemistry, and substrate composition seriously govern the spatial distribution of aquatic vegetation. Consequently, the delta's lakes are categorized into three main structural types: a) deep, relatively large lakes featuring a mineral soil substrate and an intermediate water retention timeframe; b) riparian lakes with mineral soil substrates that rapidly accumulate sediments due to high river connectivity and short water retention times; and c) isolated lakes enclosed by reed plants, characterized by an organic soil substrate and very high water retention times (Oosterberg *et al.*, 2000).

To fully understand the ecological vulnerability of the Danube Delta, it must be viewed not in isolation, but as the central element of the macro-system connecting the Danube River to the Black Sea basin (Panin *et al.*, 2016). This continuous aquatic corridor facilitates the rapid dispersal of biological invasions across multiple trophic levels and habitats. While terrestrial and marginal ecosystems face intense pressure from invasive flora such as the false indigo bush (*Amorpha fruticosa*), which outcompetes native willows (*Salix alba*) in floodplains (Anastasiu *et al.*, 2014), the aquatic realm suffers from synchronized degradation spanning from freshwater lakes to the marine coast. Invasive fish species, such as East Asian carps (*Hypophthalmichthys* spp.) and the ubiquitous Prussian carp (*Carassius gibelio*), directly disrupt freshwater food webs by consuming indigenous fish eggs and grazing heavily on local algal communities (Bănăduc *et al.*, 2023). This pressure propagates downstream into the Black Sea, where historic and recent bioinvasions - ranging from predatory mollusks (*Rapana venosa*) and planktivorous ctenophores (jellies; *Mnemiopsis leidyi*, *Beroe ovata*) to benthic brachyurans (crabs; *Callinectes sapidus*, *Eriocheir sinensis*) - have systematically restructured marine biocenoses (Shiganova *et al.*, 2001; Băncilă *et al.*, 2022).

In this interconnected context, the present study aims to map and analyze the spatial patterns of emergent aquatic vegetation within the Măța-Merhei intertributary depression, providing insights into how local morphometry and hydrological connectivity determine habitat shifts under systemic ecological pressures.

2. MATERIAL AND METHODS

2.1. STUDY AREA

The lakes investigated in this study are located within the Măța-Merhei hydrographic depression, a distinct intertributary subunit of the fluvial delta situated between

the Chilia and Sulina branches (Bondar & Panin, 2001). This depression encompasses 108 lakes larger than 1 ha, including major water bodies such as Merhei (1,057 ha), Trei Ozere (437 ha), Bogdaproste (435 ha), Roșca (222 ha), Lungu (215 ha), and Babina (529 ha). Geographically, the unit is bounded by the Cernovca Branch to the north, the Old Danube Meander (the “Big M” or Mila 23 double meander) to the south, the Stipoc Canal and Chilia Grind Field (Câmpul Chiliei) to the west, and the Letea-Răducu sandbanks to the east. Its intricate hydrological network comprises several major inlets and canals, including Eracle, Lopatna, Dovnica, Răducu, Bogdaproste, Sulimanca, and Roșca (Bondar & Panin, 2001).

While the primary water supply originates from the Tulcea Branch via the Mile 36 - Șontea route and temporarily from the Chilia Branch, the prolonged transit pathway insulates most internal lakes from direct river inflows. This configuration induces slow water circulation and stagnant conditions during the summer. Within this system, Babina and Măța lakes feature the largest open-water areas and relatively active water exchange (Gâștescu & Știucă, 2008). Despite their geographical proximity, Babina Lake (529 ha) exhibits relatively active water circulation. In contrast, Măța Lake (652 ha) remains poorly flushed, particularly during the summer-autumn low-water period (Gâștescu & Știucă, 2008).

The Lopatna Stream, Eracle Canal, Rădăcinoasele Canal, Stipoc Canal, Lopatna Canal, Suez Canal, and the connecting channel to Miazăzi Lake regulate water input and output dynamics for this lacustrine subsystem. Subsequently, all lakes in the depression exhibit poorly defined, highly variable boundaries. Their margins are obscured by surrounding common reed (*Phragmites australis*), bulrush (*Typha* sp.), and floating reed beds (*plauri*), through and underneath which the water bodies communicate even during low-water phases.

According to the Danube Delta Biosphere Reserve Management Plan, the total surface area of the Măța-Merhei aquatic complex with free water circulation spans 26,420 ha, of which 5,870 ha represent open lake surfaces (Info-Delta, 2025).

To capture diverse natural environment conditions, field investigations focused on a representative selection of lakes distributed across the Măța-Merhei hydrographic unit (Fig. 1):

- the northwestern lacustrine subsystem (Babina, Corciuvatele and Ciorticuț Lakes);
- the central lacustrine subsystem (Miazăzi, Lungu, and Sfîștofca Lakes);
- the southern lacustrine subsystem (Rădăcinos, Trei Ozere, Căzănel, La Amiază, and Bogdaproste Lakes).

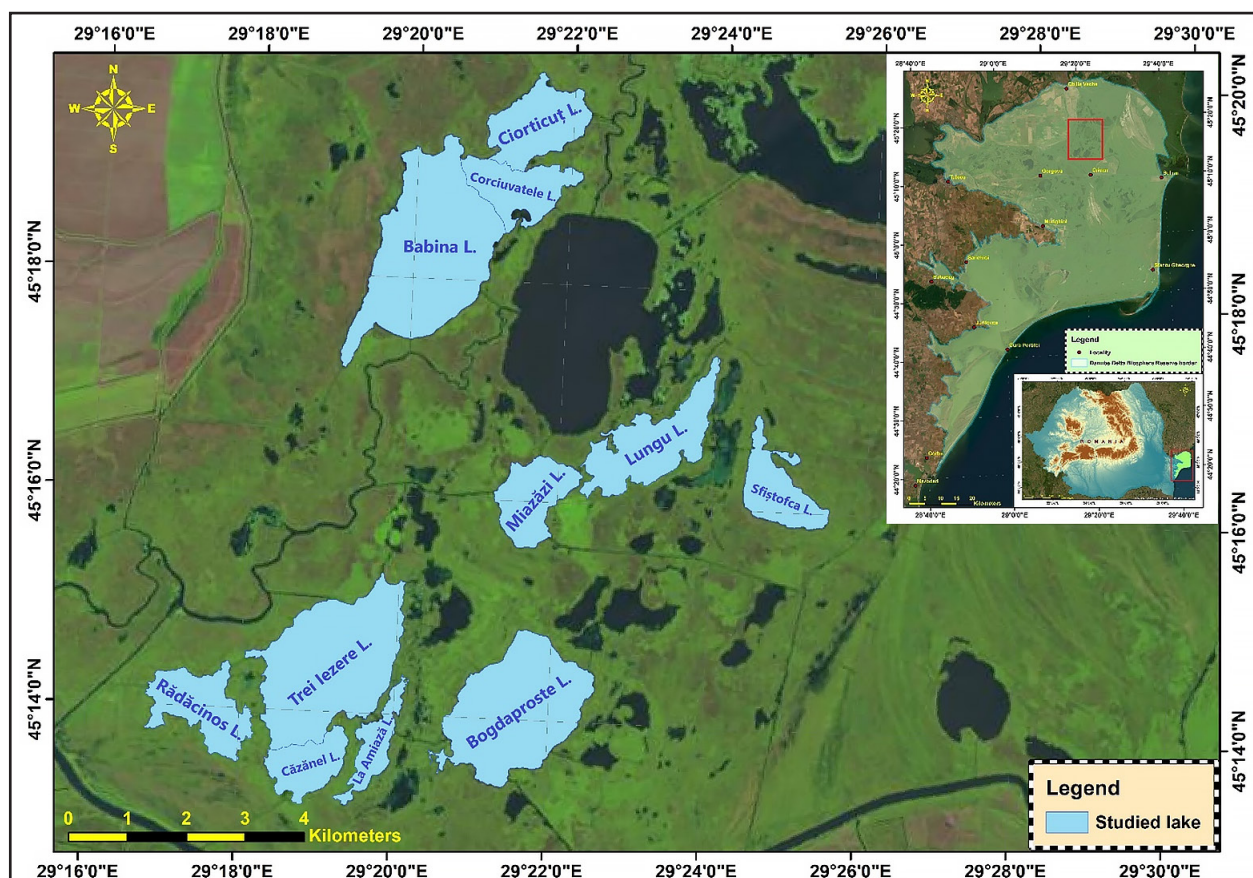


Fig. 1. The location of the investigated lakes within the Măța-Merhei intra-distributary depression, Danube Delta, Romania.

