Evolution of Sulina mouth bar (Danube river)

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Abstract. This paper studies the dynamics of the Sulina branch mouth by analyzing the influence of human intervention on sediment deposition at the point at which the Danube river empties into the sea. The surface and volume of the bar and southern spit at the Sulina branch mouth are calculated for the first time using advanced techniques.

The methodology consisted in georeferencing and vectoring the maps produced by the European Commission of the Danube (ECD), followed by a morphometrical separation of the bar and southern spit in the resulting models (from a 5 m depth to the surface). The ECD performed the first improvement works in the Danube Delta; the role of the jetties was to exceed the length of the bar which, in its natural state, extended over the entire mouth. The highest bar development rate was recorded between 1920 and 1925, when the volume of sediments in front of the jetties reached ~2.5 mil. m^3. After 1930, both the surface and volume of the sediment deposition rates sharply decreased, due to the change in jetty direction and intensive dredging at the mouth.

Keywords: Sulina, Danube, European Commission of the Danube, jetties, bar, spit

1. Introduction

Deltas are accumulations of sediment deposited where rivers enter into the sea (Masselink, 2003). Delta systems are among the most important mediums of coastal sedimentation, with important underground resources such as oil, gas and groundwater (Giosan, 2006). Deltas have always been preferred as places of human habitation, approximately 25% of the world population living in deltaic areas or at the mouth of large rivers (Szvitski, 2005). The percentage is lower in Romania, where only 6.3% of the country population lives within 100 km distance of the coastline (Schwartz, 2005). According to the latest theory of Danube Delta genesis, based on modern analysis methods, developed by Giosan et al. in 2005, the formation of the delta started approximately 5200 years ago. A key aspect to mention is the evolution of the Sulina branch, which started approx. 3640 years ago and was completed approx. 2200 – 1800 years ago, and subsequently entered an erosion stage.

The mouth bar is formed where a delta branch discharges into the sea in *hypopicnal conditions (the river water density is less than that of the water into which it discharges*) (Schwartz, 2005). The difference in density is caused by the sea water salinity; in front of the Sulina mouth it is approximately 16 ‰ at the surface and 19 ‰ in deep water (Bondar, 2011). The mouth bar represents a "*complex accumulative formation that forms at the mouth of a channel flow in the zone of sediment deposition because of the sea-water interaction*" (Dolgopolova & Mikhailova, 2008). The contact between the different masses of water is made via fluvial water flows under the influence of sea waves and tides (Bondar, 2011). This type of contact contributes to the formation of a cuspate bar (Masselink, 2003), and further into the sea sediments can be redistributed under the influence of waves, with a subsequent phase of mouth asymmetry, with the bar anchored on one of the shores (Bhattacharya, 2003; Giosan, 2005).

2. Local characteristics

Articles 15 and 16 of the Treaty of Paris, signed on 30 March 1856, establish the European Commission of the Danube (Rosetti & Rey, 1931). This institution was "*charged to designate and to cause to be executed the Works necessary below Isatcha, to clear the Mouths of the Danube, as well as the neighbouring parts of the Sea, from the sands and other impediments which obstruct them, in order to put that part of the River and the said parts of the Sea in the best possible state for Navigation. The Flags of all Nations shall be treated on the footing of perfect equality*." (Rosetti & Rey, 1931).

The Sulina mouth was chosen for the improvement works upon demand of the merchants in Brăila and Galați and initially the project was approved as a temporary measure, until the ECD found the financial resources to initiate improvement works on the Sf. Gheorghe branch. The solution proposed by Chares Hartley, engineer-in-chief of ECD, was to guide the river runoff further into the sea, by a system of parallel jetties. Practically, this method increases the speed of the fluvial current, thus enhancing the transport capacity. The expected outcome of these works was to exceed the length of the mouth bar (the main obstacle for navigation) and to cause the bar to form deeper into the sea and no longer affect navigation at the mouth.

