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RESEARCH REPORT NO. 2

Bathymetric Modeling - The Premise for Creating Flow and Sediment Transport Models

WITHIN THE RESEARCH PROJECT:

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

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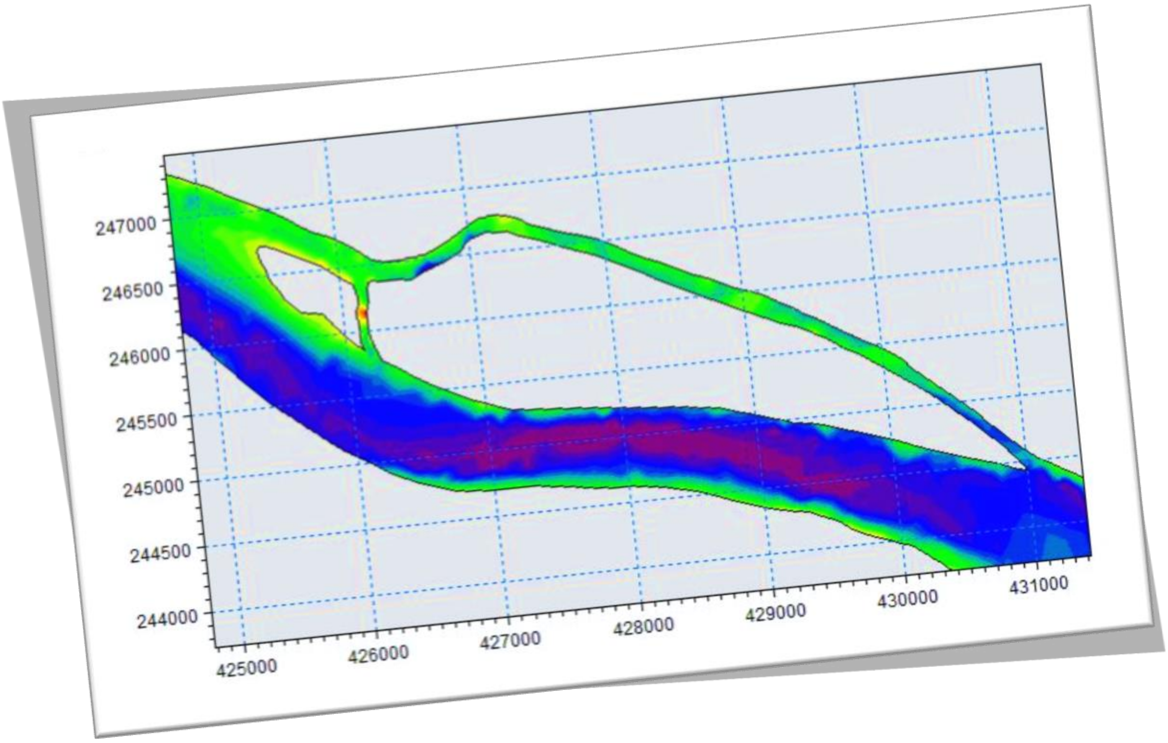

Galileo Galilei:

"It is easier to know the celestial bodies than the simplest movement of a fluid."

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BATHYMETRIC MODELING - THE PREMISE FOR CREATING FLOW AND SEDIMENT TRANSPORT MODELS

1. INTRODUCTION

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 [1].

A successful model is more accessible for research than the real object and allows new information about it to be obtained. The process of building the model is called *modeling*.

Hydraulics, like other natural sciences, uses theoretical methods and experimental methods in investigations.

Hydraulic modeling has developed as a scientific research method since the twentieth century, when the foundations of dimensional analysis (instrument of the theoretical method) and similarity theory (theoretical basis of hydraulic modeling) were laid.

In nature, there are very complex physical phenomena whose mechanism is not yet sufficiently well studied, which leads to the impossibility of establishing the general equations of the phenomenon and formulating the appropriate conditions of uniqueness. In these situations, general research methods are applied, which are less accurate, but which allow the determination of the general form of the laws of these physical phenomena. Thus, if we know the physical quantities $A_1, A_2, ..., A_n$, which intervene in the development of a phenomenon, and we assume the existence of only one unknown function among them f $(A_1, A_2, ..., A_n)$, then some links between these quantities can be established using their dimensional nature [2]. In addition, it must be borne in mind that physical relations represent relations between physical (dimensional) quantities, while mathematical relations operate with abstract numbers. This mode of research is known in science as **dimensional analysis** and is used when, on an experimental basis, the hydraulic parameters of the studied phenomenon can be known.

Regarding the **theory of hydraulic similarity**[1], its statement offered the possibility that complex phenomena in nature can be studied on small scale models, and the results obtained can be extended, according to certain laws, to a whole class of such phenomena.

The similarity can be geometric, kinematic or dynamic, depending on the proportionality of the determining quantities.

- ***The Geometric Similarity*** is the simplest form of similarity. There is a geometric similarity between the phenomenon on the model (M) and the phenomenon on the prototype (N) if the proportionality of the homologous lengths and the equality of the angles are ensured. One point on the model corresponds to a single point on the

[1] Two phenomena, M (model) and N (nature) are similar if they belong to the same class and if there are proportional relations between the homologous quantities with which these phenomena are described [17].

prototype (the real object) and vice versa, the two points arranged identically on the model and prototype being called *homologous points*. These homologous points can determine homologous lines, homologous surfaces, and homologous volumes. Therefore, the geometric similarity presupposes a unique scale for lengths (S_1):

$$S_l = \frac{l_M}{l_N}; \qquad (1\text{-}1)$$

Geometric similarity can be ensured by making the scale model, geometrically undistorted. The geometric scale is also known as the *modeling scale*.

- ***The kinematic similarity*** represents the similarity of movement and implies, in homologous points, the geometric similarity of the Hydrodynamic field (the aspect of the flow is the same on the model and prototype) and the constant ratio of the kinematic quantities of the same type (speeds, accelerations). Once the length scale is established, there is a constant ratio of the time in which the phenomenon takes place on the prototype and the time in which the phenomenon takes place on the model, that is the time scale (S_t):

$$S_t = \frac{t_M}{t_N}; \qquad (1\text{-}2)$$

- ***The dynamic similarity*** requires that the ratio of all the forces in nature, on the prototype and on the model, be constant. The result is the force scale (S_f):

$$S_f = \frac{f_M}{f_N}; \qquad (1\text{-}3)$$

However, the realization of these conditions on a hydraulic model is not entirely possible, due to the variety of forces that determine the movement of the fluid, which attracts a series of conditions that are difficult to meet regarding the physical constants of the fluids. In the practice of hydraulic modeling, the dominant forces of the modeling phenomenon are first considered and then the condition of dynamic similarity is imposed only on these forces. In this way different models ("similarity criteria") are obtained according to the category of forces taken into consideration. These criteria can be expressed by dimensionless quantities called *characteristic numbers*.

In other words, if a concrete physical phenomenon is described by several physical quantities of the same nature (with the same dimensions), any ratio of two of these quantities represents a *dimensionless complex*, which is usually denoted by the letter π, accompanied by an index. Dimensional complexes can also be seen as numbers, because they result from the ratio of two quantities of the same dimensions.

Considering some of the determinant physical quantities in the description of the phenomena within fluid mechanics, namely: characteristic length l, fluid velocity u, fluid density ρ, dynamic coefficient of fluid viscosity μ, pressure p, gravitational acceleration g, sound velocity a and coefficient of surface tension σ, the following criteria can be formed using these quantities [3]:

The Reynolds Criterion - is the basic condition for the model in which the viscosity forces are dominant:

$$Re = \frac{ul\rho}{\mu} = \frac{ul}{v}; \qquad (1\text{-}4)$$

- ***The Euler Criterion*** - used when, in addition to inertial forces, pressure forces must also be taken into account:

$$Eu = \frac{p}{\rho u^2}; \qquad (1\text{-}5)$$

- ***The Froude Criterion*** - used to model movements in which the force of gravity is predominant:

$$Fr = \frac{u^2}{gl}; \qquad (1\text{-}6)$$

- ***The Mach Criterion*** - intervenes in the modeling of movements that take into account the compressibility of the fluid:

$$Ma = \frac{u}{a}; \qquad (1\text{-}7)$$

- ***The Weber Criterion*** - is used to model those movements in which, in addition to the inertial forces, the surface tension force is predominant:

$$We = \frac{\rho u^2 l}{\sigma}; \qquad (1\text{-}8)$$

- When the movement is non-permanent, ***the Strouhal Criterion*** is introduced:

$$Sh = \frac{l}{ut}; \qquad (1\text{-}9))$$

where t represents the characteristic time.

The theory of hydraulic similarity demonstrates that not all criteria can be applied simultaneously, the best known incompatibility being Re and Fr. Solving such situations is done by developing **models with hydraulic distortion**, that is one of the two incompatible criteria is abandoned.

Hydraulic or hydrodynamic modeling operates with two types of models: physical models and numerical models [4].

Physical models are distinguished by the particularity of reproducing the studied phenomena studied on a scale other than the natural one. In the case of hydraulic phenomena, which occur in large spaces, physical models are made on a small scale [5].

In recent decades, due to the development of automatic computing hardware, as well as mathematical methods for integrating differential equations, numerical or mathematical models have experienced rapid development. They are applied in various branches of hydraulics, such as one-dimensional and two-dimensional free flows, pressure flows, underground flows, etc. These models represent sets of mathematical relationships between parameters that describe a certain physical phenomenon.

Mathematical models can be built in two fundamentally different ways, the two types being known as *deterministic models* and *stochastic models*, which reflect the methods of classical physics and statistical physics for the discovery and study of the laws governing natural phenomena.

Deterministic models refer to the phenomena described by a relatively small number of parameters. Laws that express the connection between parameters that describe one or more phenomena take the form of equations called *the equations of mathematical physics*.

Stochastic models are based on mathematical statistics. By analyzing a large number of events, statistics can discover the laws that govern them, regardless of how they are determined (without following the cause-effect relationship), through *correlations*.

A current trend is the complementary use of physical and numerical models, as the physical model provides the data needed to calibrate the numerical model.

2. THE PRINCIPLES OF HYDRAULIC MODELING

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

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 [6].

Depending on the variation in time and space of the hydraulic parameters (flow, speed, depth, slope, surface and wetted perimeter), the free-surface flow in riverbeds can be classified according to Figure 1 as follows [7]:

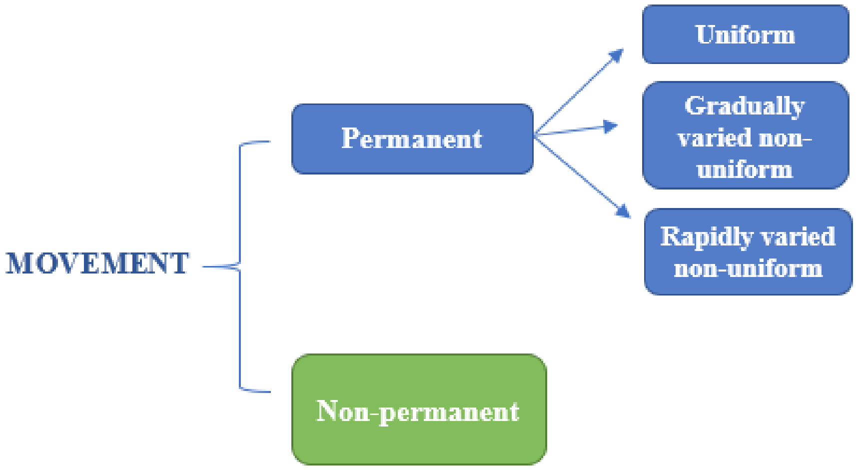

Figure 1. Classification of free-surface flow types

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

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

However, in the event that the variation of flows and levels is slow, for short periods of time, the flow can be considered permanent (uniform or non-uniform)[2].

