Frisco1

S čezmejnim sodelovanjem do zmanjšanja poplavne ogroženosti

Prekograničnom suradnjom do manjih poplavnih rizika

PROJEKT FRISCO1

ANG

CROSS-BORDER HARMONIZED COMPREHENSIVE FLOOD RISK REDUCTION STUDY FOR THE MURA RIVER BASIN

abstract

Interreg

SLOVENIJA – HRVAŠKA

SLOVENIJA – HRVATSKA

Evropska unija | Evropski sklad za regionalni razvoj

Europska unija | Europski fond za regionalni razvoj

INTERREG V-A Slovenia–Croatia 2014–2020 Cooperation Programme

Project:

FRISCO 1 – Cross-border Harmonised Slovenian-Croatian Flood Risk Reduction – Non-structural Measures

Objective:

The FRISCO1 project – Technical assistance in the elaboration of a comprehensive study in the flood risk reduction for the Mura cross-border basin

Documentation type:

CROSS-BORDER HARMONIZED COMPREHENSIVE FLOOD RISK REDUCTION STUDY FOR THE MURA RIVER BASIN

ABSTRACT

June 2019

S čezmejnim sodelovanjem do zmanjšanja poplavne ogroženosti

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1 INTRODUCTORY PRESENTATION OF THE FRISCO 1 PROJECT

The FRISCO1 project is a strategic project aimed at reducing flood risk in the basins of the Dragonja, Kolpa, Sotla and Bregana rivers and parts of the Drava and Mura river basins, which is implemented in the framework of the INTERREG V-A Slovenia–Croatia Cooperation Programme. The INTERREG V-A Slovenia–Croatia Cooperation Programme text is the main document that represents the framework for cross-border cooperation between Slovenia and Croatia in the 2014–2020 financial perspective. The purpose of cross-border cooperation is to overcome the common challenges that both countries have jointly recognised in the border area, while also taking advantage of untapped growth potentials and strengthening the process of cooperation for the overall harmonious development of the European Union.

FRISCO1 substantially examines the non-structural measures for flood risk reduction and the improvement of flood risk management system. The improved, cross-border harmonized flood risk mapping and the elaboration/improvement of cross-border flood forecasting models will provide the necessary expertise and documentation for the proposal and selection of harmonised structural cross-border flood risk reduction measures that would be carried out in the second phase of the FRISCO project, i.e. through the FRISCO2 project implemented in the basins of the Kolpa, Sotla, Drava and Mura.

The FRISCO1 project partners:

- Croatian Waters (CW, Croatian: Hrvatske vode) as the leading partner,
- Ministry of the Environment and Spatial Planning of the Republic of Slovenia (MESP, Slovenian: ministrstvo za okolje in prostor Republike Slovenije),
- Slovenian Environment Agency (SEA, Slovenian: Agencija Republike Slovenije za okolje),
- Slovenian Water Agency (SWA, Slovenian: Direkcija Republike Slovenije za vode),
- National Protection and Rescue Directorate (NPRD, Croatian: Državna uprava za zaštitu i spašavanje),
- Meteorological and Hydrological Service (MHS, Slovenian: Državni hidrometeorološki zavod),
- Institute for Hydraulic Research (IHR, Slovenian: Inštitut za hidravlične raziskave),
- Administration for Civil Protection and Disaster Relief (ACPDR, Slovenian: Uprava Republike Slovenije za zaščito in reševanje).

The FRISCO1 project consists of the following ten work packages:

M Project Management
C Project promotion
T1 Kolpa common tools, models, maps and projects
T2 Sotla common tools, models, maps and projects
T3 Drava common tools, models, maps and projects
T4 Mura common tools, models, maps and projects
T5 Dragonja common tools, models, maps and projects
T6 Bregana common tools, models, maps and projects

T7 Flood warning and alerting systems

T8 Activities For Raising Awareness and Comprehensive Concept and Programme Management – for the Flood Risk Reduction/Flood Relief Project

In the T4 Mura work package, the common tools, models, maps and projects comprise the following activities:

T4.1 Development of common tool 1 (Flood risk database)

T4.2 Development of common tool 2 (Target area study)

T4.3 Development of common model 1 (Improved hydraulic model)

T4.4 Development of common model 2 (Improved predictive model)

T4.5 Development of common map 1 (Improved flood hazard map)

T4.6 Development of common map 2 (Improved flood risk map)

T4.7 Preparation of construction projects

The planned activities and results are interconnected.

In accordance with the project application, the results of the FRISCO1 project are as follows:

- Improved databases for flood risk management
- Cross-border studies of comprehensive flood risk management
- Improved hydrological and hydraulic models
- An improved flood forecasting model
- Improved and cross-border harmonised flood hazard and risk maps
- Joint projects (preparation of project and other documentation)
- Early warning system (upgrade of the prognostic and warning alarm system)
- Raising public awareness in flood risk and institutional strengthening of the flood risk management system

The main objective of the T4.2 Joint Action 2 is "A study of cross-border harmonised reduction in flood risk for the Mura river basin".

2 CROSS-BORDER STUDY OF COMPREHENSIVE FLOOD RISK MANAGEMENT OF THE MURA RIVER

2.1 THE PROGRAMME

INTERREG V-A Slovenia–Croatia 2014–2020 Cooperation Programme

2.2 THE PROJECT

FRISCO 1 – Cross-border Harmonised Slovenian-Croatian Flood Risk Reduction – Non-structural Measures

2.3 THE SUBJECT

The FRISCO1 project – Technical assistance in the elaboration of a comprehensive study in the flood risk reduction for the Mura cross-border basin

2.4 THE SPONSOR

THE REPUBLIC OF SLOVENIA,
Slovenian Water Agency (Slovenian: Direkcija Republike Slovenije za vode)
Hajdrihova ulica 28c, SI-1000 Ljubljana

2.5 THE CONTRACTOR

Lead Partner:

Water Management Bureau Maribor (Slovenian: Vodnogospodarski biro Maribor d.o.o.)
Glavni trg 19/c, SI-2000 Maribor

Responsible task manager:
Smiljan JUVAN, M.Sc., B.Sc. Civil Engineer

Partners:

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IZVO-R, projektiranje in inženiring d.o.o.
Pot za Brdom 102, SI-1000 Ljubljana

HIDROSVET d.o.o.
Kidričeva ulica 25, SI-3000 Celje

DHD, d.o.o.
Praprotnikova ulica 37, SI-2000 Maribor

SL-Consult, d.o.o.
Dunajska cesta 122, SI-1000 Ljubljana

2.6 THE TASK MONITORING AND MANAGEMENT

One of the objectives of the FRISCO1 project is a cross-border study in flood risk reduction for the Mura area, which was carried out by a professionally qualified contractor selected through a public procurement process. The contract was officially carried out by the Slovenian Water Agency, but the study was also monitored in accordance with the project assignment by the leading structure of the FRISCO1 project, which comprises multiple project management groups and working groups:

- The Sotla Working Group (WG)
- The Project Management Team (PMT)
- The Strategic Management Team (SMT)
- The Quality Management Team (QMT)
- The Project Communication Team (PCT)
- The Expert Panel (EXP)

The study was managed by the Mura Working Group (WG), which comprised the representatives of project partners. The head of the working group was Mr Anton Kustec (DRSV), and the co-leader was Mr Leonard Sekovanić (HV).

2.7 THE PURPOSE AND OBJECTIVES OF THE STUDY

The cross-border study carried out for flood risk reduction in the Mura river basin contains an analysis of the existing situation and alternative solutions as well as the identification and justification of flood risk reduction measures in the relevant area, including the identification of key natural water retention areas and an analysis of potential green infrastructure measures, which is based on hydrological, hydraulic and technical economic analyses. The elaborated study serves as a support tool for decision makers and as an informative tool for all stakeholders. The proposed optimal flood risk management programme in the study is divided into measures that are feasible in the short term and could be implemented during the current implementation period of the European flood directive (2016–2021) as well as measures that could be implemented later.

2.8 THE PURPOSE AND OBJECTIVE OF THE SUMMARY OF THE CROSS-BORDER HARMONISED STUDY IN FLOOD RISK REDUCTION OF THE MURA

Below is a summary of the Cross-Border Coordinated Study of the Comprehensive Flood Risk Management for the Mura River, which contains summaries of key content and the results of the study.

The summary is an integral part of the T4.2 Development of Common Tool 2 (Target Area Study).

3 SUMMARY OF CROSS-BORDER HARMONISED STUDY IN FLOOD RISK REDUCTION OF THE MURA

3.1 ANALYSIS OF THE CURRENT SITUATION

3.1.1 COLLECTION AND ANALYSIS OF EXISTING DATA

For the purpose of the study, the available existing data was collected, reviewed and analysed, with quality control of the relevant data carried out at the same time. The data obtained from Slovenia and Croatia was then analysed by individual sets. The available project documentation, which had previously been created for the Mura river area, was analysed and reviewed.

3.1.2 DESCRIPTION OF THE CURRENT SITUATION

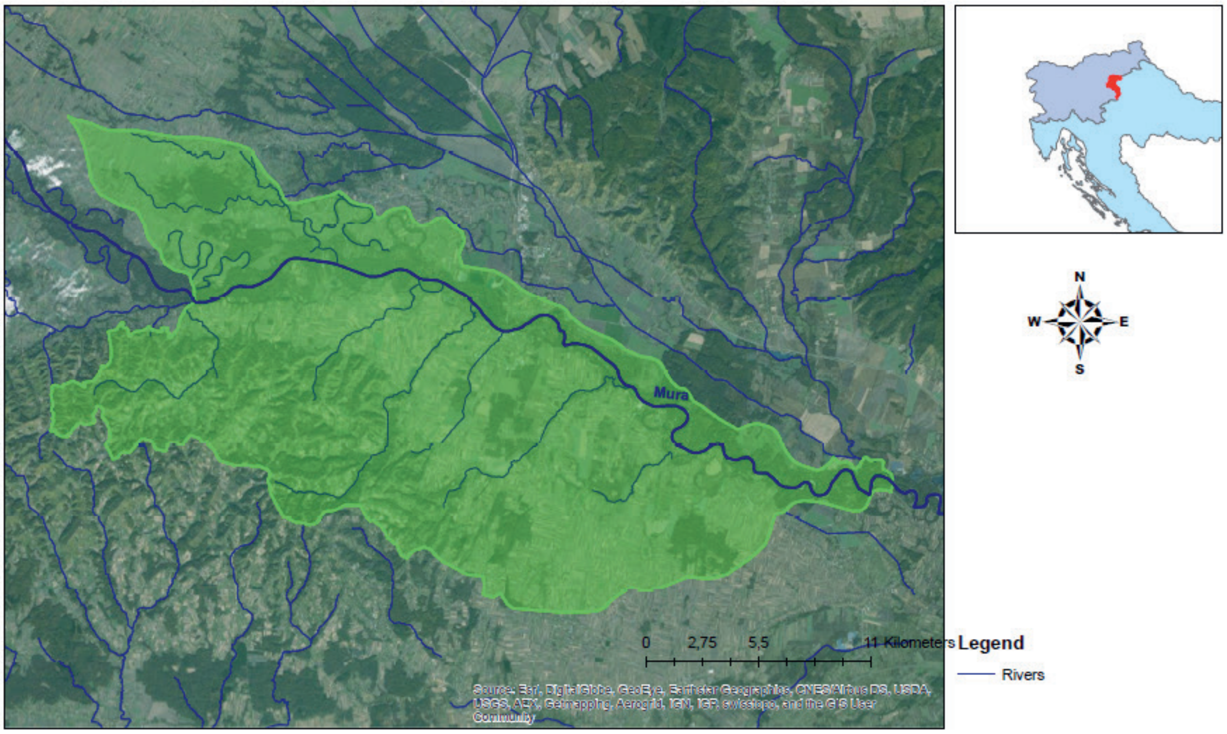
3.1.2.1 General description of the Mura river basin

The Mura river springs in Austria and at the section of about 500 km, flows through Austria, Slovenia, Hungary and Croatia, where it enters the Drava river. The Mura springs in the Austrian mountain range of the Hohe Tauern at the elevation of 1753 m. After 390 km, it crosses the Slovenian–Austrian border near the settlement of Spielfield and then the Slovenian–Croatian border near the Gibina settlement. The Mura is a border river between Slovenia and Croatia and also a border river between Croatia and Hungary. In its upper part, Mura is a typical mountain river, but in the treated area it behaves as a classic lowland river with numerous meanders and dead-branches. The river has a distinct snow–rain regime. Due to the snow melting in the highlands, its water level is the highest in May and the lowest in January, when most of the precipitation falls in the form of snow. The hydroelectric power stations are located at the Austrian part of the Mura, which means its channel is often regulated.

The annual precipitation decreases from the source towards the river mouth. At the spring, it stands at 1250–1500 mm in total, and at the river mouth the annual precipitation totals 800 mm. High water levels are the most frequent in May, June and July, occurring as a result of the melting snow and ice. The lowest flow levels occurs in December, January and February.

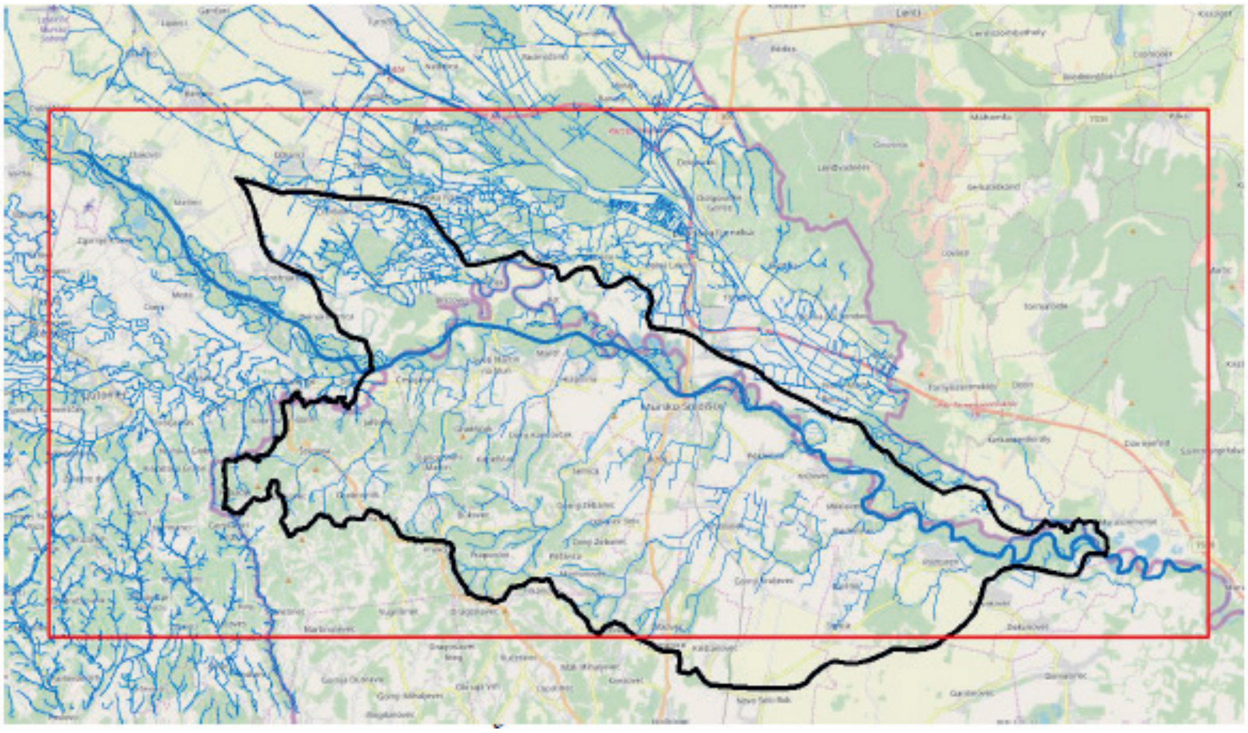
3.1.2.2 Area of the Mura river basin relevant for the FRISCO 1 project

Only a short Mura section is addressed under the FRISCO1 project. Initially, it was planned that the section between the confluence of the Mura and the Ščavnica rivers and the confluence of the Mura and the Ledava rivers, with the length of about 30 km, would be addressed as part of the project. The area covered by the project task does not include the areas of Ščavnica, Ledava, Črnec, Kopica and Ajaš. Consequently, no hydrological analysis was carried out for these areas.



