A Topo-Bathymetric Data Integration Approach to Study the Dynamics in the Danube Delta

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Abstract

Accurate acquisition of topographic data at the land-water interface is a fundamental step in bridging the gap between terrestrial and hydrographic datasets. In the complex fluvial environment of the Danube Delta, achieving a unitary representation of the riverine relief is hindered by dynamic morphological features and significant water-level fluctuations. This study presents a robust methodological framework for seamlessly integrating high-precision GNSS terrestrial measurements with bathymetric data to generate continuous topobathymetric cross-sections. The terrestrial component involved surveying the riverbanks and the immediate shoreline interface using professional-grade GNSS technology. Trimble geodetic receivers (R980, R12, and R4 models) were utilized in Real-Time Kinematic (RTK) mode, connected to the ROMPOS Romanian Permanent Stations Network. This setup ensured high-accuracy coordinates, directly referenced to the national geodetic systems. To ensure data integrity, a rigorous observation protocol was implemented, consisting of three measurement sessions per point, with extended sampling in areas of suboptimal satellite geometry. Concurrently, bathymetric measurements were carried out to determine water depths along predefined profiles, and an ADCP system was used to measure high-accuracy 3D velocities and discharges using the Doppler effect. The most important step of this research involves harmonizing these distinct datasets. Measured depths were converted into topographic elevations by referencing them to the land-water interface elevation captured during the GPS survey. This transformation facilitates the unification of submerged riverbed data with emergent bank topography into a single, coherent coordinate system (STEREO '70 and the Black Sea 1975 Vertical Datum). The resulting integrated topobathymetric profiles provide a comprehensive, high-resolution visualization of the Danube's cross-sectional morphology. This integrated geospatial approach not only ensures a coherent and continuous representation of the land–water interface, but also significantly enhances the understanding of complex fluvial processes. Accurately correlating topographic and bathymetric data enables a detailed analysis of riverbed morphological evolution and the interactions between flow dynamics, sediment transport, and terrain configuration. Consequently, the proposed methodology becomes a valuable tool for applied research and for implementing effective strategies aimed at the conservation and sustainable management of ecosystems within the Danube Delta.

Keywords: *Topo-bathymetric integration, riverbed morphology, GPS RTK surveying, Digital Terrain Model, Danube Delta*

1. Introduction

The genetic processes of a watercourse bed are the determining factors in the evolution and dynamics of its geometry, resulting from the interplay among active and passive natural factors [1]. In addition to the control exerted by natural factors, the influence of anthropogenic drivers is significant and cannot be overlooked. Over the past centuries, numerous rivers worldwide have been subjected to varying levels of human intervention, leading to substantial alterations in their hydromorphological regimes [2, 3]. Channel dynamics and sediment transport processes are fundamental elements in the evolution of fluvial systems, governing both channel morphology and the hydrodynamic flow regime [3-7]. Morphological changes within the riverbed significantly influence flood wave propagation and the extent of inundation areas [8], highlighting the importance of integrating geomorphological processes into hydraulic studies. In the case of the Danube River, anthropogenic interventions, particularly dam construction, have induced sediment imbalances and major changes in fluvial morphodynamical processes [3, 9]. Over the past two decades, high-resolution surveying technologies have been increasingly employed in fluvial geomorphology to accurately characterize both instream bathymetry and floodplain topography [10]. Watercourse mapping and related activities primarily aim to provide an accurate representation of the terrain within the surveyed area, ensuring that the resulting maps capture all significant features and provide sufficient geometric accuracy. To achieve the highest possible accuracy in mapping, particular attention must be given to the requirements of cartographic documentation during both field data acquisition and subsequent data processing [11]. This study proposes a rigorous methodological approach for the coherent integration of high-precision GNSS terrestrial measurements with bathymetric data, aiming to generate a continuous topobathymetric transverse profile. This integrated geospatial approach contributes not only to obtaining a continuous and seamless representation of the land-water interface but also to a profound understanding of the complex fluvial processes. The integration of topographic and bathymetric data facilitates a detailed analysis of the morphological evolution of the riverbed. By conducting repeated surveys of river reaches along cross-sections, it is possible to delineate spatial patterns of erosion and deposition and quantify volumetric changes, including both erosion and sediment infilling. When multiple

successive DEMs are available for the same river sector, differential analysis can be performed to quantify changes between them. The resulting outputs, typically generated using GIS software, enable the identification of zones affected by erosion and deposition [12]. Furthermore, the resulting digital models constitute an essential framework for hydrodynamic simulations and for informing decision-making in water resource management. Consequently, the proposed methodology stands out as a valuable tool in both applied research and the development of effective strategies for the conservation and sustainable management of deltaic ecosystems.