2.2. FIELD-BASED DATA ACQUISITION

Floating and emergent macrophyte communities were mapped by navigating at low speed along the lake shorelines on board a research motorboat, precisely recording the spatial distribution of aquatic vegetation belts. Concurrently, additional reference points were registered to map narrow channels and associated geomorphological features. During the *in situ* topographic surveys, lake shorelines and aquatic vegetation boundaries were delineated using high-precision geodetic equipment, specifically a Trimble R4 differential GPS (dGPS) system and a Trimble M3 DR5 total station. All research infrastructure and field equipment utilized in this study were provided by the NIRD GeoEcoMar.

To account for the distinct life-cycle stages of deltaic vegetation, field-based data acquisition was strategically divided into two seasonal windows:

Spring Campaign (May 2023): Conducted across Lungu, Sfîstofca, Babina, Corciuvatele, and Ciorticuț Lakes. This period provided high-visibility conditions to map stable, perennial macro-vegetal structures - specifically floating reed beds (*plauri*) - and baseline geomorphological shorelines before the seasonal expansion of annual macrophytes.

Autumn Campaign (September 2023): Implemented for Rădăcinos, Trei Ozere, Căzănel, La Amiază, Bogdaproste, and Miazăzi Lakes. This window captured the peak vegetative biomass stage, enabling the precise spatial delineation and ecological classification of fully developed floating and emergent macrophyte associations.

2.3. DATA PROCESSING, GIS INTEGRATION, AND INTERPRETATION

Geospatial data synthesis relied on the kinematic method, achieving high-precision point positioning in real time *via* Real-Time Kinematic (RTK) technology. Field measurements focused on collecting topographic points defining the exact boundaries of emergent vegetation, floating macrophytes, and extensive reed beds. Planimetric coordinates (X, Y) and ellipsoidal heights (Z) were converted to the Stereo 1970 Projection System (the official national geodetic datum of România), with elevations referenced to the Black Sea - Constanța 1975 official altimetric datum.

Raw field data processing, vector editing, and graphical representations were performed using AutoCAD, Global Mapper 17.2, and ArcGIS 10. The resulting spatial datasets were overlaid onto thematic maps. Topographic basemap support was provided by the 2005 orthophoto map (1:5,000 scale) sourced from the National Agency for Cadastre and Land Registration (NACLRL). To supplement the geodetic surveys, the field results were integrated with multispectral satellite data from the Landsat 8 Operational Land Imager (OLI) and Thermal Infrared Sensor (TIRS), retrieved from the USGS Earth Explorer platform.

3. RESULTS

To prevent redundant descriptions and maximize information density, the morphometric, hydrological, and plant community ecology parameters of the 11 lakes investigated within the Mătița-Merhei depression are synthesized below through comparative spatial analyses.

3.1. MORPHOMETRIC AND HYDROLOGICAL SYNTHESSES

The primary geomorphic parameters and hydrological connectivity networks of the investigated lakes are systematized below. Bathymetric ranges are referenced to a mean water level of approximately 180 cm on the Tulcea Port gauge. Individual lake perimeters exclude internal eco-geomorphological borders shared *via* floating reed beds. Siltation dynamics were qualitatively inferred based on the degree of hydrological connectivity with the Danube River distributary network and the presence or absence of direct fluvial inputs.

3.1.1. The Northwestern Lacustrine Subsystem (Babina, Corciuvatele and Ciorticuț Lakes)

This continuous aquatic system, located in the northwestern sector of the depression, spans a collective area of 831 ha.

Babina Lake is the largest water body in this group (529 ha; 12.10 km perimeter), with a bathymetric range of up to 2.0 m. It exhibits high hydrodynamics and mobile boundaries dominated by floating reed beds (*plauri*), fed *via* the Gârla Lopatna (stream), Stipoc, and Chilia bypass canals.

Corciuvatele (135 ha) and **Ciorticuț Lakes** (167 ha) form the northeastern and northern sectors of the interconnected lake system, respectively. Both share a shallow bathymetric shelf of 1.0-1.5 m and are characterized by heavy organic deposition; Corciuvatele is physically separated from Babina by a distinct NW-SE reed bed alignment. The Babina-Corciuvatele-Ciorticuț lake subsystem lacks distinct hydrological boundaries due to pervasive reedbeds and floating reed beds (*plauri*).

3.1.2. The Central Lacustrine Subsystem (Miazăzi, Lungu and Sfîstofca Lakes)

Situated in the central part of the hydrographic unit (Mătița-Merhei), these basins generally experience restricted fluvial inputs and stagnant lacustrine conditions:

Miazăzi Lake: Covering 135 ha (5.30 km perimeter), this basin has a shallow, uniform baseline bathymetric profile. It features dynamic organic-alluvial siltation concentrated near its western channel connection to the Eracle Canal, and it also links northward to the Mătița and Lungu Lakes.

Lungu and Sfîstofca Lakes: Lungu (215 ha; 11.50 km perimeter) and Sfîstofca (124 ha; 7.30 km perimeter) maintain a baseline depth of 1.0 - 1.5 m. Because fluvial exchange is

very restricted, both basins are highly susceptible to intense autochthonous organic infilling.

3.1.3. The Southern Lacustrine Subsystem (Rădăcinos, Trei Ozere, Căzănel, La Amiază and Bogdaproste Lakes)

These water bodies predominantly exhibit a baseline bathymetric range of 1.0 - 1.5 m but vary significantly in their sedimentation dynamics and fluvial connectivity:

Rădăcinos, Trei Ozere and Căzănel Lakes: Trei Ozere and Căzănel form a massive, continuous group of 564 ha (13.80 km perimeter) lined with dense *Phragmites* belts. It experiences mixed organic-mineral siltation and connects directly to the Old Danube *via* the Căzănel Canal. Positioned west of this complex, Rădăcinos Lake (159 ha) links to the wider hydrographic network only *via* minor streams and is dominated by intense autochthonous vegetal accumulation.

The adjacent **La Amiază Lake** is much smaller (72 ha), elongated, and experiences very weak direct fluvial exchange, leading to isolated organic infilling.

Conversely, **Bogdaproste Lake** represents a major basin of 410 ha sustained by direct fluvial input from the Old Danube *via* a 3.5 km canal, resulting in a dual fluvial-sedimentary and organic siltation dynamic.

3.2. QUANTIFYING PLANT COMMUNITIES AND FLOATING REED BEDS (PLAURI)

Vegetation density and percentage composition were evaluated using a semi-quantitative analysis based on a modified DAFOR scale (Hurford, 2006). Biomass was graded into six categories: absent (0%), rare (0-25%), moderate (25-50%), dense (50-75%), very dense (75-100%), and complete (100%). To avoid redundant illustrations, spatial distribution maps are selectively provided across certain lakes. These cartographic outputs directly reflect the fully delineated, peak-biomass plant communities for the lakes successfully surveyed during the investigations (Figs. 2-7).

3.2.1. The Northwestern Lacustrine Subsystem (Babina, Corciuvatele and Ciorticuț Lakes)

Babina Lake: Macrophyte distribution covered approximately 41.1 ha, classifying the lake as „rare on the DAFOR scale” (7.8% coverage), while the free water surface comprised the remaining 486 ha (92.2%). The core basin sheltered 8 scattered structures (*plauri*) totaling around 6.5 ha. At the time of the measurements, seven species of emergent aquatic vegetation were identified on the lake's water surface: *Nuphar lutea*, *Nymphaea alba*, *Trapa natans*, *Salvinia natans*, *Stratiotes aloides*, *Phragmites australis*, and *Typha* sp. Emergent aquatic vegetation is primarily present in the western section of the lake, flanking both sides of the inlet where the Rădăcinoasele Canal enters the lake. A significant feature is the presence of floating reed beds (*plauri*) on Lake Babina. Located in the northern, north-eastern, and eastern sections, these floating reed beds delineate the natural boundary with Lake Corciuvatele and consist mainly of

Phragmites australis and *Typha* sp., alongside specific plant species and *Salix retusa* (dwarf willow). In the southern part of the lake, an area populated by *Trapa natans*, *Salvinia natans*, and *Stratiotes aloides* was identified, expanding on both sides of the mouth of the small canal connecting to the Lopatna Canal. The predominant species are represented by *Nuphar lutea* and *Nymphaea alba*, occupying an area of approximately 18 ha, as well as *Phragmites australis* and *Typha* sp., which constitute the main vegetation forming the floating reed bed (*plauri*) (Fig. 2).