An overview map of the area in line with the project assignment

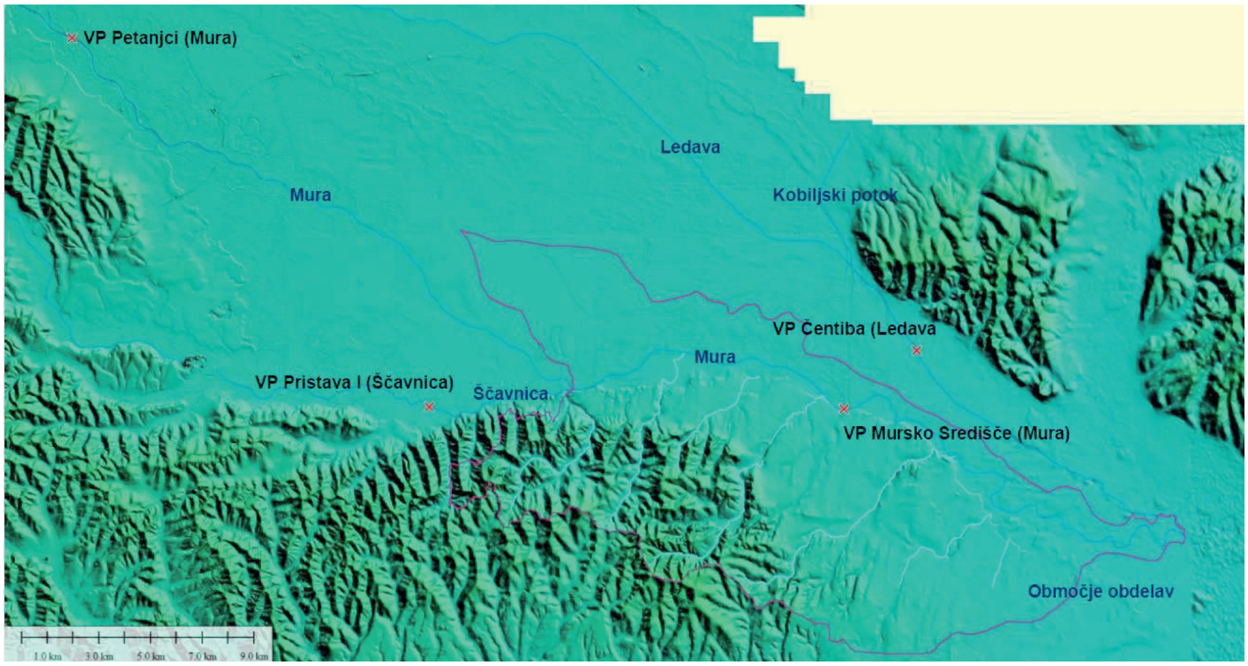
During the first phase of the study, it was established that due to the complexity of the Mura flood flows, it would be impossible to evaluate the flood conveyance routes by considering this part of the section only, as the hydraulic model could consequently give false results of the flood situation. For this reason, the model section of the Mura was extended upstream by 20 km up to the railway bridge, so the total length of the treated section is now approximately 50 km long. Such an extended area ensures the identification of the adequate inflow and outflow conditions, as it includes all flood surfaces of the target area, thus providing an appropriate basis for the needs of all substantive analyses in the context of drawing up a comprehensive study and achieving its objectives.



View of the treated area. The black line shows the FRISCO1 area, and the red line shows the area of the mathematical model

3.1.2.3 Geographical description of the relevant area

In line with the geographical regions of Slovenia, the relevant Mura river basin area belongs to the Dolinska and Ravenska regions as part of the Murska ravan plain, which is bordered by Lendavske gorice on the east, Goričko on the north, and Slovenske gorice on the west and south. In the territory of Croatia, the treated area belongs to the region of Medjimurje, consisting of Donje and Gornje Medjimurje and Medjimurske Gorice.



An overview of the treated area.

The elevation values range is between 100 and 200 m above sea level. The Murska ravan plain is the flattest region in Slovenia, with as much as 95% of its surface having a slope of under 2%. The hilly world of the Medjimurje hills represents a low hills area. The entire treated territory represents an area of 21,447 hectares. A major part of the treated area (approximately 88%) lies in the Croatian territory, while the rest is part of Slovenia. The Croatian part of the treated area is located in the following municipalities: Štrigova, Sv. Martin na Muri, Selnica, Gornji Mihaljevec, Sv. Juraj na Bregu, Šenkovec, Vratišinec, Podturen and Belica, Mursko središće and Čakovec. The Slovenian part of the treated area is located in the municipalities of Beltinci, Črenšovci, Odranci, Ormož, Ljutomer, Razkrižje, Velika Polana and Lendava.

3.1.2.4 Climatic features

The treated area has a moderate continental climate. With the average annual temperature of about 9 °C, the average temperature in January of about -2.5 °C and the average temperature in July of about 19 °C, the treated area is one of the sunniest regions in Slovenia. In the spring, the weather gets warm fast and for 6 months, the average temperature stays above 15 °C. The area has the average precipitation of 950 mm per year. The precipitation rate is lowest during winter, when only a quarter of the annual amount of precipitation falls in average. July and August are the wettest months, but due to strong evaporation, droughts are also most frequent at that time.

3.1.2.5 Soil

The Mura plain is built of Pleistocene and Holocene deposits brought by the Mura, Lendava, Ščavnica and their tributaries. The Mura river banks are made of non-carbonate gravel and sand. Such parent basis and relief formation have a significant influence on the aquatic conditions of the Pomurje plain. The flood and ground water was the decisive factor in the formation and development of hydromorphic soils that cover large parts of the plain. Smaller parts of the plain are covered in soils affected only by precipitation, which freely permeates through the soil profile to the groundwater.

3.1.2.6 The water environment

In the considered section, the Mura river has several short right tributaries, i.e. Jalšovečki potok, Gradiščak, Koncovčak, Gornji potok, Brodec and Jalšovnica. However, it was estimated that the flows of these tributaries are negligible compared to the Mura flow, therefore only the Mura river flow was taken into account for various return periods for the purposes of this study.

The treated area is very rich in terms of both surface and groundwater. According to the flood warning maps accessible through the Atlas website and data made available by the Croatian Meteorological and Hydrological Service (Državni hidrometeorološki zavod, DHMZ), the treated area is significantly exposed to flood-hazards, as overflowing of embankments occurs in particular reaches and floodplain overflowing occurs where there are no embankments. The maps show that flooding of the Mura river occurs as early as upstream, beginning at the confluence of Mura and Ščavnica. A wider flood area is also found in the area between the flood-control embankments of Mura and the watercourses of Črnec and Ledava. The floodplain exceeds the area specified within the FRISCO1 project framework.

The concerns referred to in connection to the analysed section and the flood exposure indicated by the existing flood maps proved to be justified in the past. One of the worst flood events took place in the August of 2005, when a water flow of 1196 m^3/s was estimated at Mursko Središče. During the flood event, four locations were exposed the most, namely:

- Zone 1: upstream from Hotiza (in the area of the floodplain with no embankments). According to testimonies of the 2005 flood witnesses, a mild overflowing occurred in the area between the floodplain and the beginning of embankments at Hotiza, where the water flooded the dead-branches. The Hotiza–Kapce road was not closed for transit and there was no flooding in the urbanized area of Hotiza.
- Zone 2: the embankments between the two villages of Kot and Petišovci. Another critical area is located downstream from the renovated Hotiza–Kot embankment, where overflowing of the embankments occurred, but was prevented by anti-flood bags and temporary elevation of the embankments.
- Zone 3: downstream from the Petišovci border crossing point (Kolonija Petišovci). The third zone is located downstream from the Petišovci border crossing point, where an embankment protects the settlement of Kolonija Petišovci. In 2010, this embankment was reconstructed and elevated significantly, but during the floods in 2005 it was considerably lower. Had the temporary measures of artificially elevating the embankment with anti-flood bags had not been introduced, the overflowing of this embankment would have taken place during the flood event.
- Zone 4: the area at the end of the embankments – Benica. The lower part of the Mura embankment was also critical, as the flood water reached the settlement of Benica. According to local experts (ARSO Murska Sobota) and the inhabitants, the water from Mura reached the settlement of Benica on the right bank of the Ledava river, during the flood event in 2005. At the time of the flood, the embankment was temporarily artificially raised at this place too, thus preventing greater flooding in the direction of the Benica settlement.

A large aquifer was formed along the Mura river. The groundwater level in Prekmursko polje is the lowest in Slovenia, and in some places it sometimes reaches the ground surface. This contributes to the occurrence of swamps and influences the regional groundwater sensitivity. The long-term hydrological monitoring data shows that the average groundwater level is only around 1.7 m below the surface. The groundwater level decreases the most during late summer, when the evaporation is the strongest, and water consumption increases.

3.1.2.7 Nature

The treated area is characterized by numerous regular and lateral channels, backwaters and depressions, where the extremely diverse hydrological conditions affect the existence of various aquatic, land-bordering and marshy habitats. The flood forests consist of diverse forest vegetation including willows, hornbeam forests with numerous interim groups as well as rare and endangered species. A large number of endangered plant species and many endangered and protected animal species can be found in the area. The elements of traditional fluvial cultivated landscape almost disappeared due to intense farming that engages in draining, the use of fertilisers and additional planting. The preserved wetlands are therefore especially valuable.

3.1.2.8 Cultural Heritage

The units of immovable cultural heritage in the Slovenian part of the region are registered in the Register of Immovable Cultural Heritage (Register nepremične kulturne dediščine, RKD), which is kept by the Ministry of Culture. Different legal regimes apply to different areas of immovable cultural heritage, depending on their status (cultural monument, registered cultural heritage) and type (building, settlement, garden architecture, memorial heritage, cultural landscape). In the Slovenian part of the treated area, 22 units of immovable cultural heritage are registered, one of them with a designated area of influence. In the Croatian part, the cultural heritage is defined and protected by the Spatial Plan of the County of Medjimurje (Prostorni plan Medjimurske Županije, Institute for Spatial Planning of the County of Medjimurje (Zavod za prostorsko uređenje Medjimurske županije), Čakovec, November 2001). There are 24 registered cultural heritage units in the area, including seven units of movable cultural heritage. The Ternovčak archaeological site is located in the treated area.

3.1.2.9 The Population

Medjimurje is the most densely populated area in Croatia, and the same applies to the Murska ravan plain with regard to the average population density in Slovenia. The treated area is characterized by a decline in the number of population and an unfavourable age structure, while the natural increase is minimal. The population is gradually leaving Medjimurje to move to either Zagreb or Istria. Similar trends as in population can be observed in the Slovenian part as well. The number of inhabitants (except for the Roma settlements) and population density have been decreasing due to emigration recorded in recent decades. The main reasons are poor career prospects and, as a result, above-average unemployment rates. The settlements in the area have a clustered structure and they are located at lowlands and along the roads. Most of the buildings are traditionally designed as homesteads with connected residential and farming facilities. Smaller pieces of functional land (courtyards) are also associated with these facilities. The treated area has an extremely rich national and religious structure. The area is trilingual, as the languages spoken are Slovenian, Croatian and Hungarian.

3.1.2.10 The Economy

Murska ravan has a traditionally agricultural landscape, so the food processing industry has developed in the area. Fields cover almost half of the entire territory. The largest industrial plants are engaged in the meat processing activities. Several decades ago, forestry was an important industry in the Medjimurje region. In the past, most of the industrial plants in the Medjimurje area used to be based on textiles. The area is rich in mineral resources. An over 10-m layer of sand and gravel deposited by the Mura river allows the exploitation of mineral resources. There are 12 active exploitation fields of gravel and sand in the Medjimurje county alone.

3.1.2.11 The spatial use

Given the natural conditions and the implemented agricultural-technical measures, agriculture is the prevailing method of land exploitation. More than 60% of the area is devoted to farming (e.g. 64% in the municipality of Črenšovci). This is followed by approximately 21% of forest land and, due to the densely populated areas, about 10% of building land. A relatively large share of aquatic land, which represents slightly more than 5% of the area, mostly includes the areas of watercourses, backwaters and abandoned gravel pits. Less than 1% of land falls under other land categories. The analysis of ground coverage made for the entire area showed that the largest share falls on different categories of agricultural land (63.5%), which is followed by forest land (28.7%) as well as built-up and similar land (2.8%). The smallest share falls on aquatic and marshy surfaces (2.8%).

3.1.2.12 The current state of the environment

Air quality

There are no stations neither in the treated area nor in its vicinity, where such measurements would be carried out. The decree on the designation of zones and agglomerations according to the level of air pollution in the territory of the Republic of Croatia (Official Gazette no. 1/14) classifies the Medjimurje County as area HR 1, for which the levels of air pollution are assessed in terms of protecting the human health. The below table displays detailed information on the pollution levels, which show relatively good results: the estimated values of oxides, benzene, heavy metals and CO are below the lower assessment threshold, while the values of SO_2 and dust particles are below the upper assessment threshold. The livestock farming with numerous facilities used for intensive animal breeding represent an important source of air pollution, and also the source of emissions in unpleasant odours.

Surface water status

Based on the measurements carried out during the 2008–2012 period at the measuring station of Goričani, a GOOD ecological status of the Mura river was established. The status of the Mura tributaries is also being monitored and established mostly as very POOR. According to the Water Management Plan (Plan upravljanja vodnim područjem) for the 2013–2015 period, the chemical and ecological status of the Mura body of water CDRI0003_003 was recorded as GOOD.

Groundwater status

In the framework of the national monitoring of groundwater quality in the treated area, no measurements of groundwater quality are carried out. However, such measurements are carried out in several nearby monitoring stations in the area of the same aquifer, so these results can also be regarded as relevant for the treated area. From 2015 onwards, the overall assessment of the chemical status for the Murska kotlina basin groundwater has been indicated as POOR.

Waste-water collection and treatment

A systematic collection of municipal waste-water is only partially arranged in the area. A sewerage system for the flow rate of urban waste-water is constructed in all major settlements, and most of the buildings are connected to it. The sewerage system for the settlements of Črenšovci, Žižki and Trnje was built in 1997, and for the settlements of Dolnja Bistrica, Srednja Bistrica and Gornja Bistrica one year latter, in 1998. In the settlements of Kapca, Hotiza, Kot, Gaberje, Kolonija and Kolonija, the sewerage system is only partially constructed. In the Slovenian part of the treated area, only one treatment plant is located north of the Hotiza settlement. The Croatian public sewerage network is also only partially constructed in the Croatian part of the treated area. The network is generally constructed in the centres of settlements and is, save for a few exceptions, not integrated into a coherent unit. Peripheral neighbourhoods are not connected to the network. At the moment, there are several operating treatment plants in the Medjimurje County. In the area of Sv. Martin na Muri, an urban drainage facility is planned for the municipal waste-water in the settlements of Hlapčina, Marof, Žabik, Vrhovljan, Sv. Martin na Muri, Brezovec, Jurovec, Lapšina, Čestijanec and Gradiščak. Currently, the sewerage system in Zasadberg is under construction.

The drinking water supply for the population

A water distribution system is built in each settlement. In the Slovenian part, a common drinking water supply system is in operation in accordance with the project called "Pomurje drinking water supply – system A" and is managed by the public company of Eko-park d.o.o. Lendava. A public water distribution system supplies all settlements in the Medjimurje County.

Waste management

The data for Slovenian municipalities located within the treated area reveal an increase in the amount of collected waste. But after 2009, this trend has been reversed and in recent years there has been a decline in the amount of collected waste, as the method of waste collection was adapted towards a more efficient waste management system. In the Medjimurje County, the problem of depositing residues in separately collected fractions is equally unresolved as elsewhere, because the planned waste Piškornica management centre is not yet in operation.

3.1.3 THE HYDROLOGICAL ANALYSIS

3.1.3.1 Description of starting points and used data

The hydrological analysis of Mura for the FRISCO1 project was divided into separate sets, which were reasonably sequenced and upgraded. Since the Mura hydrological system is enormous, the conceptual hydrological model of the river basin was not created for the purposes of the project, but two key pieces of data, namely the determination of project flows for different return periods for the entire section, and the determination of the project form of the flood wave, which has already been tackled by previous studies, which comprehensively addressed the return periods in the Mura interstate region covering the four countries, i.e. Austria, Slovenia, Croatia and Hungary (Brilly, 2011).

The maximum flow rates for the section treated within the FRISCO project were determined by analysing the results of measurements obtained at the Petanjci, Mursko Središče and Goričani measuring stations, which are located in the analysed area. A hydrological study of the Mura river from 2011, which statistically evaluated the measured flow rates at all measuring stations along the Mura river, was taken into account. In addition to this study, results of the statistical analysis of flow rates were also drawn from results submitted by the FRISCO project partners, where the evaluation of measured flow rates at the stations of Mursko Središče and Goričan was carried out. It was found that the flow rate does not significantly fluctuate along the stream, which confirms the finding that the coincidence of other streams, backwater inflows and own waters with the Mura river is small. According to the performed analyses, the values obtained with the Galton statistical function at the Mursko Središče water station are the most adequate and provide the expected project values of high flow rates. It was estimated that a uniform flood flow rate value has been applied for the entire upper reach for individual return periods.

The project-determined flood wave was specified based on measurements made during the past flood waves at major flood events. By analysing the shapes and volumes of the measured flood waves, three typical flood waves (normalized) were identified, which give the proposed narrow, mid and broad flood wave. A determination of the typical flood waves (normalized) was made in the framework of a preliminary study, namely the DV Cirkovce–Pince. According to the provided hydrographs, it was proposed to use a 200–hour broad flood wave showing the most unfavourable flood situation comparable to the Mura flood wave (Mursko Središče) of 2005. The created hydraulic model has only 1 inflow hydrogram for each return period.

3.1.3.2 Analysis of the quality in obtained data

For the purposes of determining the maximum flow rates in the analysed section, a series of three Mura measuring stations was taken into account, namely Petanjci (Slovenia), Mursko Središče (Croatia) and Goričan (Croatia). Within the submission of results, statistical analyses of flow rates obtained at the measuring stations of Mursko Središče and Goričan were submitted, which analysed the set of data for the 1926–2016 period. In both cases, the Galton's distribution is suggested as the most appropriate distribution.

