

Vegetation, hydrological, and morphological dynamics of natural islands in the Danube Delta

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Ključne besede: aluvialni otoki, reka Donava, hidrološka dinamika, morfodinamični procesi, mokrišča

Abstract

The Danube Delta is a unique ecosystem located in southeastern Romania. Within this ecosystem, hydrological and morphological dynamics have an important role in maintaining biodiversity. The study aimed to analyze the vegetation, hydrological factors, and morphological dynamics of seven islands in the Danube Delta. The study was carried out during 2023–2024 at Isaccea (three islands), Dunavăț (three islands) and Dranov (one island) in all four seasons. Phytocoenological relevés were carried out for the vegetation analysis, and the SonTek RiverSurveyor M9 equipment was used for the hydrological analysis. The analysis of island dynamics was carried out through morphometric methods, using ANCPI orthophotos (2004 and 2021) and Landsat satellite images (2010). In the seven islands, six associations from the *Artemisietea vulgaris*, *Lemnetea*, *Phragmito-Magnocaricetea*, and *Salicetea purpureae* classes were found. The hydrological analysis indicated seasonal fluctuations in water level, flow, and velocity, with significant increases in the autumn and winter, especially at Isaccea. The hydrological regime has an important role in the morphodynamic modelling of the Danube Delta islands, indicating the river's ability to induce rapid transformations through sedimentation and erosion processes. The island's location influences this interaction, the river flow dynamics and human interventions such as the rectification of meanders.

Izvilleček

Delta Donave je edinstven ekosistem v jugovzhodni Romuniji. Za ohranjanje biodiverzitete tega ekosistema sta pomembni hidrološka in morfološka dinamika. V raziskavi smo analizirali vegetacijo, hidrološke dejavnike in morfološko dinamiko sedmih otokov v letih 2023 in 2024 v območjih Isaccea (tri otoki), Dunavăț (tri otoki) in Dranov (en otok) v vseh štirih letnih časih. Za analizo vegetacije smo naredili fitocenološke popise, opremo SonTek RiverSurveyor M9 pa smo uporabili za hidrološke analize. Analizo dinamike otokov smo naredili z morfometrijsko metodo z uporabo ANCPI ortofoto posnetki (2004 in 2021) in Landsat satelitskimi posnetki (2010). Na sedmih otokih smo ugotovili šest asociacij iz razredov *Artemisietea vulgaris*, *Lemnetea*, *Phragmito-Magnocaricetea* in *Salicetea purpureae*. Hidrološka analiza je pokazala sezonsko nihanje vodostaja, toka in hitrosti z značilnim porastom jeseni in pozimi, še posebej na območju Isaccea. Hidrološki režim je pomemben pri modeliranju morfodinamike otokov v deli Donave in kaže na sposobnost reke, da povzroča hitro transformacijo s sedimentacijo in erozijo. Na to interakcijo vpliva lokacija otoka, dinamika rečnega toka in človekove dejavnosti, kot je uravnavanje meandrov.

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Introduction

The Danube Delta is a unique territory, Europe's most prominent and best-preserved delta (Claudino-Sales, 2019). Due to its high biodiversity and the 13 ecosystem services (Gómez-Baggethun et al., 2019) it provides, this unique ecosystem is of global importance (Heath & Evans, 2000). Located in the Pontic biogeographic region, the Danube Delta supports the migration and dispersal of species across the European continent (Tockner & Stanford, 2002; Covaliov et al., 2023). With a biodiversity of over 11.000 taxa, this delta is recognized as one of Europe's most important biodiversity hotspots. Although it is protected by various national and international agreements, as biosphere reserve, UNESCO World Heritage sites, Ramsar sites, Natura 2000 sites, and national legislation (Claudino-Sales, 2019), it faces impacts of hydrological changes and intensive agriculture, which may threaten the integrity of its natural habitats (Covaliov et al., 2023). These factors also affect soil conditions, which are important for ecosystem stability (Rusu et al., 2025). Thus, soil quality, fertility and health influence ecosystem dynamics and efficiency (Rusu et al., 2024a, b).

From an ecological perspective, the Danube Delta is a unique complex of ecosystems that hydrological factors, such as water level, flow measurements, riverbed profiles, and average water velocity, significantly influence. These factors can have an important role in shaping vegetation. Therefore, conducting a case study to ascertain the degree of influence of these factors on vegetation cover in some natural islands in the Danube Delta is a valuable strategy. Hanganu et al. (2017) studied the effects of multiple pressures, including hydrological factors, on the lower Danube basin, where they showed insights into the relationships between hydrological conditions and the overall ecological status of water bodies.

The construction of dams, modification of natural watercourses, and other anthropogenic interventions intensify the loss of riparian habitats in the Danube Delta. Due to these changes, there has been a severe alteration in the connectivity of aquatic and terrestrial ecosystems. This has affected the functioning of ecosystems and biodiversity (Schneider, 2011). Also, the construction of dams can limit the natural flow of sediments and water, which are essential for maintaining the habitats and vegetation typical of the delta (Gâstescu & Știucă, 2006). Due to these practices, many wetlands have been transformed into agricultural land. In this manner, the natural areas for the flora and fauna specific to the delta have been significantly reduced.

In addition, research in other deltas, such as the Mississippi Delta (Day et al., 2007), the Mekong Delta

(Le et al., 2007), and the Nile Delta (Frihy, 2003), shows the vital role of vegetation in supporting ecosystem services in terms of climate change impacts and biodiversity. Because of their vulnerability to anthropogenic impacts and climate change, these deltaic ecosystems have been the subject of extensive ecological studies. Vegetation in deltaic ecosystems is vulnerable to changes in hydrology, nutrient availability, and sediment dynamics (Temmerman et al., 2013).

This study aims to analyze the habitats and hydrological and morphological factors of seven islands in the Danube Delta. The objectives of the study were (1) to identify habitats and plant associations, (2) to record hydrological measurements, and (3) to analyze the dynamics of the Lower Danube islands. This study can contribute to understanding the dynamics of islands in the Danube Delta, an area with remarkable biodiversity vulnerable to climatic variations and anthropogenic impact. The study's results can also help implement conservation measures in the context of restoring affected habitats.

Materials and methods

Study area

The study was conducted on seven islands of the Danube Delta (Figure 1) in 2023 and 2024. These islands are distributed as follows: one island located (A1) on the Chilia branch with an area of 10.91 ha; three islands located (A2, A3, and A4) in the vicinity of Isaccea port, between Cotul Pisicii and Ceatal Izmail which have an area of 69 ha; and three islands (A5a, A5b, A6) located on the Sf. Gheorghe branch with an area of 32.54 ha.

