



## Master Thesis

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# Assessing the Impacts of River Regulation Structures on Flow Dynamics and Ecological Systems: A Case Study of the Drava River

by

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the Degree of  
"Master of Science", abbreviated "MSc"

Novi Marof, February 2024

## SCIENCE PLEDGE

Hereby, I certify that my Master's Thesis is entirely the result of my work. I have cited all sources I have used in my thesis, and I have always indicated their origin.



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Novi Marof, Croatia, 9<sup>th</sup> of February 2024

## ABSTRACT

Throughout history, rivers provided multiple functional applications for humans, such as hydropower utilization, irrigation, water supply, river transportation, and flood defence. Many European rivers are under pressure from engineering structures constructed to secure those functional uses. River Drava, which runs through five European countries, is not an exception. Regulation measures built on river Drava in the past century aimed to improve navigation have resulted in the isolation of the dynamic floodplains and old river channels which form important biodiversity areas. This research aims to evaluate the effects of river regulation structures on flow dynamics and ecological systems using river Drava as a case study.

The research is located in eastern Croatia in Osijek-Baranja County on the river Drava between river kilometres 0 and 12. This section of river Drava has been designated as an International Navigable Waterway Class IV. Analysis of the current state of this section in terms of navigation concluded that several sections present bottlenecks and do not conform to the safe navigation requirements. To meet these requirements, the construction of five Declinant Groynes and six Chevrons has been initiated. These alternative regulation structures are proposed to abandon the traditional approach and find solutions with minimal impact on the environment.

The purpose of this research is to utilize GIS techniques and perform computer modelling of a river in its existing state, incorporate proposed river regulation structures into the model and assess changes in river flow dynamics and ecology resulting from the construction of these structures.

The modelling has been conducted for two different water levels, the lowest navigable water, and the average water level. The tool employed for modelling was a free river analysis software HEC-RAS developed by the US Army Corps of Engineers. The results included hydrologic variables such as Depth, Velocity, Shear Stress and Stream Power. Insights into the impacts of river regulation structures were obtained by comparing hydrologic variables in the existing and post-construction states of the model. Additional assessment of the impacts of regulation structures on the ecological values of the area has been conducted using the results of biological and ecological surveys performed in the wider area of research.

The implication of this research is to showcase the use of hydrologic modelling software in river engineering projects to determine the scope of impacts of proposed structures on river dynamics and ecological values. Although the model concerns the construction of river structures aimed at providing safe navigation conditions, it can be successfully applied to any river engineering sector.

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This work is dedicated to my family, my parents Dubravka and Faruk Ibrahimovic and my daughter Lena Ibrahimovic.

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## LIST OF ABBREVIATIONS

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AGN	- Accord Européen Sur Les Grandes Voies Navigables D'importance Internationale / European Agreement on Main Inland Waterways of International Importance
AWL	- Average Water Level
CADSWES	- Center for Advanced Decision Support for Water and Environmental Systems
CRC	- Cooperative Research Centre
CWMS	- Corps Water Management System
DEM	- Digital Elevation Model
DHI	- Danish Hydraulic Institute
EPGS	- European Petroleum Survey Group
GIS	- Geographical Information Systems
HEC-FDA	- Hydrologic Engineering Center's Flood Damage Reduction Analysis
HEC-FIA	- Hydrologic Engineering Center's Flood Impact Analysis
HEC-HMS	- Hydrologic Engineering Center's Hydrologic Modeling System
HEC-RAS	- Hydrologic Engineering Center's River Analysis System
HEC-ResSim	- Hydrologic Engineering Center's Reservoir System Simulation
HTRS96/TM	- Hrvatski Terestrički Referentni Sustav za epohu 1995.55 (Croatian Terrestrial Reference System 96) / Transverse Mercator
ICPDR	- International Commission for the Protection of the Danube River Basin
LNWL	- Lowest Navigable Water Level
m asl.	- meters above sea level
PLATINA	- Platform for the Implementation of the EU NAIADES Programme
NAIADES	- Navigation and Inland Waterway Action and Development in Europe
TIFF	- Tag Image File Format
TIN	- Triangulated Irregular Network
UNESCO	- United Nations Educational, Scientific and Cultural Organization

## 1. Introduction

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The topic of this research is the assessment of the impacts of river regulation structures on the flow dynamics and ecology of the river system using hydrologic modelling software. The research is conducted using the river Drava, from 0 to 12 river kilometres, as a case study.

This chapter provides the rationale for this research followed by a literature review on this topic. The area of research covers a variety of disciplines including river hydrologic modelling, navigation, and ecology. Furthermore, the research question is formulated, and the proposed methodology is briefly covered. This chapter concludes by outlining the structure of the research, potential risks, and limitations.

### 1.1 Research Rationale

River systems are very complex and dynamic systems. While being so complex, they have multiple functional uses such as: draining floods, supplying drinking water, maintaining ecology, irrigating farmland, transporting sediment, supplying power, providing habitat for fishes, assimilating wastewater, and providing navigation (Wang, et al, 2014). To control rivers' behaviour and maximise their potential, humans have been changing river channels through the construction of various engineering structures. The second largest European river, the Danube, is an intensely engineered river in the context of hydropower utilization, navigation, and flood protection (Habersack, et al, 2016).