	CROATIA	
station code	**5044**	**5035**
station name	**Mursko Središče (Mura)**	**Goričan (Mura)**
distribution	**Galton**	**Galton**
Q1	261.3	231.5
Q2	665.9	590.9
Q5	933.6	828.8
Q10	1113.9	989.1
Q25	1344.8	1194.5
Q50	1518.7	1349.3
Q100	1694.4	1506
Q500	2114.5	1880
Q1000	2302.4	2047

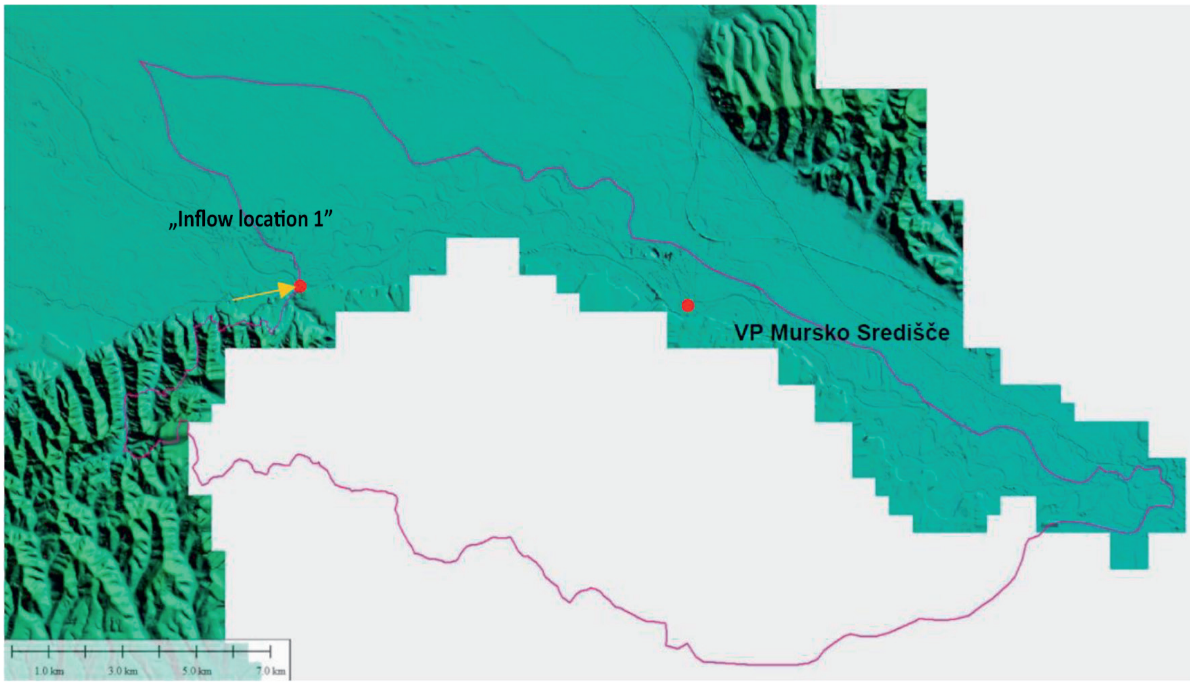
Flood probability analysis for the Mursko Središče and Goričan hydrological stations.

The hydrological study for the Mura river (Brilly et al., 2011) carried out in 2011 included the analysis of hydrological data for 24 stations located along the Mura river and its tributaries, i.e. 15 in Austria, 4 in Slovenia, 3 in Croatia and 2 in Hungary, with the date collected in the period between 1961 and 2005. The datasets were incomplete, as some data was missing or the measurements started to be carried out at a later stage. The Petanjci, Mursko Središče and Goričan stations were also included in this study.

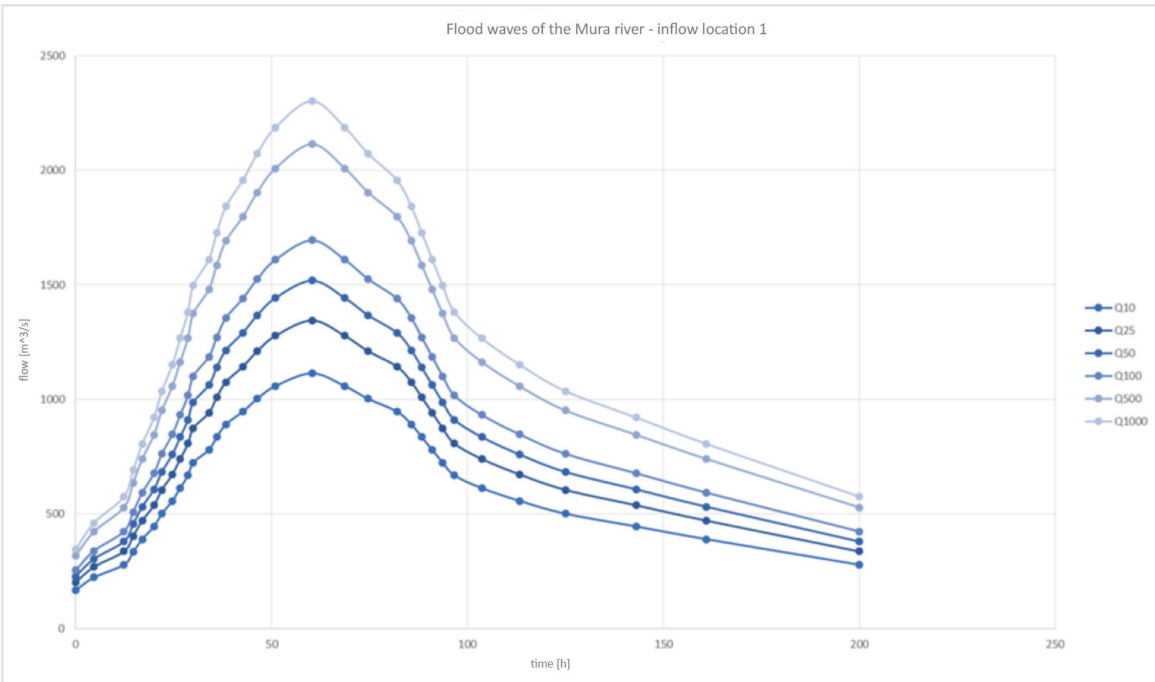
It was found that for Mursko Središče and Petanjci, the derogations were within the appropriate limits. As it turned out, the flow rate along the flow stream does not change significantly, which confirms the finding that the coincidence of other watercourses with the Mura river is small. In order to define the Mura inflow quantities in the analysed section, the values for the Mursko Središče measurement point were taken into account and evaluated by using the Galton's statistical distribution.

3.1.3.3 Flood waves of the Mura river

Flood waves are provided for the cross section or the site of the "Inflow location 1" (Figure 10). Due to a more precise definition of the upper boundary condition, the latter is extended upstream, towards the Petanjci hydrometric station. According to preliminary analyses, the proposed flood waves can also be used in case the inflow location is moved upstream towards the Petanjci hydrometric station due to an upstream expansion of the model.



View of the considered area with the "Inflow location 1" and the Mursko Središče measurement point.



The Mura flood waves in the cross section at the "Inflow location 1".

	Return period					
Time	**Q10**	**Q25**	**Q50**	**Q100**	**Q500**	**Q1000**
[h]	Flow rate **[m3/s]**					
0	167	202	228	254	317	345
4.67	223	269	304	339	423	460
12.33	278	336	380	424	529	576
14.67	334	403	456	508	634	691
17	390	471	532	593	740	806
20	446	538	607	678	846	921

22	501	605	683	762	952	1036
24.67	557	672	759	847	1057	1151
26.67	613	740	835	932	1163	1266
28.67	668	807	911	1017	1269	1381
30	724	874	987	1101	1374	1497
34	780	941	1063	1186	1480	1612
36	835	1009	1139	1271	1586	1727
38.33	891	1076	1215	1356	1692	1842
42.67	947	1143	1291	1440	1797	1957
46.33	1003	1210	1367	1525	1903	2072
51	1058	1278	1443	1610	2009	2187
60.33	1114	1345	1519	1694	2115	2302
68.67	1058	1278	1443	1610	2009	2187
74.67	1003	1210	1367	1525	1903	2072
82	947	1143	1291	1440	1797	1957
85.67	891	1076	1215	1356	1692	1842
88.33	835	1009	1139	1271	1586	1727
91	780	941	1063	1186	1480	1612
93.67	724	874	987	1101	1374	1497
96.67	668	807	911	1017	1269	1381
103.67	613	740	835	932	1163	1266
113.33	557	672	759	847	1057	1151
125	501	605	683	762	952	1036
143	446	538	607	678	846	921
161	390	471	532	593	740	806
200	278	336	380	424	529	576

Tabular view of the Mura flood waves in the "Inflow location 1" cross section.

Each return period has one flood wave, which is the result of the proposed typical flood wave (normalized) of broad shape and the proposed flow rate as obtained from statistical analysis of measurements at the Mursko Središče hydrometric station.

3.1.3.4 Water quantities of other watercourses

The remaining water systems that can indirectly influence the flood situation of the area are the following:

- Ščavnica
- Ledava with Črnec and Ajaš
- Watershed inflows from the right Mura watershed
- Kopica's own water
- Flooding of excess water from the Mura upstream area

Ščavnica

The Ščavnica watercourse flows into the treated area upstream from the point where the wave values were introduced. Since the Mursko Središče hydrometric station, which is located downstream from the Inflow location 1, was used to determine the flow rates, its contribution is already included in the analysis. The coincidence of the Ščavnica high waters and the Mura high waters is low.

Ledava with Črnec and Ajaš

Since the system flows into Mura outside the treated area, it does not directly affect the Mura flow rate and is not included in the hydrological analysis. The amount of water quantities (Q100 return period) of the system may flow to the analysed area and affect the flooding conditions in the area, but the latter is predominantly a hydraulic, not a hydrological problem.

Watershed inflows from the right Mura watershed

A hydrological treatment of such inflows from the point of hydraulic modelling of the Mura was unnecessary, as the inflows do not change the hydrological regime of the river. In addition, the coincidence of the Mura and its hinterland is negligible.

Kopica′s own water

The system of Kopica with its inflows (Libovija) is activated in the event of a ground-water rise or in the case of heavy precipitation. There is a shallow aquifer found the treated area. These are own waters, taken into account within the hydraulic model using the precipitation and infiltration simulation.

Flooding of excess water from the Mura upstream area

Similarly as with the analysis of Ledava together with Črnec and Ajaš, the problem here is both hydraulic and hydrological. It concerns the distribution of water quantities at the inflow location, which can only be determined by setting the upstream model and determining the Mura flooding water quantities as per the analysed area.

3.1.4 HYDRAULIC ANALYSIS

The results and conclusions of the Cross-border harmonised flood risk reduction study for the Mura cross-border river basin are based on the use of tools supplied by the sponsor to the contractor: the hydraulic model of the Mura river (model created by the Institute for Hydraulic Research) and bilaterally harmonised methodologies.

3.1.4.1 The treated area

Although within the Frisco defined area, the Mura section is around 30 km long, the Frisco area also extends along the left bank of the Mura upstream, all the way to the settlement of Odranci. Through the project, it was established that by analysing the Mura section within the Frisco area, it would be impossible to evaluate the overflowing flood streams that "flow" into the area of the model as a result of a possible upstream flooding of the river, which means the model would give false results of the flood situation. On this basis, the model maker has appropriately extended the model Mura section upstream to the Veržej railway bridge. By doing this, the Mura model section was extended by 20 km, so the treated section is now approximately 50 km long. The Frisco area extends beyond the model area only at the extreme southern edge, where no water flows are recorded, so this part is not essential in terms of hydraulic analysis.

3.1.4.2 Basic characteristics of the model

The Mura hydraulic analysis is based on the combined 1D + 2D hydraulic MIKEFLOOD model, which is an integral part of the MIKE DHI software package. In this model, the 1D model simulates the flow in the channel, while the 2D model is used to model water flooding outside the channel, where an intense 2D flow could possibly emerge.

The 1D model

The model starts upstream about 170 m downstream of the Mura railway bridge near Veržej (calculation chainage: 0 m) and it ends 5460 m downstream of the target area boundary (calculation chainage: 50026 m). The total length of the model section is 50,026 km, while the length of the Mura section within the target area is 32,471 km. In the hydraulic model, the calculation chainage increases in the downstream direction.

The geometry of the channel is described by 126 geodetically measured transversal profiles, of which 35 were measured by ARSO for the FRISCO1 project in April 2017, while some were taken from the TC water study of 2012 and some were provided by Croatian Waters (Hrvatske vode). All used transverse profiles were measured after 2010. Because of the numerical stability, 451 intermediate interpolated transverse profiles were incorporated in the model, so that the distances between profiles do not exceed 100 m at any point.

THE 2D MODEL

For the production of the 2D model, a rectangular grid of cells with the size of 12.5 x 12.5 m was used. The model covers an area of approximately 37.3 x 17 km, which is 2987 x 1361 cells. The 2D model integrates approximately 65 km of flood-control embankments, with approximately 37 km of these being in the target area, while the rest is located outside; the goal here is to introduce correct hydraulic picture at the edges of the treated area. Due to the specificity of the flood flow after inundation, especially on the air side of the embankments, the model contains the identified culverts under roads and the railway line. The model is manufactured in the D96/TM coordinate system.

3.1.5 Hydraulic analysis of the existing situation

Using the hydraulic model, flood events were analysed at various return periods Q10, Q25, Q50, Q100, Q500 and Q1000. The left bank flooding of the Mura can be divided into floods within the flood-control embankments and those that are the consequence of overflowing. The flood-control embankments on the left Mura bank start at the beginning of the model section at the Veržej railway bridge, continuing all the way to Benica, with short interruptions at the sections of naturally high terraces. On the right bank, the embankments are built locally along large settlements (Sv. Martin, Križovec and Podturen), while a long embankment begins only downstream from Novakovec.

At higher flows, the water level in certain places flows over the embankment crown and overflows it. The highest flood volume is expected at very high flows of Q500 and Q1000, which exceed the embankment project height and flood the extensive flatland area of Mursko polje.

In order to provide a detailed interpretation of the results for such a large area, the Mura section was divided into the following 3 sub-areas:

- The sub-area stretching from Veržej (at the beginning of the model) to Gibina
- The sub-area stretching from Gibina to Mursko Središče
- The sub-area stretching from Mursko Središče to the end of the model.

3.1.5.1.1 The Veržej–Gibina sub-are

In the Veržej–Gibina sub-area, the Frisco area is located only on the left bank of Mura. In the section from the Veržej railway bridge to Gibina, flood-control embankments were built on the left bank along Mura, which have recently been partially renovated and elevated. The last renovation was carried out in the June of 2018, when the embankment section at Melinci was elevated. The right bank terrain rises to a high terrace at the distance of 0.5–1.5 km from the channel, and in some places flood-control embankments are built on the edges of the high terrace.

The hydraulic model results show that the Mura flood waters, in the Veržej–Gibina section, would overflow the flood-control embankment on the left bank only in the case of Q100 flow rate. The results of the model show that flood water of lower rank (Q10) would overflow the embankment at Nemščak and cause small flooding. The results of the model show a relatively small flooding, which does not reach the settlement of Ižakovci and therefore poses no threat to the existing residential development. The area is located outside of the Frisco Mura target area.

Downstream, the flood-control embankment is interrupted at the Melinci gravel pit. The results of the model show that the overflowing of Mura flood waters at Q100 reaches the area of high-water terrace, but the extent is relatively small. A more detailed analysis of the Lidar terrain and the water levels showed that for the entire high terrace section, the water level at the edge of the terrace varies greatly as per the measured Lidar projection height. This is probably due to thick vegetation in the area, which additionally reduces the accuracy of the Lidar detection.

A more significant overflowing of flood-control embankments begins in the area of the Črenšovci municipality. The flood waters begin to spill at the Melinci treatment plant. The embankment gets overflown in several reaches, while the flood flow on the embankment's air side runs towards the settlement of Gornja Bistrica, where it reaches one of the local roads, and downstream it stops at the Črenšovci–Razkrižje regional road R3-1322. Here, the embankment also gets overflown in the lower return period (Q25 and Q50), with the embankment near the Gornja Bistrica 24 and 25 facilities being affected first, after which the flood flow runs downstream along the embankment and floods the settlement between the flood-control embankment and the local road.

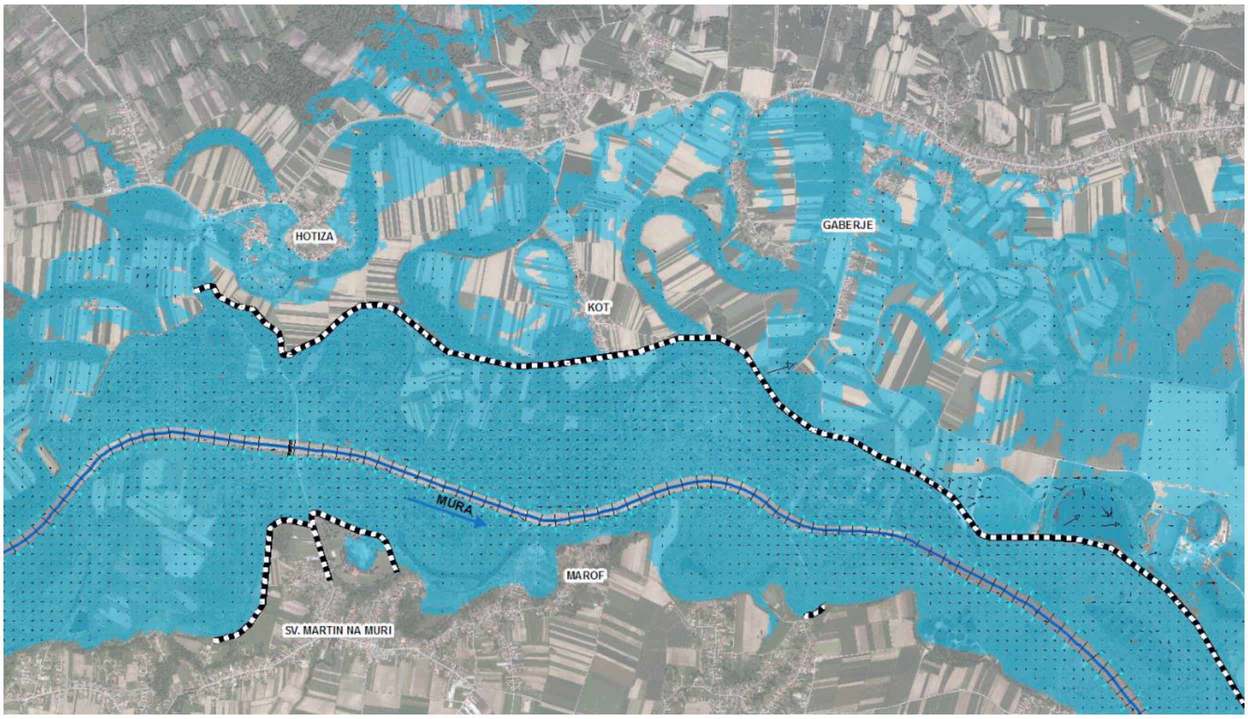
Downstream of the bridge found on the Mura regional road, the flood-control embankments get partially overflown at Q100. The flood water flows along the air side of the embankment over large areas of agricultural land towards the settlement of Dolnja Bistrica, where it floods the local roads and continues until it reaches the Črenšovci–Dol. Lakoš regional road R2-0322, where the flood flow stops. In the area of Dolnja Bistrica, the flood flow confluences with and supplies the former Mura branches.