Vegetation analysis

The size of the plots was 100 m² (Cristea et al., 2004). The vegetation was classified using the Agglomerative Hierarchical Clustering method (β -flexible method, $\beta = -0.25$ and Bray-Curtis dissimilarity) based on square root transformed data. The initial data were represented by average percentage values corresponding to the Braun-Blanquet (1964) cover-abundance scale (Cristea et al., 2004): r (0.05%), + (0.5%), 1 (5%), 2 (17.5%), 3 (37.5%), 4 (62.5%), and 5 (87.5%).

The dendrogram was made in the GINKGO software (Bouxin, 2005), and the optimal number of clusters was identified based on the average Silhouette index (Rousseeuw, 1987). The synoptic table was obtained from the Juice program version 7.1 (Tichý, 2002).

The coenotaxonomic classification of plant communities is defined according to Chifu et al. (2014a, 2014b),

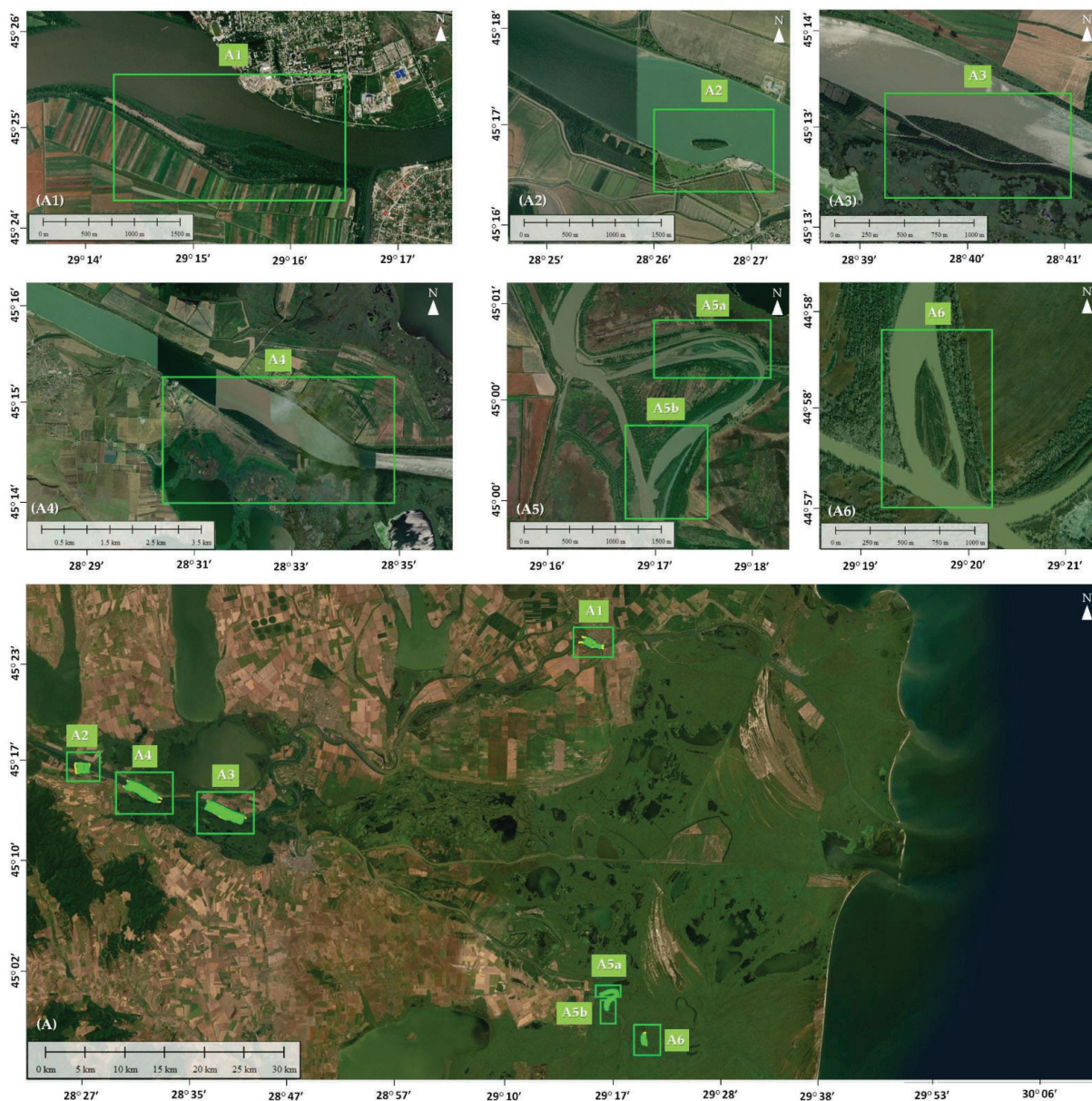


Figure 1: Study areas.

Slika 1: Preučavana območja.

Chifu & Irimia (2014). For each cluster, plant species were presented according to the phi-coefficient value (Chytrý et al. 2002; Tichý & Chytrý 2006). A fidelity threshold of $\phi = 0.4$ and Fisher's exact test ($p < 0.05$) were used.

The nomenclature of plant species followed Euro+Med (2024), and the nomenclature of associations followed Chifu et al. (2014a, 2014b), and Chifu & Irimia (2014). The nomenclature of higher syntaxa followed Mucina et al. (2016). Habitat types were classified using the EUNIS habitat classification expert system (Chytrý et al., 2020).

Hydrological measurements

In the study, bathymetric measurements were made using the SonTek RiverSurveyor M9 equipment, mounted on a HydroBoard II. The equipment uses acoustic pulses to determine water velocity, depth, flow, and riverbed elevations based on advanced technology. Multiple acoustic frequencies ensure accurate measurements at shallow and deep depths, even while moving. Data were collected on longitudinal and transverse sections at distances of 100–150 m and in critical areas at 50 m to obtain a detailed

representation of the riverbed profile. The equipment features GPS RTK for precise real-time positioning (± 3 cm), transmitting and correcting data via Bluetooth. The equipment's compass was calibrated to compensate for magnetic interference, and the sensors were positioned upstream of the boat's engine to avoid the influences of vibrations and propeller-generated currents (Sočuvka, 2024). For accuracy, additional topographic measurements were also performed using the Spectra Precision SP80 GPS and the LEICA NA 524 optical level to validate the water level. The collected data provides detailed information on the bathymetric profile, current velocity, and discharge of the riverbed's cross-sections, ensuring a general picture of the hydrological parameters of the studied area. Violin plots of hydrological factors were produced in R Statistical Software (v4.1.4; R Core Team 2024) via 'ggplot2' v.3.5.1 (Wickham, 2016).