Non-permanent free-surface flows are undulating in nature and arise as a result of changes in 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 motion 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.

Being a non-linear phenomenon, with different forms of manifestation, the calculation of non-permanent movements with free surface is very complicated.

[2] The types of permanent movement (uniform, gradually varied non-uniform and rapidly varied non-uniform) were presented in ***Report no. 2 - Hydrology and river hydraulics***.

In the case of non-permanent movements in rivers and canals, in addition to the undulating phenomenon of propagation of disturbances, there is also the phenomenon of transport, movement of water at a certain speed.

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 non-permanent motion, the speed of water also has components in the plane of the cross section of the riverbed [8], and for the mathematical modeling of non-permanent motion, it is necessary to resort to simplified schematics that include only aspects with essential influence on real processes and often, to ignore those of secondary importance.

After establishing the equations that shape the physical process in its main aspects, their mathematical or numerical treatment, executed correctly, does not change the physical nature of the analyzed process.

In most cases, a one-dimensional schematization is performed, so that the non-permanent flow in the riverbeds is described by the evolution over time, in any cross section, of two dependent variables, namely: the stage of the free-surface area of water *y* (or water depth h) and discharge *Q* (or average speed in section *v*). These dependent variables define the state of motion in relation to two independent variables: the spatial position along the riverbed *x* (relative to a conveniently chosen origin) and the time *t* (relative to the moment of occurrence of the disturbance).

The dependent and independent variables that appear in the non-permanent flow in the riverbeds are linked to each other by two equations that come from the laws of conservation of mass, momentum and mechanical energy.

The hypotheses underlying the one-dimensional model, together with the equations describing non-permanent one-dimensional motion were formulated by Barré de Saint-Venant in 1871 at the French Academy in his paper "Théorie et equations generales du mouvement non-permanent des eaux courantes"

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 the 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:

$$\partial\frac{\partial Q}{\partial x}+\frac{\partial A}{\partial t}=0; \qquad (2\text{-}1)$$

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

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

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

$$Q = A \cdot V = Q(x,t) \tag{2-3}$$

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

3. TWO-DIMENSIONAL HYDRODYNAMIC MODEL DEVELOPMENT

3.1. General Notions

In recent decades, remarkable progress has been made in the study of flow and sediment transport processes on rivers and streams, by using flow modeling tools, riverbed morphology and sediment transport.

In general, when modeling watercourses, the most used are one-dimensional (1D) models, which are based on the equations of uniform flow and those of uniform-varied flow. These models have the following advantages: simplicity of calculations, ease of parameterization, easy calibration, fewer of data required for calibration / validation [9].

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, which involves parameters such as roughness in each calculation section. These parameters are different for the low-flow channel, respectively for the flood plain, or they can be considered vertically variable. Their calibration involves adjusting their values (within acceptable limits) until accurately reproducing the levels recorded for 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 calculation time, and the data required for the construction of the geometry must have a much larger spatial distribution [9].

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 [10].

3.2. The Objectives of the Research

Within the research project entitled "Contributions Related to Usage of Geodetic Measurements to Sediment Transport Modeling on the Danube River", which aims to identify measures to contribute to the stabilization of the Danube riverbed, the objective of the research report no. 2 - *" Bathymetric Modeling - The Premise for Creating Flow and Sediment Transport Models"* is the creation of a complex hydrodynamic (2D) model of the analyzed Danube River sector, based on various types of geodetic measurements to determine the necessary elements (types of geodetic measurements were presented in detail in Research Report No. 1 - "*Current Status of Geodetic Measurements and Coordinate Reference Systems*").

The results of this report will be used further in the research report no. 3 - "*Case study and interpretation of results*", which will address in particular the issue of modeling sediment transport on the Danube River, by creating an erosion model, followed by its calibration and validation.

3.3. Study Area

The area selected 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) (Figure 2).

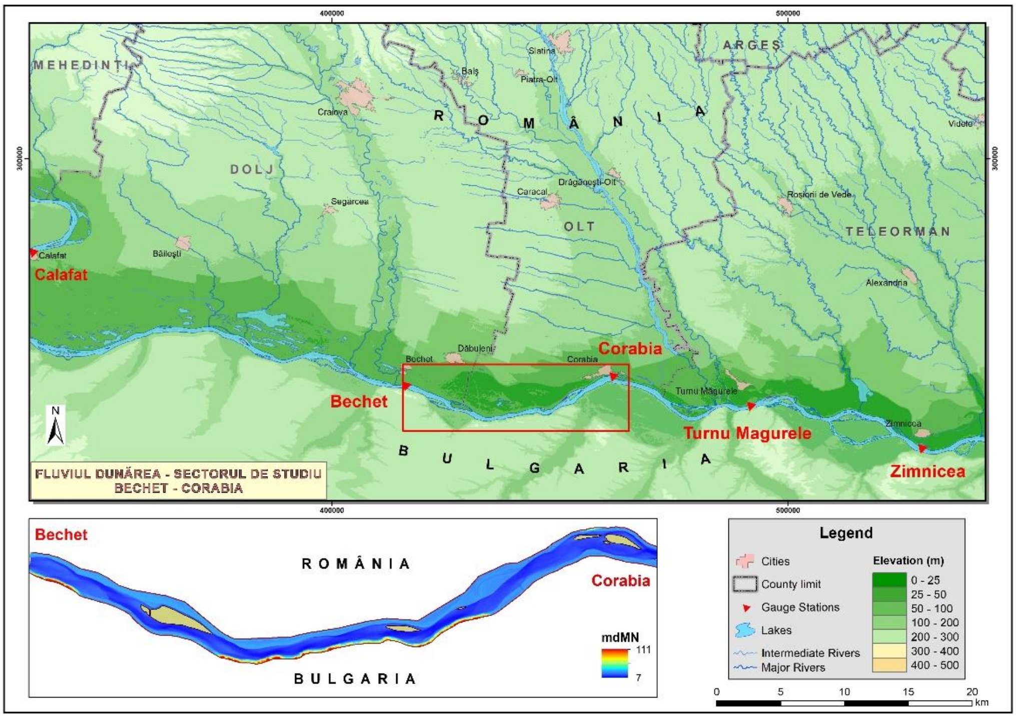

Figure 2. Study Area

With a length of 53 km, this sector is part of the Lower Danube and it can be considered relevant for research because of the difficult navigation conditions, which are consequence of the complexity of the hydraulic regime and the dynamic changes of the riverbed morphology, with damaging effects on the ***fairway***[3].

Economically viable Danube transport services are dependent on the conditions of a stable fairway. Along the Danube, navigation is impeded by several **critical navigation points**

[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.*

(bottlenecks), both during winter and ice conditions, and during late summer when river flows tend to be very low (below 3000 mc/s).

In accordance with the provisions of the "Convention regarding the regime of navigation on the Danube", signed in Belgrade on August 18, 1948, ensuring the conditions of navigation on the Danube sector between km 845.5 and km 375 is the responsibility of the two riparian countries, Romania and Bulgaria.

Based on the Romanian-Bulgarian Bilateral Agreement, signed in Sofia on November 28, 1955, the two states defined their areas of responsibility, on the common sector of the Danube, as follows:

- between km 845.5 and km 610, the responsibility for maintaining the waterway belongs to the Romanian side;
- between km 610 and km 375, the responsibility for maintaining the waterway belongs to the Bulgarian side.

The Galati Lower Danube River Administration (GLDRA) - AFDJ Galați (Romania) and IAPPD Ruse (Bulgaria) are the authorities responsible for maintaining adequate navigation conditions.

The Galati Lower Danube River Administration (GLDRA) is the waterway authority on the entire Romanian sector of the Danube. In order to ensure the minimum navigation conditions, recommended by the Danube Commission, maintenance works are performed (measurement activities, signaling and dredging), which are effective only for a short period of time.

Therefore, in 2017 the project "FAST Danube" was launched - "Technical assistance for the revision and completion of the feasibility study on improving navigation conditions, on the joint Romanian-Bulgarian Danube River sector and complementary studies", to study the geomorphological conditions and hydrological factors that influence this sector of the Danube, in order to develop complex technical solutions that will help improve navigation conditions and at the same time have a minimal impact on the environment.

As a result of a feasibility study completed in 2011 (necessary to launch the FAST DANUBE Project), in the river sector downstream of the Iron Gates II, in the common Romanian-Bulgarian sector (km 845.5 - km 375), **12 critical points for navigation** were identified (Table 1), which requires close monitoring through a series of topo-hydrographic measurements.

Table 1 – Critical points 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*

NO.	NAME	LOCALIZATION (RIVER KM)	ADMINISTRATIVE TERRITORY
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 this study, the Danube Commission recommended for the Romanian-Bulgarian sector 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 minimum depths are not ensured (Figure 3) it was proposed to reduce the width of the fairway to 150 m.

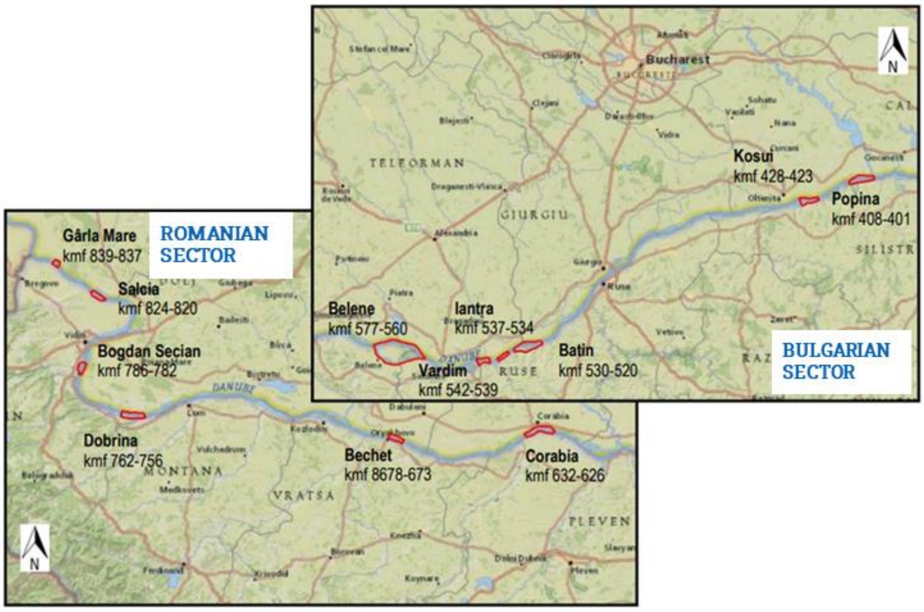

Figure 3. Location of the 12 critical points in the Romanian and Bulgarian sector
Source: http://www.fastdanube.eu/official-documents

Therefore, the Bechet-Corabia study area is part of **the critical areas for navigation** (Table 2), established, according to the same feasibility study, as follows:

Table 2 – Critical areas for navigation

CRITICAL AREA NO.	LENGTH (RIVER KM)	CRITICAL POINTS INCLUDED IN 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*

3.4. Model Input Data

The understanding of river morphological processes in order to develop a hydrodynamic model, as well as key processes such as sediment erosion, transport and deposition, represents a particularly difficult task, which requires a huge amount of data collected during field campaigns and interdisciplinary knowledge, at the border between Geodesy, Hydrology and Hydraulics.