In the event of catastrophic floods (Q500 and Q1000), the high Mura waters would extensively overflow the flood-control embankments. Two flood flows get created, with the upstream flood flow reaching the villages of Ižakovci and Melinci, as well as the southern part of Beltinci. The flood waters would overflow the Ravenska cesta local road and spill towards the settlement of Odranci, where the Beltinci–Črenšovci (Panonska ulica) regional road R2–0321 would also be flooded. The flood would reach the settlement of Črenšovci too. The second flood flow would be created near the settlements of Gornja Bistrica, Srednja Bistrica and Dolnja Bistrica. The flood flows from Črenšovci would merge and continue to move east.

3.1.5.1.2 The sub-area stretching from Gibina to Mursko Središče

A hydraulic analysis showed that the Mura level would stay within the flood-control embankments and would not overflow the elevated terrain at the flow of up to Q10. At the flow of Q25 and Q50, the water level would be higher than the high terrace on the left bank. The Mura flood waters flow mainly into the former branches (Berek). On the right bank, the flood waters Q25 and Q50 in some places also overflow the high terrace. At Marof, where the flood area on the right bank is reduced to a little over 100 m, Mura floods part of the Marof settlement and local roads.

In the event of Q100, Mura would overflow a high terrace on the left bank between Dolnja Bistrica and Hotiza. As there is no flood-control embankment in this section, the flood flow would run towards Hotiza. The flood reaches the regional road R2-0322, which connects Črenšovci and Dol. Lakoš. Culverts are built under the road, trough which flood water supplies the former branch. Although the settlement of Hotiza is protected by flood-control embankments, it gets flooded due to flood water spilling upstream and reaching the settlement from the west side.



View of the level of Q100 in the area of Hotiza–Gaberje and Sv. Martin na Muri.

In the Hotiza–Kot section, the Q100 Mura flood water does not overflow the left-bank embankment. The flood on the air side is caused by a flood flow extending along the flood area from the west. At Q100, the Mura overflows the left-bank embankment at the settlement of Gaberje. Large agricultural areas are flooded between the flood-control embankment and the regional road R2-0322, which connects Črenšovci and Dol. Lakoš. Both Gornji Lakoš and Dolnji Lakoš are typical roadside settlements, so there are some facilities between the embankment and the road that would be exposed to flood-hazards. The settlement of Gaberje, which spreads transversally across the flood area, is partially flooded. The stream of flood water on the air side of the embankment flows towards the east, where the barrier is represented by a motorway and a railway line. Inundation ponds are constructed under the motorways and the railway line, which allows the outflow of flood water downstream, thus preventing water from getting accumulated at the upstream section.

On the right bank, most of the settlements (i.e. Čestijanec, Lapšina and Jurovec) were built on a flood-safe corridor on the Mura high terrace. In the village of Sv. Martin na Muri, the flood-control embankment has already been built. The western part of the terrace is high enough to protect the settlement from the Mura at Q100, but the eastern branch of the embankment is too low, so the Mura high waters can overflow it. A small part of the uninhabited area gets flooded. A problem more serious than the flooding of embankments in the settlement of Sv. Martin na Muri is posed by the permeability, which can endanger the stability of existing embankments and pose a great danger for the local population in case of a collapse. In the event of Q100, the lower lying area of the Marof settlement would also get flooded. Due to the configuration of the terrain, the extent of flooding in this area does not significantly increase compared to Q25, but the depths do increase for about 30 cm.

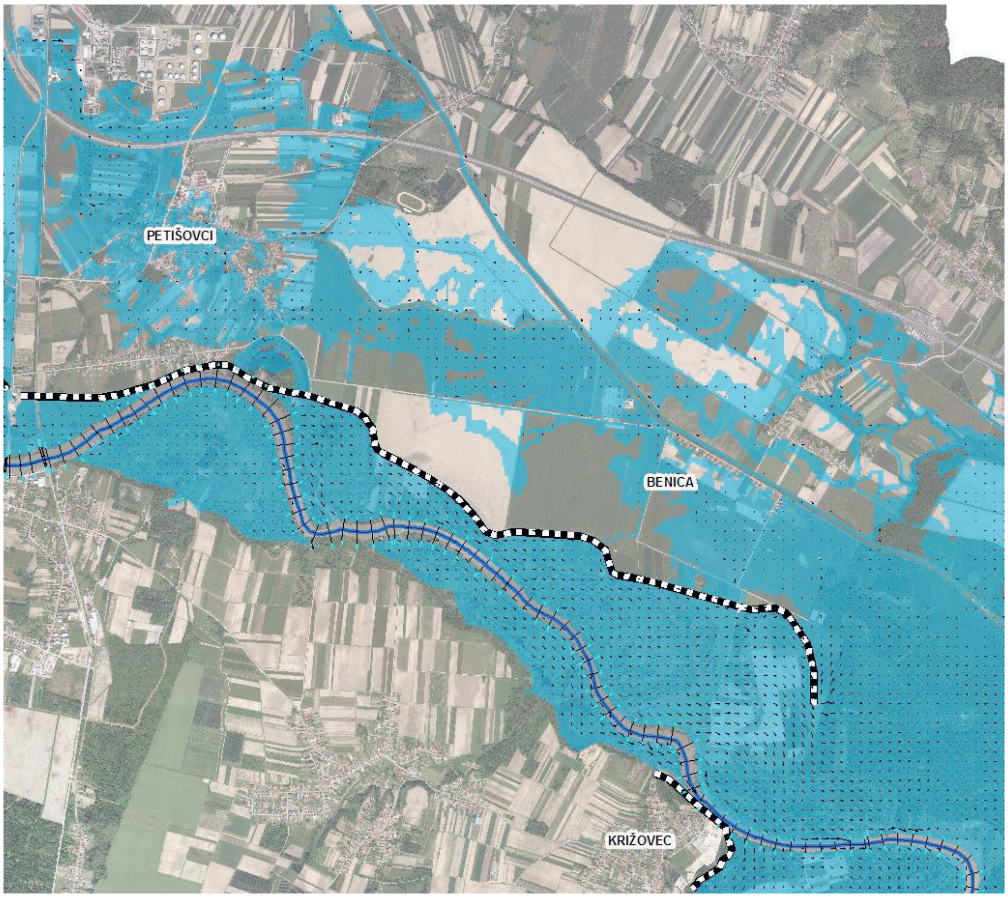
Downstream the right bank, all the way to Mursko Središče, the Mura spills only to the high-water terrace and does not endanger the settlements. The hydraulic model shows the Mura has a water accumulation effect along Gornji Potok up to the bridge over the Hlapičina–Mursko Središče road.

In Mursko Središče, the only area that gets flooded is the one at the newly-built lagoon upstream from the bridge (Trska). The lagoon area up to the flood-control wall is included in the 1D hydraulic model, so the 2D model shows no flooding at this section.

In case of Q500 and Q1000, on the air side of the embankments, a large flatland area reaching Velika Polana and Mala Polana gets flooded, and the flood runs in the direction of the motorway, which, according to the model results. is also overflown and flooded in Lendava.

3.1.5.1.3 The sub-area stretching from Mursko Središče to the end of the model

Downstream of the railway line that crosses the Mura on a bridge at Mursko Središče, there is a flood-control embankment on the left bank, which runs from Kolonija Petišovci to Benica. The hydraulic model shows that the Mura flood waters do not overflow the existing embankment even at a 1000–year return period. A more detailed analysis shows that the hinterland at Petišovci is flood-safe up to the flow rate of Q50. At the end of the flood-control embankment in Benica, the Mura return flow reaches Benica from the direction of Murska šuma and comes to the edge of the settlement as soon as the Q25 is achieved, also flooding the agricultural lands between the high-water embankments of the Ledava and Mura. At the occurrence of Q100, Mura would flood the area of Petišovci with hinterland flood flows that would come from the inundation culverts under the railway. The flood waters would partially flow into Kopica and continue to Ledava, and partially in the direction of Petišovsko polje towards Benica. At the Q100 flow rate or in case of serious floods, the water reaches Benica from two directions, i.e. as a return flow from Murska šuma and from the flood area on the west.



A view showing the Q100 Mura levels at the Petišovci–Benica section and Mursko Središče–Križovec section.

On the right bank downstream from Mursko Središče, the flood reaches the elevated terrain, but the area is unpopulated all the way to the settlement of Križovec. In Križovec, the flood-control embankment protects the settlement from the Mura flood waters up to the 1000–year return period levels. The settlements in the downstream direction (Lončarevo, Podturen, Novakovec and Dekanovec) are protected by the existing flood-control embankments, which, in view of the hydraulic model results, also ensure safety even at the Q1000 flow rate. For this section, the potential collapse or the permeability of embankments has not been considered. The flood safety calculations are based only on the height of the embankments.

3.1.6 ANALYSIS OF FLOOD RISK

3.1.6.1 Introduction

The assessment of flood risk serves as the basis for the optimisation of measures as well as financial and economic analysis. The basis for the definition of flood damages for the FRISCO1 project was the methodology from "The Basis for the Bilateral Methodology of Economic Assessment of Flood Damage on Cross-border Basins, Huizinga Methodology with Parameters for the FRISCO1 Project" (University of Zagreb). This methodology defines a limited set of damage categories, which on average account for

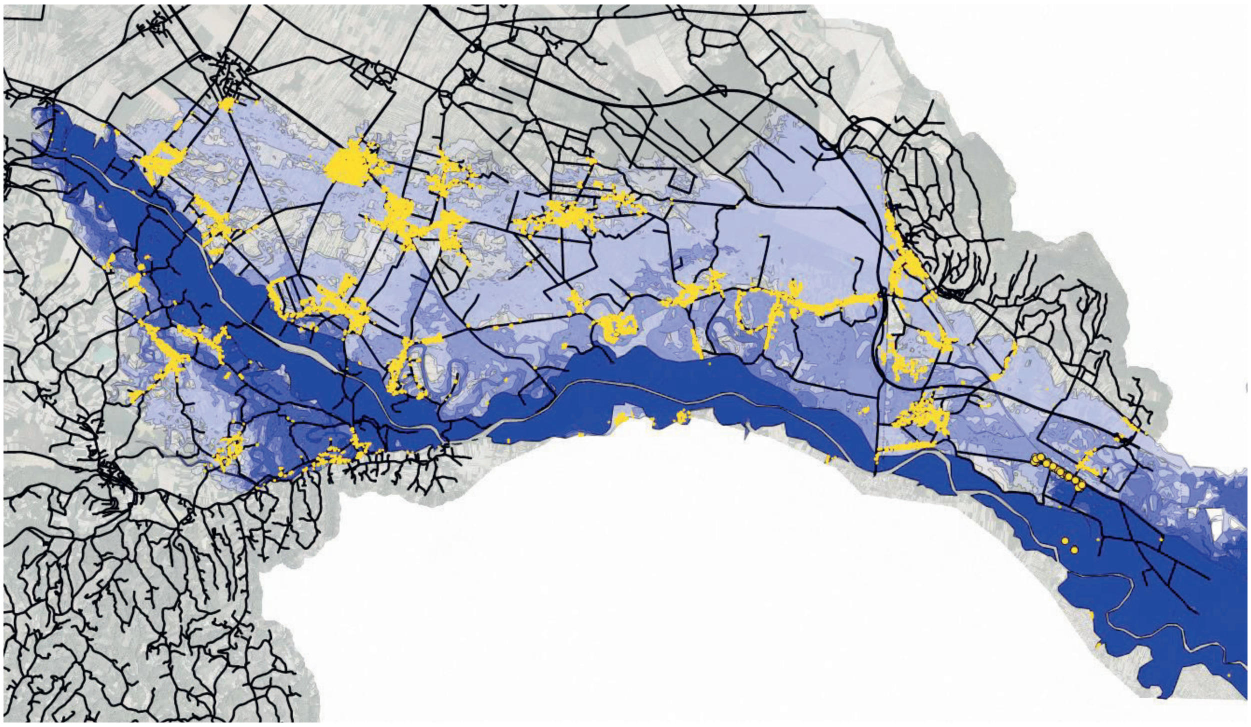
80% of the total damage in all EU countries concerned. The method covers the assessment of damage to (1) residential buildings, (2) commercial buildings, (3) industrial buildings, (4) roads, and (5) agricultural facilities.

3.1.6.2 Definition of parameters for the treated flood area

Number of buildings at risk: 8,252 buildings (both on the Slovenian and Croatian side), of which 8,153 buildings on the Slovenian and 99 buildings on the Croatian side. The method of defining (1) the buildings represents the range of 1000–years waters based on a hydraulic calculation. Buildings are identified based on the building land registry in the Republic of Slovenia (the Slovenian side) and based on an orthophoto identification for the Croatian side. A significantly smaller number of buildings was identified in the Croatian part of Mura, which is due to the fact that most building there are located on the elevated part of the terrain. On the other hand, the Slovenian side features no significant physical height barriers between the flood area and the populated areas.

The length of the threatened important linear public economic infrastructure is defined based on the data obtained from the aggregate land registry of the public infrastructure of the Republic of Slovenia. Here, in accordance to the Huizinga method used for roads, the important linear public economic infrastructure is represented by roads classified as municipal or state roads. Their total length in flood areas is 429.97 km, with the consideration of a 1000-year return period. In terms of roads that are more difficult to define, local roads (in some cases also with the status of dirt roads) stand out with a total length of 351.72 km. All mentioned analysed roads are located on the Slovenian side. The total estimated length of roads exposed to flood events on the Croatian side is approx. 1 km, so these were not specifically considered within the analysis.

Damage to roads is quite difficult to assess in view of the water depth on the roads by taking into account the damage curves (the ratio of depths – damage), because roads often run at different depths, which would have to be evaluated by defining micro-cuts of the separate road sections. For this reason, the medium submerge of the road at the depth of 0.5 meters was assumed for all roads included at a certain depth; this way, the calculation of the flood damages was made for the roads.



The extent of floods (Q1000) with a view of buildings as damage objects (source: Slovenian land registry and own entries for the Republic of Croatia; road view (municipal and state), source: Zbirni kataster gospodarske javne infrastrukture (ZKGJI, the Slovenian public economic infrastructure land registry).

Damage to agricultural land was calculated by using similar criteria as in the case of roads, since, the same as with roads, the resolution of depths on agricultural land poses a special challenge.

Damage category	**Average annual loss (EUR)**	
MAIN ENGINEERING FACILITIES	local roads*	EUR 201,747.65
MAIN ENGINEERING FACILITIES	national roads*	EUR 52,129.35
AGRICULTURE	Agriculture*	EUR 71,809.65
BUILDINGS	buildings (buildings and fixtures)	EUR 1,217,032.90
OTHER	residual damage (20% of the total damage)	EUR 385,679.89
TOTAL:		EUR 1,928,399.44

The expected annual flood damage in the flood area is EUR 1,928,399.44.

3.2 DESIGN AND ANALYSIS OF ALTERNATIVE SOLUTIONS

3.2.1 DESIGN OF ALTERNATIVE SOLUTIONS

Based on the analysis of the current situation and the hydraulic analysis results, a final set of measures for managing flood risks in the project area of the Mura River was prepared. In this regard, the priority areas were identified with the greatest loss potential, i.e. areas where the existing settlements, economic activities, infrastructure etc. are endangered.

3.2.1.1 "No measures" scenario

Within the treated area, the built-in areas and settlements are mostly protected by flood-control embankments. Most settlements have assured a flood protection in case of flood waters with a 10-year return period, and most of the embankments provide flood protection for the Q100 rate or higher. In order to maintain the existing level of flood protection, regular maintenance of the already constructed water infrastructure needs to be secured. In many places, permeability of the embankments, which poses a threat to their stability, has been identified, and in the event of a collapse, the consequences could be catastrophic. The delay in the Mura flood wave in the treated area would allows a timely preparation for the flooding. Flood safety at critical spots of embankments can to some extent be improved by additional protection with the help of anti-flood bags, as has been done in the past. In addition to direct (active) protection against flood waters, flood risk can also be reduced through indirect (passive) measures in the treated section of the Mura River. We often use methods of raising awareness and informing the local communities and residents who live in the flood area. Here, several approaches can be used:

- Raising awareness of floods with informative leaflets/brochures
- Organizing workshops
- Establishing a notification system on the expected Mura river flood waters

Taking proper and timely action in connection to the expected flood waters can significantly reduce the flood damage on property.

3.2.1.2 Measures considered in the past

based on the past flood events and knowledge about the issues, some measures were already foreseen in most critical areas, which were aimed primarily at increasing flood safety by elevating and reconstructing the existing embankments or building new embankments. A set of measures on the left and right bank is presented.