Dynamics of some islands of the Danube River

The analysis of lower Danube River Island dynamics within this study is conducted through morphometric methods based on high-resolution remote sensing techniques. This approach allows for the precise quantification of changes, whether growth, erosion, or migration, through the detailed comparison of data from various periods. The Danube River islands within this study constitute a complex natural laboratory for the investigation of fluvial morphodynamic processes, reflecting the dynamic interaction between hydrological forces and sediment transport (Leopold & Wolman, 1957; Bondar et al., 1992; Church & Ferguson, 2015). The comparative analysis, utilizing morphometric methods with data derived from ANCPI orthophotoplans (2011 & 2021) and Airbus imagery (2006–2020), reveals a significant variability in their spatio-temporal evolution.

Results

In the plots made in the seven natural islands of the Danube Delta (20 relevés), 98 taxa were identified.

Habitats

Four EUNIS habitat types are represented in: T11 Temperate *Salix* and *Populus* riparian forest; V38 Dry perennial anthropogenic herbaceous vegetation; Q51 Tall-helophyte bed; and Q54 Inland saline or brackish helophyte.

Syntaxonomic overview of relevés

The analyzed vegetation is classified into four phytocoenological classes: *Artemisietea vulgaris*, *Lemnetea*, *Phrag-*

mito-Magnocaricetea, and *Salicetea purpureae*. In the seven natural islands analyzed, six associations and one sub-associations were identified, including dominant and characteristic species for each habitat.

Artemisietea vulgaris Lohmeyer et al. in Tx. ex von Rochow 1951

Agropyretalia intermedio-repentis T. Müller et Görs 1969

Convolvulo arvensis-Agropyron repens Görs 1967

Convolvulo-Agropyretum repens Felföldy 1943

Lemnetea O. de Bolòs et Masclans 1955

Lemnetalia minoris O. de Bolòs et Masclans 1955

Lemnion minoris O. de Bolòs et Masclans 1955

Lemno-Azolletum filiculoides Br.-Bl. 1952

Phragmito-Magnocaricetea Klika in Klika et Novák 1941

Oenanthetalia aquaticae Hejný ex Balátová-Tulácková et al. 1993

Eleocharito palustris-Sagittarion sagittifoliae Passarge 1964

Bolboschoenetum maritimi Eggler 1933

Phragmitetalia Koch 1926

Phragmiton communis Koch 1926

Glycerietum maximae Hueck 1931

Salicetea purpureae Moor 1958

Salicetalia purpureae Moor 1958

Salicion albae Soó 1951

Salicetum albae Issler 1926

amorphoetosum fruticosae Morariu et Danciu 1970

Rubro caesii-Salicetum albae Doniță et Dihoru 1961 em. Doniță et al. 1966

Cluster analysis

The data obtained from the cluster analysis were presented as a dendrogram (Figure 2) and a synoptic table (Table 1). The vegetation was grouped into seven clusters and assigned to different syntax groups described in the literature.

Cluster 1: *Salicetum albae amorphoetosum fruticosae*

Structure and composition of plant community:

Vegetation cover ranged from 42% to 67%, and the number of species/100 m² ranged from 10 to 25. *Amorpha fruticosa* had a cover of 37.5%, and *Salix alba* had a cover ranged from 0.5% to 17.5%. The floristic composition of this cluster was included in the class *Salicetea purpureae*, the order *Salicetalia purpureae*, characteristic of communities in floodplain areas, and the alliance *Salicion albae*. These relevés are part of the T11 habitat, according to the EUNIS classification.

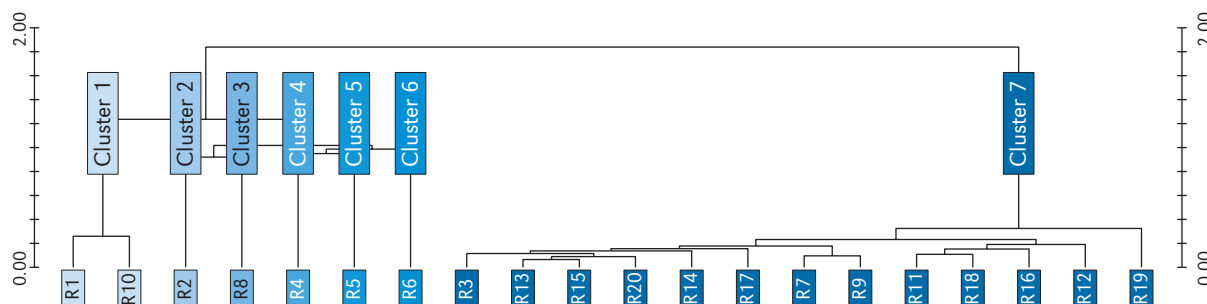


Figure 2: Dendrogram of vegetation data obtained from cluster analysis.

Slika 2: Dendrogram vegetacijskih podatkova, narejen s klasterno analizo.

Ecology: Average precipitation ranged from 26 mm in January to 57 mm in June, average temperatures ranged from -0.7°C in January to 22°C in July. These habitats thrive in conditions of high humidity and periodic flooding. The annual mean precipitation ranged from 443 to 493 mm, and the annual mean temperature was above 10.8°C .

Distribution: The two relevés included in this cluster, were distributed on two islands (A2 and A3) from Isaccea.

Cluster 2: *Convolvulo-Agropyretum repentis*

Structure and composition of plant community: The dominant species was *Elytrigia repens*, which had a cover of 62.5%. The vegetation cover was 73%, and the number of species/100 m² was 21. The vegetation belongs to the class *Artemisietea vulgaris*, the order *Agropyretalia intermedio-repentis*, and the alliance *Convolvulo arvensis-Agropyron repentis*, at the phytocoenological level. This relevé is part of the V38 habitat, according to the EUNIS classification.

Ecology: Average precipitation ranged from 26 mm in January to 57 mm in June, and average temperatures from -0.7°C in January to 22°C in July. Water level ranged from 2.8 m in spring, 2.7 m in summer, 3.3 m in autumn to 4.1 m in winter. Regarding flow measurements, it ranged from 6059 m³/s in spring, 5883 m³/s in summer, 7179 m³/s in autumn, to 7846 m³/s in winter. Regarding average water velocity, it ranged from 0.80 m/s in spring, 0.78 m/s in summer, 0.95 m/s in autumn, to 1.03 m/s in winter. Riverbed profiles ranged from -6.52 m in spring, -6.6 m in summer, -6.68 m in autumn to -6.5 m in winter.

