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Interreg
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SEDIMENT MOBILIZATION STUDY

POMGRAD VGP d.d.,
WP T1/A.T1.2 Assesing abiotic framework conditions of the river corridor/ D.T1.2.2 Sediment mobilization study, 2022

IMPRESSUM

Author: Pomgrad VGP d.d.

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Editor: Saša Sobočan

Project Manager: Saša Sobočan

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List of Abbreviations

ARSO	Agencija Republike Slovenije za okolje- Slovenian Environment Agency -
A.S.L	Above sea level
BOKU	University of Natural Resources and Life Sciences
CAD	Computer-aided design
DEM	Digital elevation model
DTP	Danube Transnational Programme
EU	European Union
FGG	Faculty of Civil Engineering and Geodesy in Ljubljana
GK	Gauss Krüger coordinate system
GPS	Global Positioning System
GS	Gauging station
HPP	Hydropower plant
IzVRS	Institute for Water of the Republic of Slovenia
LIDAR	Light Detection And Ranging
MDD	Mura- Drava- Danube
POO	Special areas of conservation
SPA	Special protected area
TBR-MDD	Transboundary Biosphere Reserve Mura-Drava-Danube
TIN	Triangular irregular networks
TM	Transverse Mercator projection
UNESCO	United Nations Educational, Scientific and Cultural Organization
VGP	Water management company
WCRP	World Climate Research Programme
WMO	World Meteorological Organization
WP	Work package
WS	Workshop
WWF	World Wide Fund For Nature

I. Introduction

• General introduction

The present report is the result of a study conducted within the DTP3-308-2.3 lifeline MDD, financed by the European Union´s Interreg Danube Transnational Programme. The area analysed and targeted by the present study (hereinafter called "target area") comprises river sections in the 5-country Biosphere Reserve Mura-Drava-Danube (TBR MDD, Figure 1), shared between Austria, Slovenia, Hungary, Croatia and Serbia. Spanning Austria, Slovenia, Hungary, Croatia and Serbia, the lower courses of the Drava and Mura Rivers and related sections of the Danube are among Europe's most ecologically important riverine areas. The three rivers form a "green belt" 700 kilometres long, connecting almost 1.000,000 hectares of highly valuable natural and cultural landscapes, including a chain of 13 individual protected areas and 3.000 km2 of Natura 2000 sites. This is the reason why, in 2009, the Prime Ministers of Croatia and Hungary signed a joint agreement to establish the Mura-Drava-Danube Transboundary Biosphere Reserve across both countries. Two years later, in 2011, Austria, Serbia and Slovenia joined this initiative. Together with Croatia and Hungary, the five respective ministers of environment agreed to establish the world´s first five-country Biosphere reserve and Europe´s largest river protected area. Step by step the TBR MDD was realized: Hungary and Croatia (in 2012), Serbia (in 2017), Slovenia (in 2018) and Austria (2019) achieved UNESCO designation. The pentalateral designation was submitted in 2020 and designation finally achieved in September 2021.

The project´s work package for *Establishing the scientific knowledge base* (Work Package T1) has proposed as its aim to establish, as a first, a scientific knowledge base regarding vertical, lateral and longitudinal connectivity within the Mura-Drava-Danube bio-corridor. All studies' results and the overlaid GIS data collected therefore build the basis for a synthesis report on biotic indicators and abiotic framework conditions. This builds the basis for long-term conservation and restoration goals within the 5-country Biosphere Reserve Mura-Drava-Danube (TBR MDD) as well as for formulation of a TBR MDD River Restoration Strategy, elaborated in the framework of the same project (Output OT2.4). The facts and results presented in this project therefore come from a first ever such scientific assessment, which was done between July 2020 and (Month) (year), harmonized on 5-country scale, setting the ground for future decision-making on 5-

country level on river management and restoration. Whereas such activities and knowledge in each of the countries involved in the TBR MDD partly exist, this was the first time methods and area were harmonized for monitoring and studies of the biotic elements and the abiotic framework conditions for the Mura-Drava-Danube river corridor.

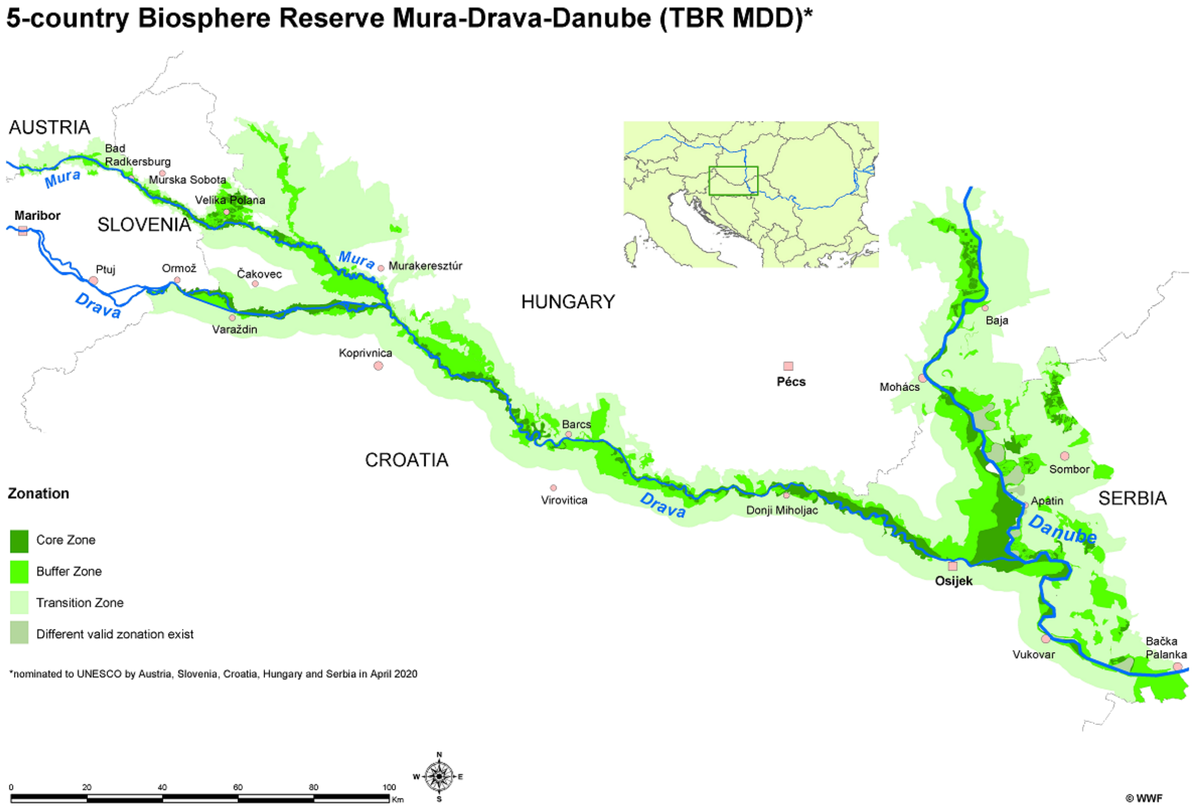

Figure 1. Map of the 5-country Biosphere Reserve Mura-Drava-Danube according to UNESCO designation in September 2021 (WWF Austria)

• Description of the study area

The Mura River originates in Austria at about 1900 m above sea level and after about 450 km it flows as a left tributary into the Drava River in Croatia. The Mura catchment area covers 13,824 km^2, of which 70% is in Austria, 10% in Slovenia, 7% in Croatia and 13% in Hungary. In Slovenia, the Mura first flows 34 km as a border river with Austria, then at Gornja Radgona it turns southeast and flows about 29 km in Slovenia (inner Mura), then it turns east again and another 33 km flows as a border river with Croatia.

The beginnings of anthropogenic interventions in the Mura River date back to the Middle Ages, while the systematic regulation of the Mura was completed at the end of the 19th century. In the 20th century, a chain of 31 (mostly flow-through) power plants was built in Austria between the towns of Bodendorf and Spielfeld, while in Slovenia and Croatia there are no power plants on the Mura. The border Mura is regulated (canalized) with a riverbed width of 60-80 m with riparian fortifications, while the inner Mura is regulated by a low, slightly winding riverbed bounded by high-water embankments built between 1972-1990. The habitat and species-varied corridor between the embankments is up to 1 km wide.

The project area of revitalization comprises the section of the inner Mura east of the settlement Hrastje-Mota across during the stationing km 95 + 100 to km 95 + 350.

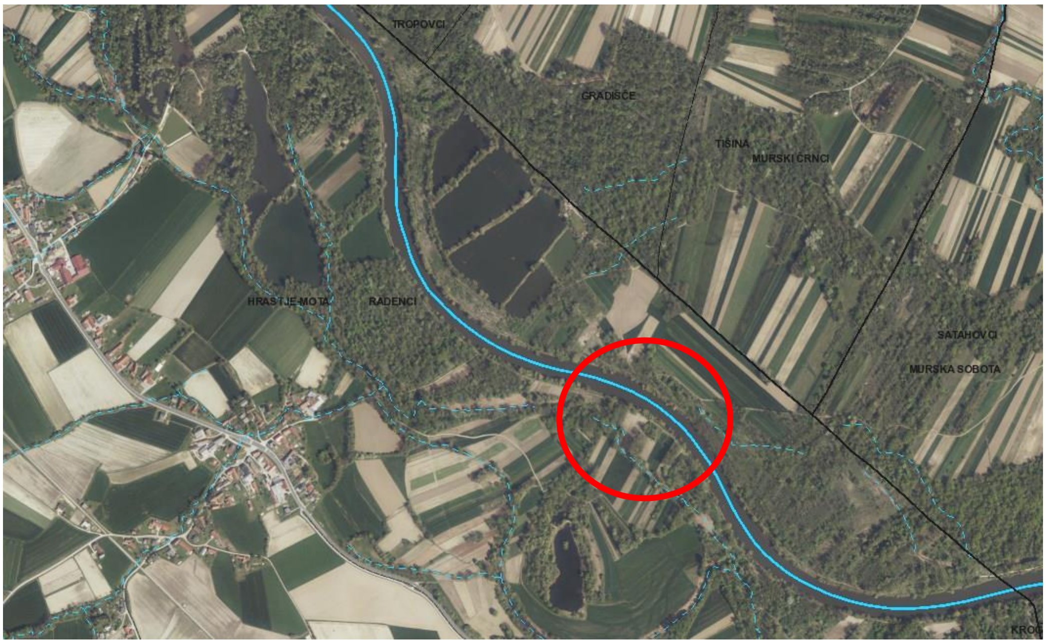

Figure 2: Map of the study area and the location of the pilot measure in WP T2

The Mura riverbed is leveled in this area and protected by riparian insurance. In the narrower area of the planned widening of the riverbed, mixed forest thrives, and behind this relatively narrow strip of forest lie cultivated fields. The location of the intervention in question is in the following protected areas:

Special protection areas (Natura 2000 sites):

• POO - Mura, code SI3000215- Decree on special protection areas (Natura 2000 areas) (Official Gazette of the Republic of Slovenia, No. 49/04, 110/04, 59/07, 43/08, 8/12, 33/13, 35 / 13-corr., 39/13-dec. US, 3/14, 21/16 and 47/18)

• SPA - Mura, code SI500010- Decree on special protection areas (Natura 2000 areas = (Official Gazette of the Republic of Slovenia, No. 49/04, 110/04, 59/07, 43/08, 8/12, 33/13, 35 / 13-corr., 39/13-dec. US, 3/14, 21/16 and 47/18)

At the location of the measure and in the area of direct and remote impact of the measure is the zone and habitat of several species of forest and water birds, fish, beetles and amphibians. The area of intervention and around its direct impact is at the same time partly a zone and an area of protective habitat type, which is a qualifying habitat type of special conservation area: riparian willow, alder and ash (softwood arch).

• Historical overview of the study area

A historical overview of the Mura River area shows that the riverbed has been regulated and leveled several times in the past. Systematic regulations have been in place since the end of the 19th century. The once diversified system with many side arms and extremely high structural diversity has been leveled. The Mura River and the Inundation area were also more than 200 m wide in the considered area.

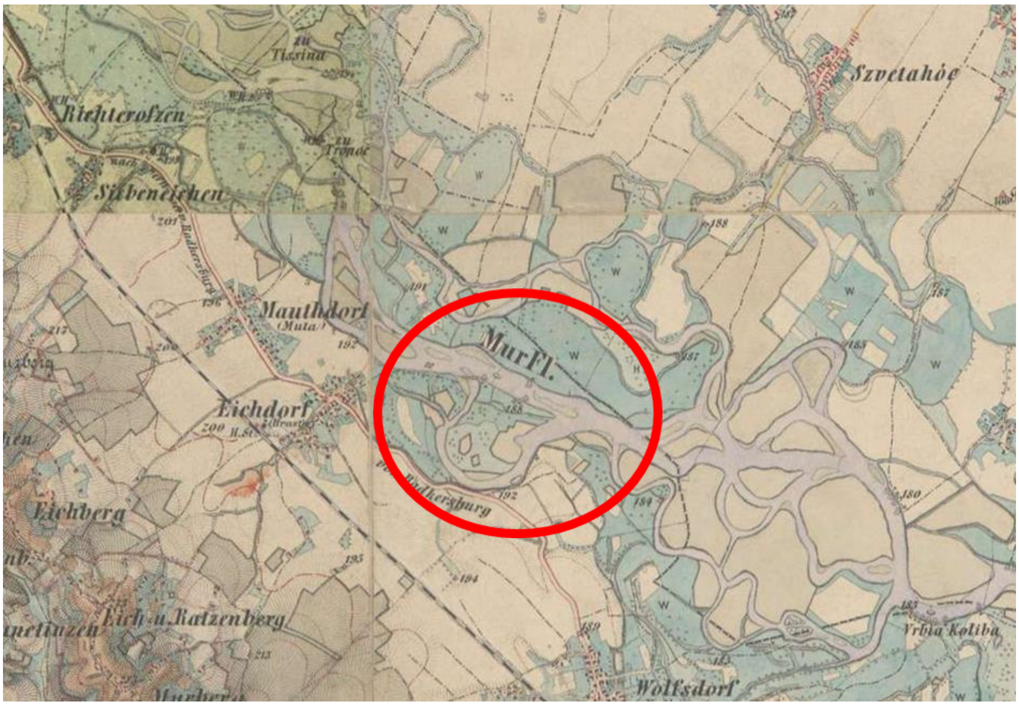

Figure 3: Considered location on a map made in 1821-1836 (Austria-Hungary) (third military dimension). Source: www.arcanum.com

Data on the drop in current, transport capacity and grain size in the upper layers of the hinterland suggest that the river was in 19. century or in equilibrium, if not in the latent state of proliferation. Frequent changes in the Mura riverbed are also an indicator of a surplus of gravel in previous periods. Today, there is an acute shortage of gravel in the Mura section on the border between Slovenia and Austria [10].