Left bank:

- Reconstruction of the embankment in the section of Gaberje–Mursko Središče–Lendava road
- Reconstruction of the embankment at Benica
- Construction of an embankment between Ledava and a high-water embankment at Mura near Benica

Right bank:

- Reconstruction of the embankment at Sveti Martin na Muri
- Hlapičina embankment
- Arrangement of a culvert under the Križovec embankment

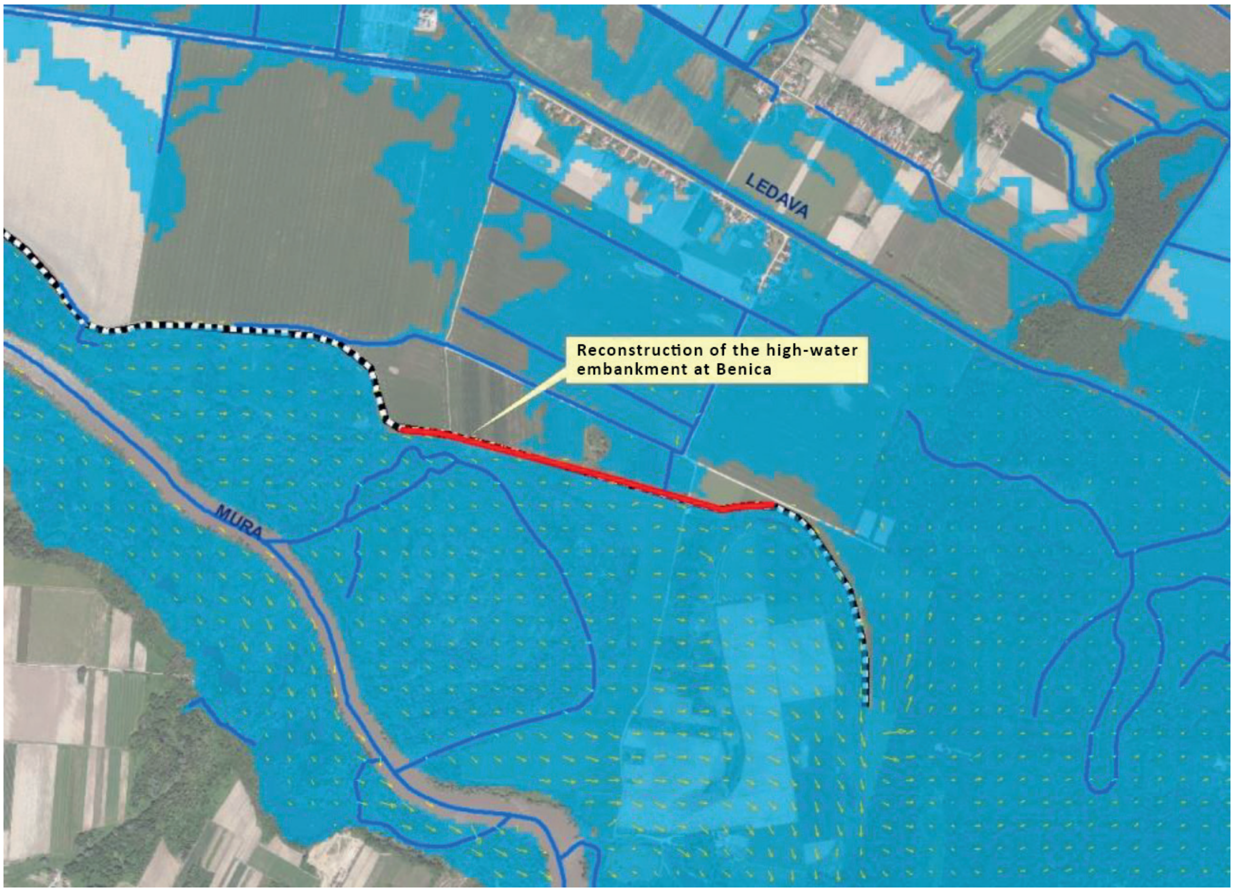
Most of these measures are based on problems identified for the terrain, while in the framework of the Frisco project, the efficiency of some measures was verified by means of the hydraulic model.

3.2.1.2.1 Reconstruction of the embankment in the section of Gaberje–Mursko Središče–Lendava road

The hydraulic analysis showed that, in the event of Q100, Mura would overflow the existing flood-control embankment at the section between Gaberje and the Mursko Središče–Lendava road. The embankment would be overflown at several places in the total length of L≈2.0 km, while the overflow height would move within the 0.2–0.5 m range. In this section, it would be necessary to reconstruct the existing embankment by elevating the crown while taking into account the safety hight at the Q100 level or higher. In order to prevent permeability through the food-control embankment, it would be necessary to increase the impermeability beside its elevation.

3.2.1.2.2 Reconstruction of the embankment at Benica

The hydraulic model results show that the existing flood-control embankment along the entire section downstream of the railway bridge at Mursko Središče ensures flood protection at the event of Mura flood waters reaching up to Q1000. The flooding on the air side of the embankment is the result of the Mura return flow coming from Murska šuma. In the area of Benica, a measure of reconstructing the embankment from 0.7 to 1.66 km is proposed. Based on the results of the model, the embankment would not need to be elevated, but it would be necessary to take measures to prevent permeability and improve the stability of the embankment (ensure impermeability).

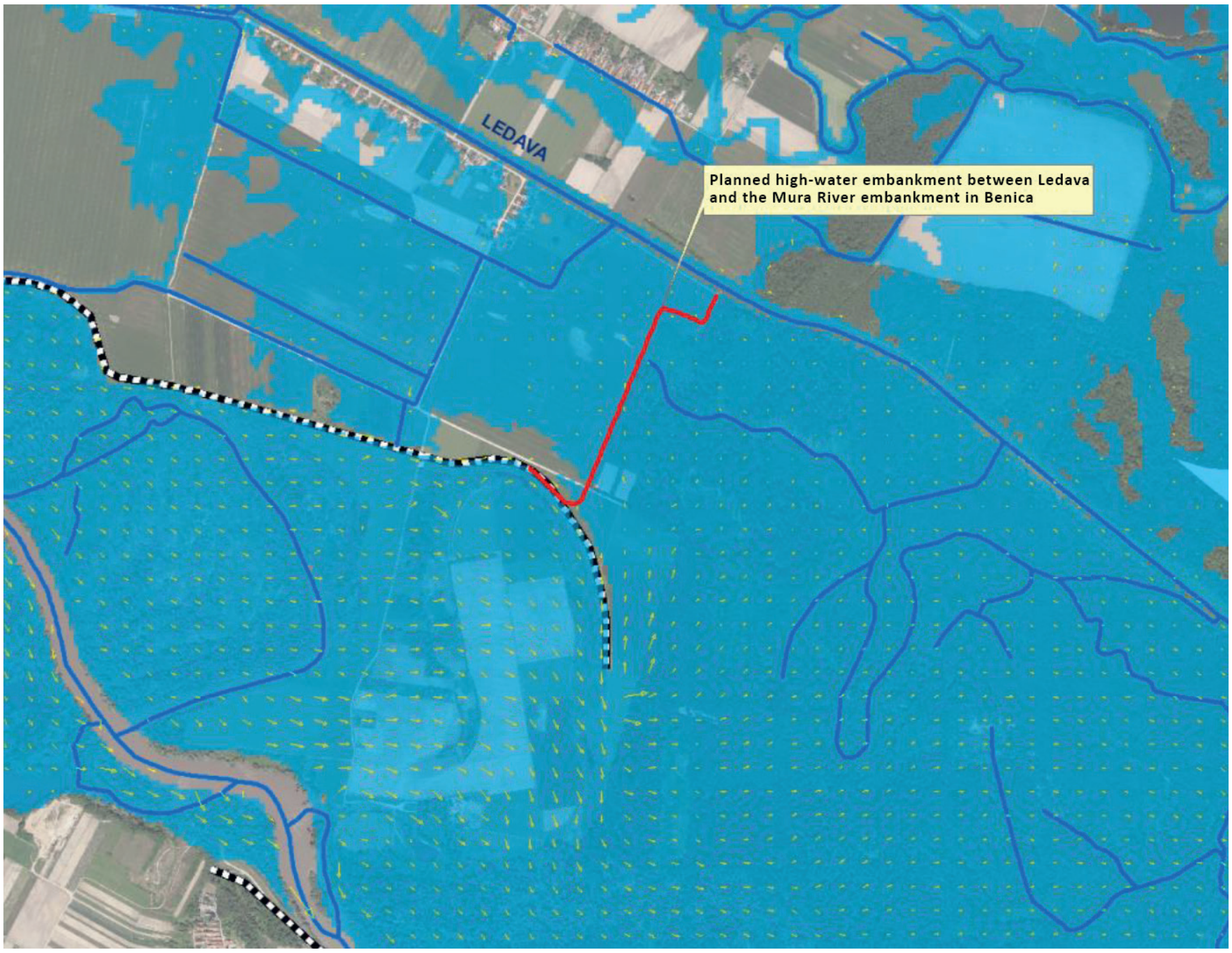


View of the location of the VV embankment in Benica

3.2.1.2.3 Construction of an embankment between Ledava and high-water embankment at Mura near Benica

The existing left-bank Mura flood-control embankment ends around 600 m downstream of the Benica settlement. Upon the occurrence of the Mura flood waters, the return flow comes from Murska šuma along the air side of the embankments and reaches the settlement whilst endangering the there facilities. The return flow reaches the settlement as soon as the 10–year Mura return period rate is reached. The Q100 flood flow also reaches the settlement from the west side. These flood waters flow over the embankments as early as the section upstream from the railway line. Due to the constructed embankments, the water cannot flow back to Mura, so it runs over the agricultural areas and downstream through parallel drainage channels. Due to the overflowing of the upstream embankments and the permeability of the existing Mura embankment in the area of Benica and, consequently, of its potential instability, the threat to the settlement is significantly higher compared to the value shown in the hydraulic model.

In order to protect the settlement of Benica, a transversal embankment between Ledava and the existing Mura embankment at Benica was proposed already in the previous documentation.



A view of the location of the transverse embankment between Ledava and the existing Mura embankment in Benica.

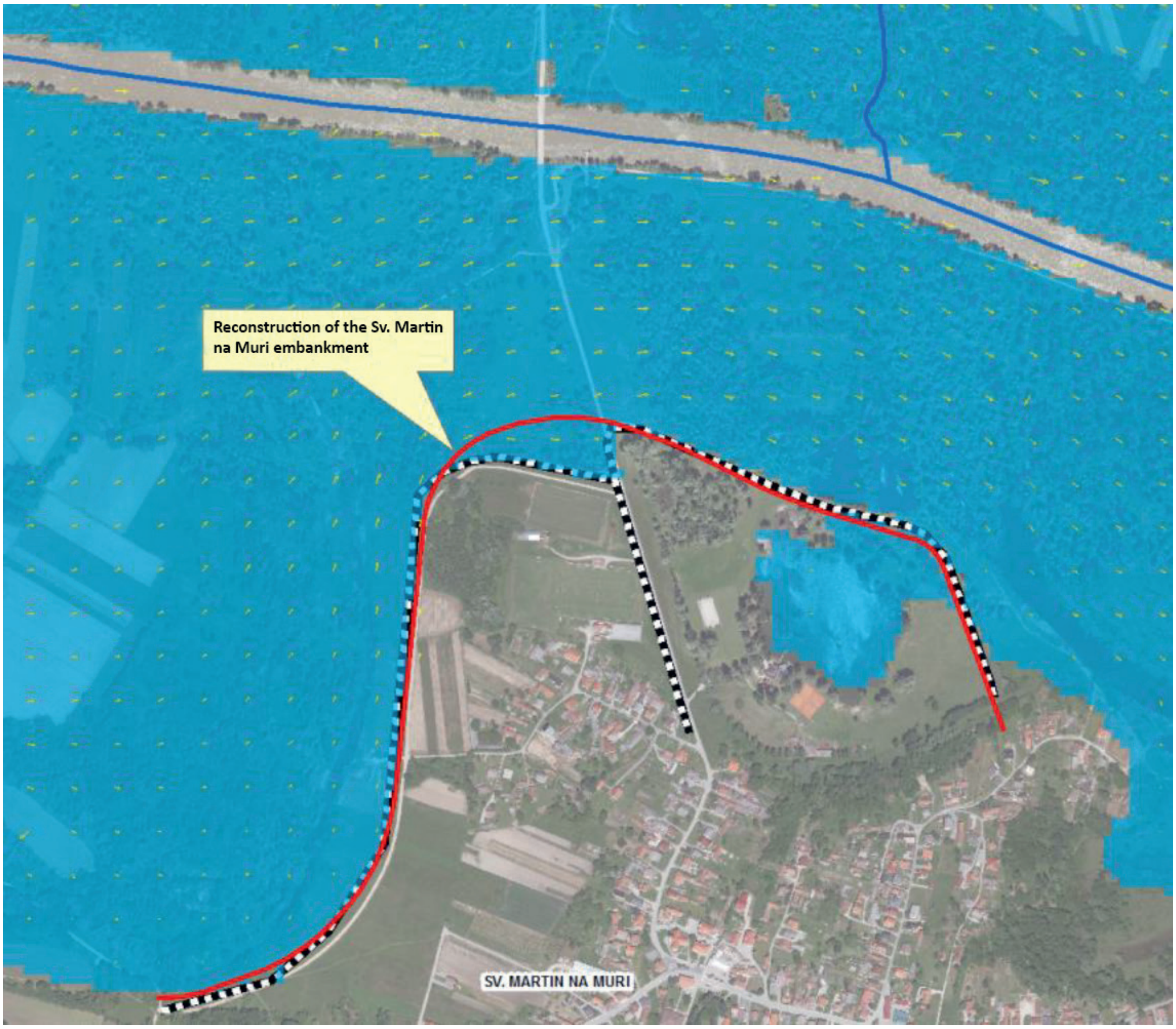
When planning the Benica embankment, it is necessary to take into account the flood water coming from the west side, as the Kopica own waters and the hinterland waters gravitating to this area were not taken into account in the model, nor was the Ledava river, which is also bounded by the flood-control embankments, included in the model. If Lendava overflows its embankments and the flow of flood water from the west side is increased, the outflow of flood waters towards Mura could be prevented by constructing the transverse embankment, which could be even at the expense of demolishing the upstream Mura embankments. The flood waters would be caught between the three embankments, which could additionally aggravate the existing flood protection of the settlement. The probability of this event must be taken into account in the project documentation of the planned embankment.

3.2.1.2.4 Reconstruction of the embankment at Sveti Martin na Muri

For the protection of the settlement of Sveti Martin Martin na Muri, flood-control embankments have been constructed, of which the Goričanec was built as a temporary embankment, albeit with an inadequate height and size. This was confirmed by the calculation of the current situation by using a hydraulic model, which shows that the Mura flood waters could overflow a part of the embankment thus flooding the hinterland.

The upstream reach of the embankment, up to the connection to the long asphalt road with the length of 1,230 m, guarantees flood safety of the settlement against the Mura high waters at the Q100 level, but there is a serious risk of collapsing due to the permeation of the embankment. For this reason, the reconstruction of both embankments is planned.

A hydraulic analysis showed that the Q100 Mura level in the downstream reach of the Goričan embankment reaches the height of the embankment crown, so it can get overflown at some in places. In case of Q500 or Q1000 Mura levels, the Mura river would flow over the upstream flood-control embankment and consequently flood the settlement of Sv. Martin na Muri.



View of the Sv. Martin na Muri embankment’s location

3.2.1.2.5 Hlapičina embankment

A hydraulic analysis of the Mura flood waters showed that the settlement of Hlapičina is not endangered by floods. The results of the model show that the Mura level of Q100 would be 0.25 m below the terrain level.

3.2.1.2.6 Arrangement of a culvert under the Križovec embankment

In the hydraulic model that was provided by the study sponsor, neither culverts nor gates were installed under the embankments, therefore the impact of the return flow through the culverts was not taken into account in the calculations. Based on the calculated level in the channel or along the embankments, we can estimate the level of the Q100 Mura in the event of failure of the gates on culverts below the embankment. Several residential buildings, which are located under the high terrace, as well as the Quadro company facility would be flooded.

3.2.1.3 Additional alternative solutions

Based on the hydraulic model results, additional measures besides the already described ones are proposed to improve the protection against flood risks. Out of the proposed measures, the measure of retention of flood waters in the dedicated upstream reservoirs was recognized as infeasible. The volume of the Mura flood wave at the treated section is too large to allow a significantly lower flood water flow rate with a viable reservoir according to the available space. The remaining alternative measures are as follows:

- To increase the Mura flow rate profile in the area of the gravel pits, 2.2 km above the Petišovci border crossing point
- To improve the flow rate of inundation culverts (Petišovci border crossing point) near Benica, 3.3 km downstream of the Petišovci border crossing point
- To increase the flow capacity of the inundation profile by reducing the flow rate profile vegetation

In addition to the aforementioned measures and those that were already dealt with in the past, the hydraulic analysis showed that further measures would be necessary to reduce the flood risks on the left bank between Gornja Bistrica and Hotiza. At some places, the Mura flood waters overflow the flood-control embankment or the elevated terrain, flooding the existing settlements in the hinterland.

In order to ensure the flood protection of settlements from Gornja Bistrica to Hotiza, it would be necessary to reconstruct the left-bank flood-control embankment by building a new embankment in the section between Dolnja Bistrica and Hotiza. In the figure below, the red line shows those sections of the embankment, where the Mura level at Q100 overflows the existing left-bank embankment or the elevated terrain.

3.2.1.4 Selected solutions

Based on a provided review of alternative solutions to improve flood safety, the following two measures seem to be the most appropriate:

- Construction of a connecting embankment between the Benica embankment and Ledava
- Reconstruction of the Sveti Martin embankment

The settlement of Benica is the only settlement on the left bank within the treated section, which is exposed the Mura flood waters as soon as the flow rates of a lower return period (Q10) are reached. The

Mura return flow, which comes from Murska šuma, floods the air side between the Ledava embankment and the Mura embankment. When planning the embankment, it would be essential to take into account the probability of the inflow in flood and hinterland waters from the west side.

The selection of the most appropriate measures also includes the embankment at Sv. Martin na Muri. During the last wave of Mura flood waters, significant permeability was detected in the upstream part of the embankment, which puts its stability at risk, while the downstream section was built in the framework of intervention works, which means it does not meet the standards in terms of embankment height and size. For both projects, the project documentation has already been prepared:

- Visokovodni nasip Benica (Flood-control embankment Benica, PGD, D-15/2018, January 2018 (ASPA-ING, projektiranje d.o.o.)
- Rekonstrukcija nasipa v Svetem Martinu na Muri (Reconstruction of the Sveti Martin na Muri embankment), idejni projekt (conceptual project), I-1654/16, March 2016 (Hidroing, d.o.o.)

3.2.2 ANALYSIS OF ALTERNATIVE SOLUTIONS

The effectiveness of the selected measures and their impact on the water regime were tested by using the hydraulic model developed in the framework of the Frisco 1 project (the model was made by the Institute for Hydraulic Research).

