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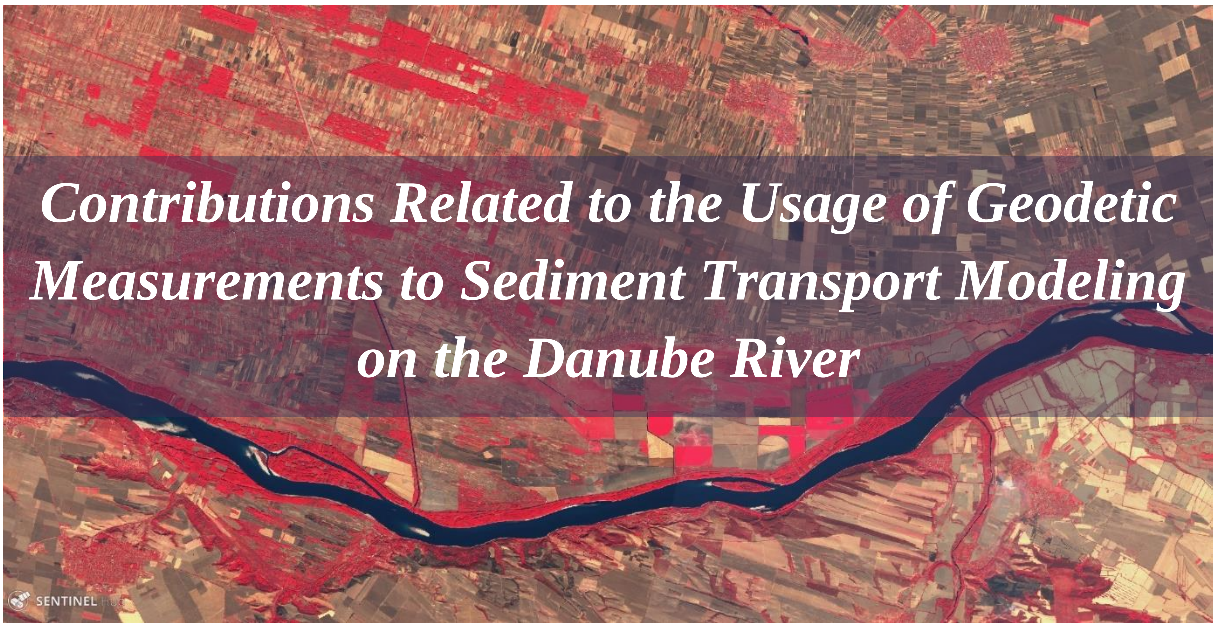
Summary



Contributions Related to the Usage of Geodetic Measurements to Sediment Transport Modeling on the Danube River

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PREFACE

Today, the Danube River, and especially the navigation on the Danube, plays a strategic role in the pan-European transport network, connecting fifteen countries through its waterway.

Romania, through the Galați Lower Danube River Administration, A.A. (LDRA Galați), is responsible for the maintenance of the longest Danube waterway sector (1075 km).

In low water conditions, due to river dynamics and complexity of hydrological regime, the navigation on the Danube River is difficult, especially downstream the Iron Gates II Hydropower and Navigation System, where there are several critical points for navigation. These critical points require careful monitoring through a series of topo-bathymetric measurements interconnected in an unitary geodetic system, respecting current European and international standards.

The doctoral thesis entitled "**Contributions Related to the Usage of Geodetic Measurements to Sediment Transport Modeling on the Danube River**" is a scientific approach that addresses the issue of sediment transport modeling on the Danube River, both theoretically and practically, by developing, calibrating and validating a mathematical model of flow and sediment transport. The impressive volume of geodetic and hydrographic data required for hydro-sedimentary modeling was collected in several field measurement campaigns, while the hydrological data were provided by the National Institute of Hydrology and Water Management.

In terms of content, the study is structured in six chapters, which include 155 figures and 17 tables.

The first chapter, called *Introductory Aspects*, highlights the importance of the Danube River in the history of our people, focusing on the navigation issues encountered on the Danube since Roman times until today. The last part of this chapter is dedicated to the purpose and objectives of the research.

The second chapter presents the *Coordinate Reference Systems used on the common Danube River sector between Romania and Bulgaria*, where the biggest navigation issues are registered, and presents a brief history of height reference systems used on the Romanian sector of the Danube River.

The third chapter, called *The Geodetic infrastructure on the Romanian-Bulgarian border area*, focuses on the national geodetic networks in the two Danube riparian states, with a review of research projects relevant to solving several geodetic infrastructure issues on the common Danube sector between Romania and Bulgaria, and ends with the presentation of the types of geodetic measurements performed in order to sediment transport modelling.

Starting from elements of river dynamics and hydrometry, continuing with the principles of hydraulic modeling, describing the mechanism of sediment transport and ending with the measurement and processing of solid flows, **the fourth chapter** summarizes the main *Theoretical aspects regarding sediment transport on the Danube River*.

The fifth chapter includes the case study, namely *Sediment transport modeling on the Bechet-Corabia Danube sector*. This chapter details all the steps followed for the developing, calibration and validation of the hydro-sedimentary model of the analyzed sector.

The last chapter, called *Conclusions, contributions, perspectives*, summarizes the conclusions that emerge from the study, the personal contributions of the author, as well as the research perspectives relevant to future studies.

* * *

CHAPTER 1

INTRODUCTORY ASPECTS

1.1. The Role of the Danube River in the History of the Romanian People

Known since ancient writings under names such as *Istros*[1] or *Danubius*[2] and transformed by the Romans into an axis of communication between Central Europe and Pontus Euxinus (Figure 1), the Danube played a decisive role in the historical evolution of the Romanian people. "The whole life of our people is connected to the Danube, as well as to the Carpathians", considered the naturalist Grigore Antipa (1921).

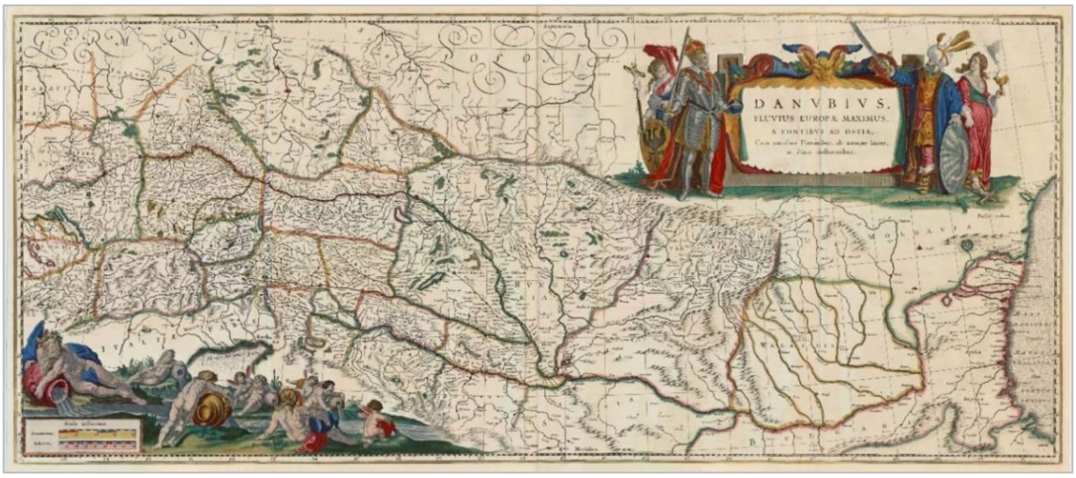

Figure 1. Old Map of the Danube River, 1649

Source: Joan Blaeu – "Danubius, Fluvius Europae Maximus, a Fontibus ad Ostia", 1649

Subject of dispute between various European powers, the great river was perceived as "an open gate to humanity", through which the Romanian space had the privilege of being permanently integrated "to an international economic, but also geopolitical framework" (Berindei, 1997) .

After centuries of Ottoman rule, in the 19th century, the "Danube problem" actually meant the rivalry between Austria and Russia for the domination of the mouths of the river. On one hand, the Danube was a valuable tool for Russia in trying to control the Balkans, and on the other hand, the Lower Danube was in the expansion zone of the Habsburg monarchy towards the Orient.

French or British traders did not bypass the Danube-Pontic basin either, considering it an attractive market for Western products.

[1] Istros - the Daco-Greek name of the Danube, especially of its lower course (source: The Explanatory Dictionary of the Romanian Language, Ed. 2016).

[2] Danubius (God of the rivers) - the name given especially to the upper and middle course of the Danube by the Romans, taken over by other peoples and modified, becoming Donau in German, Dunaj in Slovak, Duna in Hungarian, Dunav in Croatian, Danube in English and French, Tuna in Turkish (source: wikipedia.org).

Like the Black Sea, which was considered an extension of the Mediterranean Sea towards the rich eastern regions, the Danube connected the interior of the continent with the Mediterranean and the Pontus Euxinus (Figure 2).

For the inhabitants around it, (Bărbănțan, 2010) appreciates that “the Danube represented not only a means of transport and communication, but also a source of food and a place favorable to be inhabited”.

Figure 2. Map of the Danube River, Austria, 1840

Source: William Hughes - "The Danube, from its Source to the Black Sea with the adjacent Countries", 1840

The most beautiful pages in our diplomatic and political history were written when the politicians of those times "opposed and defended our rights on the river with energy and tenacity" (Botez, 1919), being aware of its geostrategic and commercial value.

"The greatest natural wealth of our country is, without a doubt, the Danube River: and this would be so even if we consider it only as a world artery of navigation and trade. Masters of its mouths, which are the gate of Europe to the East and the gate of the East towards the heart of Europe, masters of 36% of its navigable surface, with all the water bodies flowing into it along its entire length, masters of all this, we thus possess the greatest treasure that a generous nature could endow a country with. Just as the Nile made Egypt, we can also say that the Danube created the political and economic importance of Romania", declared the famous politician Alexandru Lahovary (1881).

In conclusion, political and economic interests were high, and "whoever held the mouth of the river in his hands was master of the Danube River" (Marx & Engels, 1959).

1.2. The Current Issue Regarding Navigation on the Danube River

The second longest river in Europe after the Volga River, with a river basin area of 817,000 km^2 (Figure 3), the Danube is characterized by a particularly complex hydrological regime: after a route of 2857 km on the territory of ten countries (Germany, Austria, Slovakia, Hungary, Croatia, Serbia, Romania, Bulgaria, the Republic of Moldova, Ukraine), receiving additional tributaries from six other European countries, the Danube brings, at the discharge into the Black Sea, an average multiannual flow of 6500 m^3/s and approximately 79 million tons of sediments annually.

Figure 3. The Danube River Basin

Out of a total of 2415 km of waterways, Romania, through the Galați Lower Danube River Administration, A.A. (LDRA Galați), is responsible for the administration of the longest Danube waterway sector, over a distance of 1075 km, from Baziaș to Sulina, establishing the border with Serbia (over a distance of 235.5 km), Bulgaria (469.5 km), the Republic of Moldova (0.6 km) and Ukraine (53.9 km).

On the entire Romanian sector of the Danube River, LDRA Galați is the waterway authority responsible for ensuring the minimum navigation conditions, recommended by the Danube Commission. Although maintenance activities are performed periodically, consisting of topo-bathymetric and hydrological measurements, fairway signaling and dredging works, they are effective only for a short period of time. According to (Egis, 2015), a volume of sediments is dredged annually from the Lower Danube riverbed, which varies on average between 1.5 and 3.5 Mm^3/year.

Due to the characteristics and dynamics of the riverbed morphology, the biggest navigation issues are registered on the common Romanian-Bulgarian sector.

In order to develop complex technical solutions that would lead to the improvement of navigation conditions on the Danube River and, at the same time, to have a minimal impact on the environment, in 2017 the FAST DANUBE project was launched - ***”Technical assistance for reviewing and completing the feasibility study on improving navigation conditions on the common Romanian-Bulgarian Danube River sector and complementary studies”*** (originally proposed in 2007). It refers to the Danube sector located downstream of the Iron Gates II dam, from km 845.5, to Silistra, at km 375 (Figure 4).

A part of the measurements performed within the FAST DANUBE project were the basis for the realization of this research work.

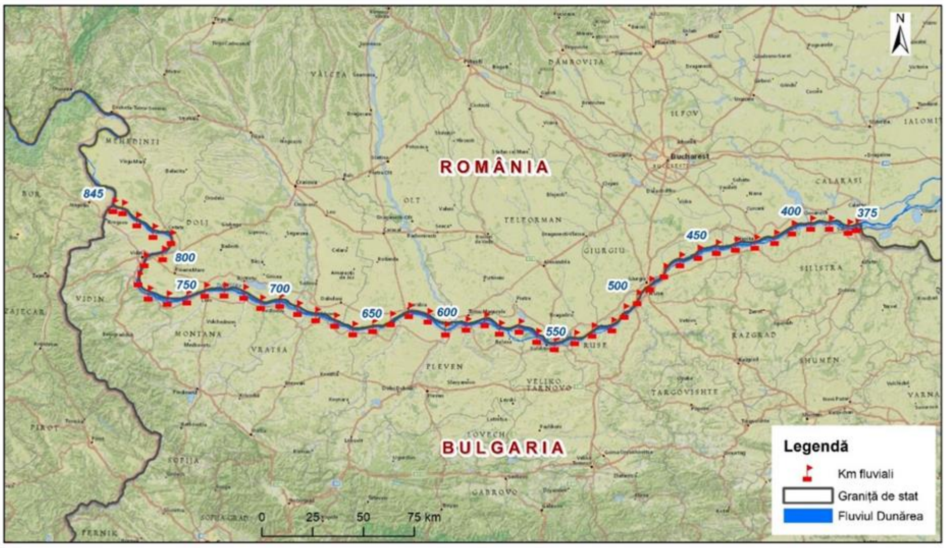

Figure 4. FAST DANUBE project – study area

The common Danube sector between Romania and Bulgaria is part of the Lower Danube sector, is characterized by a free flow and is influenced by the management of water in the Iron Gates Hydropower System reservoirs.

Over time, large variations in Danube discharges and levels, doubled by significant changes in riverbed morphology due to erosion, deposition and sediment transport, have led to **critical points** for navigation, shown in Figure 5.

In low water conditions (below 3000 mc/s), the depths are insufficient to ensure the efficient transport of goods. Very often, vessels sailing in the critical navigation areas (bottlenecks) can only be loaded at half of their capacity. This situation can cause significant losses for river transport operators and lead to lack of reliability of river transport.

The available statistical data show that the average number of days in which the navigation conditions were ensured before the launch of the project was 280 days/year. The objective of FAST DANUBE is to increase the number of days in which navigation takes place in optimal conditions to approximately 340 days / year.

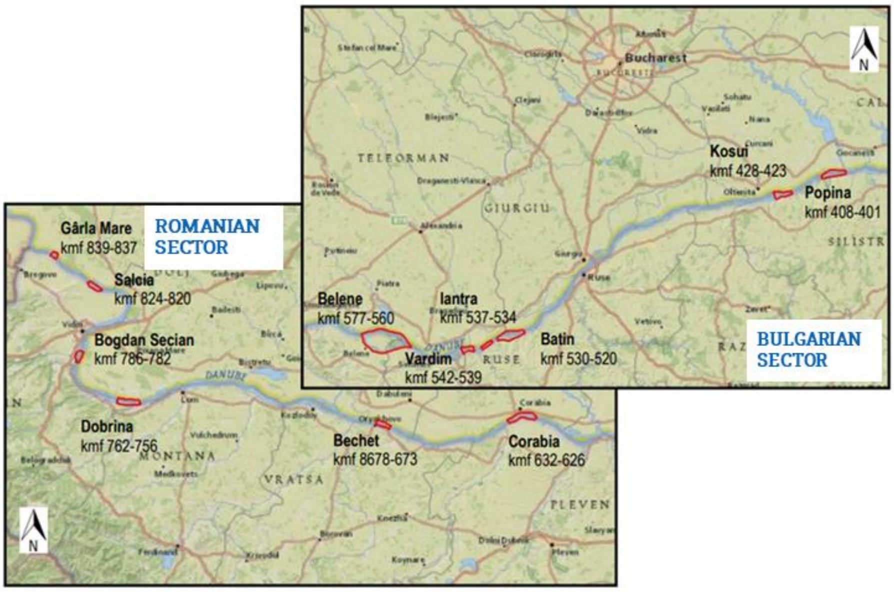

Figure 5. The location of the 12 critical points in the Romanian sector and in the Bulgarian sector
Source: http://www.fastdanube.eu/official-documents

In 2011, with the completion of a feasibility study necessary to start FAST DANUBE project, in the river sector downstream the Iron Gates II, in the common Romanian-Bulgarian section between km 845.5 - km 375, 12 critical spots for navigation were identified (Table 1), distributed in five critical areas, which require careful monitoring, through a series of topo-bathymetric measurements.