2. Materials, methods, and results

This paper examines two study areas: the first is the Mahmudia meander (Old Danube) on the Saint George branch, and the second is the Ceatal Sfântu Gheorghe bifurcation. At this point, the Danube divides into two branches: the Sulina Channel to the east and the Saint George branch to the south. Both locations are illustrated in Fig. 1.

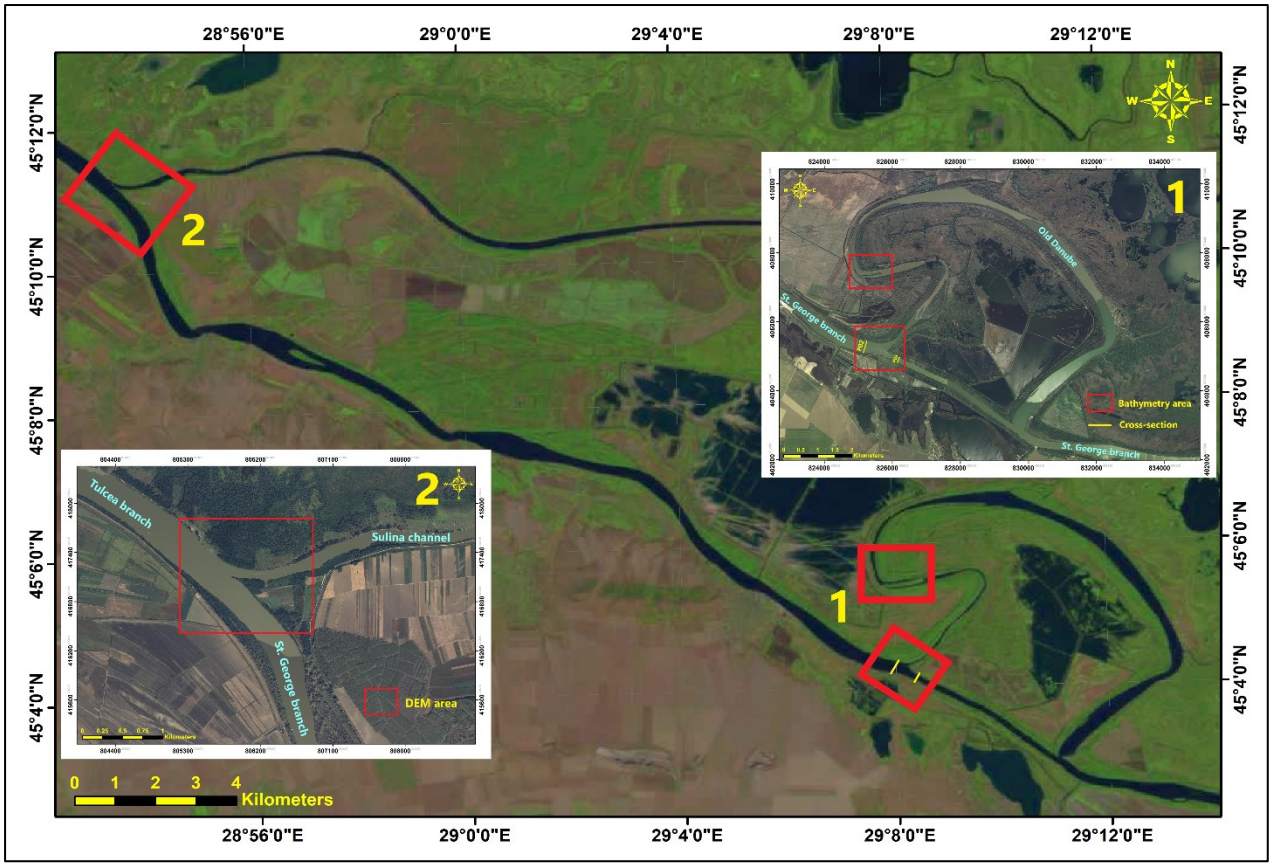

Fig. 1. Integrated bathymetric and topographic data within a cross-section located upstream of Mahmudia meander