In the past, numerous pilot projects have been carried out on the river, especially on the border section of the Mura River with the Republic of Austria, to increase the width of the Mura riverbed and to establish dynamic stability of the riverbed [10]. Such projects have been carried out in Gosdorf and Sicheldorf [6].

In the subject project, we designed solutions based on experience from past analyzes and pilot transactions, which we applied in the subject project.

Warning to mark the stations on the Mura!

According to our data, there is no official data on the longitudinal axis of the Mura, on the basis of which the stationations of the transverse profiles were determined in the past. If we take the initial stationing upstream of the bridge in Petanjci, where due to the threshold in the bridge profile we can assume the stability of the cross section, the measured stationing was km 95 + 054. The latter has also been used in all previous studies madefor the border and inland Mura. According to the published cadastre on existing gauging stations on surface waters (ARSO), the stationing of the Petanjci gauging station, located about 345 m downstream from the bridge in Petanjci, at km 100 + 470.

CODE	***STATION***	***RIVER***	***STATION***	**HINTERLAND** (km2)	**GKY**	**GKX**	**LEVEL** "0"
1070	Petanjci	Mura	100.47	10391.44	581 070	167710	193.763

Table 1: Gauging station (ARSO) Petanjci

In the subject study, we took over the official stationing of the ARSO, as it was also used in the professional basis of hydraulic calculation [4] and in the sedimentation analysis project [3].

• Problem statement

Pomgrad VGP as a project partner is included in WP T2 in O.T2.2 Pilot implementation of river restoration measures for development of the TBR. From January to March 2022 a widening of the Mura river in Hrastje Mota in Slovenia was implemented. Sediment mobilization study presented in this report is in close connection with the measure itself.

The planned measure (widening of river Mura and rock structure) will change the hydraulic conditions in the area of the performed works. With the progression of lateral erosion, a decrease in velocity in the considered area is expected, which will have a positive effect on the stabilization of the Mura bottom in this section and downstream. With detailed hydraulic analysis (2D channel modeling) it is necessary to analyze the impact of the planned works of revitalization on the currents in the area of inflow into the widened area and the results will serve to optimize the inflow section of the area. Furthermore, the same model analyzes the influence of lateral erosion on the hydraulic characteristics of the Mura section (velocity in the widening area), where lateral erosion is illustrated by a change in the bathymetry of the sleeve.

The estimate of the transport of deposited sediment from the sleeve to the bed of the riverbed is made on the basis of the 1D model of sediment transport and the calculated displacement capacity of the downstream section.

Figure 4: Section of the Mura in question east of the settlement of Hrastje Mota view downstream (source: Pomgrad VGP d.d.)

• State of knowledge

Studies on the Mura in connection with the transport of sediments were carried out mainly due to the intensive deepening of the Mura border downstream from the last HPP in Austria. In the last 20 years, several studies and expert articles have been made for the area of the border and inner Mura on transport of bed load and suspended load. Studies have been carried out on the border Mura in connection with the intensive deepening of the bottom and possible and implemented measures that will slow down this process. improved.

In the following, for individual major projects or. posts:

• Principle of water management concept for the border Mura Phase I, 1998-2000, Standing Slovenian-Austrian Commission for the Mura, June 2000

• Protection of the biodiversity of the Mura River in Slovenia (hereinafter BIOMURA), Globevnik et. al, August 2007

• Boundary conditions of morphodynamic processes in the Mura River in Slovenia, L. Globevnik, M. Mikoš, Catena an interdisciplinary jurnal of soil science - hydrology - geomorphology, volume 79, issue 3, december 2009

• Mitigating channel incision via sediment input and self-initiated riverbank erosion at the Mur river, Austria, M. Klösch et. al, Institute of Water Management, Hydrology and Hydraulic Engineering, University of Natural Resources and Applied Sciences, Vienna, January 2011

• Cross-border Water Initiative for the Drava and Mura rivers, DRA-MUR-CI, Faculty of Civil Engineering, University of Maribor, June 2013

• Hydrological and hydraulic study of the Mura for the impact section of HPP Hrastje Mota on the river Mura, No. 147 - current situation, DHD d.o.o., May 2015

• Assessment of the current situation in the Inner Mura section - Final Report, IzVRS, May 2015

• Analysis of the state of the Mura riverbed section, IzVRS, February 2016

• Hydrological and hydraulic study of the Mura for the impact section of HPP Hrastje Mota on the river Mura, No. 147 - planned balance, DHD d.o.o., March 2016

• Transport of sediments on the Mura, no. proj. 3513/14, VGB Maribor d.o.o., December 2015 (supplemented Oct 2016)

• ČEZMEJNI NAČRT ZA INOVATIVNO TRAJNOSTNO UPRAVLJANJE MEJNE MURE IN IZBOLJŠANJE OBVLADOVANJA POPLAVNE OGROŽENOSTI, GRENZÜBERSCHREITENDER MANAGEMENTPLAN ZUR INNOVATIVEN NACHHALTIGEN BEWIRTSCHAFTUNG DER GRENZMUR UND ZUR VER-BESSERUNG DES HOCHWASSERRISIKOMANAGEMENTS, ŠTUDIJA PREMEŠČANJA PLAVIN, BOKU WIEN, Deliverable D.T1.3.2, Project Interreg V-A Slovenija-Avstrija Go-Mura, 11/2021

- **Study aims**

The results of the flow analysis will be used for a detailed spatial presentation of the change of velocity currents (direction and size) and the change of shear stresses between the initial and intermediate state, from which a preliminary assessment of the most erosively exposed sections along the excavated sleeve will be made. A comparison with the final situation will show the impact of the measure on the reduction of speed on the section in question.

II. Methodology

• Theoretical background

The main cause of sediment movement is the action of moving water. The mode of water outflow determines the combined action of the component of gravity, which acts accelerating on the water particle in the direction of flow, and the friction force, which inhibits this movement. According to Newton's 3rd law, just as the bottom acts on a watercourse, so does this watercourse act on the bottom of a watercourse with the opposite of the same force. With a constant steady (1D) flow with integration along the water depth, the shear stress acting on the unit of the bottom surface is obtained τ_0:

$$\tau_0 = \rho_w \cdot g \cdot h \cdot I$$

where ρ_w represents the density of water, g the acceleration of free fall, h the depth of water (in hydrostatic pressure distribution) and I the longitudinal drop in energy, which at constant steady flow is equal to the slope of the bottom or the watercourse level [13].

Shear stress τ_0 represents the average resistance of individual grains to displacement due to water flow. Three components of forces act on the grains: the weight of the submerged grain $G\frac{S-1}{S}$ (reduced by the weight of the displaced liquid, (s represents the relative grain density of sediments relative to the density of water)), dynamic buoyancy A (resulting from pressure differences at the front and rear of the grain) and the thrust force of the water flow F_s. The resistance of an individual grain to the beginning of the grain movement (this represents the beginning of the gravel movement for an individual grain) is greater than the thrust force of the water flow F_s:

$$F_s = c_w \cdot F \cdot \rho_w \cdot \frac{v^2}{2'}$$

where c_w is the design coefficient of water flow resistance, F is the area of sediment grain exposed to water flow, ρ_w water density and v local water flow rate. It should be emphasized that due to the interdependence of the distribution of local flow velocities v, which depend on shear stresses at the bottom of the riverbed τ_0, the limit state of sediment grain stability is predominantly expressed as a function of shear stresses τ_0 (Mikoš, 2007). With the help of laboratory research, the authors determined the beginning of the gravel movement mainly for uniform grains. Shields (1936) thus determined with the help of laboratory research that the critical conditions at the beginning of gravel movement can be defined with the help of dimensionless shear stress θ.

$$\theta = \frac{\tau_0}{\rho_w \cdot g \cdot (s-1) \cdot d} = \frac{h \cdot 1}{(s-1) \cdot d}$$

where are:

θ ... dimensionless shear stress,

τ_0 ... shear force at the bottom,

h ... flow depth,

g ... earth acceleration,

d ... grain diameter,

ρ_w ... water density,

ρ_s ... grain density,

$\frac{\rho s}{\rho w}$ ... relative sediment grain density relative to water.

Shields (1936) also pointed out that the onset of gravel movement is related to the Reynols number for sediment grains $Re\,*$, which depends on shear rate v_*, mean sediment grain diameter d and kinematic viscosity of water υ ;

$$Re^* = \frac{v_* \cdot d}{\upsilon}$$

The beginning of the gravel shift is thus given in the Shiels diagram as the relationship between the critical shear stress θ_{cr} and the Reynols number for sediment grains Re^* (Mikoš, 2007).

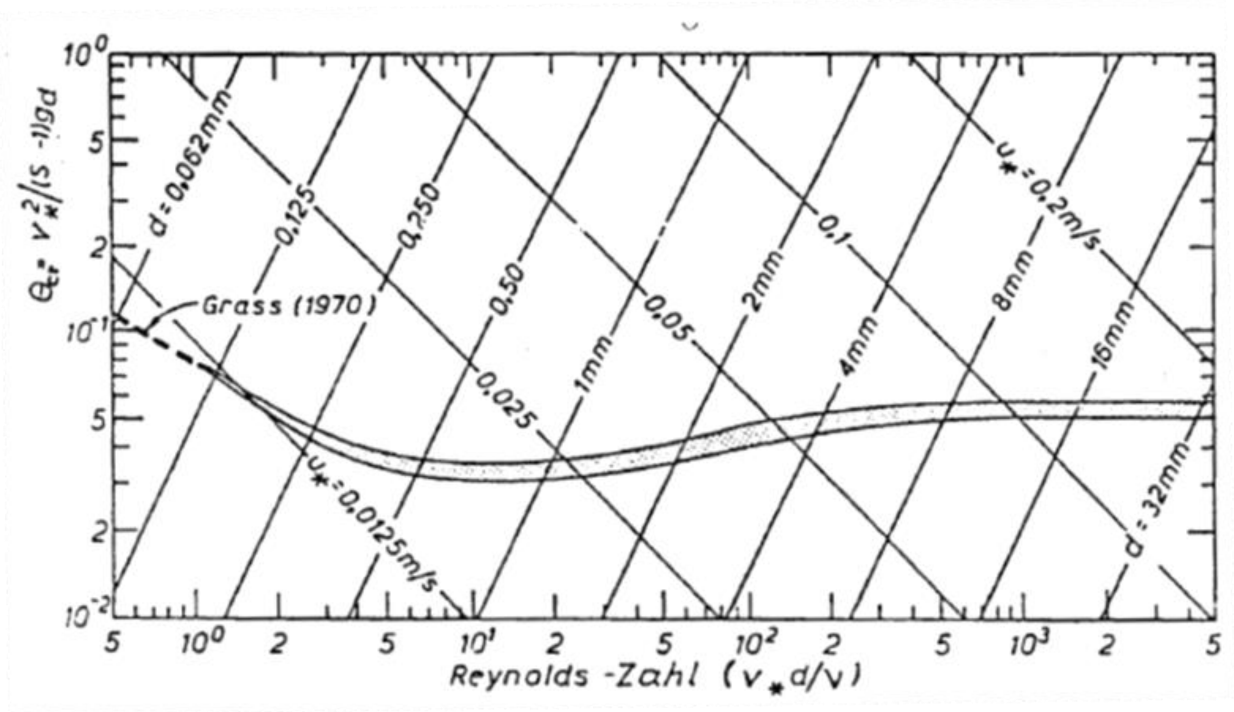

Figure 5: Shields diagram for starting gravel movement [13]

In the area of the riverbed or. the maximum shear stress is distributed according to the following figure:

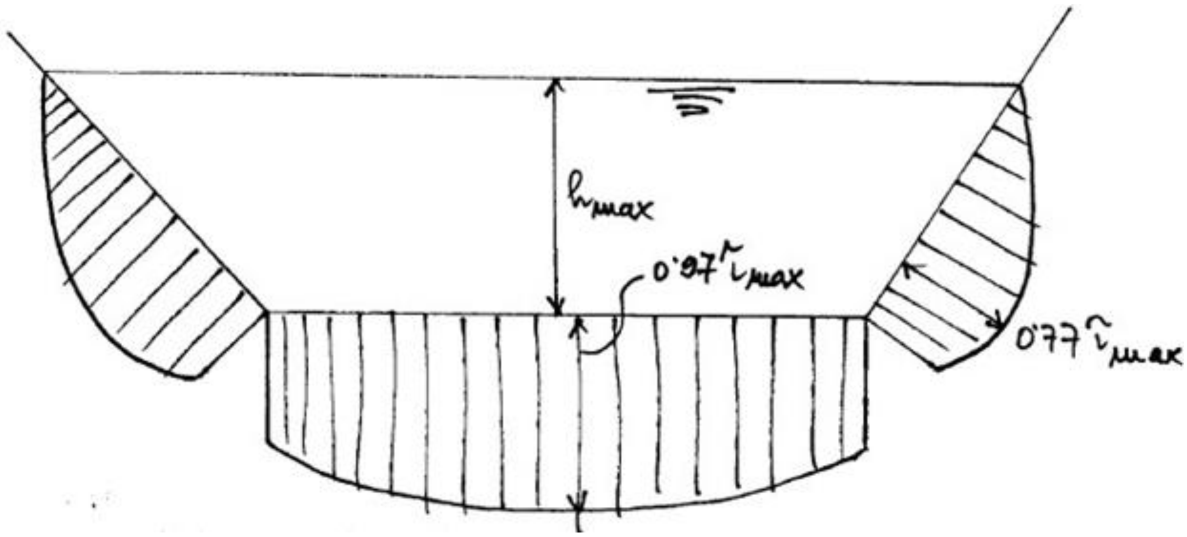

Figure 6: Distribution of shear stresses in the cross section of a watercourse [13]

The expression [13] is used for the start the gravel movement of a stone of size d [m].:

$$\theta = \frac{\tau_b \cdot max}{\rho_w \cdot g(s-1) \cdot d} = \frac{0.77 \cdot hmax \cdot l}{(s-1) \cdot d}$$

In the subject study, we defined the potential grain that can be moved by the current at that location on the basis of program-determined T shear forces at an individual location as part of a mathematical hydraulic model. Based on the relocation of an individual grain on the bank, it means demolition and removal of the bank.