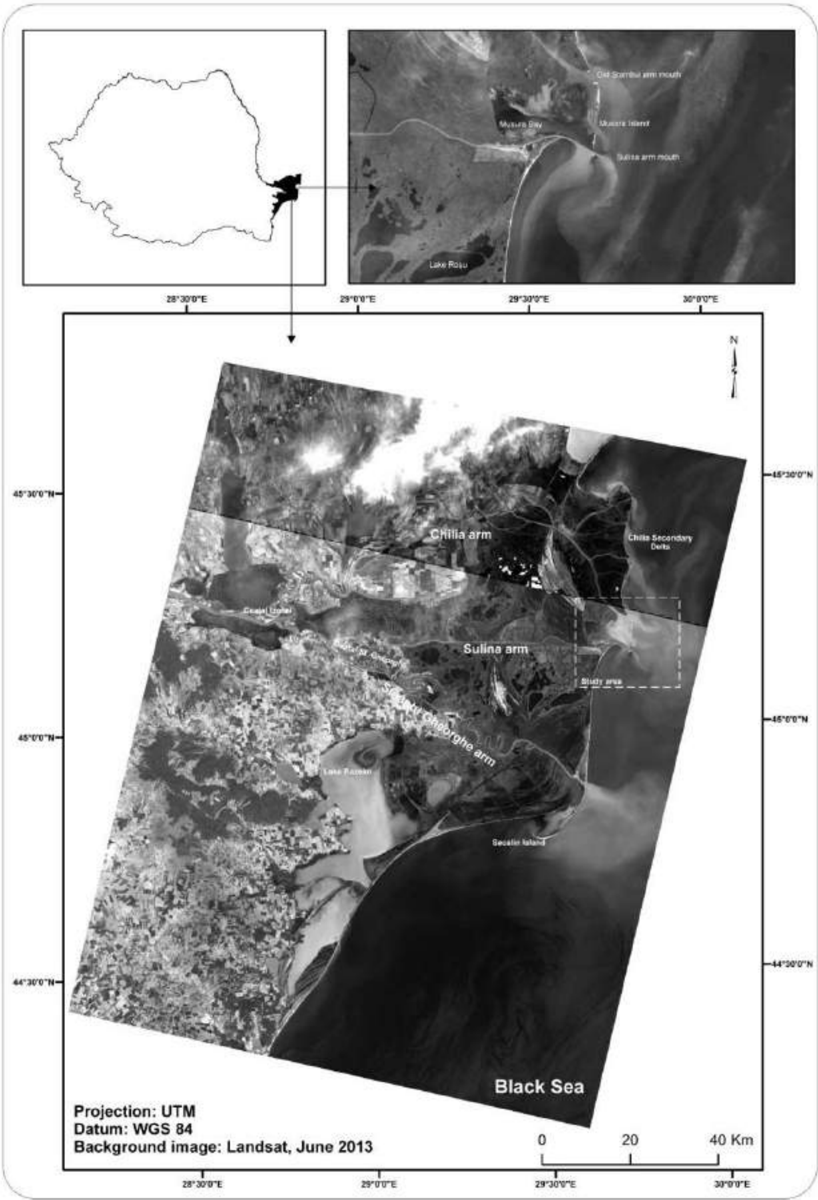

Fig. 1. **Position of the Sulina mouth within the Danube Delta**

The initial (temporary and then permanent) consolidation works started in 1858 and were completed in 1872; the jetties measured a total length of 2678.8 m (8789 feet), the northern jetty measured 1625.1 m (5332 feet) and the southern jetty measured 1053.6 m (3457 feet). (Hartley, 1862, 1873). The decision to elongate the jetties was taken in 1925, due to navigation problems caused by the southern spit. The works were performed in two stages and were completed in 12 years (1925-1932 and 1933-1937). The first stage started offshore towards the old jetties, to prevent complete obstruction of navigation in the area, and the second stage involved changing the direction of the jetties. The measure to change the jetty direction was taken to counteract the extremely high sediment deposition rates in the Musura Bay. The jetties were elongated further after 1944 and until 1982 (Vespremeanu, 1983). Two very active periods can be identified: 1944-1956 with an extension of 400 m and 1956-1982 with an extension of 3000 m. The jetties currently measure 9300 m from the point where the construction works started in 1858.

Starting with 1894, the ECD also performed regular mouth dredging works (Rosetti & Rey, 1931), and after 1940 these works were resumed by the Romanian government, which took charge of fluvial navigation (via various government agencies such as the Direction of Maritime Danube, Hydrographic Direction of the Danube, River Administration of the Lower Danube, etc.).