Engineering structures, relevant to this research, are related to the improvement of river navigation conditions and are usually referred to as river regulation structures. River engineering structures serve the purpose of directing the water flow towards the fairway, especially in low-water periods and they strongly influence fairway conditions such as water depth (ViaDonau, 2016). They include redirective structures, mainly different types of dikes such as L-dikes, T-dikes, longitudinal dikes, and spur dikes (in European literature referred to as groynes), and resistive structures such as revetments (Pokrefke, 2013). Most engineering undertakings, more than often result in changes in the river flow dynamics and have negative impacts on runoff, sediment transport, riparian and stream habitats, and water quality (Wang, et al, 2014). River regulation structures are constructed directly within the river channel and therefore directly result in a change of riverbed morphology. River regulation measures performed in the 19<sup>th</sup> century on the Danube and its tributaries, designed to improve navigation and flood protection, have resulted in the isolation of the once extensive and dynamic floodplains from the main river channel (Hein et al., 2006). Dynamic fluvial processes between floodplains and the main river channel, are responsible for habitat succession and rejuvenation (Hohensinner and Drescher, 2008), leading to high biodiversity along aquatic-terrestrial boundaries (Bunn and Arthington, 2002).

In recent years, solving river engineering problems, including but not limited to the design of regulation structures, has been greatly aided by computation and information techniques through numerical modelling of flow and sediment transport in rivers (Wu, 2007). However, river management should not solely incorporate engineering but also ecological and environmental aspects, therefore several approaches have been developed with the goal of integrated basin management by reconciling differing perspectives of river management (Hering et al., 2010).

The purpose of this research is to utilize GIS techniques and perform computer modelling of a river in its existing state, incorporate proposed changes (river regulation structures) into the model and assess changes in river flow dynamics and ecology resulting from the construction of these structures.

## 1.2 Literature Review

### 1.2.1 Computer Modelling

Computer modelling is a cost-effective computer-aided simulation that gives direct, real-scale estimates without any scale distortion (Wu, 2002). Computer models in hydrology were first used in the 1970s and 1980s when many location-specific river watershed models were developed and employed by engineers in water management organisations for the operational planning of their activities (Zagona et al., 2001). At this time there were no commercial models but rather individual development efforts. This resulted in different organisations using different approaches, hardware, and software to meet their prospective needs (Welsh et al., 2011). Before the 1970s, such river engineering problems had to be solved through field investigations and physical models in laboratories (Wu, 2002), and this was a huge step forward.

In the early 1990s, the development of hardware and software technology led to significant progress in river modelling tools. One of the first general modelling software that was developed was RiverWare in 1992, which was a collaborative effort between the Center for Advanced Decision Support for Water and Environmental Systems (CADSWES) at the University of Colorado (Frevort et al., 1999). RiverWare was one of the first software solutions that could be applied to a diverse range of river and storage systems with multiple operational objectives (Zagona et al., 2001).

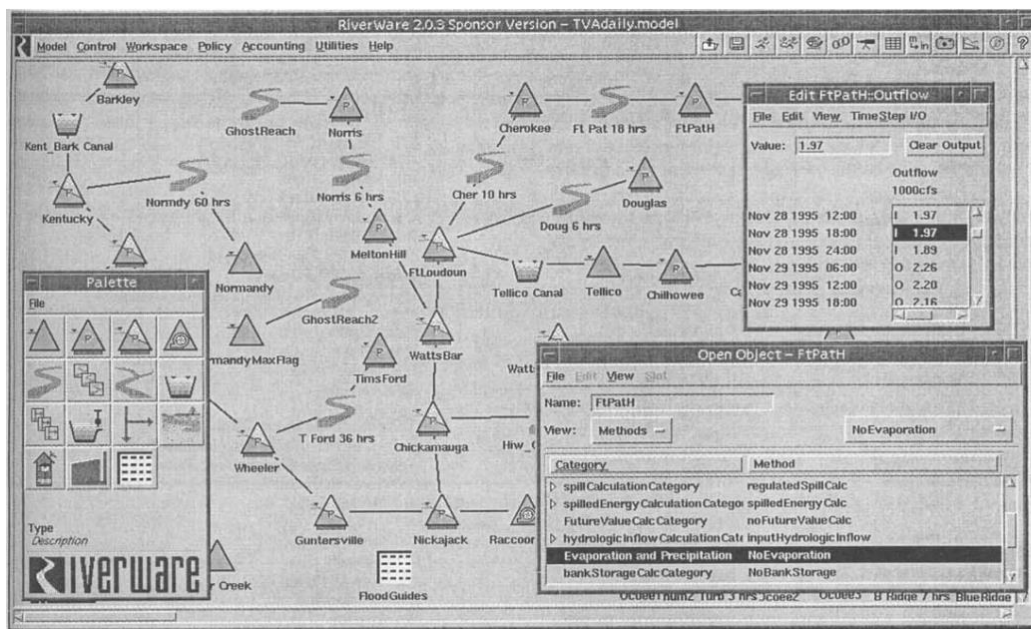


Figure 1 RiverWare workspace (Source: Zagona et al., 2001)

With further advances in computer technology, several organisations in different countries have undertaken initiatives to develop new-generation river systems modelling solutions, focusing on the ability to model any river system and include different hydrological processes (Welsh et al., 2013).

In 1990, the US Army Corps of Engineers started a five-year project “NexGen” to develop the next generation of hydrologic engineering software (Davis D. W., 1993). The result of the project was a collection of software that includes several aspects of hydrologic engineering, including rainfall-runoff analysis (HEC-HMS); river hydraulics (HEC-RAS); reservoir system simulation (HEC-ResSim); flood damage analysis (HEC-FDA and HEC-FIA); and real-time river forecasting for reservoir operations (CWMS) (US Army Corps of Engineers, 2023a).