Distribution: A relevé was included in this cluster, which was distributed on one island (A4) from Isaccea.

Cluster 3: *Rubus caesii-Salicetum albae*

Structure and composition of plant community: The dominant species was *Rubus caesius*, with a cover of 37.5%. The vegetation cover was 48%, and the number of species/100 m² was 21. The vegetation was classified within the class *Salicetea purpureae*, the order *Salicetalia*

purpureae, and the alliance *Salicion albae*. This relevé is part of the T11 habitat, according to the EUNIS classification.

Ecology: Average precipitation ranged from 26 mm in January to 57 mm in June, and average temperatures from -0.7°C in January to 22°C in July. Water level ranged from 2.8 m in spring, 2.7 m in summer, 3.3 m in autumn to 4.1 m in winter. Regarding flow measurements, it ranged from 6059 m³/s in spring, 5883 m³/s in summer, 7179 m³/s in autumn, to 7846 m³/s in winter. Regarding average water velocity, it ranged from 0.80 m/s in spring, 0.78 m/s in summer, 0.95 m/s in autumn, to 1.03 m/s in winter. Riverbed profiles ranged from -6.52 m in spring, -6.6 m in summer, -6.68 m in autumn to -6.5 m in winter.

Distribution: A relevé was included in this cluster, which was distributed on one island (A4) from Isaccea.

Cluster 4: *Bolboschoenetum maritimi*

Structure and composition of plant community: The dominant species is *Bolboschoenus maritimus*, which had a cover of 37.5%. Vegetation cover was 49%, and the number of species/100 m² was 23. The EUNIS habitat is Q54 Inland saline or brackish helophyte bed. The vegetation is part of the class *Phragmito-Magnocaricetea*, the order *Bolboschoenetalia maritimi*, and the alliance *Scirpion maritimi*.

Ecology: Average precipitation ranged from 26 mm in January to 57 mm in June, and average temperatures from -0.7°C in January to 22°C in July. Water level ranged from 2.8 m in spring, 2.7 m in summer, 3.3 m in autumn to 4.1 m in winter. Regarding flow measurements, it ranged from 6059 m³/s in spring, 5883 m³/s in summer, 7179 m³/s in autumn, to 7846 m³/s in winter. Regarding average water velocity, it ranged from 0.80 m/s in spring, 0.78 m/s in summer, 0.95 m/s in autumn, to 1.03 m/s in winter. Riverbed profiles ranged from -6.52 m in spring, -6.6 m in summer, -6.68 m in autumn to -6.5 m in winter.

Distribution: A relevé from one of the islands (A4) from Isaccea was included in this cluster.

Cluster 5: *Glycerietum maximae*

Structure and composition of plant community: *Glyceria maxima* was the dominant species and had a cover of 62.5%. Vegetation cover was 65%, and the number of species/100 m² was 5. The EUNIS habitat is Q51 Tall-helophyte bed. The vegetation belongs to the class *Phragmito-Magnocaricetea*, the order *Phragmitetalia*, and the alliance *Phragmition communis*.

Ecology: Average precipitation ranged from 26 mm in January to 57 mm in June, and average temperatures from -0.7 °C in January to 22 °C in July. Water level ranged from 2.8 m in spring, 2.7 m in summer, 3.3 m in autumn to 4.1 m in winter. Regarding flow measurements, it ranged from 6059 m³/s in spring, 5883 m³/s in summer, 7179 m³/s in autumn, to 7846 m³/s in winter. Regarding average water velocity, it ranged from 0.80 m/s in spring, 0.78 m/s in summer, 0.95 m/s in autumn, to 1.03 m/s in winter. Riverbed profiles ranged from -6.52 m in spring, -6.6 m in summer, -6.68 m in autumn to -6.5 m in winter.

Distribution: A relevé was included in this cluster found on one island (A4) from Isaccea.

Cluster 6: *Lemno-Azolletum filiculoides*

Structure and composition of plant community: *Azolla filiculoides* was the dominant species and had a cover of 37.5%. The vegetation cover was 39% and the number of species/100 m² was 3. The EUNIS habitat is C1.3 Permanent eutrophic lakes, ponds and pools. This relevé belongs to the class *Lemnetea*, the order *Lemnetalia minoris*, and the alliance *Lemnion minoris*.

Ecology: Average precipitation ranged from 26 mm in January to 57 mm in June, and average temperatures from -0.7 °C in January to 22 °C in July. Water level ranged from 2.8 m in spring, 2.7 m in summer, 3.3 m

in autumn to 4.1 m in winter. Regarding flow measurements, it ranged from 6059 m³/s in spring, 5883 m³/s in summer, 7179 m³/s in autumn, to 7846 m³/s in winter. Regarding average water velocity, it ranged from 0.80 m/s in spring, 0.78 m/s in summer, 0.95 m/s in autumn, to 1.03 m/s in winter. Riverbed profiles ranged from -6.52 m in spring, -6.6 m in summer, -6.68 m in autumn to -6.5 m in winter.

Distribution: A relevé was included in this cluster, which was distributed on one island (A4) from Isaccea.

Cluster 7: *Salicetum albae*

Structure and composition of plant community: Vegetation cover ranged from 41% to 60%, and the number of species/100 m² varied from 8 to 31. *Salix alba* had a cover of 37.5%. The vegetation corresponds to the class *Salicetea purpureae*, the order *Salicetalia purpureae*, and the alliance *Salicion albae*. These relevés are part of the T11 habitat, according to the EUNIS classification.

Ecology: Average precipitation ranged from 23 mm in January to 49 mm in June, and average temperatures from 0.2 °C in January to 22 °C in July. Water level ranged from 2.1 m in spring, 2.07 m in summer, 2.7 m in autumn to 3.3 m in winter. Regarding flow measurements, it ranged from 4116 m³/s in spring, 3978 m³/s in summer, 4996 m³/s in autumn, to 5568 m³/s in winter. Regarding average water velocity, it ranged from 0.68 m/s in spring, 0.65 m/s in summer, 0.87 m/s in autumn, to 1.00 m/s in winter. Riverbed profiles ranged from -5.27 m in spring, -5.33 m in summer, -5.28 m in autumn to -6.5 m in winter.

Distribution: In this cluster, 13 relevés were included, distributed in Isaccea (A4), Chilia (A1) and Sf. Gheorghe (A5a, A5b, and A6).

Table 1: Synoptic table of the percentage frequencies of plant species in the analyzed communities.