Other works that influenced the bar and southern spit were the meander cut-off works performed by the ECD on the Sulina branch between 1868 and 1902, as well as the construction of the Ceatal Izmail embankment. These activities were intended to straighten and shorten the Sulina branch, thus the speed of the river current increased and a direct consequence was an increase in the distributary discharge between 1900 and 1960 (Bondar, 2010, 2011).

The solid discharge of the Danube was significantly influenced by the construction of hydrotechnical facilities, registering minimum amounts of 337 kg/s after the 1950s, as opposed to the maximum amount of 4428 kg/s reached in 1870. Rădoane (2005) indicates a number of 207 dams built on the Danube and its tributaries after 1940.

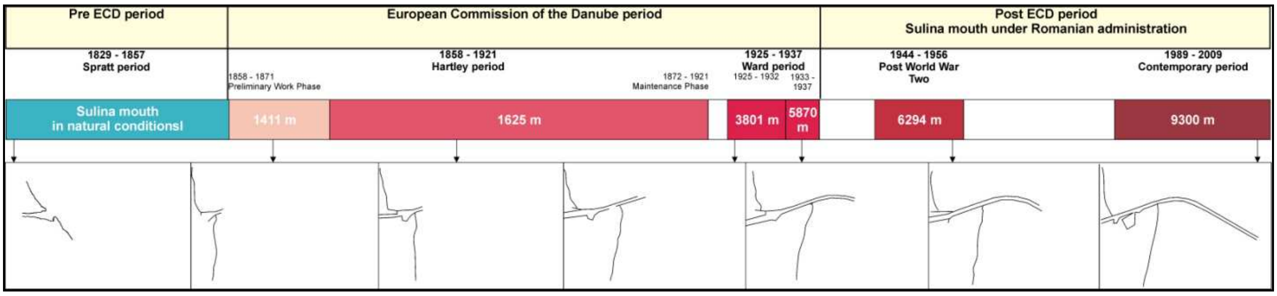

Fig. 2. **Jetties at the Sulina mouth and length per periods**

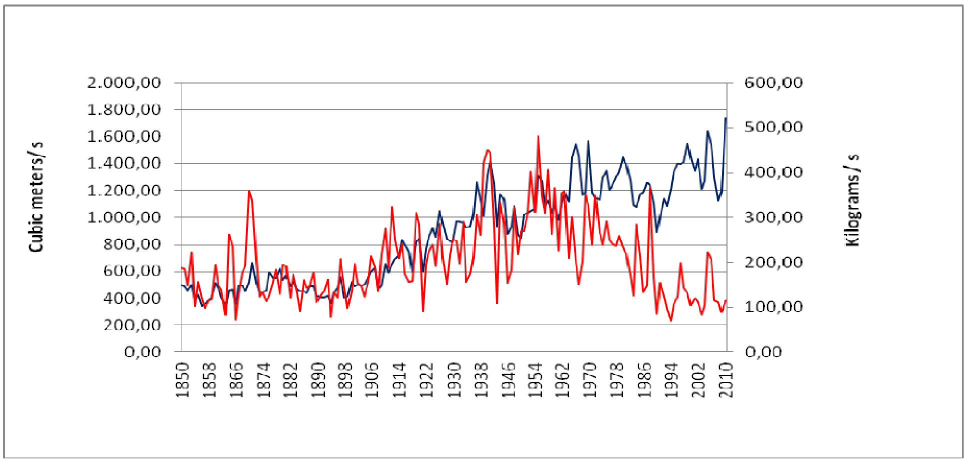

Fig. 3. **Average fluid discharge** (blue) **and solid discharge** (red) **on the Sulina branch between 1850 and 2009** (adapted from Bondar, 2010 and 2011)