• Data provided

Pomgrad VGP d.d. provided and sent the company VGB Maribor d.o.o. the following information and documents:

- Bathimetric survey of the existing state and the state after construction.
- Project documentation of the widening on the basis of which the hydraulic analysis of the planned condition is performed
- Sowing curves of the samples taken in the pilot area, and information on the amount and composition of the excavated sediment that will be introduced into the riverbed.

1. Bathimetric survey

Survey was made for the existing state and the state after construction. It has been done with the equipment bought within lifelineMDD project in the first period- drone, sonar, boat and motor. Field work to gain measurements repeated few times with sonar for better quality and precision. Contours that were created were imported to 3D Survey programme in which they were united with triangulated mesh from drone and GPS points. Sonar gave data for depth and insight to the surroundings of Mura riverbed (down view, side view). Several drone flights over the pilot site were made. The most useful was the flight right after the tree cuting and before any excavation started. It shows the most terrain possible and also the gravel pit on the other side of the pilot site. With these photos a triangulated mesh in 3D Survey was made, which represents the state before. The second flight was right after the works on the site were finished. For the input data contours, GPS data and DEM of state before the works were combined, which represented an basis for the calculations. DEM of state after the works was also provided and compared to the state before.

2. Project documentation

Project documentation with a title: Widening of the mura river as a part of the lifelineMDD project was finished in january 2022. On the basis of this documentation, the hydraulic analysis of the planned condition is performed. In 2021 5 variants of possible measures to be implemented to the pilot site were presented. Through several workshops in WP T1 and WP T2 it was discussed with other partners with past experience on river restoration, about which variant would be suitable for this individual site. Due to given budget for the works and to this individual site it was decided that a widening with realocating the riparian protection, 3 semicircular shaped areas excavation and a rock structure is made.

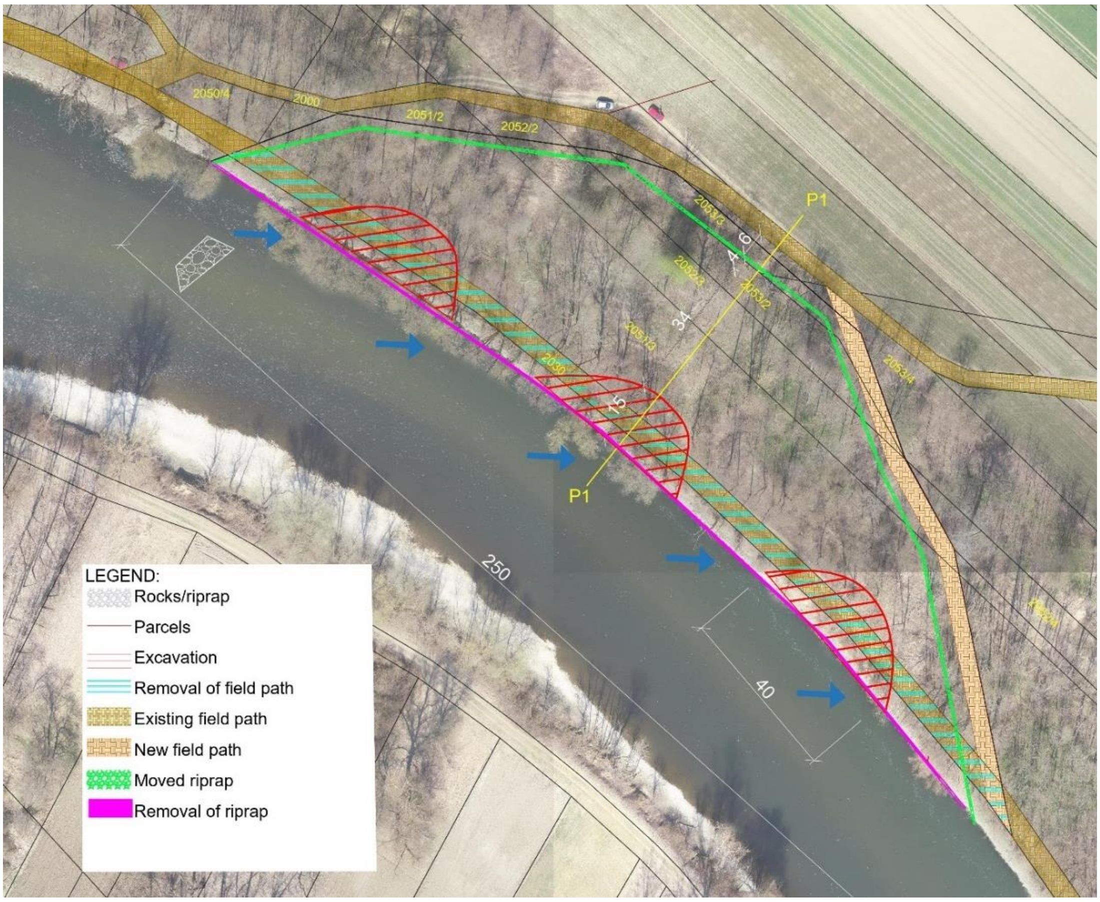

Figure 7: Situation of planned measure in WP T2

3. Sowing curves

Pomgrad VGP provided the samples taken in the study area, and information on the amount and composition of the excavated sediment that will be introduced into the riverbed. Three samples in the study area were taken and an report from the laboratory was recieved, explained in next chapters.

- **Input data**

1. Hydrological data

Hydrological data is summarized after the study of the Hydrological Study of the Mura River (FGG, January 2012, hereinafter referred to as the "FGG hydrological study"). The study examines the entire Mura River basin from its source in Austria to its confluence with the Drava on the border between Croatia and Hungary. The values of return flows from the mentioned study are summarized below.

	Q500 [m³/s]	**Q100** [m³/s]	**Q50** [m³/s]	**Q30** [m³/s]	**Q20** [m³/s]	**Q10** [m³/s]	**Q5** [m³/s]	**Q3** [m³/s]	**Q2** [m³/s]
GS Petanjci	1968	1681	1545	1439	1351	1189	1008	854	710

Table 2: Flows (in m³/s) with return periods taken from the hydrological study FGG, 2012

Based on the hydrological study of the FGG and the analysis of the shape and volume of high water waves recorded in the past, calculated ("synthetic") high water waves Q10, Q100 and Q500 were prepared for GS Petanjci, Analysis of high water waves of the Mura-GS Petanjci, VGB Maribor d.o.o., August 2014). Based on this hydrogram, hydrograms for other flows were formed based on the maximum flow ratio.

The following values of characteristic flows were also used from the hydrological study:

	Q_s 95% [a] [m³/s]	**$_mQ_s$** [b] [m³/s]	**$_sQ_s$** [c] [m³/s]
GS Petanjci	70.10	140.00	159.42

Table 3: Characteristic Mura flows taken from the FGG hydrological study, 2012

[a] 95th percentile of mean flows (Qs) for the period 1961-2005, GS Petanjci, source: (OJ FGG, January 2012)
[b] median mean flows (Qs) for the period 1961-2005, GS Petanjci, source: (OJ FGG, January 2012)
[c] mean flow for the period 1961-2005, GS Petanjci, source: (OJ FGG, January 2012)

As part of the study, the considered area was examined for several flow scenarios, namely flows Q5, Q2 and mQs. Higher flows were not taken into account in the study, as they mean significantly higher transfers and erosion of slopes in the subject study- bank erosion.

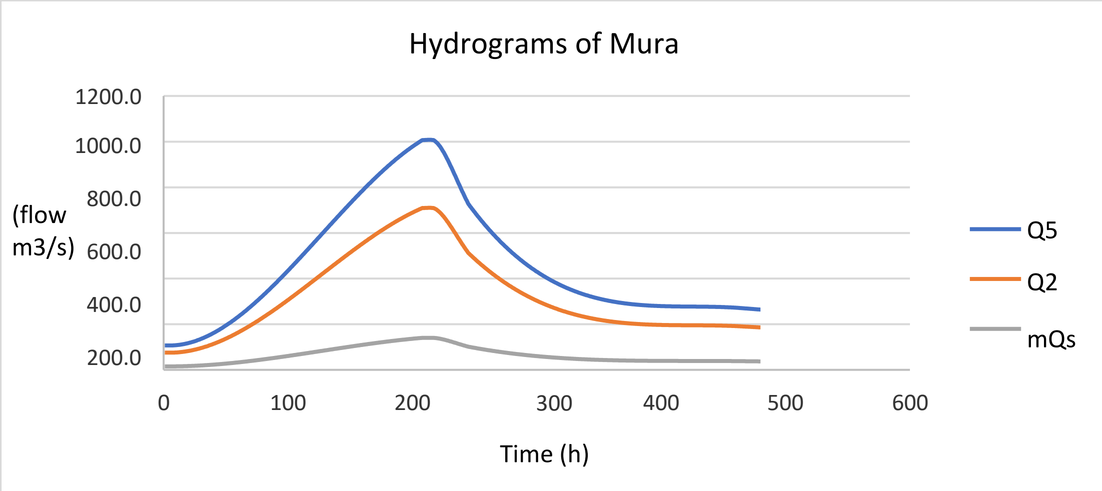

Figure 8: Used hydrograms of river Mura

2. Geodetic basis

(1) Recording of the processing area

As part of the project, bathymetry and topography data of inundations from several data sources for the considered area was obtained. For the area of the revitalization measure, a riverbed survey was performed using terrestrial riverbed bottom survey, and the banks and inundation were recorded using photogrammetry technology.

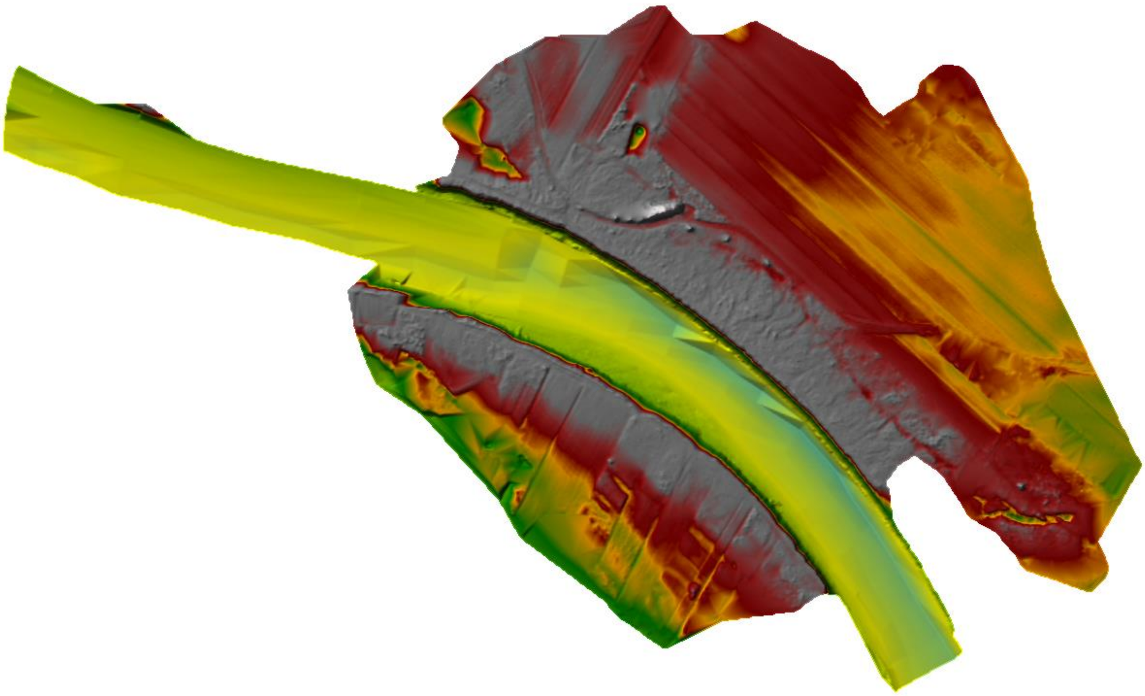

Figure 9: DEM of the revitalization area

The bases were measured in the D96/TM coordinate system and the altitude date SVS 2010 - Koper.

Based on the processing data, a TIN area network was constructed and a DEM with a cell size of 0.5 x 0.5 m was generated. Due to the "inclusion" in older data, the area was decomposed into the old GK48 coordinate system and the altitude date of Trieste with a height transformation of 16 cm.

(2) Riverbed in the wider processing area

To include the measure area in a wider range of calibrated models in the considered areas, data from past projects and analyses was used.

(3) Cross section profiles

In the past, cross section profiles were measured on the Mura in various campaigns. As part of the project for HPP Hrastje-Mota [5, 8], a 3D model of the Mura riverbed was prepared, which was applied for the needs of the subject task.

FROM PROFILE (km)	TO PROFILE (km)	L (m)	RECORDING	YEAR
P30 83+056	P1 94+185	11129	Geodetski Biro Slatinšek	2010

Table 4: Sources of geodetic data used (cross sections)

The used cross-sections were recorded at a distance of 0.5 m to 1.0 km, so it was necessary to interpolate the profiles. A condensed bed network was made for the riverbed area based on transverse profiles (Mišič, 2014). The interpolation was performed with the density of points in the transverse direction n = 50. The average width of the riverbed is W = 86 m with a standard deviation s = 13.4 m, which means that the average distance between the transverse points is 1.7 m or. considering the standard deviation between 1.98 m or 1.45 m.

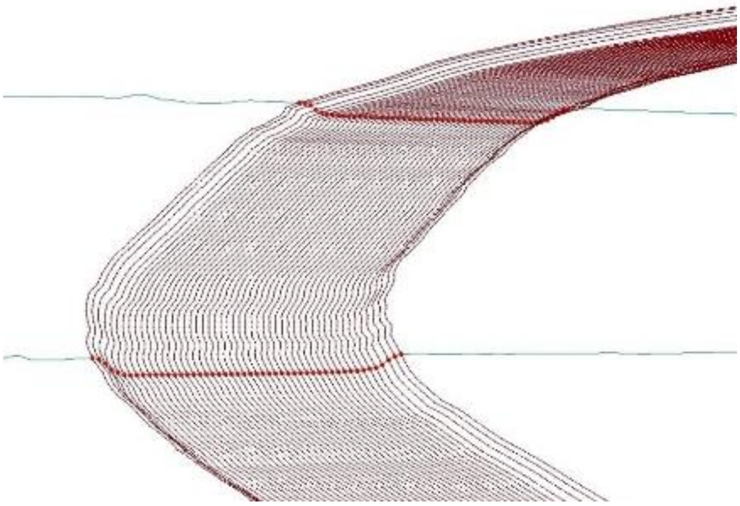

Figure 10: Mura made by interpolation of transverse profiles

The digital bathymetry model of the Mura riverbed was used in the marginal areas outside the area of the planned measure. For the inundation area, we used Lidar data from the national Lidar survey in 2011-2014 (ARSO).