Table 1. Critical spots for navigation

NO.	NAME	LOCALIZATION (RIVER KM)	ADMINISTRATIVE TERRITORY
1	Gârla Mare	km 839 – km 837	Romania
2	Salcia	km 824 – km 820	Romania
3	Bogdan-Secian	km 786 – km 782	Romania
4	Dobrina	km 762 – km 756	Romania
5	**Bechet**	**km 678 – km 673**	**Romania**
6	**Corabia**	**km 632 – km 626**	**Romania**
7	Belene	km 577 – km 560	Bulgaria
8	Vardim	km 542 – km 539	Bulgaria
9	Iantra	km 537 – km 534	Bulgaria
10	Batin	km 530 – km 520	Bulgaria
11	Kosui	km 428 – km 423	Bulgaria
12	Popina	km 408 – km 401	Bulgaria

As a result of the carried out feasibility study, the recommendation of the Danube Commission for the Romanian-Bulgarian sector stipulates a channel width of 180 m, with a minimum depth of 2.5 m and a minimum radius of curvature of 1000 m. For areas where the minimum depths are not maintained (Figure 6), it was proposed to reduce the width of the channel to 150 m.

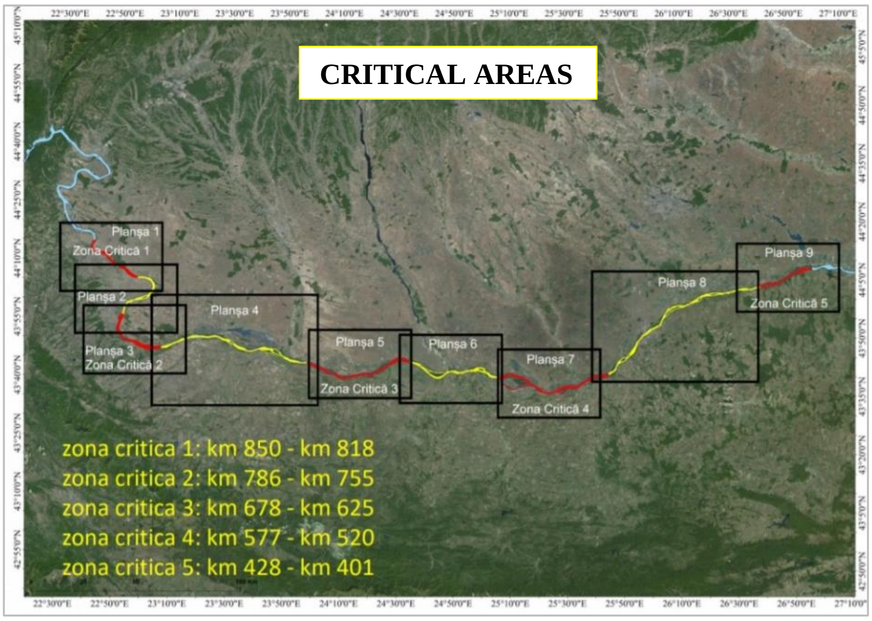

Figure 6. The location of the five critical areas in the Romanian sector and in the Bulgarian sector
Source: http://www.fastdanube.eu/official-documents

The five critical areas for navigation have been established according to Table 2, comprising at least two critical spots.

Table 2. Critical areas for navigation

CRITICAL AREA NO.	*LENGTH (RIVER KM)*	*CRITICAL POINTS INCLUDED IN THE CRITICAL AREA*
ZC1	*km 850 – km 818*	*Gârla Mare, Salcia*
ZC2	*km 786 – km 755*	*Bogdan-Secian, Dobrina*
ZC3	***km 678 – km 625***	***Bechet, Corabia***
ZC4	*km 577 – km 520*	*Belene, Vardim, Iantra, Batin*
ZC5	*km 428 – km 401*	*Kosui, Popina*

The development of navigation in optimal conditions is vital for increasing the safety of freight traffic, given the strategic position of the Danube, as part of the Trans-European Main Navigation Line Rhine - Main - Danube. It runs diagonally across the continent and connects the North Sea to the Black Sea (via the Rhine-Main-Danube canal and the Danube-Black Sea canal), including all river ports until the port of Constanța. Due to navigation problems, the volumes of goods transported on the Danube River represent only 10-20% of those transported on the Rhine.

In order for the transport on the Danube River to become more competitive compared to road, rail or air transport, it is essential to maintain ship traffic during periods of low flow and to reduce the fairway maintenance costs.

In conclusion, the development of technical solutions to reach the recommended parameters for the fairway (depth, width, radius of curvature), even in the context of low levels, depends on understanding the behavior of the river, especially on critical sectors, where sediment transport modeling is essential.

1.3. Purpose and Objectives of the Research in the Current Scientific Context

Sediment transport modeling on the Danube River and general improving of the fairway maintenance processes is still an issue of **great interest**, which has not been exhausted by past research programs and projects.

The main purpose of this paper is to develop a complex hydraulic and sediment transport model of the Bechet-Corabia Danube River sector, using various types of geodetic measurements to determine the necessary elements.

Understanding the morphological processes of a river in the context of hydrodynamic modeling, as well as sediment transport modeling is a particularly difficult task, which requires a huge amount of data collected during field campaigns and interdisciplinary knowledge, the proposed subject matter being on the border between Geodesy, Hydrology and Hydraulics.

Thus, a number of objectives are subordinated to the above-mentioned purpose:

I. The statement of the theoretical notions underlying the process of interconnection of the topo-hydrographic works performed on the Danube River in a unitary geodetic system, aligned with the current European and international standards;

II. Presentation of the geodetic infrastructure in the Romania-Bulgaria border area and highlighting its role in the activities carried out to maintain the navigability conditions on the Danube;

III. Review of the types of geodetic measurements performed in order to sediment transport modeling on the Danube River, as well as of the equipment used for the acquisition of topo-geodetic data;

IV. Presentation of the concept of "hydraulic modeling" and description of the mechanism of sediment transport;

V. Evaluation of the area of interest (Critical Area 3 - Bechet-Corabia) and generation of its digital model;

VI. Creating a geospatial database, as well as identifying an existing cartographic database in different libraries and archives, which would allow the analysis of the morphological changes of the Danube riverbed on the studied sector;

VII. The use of GIS techniques for visualizing and processing geospatial input data in the mathematical model, but also for spatial representation (such as maps) of the results obtained using hydraulic modeling software (MIKE 21);

VIII. Detailed presentation of the steps necessary to achieve the hydro-sedimentary model;

IX. Analysis of areas with depositions/erosions obtained following the simulation of sediment transport based on the developed model;

X. Highlighting possible sources of errors that may influence the final results and formulating research conclusions.

The results of this study are intended to be useful for future scientific research, and from a practical point of view is the basis for identifying measures to contribute to the stabilization of the Danube riverbed (on the Romanian sector).

CHAPTER 2

COORDINATE REFERENCE SYSTEMS USED ON THE COMMON DANUBE RIVER SECTOR BETWEEN ROMANIA AND BULGARIA

2.1. Coordinate Reference Systems - General Notions

A coordinate reference system (CRS) consists of two components: the datum and the coordinate system (Figure 7). The datum is the physical part of the CRS, and the coordinate system is the mathematical part.

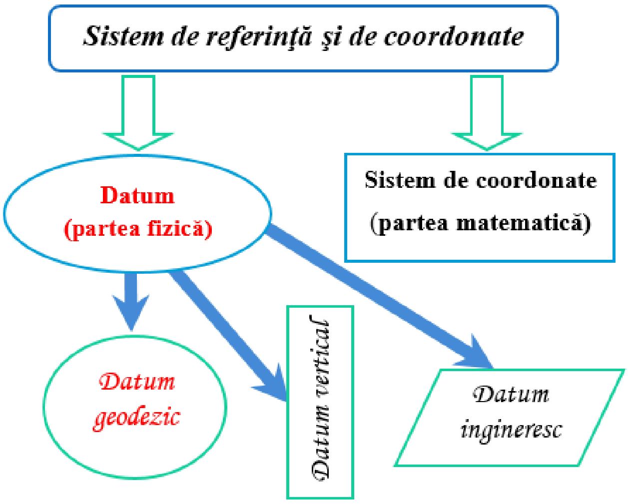

Figure 7. Components of a Coordinates Reference System

Globally, there is a variety of CRSs through which the geographical position can be described mathematically with the help of coordinates, but it receives values specific to each system. Therefore, in the case of coordinate reference systems, it is mandatory that all coordinates be certified by units of measurement and accompanied by an unambiguous identification of the system in which they are expressed.

Regardless of the space in which it takes place, the geodetic activity has as final goal the determination of the position which, as mentioned, is given by a set of coordinates. In general, it is a matter of determining the geodetic coordinates latitude and longitude (B, L) and height (H) of certain points on the Earth's surface. This activity consists mainly of performing measurements of directions, distances, height differences, observations made with the help of artificial satellites of the Earth, etc. and certain calculations necessary to obtain the coordinates (Rus, 2018).

As a rule, at least one datum has been defined for each country in the world, as well as each country has adopted at least one projection system for the representation of the earth's surface, as well as a vertical datum.

Assuming working with data represented in two or more CRSs, as is the case of the common Danube sector between Romania and Bulgaria, it is necessary to know the parameters and transformation algorithms that link those systems, although, in order to simplify calculations, the ideal solution it is the adoption of a common CRS.

In order to provide a clearer picture of the coordinate reference systems used on the Romanian-Bulgarian Danube sector, it is firstly necessary to define the notions of *datum*, *vertical datum*, *coordinate system*, *reference system*, in order to avoid any confusion about them.

2.2. National CRS S42 and the link with ETRS89

On the territory of Romania, the CRS currently used is the S42 System, which is based on the 1940 Krasovski ellipsoid (with the Pulkovo fundamental astronomical point), and the coordinate system is defined in the 1970 Stereographic projection plane.

At European and global context, cooperation in the field of geodesy and cartography is vital. Against the background of the current disadvantages of S42 and the perspectives opened by the position determinations with the help of artificial satellites, it was considered beneficial to adopt in our country the ETRS89 Coordinate Reference System, for a wide range of works in different fields of activity.

In order to make the connection between ETRS89 and S42, it is necessary to perform a composite coordinate transformation (defined according to ISO standards), from the coordinate system defined in ETRS89, to the Stereo '70 coordinate system defined in S42 and the 1975 Black Sea normal height system, linked to S42 by the quasigeoid anomalies.

This composed coordinate transformation was implemented in the TransDatRO calculation program. The application is based on an algorithm presented schematically in Figure 8 and includes a national quasigeoid model determined by the constraint of the European model EGG97, insufficiently accurate for the geodetic needs in our country.

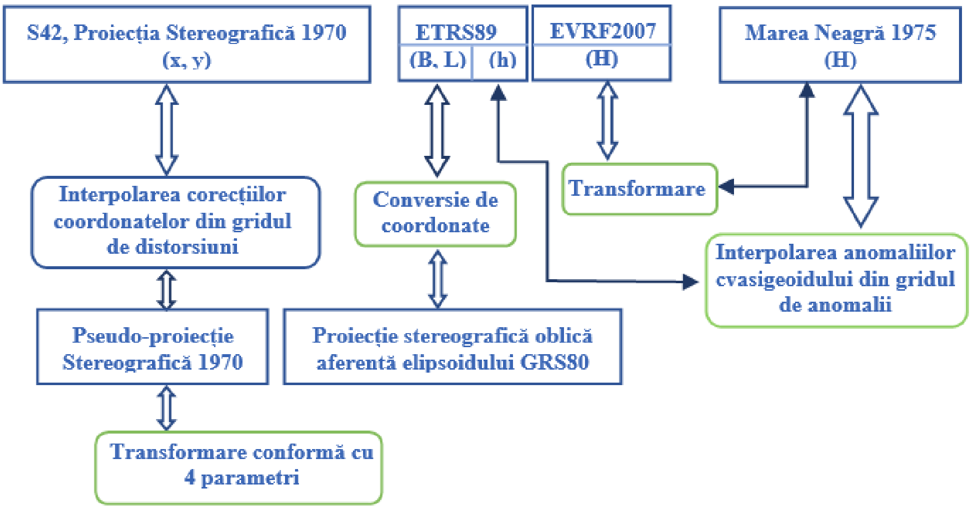

Figure 8. The connection between ETRS89, EVRF2007 and the local reference geodetic system S42, Black Sea Height System 1975

Source: (ANCPI, 2010)

2.3. Bulgarian Geodetic System 2005 (BGS 2005)

The Bulgarian Geodetic System is applied on the territory of the Republic of Bulgaria under the name "Bulgarian Geodetic System 2005" (BGS 2005), where "2005" is an index showing the "epoch" in which the coordinates of the points of the geodetic network have been established in accordance with Ordinance No 2 of 30 July 2010 on the definition, implementation and maintenance of the Bulgarian Geodetic System, which is implemented through the creation and maintenance of geodetic points, which are evenly distributed throughout the Bulgarian territory and form the basis of unified geodetic datums (Rus, 2018).

In the territory of the Republic of Bulgaria, the points of the unified geodetic datums are determined by performing high-precision measurements (satellite, geodetic, gravimetric, astronomical and geomagnetic) and by using data from permanent GNSS stations. These points are grouped into several geodetic networks: National Geodetic Network, National Leveling Network, National Gravimetric Network, Tide Chart Network, Magnetic Station Network.

The Bulgarian Geodetic System 2005 includes (Rus, 2018):

- ✓ fundamental geodetic parameters calculated in accordance with the 1980 Geodetic Reference System (GRS80);
- ✓ ETRS89 geodetic coordinate system, epoch 2005.0;
- ✓ altimetric system implemented through the leveling benchmarks of the National Leveling Network included in the Unified European Leveling Network (UELN) and defined in the European Vertical Reference System (EVRS), by using data on gravitational force in a unified gravimetric system (IGSN 1971);
- ✓ Universal Transverse Mercator (UTM) cartographic projection and the rectangular coordinate system introduced by it, called "CS2005" (Cadastral System 2005) .;
- ✓ the division on maps and the nomenclature system based on the international map of the world, on a scale of 1: 1000000, as decided by the Congress of Geographers of London, 1909.

2.4. Reference Systems for Heights

As in the past there were no precise methods for determining the geoid, the mean sea level was used to approximate the surface of the geoid. The actual determination of global geoids has been carried out by using gravimetric data, satellite-derived information related to the gravitational field of the earth, or a combination of the two techniques

Over the past decades, every country or group of countries have established those mean sea level points which are normally located close to the area of concern: for the Netherlands and Germany, the local mean sea level is realized through the Amsterdam tide gauge (zero height), for Greece - Thessaloniki, Antwerp for Belgium, in England, the Ordnance Datum was determined at Newlyn from records extending from May 1915 to April 1921, in France the local mean sea level was determined at Marseille tide gauge, etc. (Imbroane, 2013).

Due to variations in the Earth's gravitational field, "zero" in the Black Sea does not coincide with "zero" in the Mediterranean Sea, the Atlantic Ocean or other seas and oceans of the planet.

The need to define height reference systems arose in the second half of the eighteenth century, when they began to develop hydrographic maps with bathymetry of the seas and oceans and topographic maps with contour lines.

A height reference system is defined in several steps:

- choosing a reference surface;
- adopting a definition in the physical or geometric sense that describes the position of the points on the terrestrial surface in relation to the chosen reference surface;
- specifying a fundamental “zero” point considered to be the mean level of the open seas and oceans, obtained through long term observations and to which all the leveling works that use the respective datum are related.

Due to the fact that the sea level is constantly changing, the datum has a temporary validity.

The System of Normal Heights System with Black Sea 1975 fundamental "zero" point

Currently, Romania is using the system of normal heights with Black Sea 1975 (1990 edition) fundamental "zero" point (1990 Edition), located in Constanța.

Over time, several fundamental "zero" points have been used in our country: "zero" Black Sea Sulina, "zero" Adriatic Sea, "zero" Baltic Sea (most often used). The connection between these reference surfaces has always been a challenge for both surveyors and specialists in fields such as Hydrology, Hydrotechnics or Geography.

The fundamental "zero" point was considered the fundamental benchmark of type I - DTM in the Military Chapel in Constanţa, whose height was determined through geometric leveling works, which were repeated in 1962, 1963, 1964, 1970, 1972, and with the help of gravimetric determinations (Ghițău, 1983).

In order to highlight the variation of the reference level, as well as for a greater stability in time of the fundamental point, the absolute height was transferred from the seaside to approximately 53 km N-NW of Constanţa, between the Dobrogean localities Tariverde and Cogealac, in an area with green shales (stable tectonic zone). Thus, the “fundamental point of the leveling network” was built, and its connection with the Black Sea tide gauges was made through a network of high-precision geometric leveling polygons, which also connects with the tide gauges of Varna and Burgas in Bulgaria.