The quality of mathematical modeling and the spatial representation of its results are closely related to the input data used. The quality of these data is all the more important as they directly influence 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.

3.4.1. Topographic Data

The starting point in the elaboration of any hydrodynamic model of flow is the data related to the terrain, the topography of the terrain and the land cover [11].

Depending on the type of mathematical modeling used, namely one-dimensional or two-dimensional, the required topographic data are different.

1D modeling lends itself to a classical collection approach, where data collection methods using GNSS technology and the total station will replace airborne LiDAR and aerial photogrammetry, used to obtain geospatial data needed for 2D modeling [12].

To generate a one-dimensional model of rivers, longitudinal and cross section graphic profiles are required, the latter being arranged perpendicular to the longitudinal axis of the river, and their position and density are chosen depending on the terrain configuration and the importance of their area. The required accuracy must be taken into account when collecting the data, as it plays an essential role in the choice of equipment and measurement methods.

The final processing of data for its use in 1D mathematical modeling programs of rivers contains several independent steps, many of which being manual processing which is time consuming and facilitates human errors. Also, this method does not offer a high yield.

In the case of two-dimensional models, the cross sections/bathymetric measurements in the low-flow channel are coupled with topographic data sets in the floodplain, in order to obtain a continuous Digital Terrain Model (DTM) [11]. Topographic data is collected separately for dry and water-covered areas and are also processed separately. However, they must be included in a unitary DTM, covering the entire study area.

In this case, for the two-dimensional hydraulic modeling of the Danube sector Bechet-Corabia (53 km long), the digital terrain model was kindly provided to us by *GLDRA* (S.C.N. Giurgiu), the beneficiary of the Fast Danube project.

This DTM was obtained based on data collected by LiDAR (Light Detection and Ranging) technology, 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 edge of the river on both sides.

a) Establishment of Reference Geodetic Benchmarks

Within the project "BORD – Development of a support system for hydrographic works on the Danube in order to ensure minimum navigation depths", whose beneficiary is the Romanian state and the contracting authority is *LDRA* Galati, the main objective was the design, execution and materialization of three geodetic landmarks (Witness Landmark, Reference Landmark and Azimuthal Landmark) in 144 locations along the Romanian sector of the Danube. The system, called AFDJ2014, is therefore defined by the 144 locations, located less than 15 km from each other.

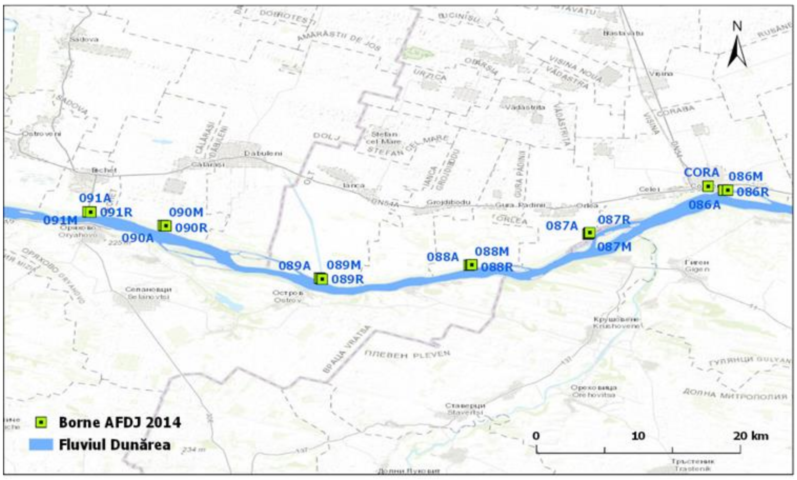

Figure 4. AFDJ2014 Geodetic Network

The final coordinates of the landmarks were provided both in ETRS89 system (to facilitate interconnection with neighboring countries) and in the national reference system S42 (with the 1940 Krasovski ellipsoid and 1970 stereographic projection system). In addition to the set of planimetric and geodetic coordinates (determined with GNSS technology), the height in the system of normal heights - Black Sea 1975 was also determined for each landmark (the elevation was transmitted by geometric leveling from landmarks in the national network), which then was transformed with TransDatRo into the EVRF2007 system (Amsterdam fundamental "zero" point).

Also through the TransDatRo software, the planimetric coordinates were calculated in the UTM (Universe Transverse Mercator) projection system.

This support network is the basis for the correct redetermination of the "zero" height of the staff 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 accuracy of determining these points, especially the elevations, significantly influences the final results: the DTM and the mathematical model of the flow.

On the analyzed sector, Bechet-Corabia, there are six locations (Figure 4) where landmarks from the AFDJ2014 support network were located (91-86).

b) LiDAR data

The LiDAR technique involves the existence of a laser sensor mounted with great precision on an airplane, helicopter or UAV (Unmanned Aerial Vehicle - drone), which transmits during the flight a laser wave to the ground and a receiver mounted behind the plane receives the reflected laser waves.

Most LiDAR systems use a scan mirror to generate a laser pulse swath. The length of the swath depends on the angle of oscillation of the mirror, and the density of the ground points depends on factors such as the speed of the plane and the rate of oscillation of the mirror.

Distances are determined by calculating the time it takes for the laser signal to travel the distance from the transmitter sensor to the ground and back to it.

In addition to the laser scanning system (Laser Scanner - Figure 5), the LiDAR technique is based on the GNSS / IMU couple (Global Navigation Satellite System / Inertial Measurement Unit), which helps to determine as accurately as possible the position and orientation of the system.

The GNSS system consists of an airborne GNSS antenna (GNSS Receiver), mounted in a visible position at the top of the aircraft, providing sufficient aperture to the satellites to record the continuous position of the aircraft, and a GNSS station located on the ground (GNSS Reference Station), with the role of correcting the measurements of the GNSS antenna, so as to obtain the best possible trajectory of the aircraft (GNSS data are processed by differential GNSS methods).

The IMU system (Inertial Measurement Unit) consists of a set of gyroscopes and accelerometers that continuously measure the height and acceleration of the aircraft *(http://www.geo-spatial.org/).*

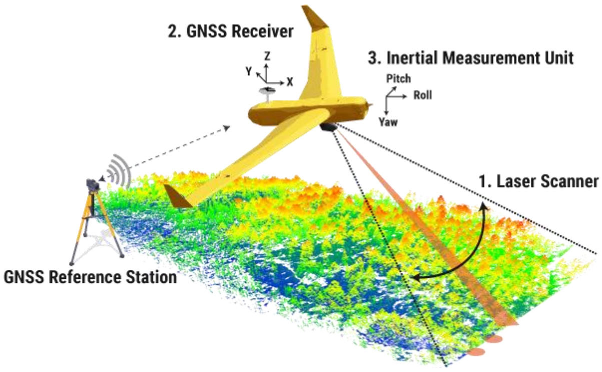

Figure 4. Components of the LiDAR system
Source: https://www.yellowscan-lidar.com/

Currently, laser scanning technology provides high-resolution topographic data and is able to quickly cover large areas, at moderate costs, with high accuracy in both horizontal and vertical planes, significantly contributing to the representation of terrain surfaces.

The three-dimensional coordinates (x, y, z or latitude, longitude and altitude) of the points corresponding to the measured objects are calculated using three main elements, namely: the time difference between the emission and return of the laser pulse, the angle at which the laser pulse was emitted and the exact location of the sensor on or above the Earth's surface.

Although this technology has some limitations due to the fact that the laser pulse does not penetrate deep water, it is certainly a useful tool for generating digital terrain models with high accuracy in complex areas such as floodplains or river islands.

Within the “Fast Danube” project, in 2017 two scanning campaigns were carried out with aircraft equipped with LiDAR systems, in April and July, the objective being to cover at least 200 m from the water limit on each side of the Danube (on the joint Romanian-Bulgarian sector) and to scan the river islands covered with forest vegetation.

To ensure the best input for the modeling process, the area of interest was extended to 250 m from the first firm shore (sandy areas were considered part of the body of water), eventually resulting in a scanned area of 1013 km^2.

Data obtained during the first survey campaign were used to calibrate the 2D models, while data obtained in the second campaign were used to validate the 2D models.

The aircrafts used for LiDAR scanning were SP-FPL-Cessna T206H (Figure 6) and SP-FPK Piper Navajo PA-31 (Figure 7).

Figure 5. Cessna T206H, modified for LiDAR scanning

Figure 6. Piper Navajo PA-31, modified for LiDAR scanning

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

They had identical scanning systems installed, consisting of the LiteMapper 6800i scanner (Figure 8) and the AeroControl series IIe 256Hz GPS / IMU system.

The LiteMapper 6800i system consists of the latest generation Riegl LMS-Q680i scanner, which uses the principle of continuous wave measurement and has the innovative Multi-Time Around function, which allows the acquisition of data from high flight altitudes, up to 3000 m AGL (Above Ground Level), depending on the scanned area.

The starting point for making the flight plans was the scanning density, the target set being 4 points / m2, but the final analysis showed that the density varied depending on the vegetation cover of each area.

The width of a scanning swath was 570 m (for an average altitude of 690 m AGL and a scanner opening angle of 45º). The average speed was 125 kts (231.5km / h).

The main result of these LiDAR scans is the 3D point clouds, that is hundreds of millions of points containing information such as x, y, z.

This huge volume of data could only be manipulated and processed with the help of powerful graphics stations and dedicated software products: RiAnalyze, RiWorld and RiProcess for LiDAR data processing, and FugroViewer for point cloud visualization.

Figure 7. LiteMapper 6800i LiDAR system installed in the plane
Source: http://www.fastdanube.eu/official-documents

The calibration of LiDAR measurements was performed based on permanent GNSS stations and ground-based control surfaces.

Unlike traditional topographic measurement techniques, this technology has offered the possibility of generating a high resolution DTM (0.5 m x 0.5 m) directly from the point cloud, following multiple stages of data processing, by applying filtering, segmentation and classification algorithms of the point clouds.

The verification of the accuracy of the obtained coordinates and the evaluation of the quality of DTM derived from LiDAR data was done by applying reliable tests, based on the data sets measured in the field.

During the ground measurement campaign, for the creation of the ground control base, the equipment used consisted of: Trimble R8s GPS receiver compatible with ROMPOS (Figure 9), Trimble M3 total laser station (Figure 10) and a transport vehicle.

Figure 8. Trimble R8s with TSC3 controller

Figure 9. Trimble M3 total station

Source: https://www.trimble.com/

c) Data from bathymetric measurements

Along with LiDAR scans, within the 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 downstream, 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. Throughout the bathymetric determinations, the ANR 1979 laboratory ship was used as a mobile support base, being stationary every 10-12 km (Figure 11).