Corciuvatele Lake: The lake's aquatic vegetation covers 13.7 ha, placing it within the „rare DAFOR interval” (10.1% coverage). This vegetation includes 6 units (*plauri*) (~6.0 ha) distributed along the northwestern, central, and southwestern margins, separated from Babina Lake by a distinct NW-SE reed line. Consequently, the open water surface spans 122.3 ha, accounting for the remaining 89.9% of the lake's total area. At the time of the measurements, four species of emergent aquatic vegetation were identified on the lake's water surface: *Nuphar lutea*, *Nymphaea alba*, *Phragmites australis*, and *Typha* sp. The predominant vegetation is composed of the floating reed beds (*plauri*), specifically *Phragmites australis* and *Typha* sp. as primary species, alongside other aquatic plants and *Salix retusa*. The floating reed beds (*plauri*) cover a total area of 7.2 ha, accounting for 5.29% of the lake's total surface area. These are located in the western and south-western parts of the lake, delineating the boundary with Lake Babina. Toward the north-eastern section of the lake, a significant area dominated by *Nuphar lutea* and *Nymphaea alba* was identified (Fig. 2).

Ciorticuț Lake: Mapped within the „rare DAFOR category” (6.0% coverage), the lake's vegetation consists entirely of 5 distinct floating reed beds (*plauri*) that total approximately 10 ha. The 3 largest structures are positioned in the south, forming a physical boundary with Corciuvatele Lake. Consequently, the open water surface spans 157 ha, accounting for the remaining 94% of the lake's total area. At the time of the measurements, no emergent aquatic vegetation was identified on the lake surface, except for the floating reed bed (*plauri*) communities. Consequently, two predominant aquatic vegetation species were identified - namely, *Phragmites australis* and *Typha* sp. - alongside other aquatic plant species that form these floating reed beds. Five floating reed beds were identified on the surface of Lake Ciorticuț, three of which are located in the southern section, adjacent to Lake Corciuvatele; these also represent the largest in size (Fig. 2).

3.2.2. The Central Lacustrine Subsystem (Miazăzi, Lungu and Sfîștofca Lakes)

Miazăzi Lake: Emergent vegetation mapping on this lake revealed five aquatic species - *Salvinia natans*, *Trapa natans*, *Stratiotes aloides*, *Nuphar lutea*, and *Nymphaea alba* - falling within the „rare DAFOR interval”. This aquatic vegetation covers 22.2 ha (16.44% of the lake), leaving an

open water surface of 112.8 ha (83.56%). Both emergent and submerged communities line the lakes without forming floating reed bed structures (*plauri*), reaching their maximum development in the western sector on both sides of the entrance from the Eracle Channel. This western inflow, along with the northwestern and northern areas, is dominated by a dynamic *Trapa natans* + *Salvinia natans* + *Stratiotes aloides* matrix. Conversely, the southern zone is uniquely dominated by submersed vegetation - predominantly *Ceratophyllum* sp. and *Chara* sp. - which grows through the entire water column to form a dense surface carpet. Finally, water lily zones (*Nuphar lutea* and *Nymphaea alba*) are distributed across the northern, northeastern, and eastern sectors, appearing only sporadically in the west (Fig. 3).

Lungu Lake: Characterized by intense spatial fragmentation during the spring survey (May 2023), the elongated basin of Lungu Lake sheltered the highest number of floating reed bed formations, totaling 21 structures across approximately 10.0 ha. Classified as „rare under the DAFOR scale” due to the early vegetative season, these perennial *Phragmites* matrices were heavily concentrated within the central and southern zones.

Sfiștofca Lake: Reflecting delayed spring growth, there was no visible sign of emergent macrophytes or floating reed beds (0% coverage) on the lake at that time. At the time of the survey (May 2023), the aquatic community was restricted solely to early-developing submerged benthic taxa, heavily dominated by *Ceratophyllum* sp. No thematic maps were presented for Lungu and Sfiștofca Lakes due to their undeveloped vegetation at the time of spring measurements.

3.2.3. The Southern Lacustrine Subsystem (Rădăcinos, Trei Ozere, Căzănel, La Amiază and Bogdaproste Lakes)

Rădăcinos Lake: This is the only water body in the „moderate DAFOR category”, with a vegetation coverage of 79.5 ha (49.97%) and 79.6 ha (50.03%) of free water surface. Surveys revealed diverse communities of five emergent species: *Stratiotes aloides* (dominant), *Trapa natans*, *Salvinia natans*, *Nuphar lutea*, and *Nymphaea alba*, forming five distinct plant associations. A massive 11.0 ha floating reed bed (*Phragmites australis*) occupied the southeastern sector. The largest community comprises *Stratiotes aloides*, *Trapa natans*, and *Salvinia natans* in the northern and central-western areas. A similarly large association incorporates submersed *Ceratophyllum* sp., forming dense vertical matrices with *Stratiotes aloides* across the western, southwestern, and southern zones. Additionally, a major *Nuphar lutea* + *Stratiotes aloides* association occupies the eastern and southeastern sectors, whereas two minor communities - one featuring *Stratiotes aloides* with submersed *Ceratophyllum* sp. and another combining *Nymphaea alba* with *Stratiotes aloides* - are restricted to small areas, the latter located in the south (Fig. 4).

Trei Ozere and Căzănel Lakes: This large combined group falls into the „rare DAFOR category”, with 124.5 ha (22.1%) vegetation coverage and 439.5 ha (77.9%) of free water surface. It features six emergent species - *Stratiotes aloides*, *Trapa natans*, *Salvinia natans*, *Hydrocharis morsus-ranae*, *Nuphar lutea*, and *Nymphaea alba* - grouped into associations with a submersed component dominated by *Ceratophyllum* species. A dense *Trapa natans* + *Stratiotes aloides* matrix covers most open water in Căzănel Lake. Meanwhile, Trei Ozere Lake hosts a large *Stratiotes aloides* + *Trapa natans* + *Salvinia natans* + *Hydrocharis morsus-ranae* community in its northern sector, and a *Nuphar lutea* + *Stratiotes aloides* + *Hydrocharis morsus-ranae* association in the west and southwest. A combined *Nymphaea alba* + *Nuphar lutea* + *Stratiotes aloides* + *Hydrocharis morsus-ranae* association spans western Trei Ozere and northeastern Căzănel Lake. Finally, 6 floating reed beds totaling 19.5 ha cover part of Căzănel Lake, clustered in southern Trei Ozere, where some form the natural boundary between the lakes (Fig. 5).

La Amiază Lake: Mapped near the upper limit of the „rare DAFOR category”, this lake has a vegetation coverage of 17.2 ha (23.24%) and 486 ha (76.76%) of free water surface. Floristic diversity is reduced to only two emergent species: *Nuphar lutea* and *Stratiotes aloides*. Their homogeneous, co-dominant association covers most water surfaces across the northern, western, and southern zones, outcompeting pure *Nuphar lutea* stands. Floating reed bed presence is negligible, with only 3 small structures (*Phragmites australis*) totaling 0.3 ha in the northern, central-northern, and southernmost sectors (Fig. 6).

Bogdaproste Lake: Classified in the „rare DAFOR category”, this lake has a vegetation coverage of 31.4 ha (7.66%), being heavily dominated by 378.6 ha (92.34%) of free water surface. Open-water floating reed bed islands are absent; emergent vegetation is restricted to the northwestern, western, southwestern, and southern sectors, featuring *Nuphar lutea*, *Stratiotes aloides*, *Hydrocharis morsus-ranae*, and *Salvinia natans*. Submersed vegetation covers vast areas independently or mixed with emergent species, with both the *Salvinia natans* + submersed species community and *Nuphar lutea* + *Stratiotes aloides* patches occupying significant surfaces. Furthermore, submersed macrophytes (*Ceratophyllum* sp., *Myriophyllum* sp., and invasive *Elodea canadensis*) form dense vegetative bands dominating a large portion of the left shoreline (Fig. 7).

Conclusively, no surveyed lakes fell within the dense (50-75%), very dense (75-100%), or complete (100%) DAFOR classification intervals during the 2023 monitoring period.