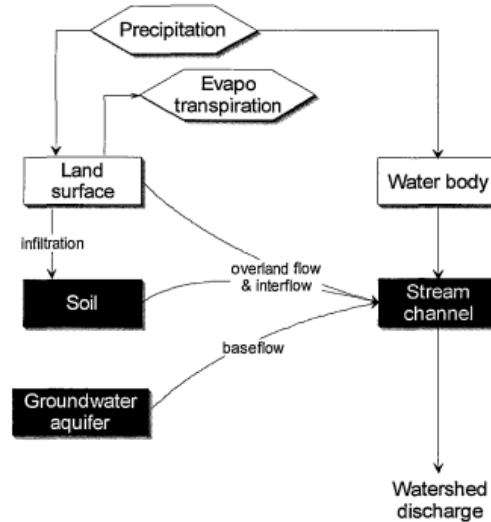


Figure 2 HEC-HMS representation of watershed runoff (Source: US Army Corps of Engineers, 2000)

There are several examples of advanced river systems computational software developed to date, including MIKE (products covering integrated platforms and individual hydrological modules), developed by DHI – Danish Hydraulic Institute (DHI, 2023) and more recently Source Integrated Modelling System – IMS developed by eWater Cooperative Research Centre - CRC, Australia (Welsh et al., 2013).

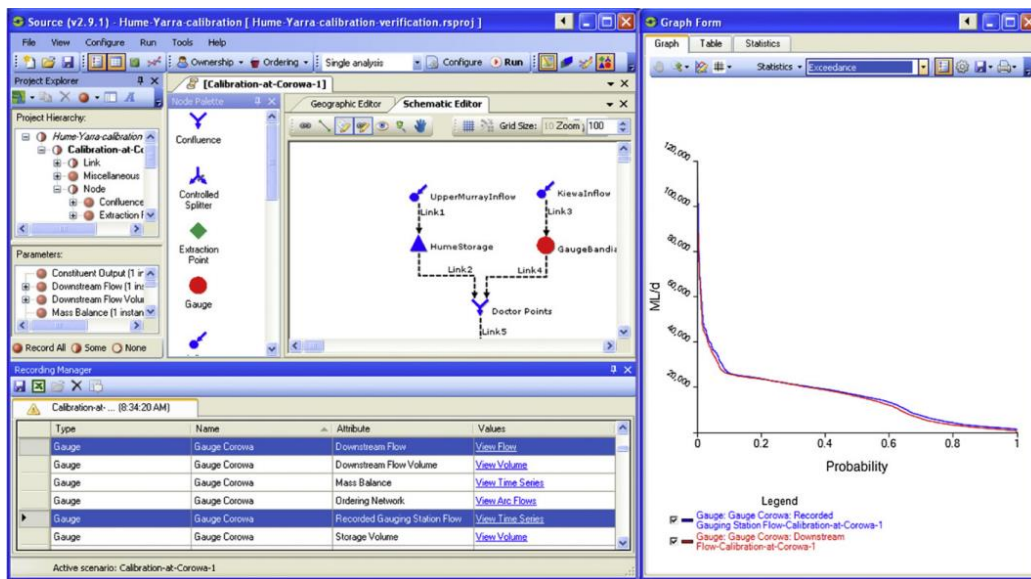


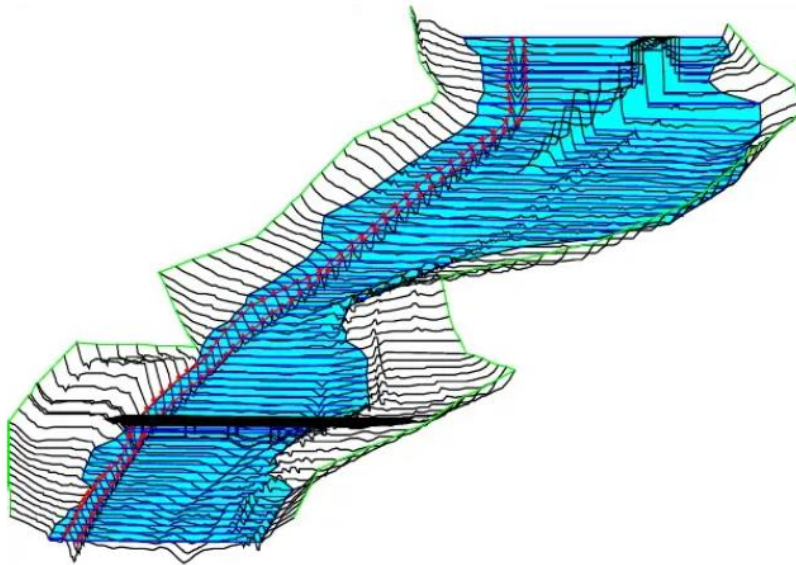
Figure 3 Source – IMS Software (Source: Welsh et al., 2011)

Various mathematical modelling software packages have been used successfully for different purposes on the Danube and its tributaries. Some examples include projects such as Floodplain evaluation on the Danube upstream of Vienna - Austria (Ferstl, 2020), Hydro-sedimentary modelling and fluvial morphological processes along the lower Danube – Romania (Gogoșe-Nistoran et al., 2022) and Simulation and evaluation of perennial rivers flows over 42 km of the Danube River – Slovakia (Yasi and Nasiri, 2017).

Today, there is a great amount of software available on the market that offers powerful capabilities for modelling and visualization of hydrologic data. Whether covering single or multiple hydrological processes and regardless of the developer, all of them rely on common mathematical foundations.

Based on their mathematical foundations, river computational models can be classified in terms of their dimensionality, flow state and numerical methods they rely on.