Figure 10. ANR 1979 laboratory ship

Three motorboats (Figure 12. a, b, c) 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 swath width.

a) *b)* *c)*

Figure 11. Motorboats used
a) Buster XL b) Shadow c) ZOPEDA
Source: https://marine-research.com/

The 500 kHz frequency was used in shallow water and cross sections, and the 250 kHz frequency for scanning deep-water areas and the fairway, all teams using GS4 software for data acquisition, calibration and processing.

Kongsberg GeoSwath Plus interferometric sonar (Figure 13) consists of: transducer, deck unit and GNSS receiver. The transducer is the submerged part of the assembly, which emits and records the acoustic signal returned from the substrate, being connected to the processing unit located on the ship.

To calculate the distance to the target, the transducer has a mini SVS (Sound Velocity Sensor) connected to continuously determine the speed of sound propagation in the water column, which is then introduced as a correction in the processing. The MRU (Motion Reference Unit) assembly of inertial position sensors and boat movement compensation is also attached on the "transducer".

Figure 12. Kongsberg GeoSwath Plus interferometric sonar components
Source: Alfred Wegener Institute Helmholtz Center for Polar and Marine Research

As a mode of operation, the interferometric sonar is similar to the side-scan sonar[4], because the acoustic pulses are emitted similarly, but for the reception of reflected signals a matrix of several transducer elements located at well-defined distances is used (Figure 14). The depth of the different points on the bottom of the riverbed (or sea) is precisely calculated by measuring the phase difference between the received signals at the level of the transducer elements (corresponding to the same point), from which it results the angles between them, and by knowing the exact speed of sound propagation in the water column (approximately 1500 m / s) and the time elapsed between the transmission and reception of the signal.

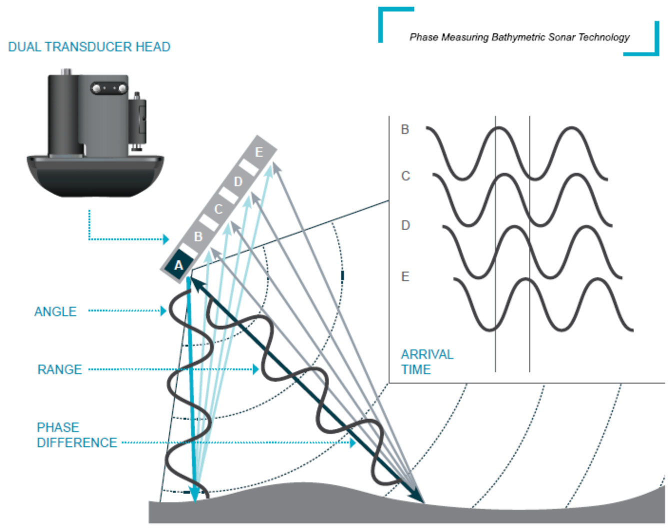

Figure 13. How the interferometric sonar works
Source: International Hydrographic Organization

[4] Side Scan Sonar was described in Research Report no. 1 - "Current status of geodetic measurements and Coordinate Reference Systems" (p.115).

On the other hand, artificial satellites evolving in outer orbit emit satellite signals broadcast in the microwave field, continuously or by pulses at regular intervals, which are received by the GNSS receiver, which decodes this signal to extract the information needed to determine position of the receiver, transmitting to the sonar the position coordinates and the time at which the determination was made.

In order to reduce positioning errors (within the limit of 3 ÷ 5 m), the differential corrections received from the base stations on the shore (points in the support geodetic network AFDJ2014) were used, in which GNSS equipment was installed (Figure 15). Following these corrections, a horizontal accuracy of 16 mm + 1 ppm from base length (base station-rover distance) and a vertical accuracy of 30 mm + 1 ppm from base length resulted.

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 pieces of equipment, so that a point with planimetric coordinates determined by GNSS technology is associated with the corresponding value of the depth measured by the sonar [13].

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

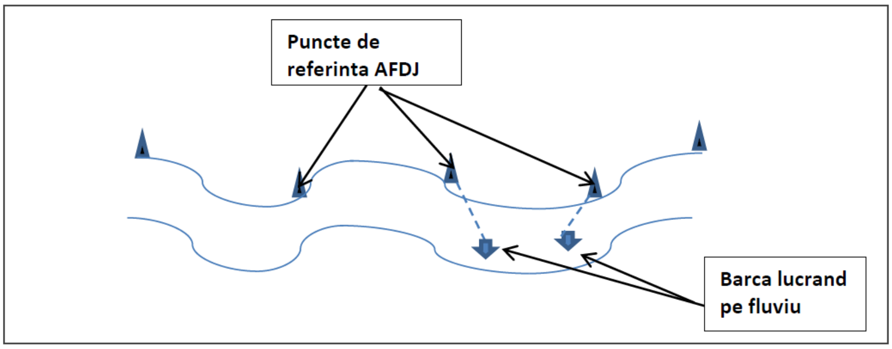

Figure 14. Transmission of differential corrections from shore base stations

When performing bathymetric measurements, it was decided to use interferometric sonar to the detriment of multibeam sonar for the following reasons:

• Interferometric sonar can also chart the banks up to the surface of the water due to the large beam transmission angle (240 degrees);

• Interferometric sonar offers a coverage of up to twice as much as the classic multibeam, being much more efficient in terms of time required and implicitly the related costs;

• Interferometric sonar provides a large number of measured points, over 5000 along the scanned swath, for each ping (sound wave emission). For the depth range foreseen for measurement, at least 10 pings / s are emitted, which means 7-8 pings / linear meter of profile, resulting in 400-800 measured points / sqm;

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

• Interferometric sonar is specially designed for operation in shallow and very shallow waters, while conventional multibeam sonar offers low coverage in these areas.

Data obtained from LiDAR surveys were combined with bathymetric and topographic data to produce a continuous DTM of high accuracy and resolution (50 cm grid), which covers the entire study area (Figure 16) - the low-flow channel and 250 m from the edge of the river on both sides.

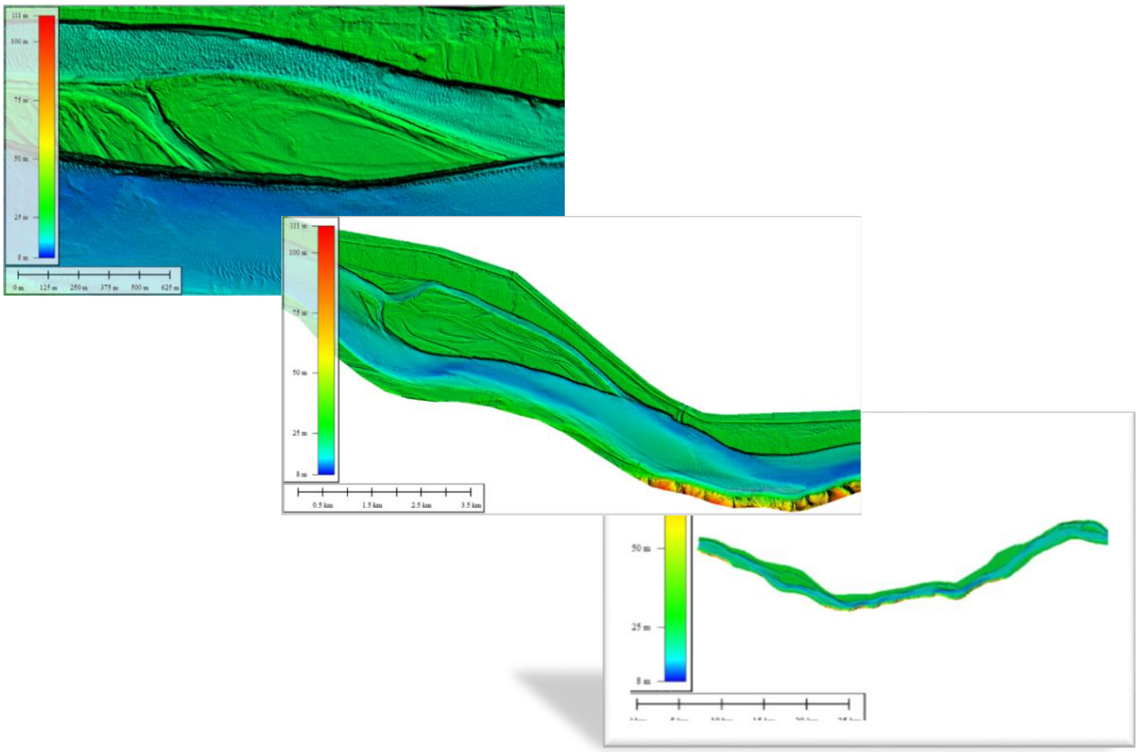

Figure 15. Unified DTM visualization and analysis using Global Mapper software

Finally, in order to assess the quality of the unified DTM, an analysis was performed on the connection areas of the DTM obtained from LiDAR data with the DTM obtained from bathymetric measurements and the global indicators of precision and accuracy were determined in accordance with the provisions of the tender book.

3.4.2. Hydrological data

The hydrological data necessary for the building of the 2D hydrodynamic model, respectively for establishing the boundary conditions were obtained from the archive of the National Institute of Hydrology and Water Management (NIHWM) and LDRA Galați. All collected data were reorganized and processed by statistical-mathematical methods (Microsoft Excel 2014). It consists of:

- Daily-mean liquid flows and daily-mean levels from Bechet and Corabia Gauge Stations for 2017 (source: NIHWM);
- Rating curve from the Corabia gauging station valid for 2017 (source: NIHWM);

- The roughness coefficients for the low-flow channel and for the flood plain, 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.

The rating curve from Corabia gauging station was purchased in tabular form, in .jpg format, and the levels were relatively expressed. The transformation of these relative values into absolute heights (Black Sea 1975 Height System) was possible by referencing to the "zero" height of the staff gauge corresponding to the Corabia Gauge Station (source: NIHWM) - Figure 17.