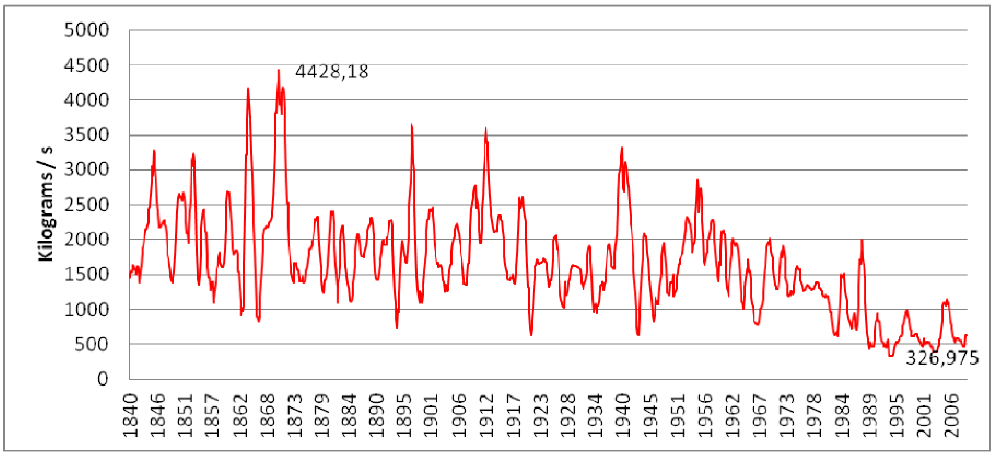

Fig. 4. **Solid discharge at Ceatal Izmail** (Bondar, 2010 and 2011)

3. Methodology

Research was primarily based on cartographic material of the European Commission of the Danube and the River Administration of the Lower Danube (AFDJ). The ECD maps have a 500-foot grid with the old lighthouse as a foundation, but there are no data concerning the geographic system of coordinates, projection, ellipsoid or datum (Constantinescu et al., 2010). The georeferencing method was *image to image*, using at least 10 control points. The UTM projection, datum WGS 84, area 35 N, was used (code EPSG 32635), the AFDJ maps were initially georeferenced using their own projection (6-degree Gauss-Krüger, zone 5, Datum S-42 [Pulkovo 1942]), and subsequently converted to UTM.

Georeferencing was followed by vectoring and creation of the digital bathymetric model (DBM). The interpolation method was *Natural Neighbor*, and the resulting model had a 20 m spatial resolution. This method is the most appropriate in this context of high point densities in certain areas and low densities in others (Giosan et. al, 2006). A total number of 422 bathymetric maps of the Sulina mouth were indexed, 190 were georeferenced and 177 were vectorized in order to create a DBM and our analysis used a total of 111 maps.

The bar and southern spit were morphometrically separated using the 1856 Spratt map. This map contains a separate inset with a cross-section profile over the bar, indicating the 16-foot depth required for the 400-ton ships to enter the mouth. DBM was delimited between -5m and 0m to identify the bar position. These calculations were performed for 115 DBMs and our research uses 14 DBMs, representing the extreme years which determined the analyzed periods (1829-1856, 1857-1871, 1871-1900, 1900-1921, 1925-1932, 1933-1937, 1944-1956, 1989- 2009).

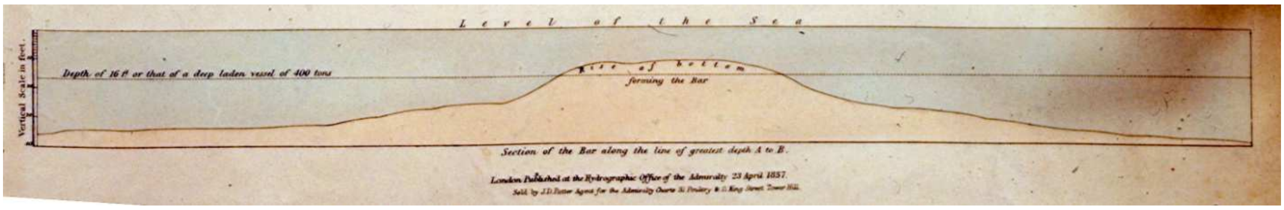

Fig. 5. **The Spratt map inset used as reference for the morphometrical separation of the bar**

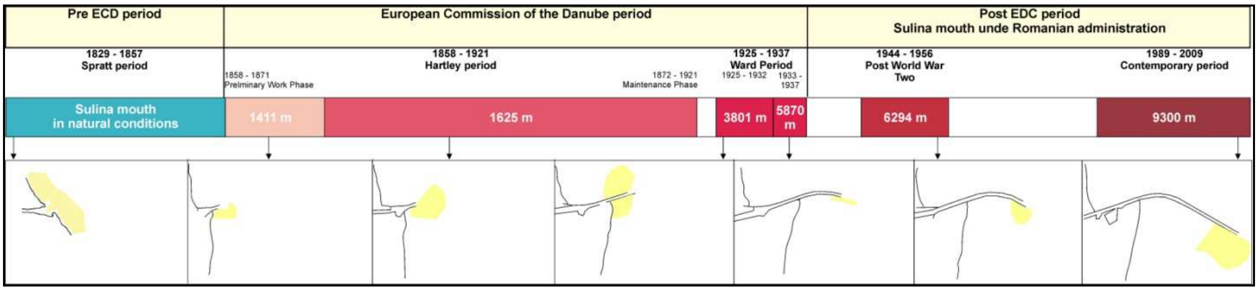

Fig. 6. **Maximum elongation of the bar and southern spit** (in front of the jetties) **per period**