The National Center for Geodesy, Cartography, Photogrammetry and Remote Sensing performed new measurements in the national leveling network and, obviously, a new processing of the network. As the accuracy obtained was better than that achieved by the DTM, it was called a "zero" order network. Also, this network contains a larger number of polygons than the first order network made by the DTM. As the height system remained the same (System of normal heights with Black Sea 1975 fundamental zero point), but the heights were also recalculated for the benchmarks of the leveling networks of order II, III and IV, this officialization is called “1990 Edition”.

Through the TransDatRo software, there is the possibility to transform the heights from the national reference system (Normal height system with Black Sea 1975 - 1990 edition fundamental “zero” point, located in Constanța) into the European Vertical Reference System (EVRS).

Baltic Sea system of normal heights

Similar to the definition and implementation of the Black Sea 1975 normal height system, in the Eastern European countries (including Romania) the “Baltic Sea” normal height system was used, having as fundamental or zero point the Baltic Sea - Kronstadt.

At present, a number of countries in this area still use this height system or newer versions of it at national level, including Bulgaria.

According to the Bulgarian Agency for Cadastre, Cartography and Geodesy, both the Baltic Sea Height System 1982 and the European Vertical Reference System (EVRS)/ EVRF2007 (Amsterdam) are currently used in the neighboring country.

The difference between the heights determined in the Baltic Sea system and the Black Sea system, measured for the reference point in Varna, is -24 cm (Rus, 2018).

Brief history of the height reference systems used on the Romanian sector of the Danube River and the connection between them

In the last 150 years, with the help of staff gauges, it has been possible to accumulate an important fund of truthful data regarding the water level regime of the Danube River, the Danube Delta and the Black Sea.

For the reference of isoline maps, three reference systems have been adopted in the Danube river basin: the Adriatic Sea, the Baltic Sea and the Black Sea. In the hydrographic system of the Black Sea there are several reference surfaces: Sulina, Constanța, Varna, Odessa, Sevastopol, Kerch, Poti, Batumi and others.

On the territory of our country, the first level measurements on the Danube River were made by Austria in Orșova in 1838, by means of a hydrometric gauge whose origin was referenced altimetrically to the surface of the Adriatic Sea. The second hydrometric gauge was installed in Drencova, in 1854, having its origin also referred to the Adriatic Sea (NIHWM, 2019).

For as accurate information as possible about the origin and situation of the hydrometric gauges installed along the Danube, gauging station journals or activity plans prepared by NIHWM specialists, as well as various national publications were consulted. In the end, it was found that the origin of hydrometric gauges placed on the Romanian sector of the Danube River is related both to the Black Sea Sulina “zero” reference surface and to the Baltic Sea Kronstadt “zero” surface and partially to the Adriatic Sea Trieste “zero” reference surface (hydrometric gauges from Baziaş, Moldova Veche, Drencova, Sviniţa, Orşova and Turnu Severin) (State Water Committee, 1965).

This subchapter presents the history of using the main height reference systems on the Romanian sector of the Danube River and, moreover, represents a review of the links between them. Although they have been determined in the past, some of them have been transposed into GIS format in order to facilitate transformations.

- *The connection between the Black Sea “Sulina” and Black Sea "Constanţa" height reference systems;*
- *The connection between the Black Sea "Constanţa" and the Baltic Sea "Kronstadt" height reference systems*

CHAPTER 3

GEODETIC INFRASTRUCTURE ON THE ROMANIAN-BULGARIAN BORDER AREA

3.1. Geodetic Networks

Regardless of the type of work performed in the field of Geodesy, it is assumed that there are points with known coordinates on which to base the work. All these points constitute an infrastructure known as the **geodetic network**.

A geodetic network consists of the set of points located on the surface on which a work is carried out, whose position is known in a unitary reference system (Moldoveanu, 2002).

The absolute or relative positioning of these points has always been a fundamental problem of Geodesy, approached depending on the type of network, its destination or the size of the area covered. Consequently, not all possible types of measurements can be found in a network (Moldoveanu, 2011).

In order to achieve this goal, Geodesy establishes the rules and methodology necessary for the execution of high-precision measurements and determinations to be rigorously processed, so that in the end, the correct positioning of the points from a planimetric and altimetric point of view is achieved. Thus, the position of a geodetic point in space is defined in relation to two distinct surfaces: on one hand the reference ellipsoid, for the latitude (B) and longitude (L) coordinates, or the projection plane, for the x, y coordinates, and on the other hand the geoid or quasi-geoid, for the determination of height (h), depending on the officially adopted system.

At present, the trends are to homogenize the three-dimensional spatial coordinates, both in terms of the coordinate system and the (single) reference surface (usually the reference ellipsoid).

In this subchapter there were presented:

- *Romania's National Geodetic Network;*
- *Bulgaria's National Geodetic Network;*
- *Romania's National Space Geodetic Network;*
- *Bulgaria's National GNSS Network.*

3.2. Geodetic Infrastructure Issues on the Common Danube River Sector between Romania and Bulgaria

Regardless of the number of height reference systems used in the past, the lack of a geodetic network in the Danube flood plain and in the adjacent areas has made it impossible, year after year, to acquire data on the Romanian Danube sector in a unitary system. Moreover, along the entire Danube River coexisted not only several height reference systems (Black Sea

Sulina, Constanța, Varna, Odessa, Baltic Sea, Adriatic Sea), but also several projection systems and several reference ellipsoids.

All these problems have led to the need to develop an adequate system for carrying out measurements along the Danube, in accordance with the European transport requirements on Corridor VII (Danube, including the Danube-Black Sea Canal), at the level of standards adopted at European and international level. : IHO S-44, S-57, 7008/1996 etc.

For this purpose, through a project of LDRA Galați completed in 2015, a network of points (144) was designed and materialized along the Romanian sector of the Danube (approximately 15 kilometers from each other), called „ AFDJ2014 ", for which the heights in the national system were determined (specified above), with the possibility to make the transformation in the European height reference system, but also in the height system used in Bulgaria.

The basic network for hydrographic works consists of benchmarks and physically worn staff gauges. Most staff gauges are of the inclined type, placed on the slopes of the riverbed and are made of metal plates in the form of rulers scaled in centimeters. Given that the absolute heights of the "zeros" of the hydrometric gauges on the Danube River differ from each other depending on the reference surface to which they were referred, the determinations of the heights of the free surface of the water could not be made in the same height reference system.

This issue was partially solved by a project of the Ministry of Environment, Waters and Forests entitled "Danube WATER Integrated Management", also concluded in 2015, which established a common coordinate reference system for hydrometric gauges that monitor the Danube River in the common sector between Romania and Bulgaria. At the same time, for the study area, the origin of the hydrometric gauges on the banks of the Danube River in the new SCR was determined.

In order to improve and extend the waterways, as well as to monitor the dynamics of the riverbed, it was and is necessary to interconnect the topo-hydrographic works in a common geodetic system: horizontal CRS, named ETRS89, and vertical CRS, named EVRS/implementation EVRF2007. A solution for complying with these current European and international standards was to create a local quasi-geoid model on the common Danube sector between Romania and Bulgaria, followed by determining the transformation parameters between geodetic reference systems used on the Romanian-Bulgarian common sector and providing the calculation algorithm and transformation parameters, all these objectives being achieved within the **FAIRway Danube** project - "**Implementation of the Master Plan for the Rehabilitation and Maintenance of the Danube Fairway**" (2015-2020).

3.3. Types of Geodetic Measurements Performed in View of Modeling the Sediment Transport on the Danube River

In the field of Geodesy, there has been an increase in positioning accuracy of about one order of magnitude every decade, starting at an accuracy of about 1-10 meters in the mid-1970s, and reaching up to about 1 millimeter at present.

This extraordinary progress is due not only to technological innovations but also to the coordination of the scientific community through global geodetic services. Scientific research in this area has also led to significant improvements in the accuracy of geodetic data.

From a technical point of view, for the performance of geodetic measurements on the Danube River or along it, currently are used both classical methods and techniques of measurement (triangulation, trilateration, leveling) and highly advanced spatial and electronic technologies (GNSS, LiDAR etc.). The required accuracy must be taken into account when collecting data, as it plays an essential role in the choice of equipment and measurement methods (Niemeier & Rohde, 1982).

Bathymetric measurements can be seen as an extension into the aquatic space of terrestrial measurements and are interdependent with them. The difference is that, in most cases, bathymetric measurements are performed using a mobile platform (ship, boat), and the instruments and equipment are adapted to the working conditions on the water. Of these, the following were presented in the paper:

- *Interferometric Side Scan Sonar;*
- *Single Beam Echosounder;*
- *Multibeam Echosounder;*
- *Acoustic Doppler Current Profiler system.*

CHAPTER 4

THEORETICAL ASPECTS REGARDING SEDIMENT TRANSPORT ON THE DANUBE RIVER

4.1. Hydraulic Modeling - the Premise for Creating Flow and Sediment Transport Models

According to the authors (Wang & Wu, 2004), sedimentation processes and morphological changes in rivers are among the most complex and least understood natural phenomena. Along with the body of water, rivers carry significant amounts of solid materials of various shapes and sizes.

"*By washing the surface of the basins and by entraining dissolved substances from the underground, river water is loaded with solid particles and dissolved substances*" (Diaconu & Șerban, 1994).

The hydrological regime of the rivers and implicitly of the Danube River is a result of natural factors (climatic conditions, lithology, relief, soil and vegetation) and anthropogenic factors, which interfere with the entire river basin (Mitof, 2016).

Bondar (2010) states that, in the last century, there are a number of changes in the flow of water and alluvium of the Danube, due to natural and anthropogenic influences.

In recent decades, remarkable progress has been made in the study of river flow and morphology and fluvial sediment transport through the use of hydraulic and sediment transport modelling tools.

In the field of Hydrotechnics, **modeling** is an extremely effective tool for solving concrete problems by reproducing the phenomena studied with the help of **hydraulic models**. In general, by "model" we mean the set of objects, including symbols or simplified representations, which are in a correspondence relationship with the phenomenon subject to knowledge (Cioc & Tatu, 1981).

A fundamental problem of Hydraulics is **the free surface movement of water** in rivers and canals (or in pipes with a partially full section).

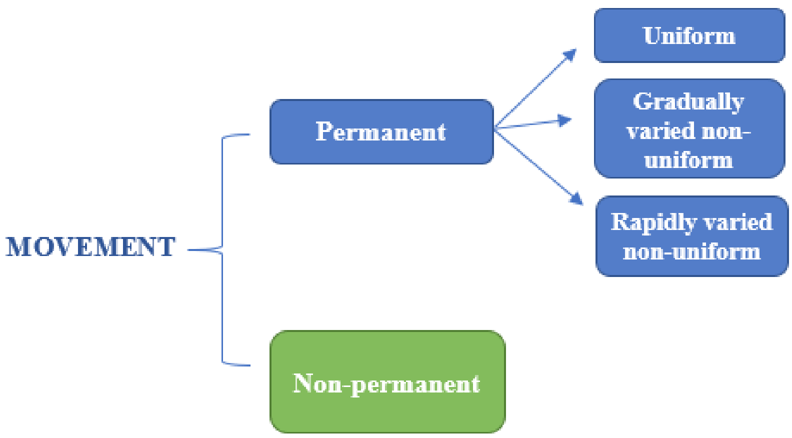

Figure 9. Classification of types of free surface movement

Free surface (or free level) movements are the movements of liquids that occur so that along the current there is a free surface in contact with the atmosphere (Diaconu, et al., 1978).

According to (Trofin, 1974), the free surface movement of riverbeds can be classified according to how the hydraulic parameters (flow, speed, depth, slope, surface and wet perimeter) vary in time and space, as shown. in *Figure 9*.

The type of flow is directly influenced by the changes suffered by the riverbed.

In general, the flow in open riverbeds has a non-permanent character, due to the way the watercourses are fed, but also due to the frequent non-uniformities in the riverbed.

Non-permanent movements with a free surface have an undulating character and arise as a result of changing boundary conditions, by changing flows or levels. These disturbances, which are transmitted with finite speed in the form of waves, simultaneously change both the flow and the level. Since the transmission of level changes leads to a change in the shape of the free surface, any non-permanent movement with the free surface can be recognized by the variation of the shape of the free surface over time, as is the case, for example, with waves.

The mathematical modeling of the riverbed consists in the simulation of the flow conditions, based on the formulation and solution of the mathematical relations that express the equations of motion of the water in the riverbed.

In the literature, the fundamental equations of non-permanent motion in open riverbeds are called the Saint-Venant equations. Several forms of the Saint-Venant equations can be used to analyze the movement of water in canals, which, compared to their original form, have undergone generalizations and improvements over time.

The Saint-Venat equations are in fact a system of equations with partial derivatives of the second order, nonlinear, of hyperbolic type:

- the continuity equation, expressing the principle of conservation and continuity of the liquid phase:

$$\frac{\partial Q}{\partial x} + \frac{\partial A}{\partial t} = 0; \qquad \textit{(4-1)}$$

- equation of motion, expressing the principle of conservation and continuity of energy:

$$\frac{\partial Q}{\partial t} + \frac{\partial (Q \cdot V)}{\partial x} + g \cdot A \cdot \left(\frac{\partial h}{\partial x} - S_0\right) + g \cdot A \cdot S_f = 0; \qquad \textit{(4-2)}$$

where:

S_0 represents the slope of the riverbed, Sf - the friction slope, V is the speed considered uniform in cross section, and A - the area of the living section; V and A are functions of x and t, so the flow rate will be:

$$\mathrm{Q} = A \cdot V = Q(x,t) \qquad \textit{(4-3)}$$

The exact solution of the Saint-Venant equation system (4-1), (4-2), in the sense of obtaining unknown values (dependent variables) at all points of the plane of independent variables is practically impossible.

4.2. The Mechanism of Sediment Transport

The alluvium in the bed and the banks of watercourses are permanently under the action of a very complex system of entrainment and resistance, depending on the intensity of which the "general state of hydrodynamic entrainment" is achieved, which includes rest, initiation, development and cessation of particle/sediment masses transport (Ichim, et al., 1989).

The system of forces consists mainly of the hydrodynamic entrainment force, which tends to move the sediment particles, and the resistance forces, which oppose the hydrodynamic entrainment, consisting of the submerged particle weight (predominant in the case of non-cohesive alluvium), cohesive forces of a physico-chemical nature (predominant in the case of cohesive alluvium) and contact forces between non-cohesive particles, due to the interpenetration and interaction of neighboring particles and in a weaker or more accentuated state of clamping.

The general state of hydrodynamic entrainment of alluvium is determined by the ratio established in time and space between the entrainment and resistance forces, or by the ratio of the moments of the two types of forces to a center of overturning / contact between sediment particles. When the flow regime of the liquid phase determines reaching subunit values of the ratio of forces or moments that stress the sediment particles, the initial phase of the general state of entrainment is achieved, namely the state of rest, corresponding to the stable equilibrium conditions of the particles. When the flow regime of the liquid phase causes the increase of the intensity of hydrodynamic force of the particle entrainment to values equal to the intensity of the resistance forces, so that approximately unitary values result for the ratio of forces or moments that stress the sediment particles, the critical entrainment state is reached, corresponding to the conditions of unstable equilibrium of particles.

This state causes slight pulsating movements of the particles, which make some local jumps, of short length, of the order of the length of the particles, followed by their repositioning on the surface of the riverbed and reaching, again, the unstable equilibrium state.

Once the critical entrainment state is reached, the increase of the intensity of the hydrodynamic entrainment force determines the beginning of the movement of the sediment particles at the level of the riverbed, a situation characterized by superunit values of the ratio of forces or moments that stress the particles.

This movement develops, at least in the first moments, by sliding or rolling (when the resultant of the two forces forms a negative angle with the bed surface) or by performing jumps along the curvilinear trajectories of increasing lengths, depending on the intensity of the entrainment (when the resultant forces form a positive angle with the bed surface). The movements are followed by moments and time periods in which the particles resettle and "rest" on the surface of the bed, then continuing the process of movement, similarly with the entrainment of an increased number of particles, as the intensity of the hydrodynamic entrainment increases.

This is the form of development of ***bedload transport***, defined as solid phase transport that develops in the immediate vicinity of the riverbed and in which the movement of sediment particles takes place by sliding, rolling and jumping.

The incipient phase of bedload transport is the sediment transport by "washing", which affects especially the finest particles, which come from soil erosion in the receiving basin of the watercourse and which usually have much smaller diameters than those of riverbed and bank materials.

In the situation where the flow regime of the liquid phase determines the further increase in intensity of the entrainment force, so as to reach much higher superunitary values for the ratio of forces or moments stressing sediment particles, their jump movement is accentuated, the length and amplitude of jumps is higher, with prolonged periods of time, during which the particles leave the riverbed and remain suspended in the liquid mass. This maintained suspension of particles for extended periods of time is favored by the intensity and fluctuations of the turbulence of the liquid phase flow, the increase of which ultimately leads to the development of ***suspended sediment transport***.