	A	B	C	D	E	F	G	H	I	J	K	L
1	H(cm)/Q(mc/s)	**0**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	
2	-70			1920	1930	1940	**1950**	1960	1970	1980	1990	
3	-60	2000	2010	2020	2030	2040	**2050**	2060	2070	2080	2090	
4	**-50**	**2100**	2110	2120	2130	2140	**2160**	2170	2180	2190	2200	
5	-40	2210	2220	2230	2250	2260	**2270**	2280	2290	2300	2310	
6	-30	2320	2340	2350	2360	2370	**2380**	2390	2400	2410	2420	
7	-20	2440	2450	2460	2470	2480	**2490**	2500	2510	2530	2540	
8	-10	2550	2560	2570	2580	2590	**2600**	2620	2630	2640	2650	
9	**0**	**2660**	2670	2690	2700	2710	**2720**	2740	2750	2760	2780	

	A	B	C	D	E	F	G	H	I	J	K	L	M	N
1		**SH Corabia**	**„Zero" mira**	**19,647** mdMN										
2														
3					18,937	18,927	18,917	18,907	18,897	18,887	18,877	18,867	18,857	
4		H(cm)	H(m)/ Q(mc/s)	**0**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	
5				0	0,01	0,02	0,03	0,04	0,05	0,06	0,07	0,08	0,09	
6	-0,7	-70	18,947			1920	1930	1940	**1950**	1960	1970	1980	1990	
7	-0,6	-60	19,047	2000	2010	2020	2030	2040	**2050**	2060	2070	2080	2090	
8	-0,5	**-50**	19,147	**2100**	2110	2120	2130	2140	**2160**	2170	2180	2190	2200	
9	-0,4	-40	19,247	2210	2220	2230	2250	2260	**2270**	2280	2290	2300	2310	
10	-0,3	-30	19,347	2320	2340	2350	2360	2370	**2380**	2390	2400	2410	2420	
11	-0,2	-20	19,447	2440	2450	2460	2470	2480	**2490**	2500	2510	2530	2540	
12	-0,1	-10	19,547	2550	2560	2570	2580	2590	**2600**	2620	2630	2640	2650	
13	0,0	**0**	19,647	**2660**	2670	2690	2700	2710	**2720**	2740	2750	2760	2780	

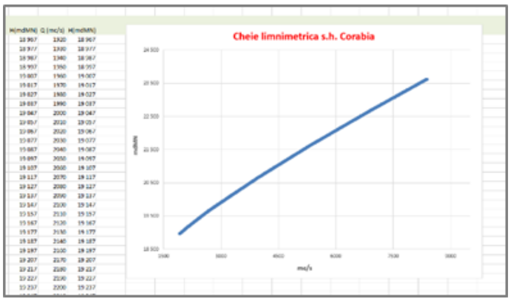

Figure 16. Example of analysis and processing of raw data for use as input data in the mathematical model

3.4.3. Geospatial database

The issue of sediment transport modeling on the Danube and improving, in general, waterway maintenance processes is of great interest, although it has been addressed in the past in several research projects and programs.

Building the mathematical model is a very important step in achieving the objectives of this research project (presented in the *Project of the scientific research program, 2018*).

For this purpose, bibliographic materials were consulted to provide a general framework for research: doctoral theses, specialized journals, geography treatises, hydrological studies, regional studies, websites, etc.

The documentation phase for the elaboration of this *research report* culminated with the creation of a database containing as detailed information as possible on the Danube River in general and the Bechet-Corabia sector in particular.

The geospatial data in vector file formats were organized in thematic layers (Table 3), which would allow analyses in the GIS (Geographic Information System) environment.

Usually, the basic sources are raster data, which is vectorized, resulting in other data to which an attribute table with several characteristic fields is added. These fields are in turn used for design (labels, classifications) or to generate new information.

Table 3. Primary spatial database used in the study

PRIMARY DIGITAL DATA	*FORMAT*	*DATA SOURCE*
Hydrographic network	*Vector; line*	*Vectorization of the 1:25000 topographic map*
Gauge stations	*Vector; point*	*NIHWM Database*
Localities	*Vector; point*	*geo-spatial.org*
State border	*Vector; polygon*	*geo-spatial.org*
W.B.A. Limits	*Vector; polygon*	*NIHWM Database*
River Basins	*Vector; polygon*	*NIHWM Database*
Banks	*Vector; line*	*Vectorization of orthophotoplanes with a resolution of 0.5 m (2013-2017 edition);*
Flood Plain	*Vector; line*	*Vectorization of orthophotoplanes with a resolution of 0.5 m (2013-2017 edition);*
Thalweg	*Vector; line*	*LDRA Galați (Fast Danube Project)*
River Islands	*Vector; polygon*	*Vectorization of orthophotoplanes with a resolution of 0.5 m (2013-2017 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*

Until the completion of the research project, this database will be constantly completed and updated, because the application of specific GIS operations on raw vector data can generate data in raster format, much more useful for analysis and predictions on certain current geomorphological processes, existing the possibility to process it in order to simulate the conditions in the field and to quantify their influences in the triggering and evolution of some processes invisible to the human eye or not represented on the topographic map.

3.4.4. Other Data Sources

In general, hydrological processes, both those that characterize liquid runoff and those that describe alluvial runoff, take place at the scale of river basins and are determined by a number of environmental factors, the most important of which being the lithological substrate (geology), geography, soils, land use, climatic elements and groundwater.

Except for the parameters considered input data for the two-dimensional hydrodynamic modeling of the Bechet-Corabia Danube River sector, analyzed in this Research Report, we will return to the other ones in the *Research Report no. 3 - Case study and interpretation of results*", which has as main objective the modeling of sediment transport on the Bechet-Corabia Danube River sector.

3.5. Work Stages

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

3.5.1. Specialty Software Used

The following GIS applications were used for digitizing, processing and exporting data required for bathymetric modeling, as well as for spatial transposition of data and information into sketches and maps: ArcMap 10.5, ArcGIS PRO 2.1 and Global Mapper v18.

The 2D hydraulic model of the studied 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 for 2D modeling of rivers, waves, sediment transport, water quality and advection / dispersion *(https://www.mikepoweredbydhi.com/).*

The *MIKE 21 Flow Model HD FM* solution is based on the integrated Navier-Stokes equations in relation to depth (for free surface flow) and uses a finite element network (Flexible Mesh) [14]. The program calculates the water level, depth, velocity and direction of each finite element of the model network and at each time interval of the model simulation.

MIKE 21 FM also allows the simulation of sediment transport using a non-cohesive sediment transport module ("Sand Transport"), a cohesive sediment transport module ("Mud Transport") and a morphology module for updating the elevations in the during model simulation).

The *FM* module in the *MIKE 21* package allows a better simulation of the combined coarse and fine sediment systems than other 2D flow modules, such as the MIKE21C package (which uses a curvilinear mesh network), where the simulation of fine sediment transport is simpler.

3.5.2. Geospatial Data Preprocessing Using GIS Applications

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). As previously mentioned, the DTM corresponding to the Bechet-Corabia sector covers the low-flow channel and 250 m from the water boundary. It comes from the processing and unification of LiDAR data and bathymetric data, being a unitary DTM of high accuracy and high spatial resolution: 0.5 m x 0.5 m.

In most cases, the 2D hydraulic modeling process requires a hardware component with a special configuration, so that the export / import of data and simulations over large areas can be performed in a reasonable time.

Since we had a high-performance computer, but not a graphics station (Workstation) built and prepared to withstand continuous demands throughout the day, we opted for resampling DTM at a spatial resolution of 1 m x 1 m.

First, the resizing of the DTM (raster file) according to the study area was performed using the *Extract by Mask* tool from the Spatial Analyst Module in ArcMap 10.5, then the *Resample* function was accessed (Fig. 18) from ArcToolbox: Data Management Tools → Raster → Raster processing → Resample. At “input” the Digital Terrain Model was selected, for X and Y we entered the value 1, and at Resampling Technique the Nearest method was selected.

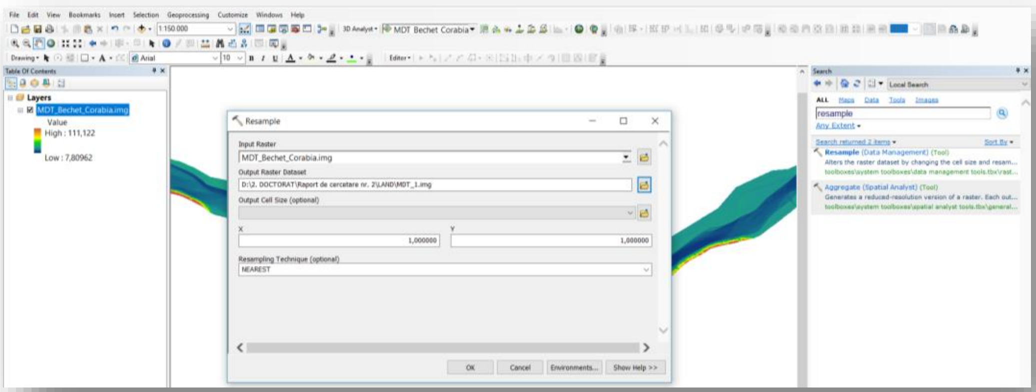

Figure 17. DTM resampling using the Resample function

Global Mapper software was used to convert this raster file from .img format to the format supported by Mike 21, namely *xyz*, following the steps *File → Export → Elevation Grid Format → XYZ Grid*. The resulting *xyz* file contains over 100 million values.

The vectorization of the river banks, the flood plain or fluvial islands (Figure 21) was performed in *ArcMap 10.5*, based on the DTM, the orthophotoplanes 2013-2017 edition (Figure 20), with a spatial resolution of 50 cm, made by the Military Topographic Directorate, but also based on Sentinel 2 satellite images (Figure 19) corresponding to the measurement campaign period.

The *Shape to XYZ Conversion tool* created by DHI was used to export *shapefile* data in *xyz* format (the maximum distance allowed between points was 100 m).

Figure 18 - Sentinel 2 satellite image (IR - bands 8, 4, 3)

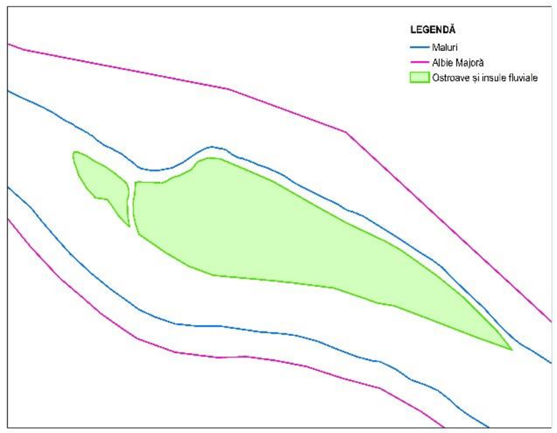

Figure 19. Vectorization of shores, flood plain and river islands based on DTM, orthophotoplane and Sentinel 2 satellite images (IR band)

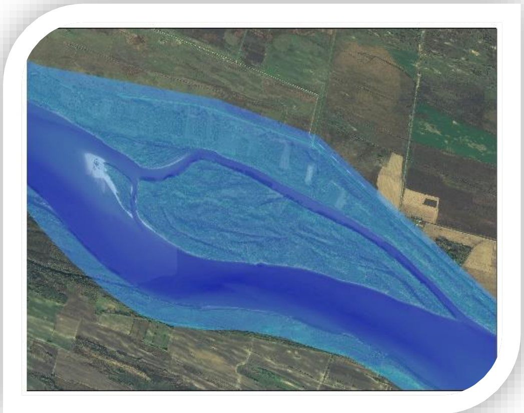

Figure 20. DTM superimposed over orthophotoplane

The last step in preparing the data before importing it into Mike 21 was to create the *xyz* file with the values of the *Manning roughness coefficient* (M = 1 / n, where n is the roughness coefficient), which differs for the main channel, islands and flood plain, with values included in the interval 10 - 38.46 (Figure 22). The lower the value of the Manning number, the higher the resistance of the terrain (respectively the discharge rate decreases) [15].