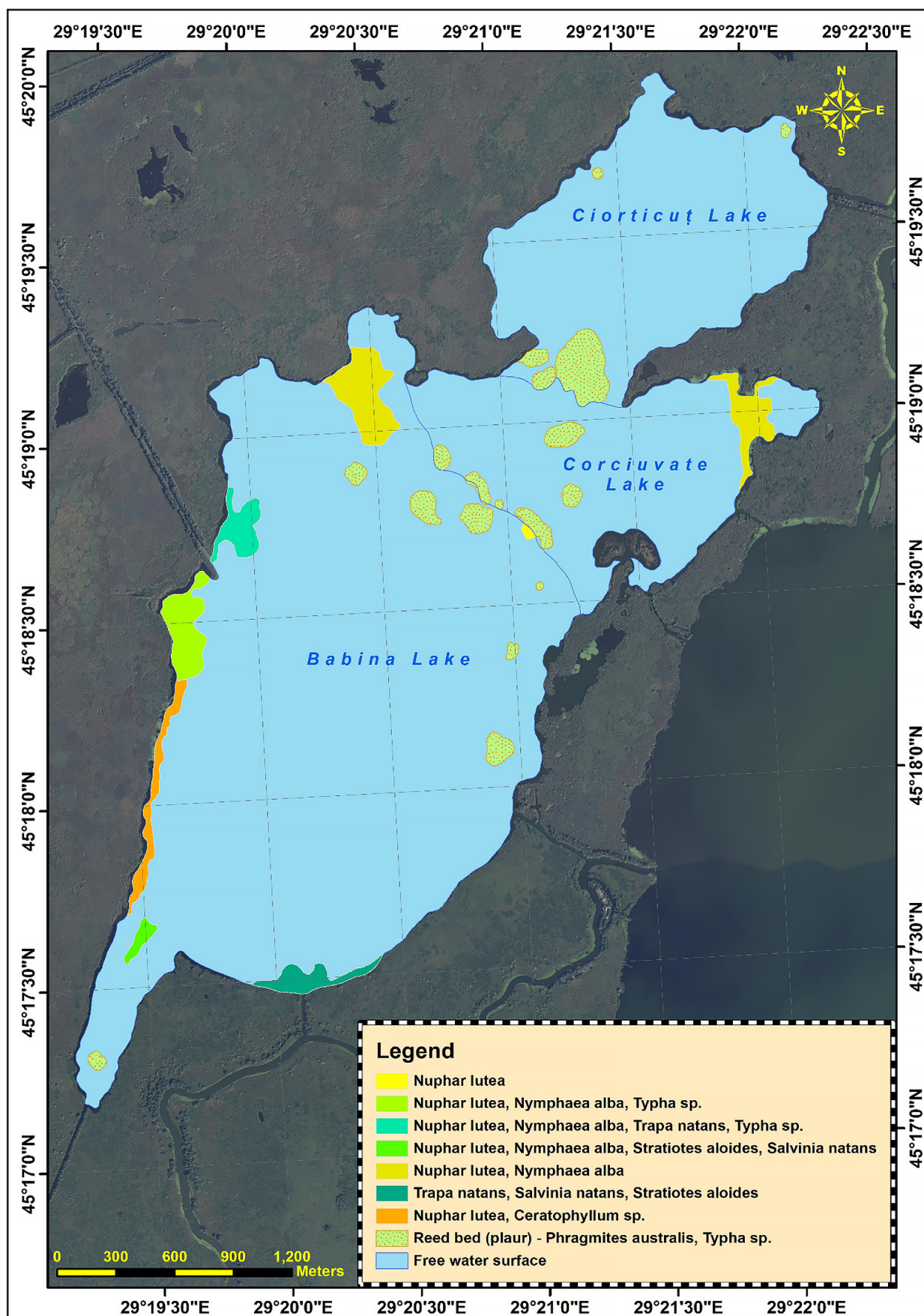


Fig. 2. Spatial distribution map of aquatic vegetation in Babina, Corciuvatele and Ciorticuț Lakes.

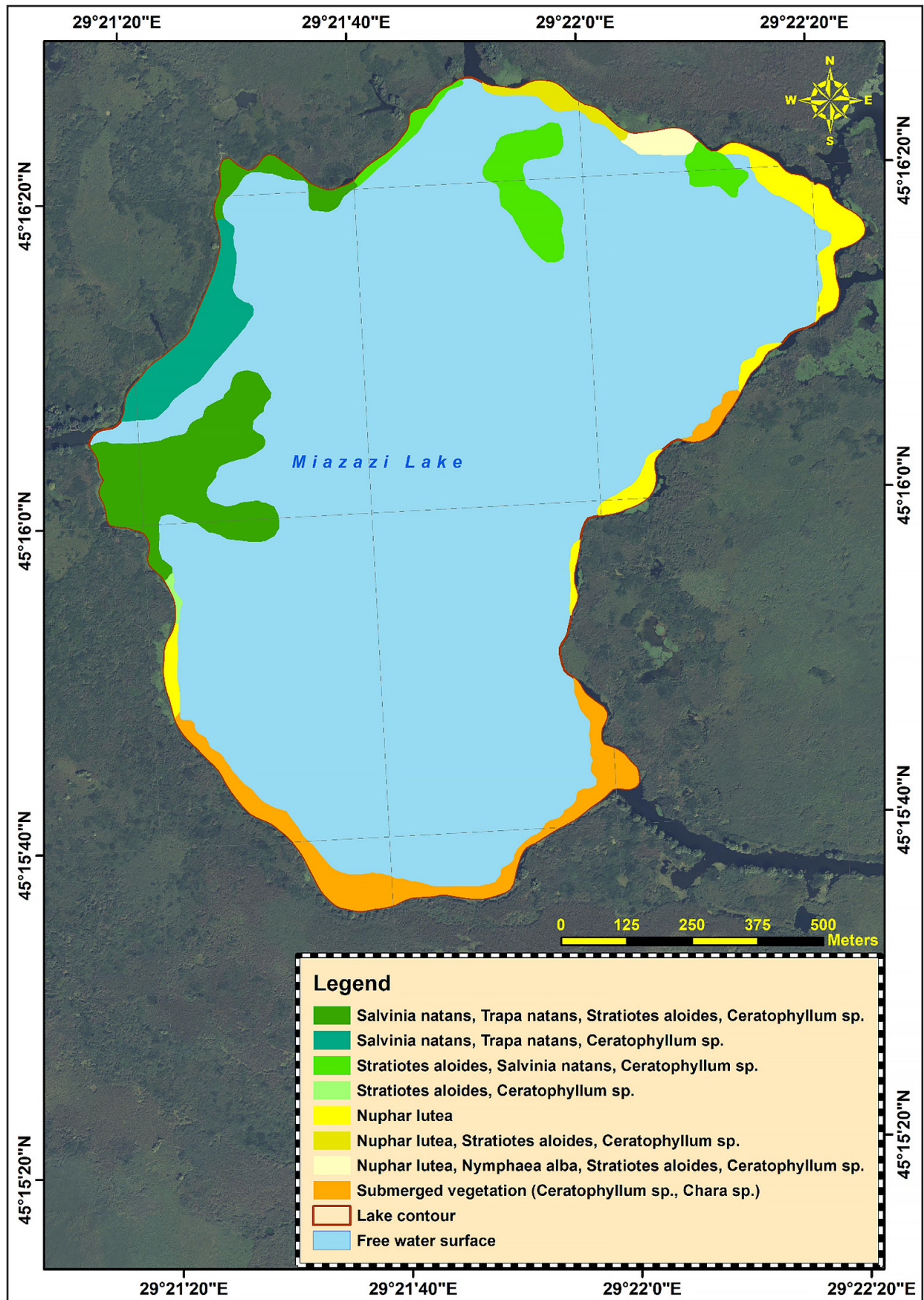


Fig. 3. Spatial distribution map of aquatic vegetation in Miazazi Lake.