In this form of transport of the solid phase are entrained both the larger sediment particles in the riverbed and the much finer particles, which are washed so that, practically, there is a permanent reciprocal exchange of solid phase between the mass of liquid loaded with sediment and sediment mass from the surface of the riverbed. It is obvious that the suspended transport intertwines with the bedload transport and the one carried out by washing.

Due to this complex physical mechanism, it is not possible to clearly delimit between these ways of developing sediment transport in riverbeds, which is why the broader notion of total sediment transport, developed over the entire depth of flow and defined as the sum of the bedload and suspended sediment transport.

Once the sediment transport is developed on the entire depth of the riverbed, the hydrological and hydraulic regime of the liquid phase flow gradually determines, as the speed decreases, the hydrodynamic force decreases or the resistance forces increase and the state of "sedimentation/deposition" of the alluvium is reached.

The deduction of sediment transport equations has been the concern of several authors, such as: Engelund-Hansen (1967); Ackers-White (1973); Smart-Jaeggi (1983); Engelund-Fredsøe (1976); Van Rijn (1984), Meyer-Peter & Müller (1948); Sato, Kikkawa & Ashida (1957); Ashida & Michiue (1972); Lane-Kalinske (1941); Yang (1973) etc.

CHAPTER 5

MODELING THE SEDIMENT TRANSPORT ON THE DANUBE RIVER. CASE STUDY – BECHET-CORABIA DANUBE RIVER SECTOR

5.1. Introduction

In general, when modeling long river sectors, the most used are the one-dimensional (1D) models, which are based on the equations of uniform flow and those of uniform-varied flow. (Nistoran, et al., 2008) consider that these models have the following advantages: simplicity of calculations, ease of parameterization, easy calibration, smaller number of data required for calibration/validation. The development of a numerical model of fluid mass displacement, especially during floods, is a complex process, as it is based on the Saint-Venant system of equations, in which parameters such as the roughness defined for each calculation section can be found. In general, these roughness coefficients take different values for the low-flow channel and for the floodplain, or they can vary vertically. Their calibration actually means adjusting their values within acceptable limits in order to accurately reproduce the levels recorded in situations that have been very well monitored.

2D hydrodynamic propagation models are able to reproduce spatially distributed phenomena in a very realistic way, although they are more difficult to calibrate and validate than 1D models, as the necessary data is obtained through modern measurement technologies. In addition, 2D hydraulic models require a longer computation time, and the data required for the construction of the geometry must have a much larger spatial distribution (Nistoran, et al., 2008). 2D models integrate depth-mediated Saint-Venant equations by the finite element method.

Two-dimensional models can be divided into three categories: quasi-2D models, full 2D models and combined 1D-2D models. There are also situations in which a three-dimensional approach to the flow is required, especially when it passes from the riverbed to the floodplain (Văduva, 2012). 3D models are able to reproduce secondary vortices in meanders and vertical variations in hydraulic sizes. They solve the Reynolds equations and provide a better description of the turbulence and sediment transport initiated by it, but the calibration of these models requires very detailed flow field measurements.

Hydro-sedimentary modeling is a tool for predicting the behavior of a river on the short or long term, which helps to study the phenomena of erosion or deposition, as well as to quantify sediment transport and changes in the riverbed.

The hydro-sedimentary models treat separately the flow part of the clean water from the diffusion-advection phenomenon associated with the sediment transport, taking into consideration the deformable bed. These models also include the continuity equation for the sedimentary material and take into account the entered amount of sediment, being able to predict an exiting solid flow (current carrying capacity) and quantify the processes of aggradation and degradation (evolution of deformation) of the riverbed on the respective sector. These morphological changes can be calculated either in equilibrium conditions, for a given set of stationary conditions of hydraulic parameters and sedimentary material, or in non-stationary conditions, by using certain mathematical functions (AMTRANS Software, 2006).

In some cases, in order to simplify the calculations, a single particle size class can be used (taken as the average diameter of the particle size curve, d_{50}), and with the help of mathematical functions the solid flow can be predicted, either for bedload, for suspended transport, or for both.

5.2. Study Area

The area selected (Figure 10) to elaborate a complex hydrodynamic and sediment transport model refers to the Danube critical sector extended between Bechet Gauge Station (rkm 625) and Corabia Gauge Station (rkm 678).

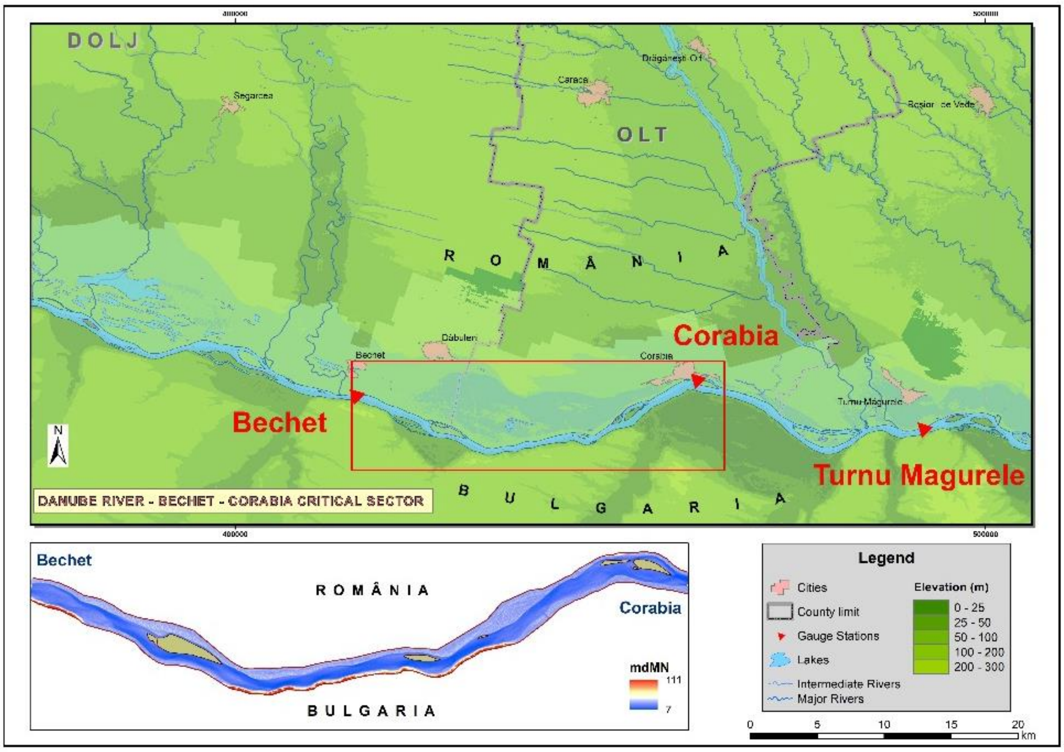

Figura 10. Study Area

This sector is representative for the research because, on the approximately 53 km of the watercourse, navigation is very difficult due to the complexity of the hydraulic regime and the dynamic changes of the riverbed morphology, with unfavorable effects on the **fairway**[3].

[3] The fairway is a navigable section along a watercourse, canal or lake. It is continuous, sufficiently wide and deep to ensure the movement of ships, the entry of ships into port or their passage through a narrow place. The fairway is maintained and marked for the purpose of safe navigation. *Source: www.wikipedia.org.*

Geodetic Infrastructure on the Critical Area 3 – Bechet-Corabia

On the analyzed Danube River sector, Bechet-Corabia (critical area 3), there are six locations (figure 11) where benchmarks from the AFDJ2014 geodetic network (86-91) were located - Lot 4.

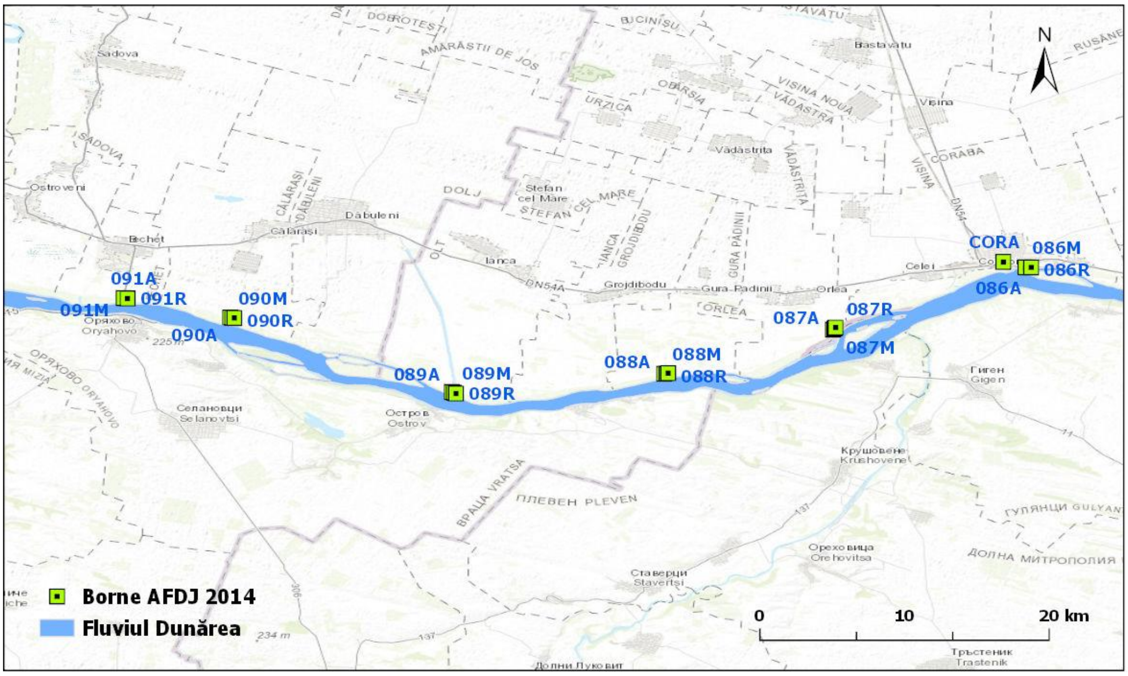

Figure 11. AFDJ2014 support network on the Bechet-Corabia sector

This support network is the basis for the correct redetermination of the origin of the hydrometric gauges, thus making it possible to determine as accurately as possible the absolute height of the free surface of the water. These reference points were also used as base stations where GNSS equipment was installed to generate differential corrections, which were then transmitted by radio waves to the GNSS receiver in the sonar-equipped boat (from which bathymetric measurements were made). The determination accuracy of these points, especially the heights, significantly influences the final results: the DTM and the mathematical model of sediment flow and transport.

5.3. Data Necessary for the Building of the Mathematical Model

The quality of mathematical modeling and the spatial representation of its results are closely related to the input data used. The quality of this data is extremely important, because it directly influences the representation of natural phenomena in a form as close as possible to reality. Consequently, there is a great demand for accurate and precise information, in order to minimize the uncertainties resulting from the simulations.

Data and Products resulted from field measurement campaigns

a) LiDAR data

Within the FAST DANUBE project, in 2017, two scanning campaigns were carried out with aircraft equipped with LiDAR equipment, in April and July, the objective being to cover at least 200 m from the banks of the river (on the common Romanian-Bulgarian sector) and scanning of river islands covered with forest vegetation.

In order to ensure the best input data for the modeling process, the area of interest was extended to a distance of 250 m from the first firm bank (sand areas were included in the water body).

Data obtained during the first survey campaign were used to calibrate the 2D model, while data obtained in the second campaign were used to validate the 2D model. of the Bechet-Corabia sector.

b) Data from Bathymetric Measurements

Along with LiDAR surveys, within the on-going FAST DANUBE Project, two bathymetric survey campaigns were carried out along the Romanian-Bulgarian common sector of the Danube river, in April-May 2017 (68 days, from Călărași to upstream, at the Iron Gates II), respectively July-August 2017 (47 days - from upstream, from the Iron Gates II, to downstream, to Călărași).

Hydrographic, hydrodynamic and sediment data were collected simultaneously.

- **Hydrographic Data**

Three boats equipped with Kongsberg GeoSwath Plus interferometric sonar, operating at 250 kHz and 500 kHz, were used to collect hydrographic data. A higher frequency provides better resolution, but at the same time limits the range. Therefore, the difference between the two frequency classes lies in the width of the swath width.

In order to perform bathymetric measurements, it was preferred to use interferometric sonar, to the detriment of multibeam ones, for the following reasons:

• Interferometric sonar has the ability to chart the banks to the surface of the water thanks to the large beam transmission angle (240 degrees);

• Compared to classic multibeam sonar, interferometric sonar offers up to twice the coverage and is much more efficient in terms of time required and thus the associated costs;

• Interferometric sonar provides more than 5,000 points measured along the scanned swath for each ping (sound wave emission). For the depth range foreseen for measurements, a minimum of 10 pings / s is emitted, which means 7-8 pings / linear meter of profile, resulting in 400-800 measured points / sqm;

• Depth is measured to the surface of the water at a safe navigation distance from dams or underwater obstacles;

• Interferometric sonar is mainly designed to operate in shallow and very shallow waters, while conventional multibeam sonar offers low coverage in these areas.

• The interferometric sonar used can record speeds of up to 7 knots (approx. 13 km / h), more than a conventional multibeam sonar.

Because the GNSS receiver and the sonar, although having different reference systems, perform measurements on the same point, it is necessary to correlate the data provided by the two equipments, so that a point with planimetric coordinates determined by GNSS technology is associated with the corresponding value of the depth measured by the sonar (Constantinescu, et al., 2007).

According to the technical documentation of the system, the accuracy of measuring the depths with GeoSwath Plus systems is ± 3 mm.

Hydrographic, hydrodynamic and sediment data were collected simultaneously.

- **The Digital Terrain Model of the Study Area**

For Bechet-Corabia critical sector, the DTM was obtained based on LiDAR (Light Detection and Ranging) data combined with topo-geodetic and bathymetric data, covering the entire river channel, the adjacent river banks and adjoining land up to a minimum distance of 250 m from the banks of the river on both sides (Figure 12).

In the data processing stage, the Danube River banks and islands were digitized based on LIDAR data. In shallow areas, where scans could not be performed, the remaining gaps between the LIDAR grid and the bathymetric grids were filled with interpolated data using the Surfer software. The resulting interpolated grid was later integrated into the original one.

This high spatial resolution DTM is vital for building the hydro-sedimentary model.

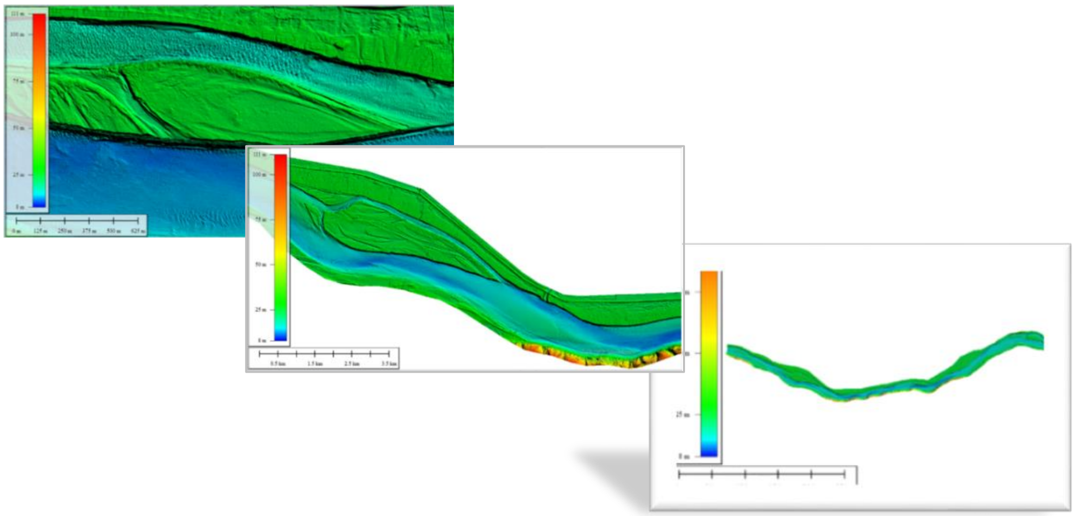

Figure 12. Unified DTM visualization and analysis for critical area 3 (Bechet-Corabia), using Global Mapper software

Hydrodynamic Data

Hydrodynamic measurements were performed using two Teledyne RDI RiverRay 600 Acoustic Doppler current profiler (ADCP) (Figure 13). They adjust the size of the measuring cell according to the depth of the water. The cell size was limited to 50 cm. The two ADCP systems were towed by catamarans for scans (Figure 14).