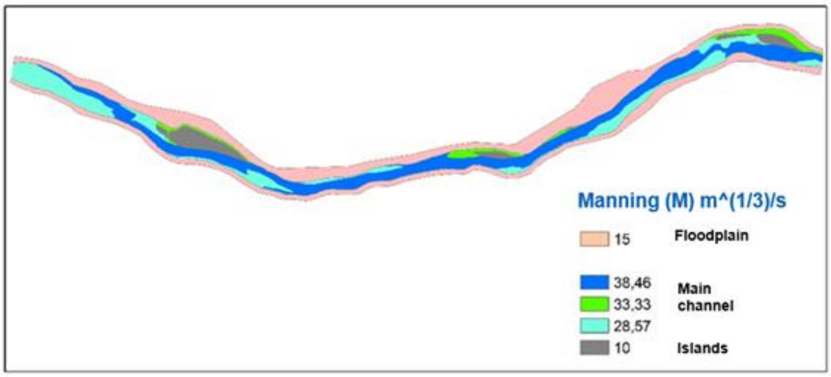

Figure 21. Roughness coefficients for flood plain, low-flow channel and islands

3.5.3. Creating a Computational Mesh in Mike Zero

In Mike Zero (name of the DHI graphical interface from which all available modules are accessed: Mike HYDRO, Mike 11, Mike 21, Mike 3, Mike Flood, Mike SHE etc.), select *New → File → Mesh Generator*.

The first step in obtaining the flexible (triangular) grid of finite elements is the setting of the cartographic projection, namely “Stereo_70” in the case of this study.

The next step is to import the boundaries of the work domain in *Mesh Generator*: *Data → Import Boundary* (xyz files for low-flow channel, fluvial islands and floodplain previously exported from GIS environment). In “*Boundary properties*” select “*X, Y, Connectivity and Z*” (Figure 23).

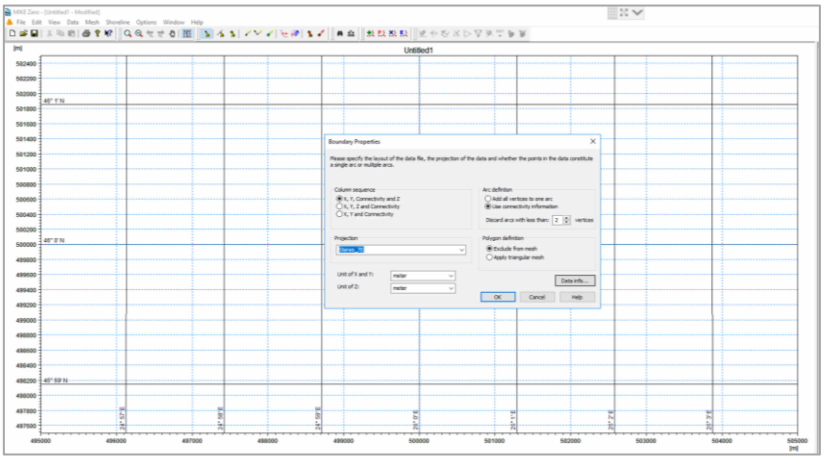

Figure 22. Setting the projection and xyz file type

It is very important to mention that “*Exclude from mesh*” will be ticked for all islands and “*Apply triangular mesh*” only for the main channel, because it is assumed that during low and medium water does not flow over those island formations covered with vegetation.

After editing the vertices and nodes of the domain boundaries, the finite element grid will be generated as follows: *Mesh → Mesh Generation (Figure 24)*, with the following settings:

- *Maximum element area: 5000 m^2;*
- *Smallest allowable angle: 30;*
- *Maximum number of nodes: 80000.*

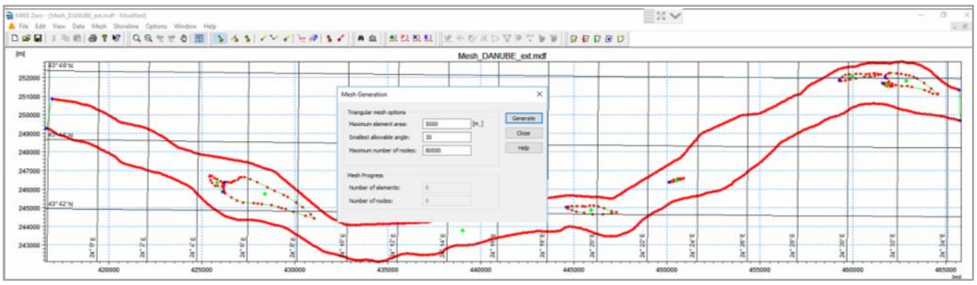

Figure 23. Mesh network generation

Through this operation, the model domain is represented by a network of interconnected triangular finite elements (Figure 25). Such a network is automatically generated by the computer system, and the resolution of the model is controlled by specifying the maximum area that an individual element can occupy in the network. For example, if the maximum area of the element has been set to 5000 m2, then each element in the network will have an area of no more than 5000 m^2. The resolution of the network can vary in different parts of the modeled domain (at the end I also applied the "Smooth Mesh" function). As the cell size decreases, both the number of elements in the model and the computation time required for model simulations increase.

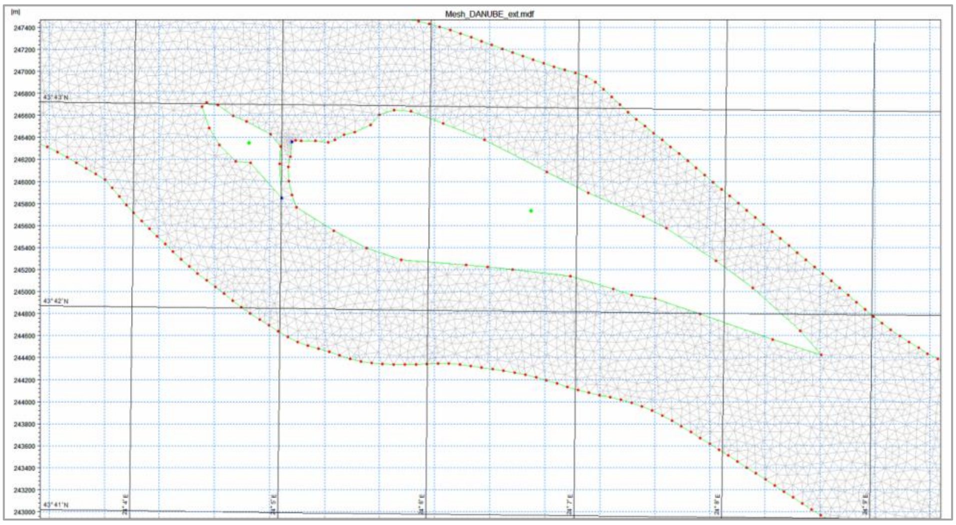

Figure 24. Network of interconnected triangular finite elements (Triangular Mesh)

After this step, the points resulting from the export of the DTM in *xyz* format were imported into the *Mesh*, by accessing the "*Manage Scatter Data*" tool from the *Data* menu (Figure 26).

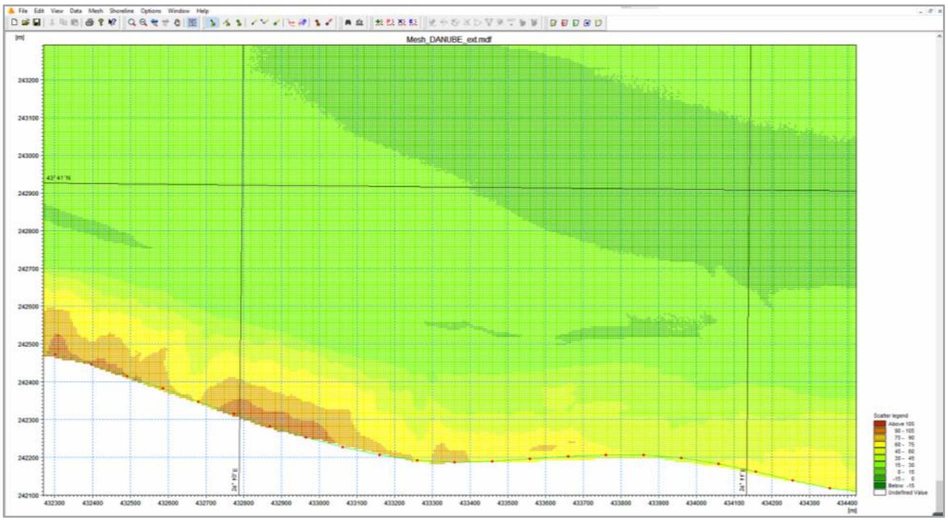

Figure 25. Importing the xyz file with the points extracted from the DTM

Interpolating these millions of points using the "*Interpolate*" function in the "*Mesh*" menu is the last step in obtaining the bathymetry file. The elevations of the points are expressed in the 1975 Black Sea Height System (Figure 27).

The result was later exported by accessing the menu *Mesh → Export Mesh → Mesh File (Item type - Bathymetry)*.

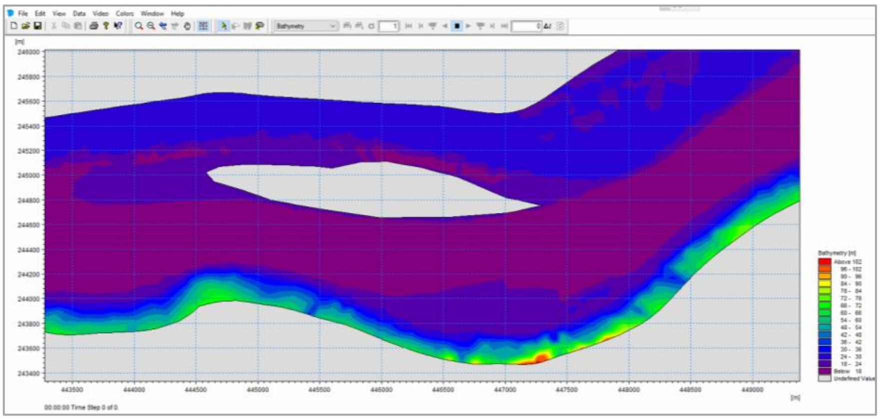

Figure 26. Mesh file for bathymetry in the Danube River sector Bechet - Corabia

Similarly, the *xyz* file with the *Manning* roughness coefficients - *bed resistance* (created *in ArcMap*) was imported into the *Mesh*: *Data → Manage Scatter Data* (Figure 28).

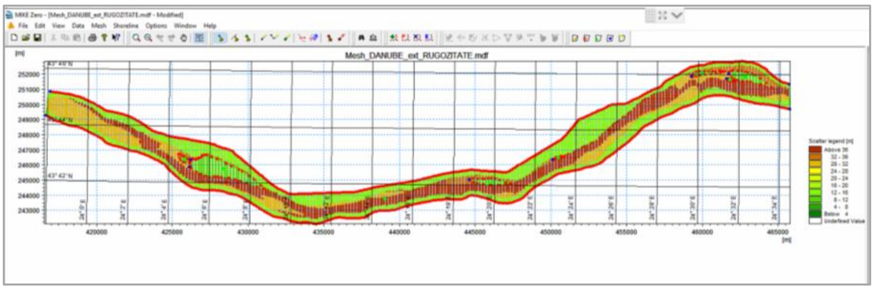

Figure 27. Importing the xyz file with the Manning roughness coefficients

These values were interpolated, and the result was exported as a *DFSU Data-file*, according to Figure 29 (from the *Mesh → Export Mesh* menu), a *Mike*-specific format, with the specification "*Manning's M*" for *Item type*.