(4) Inundation area – Lidar

For the flood area, the state Lidar image was used, from which a digital relief model for the considered area was made. The National Classified Point Cloud (LIDAR), recorded in 2011, was used to create the digital elevation model (DEM).

Lidar bases are in the coordinate system D48/GK and altitude date Trieste.

In the process of DEM preparation, which is the basis for the mathematical hydraulic model, the TIN Lidar network layers, and the points of classical geodetic measurement in the CAD software environment in the processing area were compared. In the analysis of points, the deviations are in the range of expected deviations. Larger deviations were in the area of dense overgrowth (up to 20 cm), where we had a more extensive geodetic survey, and smaller in the area of arable land (up to 10 cm). Based on the analysis, we find that there are no major deviations and that the Lidar bases and classical geodetic measurements match accordingly and are suitable for use.

Based on the DEM of the riverbed from 2010 and Lidar data from 2011, the DEM of a wider area of the riverbed was formed. areas of boundary conditions. For the extended one, it was classified into a 2.5 x 2.5 m raster grid.

Extended DEM is needed to make the entire inundation area of the Mura River between the embankments on the left and right banks.

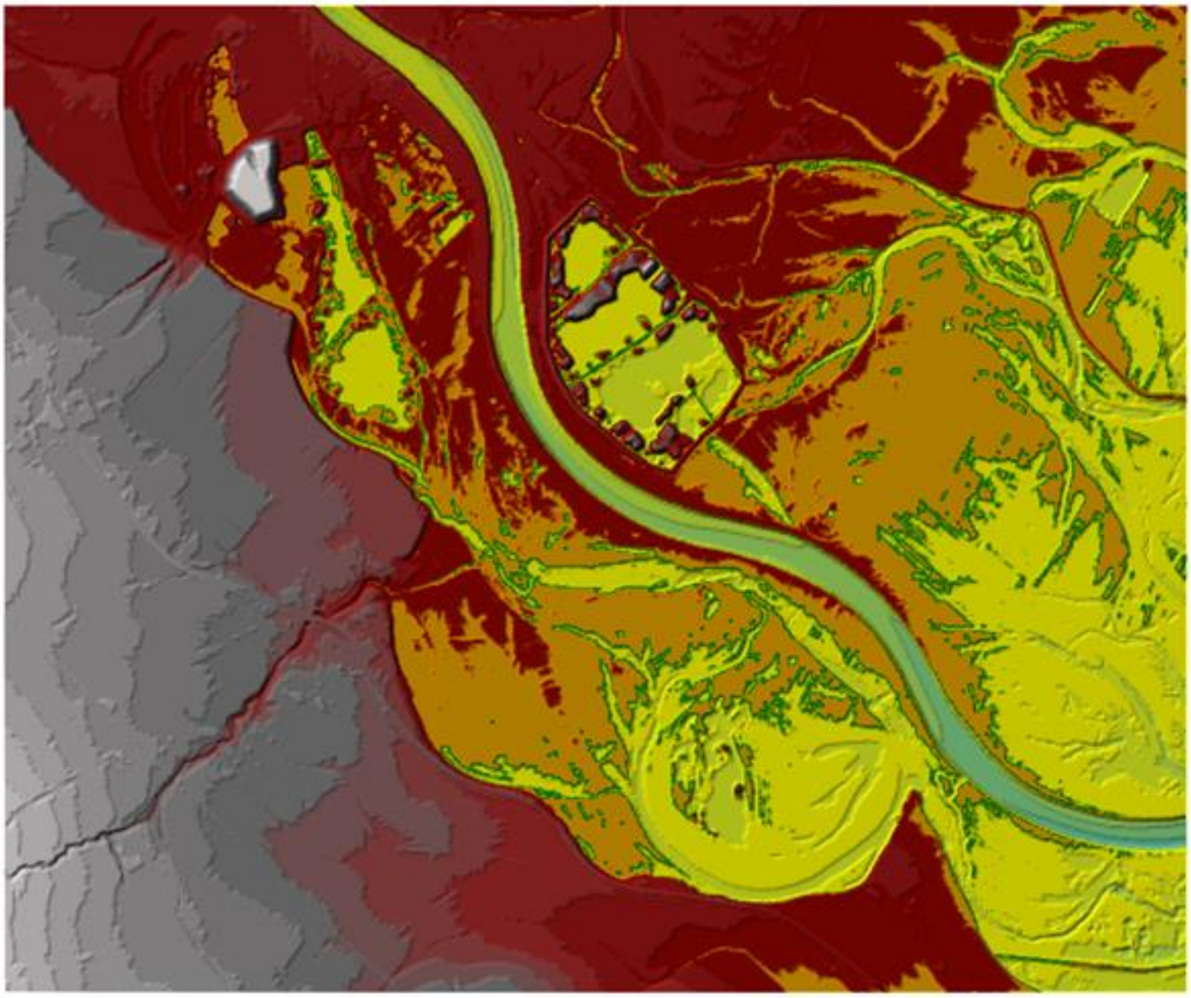

Figure 11: Area of extended DEM of Mura inundations

(5) Modifications of the 3D model of the Mura riverbed - Planned condition

For the planned measures, the geometry of the riverbed for Revitalization Scenarios was modified in the Autodesk Civil 3D software environment or ArcGIS.

Based on the proposed methodology set out in the instructions or. guidelines developed as part of the project "River restoration toolbox" [12] and implementation plan "Proposal for the widening of the Mura riverbed as part of the lifeline MDD project" [1] a 3D model of the left bank of the Mura in the considered area was designed. The implemented measures in the area were embankment removal, initiation of side erosion with three consecutive excavations and an upstream rock structure in the channel for partly deviating the flow into the area of planned side erosion.

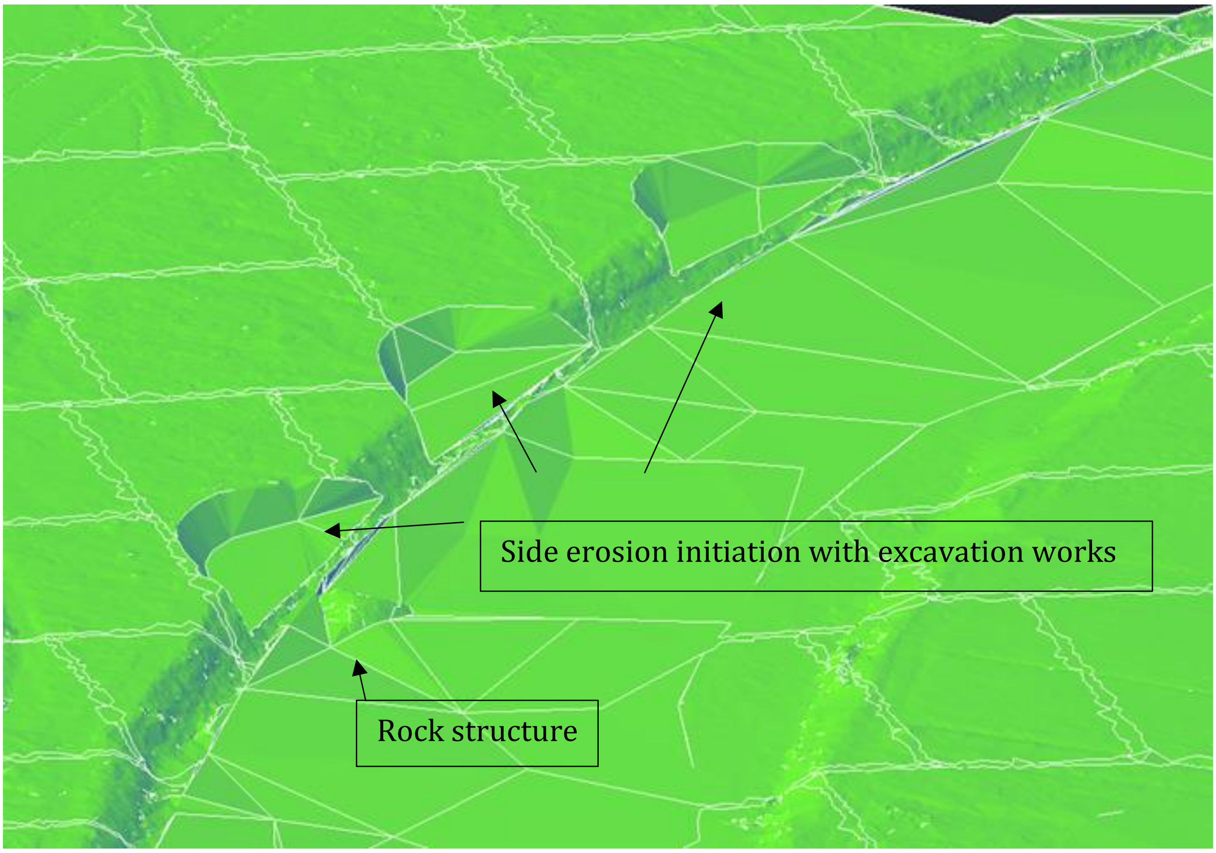

Figure 12: DEM on the pilot site of the planned measure

For the planned condition, in scenario two, the hydraulic conditions during the widening to the allocated riparian protection to the hinterland and the theoretical removal of all material was checked. It is shown in the picture below.

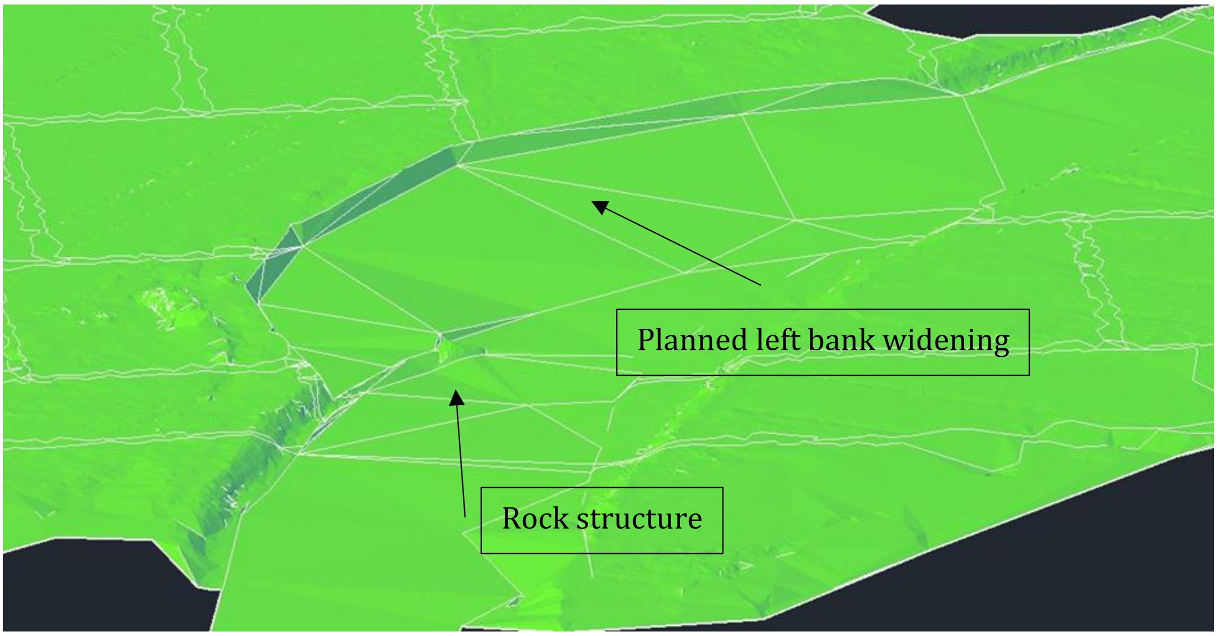

Figure 13: Expected DEM on the whole pilot site

The measures taken in the area should result in eroding and contributing ca. 30,000 m³ of material into the main riverbed. This estimated volume was calculated over the entire pilot site area from the main channel to the reallocated bank protection and down to 188 m a.s.l. terrain height.

3. Data on bed load and suspended load

As part of the project, field analyzes were performed by taking a sample of bed load and a summary of measurements from previous studies in the considered area.

(1) Suspended load (turbidity)

Data on suspended load are summarized according to the existing study "Transport of sediments on the Mura" [3]. As part of the project, the analysis of suspended load was performed using laser diffraction directly upstream of the Petanjci gauging station;

“The grain composition of the suspended load in the sample was also made from the samples taken during the wave. The grain curves show that the change in concentration also changed the grain composition, so during the maximum concentration in the sample a high proportion of the smallest grains (2.6 microns) was measured, the average grain was d_m = 40-50 * 10-6 m. With increasing flow, the concentration of suspended particles began to decline, as did the proportion of very fine particles, the samples were dominated by grains ranging in size from 10-45 microns, and the medium grain increased from 50 to 126 * 10-6 m.