Tabela 1: Sinoptična tabela preučevanih združb in pogostosti rastlinskih vrst v odstotkih.

No. cluster	Phi	1	2	3	4	5	6	7
No. relevés		2	1	1	1	1	1	13
Cluster 1: <i>Salicetum albae: amorphoetosum fruticosae</i>								
<i>Brachypodium sylvaticum</i> (Huds.) P. Beauv.	0.688	50	.	.	.	.	.	.
<i>Digitaria sanguinalis</i> (L.) Scop.	0.688	50	.	.	.	.	.	.
<i>Fumaria officinalis</i> L.	0.688	50	.	.	.	.	.	.
<i>Helianthemum nummularium</i> (L.) Mill.	0.688	50	.	.	.	.	.	.
<i>Aristolochia clematitis</i> L.	0.577	100	100	.	.	.	.	15
<i>Vitis vinifera</i> L.	0.454	100	100	100	.	.	.	23
<i>Fraxinus pennsylvanica</i> Marshall	0.444	50	100	.	.	.	.	.
<i>Glechoma hederacea</i> L.	0.444	50	.	.	.	.	.	8
<i>Potentilla reptans</i> L.	0.444	50	.	.	.	.	.	8
Cluster 2: <i>Convolvulo-Agropyretum repentis</i>								
<i>Urtica dioica</i> L.	0.793	.	100	100	.	.	.	8

No. cluster	Phi	1	2	3	4	5	6	7
No. relevés		2	1	1	1	1	1	13
<i>Dactylis glomerata</i> L.	0.688	.	100	.	.	.	.	.
<i>Drymochloa sylvatica</i> (Pollich) Holub	0.688	.	100	.	.	.	.	.
<i>Elytrigia repens</i> (L.) Nevski	0.688	.	100	.	.	.	.	.
<i>Hordeum murinum</i> L.	0.688	.	100	.	.	.	.	.
<i>Lolium perenne</i> L.	0.688	.	100	.	.	.	.	.
<i>Potentilla recta</i> L.	0.688	.	100	.	.	.	.	.
<i>Fraxinus angustifolia</i> Vahl	0.577	50	100	100	.	.	.	15
<i>Acer negundo</i> L.	0.509	50	100	100	.	.	.	23
<i>Cirsium arvense</i> (L.) Scop.	0.454	50	100	100	100	.	.	23
<i>Sonchus asper</i> (L.) Hill	0.454	50	100	100	.	.	.	31
<i>Vitis vinifera</i> L.	0.454	100	100	100	.	.	.	23
<i>Agrostis capillaris</i> L.	0.444	.	100	.	.	.	.	8
<i>Bromus hordeaceus</i> L.	0.444	.	100	.	.	.	.	8
<i>Fraxinus pennsylvanica</i> Marshall	0.444	50	100	.	.	.	.	.
Cluster 3: <i>Rubio caesii-Salicetum albae</i>								
<i>Chenopodium album</i> L.	0.577	.	.	100	.	.	.	31
Cluster 4: <i>Bolboschoenetum maritimi</i>								
<i>Bolboschoenus maritimus</i> (L.) Palla	1.000	.	.	.	100	.	.	.
<i>Carduus acanthoides</i> L.	1.000	.	.	.	100	.	.	.
<i>Carex elata</i> All.	1.000	.	.	.	100	.	.	.
<i>Phalaroides arundinacea</i> (L.) Rauschert	1.000	.	.	.	100	.	.	.
<i>Polygonum aviculare</i> L.	1.000	.	.	.	100	.	.	.
<i>Rorippa austriaca</i> (Crantz) Besser	1.000	.	.	.	100	.	.	.
<i>Althaea officinalis</i> L.	0.688	.	.	.	100	.	.	8
<i>Convolvulus arvensis</i> L.	0.688	.	.	.	100	.	.	8
<i>Myosotis scorpioides</i> L.	0.546	.	.	.	100	.	.	15
<i>Plantago major</i> L.	0.546	.	.	100	100	.	.	8
Cluster 5: <i>Glycerietum maximae</i>								
<i>Azolla filiculoides</i> Lam.	0.459	.	.	.	100	100	100	8
<i>Glyceria maxima</i> (Hartm.) Holmb.	0.459	.	.	.	100	100	.	15
Cluster 6: <i>Lemno-Azolletum filiculoides</i>								
<i>Potamogeton natans</i> L.	1.000	.	.	.	.	.	100	.
<i>Azolla filiculoides</i> Lam.	0.459	.	.	.	100	100	100	8
Cluster 7: <i>Salicetum albae</i>								
<i>Phragmites australis</i> (Cav.) Steud.	0.798	.	.	.	100	.	.	62
<i>Stachys palustris</i> L.	0.698	50	.	.	.	.	.	54
<i>Calamagrostis arundinacea</i> (L.) Roth	0.638	.	.	.	.	.	.	38
<i>Salix cinerea</i> L.	0.638	.	.	.	.	.	.	38
<i>Solanum dulcamara</i> L.	0.596	50	.	100	.	.	.	85
<i>Jacobaea paludosa</i> (L.) G. Gaertn. & al.	0.553	.	.	.	.	.	.	31
<i>Populus alba</i> L.	0.553	.	.	.	.	.	.	31
<i>Sium latifolium</i> L.	0.553	.	.	.	.	.	.	31
<i>Typha angustifolia</i> L.	0.553	.	.	.	.	.	.	31
<i>Symphytum officinale</i> L.	0.504	50	.	.	.	.	.	38
<i>Alisma plantago-aquatica</i> L.	0.464	.	.	.	.	.	.	23
<i>Lemna minor</i> L.	0.464	.	.	.	.	.	.	23
<i>Lemna minuta</i> Kunth	0.464	.	.	.	.	.	.	23
<i>Lycopus europaeus</i> L.	0.414	50	.	.	100	.	.	69

Hydrological analysis

Water level (Figure 3; Table 2). The water level measured at different points showed significant seasonal fluctuations. At Isaccea, levels remained relatively stable in spring and summer (approximately 2.86 m in spring and 2.73 m in summer). However, it increased considerably in autumn and winter, reaching 4.12 m in winter. The same trend was observed at locations such as Dunavăț and Dranov, where winter values were higher than summer values (for example, at Dranov, the water level increased from 0.87 m in summer to 2.00 m in winter).