Figure 13. Teledyne RDI RiverRay 600 ADCP System

Figure 14. Towing the ADCP systems during measurements Tractarea

Source: http://www.fastdanube.eu/official-documents

On the critical area 3 - Bechet - Corabia, 124 hydrodynamic cross sections were executed (Figure 15), at equidistance of approximately 500 m on the navigable branch, and on the secondary branches profiles were made at the entrance, in the middle and at the exit.

Figure 15. Position of hydrodynamic profiles on critical area 3 (Bechet-Corabia)

Sediment data

For each critical area, including for critical area 3 - Bechet-Corabia, within the FAST DANUBE project, two sediment survey campaigns were carried out, which aimed to collect information on particle size and physical-mechanical properties of sediments.

- ***Suspended sediments***

Suspended sediments were analyzed in-situ (no physical samples were taken) using a laser granulometer called LISST (Figure 16), a state-of-the-art instrument specially developed for the on-site determination of the grain size distribuition of the suspended sediment and total concentration (Bogen, et al., 2003).

Figura 16. LISST-200X instrument during use
Source: http://www.fastdanube.eu/official-documents

On the critical Bechet-Corabia sector, along 74 cross sections, the analysis of the 1315 suspended sediment samples collected indicates that the proportion of fine sediments (less than 0.063 mm in diameter) in the riverbed is very small, below 3% of the total, and significant quantities tend to exist only in certain small areas, such as secondary canals. As they are not a significant component of the river morphology in the area of interest, this model does not require the modeling of cohesive sediments. These fine particles are actually "washed" or suspended sediments, having no contact with the riverbed.

- ***Bottom Sediments***

On the Bechet-Corabia critical sector, along 74 cross sections, sediments were extracted from the riverbed with the help of a 25 kg Van Veen type Hydrobios grapple, operated with an electric winch (Figure 17).

Figure 17. Hydrobios grapple and electric winch used for sampling from the riverbed
Source: http://www.fastdanube.eu/official-documents

A total of 279 bedload samples were collected (Figure 18), for which Grain size distribution (GSD) curves were performed (Figure 19) and the statistical parameters of the granulometric distribution were calculated.

Figure 18. Sediment sampling points (Bechet-Corabia Danube sector)

The analysis of the samples was performed in the laboratory, where they were sifted by means of a sieve battery with mesh sizes of 2, 4, 8, 16 and 32 mm. The fractions with pebbles were weighed individually and their percentage was recorded in a table. The fraction less than 2 mm was analyzed separately to determine the distribution and particle size parameters. The analyzes were performed using a laser particle size analyzer called Malvern 3000.

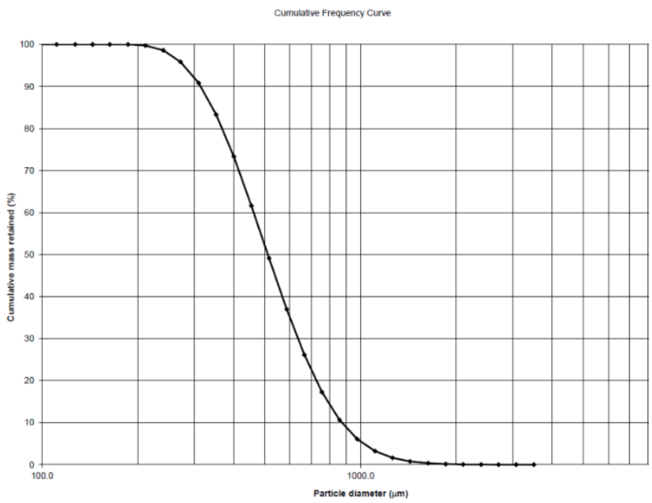

Figure 19. Example of granulometric curve performed for a sediment sample from the riverbed

c) Hydrological Data

The hydrological data necessary for the building, calibration and validation of the hydro-sedimentary model were obtained with the support of the National Institute of Hydrology and Water Management (NIHWM) and of the LDRA Galați - S.C.N. Giurgiu.

All collected data were processed by statistical-mathematical methods (Microsoft Excel 2014) or methods specific to the GIS environment (cartographic, geostatistical).

The hydrological data consist of:

- Daily-mean liquid discharges and daily-mean levels from Bechet and Corabia gauging stations for 2017 (source: NIHWM archive);
- The rating curve (in tabular format) from the Corabia gauging station valid for 2017 (source: NIHWM).
- The value of the "zero" staff gauge corresponding to Corabia Gauge Station (source: NIHWM archive);
- Grain size distribution curves of the samples taken from the riverbed and from the water current (source: FAST DANUBE);
- D_{50} diameter of bedload and suspended sediments (source: FAST DANUBE);
- The roughness coefficients for the low-flow channel and for the floodplain, established following the analysis of several data sets provided by LDRA Galați - S.C.N. Giurgiu and the Corine Land Cover (2012-2018) .shp file with land cover.

d) Other Data Sources

In general, hydrological processes, both those that characterize liquid runoff and those that describe sediment transport, take place at the scale of river basins and are determined by a number of environmental factors, including: lithological substrate (geology), relief, soils, land use, climatic elements, groundwater.

5.4. Geospatial Database

The documentation stage ended with the development of a digital geospatial database in a format specific to Geographic Information Systems - GIS, containing as detailed information as possible on the Danube River in general and the Bechet-Corabia sector in particular.

Geospatial data can be mainly classified into two categories of data representation / models: vector and raster.

In this paper, the following sets of geospatial data in raster format were used:

- Digital terrain model with spatial resolution 0.5 m (source: LDRA - FAST DANUBE project);
- Orthophotoplanes with a spatial resolution of 0.5 m, 2013-2017 and 2017-2019 edition (source: ANCPI, 2020);
- Drawing Master Plans (1889-1916) – source: geo-spatial.org;
- Sentinel 2, Landsat 8, MODIS etc. satellite images of different resolutions. In a first phase, the satellite data do not represent images, but matrices that contain values of the level of electromagnetic radiation, measured in different spectral bands (source: https://www.sentinel-hub.com/explore/sentinel-playground).

Geospatial data in vector format were organized into thematic layers (Table 3), allowing analysis in the GIS environment.

Table 3. The structure of the vector-type geospatial database used in the study

PRIMARY DIGITAL DATA	FORMAT	DATA SOURCE
Geodetic benchmarks	Vector; point	LDRA Galați ("BORD" project)
Hydrographic network	Vector; line	Vectorization of the 1:25000 topographic map
Gauge stations	Vector; point	NIHWM Database
Localities	Vector; polygon	geo-spatial.org
County limits	Vector; polygon	geo-spatial.org
State border	Vector; line	geo-spatial.org
WBA limits	Vector; polygon	NIHWM Database
River Basins	Vector; polygon	NIHWM Database
Banks	Vector; line	Vectorization of orthophotoplanes with a resolution of 0.5 m (2017-2019 edition);
Flood plain	Vector; line	Vectorization of orthophotoplanes with a resolution of 0.5 m (2017-2019 edition);
Talweg	Vector; line	LDRA Galați (Fast Danube Project)
Cross Sections	Vector; line	LDRA Galați (Fast Danube Project)
Sediment Samples	Vector; point	LDRA Galați (Fast Danube Project)
River Islands	Vector; polygon	Vectorization of orthophotoplanes with a resolution of 0.5 m (2017-2019 edition);
Dykes	Vector; point	NIHWM Database
Level Curve	Vector; line	Vectorization of the 1:25000 topographic map
Land Use	Vector; polygon	Vectorization of Corine Land Cover 2012-2018
Soils	Vector; polygon	Vectorization of the 1:200000 soil map
Geology	Vector; polygon	1:200000 Geological Map of Romania

5.5. Specialized Software Used

In order to perform the statistical analyzes and calculations required for this study, several data sets were processed using Microsoft Excel software.

Digitization, processing and export of data required for hydro-sedimentary modeling, as well as volume calculation and spatial transposition of data and information in sketches and maps, were performed using GIS/CAD applications: ArcMap 10.5, ArcGIS PRO 2.1, ArcScene 10.5.1, Global Mapper v18, AutoCAD 2016.

The 2D hydraulic model of the studied critical area (Bechet-Corabia) was developed using the **MIKE 21 Flow Model (FM)** hydrodynamic module from the **MIKE 21** software package, developed by the independent international consulting and research organization DHI.

The 1D hydrodynamic model, required for the roughness coefficient calibration process, was built using the **MIKE HYDRO River** module in the **MIKE 21** package.

The **MIKE Sand Transport (ST)** module was used to simulate sediment transport.

5.6. Sediment Transport Model development on the Bechet-Corabia Danube River Sector

In order to describe and exemplify the ways in which hydrodynamic factors act on the riverbed and implicitly on formations specific to the riverbed, specific methods of hydraulic modeling corroborated with geospatial techniques were used.

The entire workflow is shown in Figure 20. The methodology and techniques used are perfectly replicable for any other river sector, with restrictions on the availability of input data.

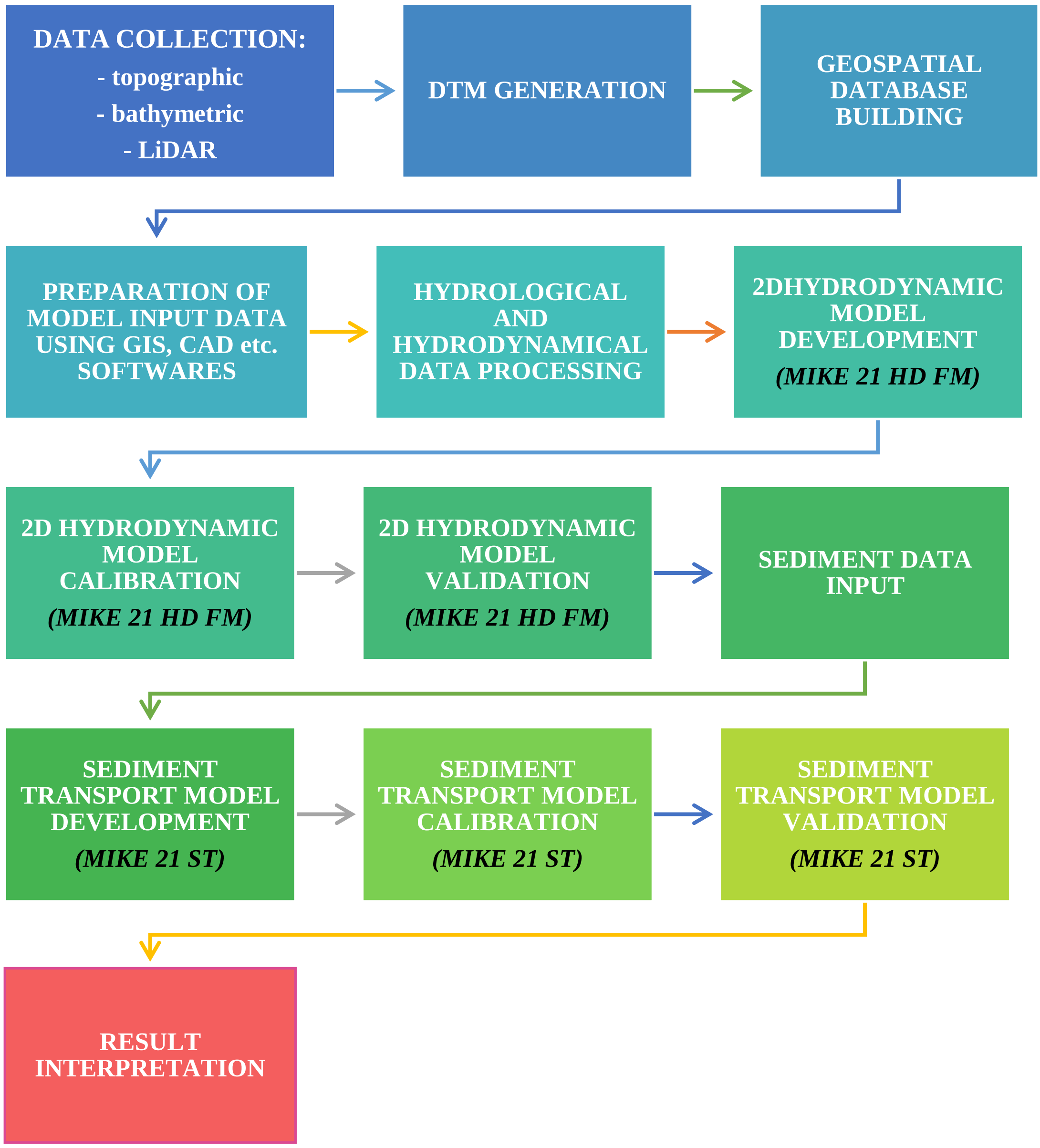

Figure 20. Work Flow

The stage preceding the sediment transport model development is represented by the elaboration of the 2D hydrodynamic (or hydraulic) model. The most important parameter in the construction of the two-dimensional hydrodynamic model of the flow is the coupled bathymetry and floodplain topography or the integrated Digital Terrain Model (DTM).

2D hydrodynamic model development using MIKE 21 FM

After processing all geospatial data using GIS applications and preparing files in MIKE 21 specific formats, the following information and data sets are required in the MIKE 21 FM module:

➢ The Hydrodynamic module was set as follows:

- **Domain:** the *.mesh file previously created for the bathymetry of the Bechet-Corabia Danube River sector*; the network of interconnected triangular finite elements (called Flexible Mesh) was defined as follows:
  - o ***Maximum element area:*** 5000 m^2;
  - o ***Smallest allowable angle:*** 30;
  - o ***Maximum number of nodes:*** 80000.
- **Time:** *23.04.2017 - 05.06.2017*, meaning 44 days, with a time step of 30 s, resulting in a total number of time steps of 123840;
- **Selection module:** *Hydrodynamic Module*.

In order to obtain the 2D hydrodynamic model, the **Hydrodynamic Module** was set as follows:

- **Technical solution:** Low order, fast algorithm (in this way the simulation is faster);
- **Flood and dry (conditions of grid cell "flooding / drying")**: Drying depth - 0.01m; Wetting depth - 0.1 m;
- **Density:** Barotropic;
- **Eddy Viscosity:** Constant Eddy formulation;
- **Bed resistance (roughness):** Manning number - the previously created .dfsu file was introduced;
- **Initial condition:** the .dfsu file resulting from the constant discharge simulation (4461 m3/s) upstream and the downstream rating curve was selected; Item: Surface elevation;
- **Boundary conditions:** Boundary conditions: the .dfs0 file with the hydrograph of the daily-mean flows recorded at Bechet Gauge Station (upstream) during the simulation period; Type: Specified discharge, Format: Strong formulation, Varying in time; and downstream the .dfs0 file with the rating curve valid for 2017 at Corabia Gauge Station; Type: Specified level, Format: Rating Curve.

The model simulates the unsteady flow taking into account density variations, bathymetry and external forcings. At the end of the simulation (of approximately 38 hours running time) there were calculated, for each mesh element and time step of the model:

- **Surface elevation related to MN75** (Surface elevation) - Figure 23;
- **Total water depth** - *Figure 5.24;*
- **Current speed** - *Figure 5.25;*
- **Speed direction** (components U and V - *U velocity, V velocity*) - *Figure 5.26 and Figure 5.27.*

These results are stored in a .dfsu file and can be viewed, queried and processed using the MIKE Zero Data Manager and MIKE Zero Data Viewer modules.