For the sake of clarity, the measures are divided into several sets:

A – Measures that have been dealt with in the past

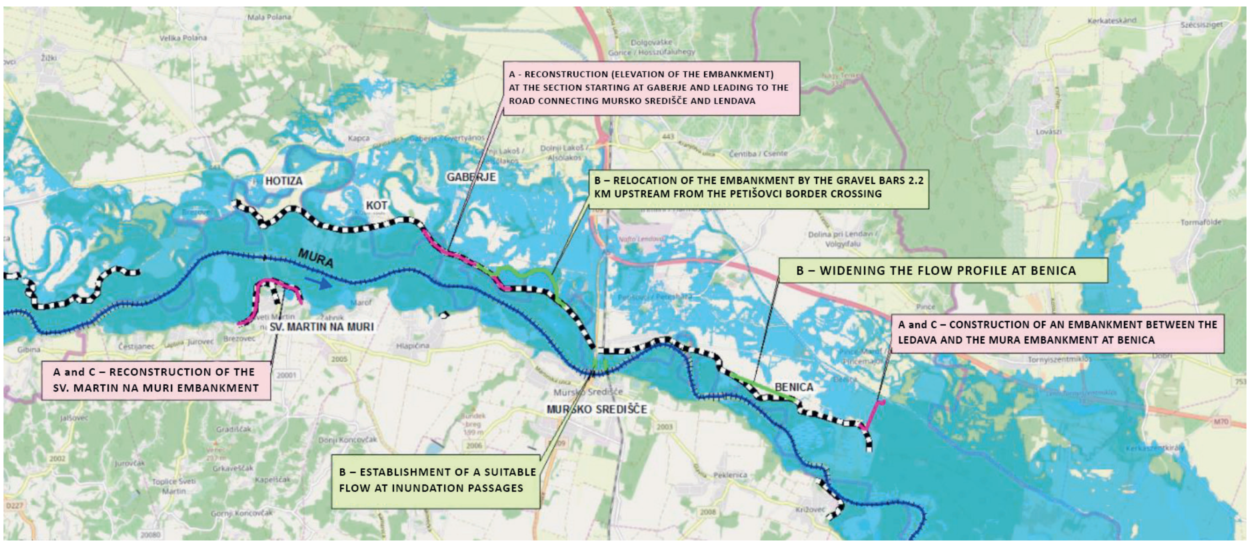
B – Alternative measures stemming from newly arisen conditions and knowledge (green measures)

C – Selected (most appropriate) measures

According to the results of the hydraulic analysis, the economic efficiency of the measures was assessed, and their cross-border impact, the costs of implementation and maintenance, etc. were evaluated. The analysis of the selected alternative solutions is based on the results of hydraulic modelling. The flooding of the area, as described and as taken into account in all elements of the study, is presented based on the hydraulic model results developed under the FRISCO1 project (the model was made by the Institute for Hydraulic Research).

The model was used for hydraulic testing only in those measures, for which the analysis of the current situation showed that they were necessary or the testing was justified. The evaluation of the hydraulic effects of individual measures or the cumulative impact of the measures was made for 3 selected characteristic flow rates (Q50, Q100 and Q1000).

MEASURE	Q50	Q100	Q1000
A. MEASURES PROPOSED IN THE PAST			
Reconstruction of the embankment at the section between Gaberje and the Mursko Središče–Lendava road			
Construction of an embankment between Ledava and a high-water embankment at Mura near Benica			
Reconstruction of the embankment at Sveti Martin na Muri			
Cumulative impact of the A measures	X	X	X
B. ALTERNATIVE MEASURES			
To increase the flow rate profile in the following areas:	X	X	X
- the gravel pit area approximately 2.2 km above the Petišovci border crossing point,			
- the area of the Petišovci border crossing point (the inundation culverts),			
- the area of Benica approx. 3.3 km downstream of the Petišovci border crossing point.			
To reduce the flow rate profile vegetation	X	X	X
Cumulative impact of the B measures	X	X	X
C ANALYSIS OF THE SELECTED (MOST APPROPRIATE) MEASURES – CUMULATIVE IMPACT			
Construction of an embankment between Ledava and a high-water embankment at Mura near Benica			
Reconstruction of the embankment at Sveti Martin na Muri			
Cumulative impact of the C measures	X	X	X



The locations of the Group A, B and C measures. The Group C measures overlap the Group A measures.

3.2.2.1 The hydraulic analysis of the planned measures

The results of the hydraulic simulations are presented for each set of measures, i.e. for the Group A, B and C measures. The impact analysis of the planned measures for Group A, B and C was made primarily for the flow rates of Q100 and Q1000.

3.2.2.1.1 A – Measures proposed in the past

Based on previous experience acquired from the Mura floods in 2005 and 2014, three measures were proposed to ensure the protection of settlements from the Mura flood waters. These include:

- Reconstruction of the embankment in the section of Gaberje–Mursko Središče–Lendava regional road

- Construction of an embankment between Ledava and a high-water embankment at Mura near Benica
- Reconstruction of the embankment at Sveti Martin na Muri

All three measures were included in the existing Mura hydraulic model, taking into account a 1 m elevation of the embankment crown above the Q100 level. The **cumulative impact of the A measures** was analysed on the Mura water and flood regime by using the model.

The embankment in Sv. Martin na Muri is problematic due to permeability and therefore also the endangered stability of the embankment, while the eastern branch of the embankment is too low, which means that the Q100 flood water level would overflow it. After the reconstruction, the embankment would be fully permeability-resistant, and the level of the embankment crown is planned with a safety height above the Q100 level for the entire section. The hydraulic model results show that the settlement of Sv. Martin is fully protected against flood in case of the Q100 Mura flood waters. The level of Q1000 will also be within the safety height.

On the left bank, the Mura floods the flood-control embankments in several parts, and also floods the high terrace, where the embankments are not built. Due to the overflowing of the flood-control embankment near Gaberje, several facilities in the settlement are endangered; besides, the flood water flows out in the form of hinterland flows through the inundation culverts in the direction of Petišovci and further towards Benica. Due to its permeability and overflowing, the embankment's stability is endangered; in case of a potential collapse of the embankment, the flood damage would be significantly higher than the one demonstrated by the flood simulation results in the current situation. For this reason, a reconstruction of the flood-control embankment in the section between the Gaberje settlement and the Mursko Središče–Lendava road was envisaged.

The hydraulic model results show that the reconstruction of the embankment near Gaberje would significantly improve flood safety and reduce risks at the section downstream of the Mursko Središče–Lendava road, but the Gaberje settlement would still be partially exposed to flood risks due to the Mura flood flows coming through the hinterland from the upstream direction as the result of overflowing the embankments and the elevated terrace upstream of Hotiza. The hinterland flood flow would also partially reach the air side of the reconstructed embankment.

By the reconstruction of embankments, the overflowing at the section of Gaberje–regional road (Lendava–Mursko Središče) will be prevented and the flood flow will be limited to the corridor between the flood-control embankments. A higher flow rate between flood-control embankments would lead to a rise in water level compared to the current situation, even downstream of the site of planned interventions. At the Q100 rate, the rise of water level within the range of approx. 10 cm would extend up to the edge of the Petišovci settlement, while in Benica the impact would be within the range of 5–6 cm.

In analysing the effect the transverse embankment at Benica would have on the Mura water and flood regime, it should be taken into account that the cumulative impact of all A measures was analysed. A transverse flood-control embankment between Ledava and Mura will prevent the Mura return flood flow towards the settlement of Benica. The results of the model indicate that the Mura level along the embankment would increase by a maximum of 13 cm, while 1 km downstream the impact would be less than 5 cm. The scale of the elevation in the Benica area is the result of a cumulative effect of all analysed A measures.

The simulation using the mathematical model showed a greater influence on the current water level downstream of Benica as well, as Mura would flood the hinterland through Ledava (local rise of the water levels >40 cm). The Ledava stream flow is not included in the hydraulic model since it is located outside of the Frisco target area, which means the results for this area are not within the validity limit. Nevertheless, the results of the model draw attention to a change in the Mura flood regime in this section as well. In order to effectively assess the downstream and cross-border cumulative impacts of the A measures on the Mura flood regime, the model will need to be upgraded in the next stages of the design and expanded to include Ledava and other tributaries which could be affected by the measures.

On the Mura right bank, the flood area is currently bounded by a flood-control embankment or a natural elevated terrace, which means the planned measures would not significantly change neither the water level nor the size of the Q100 flood area related to the right bank. Within the current situation, the flooded surface at the flow rate of Q100 in the entire area of the model totals 105 km^2. After the implementation of the A measures, the surface, especially with the reconstruction of the Gaberje embankment on the Mura left bank, gets reduced to 95 km^2. On the right bank part within the Frisco area, the surface at the Q100 Mura flow rate in the current situation totals 12.7 km^2; after the implementation of the A measures, the surface would be reduced by 3.9 hectares, which equals the extent of the flood area elimination at the Sv. Martin embankment. This proves that, on the right bank within the Frisco area, after the implementation of the A measures, the extent of the Q100 flood will not significantly increase.

A comparison of the results for the Q1000 Mura flow rate showed a significantly lower water level on the air side of the embankments on the Mura left bank. The planned measures would also provide flood protection against the Q1000 flood waters, however, while the area from Gaberje to Benica would remain flooded at the Q1000 rate due to the embankments upstream and downstream of the planned reconstruction of the Gaberje embankment being flooded. On the right bank, the reconstruction of the Sv. Martin embankment would protect the settlement from the Q1000 Mura flood waters, together with the other existing right-bank embankments along the analysed Mura section. Due to the increased flow rate within the flood-control embankments, the water level at Q1000 would rise the most in the reconstructed part of the Gaberje embankment, namely by 30–40 cm. Due to the elevated terrace on the right bank, the rise in water level increases neither the existing flood risks nor the extent of the Q1000 flood area. The impact of Q1000 at the Sv. Martin na Muri section is less than 10 cm and disappears after about 3.5 km upstream along the river channel. Even downstream of Mursko Središče, the influence on the water level is decreasing and in Benica it totals only about 10 cm. The results of the model calculations show that the negative impact would disappear downstream of the Podturen settlement.

In the current situation, the flooded surface at the Q1000 flow rate in the entire area of the model totals 195 km^2. After the implementation of the A measures, the surface size would not change significantly, as most of the area would remain flooded due to the overflowing of the existing embankments in those parts that would not be subject to reconstruction. After the implementation of the A measures, the size of the flood area would total in 190 km^2. On the right bank within the Frisco area, the surface of the Q1000 Mura flood in the current situation totals 13.07 km^2, and after the implementation of the A measures, the size would be reduced to 12.8 km^2. The surface of the flooded area at the Q100 and Q1000 flow rates on the right bank will remain almost the same after the implementation of measures. This is expected as the flood area at Q100 and Q1000 on the right bank is bounded by an elevated terrace and existing embankments.

3.2.2.1.2 B – Alternative measures

For analysing the alternative measures, a separate calculation simulation of the effect of the implementation of measures for increasing the flow rate profile at three locations was elaborated, as well as the analysis of impact in reducing the vegetation at the inundation cross section. An analysis of the cumulative impact of alternative measures was also performed.

<u>Hydraulic analysis of the flow-rate profile increase</u>

The existing inundation area between the Mura flood-control embankments is sometimes reduced to as little as 100–300 m. After considering the spatial features, two locations were identified, where the embankment could be moved to the hinterland, which could improve the drainage conditions within the inundation embankments, and consequently mitigate flood risks and threats in the wider area. The improved flow characteristics could also be achieved by restoring an unhindered flow through the inundation culverts at the Petišovci border crossing point. In the hydraulic model, improving the flow conditions at the inundation culverts was taken into account by using a more favourable roughness coefficient, whereby the coefficient was decreased from the existing value of ng = 0.25 to ng = 0.1. The hydraulic model tests the cumulative impact of arrangements at all three locations, while other measures were not taken into account in the model.

The hydraulic model results for the Q100 flow rate indicate that a cross-section flow rate increase at the gravel pits would have a positive effect on the Mura water level upstream, all the way to Hotiza. The greatest decrease in water level would occur at the spot where the inundation is currently at the lowest point, because the narrowing of the flow rate profile between the flood-control embankments would cause an obstruction in the outflow of flood waters. By moving the left-bank flood-control embankments to the air side of the existing gravel pits, the flow rate cross section between the flood-control embankments would increase, and consequently the water levels would decrease by a maximum of 0.5 m. Despite the water level decrease, the Q100 Mura flood water would overflow the embankment at the Gaberje section, but since the overflowing would be considerably lower than in the current situation, the measure would have a positive effect on the reduction of flood hazard and risks on the air side of the embankment at the settlements of Gaberje and Petišovci (the demolition of embankments was not counted in). On the right bank at the Sv. Martin na Muri settlement, the water level would decrease by a maximum of 3 cm, which would suffice for the eastern branch of the embankment to not get overflown. However, the aforementioned measures would not eliminate the current permeability of embankments and the risk of collapse.

The increased flow rate cross section at the gravel pits would result in the flow rate increase downstream, i.e. the total flow rate between the flood-control embankments (1D + 2D) downstream would increase by approx. 50 m^3/s, which would be reflected in a locally increased water level.

The more favourable roughness coefficient in the Petišovci border crossing area would improve the flow rate of the inundation culvert, which would increase from the existing 85 m^3/s to 170 m^3/s. As a result, the water level between the flood-control embankments downstream of the Petišovci border crossing point would increase by a maximum of 10 cm compared to the current situation.

The mathematical model also takes into account the expansion of flood area between Petišovci and Benica, where the existing left-bank embankment is moved towards the channel to the distance of only 130 m. The expansion of the floodplain and relocation of the left-bank embankment to the distance of 350 m from the channel is taken into account. The results of the simulation show that the water level upstream would decrease by a maximum of 30 cm, and the impact would go as fas as approximately 2.8 km upstream.

Due to the increased flow rate within the flood-control embankments, the envisaged measures would lead to a rise of water level downstream, with the Q100 water level in Benica increasing by 5 cm. The measures would also have a cross-border impact, as the Q100 water level would increase in the range of up to 5 cm.

<u>Hydraulic analysis of the reduction in the cross-section profile vegetation</u>

The Mura inundation profile is heavily vegetated in between the flood-control embankments. The heavy vegetation increases the roughness of the flood area, which on the one hand contributes to greater retention or slower outflow of flood waters, and on the other hand, to the raising of water level in the flood area. The flood-control embankments protecting the predominant part of the left-bank and partially also the right-bank settlements were planned for the state of vegetation during the planning and construction of the embankments. In the event of a significant increase in the vegetation of the inundation profile, the primary function of embankments may be jeopardized and, at the time of overflows, also their stability.

In the calculation scenario of decreased vegetation in the flow rate profile in between the flood-control embankments, the reduction of vegetation was taken into account by using a more favourable roughness coefficient for the entire calculation-related Mura section (50 km). The analysis takes into account the 150 m wide corridor of reduced roughness coefficient on the left bank, with the reduction from ng = 0.15-0.25 to a uniform value of ng = 0.08.

The results of the model show that by reducing the vegetation of the inundation profile, flood hazard and risks would be substantially reduced in almost the entire modelled area of the Mura river. The flood-control embankments would still be overflown at places, but the extent of floods in the hinterland would be significantly lower than in the current situation. The level within the flood-control embankments would decrease in the Frisco target area by a maximum of 10 cm. On the right bank along the existing embankment at Sv. Martin na Muri, the water level would decrease by a maximum of 6 cm, while in the area of the settlement of Benica it would decrease by 2 cm. The more favourable hydraulic conditions for the outflow of flood waters would consequently cause a flow rate increase in the area in between the flood-control embankments. The cross-border impact of water level rise would be within the 7 cm range.

<u>The cumulative impact of alternative measures (group B measures)</u>

The cumulative impact of the proposed alternative measures was also hydraulically tested. The model takes into account the measures to increase the inundation profile flow rate by increasing the inundation area within the flood-control embankments, as well as the measure of reducing the inundation profile vegetation.

The results of analysis in the comparison of water levels after the implementation of the measures compared to the current situation show that the water level in the greater part of the Frisco target area would decrease. The largest water level decrease within the flood-control embankments would occur directly above the gravel pits at Gaberje, where the level at the Q100 rate would decrease by up to 50 cm. The water level would in increase locally on the left bank in the area of the inundation extension (at gravel pits upstream of Benica), and downstream from Benica. The increase of the water level is caused by a more concentrated flow rate between the flood-control embankments, which increases from 1545 to 1615 m^3/s in the area of Benica. The water level increases locally by a maximum of 7 cm, and on the large part by less than 4 cm. Because of the more favourable roughness coefficient on the entire model section, the effect is cumulative.

Taking into account the B measures, the flood area does not significantly change on the right bank compared to the current situation. Taking into account the cumulative effect of the B measures, the total flood surface in the model area would be decreased by approximately 16 km^2. On the right bank, within the Frisco area boundaries, the Q100 Mura flood area would decrease from 12.7 km^2 to 12.6 km^2. Due to the geometry of the terrain, the measures do not have extensive influence on the right bank.

Also at Q1000, the difference in the water levels on the air side of the left-bank embankments shows a significant water level decrease and improved flood safety as well as reduced risks. Despite the fact that the water level on the air side of the embankments decreases along the entire analysed section, locally by more than 40 cm, the left bank area remains flooded almost to the same extent as in the current situation at Q1000. Due to the less extensive overflowing of embankments, the level increases within the flood-control embankments, at the section downstream of Gaberje. The water level would increase the most (up to 2 m) at cross sections of the increased flow rate (at Gaberje and the section between Petišovci and Benica), since these areas are currently located outside the embankments. Everywhere else the effect would be smaller, within the range of up to 25 cm. The influence of high water levels would end downstream of Podturen.