According to their dimensionality, flow and sediment transport models can be classified as 1-D, vertical 2-D, horizontal 2-D, and 3-D (Wu, 2002). This aspect covers the number of dimensions that we are modelling in terms of flow movement. 3-D models give the best representation of reality as the natural processes within the river are 3-D phenomena. However, the complexity of the riverbed over 12 kilometres of the project area, would be time and resource-consuming to model. On the other hand, 1-D modelling is simplified and provides results based on cross-sections distributed along the river.



*Figure 4 HEC-RAS 1-D model – perspective plot (Source: US Army Corps of Engineers, 2016)*

According to their flow states, computational river models can be defined as steady, quasi-steady, or unsteady models (Wu, 2002). Unsteady flow computation is the most advanced and can be used for general calculations as it covers both steady and quasi-steady fluvial processes. It provides the best approximation of processes in nature. Unsteady flow modelling of a river system can be described as the propagation of shallow water waves across the river channel (Tsai, 2003).

When it comes to numerical methods, flow and sediment transport, all computer models can be classified as finite difference, finite volume, finite element, finite analytic, or efficient element models (Wu, 2002). All these methods aim to mathematically approximate the natural phenomena of water and sediment movement and have their advantages and disadvantages. But the final choice depends on the software capabilities, nature of the problem and available computing power. However, the finite volume method provides improved stability and reliability over traditional finite difference and finite element techniques (Brunner et al., 2015).

HEC-RAS (Hydrologic Engineering Center's River Analysis System) software was selected for this research as it is a free option successfully used on similar projects (including three projects on the Danube River listed above). The first version of HEC-RAS was released in July 1995 and since that time there have been several major releases (US Army Corps of Engineers, 2023a).

The latest version of HEC-RAS software is 6.4.1 and provides river analysis components for:

- one-dimensional steady flow water surface profile computations,
- one-dimensional and/or two-dimensional unsteady flow simulation,
- quasi unsteady or fully unsteady flow movable boundary sediment transport computations (1D and 2D), and
- one-dimensional water quality analysis.

Based on the data available (bathymetric survey, water flow and water levels), the above-elaborated classification of computational models and the capabilities of HEC-RAS, the most appropriate option for this research would be 2-D modelling with an unsteady flow. Unfortunately, the sediment data is not available for this project as there are not many gauge stations on river Drava that monitor sediment.

The HEC-RAS 2D modelling engine uses a finite-volume numerical method (US Army Corps of Engineers, 2023a). This algorithm was developed to allow for the use of a structured or unstructured computational mesh. Such mesh is produced from a digital terrain model (DEM) and can allow for detailed modelling of engineering structures within the river as can be seen in Figure 5.

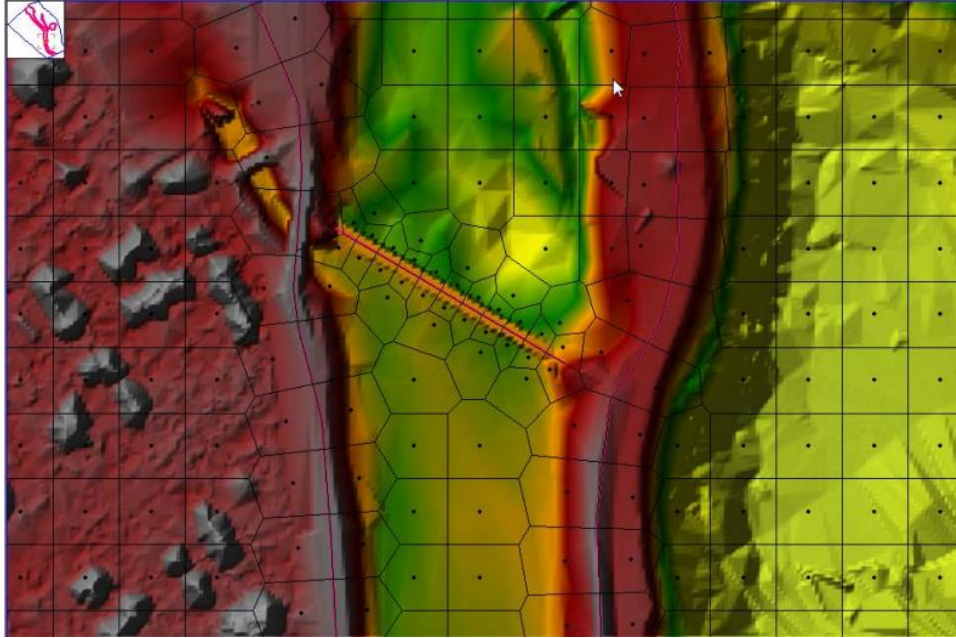


Figure 5 Unstructured mesh (US Army Corps of Engineers, 2022).

In HEC-RAS two-dimensional unsteady-flow analysis has two equation sets that can be used to solve the propagation of water flowing over the computation mesh: Saint Venant equations and Diffusion Wave equations (US Army Corps of Engineers, 2023b). The use of equations is user-selectable within the software.

$$\frac{\partial A}{\partial t} + \frac{\partial Q}{\partial x} = q_l \quad \frac{\partial Q}{\partial t} + \frac{\partial}{\partial x} \left( \frac{\beta Q^2}{A} \right) + gA \frac{\partial z_s}{\partial x} + gAS_f = q_l v_x$$

Figure 6 Saint Venant equations (Wu, 2002)

$$gA \frac{\partial z_s}{\partial x} + gAS_f = q_l v_x$$

Figure 7 Diffusion wave equation (Wu, 2002)

A - the flow area;  
 t - the time;  
 Q - the flow discharge,  
 x - the spatial coordinate representing the streamwise distance;  
 $q_l$  - the side flow discharge per unit channel length;  
 $\beta$  - the correction factor for momentum due to the non-uniformity of streamwise velocity over the cross-section;  
 g - the gravity;  
 $z_s$  - the water stage  
 $v_x$  - the velocity of side flows in the direction of the x-coordinate; and  
 $S_f$  - the friction slope

In general terms, the 2D Diffusion Wave equations provide faster computational times and greater model stability, while the 2D Full Saint Venant equations are more applicable to a broader range and more complex problems (Brunner et al., 2015).