2.1 Materials and Methods

Topographic surveys were conducted by determining topographic points with coordinates (X, Y) in the National Planimetric System STEREO 1970 and elevations (Z) in the National Altimetric System, Black Sea 1975 – Constanța. For each measured topographic point, three 5-second measurement sessions were performed. When accuracy was lower, more than three sessions were conducted. Topographic measurements at the land–water interface provide terrain elevation values required for processing both bathymetric cross-sections and ADCP-derived data. These measurements also ensure the bathymetric profile continues into the terrestrial zone. This result, the topobathymetric profile, represents the elevations of the minor channel and integrates seamlessly with those of the floodplain in the same National Altimetric System (Black Sea 1975 – Constanța). High-performance GPS systems equipped with geodetic-grade receivers (TRIMBLE R980, R12, and R4) were used to acquire raw field data. The GPS receivers were connected via the internet to the nearest permanent GNSS station within the ROMPOS network. Corrected data streams from the network enabled differential corrections of the measured points. The actual measurements consisted of acquiring topographic points along the land–water boundary. GPS measurements are typically carried out using two main methods: static and kinematic. Each has multiple variants, depending on equipment and conditions. In this study, the kinematic method was used. Coordinates were obtained in real time using RTK (Real-Time Kinematic) technology. This enabled immediate access to field data for detailed point determination. The technology also enables on-site verification of known topographic control points. At the beginning and throughout the survey campaigns, accuracy verification procedures were conducted using benchmarks from the National Geodetic Network and benchmarks from the Lower Danube River Administration (AFDJ). For these checks, one geodetic benchmark from the National Geodetic Network located in the Mahmudia area and another benchmark from the AFDJ network, situated along the Danube bank near Sfântu Gheorghe, were used. Multiple verification measurements were performed on each benchmark, and the results fell within the accepted tolerances for both coordinates and elevations. To investigate channel dynamics, a series of hydrometric cross-sectional profiles was carried out along the Mahmudia meander. Discharge, flow velocity, and current structure were measured using an ADCP RiverRay system. The profiles were positioned in key sectors, including bifurcation, confluence, and apex zones, to determine the distribution of water and sediment fluxes between the artificial cutoff channel and the natural channel. This approach allows comparative analysis of channels across different sectors of the Danube while maintaining identical precision standards and reference systems. In addition to cross-sectional profiles, a dense bathymetric survey was performed with a parallel

lines network with an equidistance of 50 m. Processing these datasets with GIS software generated a Digital Elevation Model (DEM), which serves as a critical tool for spatial visualization of channel morphology and three-dimensional analysis of sediment dynamics in the study area. Bathymetric measurements were conducted using the CEEDUCER™ Legacy Single Beam Hydrographic Echo Sounder system, which operates at 200 kHz, provides a resolution of 1.0 cm, and achieves an accuracy of 0.01 m ± 0.1% of depth. Compared to traditional approaches that treat the two types of data separately, the methodology yields a much more realistic representation of cross-sections. The topo-bathymetric profiles provide a detailed representation of the morphological variability of the fluvial channel within the analyzed sectors. The results highlight a smooth transition between the dry land area and the submerged zone, without breaks or altimetric inconsistencies (Fig. 2).

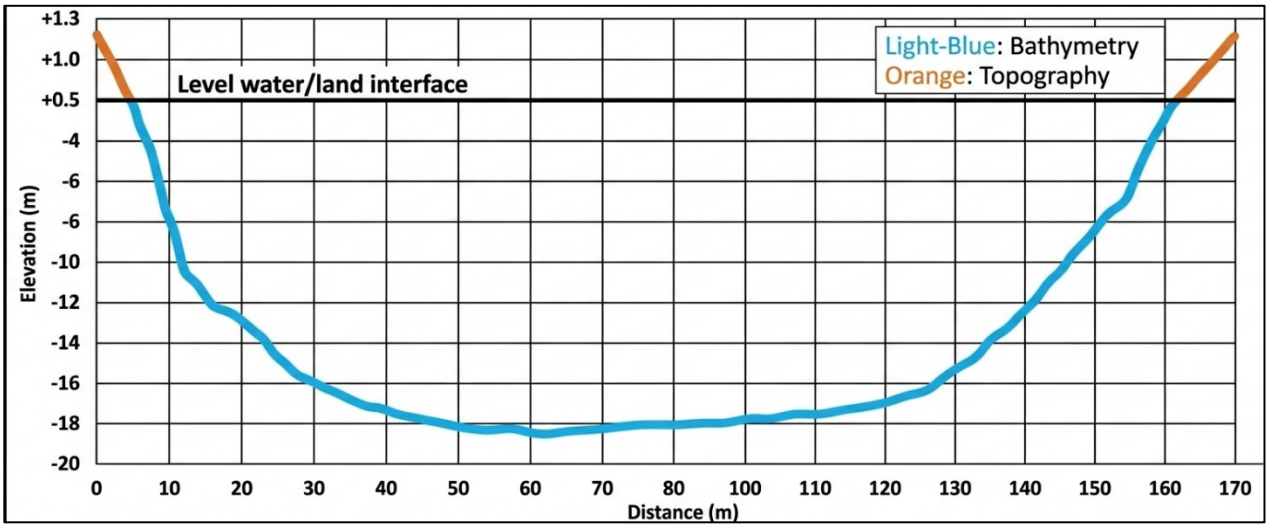

Fig. 2. Integrated bathymetric and topographic data within a cross-section located upstream of Mahmudia meander