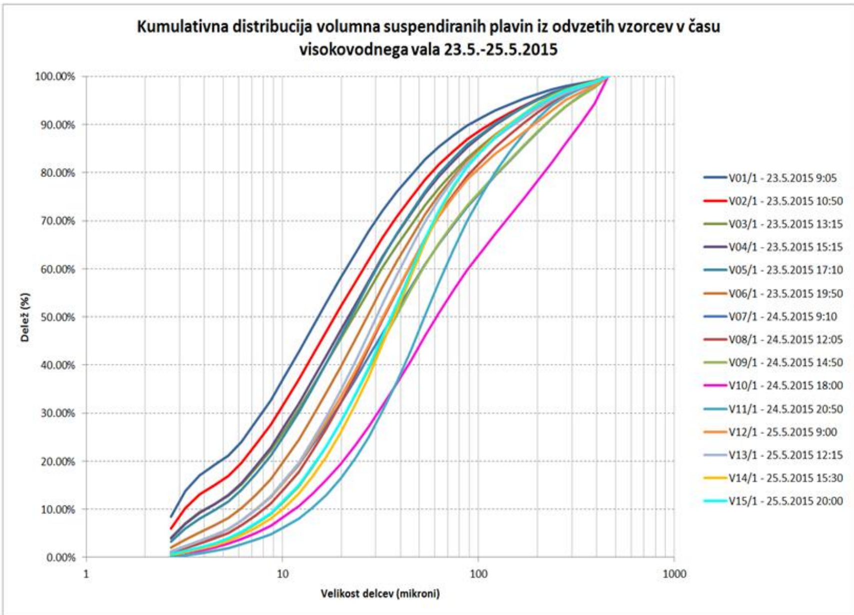

Figure 14: Results of laser diffraction of samples taken during the duration of the high-water wave 23.5.-25.5.2015 [3]

(2) Bed load sediment

As part of the project in question, sampling of bed load sediments in the area of the considered riverbed widening and a sample in the downstream section was performed. Sampling was carried out in 2021. The location of sample G was on the left bank of the Mura River, namely on the section upstream of the planned measure. The location of the collection and analysis of the HM sample was on the right bank directly next to the planned measures, and the location of the B sample was about 2 km downstream from the planned measure, under the highway bridge.

As part of the project, we compared the results of samples taken in the project with the results of sediment removal in 2015, when sediment was analyzed in a study for HPPs [4].

MARK	YEAR	SHORT FORM	DESCRIPTION	X-GK	Y-GK	STATION OF MURA (m)
SAMPLE 1	2015	V1	PETANJCI - RIGHT B.	580856.5	167699.2	100660.97
SAMPLE 2	2015	V2	RIHTAROVCI - RIGHT B.	581990.8	166237.3	98651.89
SAMPLE G	**2021**	**G**	**HRASTJE-MOTA - LEFT B.**	**583976**	**164206**	**95709**
VZOREC HM	**2021**	**HM**	**HRASTJE-MOTA - RIGHT B.**	**583976**	**164206**	**95291**
SAMPLE 3	2015	V3	VUČJA VAS - RIGHT B.	586839.8	163198.1	92328.55
SAMPLE B	**2021**	**B**	**KROG - RIGHT B.**	**583976**	**164206**	**92300**
SAMPLE 4	2015	V4	BAKOVCI - LEFT B.	587575.5	162833.9	91471.28
SAMPLE 5	2015	V5	VERŽEJ – LEFT B.	590767.3	161206.5	87989.93

Table 5: Locations of collection sites from the project [4] and withdrawals under the project in 2021

Based on the comparison of grain curves, we find that the samples taken are consistent with the grain curves taken in 2015.

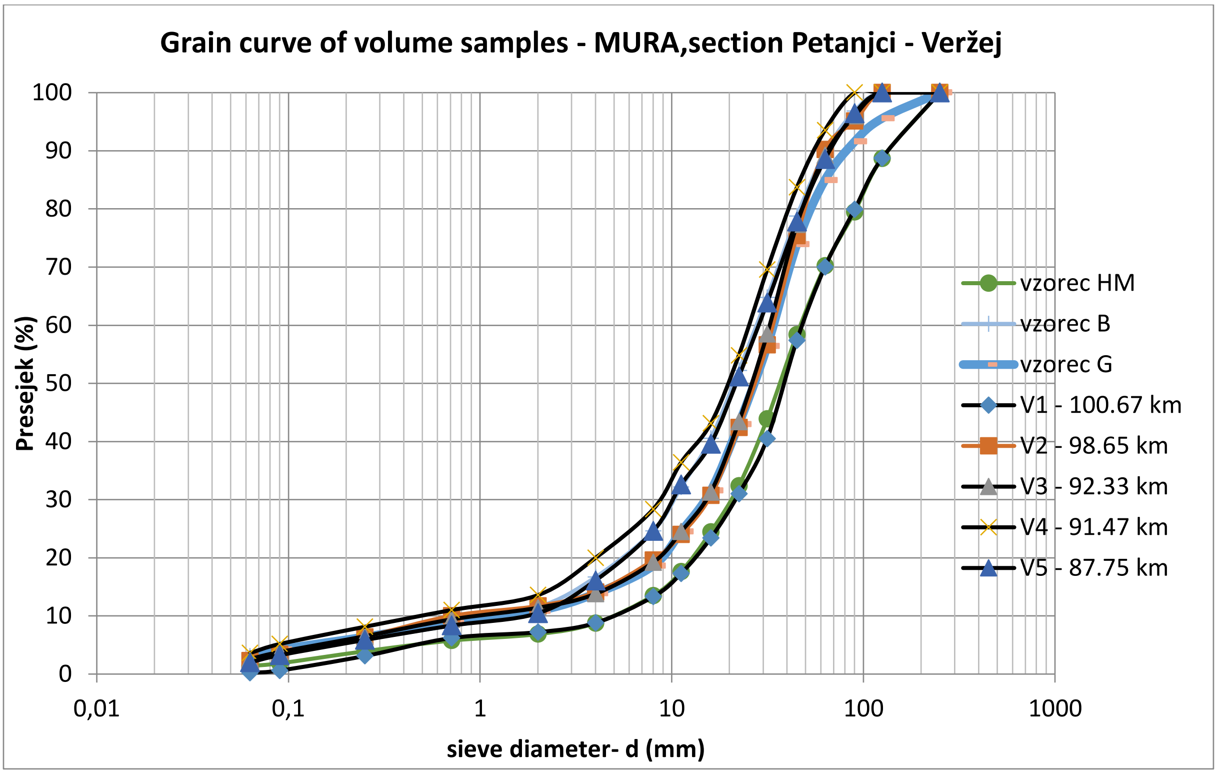

Figure 15: Comparison of grain curvatures of flooded sediments on the Mura River [4]

Data on the grain size of bed load and suspended load are one of the basic and very important data in the calculation of sediment transport. Their quality also determines the reliability of the model results. Within the scope of this task, only one-time sampling and analysis of suspended load grain size was performed, which is significantly insufficient to define the grain size of suspended load inflow more accurately. To improve the input data and consequently the reliability of the model results, it would be recommended to establish an appropriate monitoring program for sediment transport on the Mura in the further stages of project documentation preparation for planning and monitoring measures on the Mura River [4].

MARK	YEAR	SHORT FORM	DESCRIPTION	STATION OF MURA (m)	d50 (mm)	d80 (mm)
SAMPLE 1	2015	V1	PETANJCI - RIGHT B.	100660.97	42	/
SAMPLE 2	2015	V2	RIHTAROVCI - RIGHT B.	98651.89	27	/
SAMPLE G	**2021**	**G**	**HRASTJE-MOTA - LEFT B.**	**95709**	**27**	**62**
VZOREC HM	**2021**	**HM**	**HRASTJE-MOTA - RIGHT B.**	**95291**	**38**	**92**
SAMPLE 3	2015	V3	VUČJA VAS - RIGHT B.	92328.55	26	/
SAMPLE B	**2021**	**B**	**KROG - RIGHT B.**	**92300**	**21**	**/**
SAMPLE 4	2015	V4	BAKOVCI - LEFT B.	91471.28	20	/
SAMPLE 5	2015	V5	VERŽEJ – LEFT B.	87989.93	22	/

Table 6: Diameter of the middle grain of the bed load sediments d50

In the analysis of bed load, the subject study pays attention to the size of the mean d50, on samples G and HM, which are taken at the location of the planned measures. We assume that the bank consists of grains of similar grain composition. This grain composition will be taken into account when testing the erosion potential of the bank. We also evaluated the d80 grain, which means that 80% of the grains are at a location of smaller diameter than the d80 grain.

Based on the field visit and the fact that the riverbed in this part has deepened in the past, we put forward the thesis that the bank and the area of the planned abyss are made of material with smaller grain diameters than in the watercourse itself. With the hypothesis, we are on the safe side by considering the grains from the riverbed in the calculation.

- ## Hydraulic model

Hydraulic surface calculations were prepared using the 1D and 2D mathematical hydraulic model of quasi-unsteady flow in the software environment HEC-RAS 6.1.0, developed at the Hydrological Center of Engineering Units of the US Army (Hydrologic Engineering Center -HEC, US Army Corps of Engineers).

For the considered area, we established an accurate full 2D mathematical hydraulic model with a quasi-unsteady flow regime. In this way, we were able to summarize the implemented measure and determine the level and current state and distribution to individual sub-segments in the narrower area geometrically very accurately.

The area of the 2D model covered a 1990 m long section of the Mura River. The bathymetry of the riverbed and banks was generated based on geodetic data of the considered area, which is presented in Chapter GEODETIC BASIS.

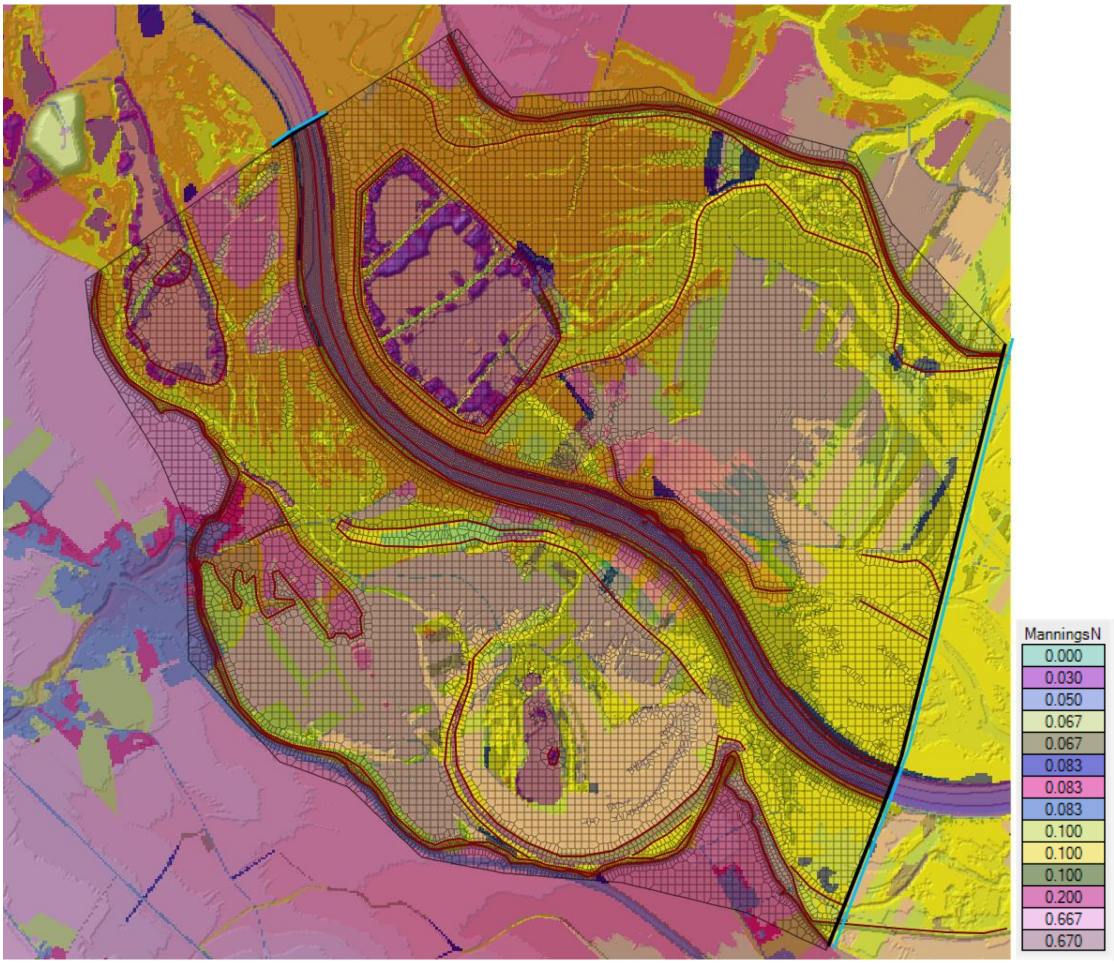

Figure 16: Display of the range of the hydraulic model and the applied roughness coefficients ng and display of the range of boundary conditions (blue line)

The DEM included cells generated from a triangulation network based on topographic data. The cells are condensed and smaller areas in the area of the planned measure and larger areas in the area of inundation areas. The mathematical model included 35584 cells, with an average size of 69.4 m2 (min 0.11 m2 and max 532 m2). Roughness coefficients were determined based on land use and experiential value on the basis of field visits. In the main channel area, the Manning roughness coefficient ng = 0.285 was summarized according to the data of a calibrated study for HPPs [4].

The lower boundary condition of the model is the calculated normal level on the downstream profile with respect to the slope of the riverbed downstream. Upstream and downstream sections at a sufficient distance to avoid the influence of edge sections.

II. Results of the hydraulic model

As part of the hydraulic analysis, we performed a check of the hydraulic properties of the current over a wider and narrower considered area for the existing and planned condition.

• Existing state

In the current state, the wider area of considered shows the overflow of flood waters along the retention area of the Mura River, which extends between the left-bank and right-bank high-water embankments. As part of the project, we analyzed flood conditions for flows Q5, Q2 and mQs.

The Mura River overflows its main channel banks at flows lower than the 2-year return period. The floods of the Mura River spread along the retention area parallel to the course of the main riverbed, namely with the flow along the old riverbeds and depressions in the area of the floodplain. In the case of flood maps, a network of drainage ditches and backwaters can be seen. In the floodplain itself, gravel pits are present on the left bank, and there is a small lake on the right bank. The water level in these lakes is mainly a reflection of the groundwater level and the Mura River. During floods, lakes are flooded. On the right bank, the Hraševski potok flows from the area of the Hrastje-Mota settlement, which is not taken into account in the hydraulic model, as the inflow is negligible compared to the Mura river. Depths at Q5 flows are in the considered area (between profiles P13 and P14) in the riverbed area up to 7 m, in floodplain areas the depths are shallow <0.5 m, except in the area of depressions and drainage lateral backwaters, where the depth reaches up to 2.8 m.