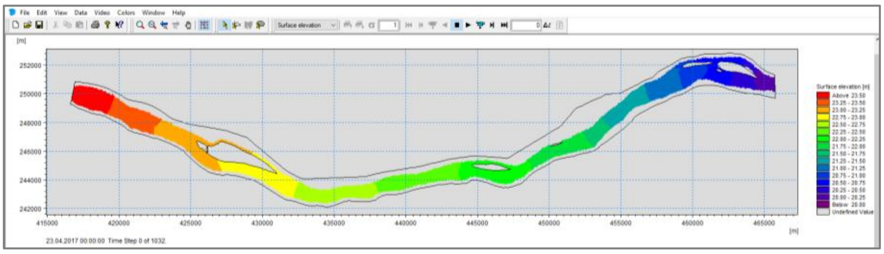

Figure 23.1 Surface elevation

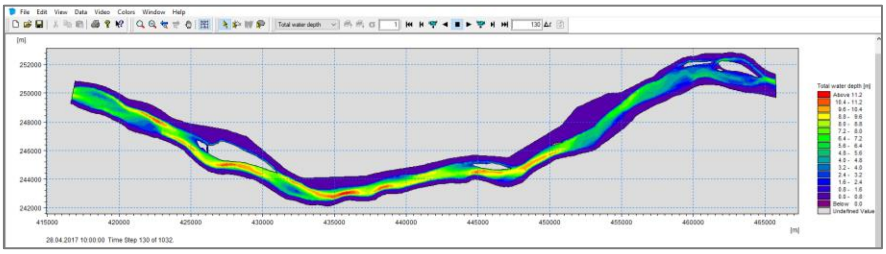

Figure 24. Total water depth

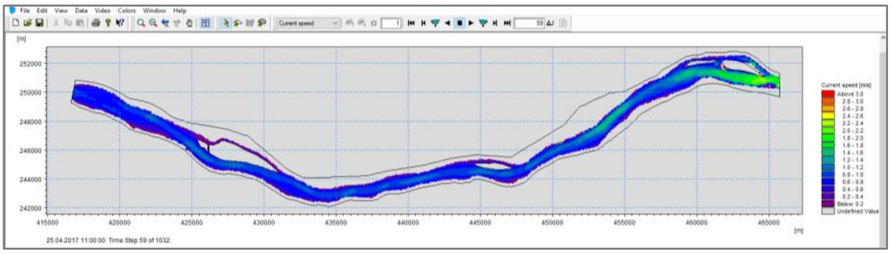

Figure 25. Current speed

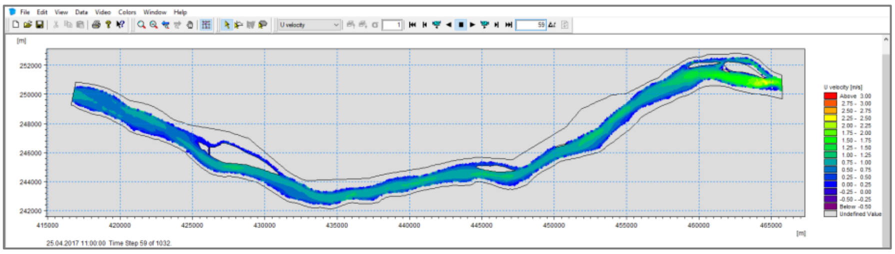

Figure 26. U velocity

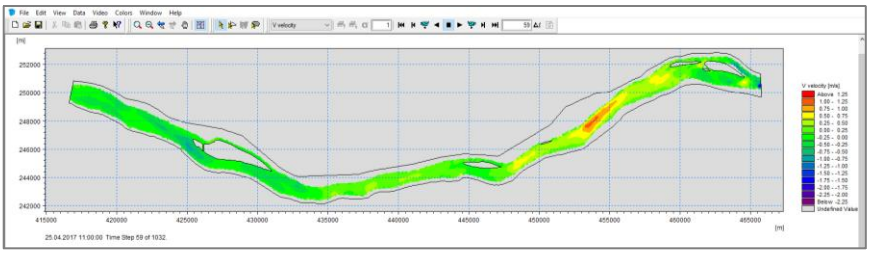

Figure 27. V velocity

After setting-up the model, in order to demonstrate the ability of the two-dimensional hydrodynamic model to accurately reproduce the behavior of any other similar hydrological event, the next step refers to model calibration and validation.

The calibration of the 2D hydrodynamic model

The calibration of the one-dimensional model has been achieved gradually through adjustments of the Manning's roughness coefficients along the river, in order to achieve a satisfactory difference between simulated values of water levels and measured values of water levels in the downstream section.

The first step in the calibration process was to create a one-dimensional hydraulic model using the MIKE Hydro River module, based on 27 cross-sections (Fig. 24) extracted from the DTM available for the Bechet-Corabia critical sector and keeping the same input data as for the 2D model, including the common simulation period (23.04.2017 - 05.06.2017).

The values of the roughness coefficients were defined based on the orthophotoplans and the Corine Land Cover layer, separately for the flood plain, islands and the main channel, according to Figure 28. The roughness depends on the size of the particles that make up the riverbed.

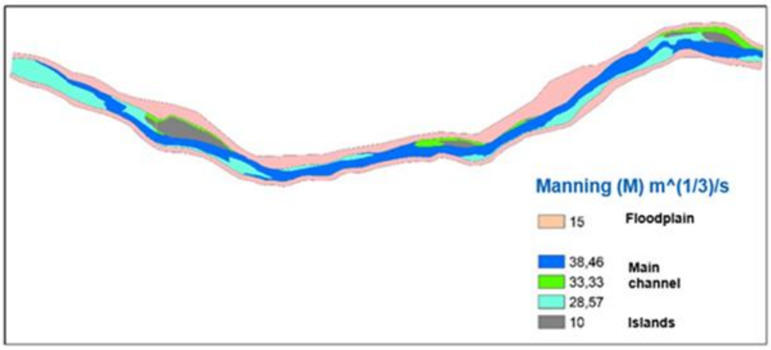

Figure 28. Roughness coefficients established for the flood plain, the low-flow channel and the river islands

After running the 1D model with *unsteady flow*, using the previously adjusted M values, the hydrograph of the simulated daily-mean water levels was compared with the hydrograph of the measured daily-mean water levels at Corabia Gauge Station, the differences being included in the [-10.3 cm, +7.9 cm] interval, with a mean value of -1.6 cm (Figure 29).

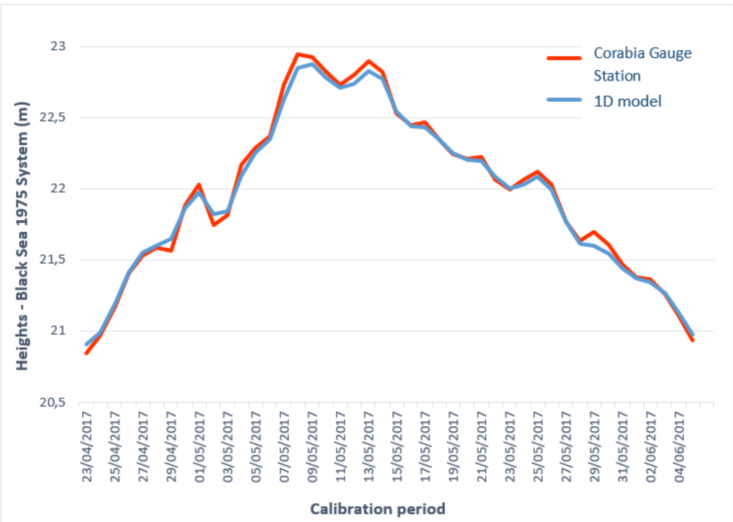

Figure 29. Calibration of the 1D hydrodynamic model

For the calibration of the 2D hydrodynamic model, the file obtained by adjusting the values of the roughness coefficients was used, following the tests performed by 1D modeling. The comparison performed with the help of the “Data extraction FM” module accessed from MIKE Zero, between simulated and measured values of daily-mean water levels at Corabia Gauge Station is shown in Fig. 26. The differences were included in the [-5.35 cm, +12.35 cm] interval, with a mean value of +2.25 cm (Figure 30). By obtaining these values, it is considered that the model has been successfully calibrated.

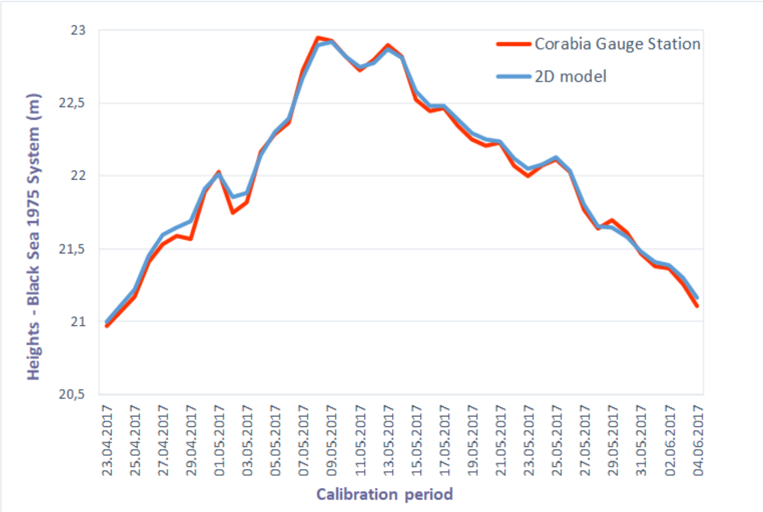

Figure 30. Calibration of the 2D hydrodynamic model

Validation of the 2D hydrodynamic model

The validation of the hydraulic model involves the use in numerical modeling of different hydrological data sets than those used in the calibration stage. In order to demonstrate the stability of the two-dimensional hydrodynamic model, the results of the simulations must be as close as possible to the data obtained from the measurements.

In this case, the validation was performed on the basis of two data sets from different periods than the calibration period (Figure 31).

- The first validation was performed by simulating the daily-mean flows recorded at the Bechet Gauge Station between **03.03.2017 - 31.03.2017**.
- The second validation was performed by simulating the daily-mean flows registered between **16.09.2017-15.10.2017** at Bechet Gauge Station.

Conclusions:

- The results obtained from the calibration and validation processes confirm that the developed 2D model can reproduce with a high level of confidence any other similar hydrological event.
- This model represents a very useful tool for understanding and predicting river behaviour. Furthermore, this is the starting point in obtaining a sediment transport model of the Bechet-Corabia critical sector, to support the selection of technical solutions that must be implemented.

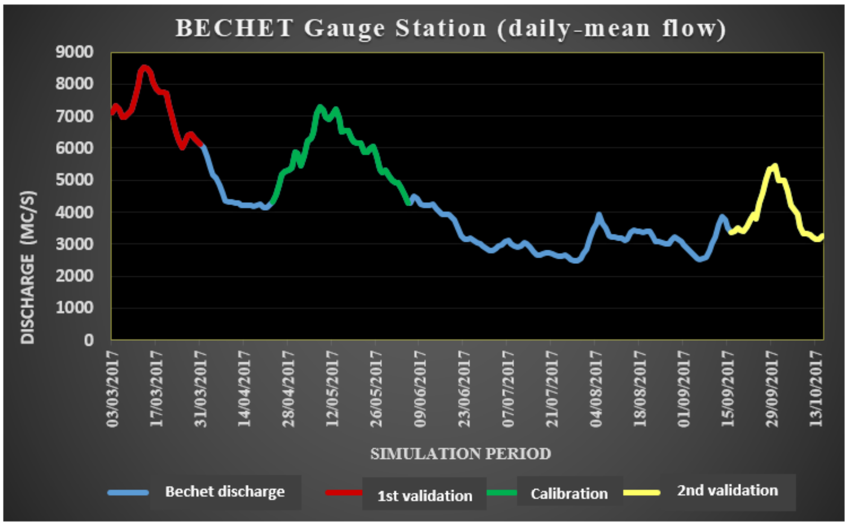

Figure 31. The flow hydrograph from Bechet gauging station for the calibration period and the two validation periods

Sediment Transport Modeling on the Bechet – Corabia Danube River Sector

The Danube River is part of the general picture of important rivers in Europe affected by anthropogenic activities (started in the seventeenth century) that contribute to substantial changes in the hydrological regime and morphology of the low-flow channel. The most important anthropogenic works performed over time on the Danube River are: hydrotechnical constructions, carried out both upstream of the analyzed sector and on the tributaries of the river, embankment works, dredging works to maintain navigation, but also to extract sand in commercial purpose, submerged barges and exploitation of forest vegetation (Marin, 2017). Hydrotechnical works influence the hydrological regime by retaining a significant amount of sediment.

In the period 1921-1960, prior to the construction of the large dams, the average flow of suspended sediment on the Danube reached 67.6 million tons/year, in the period 1970-1980 it was reduced by 39%, and in the decade 1980-1990 it reached 29.2 million tons/year (Chirica, 1992).

The Iron Gates I and II Hydropower and Navigation Systems, built in collaboration with Serbian partners, have had a major impact on the river's hydrological regime, leading to a decrease in alluvium by retaining the sediments behind them.

Regarding the simulation of the transport of non-cohesive sediments (sands, gravels, etc.), the MIKE Sand Transport (ST) module from the MIKE 21 FM package, coupled with a morphology model (Morphology), was used to update the elevations in the riverbed during the time the model was run.

Based on the D_{50} diameter of the alluvial granules (extracted from the reports generated using the GRADISTAT program), the .dfsu file presented in Figure 32 was made, essential for modeling sediment transport.

The average value of parameter D_{50} is 0.28 mm, which shows, according to (Inman, 1949), that the particles are easily eroded by aquatic currents.

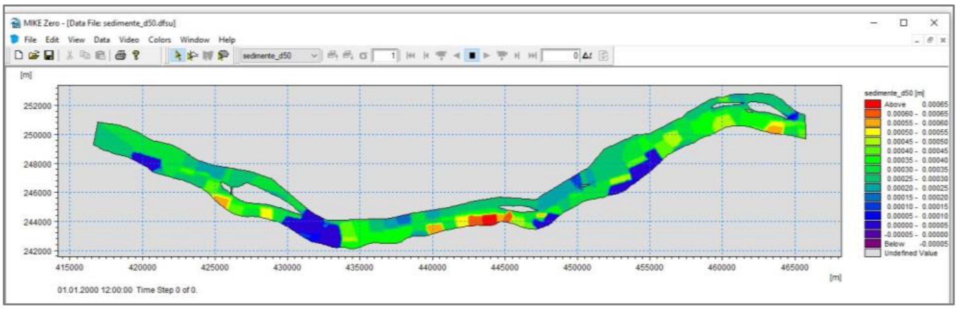

Figure 32. .Dfsu file with the distribution of D_{50} diameter values on the Bechet-Corabia sector

After processing all the data and preparing the files in specific MIKE 21 formats, the **Sand Transport** module simulates the transport of non-cohesive sediments based on the following information and data sets:

- **Time period**: the simulation period of the sediment transport model was longer than in the case of hydrodynamic modeling, namely 23.04.2017-05.08.2017, meaning 103 days, with a time step of 30 s, resulting in a total number of time steps of 299520; this corresponds to the time interval in which the two measurement campaigns were carried out (including the period between them), on the model domain related to Critical Zone 3;
- **Defining the model/ description of the type of transport**: "Pure current/non-equilibrium" - the transport is studied in conditions of "pure/unbalanced current" (Beibei, et al., 2018); the classical approach in this case involves the application of transport formulas and different mass conservation equations for each particle size class (Church, et al., 2012);
- **The sediment transport equation**: both for bed load transport and for suspended sediments, the Engelund-Hansen calculation formula was chosen (Gray & Simões, 2008);
- **The technical solution**: we opted for the Low order, fast algorithm variant (in this way the simulation is faster);
- **Sediment properties**: the sediment porosity value was set to 0.4, the relative density 2.65, and in the "sediment data" section the .dfsu file was introduced with the distribution of D_{50} values (created previously), to express the spatial variability of the particle size within the model range ("Varying in domain");
- **Roughness**: Manning number - the .dfsu file created for the hydrodynamic model was introduced;
- **Initial condition**: "equilibrium";
- **Morphological modeling**: simulation of the bed morphology allows updating the changes in the riverbed after the hydraulic modeling stage, for each time step (Drobot, et al., 2011), highlighting the erosion or deposition processes calculated for each mesh cell. This ensures a constant evolution of the riverbed, thus preventing the destabilization of the hydrodynamic simulation.
- **Boundary conditions**: for morphology, the boundary conditions are specified separately - at the upstream limit of the model (input) the zero modification condition of the bed is set, and at the downstream limit of the model (output), the zero gradient condition on the flow sediments ("zero sediment flux gradient").
- **Results obtained**: "Rate of bed level change", "Bed level change", "Bed level" etc.

At the end of the simulation, which lasted more than 6 days, the following parameters were calculated for each mesh element and time step of the model:

- Surface elevation related to MN75 - Figure 33;
- Rate of bed level change (Figure 34);
- Bed level change (depositions/erosions) - Figure 35;
- Bed level - Figure 36.