2.2 Results

The resulting topo-bathymetric profiles provide a detailed view of morphological variability in the Danube riverbed within the analyzed sector. To clarify these findings, the next section presents results regarding morphological changes in several cross-sections of the Saint George branch, focusing on the periods June–September 2025 and July–November 2025. Specifically, the changes occurring in the riverbed at the cross-section located near the diffluence between the natural and artificial channels at the entrance to the Mahmudia meander are shown below.

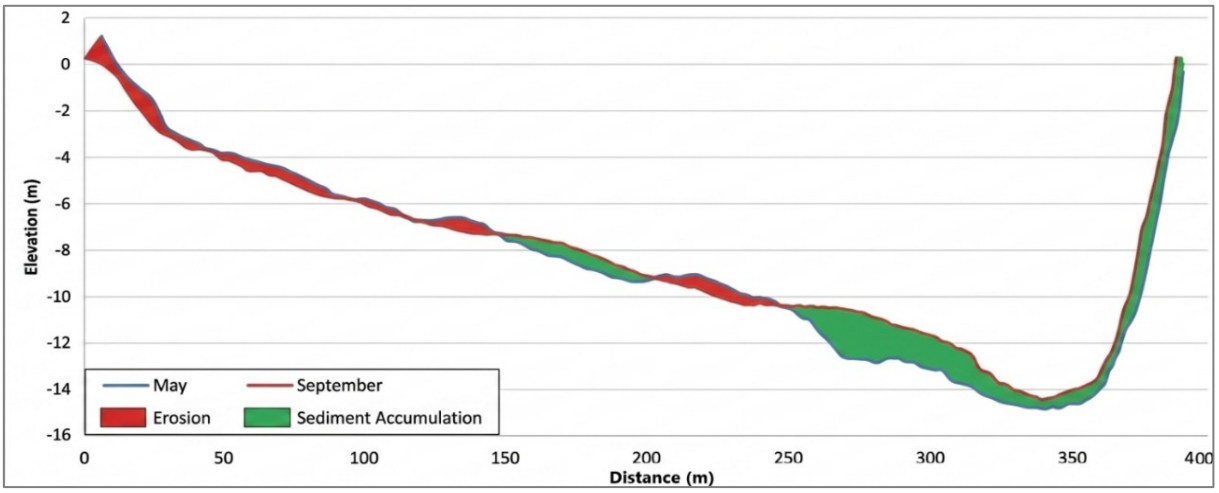

Fig. 3. Temporal changes of the topo-bathymetrical profile with erosion and deposition areas – Mahmudia meander at the bifurcation, P02

The analyzed cross-section reveals an active fluvial dynamic, characterized by a clear asymmetry toward the right bank. The left bank exhibits a gentle but continuous slope over a distance exceeding 200 m, which, during the analyzed period, underwent mixed but predominantly erosional processes. The right bank is markedly steep, indicating that the zone of maximum flow energy is located in its proximity. The thalweg is also situated in this area, approximately 40 m from the right bank. From the perspective of erosion and sediment deposition processes, morphological changes occurred in this section during June–September 2025. Continuous erosion is observed along the slope of the left bank over a distance of approximately 120 m, as well as in a smaller sector in the central part of the section. This suggests channel deepening, likely due to increased flow velocity in this part of the cross-section, which entrained the existing sediment. Sediment accumulation is present in two sectors: one in the central-left area and another on the right side of the section. On the right bank, significant changes are observed, with the deposition of a 2 m-thick sediment layer in certain sectors during the analyzed period. This deposition suggests a decrease in flow energy in that area or a migration of the main current toward the center. In conclusion, the comparison of the two profiles indicates that, although the cross-section remains asymmetrical, the channel tends to undergo sediment infilling in the thalweg and erosion along the left bank's gentler slope. Furthermore, sediment

accumulation appears to be the dominant process in this section. Following the analysis of sediment dynamics in the bifurcation zone, where the interaction between the natural and artificial branches dictates the initial distribution of flows, a cross-section analysis was conducted along the artificial cutoff channel. This was intended to assess how channel geometry and the new flow distribution influence local erosion and deposition. Thus, the morphological changes that occurred during the June–September 2025 period are presented for the cross-section located on the Saint George branch (Fig. 4), within the artificially rectified channel sector in the Mahmudia meander area.