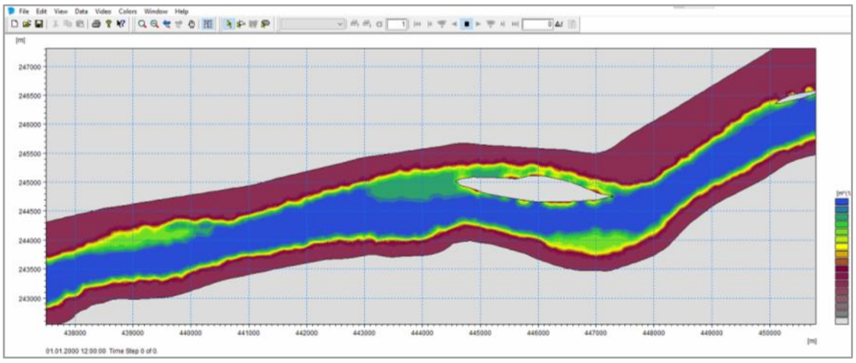

Figure 28. dfsu file for the roughness of the Danube River sector Bechet - Corabia

3.5.4. Boundary Conditions Input

The establishment of Boundary conditions for the model refer to:

- The hydrograph of daily-mean flow at Bechet gauge station (upstream) on the Danube river, available for the simulation period (23.04.2017 – 05.06.2017);
- The rating curve at Corabia gauge station (downstream) on the Danube river.

It is also necessary to introduce an Initial Condition consisting of:

- The mean annual flow for 2017 at Bechet gauge station (upstream) on the Danube river, with a value of 4461 m^3/s, which is used in steady state simulation to produce a hot-start, used later for flow propagation;
- The rating curve at Corabia gauge station (downstream) on the Danube river.

To set the boundary conditions using *Mike*, it is necessary to create certain .dfs0 files, both for the discharge hydrograph at Bechet Gauge Station (Figure 30), as well as for the rating curve at Corabia Gauge Station (Figure 31).

a) For discharges:

➢ From *Mike Zero* we select *New → File → Time Series (.dt0, .dfs0) → Blank Time Series*, and in the window that opens, the following settings are made for the axis type, start date, time step, number of time steps, file name, record type, measuring unit:

- Axis Type: *Equidistant time axis*;
- *Start time:* 23.04.2017 (the period in which the bathymetric measurements were performed, source: *http://www.fastdanube.eu/*);
- *Time step:* 1 day;
- *Number of Time Steps:* 44;
- *Name:* Bechet Discharges;
- *Type:* Discharge;
- *Unit:* m^3/s;

The discharges entered in the .dfs0 file must be those recorded at Bechet Gauge Station during the simulation period (23.04.2017 - 05.06.2017) of the model.

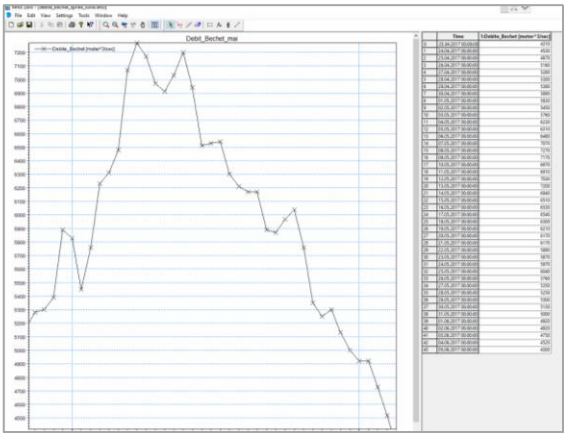

Figure 29. DFS0 file with hydrograph of the daily-mean flow recorded at Bechet Gauge Station

b) For the rating curve:

- From *Mike Zero* we select *New → File → Time Series (.dt0, .dfs0) → Blank Time Series*, and in the window that opens the following settings are made:
  - *Axis Type: Relative Item Axis*;
  - *Number of Time Steps: 467* (how many rows are in the rating curve in .xls format);
  - *Axis Units: m*;
  - *Name: Corabia rating curve;*
  - *Type: Water level;*
  - *Unit: m;*

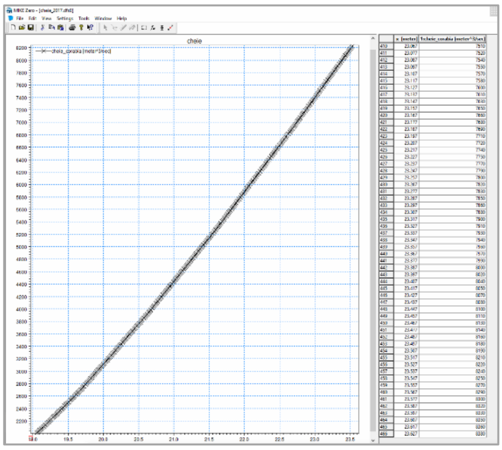

Figure 30. dfs0 file with rating curve valid for 2017 at Corabia Gauge Station

The .dfs0 file with the rating curve valid for 2017 at Corabia Gauge Station will be used both for running the initial condition (with constant flow), and for the boundary condition downstream.

3.5.5. Set-up of Mike 21 Flow Model (FM)

The dialogue for setting-up the Mike 21 FM model, is initiated from MIKE Zero: *MIKE Zero → Mike 21 → Flow Model FM*, then the window in Figure 32 will open:

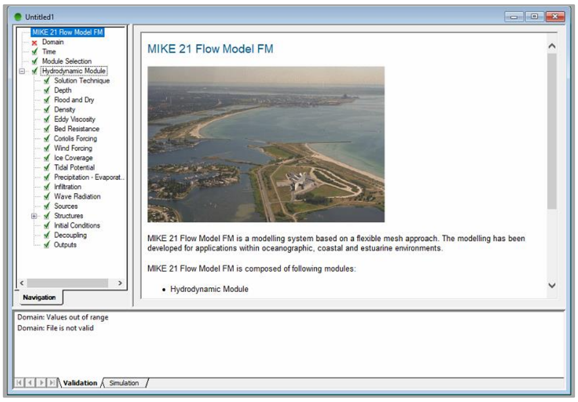

Figure 31. Mike 21 FM Module

The following information and data sets are required:

- *Domain:* the .mesh file previously created for the bathymetry of the Bechet-Corabia Danube River sector;
- *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;
- *Selected module*: Hydrodynamic.

➢ The Hydrodynamic module was set as follows:

- Technical Solution: Low order, fast algorithm (in this way the simulation is faster);
- Flood and dry: 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 m^3/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.
- Output items (results obtained - Figure 33): Surface elevation, Total water depth, Current Speed, U velocity, V velocity.

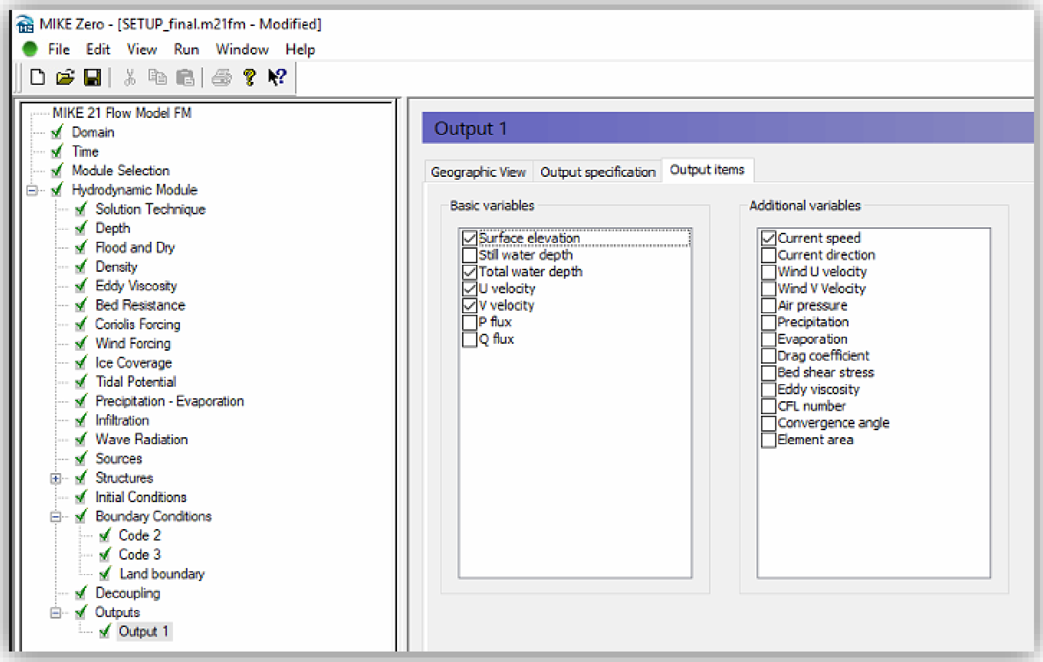

Figure 32. Simulation Results

4. RESULTS AND CONCLUSIONS

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* - Figure 34, *Total water depth* - Figure 35, *Current speed* - Figure 36 and *Speed direction* (components U and V - U velocity, V velocity) - Figure 37 and Figure 38. This information is stored in a .dfsu file format.

Etymologically, the concept of "simulation" comes from the Latin *simulatio*, which represents the ability to reproduce, imitate or represent a phenomenon.