Once the modelling variables are selected and computation is performed, HEC-RAS can produce a wide range of outputs. These outputs can be directly previewed in the HEC-RAS graphical interface or exported in different formats for use in other software.

The basic set of outputs that HEC-RAS generates by default consists of Water surface elevation, Depth and Velocity. Other outputs can be requested by the user and are additionally calculated by HEC-RAS. Available types may vary depending on the type of simulation performed (US Army Corps of Engineers, 2023a).

### 1.2.2 Location of the Project and Navigation

The research is located in eastern Croatia in Osijek-Baranja County on the river Drava between river kilometres 0 and 12. River Drava is one of the biggest rivers in Croatia and one of the largest tributaries of the Danube.



Figure 8 Location of the project

This section of river Drava has been designated as an International Navigable Waterway Class IV based on the “Ordinance on the Classification and Designation of Inland Waterways (Official Gazette of Republic of Croatia no. 77/11, 66/14, 81/15)”.

“European Agreement on Main Inland Waterways of International Importance – AGN (United Nations, 1996)” that has been signed by Croatia on 27<sup>th</sup> of April 1999, states that for the Class IV of the inland waterway, safe navigation conditions correspond to the draught reached or exceeded for 240 days on average per year (or for 60% of the navigation period). These navigation elements have been integrated into Croatia’s national legislation and various development strategies.

### 1.2.3 Proposed Engineering Structures

The basis of this research is “The Prefeasibility Study – Improvement of navigation conditions on river Drava from 0 river km to 12 river km (confluence into Danube - Osijek Port Nemetin), Hidroing Ltd. Osijek (2019)”, later in the text referred as “The Study”. The main purpose of the Study was to assess the optimal technical solution for the improvement of navigation conditions while considering environmental and economic factors.

Analysis of the current state of this section in terms of navigation was undertaken and presented as a part of the “Conceptual design for the improvement of navigation conditions on river Drava from the confluence - river km 0, to Port of Osijek - river km 12 (Hidroing Ltd. Osijek, 2016)”. The document concluded that several sections present bottlenecks to the navigation and do not conform to the abovementioned requirements (Figure 9).

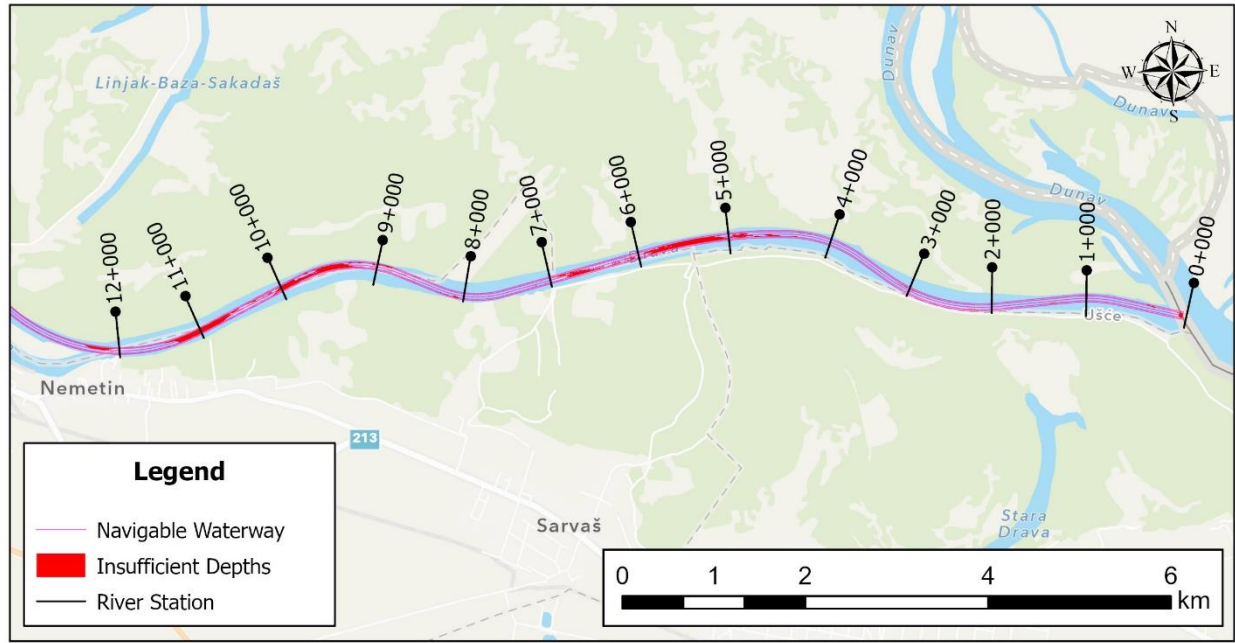


Figure 9 Closer look at the project area and identified bottlenecks (Data source: Hidroing, 2016)

Based on the abovementioned European and Croatian legislation, the Navigable waterway for Class IV, which is assigned for the river Drava from 0 to 14 river km has the following parameters:

- Two-way navigation on the entire stretch
- Acceptable dimensions of pushed convoys:
  - o length 80 – 85 m
  - o beam 9,50 m
  - o draught 2,50 – 2,80 m
  - o tonnage 1250 – 1450 t
- Minimal radius of navigable waterway 650 m
- Navigable conditions during Low Navigable Water Level\*
  - o Minimal depth 2,5 m
  - o Minimal width of waterway in straight lines 50 m
  - o Minimal width of waterway in curves with inner radius of 650 m 75 m
- Minimum height under bridges 5,25 – 7,00 m.