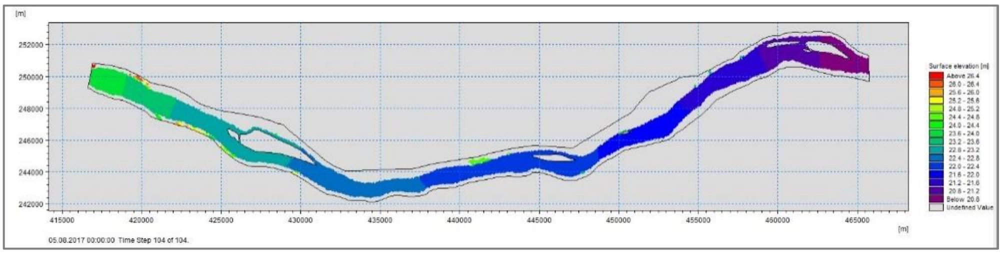

Figure 33. Surface height

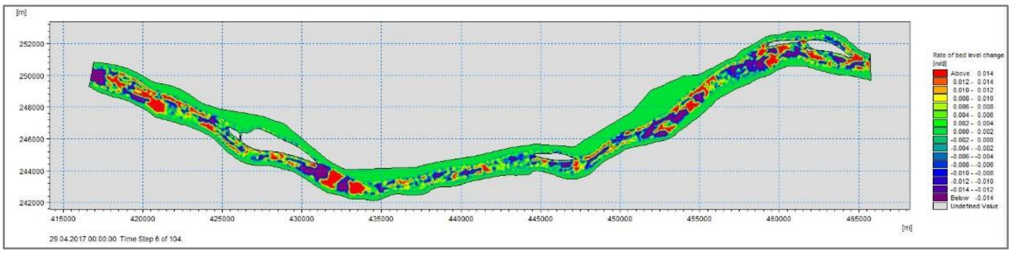

Figure 34. Rate of bed level change

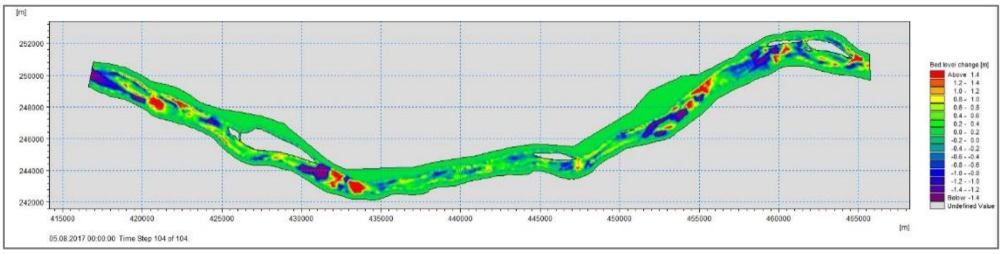

Figure 35. Bed level changes (depositions/erosions)

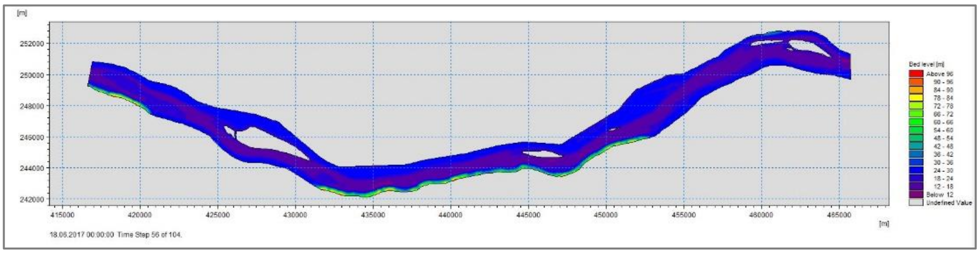

Figure 36. Bed elevation

The hydro-sedimentary model was developed in order to follow the morphological changes in the critical Bechet-Corabia sector within 4 months. The permanent change of the bed elevation automatically leads to the change of the depth information on the navigation maps.

5.7. Calibration and Validation of the Sediment Transport Model

In order to demonstrate the ability of the sediment transport model to accurately reproduce the phenomena of erosion or deposition on the critical sector analyzed, the next stage of the study concerns its calibration and validation.

During the **calibration** process, several configurations of the developed sediment transport model were tested, by changing the sediment transport equations and their parameters. The performance of the calibrated model was evaluated by comparing the elevation changes in the riverbed resulting from the running of the model with the elevation differences between the two bathymetric measurement campaigns.

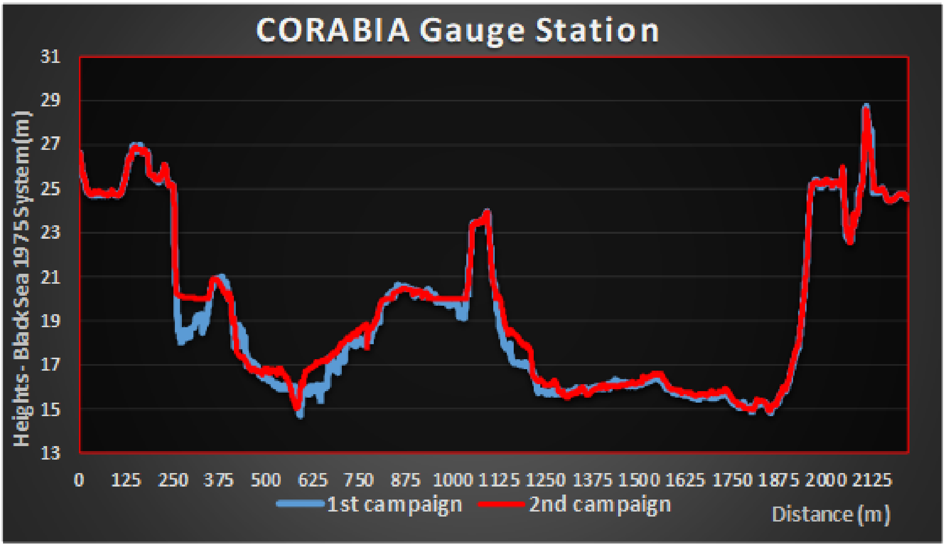

Figure 37. Example of bed changes between the two bathymetric measurement campaigns: Corabia critical spot Corabia

Based on the grid files, the elevation changes in the riverbed were represented, as well as from the alignment of any cross-section in the digital model. The change in elevation provides an indicative assessment of erosion or net deposits in the riverbed, on each cross section, to be compared with the results of the sediment transport model.

The graph in Figure 37 shows an example of changes between the two bathymetric measurement campaigns, in cross section, at the Corabia critical point.

In certain areas, the elevation in the second measurement campaign is up to 2 m higher than in the first, which corresponds to the deposition phenomenon, but there are also areas where the elevation of the riverbed is even 1.50 m lower than in the first campaign of bathymetric measurements, being able to interpret this variation as a phenomenon of erosion.

Figure 38 illustrates that the type and size of the morphological changes in the riverbed obtained by modeling are similar to those resulting from measurements. Sediment samples taken in the two bathymetric campaigns indicate a predominantly sandy bed.

The developed model reveals a correlation between the amount of alluvium and the speed of the current. In areas where the speed decreases in the sector, deposits occur, and where the speed increases, erosions arise.

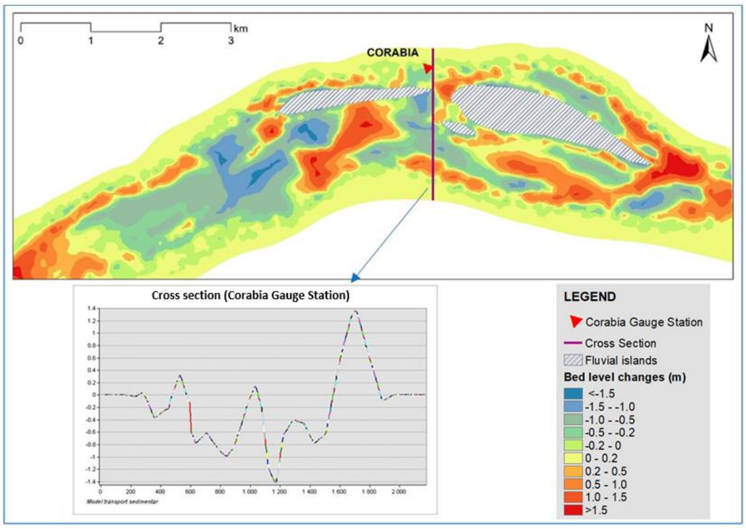

Figure 38. The result of sediment transport modeling at the Corabia critical spot

The sediment transport model was subjected to a **sensitivity analysis**, which studies how the variation of the numerical result can be attributed quantitatively to different sources of variation of the basic input parameters.

Figure 39 illustrates the main result of the simulation of the validated model for the 23.04.2017-05.08.2017 period, which consists in identifying the areas with deposits, respectively erosions, on the Bechet - Corabia critical sector. Erosion areas alternate with those of deposition along the entire length of the analyzed sector. Some erosions are produced artificially, due to dredging works carried out in the riverbed, in order to maintain the waterway and to exploit the sand and gravel in the riverbed.

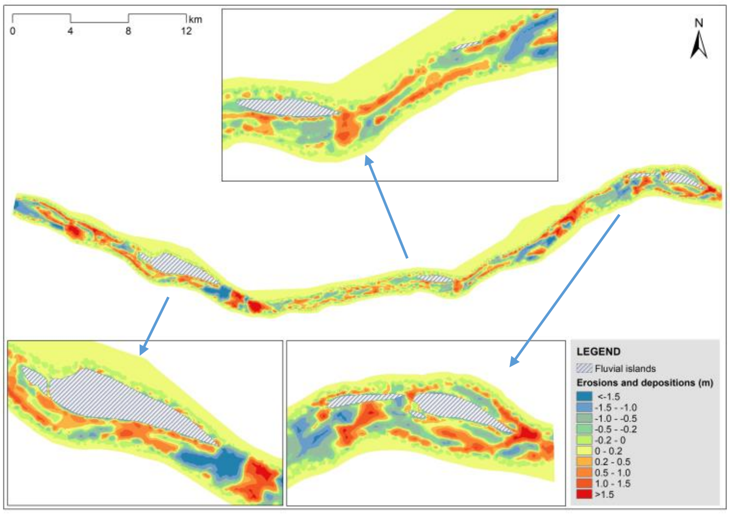

Figure 39. Areas with erosions and depositions on the Bechet-Corabia Danube River sector

In the case of the Bechet-Corabia critical sector, it was found, using calculations performed through ArcGIS Pro tools (Surface Volume), that the total volume deposited in the riverbed is higher than the total eroded volume by 1.05 million m^3 (Table 4). The results of the model of global volume changes in the riverbed are consistent with the corresponding volume changes obtained on the basis of bathymetric measurements.

Table 4. The total volume of deposited/eroded sediments

Critical area	*Surface (m^2)*	*Total deposited volume (mil. m^3)*	*Total eroded volume (mil. m^3)*
Bechet-Corabia (ZC3)	*107390484*	*16,236*	*15,191*

At the **Bechet critical point** (Figure 40), the riverbed widens from 900 m upstream to 1,400 m downstream. The banks are flat, covered with abundant vegetation (trees/shrubs). Erosion processes manifested especially on the left bank (between km 675 and km 678) lead to a rapid retreat. In the center of the riverbed there is a sand bank that affects the smooth running of navigation.

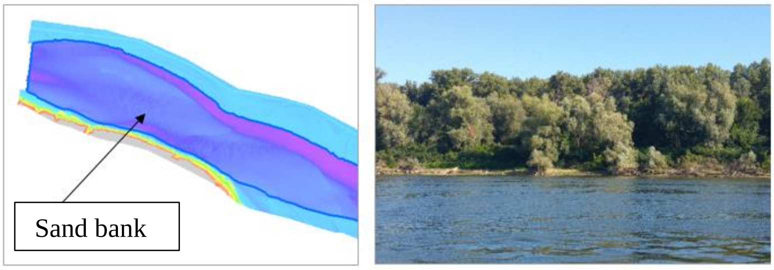

Figure 40. Bechet critical point

At the **Corabia critical spot** (Figure 41), the Danube riverbed widens from 900 m upstream to 1,600 m downstream. In the northern part of the river, two large river islands can be distinguished, a smaller island, as well as numerous sandbanks in the canals around the islands. The banks are covered with natural vegetation and massive hydrotechnical structures. There are anchor points along the left bank. In this section, both the measurements and the sediment transport model indicate the predominance of deposits, especially on the side channels near the left bank, but there are also areas with significant erosion, both in the riverbed and on the Romanian river bank. The low values of erosion on the right bank (which is higher) indicate the presence of a harder substrate, not erodible in this region.

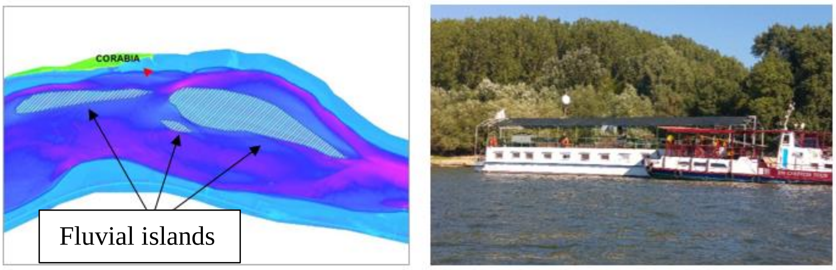

Figure 41. Corabia critical point

On the Bechet - Corabia critical sector there were identified a total of 7 river islands, characterized by abundant vegetation (trees and shrubs) and locally flooded (Figure 42):

- island in the vicinity of the Romanian bank, between km 669 and km 668;
- Papadia island, close to the Romanian bank, between km 668 and km 662 + 500;
- Grădiștea island, close to the Romanian bank, between km 648 and km 646;
- island near the Romanian bank, km 643 area;

- Baikal island, close to the Romanian bank, between km 630 and km 631;
- island in the vicinity of the Romanian bank, between km 629 and km 628;
- Băloiu island, between km 629 an km 626.

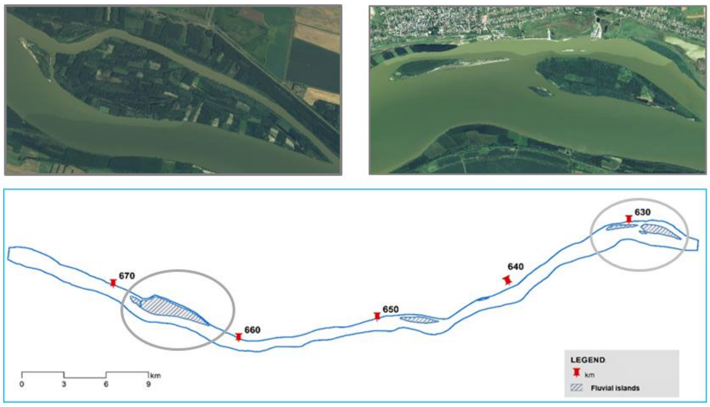

Figure 42. River islands on the Bechet-Corabia critical sector

Following an analysis carried out in the GIS environment having as cartographic source the *Drawing Master Plans* (1889 - 1916), it was found that, within 100 years, the Danube was subjected to a complex and continuous hydromorphological process, resulting in a large spatial variability of of the riverbed (Figure 43).

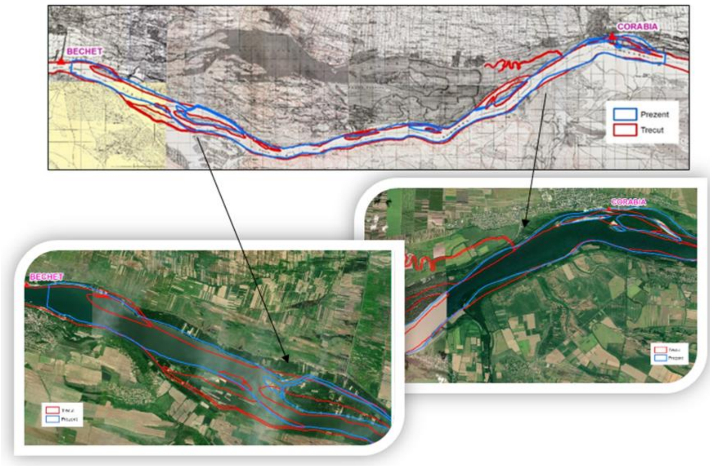

Figure 43. Changes in the morphology of the Bechet-Corabia riverbed from the Drawing Master Plans, 1889-1916 (red line), to the present (blue line)

These strong morphological changes are in fact a consequence of the anthropogenic pressures to which the Danube River was subjected. Over time, they have contributed to significant changes in sediment transport along the river, leading to increased flooding risk and biodiversity prejudice in the Danube River basin.

These issues can be solved only by an efficient management of sediments along the entire length of the Danube River, but also on its tributaries, highlighting the areas where erosion and sedimentation in the riverbed occur.

"In river projects, time is our enemy, friend and teacher" (Watson et al, 1999).

CHAPTER 6

CONCLUSIONS, CONTRIBUTIONS, PERSPECTIVES

6.1. Conclusions

Although remarkable progress has been made in recent decades in the study of of river flow, morphology and fluvial sediment transport through hydraulic and sediment transport modelling tools, this topic remains difficult to address, requiring a huge amount of interdisciplinary data and knowledge.

The main objective of this research paper was to obtain a complex hydraulic and sediment transport model, starting from various types of geodetic measurements to determine the necessary elements.

The studied Danube River sector, Bechet-Corabia, is part of the "critical areas" for navigation on the Danube. This 53 km sector is characterized by important changes in the morphology of the riverbed, caused by the phenomena of erosion, deposition and sediment transport. During low-flow periods, corresponding to a flow rate of less than 3000 m^3/s, the minimum navigation conditions recommended by the Danube Commission are not ensured on certain sections.