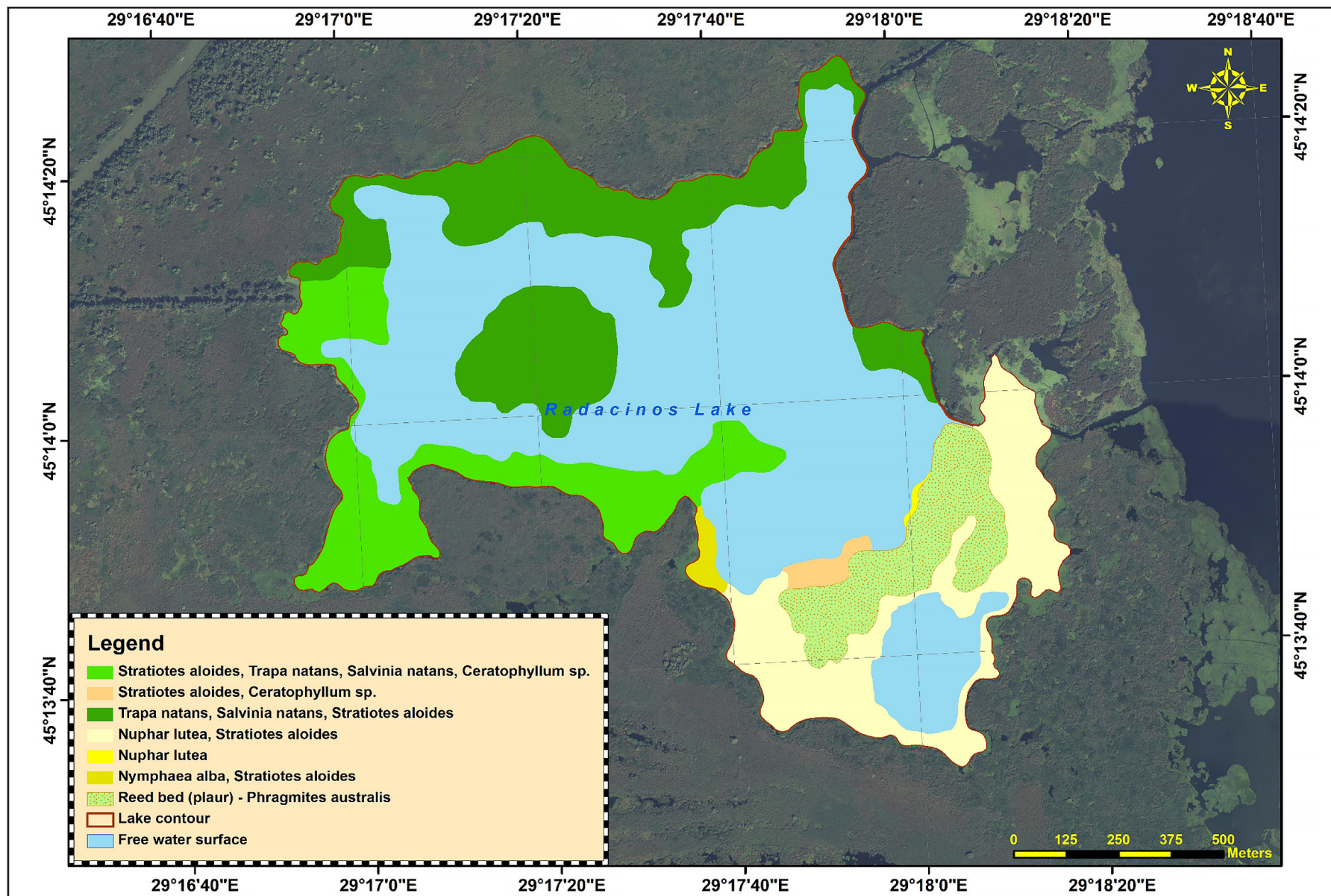


Fig. 4. Spatial distribution map of aquatic vegetation in Rădăcinos Lake.

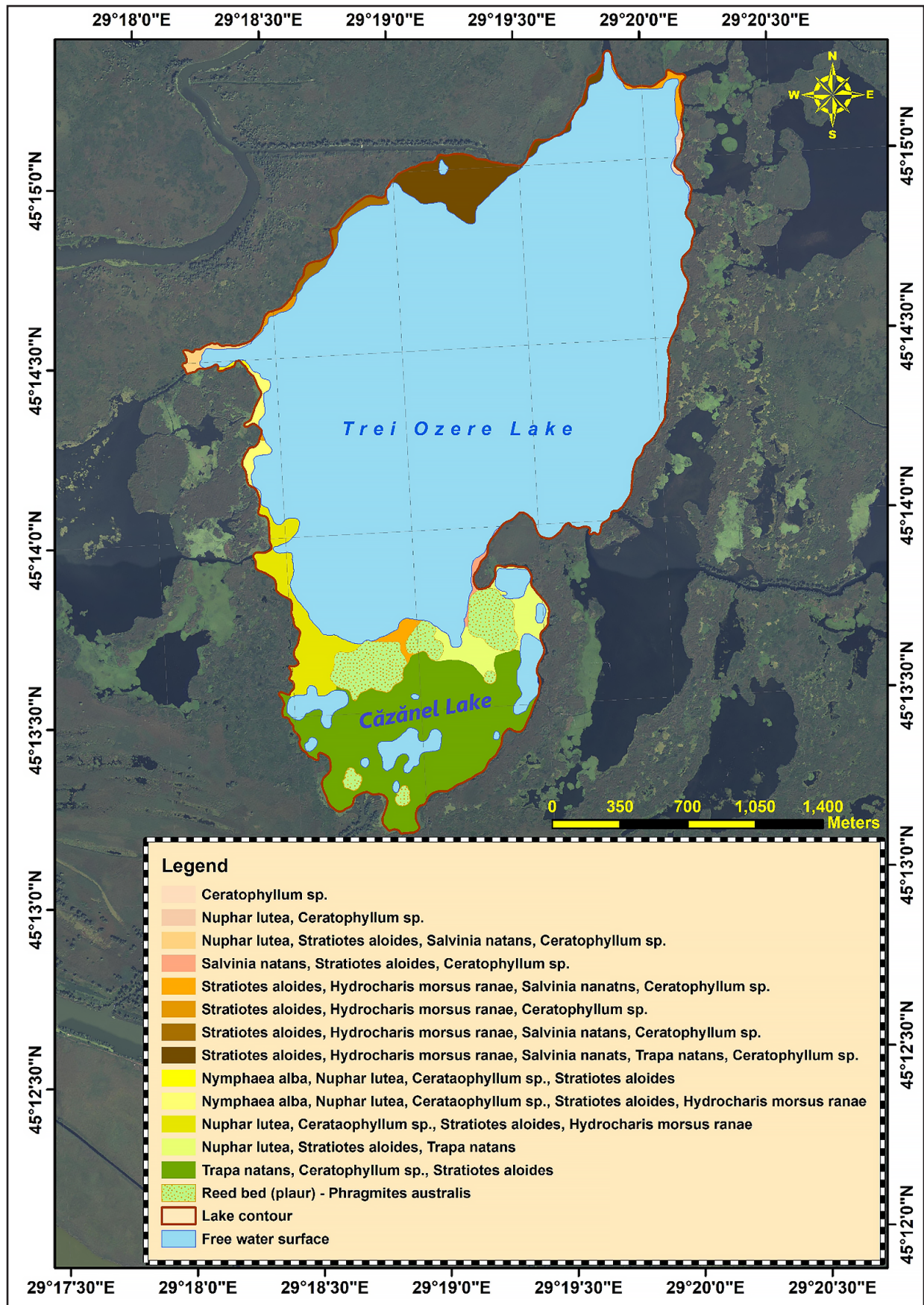


Fig. 5. Spatial distribution map of aquatic vegetation in Trei Ozere and Căzănel Lakes.