*\*Low navigable water level (LNWL) is “the water level reached or exceeded at a Danube water gauge on an average of 94% of days in a year (i.e. on 343 days) over a reference period of several decades (ViaDonau, 2023)”.*

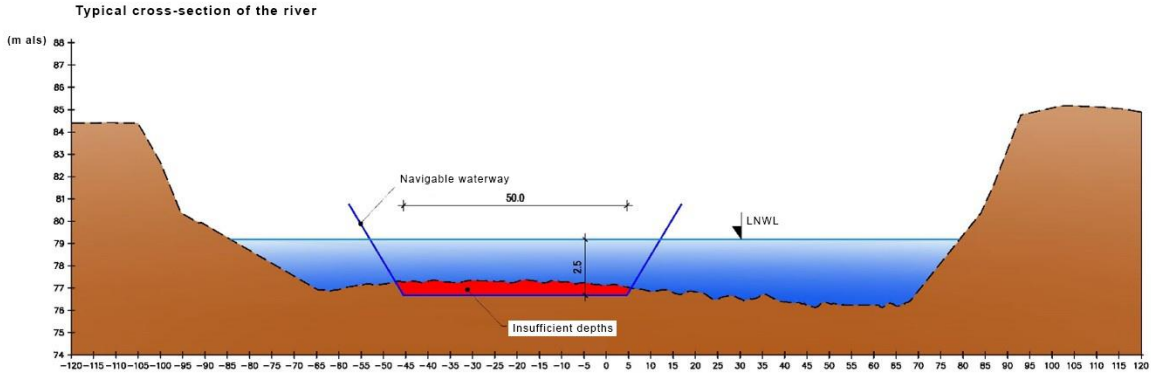


Figure 10 Cross section of the river with navigable waterway – insufficient depths shown in red (Source: Hidroing, 2019)

Following the key water management issues identified in the Danube River Basin Management Plan (ICPDR, 2021), the Study analysed the construction of traditional structures such as embankments, longitudinal groynes, groynes, and t-groynes, but also alternative structures such as declinant groynes and chevrons. These alternative structures, as suggested by the Good Practice Manual on Inland Waterway Maintenance (ViaDonau, 2016), proved to be beneficial for fauna and flora, especially aquatic life.

The results of the Study proposed one unified solution across the entire stretch of the project including the construction of declinant groynes and chevrons, but also simple measures such as regular dredging of the sediment to conform to the required navigation depths.

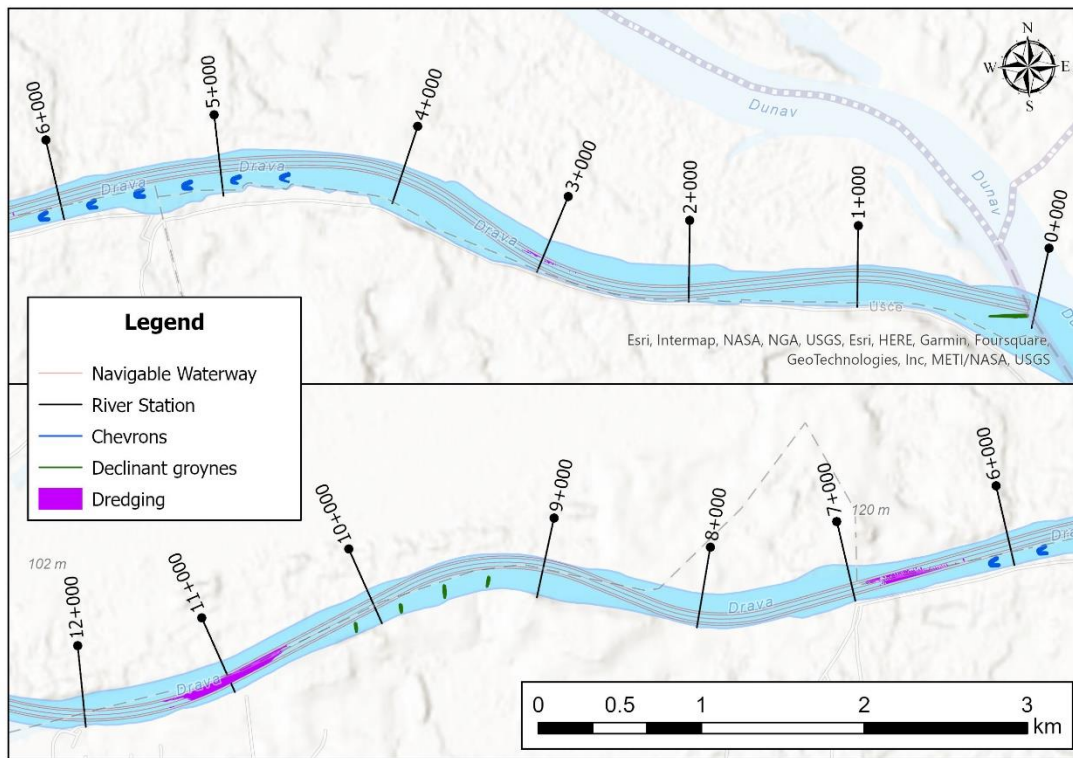


Figure 11 Proposed structures (five Declinant Groynes and six Chevrons) and dredging areas (data source: Hidroing, 2019)

## Declinant groyne

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The declinant groyne is a type of groyne that is inclined facing downstream and disconnected from the riverbank. These are innovative structures that were first implemented on the Danube as a part of Pilot Project Witzelsdorf (Austria) between 2007 and 2009 (ICPDR, 2010). The riverbank restoration project included the removal of traditional groynes and the construction of four new ones. Declinant groynes are lower in height than traditional structures and provide fish by-pass along the bank while still meeting navigation requirements.