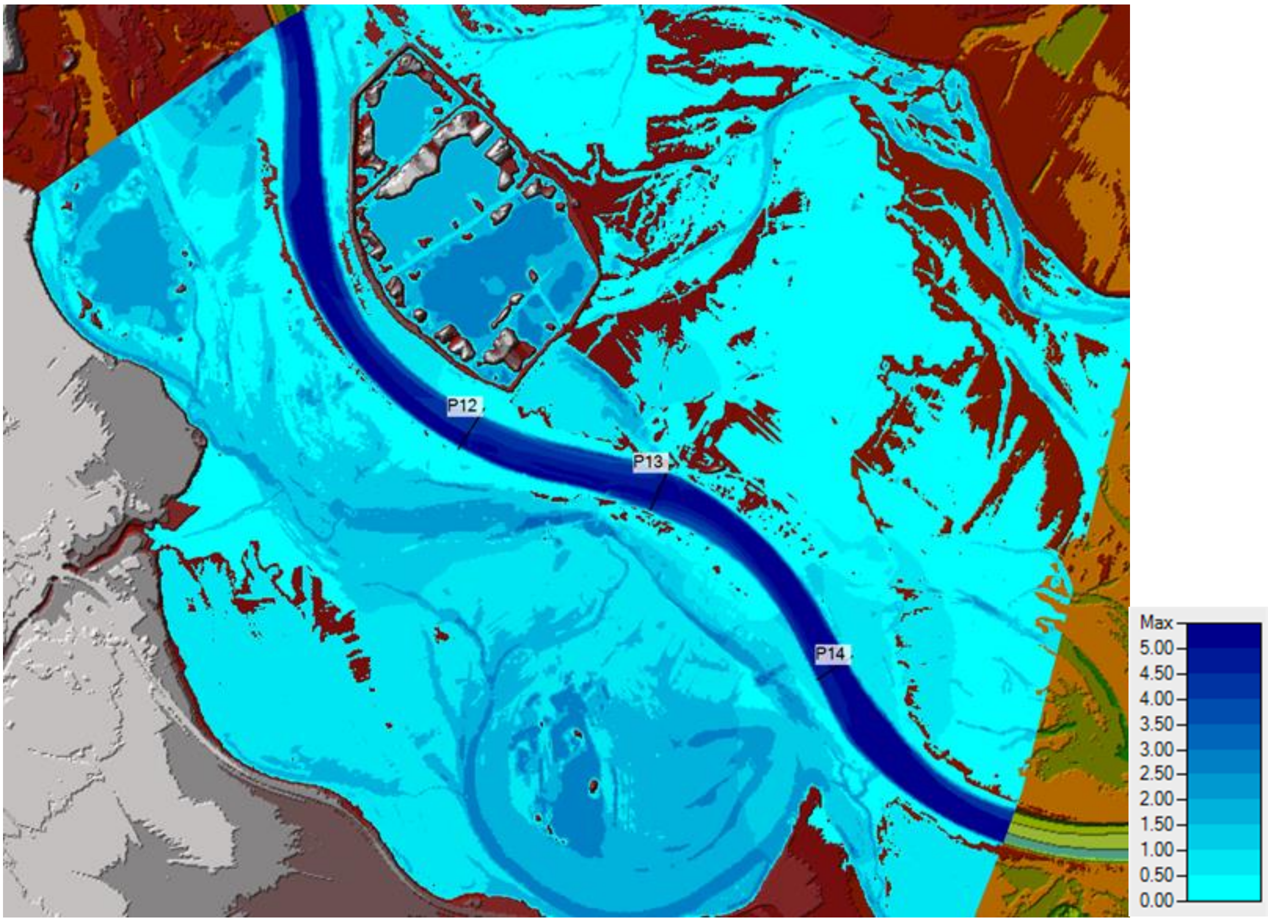

Figure 17: The Mura riverbed model of the existing state, floods at Q5 flows

Based on the analysis of the existing situation, we were able to analyse the course of the velocity field in the area of the Mura riverbed due to the use of a full mathematical hydraulic model. The results of the velocity distribution at all calculated flows show that the maximum cross section velocity area upstream of the P12 profile is located on the right side of the riverbed and remains on the right part of the riverbed between the P12 and P13 profiles.

In the area of the planned measure, the maximum cross section velocity area passes from the right to the left side of the riverbed. The planned measure is thus located in the section where maximum cross-section velocities switch to the left bank of the main channel. The velocities in the main flow reach speeds of up to 5 m/s at Q5 flows.

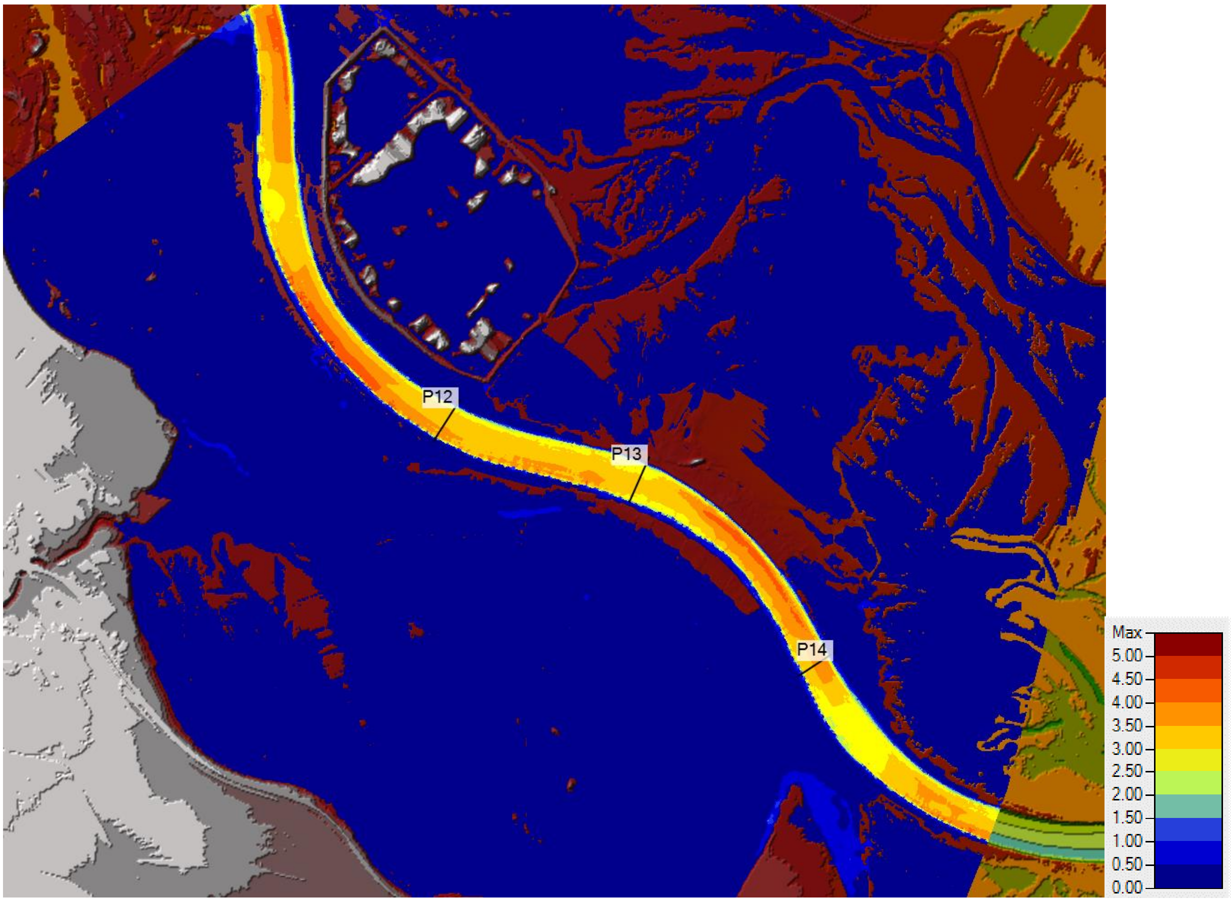

Figure 18: Demonstration of the velocity field in the Mura riverbed at flows Q2, where the course of the main flow is shown

Based on the analysis of the existing situation, we expect the highest velocities in the area of excavation AREA 3.

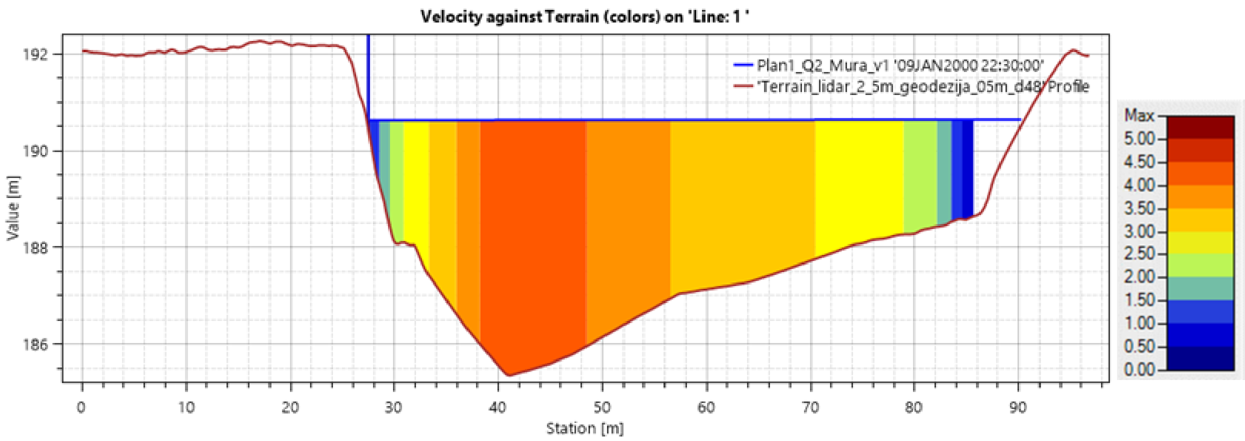

Figure 19: Cross-section in the area of the planned measure "AREA 2" with the display of the velocity field in the riverbed at flow Q2

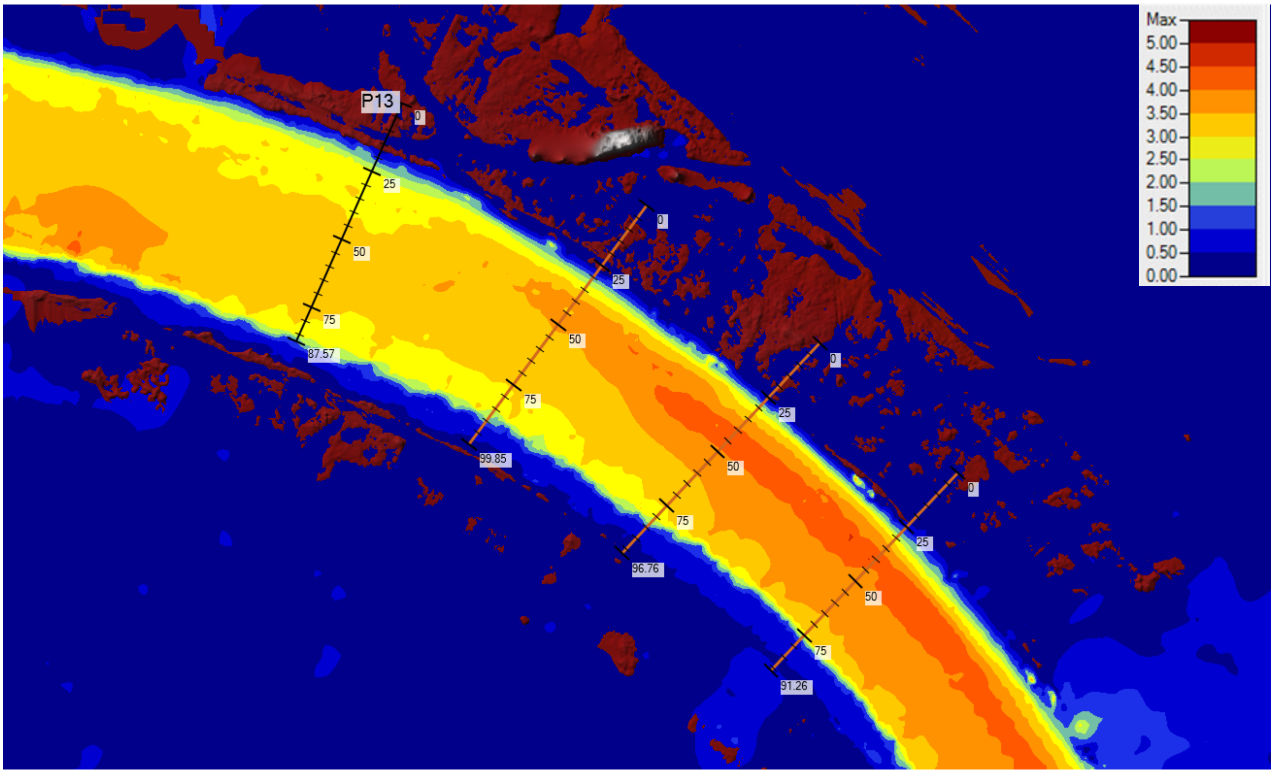

Figure 20: Velocity field in the area of planned measure in the existing state at flow Q5

Based on the hydraulic analysis, we evaluated the amount of flow in the main channel and the left and right overbanks at pilot site area, more precisely the cross section P13 (stat. Km 95 + 405)

	Q_5 [m^3/s]	Q_2 [m^3/s]	$_mQ_s$ [m^3/s]
Profile P13	917	618	140

Table 7: Flows on the considered cross section P13

The analysis of the flows shows that part of the flow is diverted along the overbanks. For flow Q5, the part of overbank flow is ca. 9%, for flow Q2 ca. 13% and for flow mQs the entire flow is maintained in the main channel of the Mura.

- **Planned state**

In the planned state, we hydraulically checked the measure in accordance with the implementation plan "Proposal for the widening of the Mura riverbed as part of the lifeline MDD project" [1], which includes measure in the Hrastje-Mota location on an area of ca. 10.000 m^2.

1. Planned state after the implementation of measures

The task includes several measures to improve the morphological and habitat status of the Mura River:

- Removal of the existing riparian (embankment) protection in the length of approx. 250 m (from stat. km 95 + 400 to km 95 + 150)
- Excavation of three semicircular shaped areas measuring approx. 15 m wide and 40 m long (AREA 1 on (stat. km 95 + 325), AREA 2 on (stat. km 95 + 260) and AREA 3 on (stat. km 95) +200)
- Installation of a rock structure for flow deviation - secured with wooden piles (stat. km 95 + 325)

The project envisages the reallocation of protection in the hinterland (approx. 55 m from the existing bank), which will protect against further expansion of the Mura riverbed. As part of the project, the relocation of the field path is also planned.

A graphic illustration of the planned measure is presented in Figure 7 of the present report.