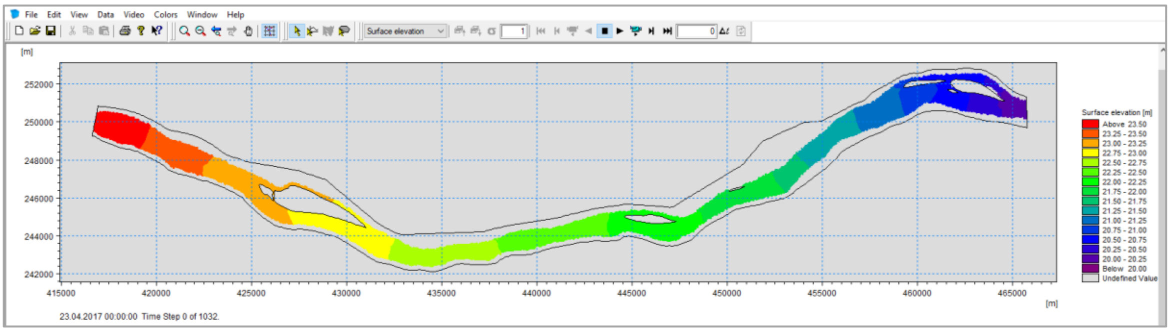

Figure 33. Surface elevation

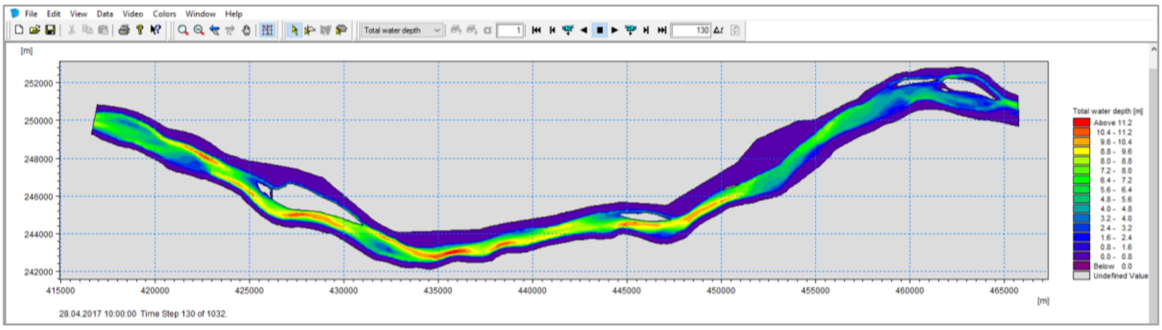

Figure 34. Total water depth

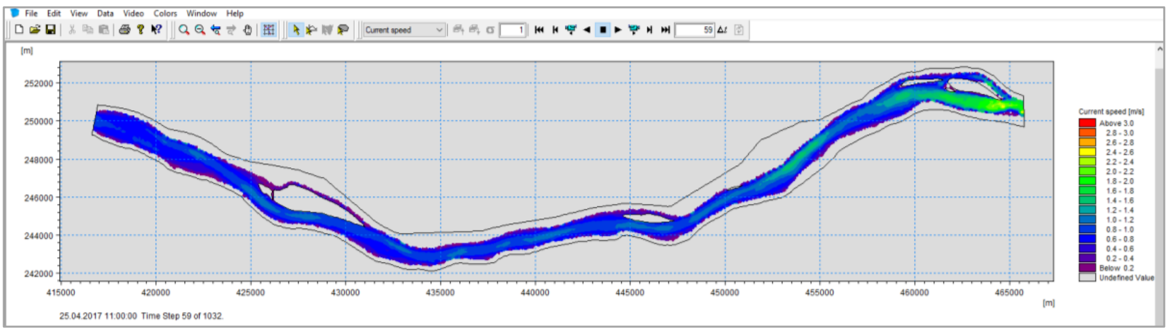

Figure 35. Current speed

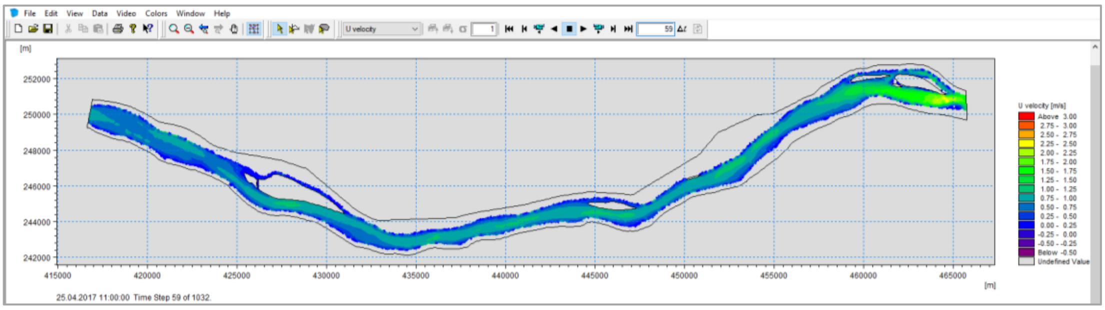

Figure 36. U velocity

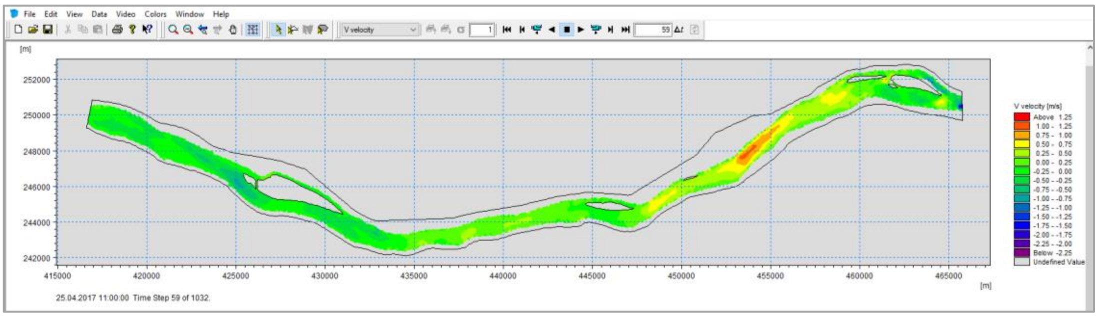

Figure 37. V velocity

The MIKE 21 HD output results can be used as input for other MIKE 21 modules, such as the Sediment Transport Module, the Advection-Dispersion module (AD), the Particle tracking (PA) and the Environment module (MIKE ECO Lab).

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.

Calibration of the 2D hydrodynamic model

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 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 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 cross sections can be divided in main channel and overbank sections, with different roughness properties. Finally, the best results were obtained for values of the Manning roughness coefficient (M) which differ for the main channel, islands and floodplain. The values were included in the interval 10 - 38.46, as presented in Figure 22.

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 39).

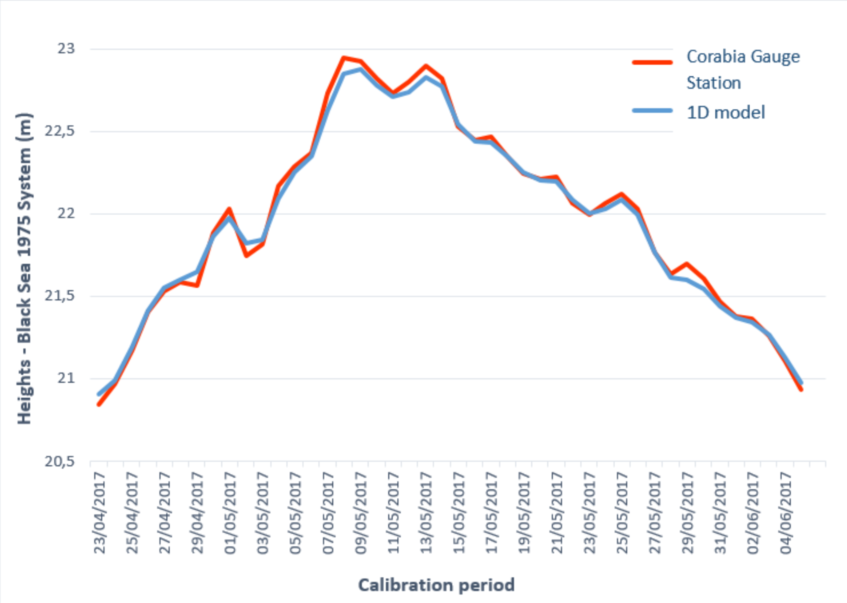

Figure 39. 1D Hydrodynamic Model calibration

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 between simulated and measured values of daily-mean water levels at Corabia Gauge Station is shown in Figure 40. The differences were included in the [-5.35 cm, +12.35cm] interval, with a mean value of +2.25 cm.

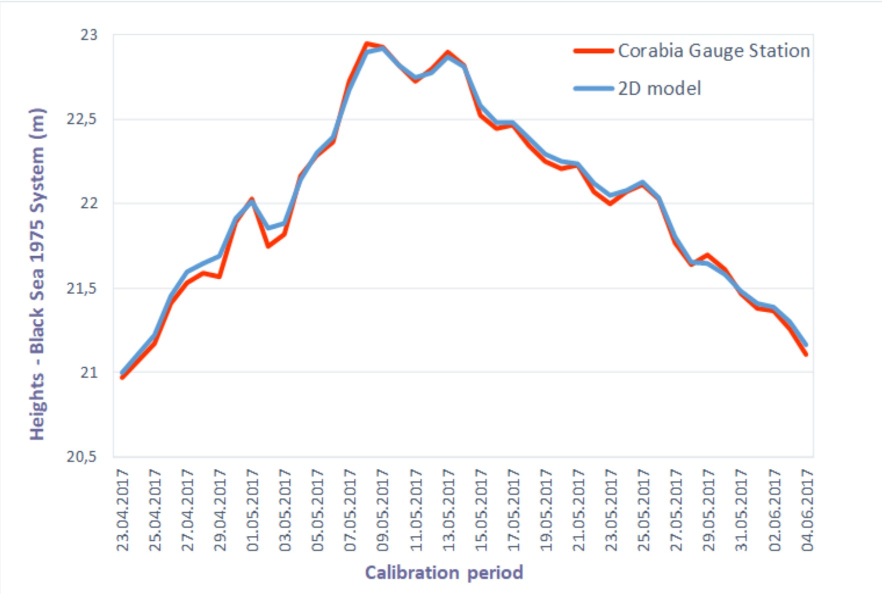

Figura 40. 2D Hydrodynamic Model calibration

Validation of the 2D hydrodynamic model

Validation of the 2D hydraulic model has been performed by simulating the hydrograph of the daily-mean flows recorded at Bechet gauge station between 03.03.2017 to 31.03.2017. The daily-mean flows in this interval are higher than those recorded during the calibration period. The maximum flow value recorded in the validation period was 8010 m^3/s, and the minimum was 6010 m^3/s, while the maximum flow value recorded during the calibration period was 7270 m^3/s and the minimum only 4300 m^3/s.

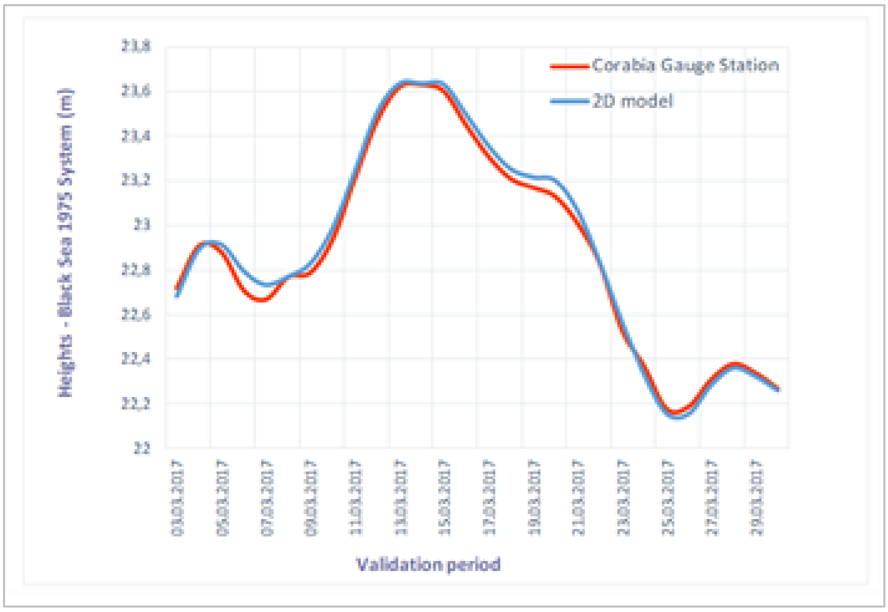

Figure 41. Daily-mean water level comparison at Corabia gauge station for the validation period (03.03.2017 - 31.03.2017)

The differences between simulated and measured values of daily-mean water levels at Corabia gauge station were included in the [-3.44 cm, +8.76 cm] interval, with a mean value of +2.24 cm (Figure 41).

Conclusions

Considering the obtained results, it can be concluded that the two-dimensional hydrodynamic model has been fully calibrated and validated. 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.

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