Water velocity (Figure 3; Table 2). The water velocity had prevailing values between 0.3 and 0.9 m/s throughout the year, suggesting a consistency in moderate flow areas. The highest velocities were recorded in autumn and winter, reflecting the water accumulations in these periods. At Isaccea, the water velocity increased constantly throughout the year, from spring to winter, which indicates an intensification of the water flow, especially during the rainy season and snowmelt. Thus, at Isaccea, the water velocity was 0.68 m/s in spring, decreased slightly in summer to 0.66 m/s, but showed a significant increase

in autumn (0.81 m/s) and reached 0.88 m/s in winter. In Dunavăț and Dranov, the water velocity was lower but followed the same trend. At Dranov, the water velocity increased from 0.13 m/s in summer to 0.27 m/s in winter.

Flow measurements (Figure 3; Table 2). At Isaccea, the water flow was 6052 m³/s in spring and decreased slightly in summer to 5876 m³/s. It increased considerably in autumn (7171 m³/s) and reached a maximum of 7859 m³/s in winter. At Dranov, the flow was significantly lower but followed a similar trend, increasing from 508 m³/s in summer to 1089 m³/s in winter.

Riverbed profiles (Figure 3; Table 2). Bathymetric measurements indicate the elevation of the riverbed, helping to assess changes in its structure. At Isaccea, Dunavăț, and Dranov, the values were relatively constant throughout the year, with slight variations, suggesting the stability of the riverbed in these areas. At Isaccea, the depth of the riverbed varied very little from -6.52 m in spring to -6.50 m in winter, indicating sediment accumulation. At Dranov, the values showed a linear trend, ranging from -3.87 m in spring to -3.99 m in winter. The intermediate range remained relatively constant in all seasons, varying very little between -3.87 and -3.99 m.

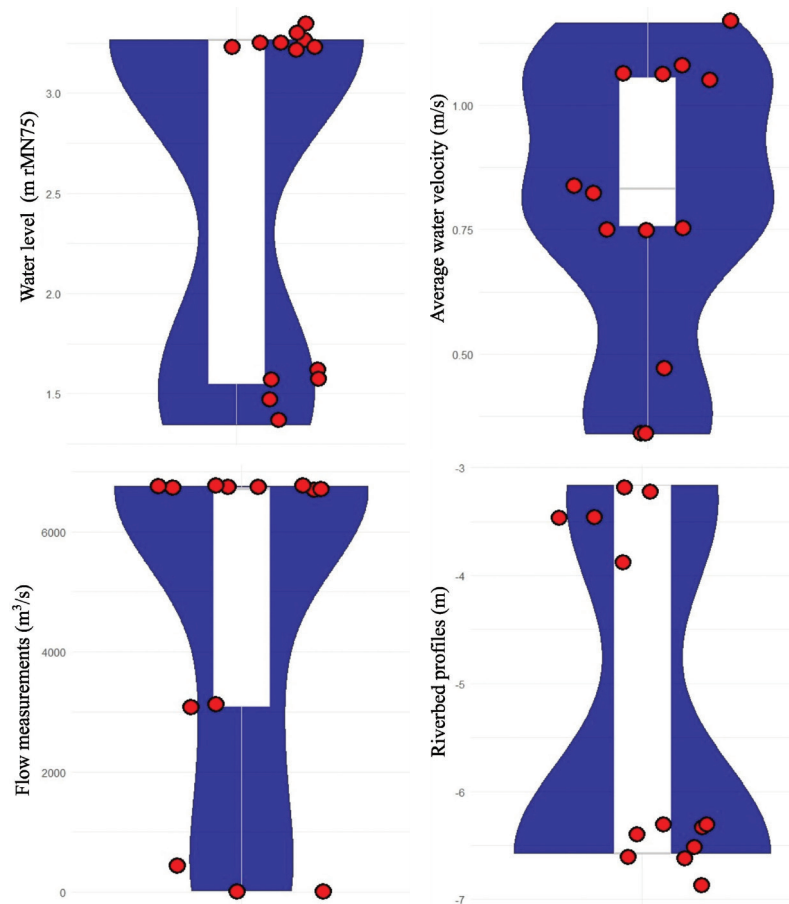


Figure 3: Variation of hydrological measurements in the analyzed areas.

Slika 3: Variacija hidroloških meritev na preučevanih območjih.

Table 2: Results of hydrological measurements.

Tabela 2: Rezultati hidroloških meritev.

	Location	Spring	Summer	Autumn	Winter
Water level measured in the field (m rMN75)	Isaccea	2.86	2.73	3.36	4.12
		2.86	2.73	3.36	4.12
		2.86	2.73	3.36	4.12
	Dunavăț	1.17	1.07	1.74	2.23
		1.17	1.07	1.74	2.23
		1.17	1.07	1.74	2.23
		1.17	1.07	1.74	2.23
		1.17	1.07	1.74	2.23
		1.17	1.07	1.74	2.23
		1.17	1.07	1.74	2.23
	Dranov	0.97	0.87	1.54	2.00
		0.97	0.87	1.54	2.00
		0.97	0.87	1.54	2.00
		0.97	0.87	1.54	2.00
		0.97	0.87	1.54	2.00
Flow measurements (m ³ /s)	Isaccea	6052	5876	7171	7859
		6034	5858	7149	7793
		6083	5906	7207	7867
	Dunavăț	17	16	26	32
		10	9	15	19
		15	14	23	29
		18	17	27	35
		16	15	24	31
		2314	2143	3463	4438
		2355	2181	3524	4517
	Dranov	574	508	825	1089
		356	315	517	637
		344	304	498	612
		368	326	537	662
		23	20	33	37
Average water velocity (m/s)	Isaccea	0.68	0.66	0.81	0.88
		0.75	0.73	0.89	0.96
		0.95	0.92	1.13	1.22
	Dunavăț	0.36	0.34	0.55	0.67
		0.32	0.3	0.49	0.62
		0.19	0.18	0.29	0.37
		0.29	0.27	0.43	0.55
		0.11	0.1	0.16	0.21
		0.81	0.75	1.21	1.55
		0.87	0.81	1.31	1.67
	Dranov	0.14	0.13	0.2	0.27
		0.47	0.43	0.69	0.85
		0.51	0.46	0.75	0.91
		0.49	0.45	0.73	0.89
		0.22	0.20	0.32	0.36
Riverbed profiles (m)	Isaccea	-6.52	-6.60	-6.68	-6.50
	Dunavăț	-3.12	-3.15	-3.19	-3.19
	Dranov	-3.87	-3.99	-3.95	-3.97

Dynamics of the Lower Danube islands

The Danube Delta, a dynamic fluvial-marine environment, showcases a complex interplay of erosion and accumulation, influencing the morphology of its numerous islands. An analysis of seven islands, reveals distinct patterns of sediment redistribution. Particularly, all islands exhibit a net positive accumulation, a testament to the delta's robust depositional regime. However, the magnitude of this accumulation varies significantly, highlighting the influence of local hydrodynamics and island positioning.