Based on the hydraulic calculations of the planned state, we find that the planned measures in the pilot area expose the left bank to the side erosion.

Changes in the flood area are negligible in the planned state of regulation. Larger differences occur in the distribution of velocity fields in the 3 semicircular shaped areas and rock structure. Display of speed distribution or the placement of the maximum cross-sectional velocity is shown in the figures resulting from the full 2D mathematical hydraulic model at different flow return periods.

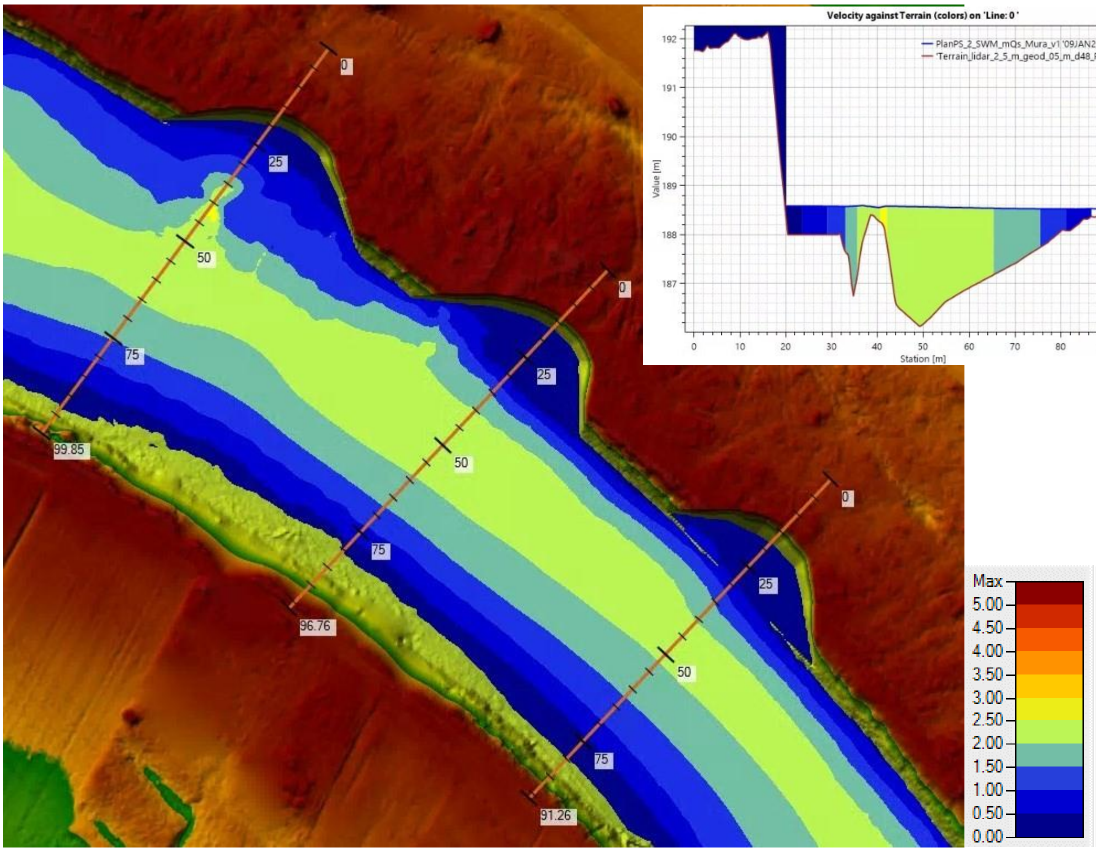

Figure 21: Flow velocity field in cross section P0 (AREA 1) at mQs flow

At the lowest considered flow of mQs, the distribution of velocity conditions in the Mura riverbed is clearly visible. The maximum cross-sectional velocity moves from the right bank to the left bank in the area of the planned measure. Velocities are increased in the area of the structure that is minimally flooded at this flow. Along the banks and in the area of the indentations, the velocities are low, and consequently the erodible potential the water flow.

The highest shear stresses are in the area of AREA 1 <u>τ = ca. 15 N/m^2</u>, and in AREA 2 and 3 it is lower than <u>5N/m^2</u>. In AREA 1 and on the bank between AREA 1 and 2, leaching of fine fractions (d_{max} <2cm) can occur. At this flow, we do not expect the erosion of the bank or the widening of the watercourse or these processes would be extremely slow.

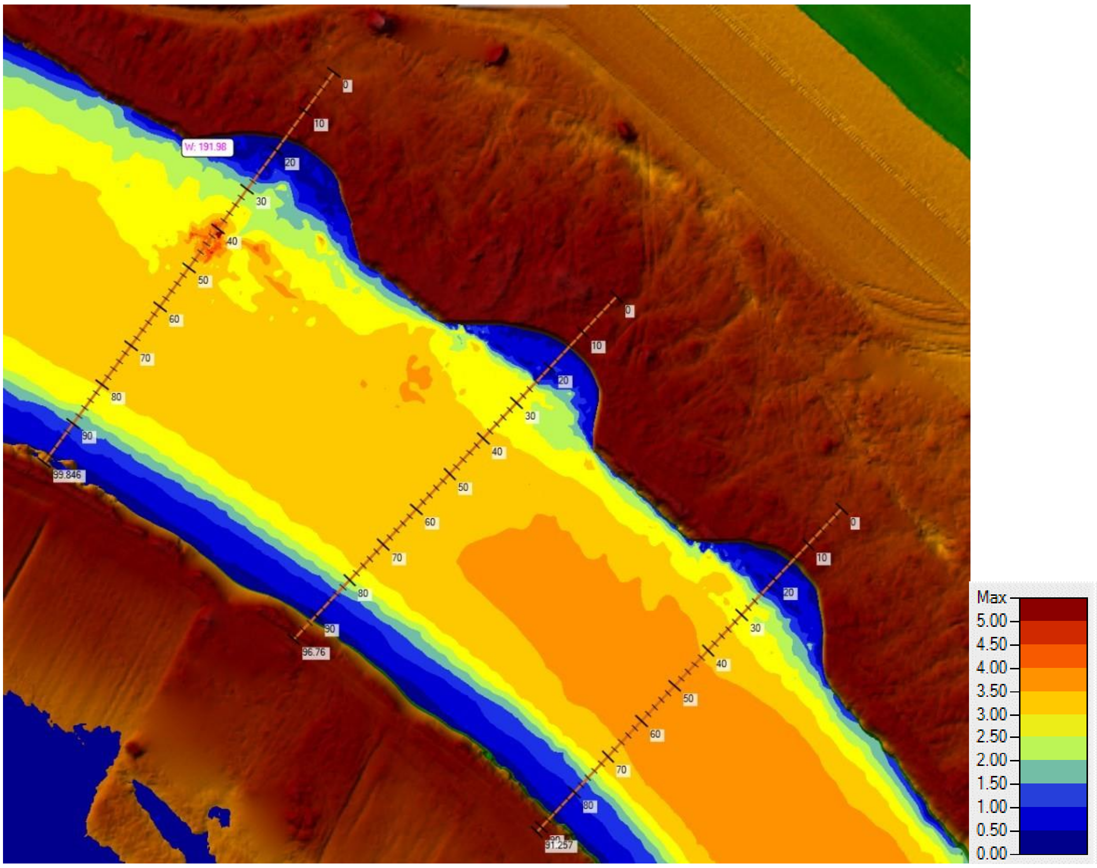

Figure 22: Velocity field at Q2 flows in the Mura riverbed

With a return period flow of 2 years, the velocities in the riverbed are significantly higher. They increase from the upstream part towards the downstream profile. The maximum velocity in the cross sections move towards the middle of the main channel.

The most exposed point for the onset of erosion and collapse of the bank is based on calculations of the bank between AREA 1 and 2 and the bank between AREA 2 and AREA 3. Velocities on these sections are up to 2.8 m/s, resulting in shear stresses at these locations in the range of $\underline{\tau = 50\text{-}95\ N/m^2}$, where the grain displacement of the minimum diameter d_{min} = 7-12 cm occurs, which is more than the size of the average grain at the location.

At these flows, we can expect the removal of the bank heel and intense erosion of it. As a result, the area of the riverbed will expand in the direction of the left bank.

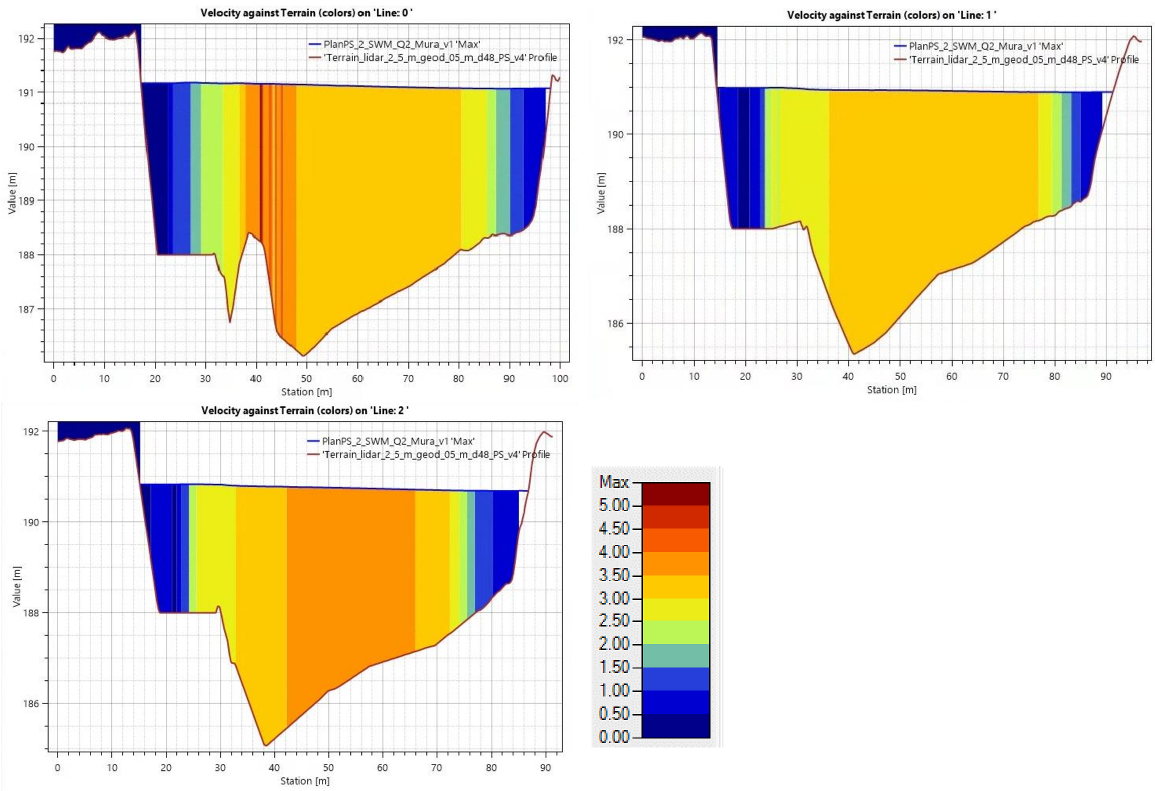

Figure 23: Velocity distribution in cross sections P0 (AREA 1), P1 (AREA 2) and P2 (AREA 3) at flow Q2

At flow Q5, the velocities in the watercourse bed are significantly higher. Maximum velocities in the cross sections of profile P0 (AREA 1) increase up to 3.3 m/s and 4.5 m/s in the area of the structure. At profile P1 (AREA 2) they increase up to 3.5 m/s and at profile P2 (AREA 3) ca 3.7 m/s.

Along the left bank, the speeds are lower and reach a size of approx. 2.5 m/s, and in the area of excavations of up to 1 m/s. Higher velocities are in the AREA 1, where the rock structure redirects part of the flow in the direction of the excavations.

Similar to the flows Q2, the most exposed point for the onset of erosion and collapse of the bank is based on the calculations of the bank between AREA 1 and 2 and the bank between AREA 2 and AREA 3. Velocities on these sections are up to 3 m/s, consequently, shear stresses at these locations in the range of τ = 50-120 N/m^2, where there is a change of grains of minimum diameter d_{min} = 7-15 cm, which is more than the size of the average grain at the site.

At these flows, we can expect the removal of the bank heel and the erosion of it. As a result, area of the main channel (riverbed) will expand into the left bank.

At initial state, at low flow velocities in the excavated areas backflow (eddys) are visible. After the collapse of the left bank, the current conditions will change in accordance with the course of the erosion and the removal of the bank heel.