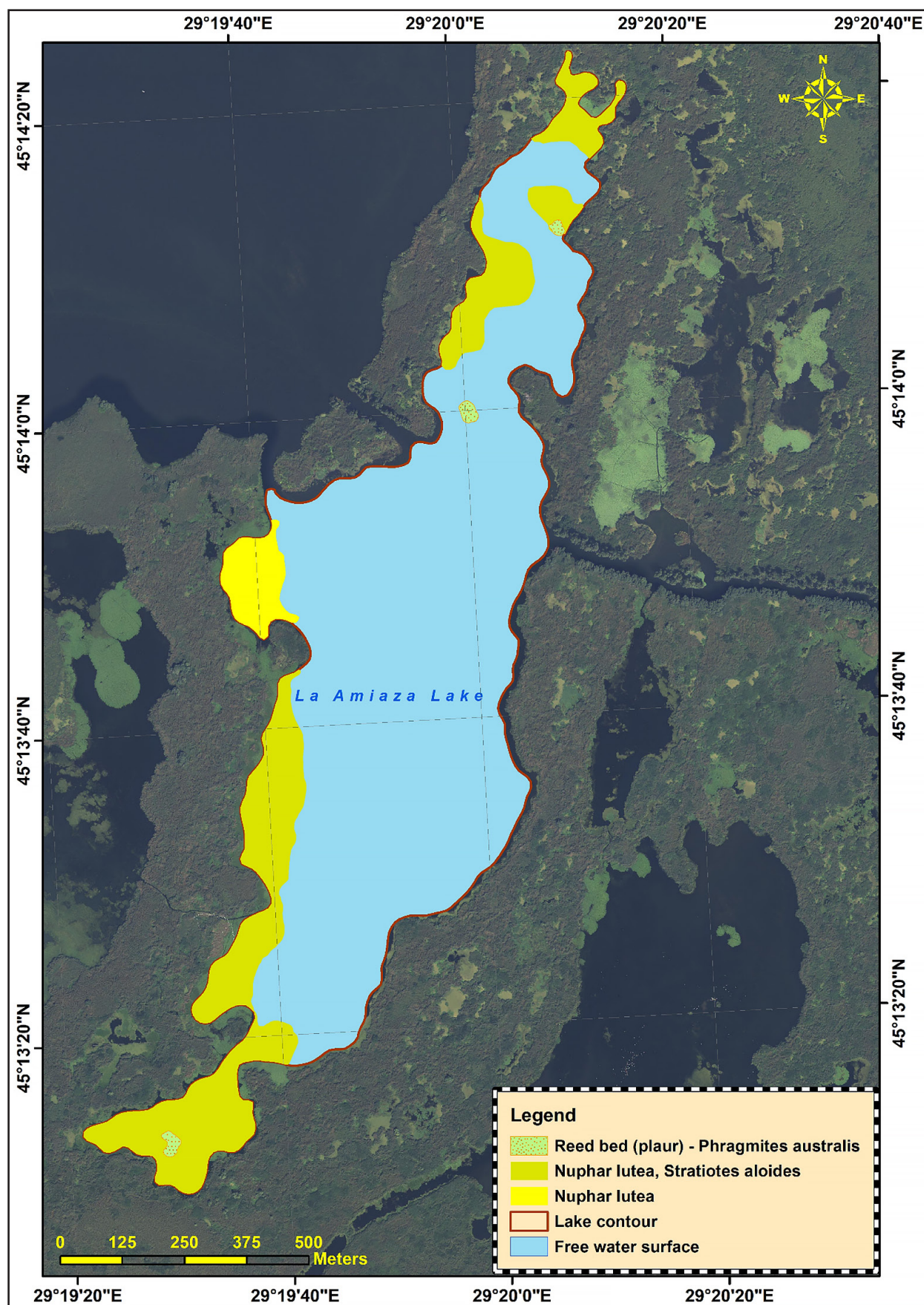


Fig. 6. Spatial distribution map of aquatic vegetation in La Amiază Lake.

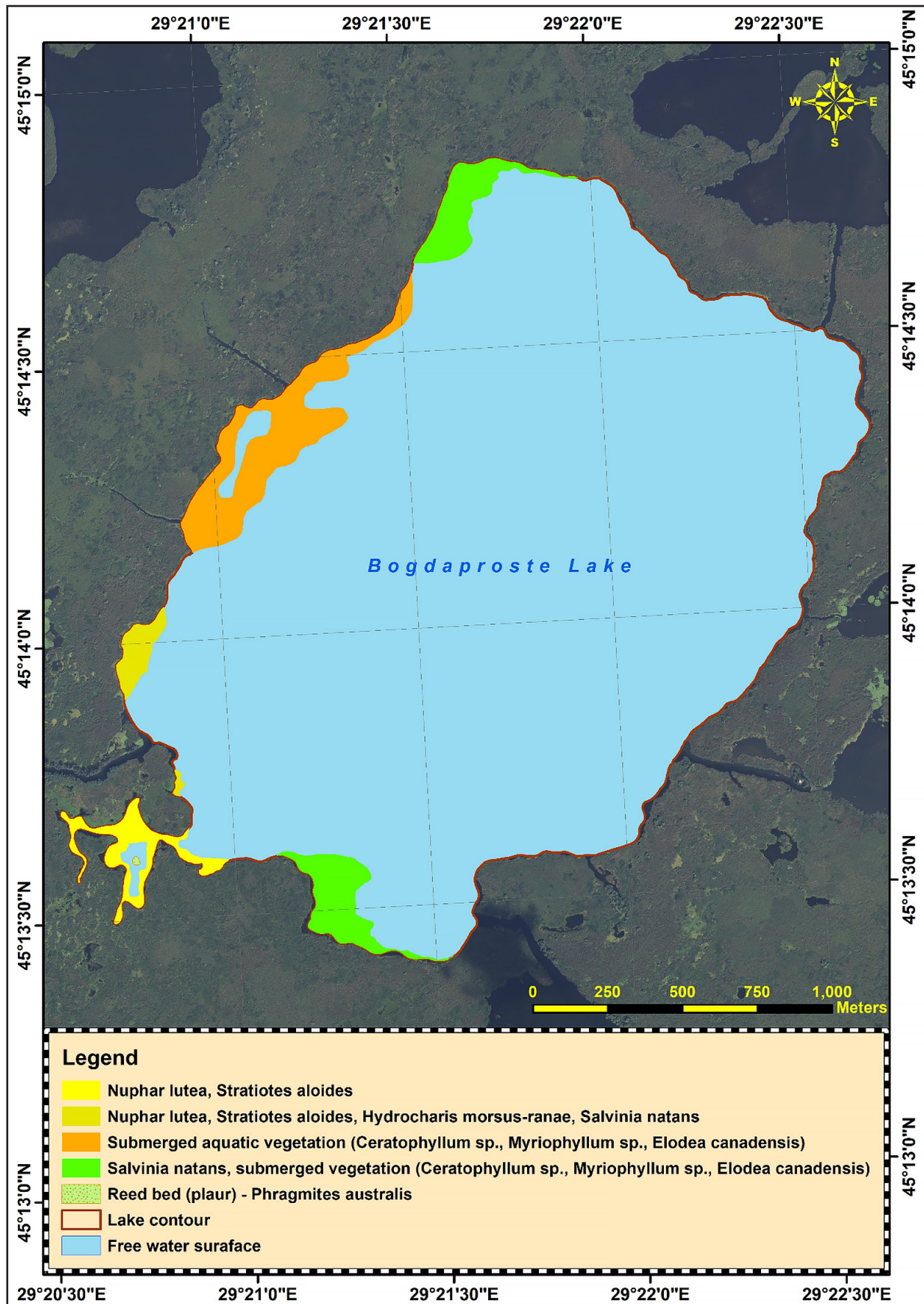


Fig. 7. Spatial distribution map of aquatic vegetation in Bogdaproste Lake.

3.3. MAPPING SPATIAL AND ENVIRONMENTAL GRADIENTS

The spatial analysis derived from topo-geodetic field mapping highlights distinct ecological gradients governed by hydrographic connectivity, hydrodynamic energy, and localized siltation dynamics. Rather than reflecting mere seasonal fluctuations, the distinct vegetative patterns indicate a structural transition along well-defined environmental axes.

Fluvial Connectivity and Hydrodynamic Gradients.

The degree of direct connection to the Danube River's primary distributary network emerges as the main driver of macrophyte community composition. In high-volume distributary zones characterized by active fluvial exchange - such as the western sector of **Miazăzi Lake** (directly influenced by the Eracle Canal) (*i.e.*, central lacustrine subsystem) and the open waters of **Căzănel Lake** (fed by the Căzănel Canal) (*i.e.*, southern lacustrine subsystem) - the hydrodynamics favor mobile, anchored floating species. In these sectors, *Trapa natans* and *Salvinia natans* exhibit maximum structural development. The constant water turnover in these areas prevents extreme summer stagnation and limits total organic clogging, sustaining an environment driven by pulsing river inputs.