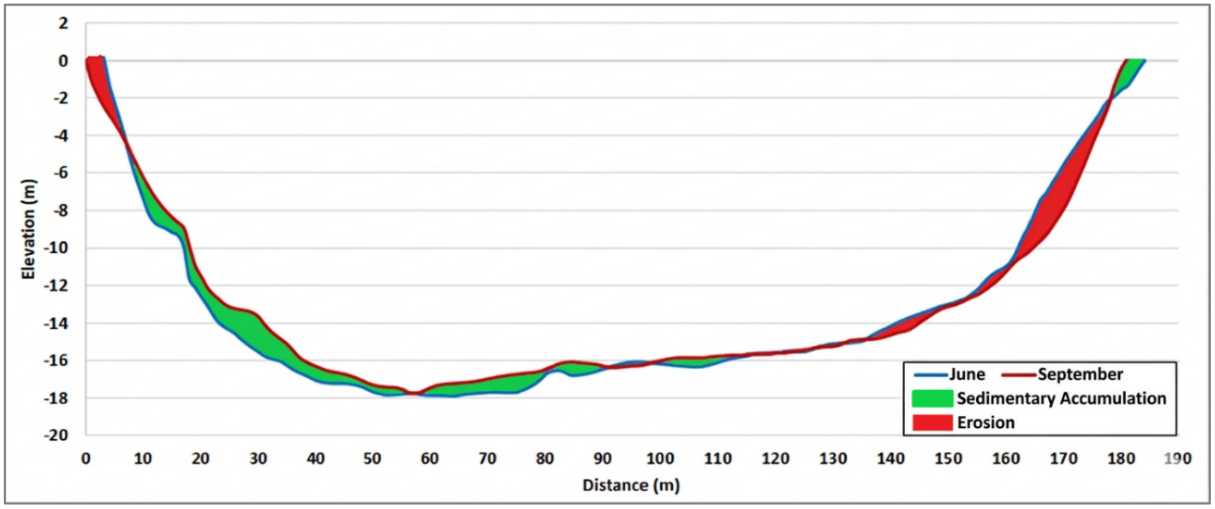

Fig. 4. Changes in the cross-section due to erosion and deposition in the artificial channel (Mahmudia meander, P03)

The cross-section shows asymmetry to the left, with the thalweg closer to the left bank. A certain stabilization of the thalweg is observed, both in elevation and position, despite sediment deposition in this area. Within this cross-section, sediment deposition is particularly evident along the left bank and extends into the central area over approximately 100 m. Additionally, a smaller accumulation zone has been identified along the right bank. The accumulation observed on the left bank can be attributed to its proximity to a sedimentation zone located on the right side at the entrance to the natural channel. On the right bank, erosion is the dominant process, extending over approximately 40 m. A smaller erosional sector is also identified along the left bank. The erosion observed on the right bank can be attributed to the flow concentration in this part of the cross-section. At the entrance in the former meander, the discharge of the St George branch (of 1253 $m^3.s^{-1}$) was unequally distributed between the former meander (18 $m^3.s^{-1}$, around ~1.2% of the upstream discharge) and the artificial canal (1235 m^3.s-1). The average velocities ranged between 0.01 and 0.03 m/s along the former meander and between 0.48 and 0.52 $m.s^{-1}$ (Fig. 5 and 6).

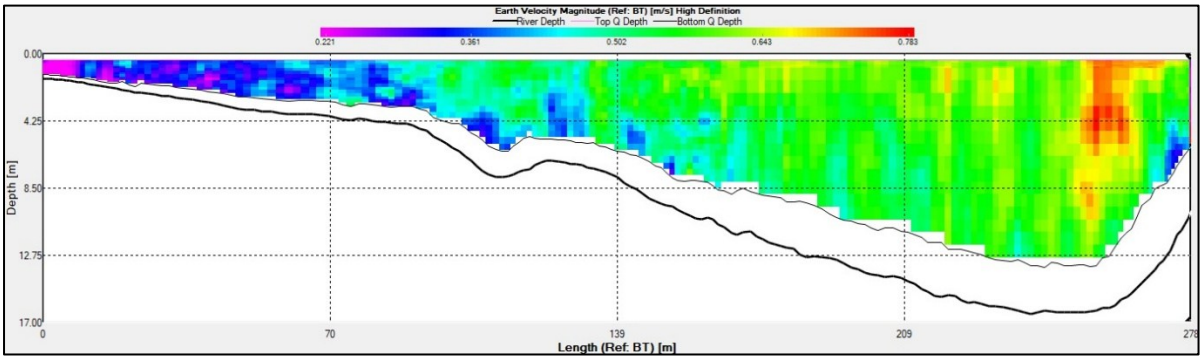

Fig. 5. The distribution of the velocities on the cross-section situated upstream of the bifurcation (P02)