4. Results and discussions

In its natural state, the Sulina mouth was covered by a continuous spit up to 5 m depth. Following the jetty construction and dredging works, the bar has a southern position, with different rates of elongation toward the North (in 1921 and 1925) and after 1937 the deposition tends to develop southward, partly due to the more and more southern direction of the jetties. It is important to note that the bar position in 1925, covering the navigable channel, is somewhat similar to the bar position in 1829. This cancellation of the jetty effects was mainly determined by the fact that ECD stopped its activities during the First World War.

The analysis of the southern spit volume and surface included the extreme years of the analyzed periods (1829-1856, 1857-1871, 1872-1921, 1925-1932, 1933-1937, 1944-1956, 1989-2009). To achieve an accurate comparison between the volumes of sediment deposits, the volume was calculated using the standard 1 km^2 unit.

In its natural state, the surface and volume were very high (over 3.5 km^2 and ~2.1 m^3), but this is due to the fact that the spit was not in its final form and the depth over the entire mouth was less than 5 m (the morphometrical limit of the spit). The largest sediment volume, 2.5 mil. m^3, was recorded in 1921, and the largest surface of the mouth bar, 4.1 km^2, in 1925. These values correlate very well with the sediment deposition rates at the mouth (reaching 25 cm/year in the years between the two World Wars) and in the Musura Bay (the period between

1850 and 1920 showed significant southern development of the Chilia lobe and significant sediment deposition rates at the Musura Bay (Giosan, 2005). Between 1932 and 1956, the sediment deposition volume is approximately 1.5 mil m^3, and the surface of the bar sharply decreases. This demonstrates the efficiency of the jetty elongation and direction shifting works. After 1937, the bar tends to become a spit, given that the mouth takes an almost southward direction. The shift in jetty direction and the north-south direction of the main current lead to the formation of longshore currents (Stănică, 2007), and therefore the sediments end up being deposited behind the jetties. Between 1960 and 1980, the length of the southern spit increased significantly (~1.5 km) and the width doubled from 0.5 km to 1 km (Vespremeanu, 1983). In 1989 the southern spit had a considerable size, but, given that it endangered the navigation, intensive dredging works were initiated in this area. Consequently, between 1989 and 2009 the volume decreased by ~ 1 mil m^3, and the surface decreased by more than 1 km^2.

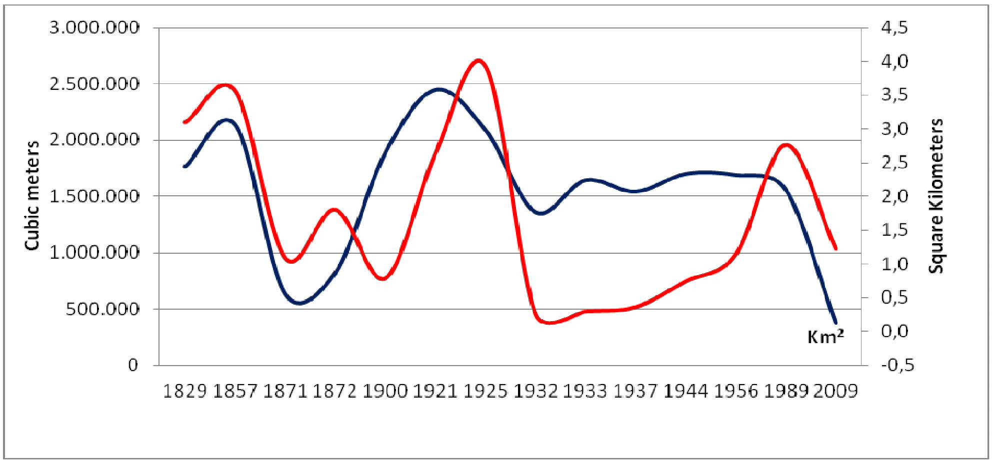

Fig. 7. **Volume** (blue) **and surface** (red) **of the southern bank**

A cross-section analysis of the mouth bar dynamics was only possible for the 1876-1921 period, hence a multi-annual dynamics, in 5-year ranges, was chosen instead. Restrictions were determined by the jetty elongation and advancement of the branch mouth into the sea. The research methodology consisted in creating profiles on the navigation direction, as indicated on the ECD maps, with the imaginary line between the jetty extremities as the starting point. This reveals how the bar influenced navigation.