3.2.2.1.3 C – Analysis of the selected measures

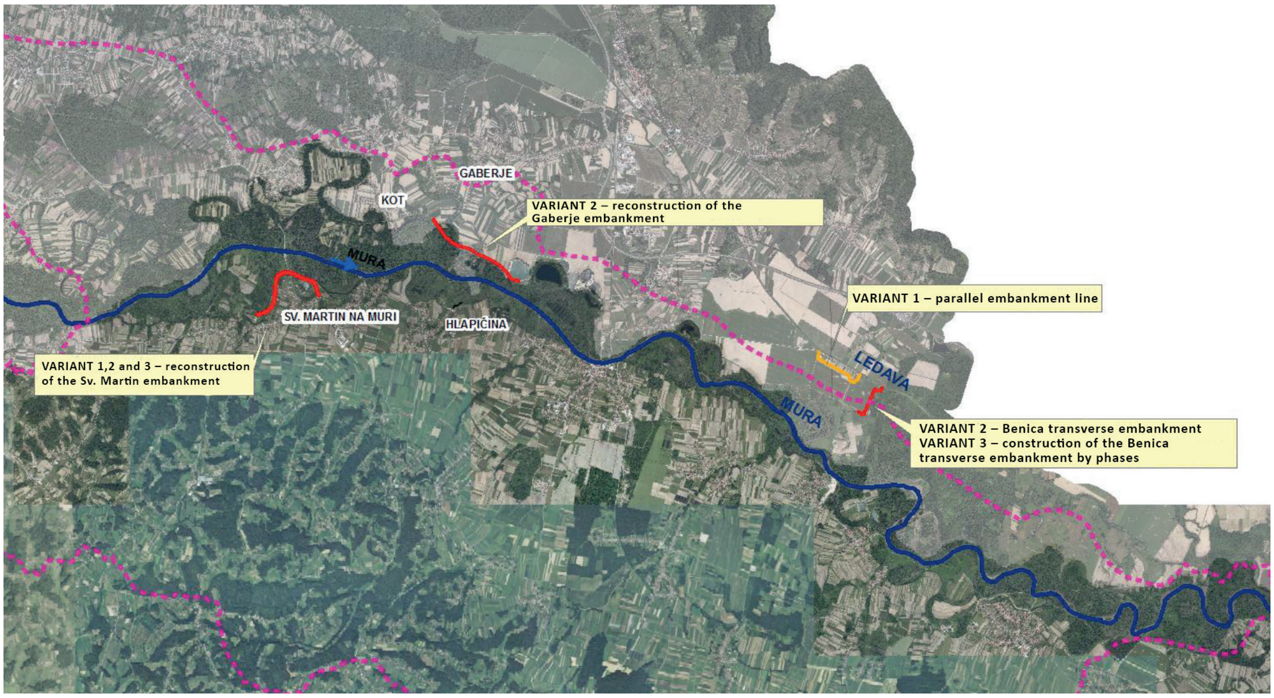
The impact of the reconstruction of flood-control embankment at Sv. Martin na Muri and the construction of a new embankment at Benica was also tested by a hydraulic model. Other measures have not been taken into account in the model.

Based on the model analysis of the current situation in view of the flood hazard and risks at the Q100 flow rate, it was found that the Benica area is exposed to the Mura return flood flow, as well as to flood waters that flow over the embankments upstream near Gaberje. The flood waters run through inundation culverts below the road and the railway line, first in the direction of Petišovci and then over agricultural land and gullies downstream towards Benica and further to Murska šuma. In case the embankments get overflown, their partial or full collapse would occur at the section of the overflowing, and consequently a substantially larger amount of flow rate would flow into the hinterland than demonstrated by the model, which considers only the overflowing of embankments. The flood water flow from the upstream section to Benica could increase to more than 100 m^3/s. In this case, the transverse embankment at Benica would obstruct the outflow of flood water and at the same time, further aggravate the current flood risk of the area.

Based on findings derived from the hydraulic model results, a modification of the measure to protect the settlement of Benica is proposed with the following 3 variants.

- VARIANT 1: Change of the embankment route. The settlement of Benica could be protected from the Q100 floods with a longitudinal embankment along the settlement. The embankment would be connected to the existing flood-control Ledava embankment at both the upstream and downstream ends.
- VARIANT 2: A reconstruction of the Gaberje flood-control embankment, which would adjust it to the Q100 flood waters, is included in the set of measures. The reconstruction of embankment would prevent it from getting overflown and collapsing at Gaberje, and would consequently also prevent the flow of the flood waters along the hinterland streams all the way to Benica.
- VARIANT 3: The proposed Benica embankment is planned in phases, whereby in the first phase is planned to the height of 156 m above sea level, which is the calculation Mura water level of

between Q25 and Q50. After the reconstruction of flood-control embankments at Gaberje, the Benica embankment could be raised to the design level of Q100 + safety height.



View of the location in proposed implementing measures

Based on the Frisco1 and Frisco2 project activities that have already been performed as well as parallel activities in designing the flood prevention measures, a variant 3 of the implementation of flood prevention measures in Benica was proposed.

According to variant 3, a phase design of the height of the flood-control embankment is proposed. The phase approach is conditioned by the reconstruction of the upstream embankment at Gaberje, which gets overflown in case of Mura flood waters >Q50. During the overflowing or possible collapse of the flood-control embankment at the Gaberje settlement, the flood flows would reach the Benica area as well, where the water would get accumulated within the three embankments (Ledava, Mura and Benica). According to variant 3, a phase construction of the embankment is proposed in order to avoid the increase of flood risks near Benica. The height achieved during the first phase is determined based on the height of the lowest lying residential buildings in Benica, which are located at approx. 156.05 m above sea level. The geodetic height of ground floors of those buildings has not been recorded within the project, therefore the height level of the lowest lying objects has been taken from the Lidar data. Due to the unreliability of the Lidar image, we propose that a picture of ground floors in the objects is made during the design phase and phase construction is defined based on the actual height of the embankment.

The elevation level of the first phase of embankment construction is approximately 0.1 m below the calculated level of the Q100 Mura return flow at Benica, whereby the calculation accuracy of ±20 cm also needs to be taken into account. The second phase of the embankment construction up to the Q100 design level + safety height can be carried out once the upstream Gaberje flood-control embankment is reconstructed.

The hydraulic analysis results for variant 3 show that the impact of the planned measures in Sv. Martin na Muri and Benica do not have a cumulative effect.

The comparison of levels in the planned and current situation shows that the impact of the planned reconstruction of the embankment at Sv. Martin is of local nature, which mean, the water level gets increased for a maximum of 6 cm immediately at the embankment, where its route is moved closer to the channel. The impact decreases radially and after 200 m from the embankment, the difference in the water level is less than 2 cm. The impact disappears about 1.8 km upstream, while downstream of the bridge over the Mura, there is no significant raise in the water levels.

The hydraulic model also took into account the impact the new Benica flood-control embankment would have on the flood regime. The model considered the embankment phase height of 156 m above sea level. The model calculation also took into account the overflowing of embankments in the Gaberje area, while the collapse of embankments was not considered, which means the results do not show the boundary impact scenario.

The hydraulic flow analysis of Mura Q100 flow rate showed that the Mura return flow would overflow the proposed flood-control embankment at Benica and floods would occur to a similar extent as in the current situation. Once the levels on the Mura water side would fall, the overflow water would drain through the culverts below the embankment in the direction of Mura.

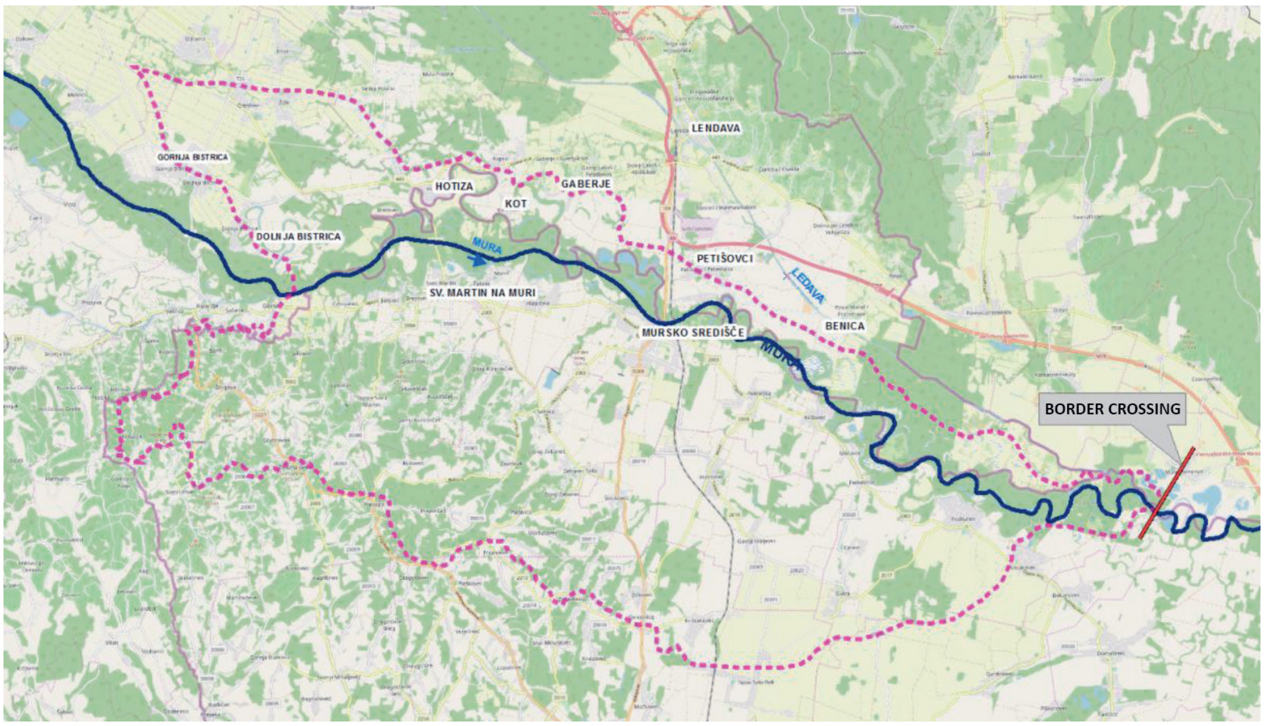
The Q100 water level comparison results show that the impact on the current flood regime would be minimal. In the selected calculation scenario, the water levels get increased on the air side of the embankment for a maximum of 1 cm.

The hydraulic analysis of the impact at the Mura Q100 flood water levels showed that the implementation of the planned measure in Benica does not have a significant impact on the levels. A comparison of the levels shows a decrease in the level on the Ledava left bank, but the model is unreliable for this section. Since the Ledava was not included in the calculation simulation, this area falls beyond the validity of the model and outside the Frisco target area.

The existing concept of ensuring flood safety along the treated Mura section is based on the protection of settlements by flood-control embankments up to the level of Q100 with a 1 m safety height. In some places, the existing embankments do not meet this criterion, and get partly overflown at Q100. For these parts, a reconstruction of embankments to the adequate design height is foreseen in the short term. Upon completion of the ultimate goal of flood protection arrangement, i.e. flood protection of the existing settlements on the air side of the embankments, the Mura flood waters will be concentrated within the corridor between the flood-control embankments. For this reason, the Q100 water level condition should be taken into account in the flood protection projects, which will be established at the final flood protection regulation arrangement in the wider treated area. For determining the Q100 project water levels along the embankment of Sv. Martin na Muri as well as water levels after the construction of the Benica embankment, an additional simulation of water level testing was made for the scenario of elevating all embankments above the Q100 level. The results show that the Q100 calculation water level along the embankment of Sv. Martin na Muri rests at 165.6 m in the eastern part and 167 m above sea level in the western part of the embankment. The Q100 water level for the design of the final embankment at Benica ranges between 156.15 m and 156.4 m above sea level. When planning both embankments, a 1 m safety height above the Q100 water level must be considered.

3.2.2.2 Cross-border impact analysis

For all analysed scenarios of the cumulative impact, the cross-border impact of the planned measures was also tested. For the analysis, a cross section at the end of the model section, i.e. at the downstream edge of the Frisco area, has been selected.



A view of the location of the selected cross section at the end of the model section, i.e. at the downstream edge of the area.

Comparison of hydrograms for the Q1000 flow shows a change in the hydrogram shape for the A and B measures, which is caused by a more concentrated flow between the flood-control embankments. In the current situation, a large share of the flow spills over the flood-control embankments if compared to calculations of the A and B measures. The flow is slower along the air side of the embankment and faster when taking a longer route to finally reach the edge cross section, so the wave (flow rate) in the current situation initially increases at a slower pace than in case of the A and B measures scenario, where greater flow rate is concentrated within the flood-control embankments. Despite the results indicating that the peak of the wave in the current situation would be somewhat higher than for the A and B measures, the results should be taken with reservation. The Q1000 flood, which flows along the air side of the embankment, is largely outside of the hydraulic model validity, which means that the flood flow is not modelled with the same accuracy as within the flood-control embankments. For a more detailed analysis of flood water waves in the border cross section, the existing model needs to be upgraded to the extent where the results on the air side of the embankments will be reliable. Given that the C measures do not significantly affect the flow regime, the planned curve matches the curve in the current situation, as expected.

3.3 SELECTION OF THE MOST SUITABLE SOLUTION

3.3.1 DEFINITION OF THE SET OF MEASURES

All of the analysed variants of the proposed measures have their advantages and disadvantages. In the light of the latest guidelines for water management and flood risk management, finding a solution in green infrastructure is certainly one of the primary ways of managing flood risks. Through hydraulic analysis, alternative measures have proven to be the most effective in reducing flood risks and threats in the entire Frisco target area. According to the impact, a measure of reducing the vegetation of the inundation area by maintaining the corridor with a "hydraulically favourable" vegetation is particularly noticeable. In fact, this measure at least partially establishes the original state of the vegetation as it was present during the construction of the embankments. The intensity of vegetation growth in the inundation area increases the retention effect, and as a result, the water levels are increased, although the current flood-control embankments were not originally designed for such a situation. Without significant measures implemented to reduce vegetation, the water levels will continue to increase in the future, and if we add the impact of climate change, a constant elevation of the already relatively high embankments will be necessary to implement in the long run. In the river-bordering area along the channel heavy forest and bush vegetation developed on the entire analysed section over the years. The cost of reducing the vegetation that has reached this extent would be extremely high, and the cost of regular annual maintenance would also not be negligible. Despite the high costs, however, in terms of ensuring sustainability of the existing measures, it would be necessary to consider such long-term measures to reduce the flood risks.

By implementing the green infrastructure measures, the current flood risks and threats would be improved, but while this would not guarantee a full-proof flood safety, the maintenance of present infrastructure also cannot be avoided. Likewise, the results of analysis show that in case of an optimistic scenario connected to the reduced vegetation, the settlement of Benica would still remain exposed to the flood risks. Furthermore, the issue of permeability in the current embankments (Sv. Martin na Muri, Benica) would remain unresolved.

From the comparison of hydraulically analysed variants of the measures, two measures were identified as short-term solution, i.e. the reconstruction of the Sv. Martin na Muri embankment and the first phase of the new Benica embankment. Both measures show no downstream or cross-border impacts and are aimed at the mitigation of local flood risks and threats. In order to ensure adequate flood safety for the Q100 flow rate in the case of Benica, it would be necessary to start with the reconstruction of the existing embankment at the settlement Gaberje as soon as possible. After the reconstruction of the Gaberje embankment, the second phase of the Benica flood-control embankment construction will be carried out, which will provide flood protection up to the Q100 level with a safety height of 1 m.

Resolving the flood risks in Benica and the reconstruction of existing embankments in Sv. Martin and Gaberje are completely covered by measures analysed in the A measures scenario of this study. The results show effectiveness in the reduction of flood risk in the target area, but they also have a cumulative impact causing the increase of water level in the entire section within the flood-control embankments between Hotiza and Benica, as well as a cross-border downstream impact.

3.3.2 NEW FINDINGS/CONCLUSIONS – AMENDMENTS TO THE PROPOSED SOLUTIONS

In the final phase of the Frisco1 study project, it was found that the Gaberje embankment, which needs to be reconstructed and which preconditions the completion of the Benica embankment, is partially being carried out in the territory of the Croatian cadastre, which requires a bilateral harmonization.

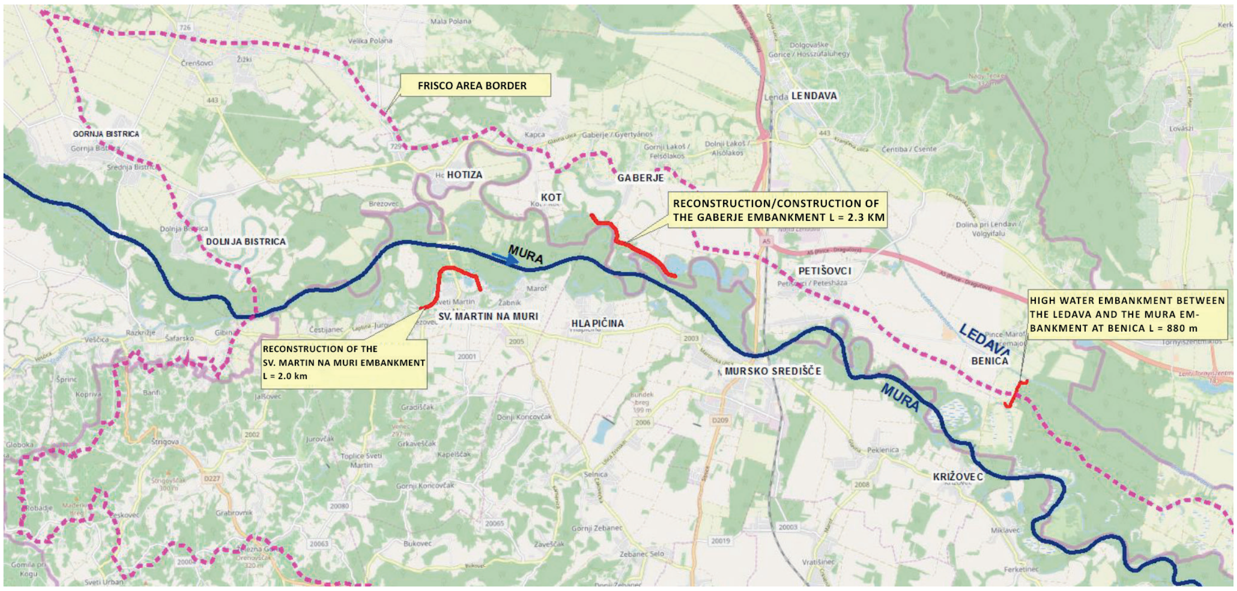
After several coordination meetings held between representatives of both countries (Slovenian Water Agency and Croatian Waters), it was agreed that the reconstruction of the Gaberje embankment will be carried out simultaneously with the implementation of Frisco project measures through the investment works programme of the Republic of Slovenia. With the aim of following the Frisco project schedule, a proposal has been made for the reconstruction of the current embankment to be carried out at the Gaberje section, which runs through the Slovenian cadastre, and at the section where the existing embankment runs through the Croatian cadastre, and a parallel route of a new embankment would be constructed, which would run entirely on the Slovenian territory and would be connected to the newly reconstructed embankment.