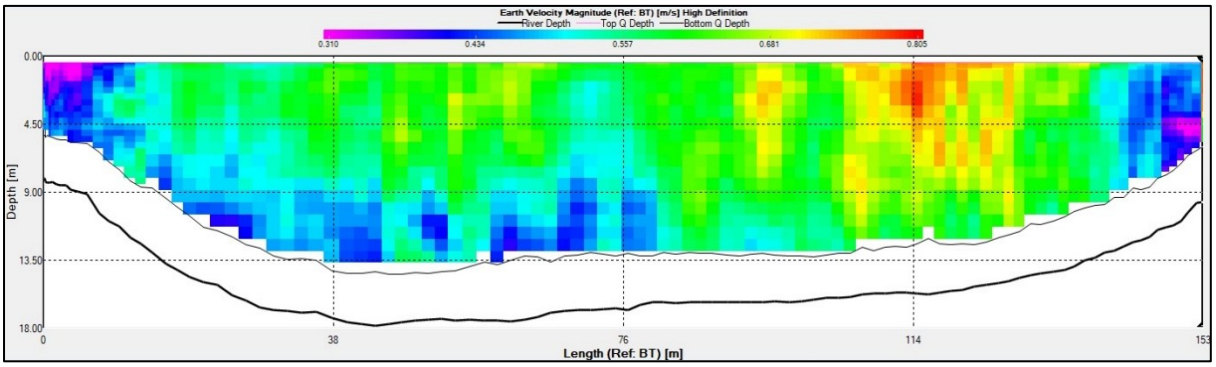

Fig. 6. The distribution of the velocities on the cross-section situated downstream of the bifurcation, on the artificial canal (P03)

During the June–September period, the cross-section underwent recalibration, as the left bank tends to stabilize through sediment deposition, while the current energy appears to have concentrated along the right flank of the section, intensifying the slope through erosion. In parallel, detailed bathymetric measurements were conducted in several areas characterized by intense sedimentation (Fig. 7). The bathymetric map of the bifurcation area at the entrance to the Mahmudia meander (Fig. 7) shows that depths are relatively shallow at the entrance in the former meander, where flow velocity decreases significantly. As a result, an extensive sedimentation area has developed. A shallow threshold (less than 2–3 m depths) can be observed at the entrance to the natural channel, acting as a natural barrier. During low discharge periods, most of the water is directed toward the artificial channel, while the natural branch receives only minimal discharge. Downstream, along the artificial channel, deeper depths are recorded, representing the river's main current, where flow velocities are also highest.