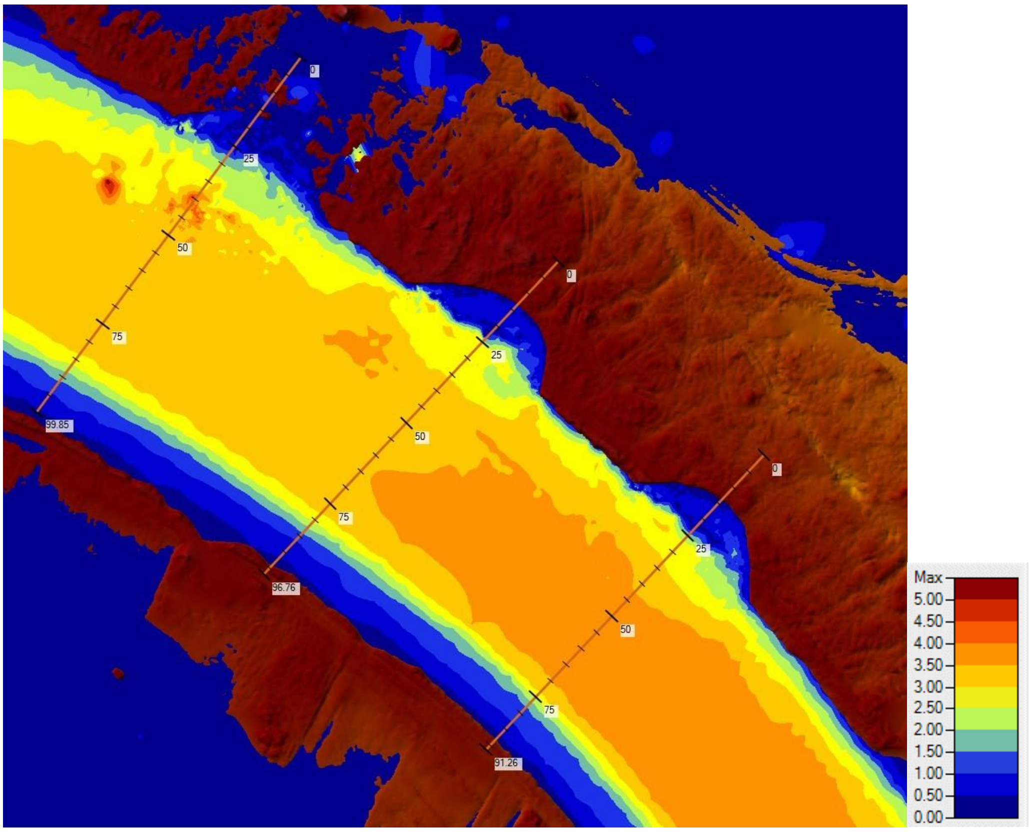

Figure 24: Distribution of the velocity field in the Mura riverbed at the return period flow Q5 for the planned state

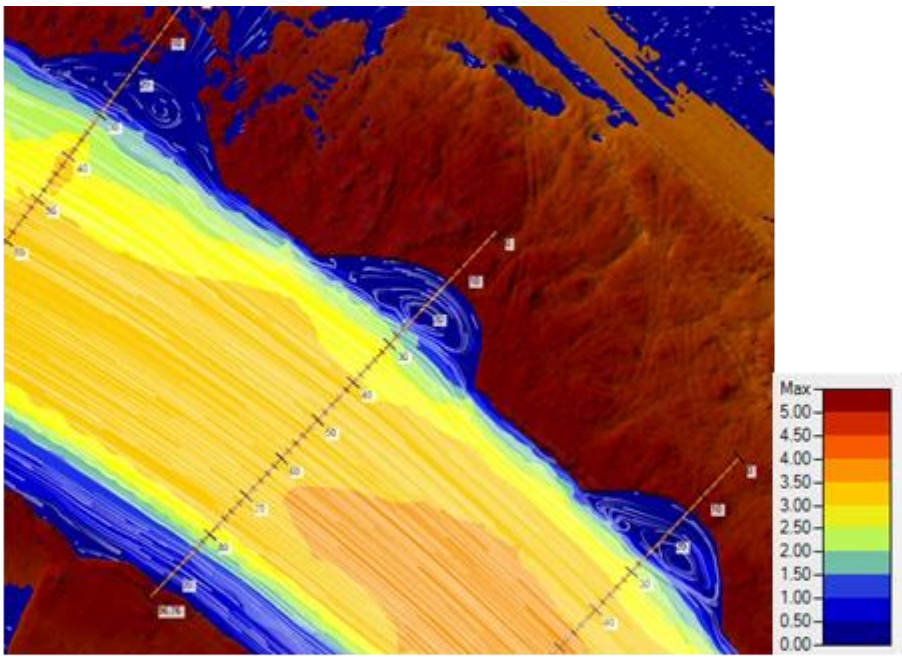

Figure 25: Backflow in the area of excavations

2. Planned situation after the widening of the left bank to the reallocated embankment

In this chapter, the current conditions in the area of the planned measure after the widening and theoretical flooding of the entire area planned for the widening of the riverbed were checked. This is a theoretical range where the widening of the riverbed stops at the location of the reallocated embankment.

The bottom of the eroded widening was assumed at 188 m a.s.l.

Based on the hydraulic calculation at the flow Q5, we find that there will be a change in the current conditions in the area of the planned excavations, which is evident mainly in the form of a decrease in speed in the riverbed as a result of widening. In the area of the excavations, vortexing and backflow are expected in the upstream section, and accelerated flow and the highest shear stresses in the downstream section and along the bank. Maximum shear stresses will be present in the area of the bank- the left bank edge downstream of the rock structure.

Shear stresses will locally reach values of $\tau = 130\ N/m^2$ in this edge, which means a displacement of grains of size d=ca 15 cm or eroding more than 80% of all grains. The rock structure achieves its purpose of dividing and redirecting the flow in the direction of the excavations by concentrating and diverting the current. Due to the reduction of the average speeds in the riverbed, we expect a change in the subsidence on the section in question.

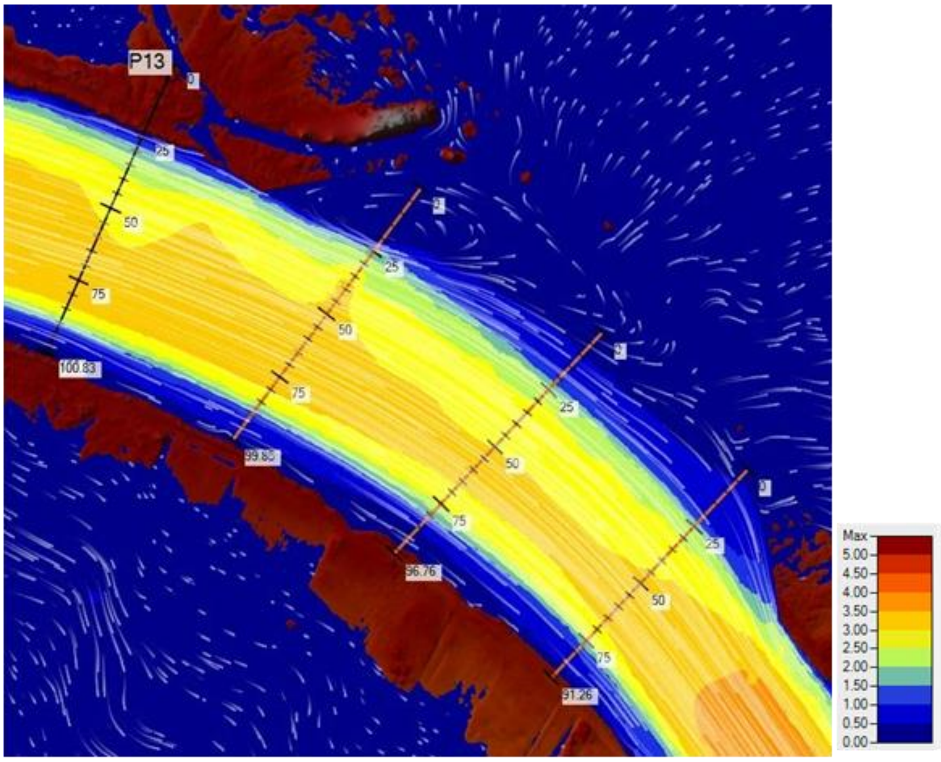

Figure 26: Velocities in the area of the bed widening in the entire area of the planned measure at flow Q5

At 2-year return flows, the flow picture is similar to that at Q5. The highest shear stress occurs on the left bank and the downstream part at the outflow from the excavations, which can be seen in the figure below.

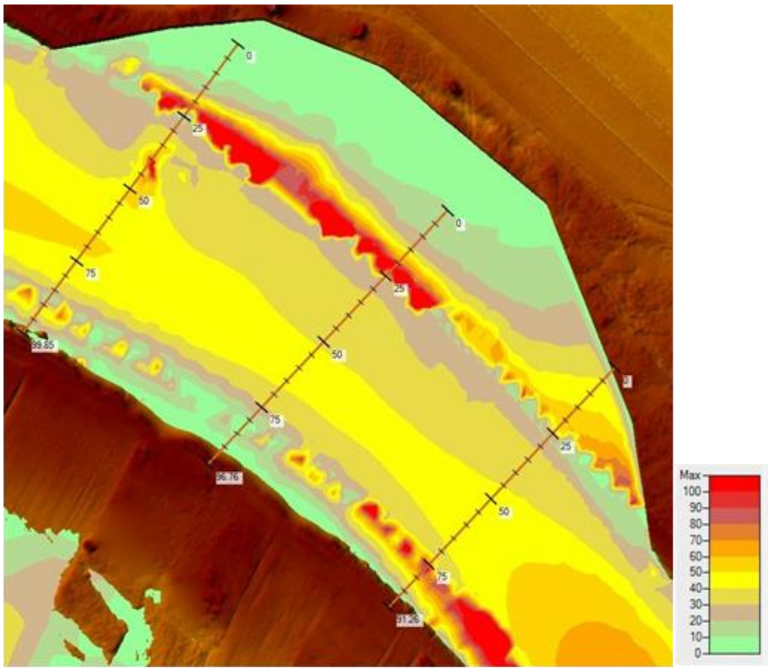

Figure 27: Shear stresses in the excavation area at flows Q2

Based on this analysis, we conclude that the erosion dynamics of the excavation areas that will be carried out as part of the project [1] spread mainly east of AREA 1 and the current will erode the area mainly of the banks upstream and downstream of AREA 2, which are most exposed. As the bank deepens and erosion will penetrate to the reallocated riparian protection in the eastern part of the pilot area. We estimate that the northern part of the prepared area for gravel movement will remain unused or as it is not so exposed to current processes. After the relocation of most of the material from the excavated area, the most exposed part will be on the downstream section when connecting to the existing riverbed protection.

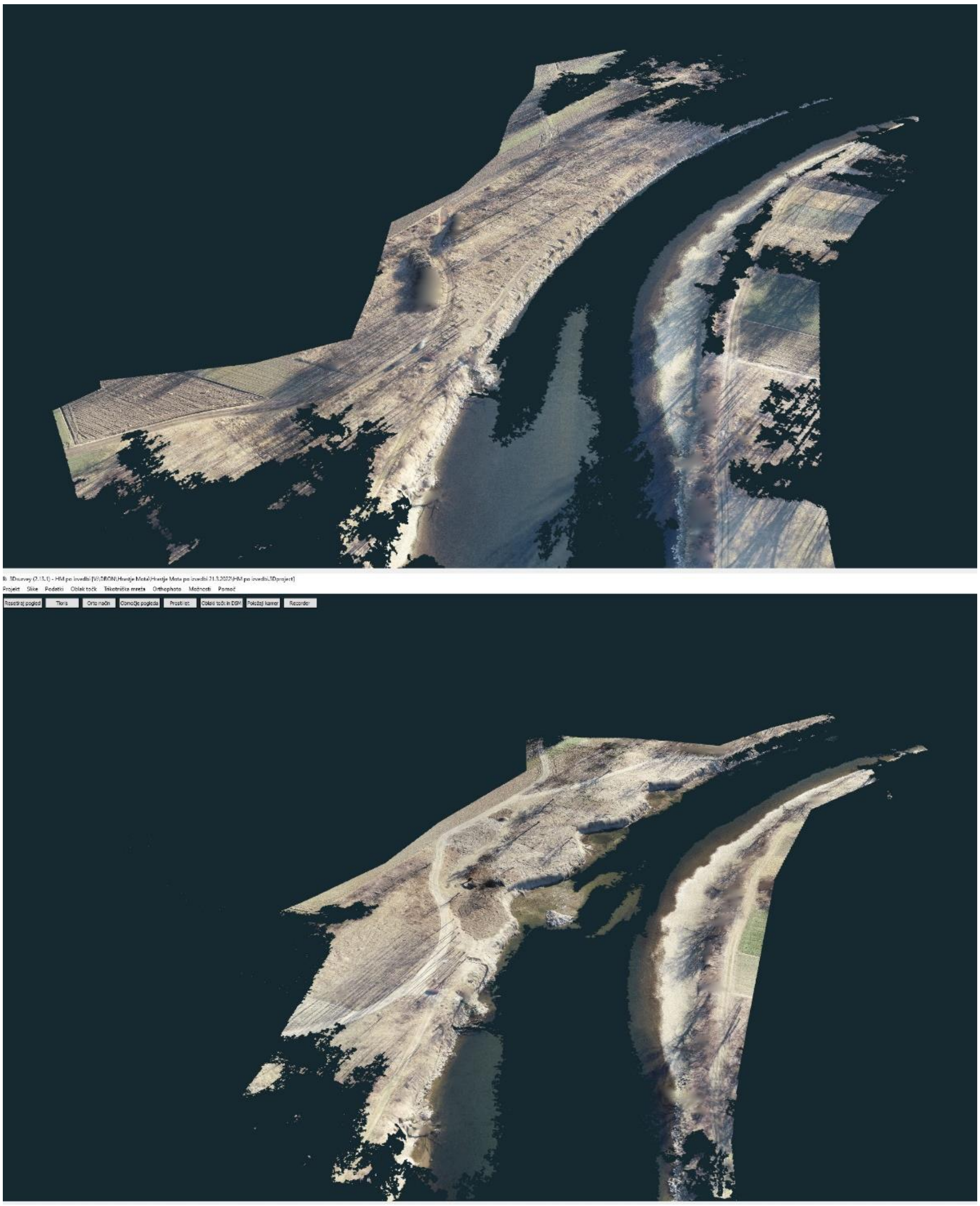

Figure 28: 3D model of the pilot site before and after planned measure implementation (source: Pomgrad VGP d.d.)

III. Conclusion

As part of the hydraulic analysis, we performed a detailed hydraulic analysis of runoff conditions in the area of the planned measures along the Mura River based on the documentation of the planned works within the project "Proposal for the widening of the Mura riverbed within the LIFELINE MDD project" [1].

The results of the models of the proposed measure only reflect the static situation that would be established in approximately such a form when the measures are implemented. However, there are dynamic processes in the river that could change abiotic factors in a short time. We know from experience that riverbed widening in principle increase hydromorphological dynamics and thus also the variance of hydraulic quantities and consequently abiotic factors in the riverbed.

The hydraulic analysis confirms that the measures planned in the project meet the requirements regarding the crucial hydraulic parameters (speed, depth, shear stress). With the removal of the existing riparian protection, the bank is exposed, which does not provide sufficient resistance to the river flow at higher flows. In accordance with experience, high-water events will lead to the bank erosion and the sediment mobilization. Hydromorphological conditions will be improved and gravel will be added to the Mura River. The impact of the deepening of the riverbed and the widening of the main channel will be partially reduced.

By creating a complex full 2D hydraulic mathematical model in the area of the measure, we summarized the geometric characteristics of the topology of the area before and after the planned measure. The hydraulic topology model was based on a digital terrain model from various data sources and thus covered a wider area of consideration. The full 2D model enabled us to analyze the current conditions in each cross section in the entire Mura riverbed, especially in the area of planned measure, determine the most exposed places and analyze the riverbank exposure to hydraulic forces and assess the desired effects of measure.

Based on the hydraulic verification of the implemented measures in the area of the Mura river basin, we find that the measures provide conditions that are in line with the objectives of the project lifelineMDD.

Figure 29: Pilot site after performed measures (source: Pomgrad VGP d.d.)

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