This problem can be solved by developing modern technical solutions to achieve the recommended parameters for the waterway, but the design of structures is closely related to understanding the behavior of the river, and in this pupose hydro-sedimentary modeling has an essential role.

Another issue related to the improvement and extension of waterways, as well as monitoring the dynamics of the riverbed, is the need to interconnect topo-hydrographic works in a unitary geodetic system that meets current European and international standards, namely ETRS89 for planimetry and EVRS / EVRF2019 for altimetry.

The permanent change of the bottom of the riverbed automatically leads to the change of the depth information on the navigation maps. The development of a monitoring and control system for navigation on the Danube requires the correlation of water levels with the shape and depth of the Danube riverbed.

In several research projects presented in the paper, several solutions have been identified to contribute to solving the issues of geodetic infrastructure on the Danube River, such as:

- the realization of a geodetic network, called “AFDJ2014”, designed and materialized along the Romanian sector of the river, for which the heights of the points in the national system were determined, with the possibility to make the transformation into the European elevation system, but also in the elevation system used in Bulgaria (“BOARD” project - completed in 2015);
- establishing a common coordinate reference system (CRS) for gauge stations that monitor the water level on the common Danube River sector between Romania and Bulgaria, including redetermining the "zero" position of hydrometric gauges on the

banks of the Danube in the new CRR (project "Danube WATER Integrated Management ”- completed in 2015);

- obtaining a local quasigeoid model on the Romanian-Bulgarian common sector, followed by the determination of the transformation parameters between the reference geodetic systems used on the common Danube sector between Romania and Bulgaria, and providing the calculation algorithm and transformation parameters (FAIRway Danube project - 2015-2020).

Starting from the reliable geodetic infrastructure, two topo-bathymetric measurement campaigns could be carried out, in 2017, within the “FAST DANUBE” project (beneficiary: LDRA Galați), which aims to develop complex technical solutions to improve navigation conditions on the Danube and, at the same time, have a minimal impact on the environment. FAST DANUBE was the main data source of this study, along with the hydrological data provided by NIHWM.

The huge amount of collected data (LiDAR, bathymetry performed with interferometric sonar, hydrodynamic cross sections with the help of ADCP system, data on suspended and bedload sediments, etc.) was a challenge in terms of handling very large data sets, both in terms of softwares and licenses used, as well as from the point of view of the hardware component.

The hydro-sedimentary model was elaborated to follow the morphological changes in the critical sector Bechet-Corabia for a period of four months. The running time of each of the 8 simulations performed for the calibration and validation of the model was 6 days. Although a high-performance computer was used (Intel (R) Xeon (R) system E5-2640 (2x2.60 Hz), 64 Gb RAM), these types of models are rather suitable for running on workstations built and prepared to withstands continuous demands throughout the day. The long waiting time to obtain each intermediate result from the calibration stage was an impediment in obtaining the final model faster. There were at least 48 days in which the model ran continuously.

For the calibration of the 2D models, the data from the first measurement campaign was used (April-May 2017, in total 68 days), while the data from the second campaign (July-August 2017, in total 47 days) was used to validate the performance of calibrated 2D models. In the case of hydrodynamic modeling, the results obtained from calibration and validation indicate a high level of confidence for the simulated dimensions of the free surface of the water. They are relatively sensitive to small adjustments in the roughness coefficient, which was defined differently for the main channel, fluvial islands and floodplain.

The final result of the sediment transport model presents the layout of the problem areas on the Bechet-Corabia Danube river sector: on the one hand there are massive sediment deposits in the riverbed, especially in the Bechet and Corabia critical points, but also on the lateral channels, which prevents the development of navigation in optimal conditions, and on the other hand there are many areas with erosion of the riverbed, as well as the Romanian bank, especially due to the confirmed sandy substrate and the analysis of sediment samples taken (the Bulgarian shore is unaffected by erosion due to the fact that it is higher and rockier). From the analysis of the deposited/eroded volumes, results the predominance of deposits on this critical sector.

Both the measurements and the model results indicate a relatively small net sediment transport at the scale of the time interval between measurements. This situation is in line with the short period between data collection campaigns and the low levels of the river corresponding to the analyzed interval.

6.2. Personal Contributions

The elaboration of this scientific research project gave me the chance to combine my passion for the field I studied, that of Geodesy, with the desire to evolve and improve in the field of Hydrotechnics and Hydrology, in which I am currently active.

The complexity of the topic approached in the doctoral thesis involved the study of numerous scientific papers in extremely varied fields: Geodesy, Hydrology, Hydrotechnics, History, Geography or Historical Cartography, the documentation being carried out continuously, from the autumn of 2017 to August 2020. In order to successfully achieve the set objectives, it was also necessary to complete training courses in the field of hydraulic modeling and sediment transport, a stage that opened new horizons of knowledge.

The originality of this dissertation comes from the interdisciplinary nature of the research, as well as from the combination of methods specific to geospatial techniques with those of mathematical modeling. Moreover, the paper involved the description of the types of geodetic measurements performed in view of modeling the sediment transport on the Danube River, as well as the high-performance equipment used in the process of collecting geodetic data.

Although the proposed subject is a purely technical one, the first part of the paper represents an incursion in the history of navigation on the Danube River, bringing front the navigation issues encountered since Roman times and until now, focusing on current critical areas and spots. The morphological changes of the riverbed in the last century have been studied in the GIS environment, based on old cartographic materials.

A dilemma that specialists in the field of geodesy, hydrology or water management often face is related to the use of several height reference systems in our country. Over time, several fundamental "zero" points have been used in Romania: "zero" Black Sea Sulina, "zero" Adriatic Sea, "zero" Baltic Sea. Regarding the Romanian sector of the Danube, all bathymetric navigation maps use as reference system the Black Sea Sulina fundamental “zero” point. In practice, height transformations between different height reference systems used along the river are still a real challenge. This study supports those who want to understand the history of the main reference systems used on the Danube and, in addition, presents the links between them. Despite being determined in the past, some of them have been transposed into GIS to facilitate transformations.

The main contribution of this research project to solving the navigation problems on the Bechet-Corabia Danube River sector is the hydro-sedimentary model obtained, together with the map of the areas where erosion phenomena occur, respectively sediment deposition.

The novelty element of the study derives from the automation of the workflow for the development of a numerical model, having at its disposal the most modern software for data processing. At the same time, **the limitations** of the study are related to the very high cost of software licenses used, as well as the hardware component, which plays a decisive role in performing the simulations.

The detailed presentation of the steps necessary to obtain the mathematical model, of the steps taken for the building, calibration and validation of the two-dimensional hydro-sedimentary model, as well as the translation of specialized terms from English, is a valuable contribution for this field, as the Romanian bibliography in the field is scarce and often incomplete.

All the data necessary for hydro-sedimentary model development were first processed through GIS, CAD and statistical-mathematical analysis software. Also, the modeling results were processed and then presented as maps also using GIS tools, which provide speed and accuracy in handling large volumes of data. Finally, a geospatial database was created, which includes both vector and raster data.

6.3. Perspectives

The results of the study may be useful to the authorities in charge for improving navigation conditions on the Danube River, as the developed hydro-sedimentary model is the starting point for implementing certain technical solutions to help ensure optimal navigation depths and safe transport on the Danube River all year round. Continuing to perform field measurements is vital to the maintenance of the model.

Regardless of the proposed works (chevrons - horseshoe/arch dams, embankments, bank defense, fairway realignment, dredging, storage of dredged material or creation of artificial islands), in the end, it is necessary to perform predictive simulations in the context of a developed riverbed. This ambitious goal cannot be achieved without taking into account the impact of the works on biodiversity, in particular on aquatic flora and fauna, which must be protected. At the same time, there is a risk of accidental pollution with spent fuels or oils, as a result of the operation of barges, dredgers and floating equipment.

Considering the current climate regime, a new direction of research may be to develop a study on the assessment of sediment transport on the Danube River in the context of climate changes that humanity is currently facing.

SELECTIVE BIBLIOGRAPHY

1. Anderson, J. T. et al., 2008. Acoustic seabed classification: Current practice and future directions. *ICES Journal of Marine Science,* 65(6), pp. 1004-1011. 10.1093/icesjms/fsn061.

2. Bogardi, J. L., 1974. *Sediment transport in sediment streams,* Budapest: Academiai Kiado.

3. Bogen, J., Tharan, F. & Walling, D. E., 2003. *Erosion and sediment transport measurement in rivers: Technological and methodological advances.*. Wallingford, UK: IAHS Publication 283.

4. Bondar, C., 2010. *Date privind evidenţierea schimbărilor climatice şi a impacturilor antropice produse asupra regimului hidrologic şi morfologic al Dunării, Deltei Dunării şi Mării Negre.* București: INHGA Conferinţa Ştiinţifică Jubiliară.

5. Budileanu, M., 2018. Evoluţia gurii de vărsare Sulina pe baza modelelor numerice batimetrice. București: Ars Docendi, p. 17.

6. Chendeș, V., 2011. *Resursele de apă din Subcarpaţii de la Curbură. Evaluări geospaţiale.* București: Editura Academiei Române.

7. Chow, V., 1959. *Open Channel Hydraulics.* New York: McGraw-Hill, ISBN 07-010776-9.

8. Church, M., Biron, P. M. & Roy, A. G., 2012. *Gravel Bed Rivers. Processes, Tools, Environments.* s.l.:Wiley-Blackwell.

9. Cioc, D., 1975. *Hidraulică.* București: Editura Didactică și Pedagogică.

10. Diaconu, C., Blaga, O. & Lăzărescu, D., 1978. *Hidraulică și Hidrologie,* București: Editura Didactică și Pedagogică.

11. Diaconu, C. & Şerban, P., 1994. *Sinteze şi regionalizări hidrologice.* ISBN/Cod: 973-31-0638-0, București: Editura Tehnică.

12. Dragomir, P., Rus, T. & Avramiuc, N., 2008. *Implementarea Sistemului de Referinţă Terestru European 1989 (ETRS89) în România,* București.

13. Drobot, R., 2008. URBWATER – Sistem Suport de Decizie în gestiunea situațiilor de criză generate de apă în zonele urbane. București: Editura Conspress, pp. 3-9.

14. Engelund, F. & Fredsoe, J., 1976. *A Sediment Transport Model for Straight Sediment Channels.* s.l.: Hydrology Research.

15. Ghițău, D., 1983. *Geodezie și gravimetrie geodezică.* București: Editura Didactică și Pedagogică.

16. Gray, J. & Simões, F., 2008. *Estimating sediment discharge,* Sedimentation Engineering-Processes, Measurements, Modeling, and Practice.. 10.1061/9780784408148.apd..

17. Ichim, I., Bătuca , D., Rădoane, M. & Duma, D., 1989. *Morfologia și dinamica albiilor de râuri.* București: Editura Academiei.

18. Ihde, J. et. al., 2002, *European Spatial Reference Systems.* Disponibil la adresa: *http://crs-geo.eu /References* [Accesat 10.03.2020].

19. Iorga, N., 1913. Chestiunea Dunării. Vălenii de Munte: Editura Societății „Neamul Românesc", pp. 83-84.

20. Lemoine, F. G. et al., 1998. *The Development of the Joint NASA GSFC and the National Imagery and Mapping Agency (NIMA) Geopotential Model EGM96, NASA Technical Report NASA/TP-1996\8-206861*.

21. Lurton, X., 2010. *An Introduction to Underwater Acoustics: Principles and Applications.* 2nd ed. Berlin: Springer Berlin Heidelberg.

22. Mateescu, C., 1961. *Hidraulica.* București: Editura de Stat Didactica și Pedagogică.

23. Mayer-Gürr, T., Eicker, A. & Ilk, K., 2010. ITG-GRACE: Global Static and Temporal Gravity Field Models from GRACE Data. *In: Flechtner F. et al. (eds) System Earth via Geodetic-Geophysical Space Techniques. Advanced Technologies in Earth Sciences (2190-1643).* Springer, Berlin, Heidelberg. https://doi.org/10.1007/978-3-642-10228-8_13.

24. Moisoiu, I. M., 2013. *Contribuţii la culegerea datelor spaţiale în bazine hidrografice prin metode geodezice şi modelarea lor matematică. Teză de doctorat.* București: Universitatea Tehnică de Construcții București, Facultatea de Geodezie.

25. Moldoveanu, C., 2002. *Geodezie. Noțiuni de geodezie fizică și elipsoidală, poziționare.* București: Editura MatrixRom.

26. Moldoveanu, C., 2010. *Bazele geodeziei fizice.* București: Editura Conspress.

27. Moldoveanu, C., 2015. *Sisteme de coordonate și de referință,* București.

28. Mugnier, C. I., 2001. Grids & Datums – România. *Photogrammetric Engineering & Remote Sensing*, May, p. (p. 545–548).

29. Neuner, J., Balotă, O. & Sava, C. Ș., 2015. *Sistem topo-hidrografic inteligent pentru îmbunătăţirea navigaţiei fluviale pe sectorul românesc al Dunării,* București.

30. Olsen, N. R., 2012. *Numerical Modelling and Hydraulics,* s.l.: Department of Hydraulic and Environmental Engineering, The Norwegian University of Science and Technology.

31. Pail, R. et al., 2011. First GOCE gravity field models derived by three different approaches. *Journal of Geodesy, 85, 819 (2011). https://doi.org/10.1007/s00190-011-0467-x.*

32. Pavlis, N., Holmes, S., Kenyon, S. & Factor, J., 2012. The development and evaluation of the earth gravitational model 2008 (EGM2008). *Journal of GeophysicalResearch: Solid Earth,* http://dx.doi.org/10.1029/2011JB008916, 117(B4).

33. Pavlis, N. K., 2011. *Geodesy and Geophysics Basic and Applied Research,* Reston: National Geospatial-Intelligence Agency (NGA).

34. Păunescu, C., Dimitriu, G. S. & Mocanu, V., 2012. Sisteme de determinare a poziției utilizând sateliți (GNSS). București: Editura Universității din București.

35. Poder, K. & Hornik, H., 1989. The European Datum 1987 (ED87) - Report on the Symposium of the IAG Subcommission for the New Adjustment of the European Triangulation (RETrig). *lAG Section 1 - Positioning, Subcommission for tlte New Adjustment of the European Triangulation (RETrig),* vol. 18.

36. Rus, T. et. al., 2019. *Developing Conversion And Transformation Parameters To Improve Navigation On Lower Danube.* Albena, Bulgaria.

37. Rus, T., Moldoveanu, C. & Danciu, V., 2014. *Geodesy Contribution to the Danube Water Project.* Albena, Bulgaria.

38. Savu, E. A., 2020. Brief History of the Height Reference Systems Used along the Romanian Sector of the Danube River. *RevCAD Journal of Geodesy and Cadastre, v*ol. 28, pp. 95-104.

39. Simav, M. & Yildiz, H., 2019. Evaluation of EGM2008 and latest GOCE-based satellite only global gravity field models using densified gravity network: A case study in south-western Turkey. *Bollettino di Geofisica Teorica ed Applicata,* vol. 60, pp. 49-68.

40. Stănescu, V. A. & Drobot, R., 2002. *Măsuri nestructurale de gestiune a inundațiilor.* București: Editura *H*G*A*.

41. Tilleard, J. W., 2001. *River channel adjustment to hydrologic change. PhD thesis, Department of Civil and Environmental Engineering, The University of Melbourne.*

42. Torge, W., 2001. *Geodesy.* Berlin: Walter de Gruyter.

43. Trofin, E., 1974. *Hidraulică și hidrologie.* București: Editura Didactică și Pedagogică.

44. Ungureanu, V., 2005. *Geologie Marină.* București: ARS DOCENDI.

45. Vasilca, D. & Ilieș, A., 2002. Deformațiile suprafețelor în proiecțiile cartografice. *Revista de Geodezie, Nr. 1-2.*

46. Wang, S. & Wu, W., 2004. Depth-average 2D calculation of flow and sediment transport in curved channels. *Journal of Hydraulic Engineering*, pp. 241-257.

47. Weiyong, Y. & Rummel, R., 2014. A comparison of GOCE Gravitational Models with EGM2008. *Journal of Geodynamics,* 73(ISSN 0264-3707), pp. 14-22.

48. ***, 2019, *Îndrumar pentru prelucrarea datelor de la stațiile hidrometrice de pe fluviul Dunărea,* Institutul Naţional de Hidrologie şi Gospodărire a Apelor, București.

49.****, 2016, Science background - General concepts,* ITRF & ITRS, disponibil la adresa *http://itrf.ensg.ign.fr/general.php* [Accesat 06.10.2018].

50. ***, 2015, *Realizarea unui sistem de sprijin pentru lucrările hidrografice pe Dunăre în scopul asigurării adâncimilor minime de navigare,* Tehnogis Grup, București.