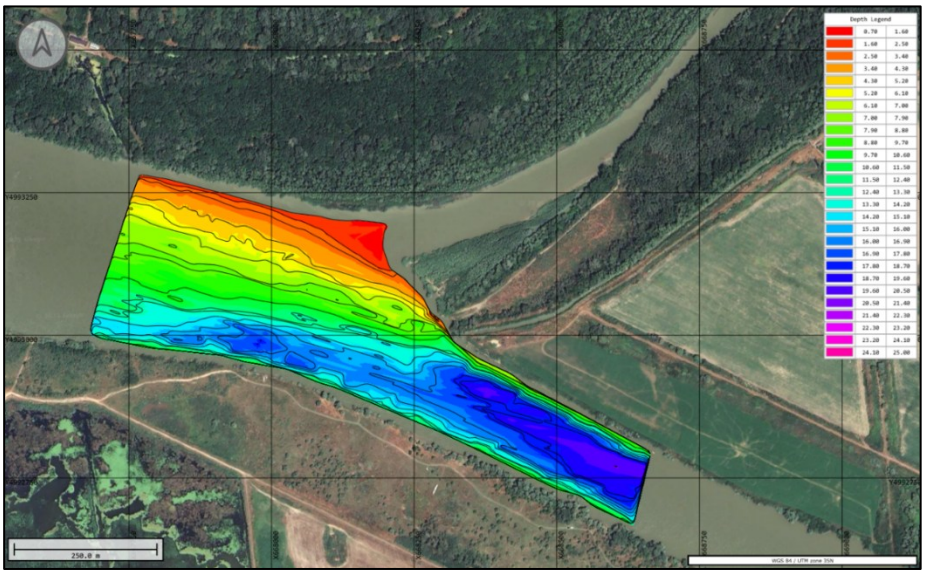

Fig. 7. Bathymetric map of the bifurcation area of the Mahmudia meander

Another sector characterized by intense sedimentation is located at the second apex of the Mahmudia meander. Here, a detailed bathymetric survey was conducted to characterize channel morphometry and determine the spatial configuration of depths. The bathymetric map (Fig. 8) indicates predominantly shallow depths, in some areas even below 1 m. A well-developed island (sandbar) is present in the middle of the channel, formed over time due to the significant reduction in flow energy, which allowed fine sediments transported by the river to accumulate continuously. On the left side of the island, an advanced sedimentation area is present, where water depths drop below 50 cm during low-water conditions, making navigation impossible. Additionally, the cross-section in this area is progressively narrowing. Although the branch is undergoing sedimentation, significant depths of up to 10 m can still be observed along the concave bank, due to erosion processes specific to such geomorphological settings.

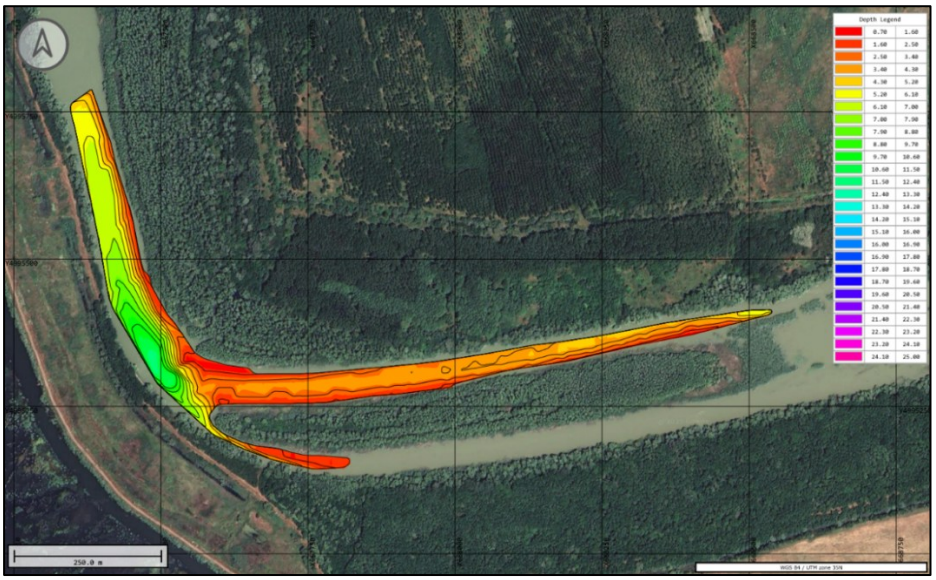

Fig. 8. Bathymetric map of the second apex of the Mahmudia meander

Extending the analysis beyond local morphometry, understanding channel evolution requires a comparative approach to erosion and deposition dynamics at critical points in the flow distribution. In this regard, two Digital Elevation Models (DEMs) from the Ceatal Sfântu Gheorghe bifurcation were analyzed, where the Danube waters split into two branches: the Sulina branch to the north and the Saint George branch to the south. The datasets were derived from detailed bathymetric surveys conducted along transverse

profiles spaced at 50 m intervals. This diachronic analysis aimed to identify morphological changes in the Danube channel and to accurately quantify transformations in both cross-sectional and longitudinal profiles in this hydraulic divergence zone. Fig. 9 shows a comparative analysis of the two DEMs, revealing elevation changes in the riverbed ranging from −3.00 m to +3.00 m. Significant erosional processes are observed at the bifurcation apex and along the thalweg of the Sulina branch, driven by flow concentration toward the right bank and increased velocities downstream of the bifurcation. Erosion is also evident along the thalweg of the Saint George branch immediately downstream of the bifurcation, as well as along the left bank of the Tulcea branch (sector km 34 – km 34.4). Overall, erosion across all three branches is attributed either to flow concentration in specific channel zones or to the localized action of turbulent currents on the riverbed. Significant sediment accumulations were identified along all three branches. The sectors with the most extensive deposition include the right bank of the Tulcea branch (particularly between Mile 34 and the bifurcation apex), the right bank downstream of km 108, and the left bank of the Saint George branch upstream of km 108.