Based on the above findings, the following is proposed as short-term measures to be implemented on the Mura river:

- Construction of the Sv. Martin na Muri embankment
- Construction of the Benica embankment
- Reconstruction/construction of the Gaberje embankment

Out of the proposed short-term measures, the Sv. Martin na Muri embankment and the Benica embankment will be implemented through the Interreg Slovenia–Croatia programme (Frisco 1 and Frisco

2), while the Gaberje embankment will be financed through the Water Fund financing programme of the Republic of Slovenia.



In light of the analysis of impact on the current flood safety situation, the proposed measures correspond with the impact analysis according to the A measures scenario. The results show a great deal of effectiveness in reducing the flood risks on the left bank since, after the implementation of measures, flooding along the existing Gaberje embankment will be reduced, resulting in the reduction of flood risk jeopardizing the settlements on the air side of the embankment leading from Gaberje to Benica.

In the Gaberje case, the proposed set of measures differs from the scenario A measures in the method of construction. In the A measures scenario, a full reconstruction of the existing embankment was envisaged. According to the new proposal, however, a reconstruction of the embankment is planned in the length of 1,560 m and the construction of a new embankment is planned in the length of 730 m. The new embankment would be constructed with the following dimensions:

Crown width: 4 m

The banks slope: 1:x=1:3

A maintenance path would be constructed on the air side of the embankment.

After reconstruction of the existing and the construction of a new embankment, the function of the existing embankment running through the Croatian cadastre, will be abandoned. A gradual removal of the abandoned embankment is proposed to be carried out. This will extend the flood area on the left bank, which will have a positive impact on the Mura flood regime within the flood-control embankments, while at the same time the measure of increasing the existing inundation area is recognized as a green infrastructure measure. Due to a failure to maintain its abandoned section, the embankment would eventually collapse, and the collapse wave could cause damage to the new embankment.

From the perspective of the timetable set for the implementation of the proposed short-term measures, the embankment of Sv. Martin can be carried out independently of the Gaberje and Benica measures, as it has no significant impact on the flood safety and flood risks on the left bank.

Through the analysis of impact the new Benica embankment would have on the flood risk of the existing settlement, it was found that the reconstruction of the Gaberje embankment in the length of 2.3 km would need to be carried out before or simultaneously with the construction of the Benica embankment. If the Benica embankment is built anew before the Gaberje embankment is reconstructed, it will be necessary to provide additional non-structural flood risk reduction measures in the form of anti-flood bags or temporary safety fences (e.g. lamellar IBS fences or the Beaver tube protection) at the section where the Gaberje embankment is reconstructed. It will also be necessary to implement non-structural measures in the case of the Gaberje embankment collapse (immediate removal of the Benica embankment).

Through the analysis of alternative solutions, it has been found that the reconstruction of the Gaberje embankment can be carried out in the following two ways:

- The reconstruction of the embankment is carried out along the existing route of the embankment. Since part of the embankment runs through the Croatian cadastre, further bilateral harmonization of the final solution would be necessary.
- The part of the embankment, which runs through the Croatian cadastre, would be removed and a new flood-control embankment constructed in this section, which would run entirely in the territory of the Slovenian cadastre. Although the proposed solution is more favourable compared to the previous one from the viewpoint of delivery schedule, it is economically less favourable.

However, the solution that is the most feasible would be implemented. The first method, which uses the existing route of the embankment, is proposed as a primary solution. Although the implementation here will need to be harmonized bilaterally, such a solution will avoid the long-term land acquisition procedures, and the measure can be implemented simultaneously with the construction of the Benica embankment.

In both cases, the Gaberje embankment would be financed through the investment works programme of the Republic of Slovenia. The decision on the final selection of a technical solution for the Gaberje embankment reconstruction will have to be adopted in the subsequent bilateral harmonization between the two countries.

From the perspective of the timetable set for the implementation of the short-term measures, the embankment of Sv. Martin can be carried out independently of the Gaberje and Benica measures, as it has no significant impact on the flood safety and flood risks on the left bank.

3.3.3 Investment costs of the arrangements & financial and economic viability

The estimated investment value for the proposed short-term measures stands at EUR 3,435,174.00.

MEASURE	Investment estimation (EUR)
PROPOSAL OF SHORT-TERM MEASURES	
Reconstruction/construction of the embankment in the section of Gaberje–Mursko Središče–Lendava road	1,450,000.00
Construction of an embankment between Ledava and a high-water embankment at Mura near Benica	1,070,700.00
Reconstruction of the embankment at Sveti Martin na Muri	914,474.00
TOTAL, exclusive of VAT	**3,435,174.00**

The financial net present value of the investment is negative and totals EUR 3,100,314. The financial rate of return is also negative and totals 29.14%.

The economic net present value of the project is positive (EUR 1,666,035), which means that the cost of the project is equal to its benefits. This is also confirmed by the economic internal rate of return of 7.95% for the project. Similarly, the project has a favourable benefit-cost ratio of 1.43.

3.3.4 Multicriterial analysis

The common bilateral harmonized methodology for the economic assessment of flood damages in the cross-border river basins (September 2018) is intended for the assessment of flood damages in the cross-border river basins of the rivers of Kolpa, Sotla, Drava, Mura, Dragonja and Bregana for the purpose of implementing the FRISCO1 project activities.

The methodology was developed based on a bilaterally harmonized and accepted document called Basis for the Bilateral Methodology for the Economic Assessment of Flood Damages in the Cross-border River Basins (hereafter: "Methodology Basis"), which was elaborated by the Faculty of Civil Engineering at the University of Zagreb (Građevinska fakulteta Sveučilišta u Zagrebu) in August 2018.

The adopted Methodology Basis suggests that, with the aim of a comprehensive flood risks assessment, pursuant to the presented methodological approach to demonstrating the economic viability and feasibility of the proposed flood risk reduction measures, the analysed proposals of the measure variants additionally take into account the damage consequences related to the human health and the environment.

In the preparation of the Cross-border coordinated studies of integrated flood risk management in the cross-border basins of the Kolpa, Sotla, Drava, Mura, Dragonja and Bregana rivers within the project, the following the calculation of economic viability and feasibility of the proposed variants of flood risk reduction measures, as an additional aspect of choosing the most appropriate solution, i.e. the effect of all "acceptable solutions" on reducing the impact of floods on human health and the environment, will be taken into account. An additional procedure of selecting the most suitable solution is performed for all variants of the acceptable solutions in the following steps:

A. Assessment of positive effects of the acceptable solutions on human health
B. Assessment of positive effects of the acceptable solutions on the environment
C. A joint assessment of consequences of flood events on human health and the environment
D. Selection of the best solution

A joint assessment of consequences of flood events on human health and the environment for the FRISCO Mura area

For the area that was the subject of the FRISCO project, the number of affected residents was analysed based on the Central Population Register of the Republic of Slovenia (data from 2015). For the Croatian side, an impact assessment for the flood area was elaborated in connection to the reconstruction of the embankment at Sveti Martin na Muri (the A and C measures). According to the data of the Croatian Statistical Office (Statistical reports, Statistička izvješča 1583/2016), the municipality of Sveti Martin na Muri has 803 inhabitants, which is 3.24 inhabitants per household as per the 2011 census. We estimate that 16 inhabited buildings are exposed to the 100-year return period floods in the said flood area, which means that 52 resident are exposed.

3.4 CONCLUSION

The Mura has a total length of about 500 km, with the section considered under the FRISCO1 project representing a small part with respect to the entire Mura river basin, as it is about 50 km long. Given the treated natural features of the section, agricultural land is strongly prevalent. The treated territory is a flood area, which is also reflected in the history of past events. An analysis of the current situation showed that the flood protection measures were carried out in the past in such a way that, each time the flood water would spill over the flood-control embankments, these were subsequently raised and reconstructed. Although embankments were built gradually, the overflowing would still occur. In the past, intervention measures would be implemented in the even of flood. Due to various influences, the water levels rise due to the increasing growth of vegetation in the inundation profiles.

The analysis of past flood events from 2005 and 2014, a field inspection, and analysis of other available documentation were the important starting points for the identification of locations, measures and further analysis. One of the worst flood events took place in August 2005, when the following four locations were heavily exposed during the flood event:

- Zone 1: Upstream of Hotiza (in the area of the floodplain with no embankments)
- Zone 2: Embankments between Kot and Petišovci
- Zone 3: Downstream of the Petišovci border crossing point (Kolonija Petišovci)
- Zone 4: Area at the edge of the embankments – Benica

The first phase of the study, which was designed as an expert opinion based on knowledge about the flood water conditions and the available data, provided the following array of potential short-term measures that were proposed for further analysis:

- Reconstruction of the embankment at the section between Gaberje and the Mursko Središče–Lendava road
- Reconstruction of the embankment at Benica
- Construction of an embankment between Ledava and high-water embankment at Mura near Benica
- Reconstruction of the Sv. Martin na Muri embankment
- Hlapičina embankment
- Arrangement of a culvert under the Križovec embankment

The model will be used for hydraulic testing in only those measures, for which the hydraulic analysis of the current situation and the Design of alternative solutions – phase 2 shows that they are either necessary or their testing is justified.

Each of the analysed measures has its advantages and disadvantages. based on the analysis and expert assessment of the proposed measures, two of them were identified as short-term measures in the first phase of the study, namely:

- Reconstruction of the Sv. Martin na Muri embankment
- Reconstruction of the new embankment at Benica

Based on experience acquired during the floods of 2005 and 2014, it was established that the return flow of the Mura flood waters from Murska šuma poses a threat to the settlement of Benica, the agricultural lands, and the existing infrastructure. The construction of a flood-control embankment would reduce the current costs associated with the protection of the settlement from the Mura flood waters (placement of anti-flood bags, costs of electricity related to waste water pumping, elimination of damage effects on existing roads and other infrastructure).

In view of the identified poor condition of the existing Sv. Martin na Muri embankment due to its permeability, the stability of the latter will be seriously threatened at future occurrences of the Mura flood waters. In the event of the embankment collapse, the lives and possessions of many people within the settlement, the existing infrastructure, etc. would be endangered. For this reason, the measure of reconstruction of the Sv. Martin na Muri embankment is recognized as a "no-regret" measure.

In the second phase of the study, based on the collected data and documentation, the analysis of the current situation as well as the hydrological and hydraulic analysis was made based on results from the combined 1D+2D hydraulic model, and the permeability of the treated area was defined. The hydraulic analysis revealed great complexity of the Mura flood streams, which spill to the air side of embankments or over the elevated terrain and flood extensive portions of the hinterland in several sections. The most intense floods occur at the section from Gibina to Mursko Središče, where the overflowing of flood-control embankments is the strongest. Flood waters on the air side of the embankments flood both settlements, as well as important infrastructure (regional and interstate roads).

In the second phase of the Mura basin study, the effectiveness of the proposed measures was tested with the help of a hydraulic analysis. Through the analysis of impact the new Benica embankment would have on the flood risk of the existing settlement, it was found that the reconstruction of the Gaberje embankment in the length of 2.3 km would need to be carried out before or simultaneously with the construction of the Benica embankment. If the Benica embankment is built anew before the Gaberje embankment is reconstructed, it will be necessary to provide additional non-structural flood risk reduction measures in the form of anti-flood bags or temporary safety fences at the section where the Gaberje embankment is reconstructed. The results show a great deal of effectiveness in reducing the flood risks on the left bank since, after the implementation of measures, flooding along the existing Gaberje embankment will be reduced, resulting in the reduction of flood risk jeopardizing the settlements on the air side of the embankment leading from Gaberje to Benica.

Based on the above findings, the following is proposed within the study as short-term measures to be implemented on the Mura river:

- Construction of the Sv. Martin na Muri embankment
- Construction of the Benica embankment
- Reconstruction/construction of the Gaberje embankment

Considering that the reconstruction of Gaberje embankment preconditions the construction of Benica embankment, the reconstruction of the Gaberje embankment will be carried out simultaneously with the implementation of the FRISCO project measures through the investment works programme of the Republic of Slovenia.

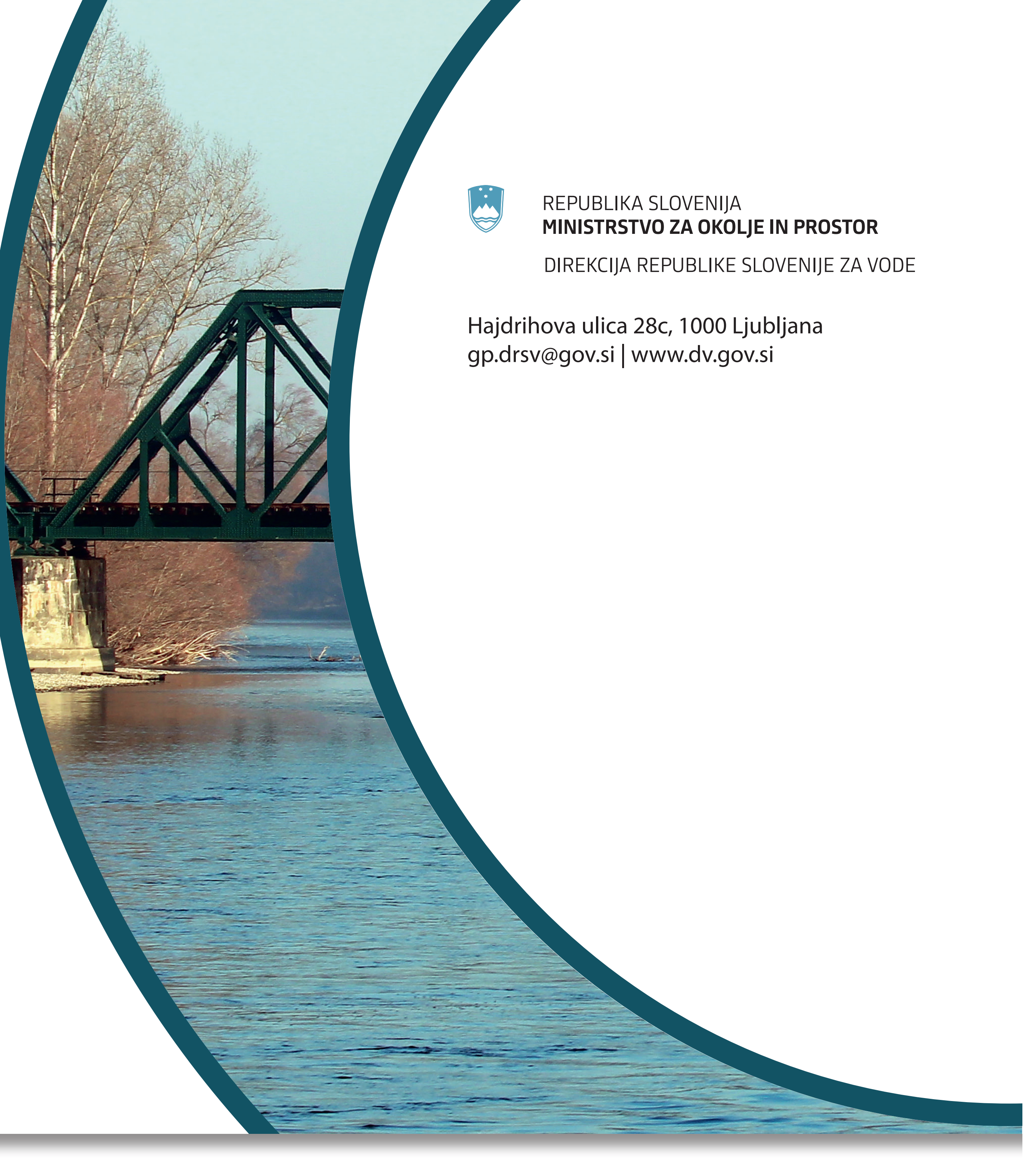
The reconstruction of the Gaberje embankment can be carried out in the following two ways:

- The reconstruction of the Gaberje embankment is carried out along the existing route of the embankment. Since part of the embankment runs through the Croatian cadastre, further bilateral harmonization of the final solution would be necessary.
- The part of the embankment, which runs through the Croatian cadastre, would be abandoned and a new flood-control embankment constructed in this section, which would run entirely in the territory of the Slovenian cadastre.

The solution that is the most feasible would also be implemented. The first method, which uses the existing route of the embankment, is proposed. Although such implementation will need to be harmonized bilaterally, such a solution will avoid the long-term land acquisition procedures, and the measure can be implemented simultaneously with the construction of the Benica embankment.

In both cases, the Gaberje embankment would be financed through the investment works programme of the Republic of Slovenia. The decision on the final selection of a technical solution for the Gaberje embankment reconstruction will have to be adopted in the subsequent bilateral harmonization between the two countries.

From the perspective of the timetable set for the implementation of the short-term measures, the embankment of Sv. Martin can be carried out independently of the Gaberje and Benica measures, as it has no significant impact on the flood safety and flood risks on the left bank.



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