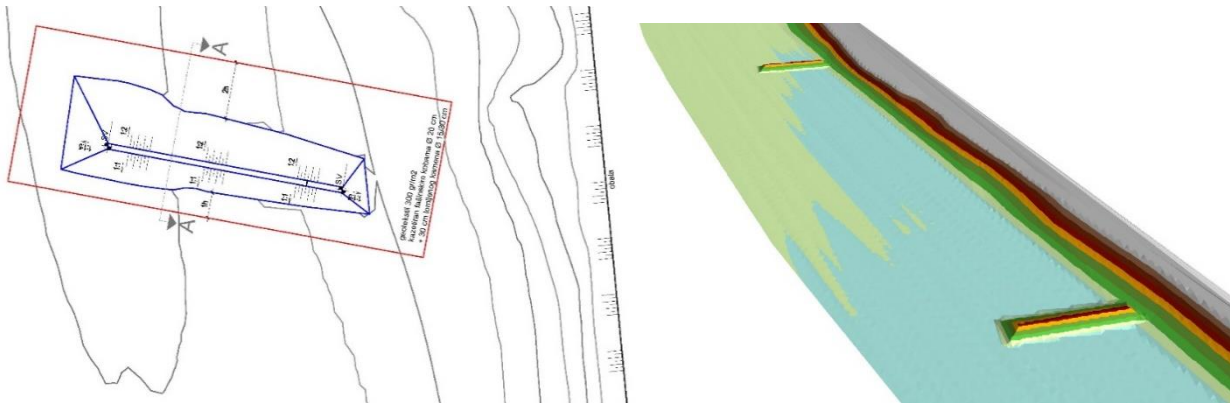


Figure 12 Ground plan and 3-D view of Declinant Groyne (Source: Hidroing, 2019)

## Chevron

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Chevron is also an alternative river engineering structure previously constructed on various rivers in the USA (Pokrefke, 2013). It's a U-shaped structure with a blunt nose and open end facing downstream (ViaDonau, 2016). They are not connected to a riverbank and their purpose is to minimise engineering impact and potentially create river habitats in their backside (Hidroing, 2019).

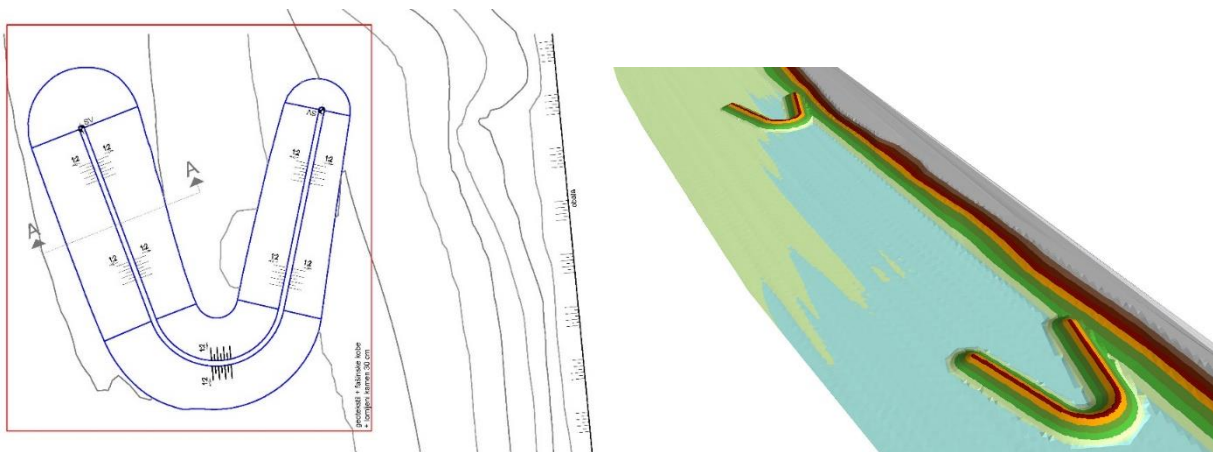


Figure 13 Ground plan and 3-D view of Declinant Groyne (Source: Hidroing, 2019)



Natura 2000 site located in the wider area of the research include:

- Podunavlje i Donje Podravlje HR1000016 – Protected under the EU Birds Directive (70 species)
- Kopački rit HR2000394 – Protected under the EU Habitats Directive (5 habitats and 24 species)
- Donji tok Drave HR2001308 – Protected under the EU Habitats Directive (1 habitat and 21 species)
- Dunav – Vukovar HR2000372 – Protected under the EU Habitats Directive (4 habitats and 11 species)