The recent emergence of A5a and A5b islands, around 2010, along with the substantial accumulation observed in A1, A2, and A3, suggests a modification of this regime, most likely associated with a significant change in the am-

plitude of the water level and river discharge (Figure 4). Principally, decreases in flow promote rapid sediment deposition. These hydrological events favored rapid sediment accumulation, leading to the formation and expansion of the islands. In this respect, island A5a demonstrated a spectacular area increase, from 3.64 to 18 ha in 10 years, surpassing the expansion rate of island A5b (Figure 4), while A4 demonstrates a dual pattern of erosion and sedimentation. This pronounced accumulation may be attributed to its location within the rectified Perivolovca meander, where altered flow dynamics promote enhanced sediment deposition. In contrast, A2 exhibits the lowest accumulation, only 0.28 ha, concentrated on its right bank, shielded from the direct river discharge. This island, however, experiences 0.88 ha of erosion on its left bank, facing the primary river flow, illustrating a localized disparity in morphometric processes. A1, initially showing

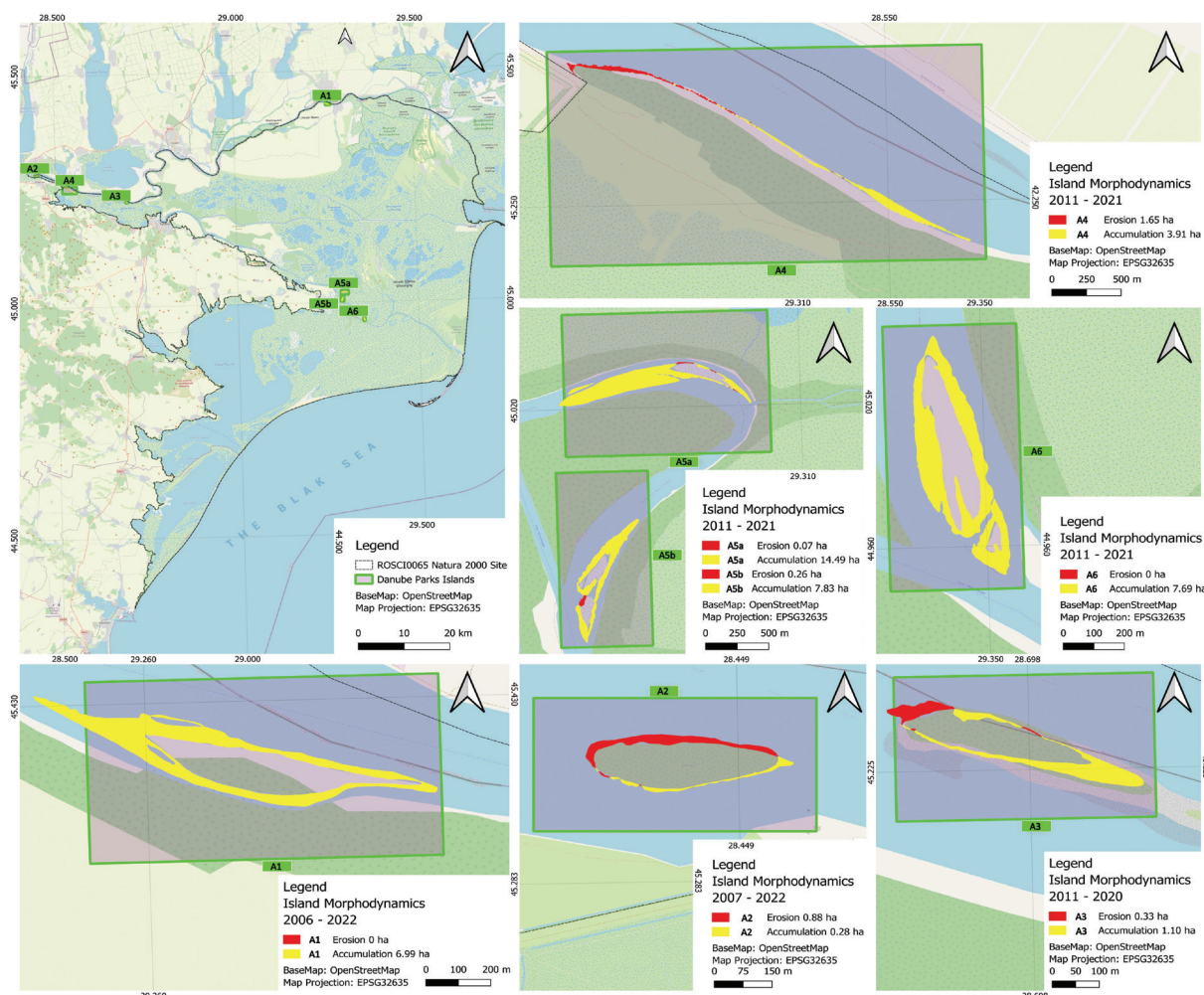


Figure 4: The location of the study's islands along the lower Danube River – islands morphodynamics.

Slika 4: Lokacija preučevanih otokov ob spodnjem teku reke Donave – morfodinamika otokov.

exclusive accumulation, has since migrated and become a definitive part of the Danube's right bank. A2 and A3 display both erosion and accumulation, with accumulation exceeding erosion. This variability highlights the local influences of flow conditions and sediment availability.

The tendencies of sedimentation and stabilization are observable in the advancement of islands A5a and A5b toward the river banks, and in the land-tied evolution of islands A4 and A1 to the Danube's right bank. A5b, also located within the rectified Perivolovca meander, demonstrates a significant accumulation of 7.83 ha, further supporting the fact that meander rectification can amplify sediment deposition. A6, situated in the rectified Dranov 1 meander, displays a similar trend, with 7.69 ha of accumulation and no recorded erosion, reinforcing the influence of altered channel geometry on sediment dynamics.

Although less widespread than accumulation, erosion remains a noteworthy factor. The dual dynamics, characterized by upstream erosion, where river erosion is strongest, and downstream sedimentation, as observed in island A4. Thus, the first half of island A4 was eroded of 1.65 ha in its upstream over 10 years, while the downstream half exhibited emergent zones totaling 3.9 ha within the same period (Figure 4). Conversely, A5a registers minimal erosion, a mere 0.07 ha. A3 and A2 show intermediate erosion values, 0.33 and 0.88 ha respectively, indicating localized erosion patterns influenced by their position relative to the river's flow. A5b displays 0.26 ha of erosion. A1 and A6 register zero erosion. The varied sedimentation rates, again, evidenced by the spectacular area growth of island A5a, suggest an intense sediment transport dynamic by the river, exceeding the expansion rate of island A5b.