Nutrient Pulses and Invasive Vectors. A distinct environmental gradient is mapped along the channelized pathways connecting the main river branches to the internal deltaic depressions. The left bank of **Bogdaproste Lake** (*i.e.*, southern lacustrine subsystem) represents a prime example of this phenomenon; its direct 3.5 km connection to the Old Danube subjects the basin to continuous nutrient pulses and high influxes of vegetative spores. Consequently, this corridor is uniquely colonized by highly abundant submerged belts of *Ceratophyllum* sp., *Myriophyllum* sp., and the invasive alien species *Elodea canadensis*. This spatial distribution demonstrates that open artificial canals act as ecological highways for biological invasions, propagating degradation from the main fluvial axes deep into the lacustrine space.

Hydrodynamic Isolation and Autochthonous Infilling.

Conversely, isolated, organically silted lakes show a marked reduction in active floristic diversity and a shift toward structural stagnation. As fluvial energy dissipates through expansive reed bed filtration barriers, lakes such as **La Amiază Lake** (*i.e.*, southern lacustrine subsystem) experience an impoverished, highly homogeneous ecosystem. Here, the lack of active water exchange leads to intense autochthonous vegetal accumulation, allowing the outcompeted *Nuphar lutea* - *Stratiotes aloides* association to dominate almost the entire lake margin. In these isolated basins, *Stratiotes aloides* functions as a ubiquitous ecosystem engineer, exploiting the organic substrate and stable, low-energy water columns. A unique manifestation of extreme ecological isolation is observed in **Sfiștofca Lake** (*i.e.*, central lacustrine subsystem); despite sharing shallow bathymetric conditions with adjacent basins, its geographic position at the easternmost boundary

shields it entirely from macro-vegetal encroachment, leaving it as a benthic-dominated exception.

Macro-Vegetal Fragmentation and Geomorphic Dynamics. Beyond species distribution, the spatial gradients illustrate varying stages of lake senescence and geomorphic fragmentation. The northwestern lacustrine subsystem - **Babina, Corciuvatele, and Ciorticuț Lakes** - alongside the centrally located **Lungu Lake** - represents the most advanced successional stage within the hydrographic unit. In these basins, the open water areas are actively carved, restricted, and bounded by large, perennially stable *Phragmites australis* matrices. The high count of fragmented, isolated structures (*plauri*) (totaling 21 units in Lungu Lake and 19 units across the northwestern lacustrine subsystem - Babina, Ciorticuț, Corciuvatele) highlights an ongoing geomorphic decline of the classic lake shorelines. These floating reed beds act as mobile physical barriers that dynamically alter internal lake circulation, accelerate lake infilling, and dictate local successional trajectories.

4. DISCUSSIONS

4.1. ANALYZING PLANT INTERACTIONS AND COEXISTENCE

The spatial and plant community ecology configurations identified across the investigated lakes suggest complex biological mechanisms of competition and mutual facilitation. A major structural pattern observed during peak biomass is the competitive dominance of *Stratiotes aloides*. Acting as a keystone "ecosystem engineer" (Jones *et al.*, 1994), *S. aloides* forms dense, expansive vegetation mats that heavily restrict light penetration and available volume within the photic zone (Strzałek & Koperski, 2019). This high horizontal expansion may induce a process of competitive exclusion, suppressing rooted, floating-leaved macrophytes (*Nuphar lutea* and *Nymphaea alba*) by physically blocking their petioles from reaching the water surface (Smolders *et al.*, 2003). This mechanism directly explains the comprehensive colonization patterns mapped in the isolated environments of **Rădăcinos** and **La Amiază Lakes** (*i.e.*, southern lacustrine subsystem).

In contrast, a clear mechanism of ecological facilitation is identified within the *Trapa natans* - *Salvinia natans* communities, which dominate high-energy zones such as **Căzănel** (*i.e.*, southern lacustrine subsystem) and **Miazăzi Lakes** (*i.e.*, central lacustrine subsystem). *Trapa natans* is a well-anchored, morphologically robust macrophyte that develops massive floating rosettes (Groth *et al.*, 1996). This anchored structure provides a rigid physical framework that actively attenuates local wave action and water currents (Groth *et al.*, 1996; Thomaz & Cunha, 2010). Conversely, *Salvinia natans* is a small, free-floating aquatic fern lacking true root anchoring systems, making it highly vulnerable to wind-driven drift and fluvial flushing (Thomaz & Cunha, 2010). By nesting within the micro-habitats and physical boundaries generated by the *T. natans* rosettes, *S. natans*

finds shelter against these disruptive hydrodynamic forces (Thomaz & Cunha, 2010; Bornette & Puijalon, 2011). This structural protection enables the free-floating fern to establish the high-density populations mapped along the active open deltaic corridors of the Matița-Merhei complex, where it would otherwise be flushed out.

4.2. NATIVE PLANTS: BIOINDICATORS OF ECOLOGICAL STATUS

Except for the alien invasive *Elodea canadensis*, the macrophyte assembly identified across the investigated lakes consists of indigenous, evolutionarily adapted European species. Many of these taxa characterize aquatic phytocoenoses typical for EU-protected habitats, thereby confirming a high baseline ecological integrity (Gâstescu & Știucă, 2008).

In this context, the localized presence of *Chara* sp. (charophyte green algae) within the southern sector of **Miazăzi Lake** (*i.e.*, central lacustrine subsystem) is highly significant from a water quality perspective. Charophytes are sensitive bioindicators restricted to oligotrophic-mesotrophic freshwater environments with minimal vertical turbidity and low nutrient loads. Their capability to form dense benthic mats stabilizes bottom sediments, limits resuspension, and maintains the distinct clear-water stable state documented in this specific basin (Van Donk & van de Bund, 2002).

Similarly, the occurrence of healthy *Nymphaea alba* and *Hydrocharis morsus-ranae* clusters marks well-established, functional, and mature lacustrine habitats (Gâstescu & Știucă, 2008). Furthermore, while *Trapa natans* behaves as an aggressive, problematic invasive weed across several non-European continents, such as North America (Groth *et al.*, 1996), it represents a protected native element within the Danube Delta Biosphere Reserve under the framework of the Council of Europe (1979). Consequently, its expansive seasonal development in channels and open-water margins represents a characteristic, autochthonous successional stage of deltaic lacustrine systems rather than an unequivocal index of ecological degradation (Cristofor *et al.*, 1994; Gâstescu & Știucă, 2008).

The structural matrix of the ecosystem is further completed by ubiquitous, deeply rooted *Phragmites australis* stands - which drive the geomorphic evolution of floating reed beds (*plauri*) (Covaliov *et al.*, 2010) - and *Ceratophyllum* sp., which plays a major role in vertical water column oxygenation (Cristofor *et al.*, 1994).

4.3. FLUVIAL CONNECTIVITY AND THE EXPANSION OF INVASIVE ALIEN SPECIES

The most critical biogeographical finding within this study is the strict restriction of the submerged invasive alien species *Elodea canadensis* (Canadian waterweed) to **Bogdaproste Lake** (*i.e.*, southern lacustrine subsystem). Native to North America and introduced to European inland waters in the 19th century, *E. canadensis* is a highly aggressive submerged

invader characterized by rapid vegetative fragmentation, high growth rates under varied nutrient configurations, and the capacity to form dense monospecific stands that displace local vegetation (CABI, 2022). The exclusion of *E. canadensis* from the isolated lakes - such as **Rădăcinos**, **La Amiază** (*i.e.*, southern lacustrine subsystem), and **Lungu Lakes** (*i.e.*, central lacustrine subsystem) - and its unique presence in **Bogdaproste Lake** may be directly correlated with the lake's distinct hydrographic connectivity network. As previously presented, Bogdaproste Lake (*i.e.*, southern lacustrine subsystem) receives a direct, continuous freshwater and sediment supply from the Old Danube *via* an open canal corridor. This active connection exposes the basin to a dual ecological pressure: a high influx of vegetative fragments and turions (hibernacula) carried by fluvial currents directly from the main river branches into the lacustrine inlet (Lockwood *et al.*, 2005), coupled with intermittent pulses of dissolved nutrients and suspended mineral sediments. This nutrient enrichment creates a highly fertile environment that fuels the aggressive vegetative reproduction of the invader.

In contrast, the isolated lakes within the Matița-Merhei complex rely on filtered, low-energy water exchange through expansive reed beds. These dense macrophyte rings act as natural biophysical barriers that mechanically filter out external macro-vegetal fragments and suppress the initial establishment of alien invaders.