Until 1911, the ECD engineers maintained the bar crest position at approximately 5 m depth. Later on, the bar developed significantly, its crest reaching -4 m in 1916 and -2.5 m in 1921. This bar depth, even lower than the depth recorded in 1829, was reached in the context of the First World War and of the very high sediment deposition rates during these years (Fig. 3).

In 1921, the bar crest shifted 1.5 km offshore from the jetty mouth, which caused a complete obstruction of navigation on the normal routes. This shift is explained by significant sediment depositions at high depths transported from the North.

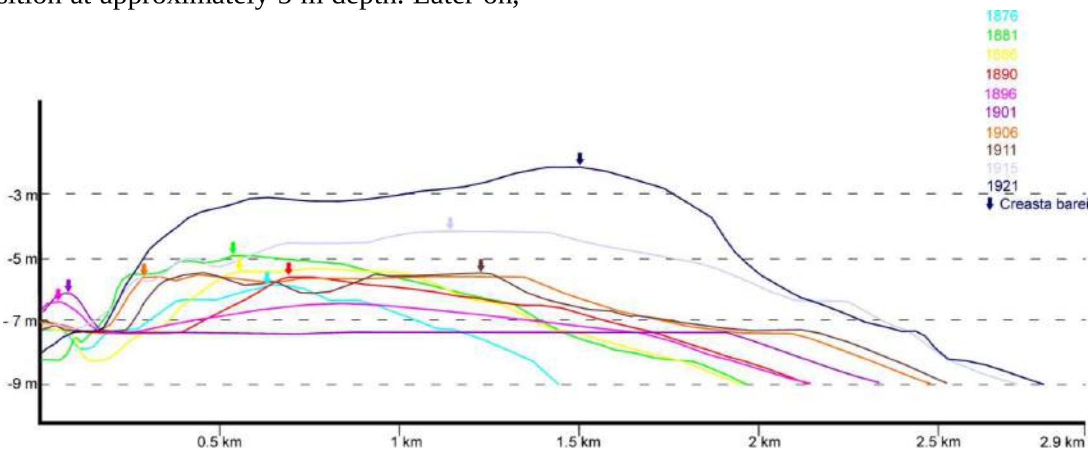

Fig. 8. **Cross-section profile of the bar dynamics**

5. Conclusions

The Sulina bar, the name given in the 19th century to the sediment deposition phenomenon at the river mouth, caused serious problems to navigation in the area, and the European Commission of the Danube tried to find a solution to this issue by building a system of jetties. The jetty elongation and dredging works at the mouth considerably influenced the bar morphodynamics.

These interventions separated the spit which normally extended over the entire mouth and represented the beginning of a new phase of permanent continuous asymmetry (Bhattacharya, 2003; Giosan, 2005). In the years between the two World Wars, the mouth bar increased in size to the level recorded in 1830, and this situation dictated the beginning of jetty elongation and direction shifting works. After 1940, the bar enters a new morphological phase, taking the shape of a spit located south of the jetties and permanently dredged to the north to prevent navigation issues. The dredging works significantly influenced the bar morphometry, which was kept at high depths until 1911-1915. Subsequently, the dredging works continued only on the northern side of the spit, at high intensity between 1980 and 2000.

The bar dynamics and evolution of the southern spit can only be understood in close relation with the works at the Sulina mouth which started in 1858 and continue to the present day.

Acknowledgements

This research has been made possible by the financial support of the Sectorial Operational Program for Human Resources Development 2007-2013, co-financed by the European Social Fund, project number POSDRU/107/1.5/S/80765.

The author wishes to thank Ms. Florina Grecu for the help and support she provided during the PhD studies and for accepting to supervise the PhD thesis called *Evolution of the Sulina mouth based on digital bathymetric models.*

A warm thank you to Ştefan Constantinescu for his support and patience during our research and for the critical review of this text.

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