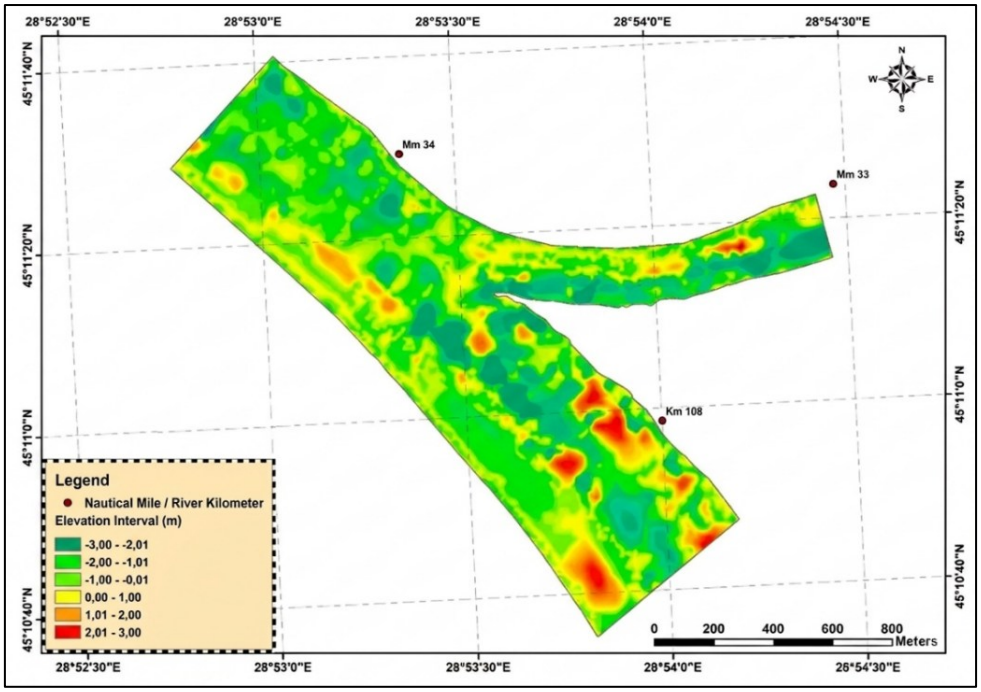

Fig. 9. Changes in the riverbed at the Ceatal Sfântu Gheorghe bifurcation between 2019 and 2023

3. Conclusions

This study demonstrated the effectiveness and importance of integrating high-precision terrestrial topographic measurements, obtained through modern GNSS technologies, with bathymetric data (single-beam), with the aim of generating continuous topo-bathymetric cross-sections. These profiles enable the monitoring and analysis of hydromorphodynamic processes acting upon the Danube River channel. The correlation between information derived from the analysis of cross-sections along the Saint George branch (Mahmudia meander) and the comparative analysis of Digital Elevation Models (DEMs) from the Ceatal Sfântu Gheorghe bifurcation highlights a fluvial system undergoing continuous morphodynamic adjustment. It was observed that the secondary branch (Mahmudia meander) is undergoing advanced sediment infilling and loss of hydraulic connectivity, characterized by reduced depths that, during low-water conditions, hinder navigation in certain critical sectors. In contrast, the artificially rectified channel exhibits an asymmetric redistribution of flow energy, becoming the main conveyance channel, with depths reaching 25 m and significant erosion in the channel bed and along the banks. The comparative DEM analysis at the Ceatal Sfântu Gheorghe bifurcation revealed a highly active hydrodynamic regime, with erosion and sediment deposition zones ranging from −3 m to +3 m. Erosional areas were identified at the bifurcation apex and along the thalwegs of the Sulina and Saint George branches, primarily due to flow concentration and downstream turbulent currents. Sediment accumulation zones were identified along convex banks and in hydraulically sheltered areas (such as the right bank of the Tulcea branch and the left bank of the Saint George branch). The use of Digital Elevation Models enables not only the inventory of submerged landforms but also the quantification of sediment volumes transported within the system. This integrated approach represents an essential diagnostic tool for the sustainable management of the Danube Delta, providing decision support for navigation channel maintenance and ecosystem conservation in secondary branches. Overall, the results indicate that the morphology of the Danube channel in this sector is shaped by a complex interaction between natural hydrodynamic forces and anthropogenic structural modifications. These local transformations of the submerged channel profile, whether manifested as erosion zones or sedimentation thresholds, form the basis for forecasting the long-term evolution of the Danube branches. This study emphasizes that the Danube Delta remains a geomorphological system undergoing rapid and continuous transformation, where monitoring both submerged relief (minor channels) and emergent relief (floodplains) is essential for understanding the river's response to anthropogenic pressures and environmental changes at a regional scale.

Acknowledgments

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