Furthermore, the land-tied evolution observed in A1 and A4 underscores the dynamic nature of island development. A1, exhibiting 6.99 ha of accumulation, is undergoing land-tied evolution towards the right bank, indicating a process of gradual connection to the mainland. Similarly, A4, with 3.91 ha of accumulation in its downstream segment, displays land-tied evolution towards the right bank and underwent significant changes along its left bank at fluctuating rates being exposed to the river's discharge. These processes are indicative of the delta's continuous shaping by sedimentary processes. The predominant upstream extension of island A5a indicates progressive sedimentation of the Perivolovca meander, while lateral extension and bank land-tied evolution, observed in island A5b, reflect lateral deposition processes (Figure 4).

Discussions

The Danube Delta is a dynamic territory and complex of ecosystems with an area of approximately 5,800 km² (Hanganu et al., 2017). It is located at the confluence of the Danube River and the Black Sea, which gives it a special ecological importance (Catianis et al., 2016).

Vegetation analysis

In the analysed islands, the communities of *Salix alba* and *Amorpha fruticosa* predominate. According to Sitzia et al. (2018), *S. alba* has an important role in the ecology of the Danube Delta. Thus, through its root structure, *S. alba* can increase soil resistance and provide additional support through bioengineered structures (Zhang et al., 2013). At the same time, it has been shown that at high phosphorus concentrations (Hryniewicz et al., 2015), a decrease in ectomycorrhizal colonization of *Salix viminalis* and *Betula pendula* seedlings was recorded. In contrast, *Amorpha fruticosa* can fix nitrogen and enrich the soil with nitrogen compounds, which causes changes in natural habitat conditions (Gudžinskas & Žalneravičius, 2015). This species also has significant regeneration ability (Avramidou et al., 2023) and is a threat to native ecosystems (Nagy et al., 2018).

Riparian vegetation is strongly influenced by hydrological factors (Dijk et al., 2013; James et al., 2016; Zhu et al., 2017) along river systems. Variation in flow patterns and water depth influences seed distribution, which can affect vegetation stability (Dijk et al., 2013; Zhu et al., 2017). Also, topographic factors and landscape structure control the hydrological response, which will subsequently shape the spatial distribution and diversity of riparian vegetation (Jencso & McGlynn, 2011; Hwang et al., 2012).

Hydrological analysis

In the study, the data obtained showed a significant seasonal fluctuation of the water level, with minimum values in summer and spring, and maximum values in autumn and winter. These values are comparable with the data in the literature (Romanescu, 2014; Trifanov et al., 2019), which show that precipitation and anthropogenic processes influence the water levels in the Danube Delta. In this context, the variations recorded in this study confirm the characteristic hydrological dynamics of the Delta, being highlighted by seasonal water accumulations. Regarding the water velocity, the data from this study showed an increase in the water velocity in autumn and winter. These

results are consistent with the observations in the literature (Pekárová et al., 2019; Crețescu et al., 2021) which show that snowmelt and intense precipitation upstream contribute to the variation of natural factors. Moreover, constant and moderate velocities in the other seasons indicate hydrological stability, in which the redistribution of the flow between the Chilia, Sulina, and Sf. Gheorghe arms influences the water flow regime (Pekárová et al., 2019). In the case of water flow, a significant increase was observed in winter.

According to the literature (Pekárová et al., 2019; Crețescu et al., 2021), the Danube acts as a major water collector, in which the discharges are influenced by climatic conditions and flows from upstream countries. At the same time, our study indicates a significant correlation between flow and water velocity during periods of maximum water accumulation. The data obtained for riverbed profiles showed the stability of the riverbed, with minimal variations in depth. According to the literature (Romanescu, 2014; Bănescu et al., 2020), the stability of the riverbed profile is the result of geomorphological processes. In this context, our results confirm that the riverbed is stable and characterized by reduced erosion processes.

Dynamics of the Lower Danube islands

The observed morphogenetic processes are closely linked to the Danube's hydrological regime (Leopold & Maddock, 1953; Bondar, 1992). The intensified dynamics of these sediments are evidenced by considerable changes in shape and area, reflecting their sensitivity to hydrological fluctuations (Knighton, 1998; Gordon et al., 2004). With this sediment accumulation, the rapid colonization of emergent vegetation plays a vital role in soil stabilization, contributing to sediment fixation and the consolidation of island morphology (Bondar, 1992). The dual dynamics, characterized by upstream erosion, reflect a dynamic and unstable morphological equilibrium, influenced by local variations in current and sediment distribution patterns (Panin, 1996). The direction of island A4 expansion is controlled by the complex interaction between water level, velocity, and current direction (Knighton, 1998).

The morphodynamic analysis of the Danube Delta's islands show the important role of the hydrological regime in shaping this complex ecosystem, highlighting the river's capacity to induce rapid transformations through sedimentation and erosion processes. The comparative study, utilizing geomorphological methods and

remote sensing, has indicated the complex interactions among hydrological, sedimentary, and vegetative factors, offering a detailed perspective on the riverbed including island's morphological evolution. The data obtained through morphometric analysis signals the necessity for sustainable management, which takes into account the river's natural dynamics and the potential impact of climate change. Finally, the remarkable intensity of morphodynamic processes, manifested by accelerated rates of sedimentation, erosion, and island shape modification, underscores the highly dynamic nature of the Danube River, where even minor hydrological fluctuations can generate significant morphological transformations within a short timeframe (Bondar et al., 1992; Church & Ferguson, 2015).

Conclusions

Seasonal fluctuations of hydrological factors highlight the influence of natural factors and anthropogenic interventions on the hydrological regime. Also, the stability of the riverbed profile indicates a local geomorphological balance.

From a phytocoenological perspective, six associations and one subassociations were identified, included in four classes: *Artemisietea vulgaris*, *Lemnetea*, *Phragmito-Mag-nocaricetea*, and *Salicetea purpureae*.

The morphodynamic analysis of the islands in this study highlights the complexity and dynamics of fluvial processes. The comparative study, utilizing geomorphological methods and remote sensing, provides valuable information for understanding the Danube riverbed morphological evolution and for the sustainable management of its complex ecosystem. The morphometric analysis of these seven Danube Delta islands reveals a complex interplay of erosion and accumulation, influenced by factors such as island location, river flow dynamics, and human interventions like meander rectification.

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