Consequently, maintaining or controlling the degree of direct channelized connection to the main Danube River branches represents a critical management driver governing the vulnerability of deltaic lakes to biological invasions. These localized lacustrine invasions, therefore, cannot be viewed in isolation; they represent specific components of a broader, multi-trophic degradation that ripples throughout the entire Danube River - Danube Delta - Black Sea continuum.

4.4. ECOLOGICAL IMPLICATIONS AND CONSERVATION CHALLENGES: THE DANUBE RIVER - DANUBE DELTA - BLACK SEA CONTINUUM

The local plant community ecology shifts documented in this study - ranging from the competitive dominance of *Stratiotes aloides* (Section 4.1) and the identification of *Chara* sp. native clear-water bioindicators (Section 4.2) to the channel-driven expansion of *Elodea canadensis* (Section 4.3) - are generally interconnected with a larger ecological crisis. The spatial patterns and expansion rates of deltaic vegetation cannot be decoupled from the broader, multi-trophic degradations occurring along the Danube-Danube Delta-Black Sea continuum. While our spatial analysis maps the physical intrusion of macrophyte stands, the underlying ecological resilience of these lake systems is systematically undermined by synchronized bioinvasions across all environmental transitional zones. For instance, the aggressive surface carpets formed by regional invasive macrophytes such as *Ludwigia peploides* or *Azolla filiculoides* alter local hydrodynamic and light conditions, potentially restricting

the initial colonization zones of native emergent seedlings along lake margins.

Furthermore, the restructuring of lower trophic levels by invasive ichthyofauna (*Carassius gibelio*, *Hypophthalmichthys* spp.) within the Danube Delta lakes, combined with downstream marine invaders (*Rapana venosa*, *Mnemiopsis leidyi*) along the coast, may induce profound shifts in nutrient cycling and water turbidity. This regional biological pressure accelerates eutrophication dynamics, which in turn acts as a primary fertilizer for the aggressive expansion of *Phragmites australis* in the delta. Therefore, the described spatial distribution of emergent vegetation in the Matița-Merhei complex reflects not only localized wetland succession, but also a structural response to systemic ecological pressures propagated throughout the entire river-delta-sea corridor. This interconnected impairment across the continuum is driven by a cascade of biological invasions that simultaneously disrupt terrestrial, freshwater, and marine trophic webs.

4.5. SYSTEMIC BIOINVASIONS AND MULTI-TROPHIC IMPACTS ACROSS THE CORRIDOR

To fully comprehend the scale of these multi-trophic impacts, systemic bioinvasions must be investigated across three interconnected ecological domains along the corridor: terrestrial margins, freshwater lakes, and marine coastal environments. Within the riparian habitat corridor, the integrity of the terrestrial margins is severely compromised by aggressive alien flora. Specifically, the false indigo bush (*Amorpha fruticosa*) encroaches rapidly onto the riverbanks, where this invasive plant establishes dense monocultures that completely replace native *Salix alba* floodplains, thereby altering the natural structural configuration of deltaic riparian galleries (Anastasiu *et al.*, 2014).

This marginal degradation occurs simultaneously with intense pressures inside the freshwater lacustrine environments, where invasive aquatic macrophytes and non-native ichthyofauna collectively disrupt indigenous community successions. Among the aquatic macrophytes, the floating primrose-willow (*Ludwigia peploides*) forms dense, impenetrable surface carpets that block light penetration, induce severe water column hypoxia, and ultimately annihilate native macrophyte assemblages (Doroftei *et al.*, 2026). In heavily eutrophic lakes, this phenomenon is accompanied by the water fern (*Azolla filiculoides*), which develops massive seasonal blooms, creating a suffocating surface blanket that impairs overall ecological functioning (Chirilă *et al.*, 2026). Furthermore, the least duckweed (*Lemna minuta*) effectively outcompetes the native *Lemna minor*, exploiting its high thermal tolerance to dominate the water surface during intense summer heatwaves (WWF-România, 2014).

These botanical shifts operate in tandem with profound alterations to the trophic web structures induced by exotic fish species. The silver carp (*Hypophthalmichthys molitrix*) and

bighead carp (*H. nobilis*), which were intentionally introduced for aquaculture, drastically modify nutrient cycling through heavy, unregulated feeding on local phytoplankton and algal communities (Jawdhari *et al.*, 2022). Additionally, the Prussian carp (*Carassius gibelio*) proliferated widely following devastating aquaculture facility floods, enforcing intense biological pressure by actively competing with native fish for resources and consuming indigenous fish eggs (Bănăduc *et al.*, 2023).

Ultimately, the ecological pressures propagated down the Danube corridor extend directly into the marine coastal zones of the Black Sea, where ballast water discharges and historical runoffs have triggered massive structural shocks across both pelagic and benthic biocenoses. In the pelagic realm, the warty comb jelly (*Mnemiopsis leidyi*) devastated local zooplankton populations and fish larvae following its introduction, triggering a harmful food web collapse during the 1980s (Shiganova, 1998). This pressure was only partially mitigated in the late 1990s by the accidental arrival of another ctenophore (comb jelly), *Beroe ovata*, which now acts as a natural biocontrol agent due to its exclusive predatory focus on *M. leidyi* (Finenko *et al.*, 2003).

Simultaneously, benthic marine habitats face severe predatory and spatial competition. The veined rapa whelk (*Rapana venosa*), first recorded in the basin in 1948, exerts massive, unyielding predatory pressure on native oyster and mussel beds (Sağlam & Düzgüneş, 2016; Dağtekin, 2023). In shallow sandy biocenoses along the Romanian coast, the incongruous ark clam (*Scapharca inequivalves*, recently known as *Anadara kagoshimensis*) has adapted successfully, spreading massively and reshaping soft-bottom communities (Gomoiu, 1986; Abaza *et al.*, 2021). Finally, decapod species (crustaceans) introduced via ballast waters - such as *Callinectes sapidus* and *Eriocheir sinensis* - actively alter benthic macroinvertebrate communities while causing economic damage by destroying commercial fishing nets (Oțel, 2004; Băncilă *et al.*, 2022).

5. CONCLUSIONS

High-precision topo-geodetic mapping of the Matița-Merhei hydrographic unit provides key insights into the eco-geomorphic evolution of deltaic environments. Spatial analysis reveals heterogeneous macrophyte development across the lacustrine landscape. According to the modified DAFOR scale, surveyed lakes exhibit varying coverage, from „moderate” in Rădăcinos Lake (49.97 %) to „rare” across the remaining lakes. Despite this variance, widespread emergent communities and localized floating reed beds (*plauri*) signal an ongoing transition toward advanced successional ecological phases. This transformation features a distinctive plant stratification: the surface mat is dominated by a native matrix of *Trapa natans*, *Stratiotes aloides*, *Salvinia natans*, and *Nuphar lutea*, while the vertical water column is anchored

by dense submerged *Ceratophyllum* sp. and high-quality bioindicators like *Chara* sp.

From a hydro-morphological perspective, these lakes are semi-closed, low-energy basins characterized by restricted water exchange and negligible bottom currents. Sheltered from significant wind-driven waves, their sedimentological regime is driven by hydrodynamic isolation and autochthonous organic infilling, where internal vegetative decay outpaces external alluvial inputs.

Furthermore, the transitional shorelines lack rigid geomorphic boundaries. Instead, they are defined by a dynamic, expanding ecotone belt dominated by *Phragmites australis*, often associated with *Typha latifolia* and scattered shrub willows (*Salix* spp.). This dense shoreline matrix actively drives the development of stable floating reed beds (*plauri*), obscuring open-water limits while sustaining subsurface hydrological communication even during low-water phases.

Ultimately, these findings may indicate that localized wetland successional dynamics are closely coupled with systemic corridor vulnerability and macro-regional

environmental pressures. The deltaic lakes function as a sensitive ecological bridge within the continuous Danube - Danube Delta - Black Sea corridor. Consequently, synchronized multi-trophic bioinvasions - ranging from riparian flora (*Amorpha fruticosa*) and aggressive macrophytes (*Ludwigia peploides*, *Azolla filiculoides*) to invasive ichthyofauna and marine competitors - alter nutrient cycling and accelerate eutrophication.

These synchronized pressures underscore that localized wetland conservation and vegetation management within the Danube Delta must be integrated into large-scale, cross-ecosystem environmental strategies addressing the entire river-delta-sea continuum.

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