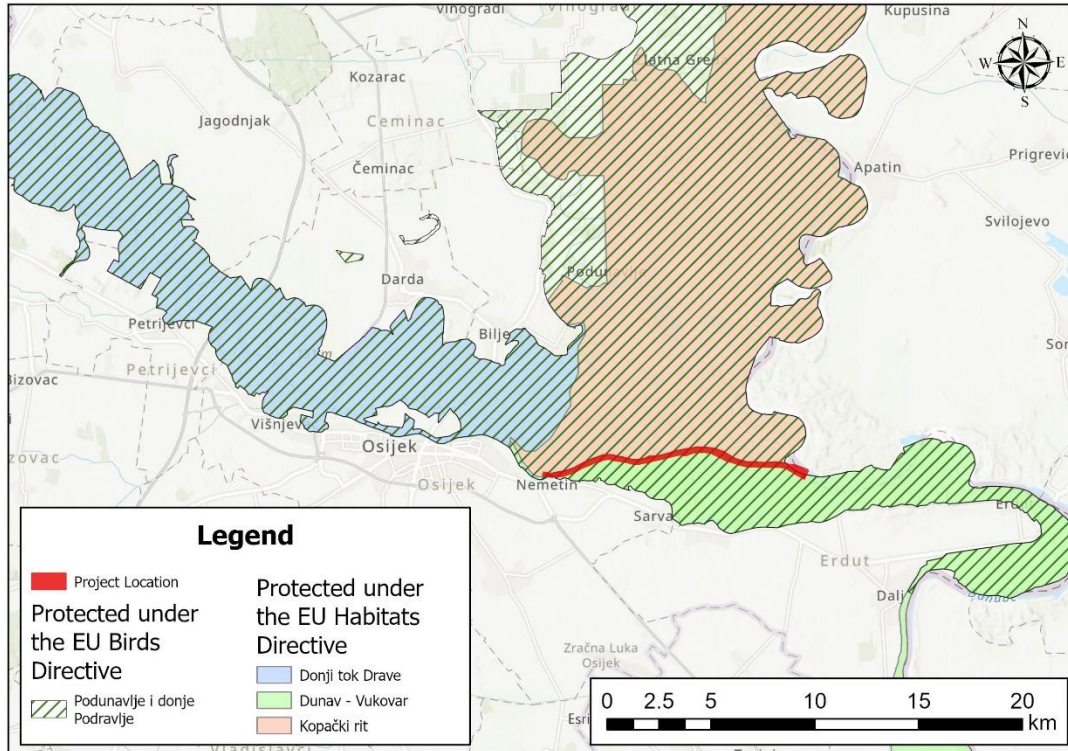


Figure 15 Areas protected Natura 2000 Ecological Network (data source: National Spatial Data Infrastructure, 2023)

Kopacki Rit is the most important protected area in the wider region of the research. It is located along the left bank of the river Drava within the research area.

Kopacki Rit is an area located between the Danube and Drava rivers. It's a natural wetland formed by a multitude of morphological processes such as meandering and flooding. It consists of old riverbeds, channels, lakes, floodplains, forests, and marshes, which altogether provide a habitat for many plant and animal species (Ministry of Environmental Protection, Spatial Planning and Construction, 2006).

As described on the Ramsar website (2023), Kopacki Rit provides habitat to over 522 vascular plants, 300 birds, 55 mammals, 53 fish, 12 amphibians and 12 reptile species. Some of these are internationally threatened, including but not limited to the eastern imperial eagle, the common pochard, the saker falcon and the leather carp.

It also forms a part of the Mura-Drava-Danube Transboundary Biosphere Reserve (UNESCO, 2023) and is also designated as a Ramsar site (The Convention on Wetlands, Ramsar, 1994).

### 1.3 The Research Question

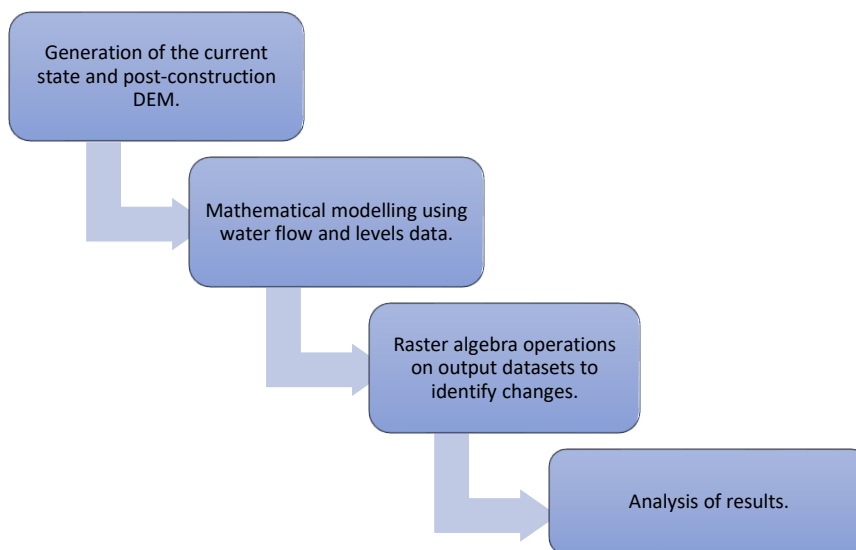
The research question is formulated as follows:

***What impacts does the construction of river regulation structures have on the flow dynamics and ecology of the river system?***

The category of question for this research is: Effect Question - What effect did the action **construction of river regulation structures** have on **river morphology and the ecology of the river**?

### 1.4 The Approach

The following workflow diagram shows the proposed steps as a part of the empirical approach to solving the hypothesis.



Data:

- Bathymetric survey of river Drava, used to generate current state DEM,
- Technical drawings of proposed river regulation structures, used to generate post-construction DEM,
- Water flow (Q) and water surface level (h) data for two characteristic water levels (Average water level and Lowest navigable water level) – based on analysis of data available from the closest water gauge stations as provided by the Croatian Water Management Authority, and
- A biological and ecological study performed in the wider project area including a survey of key habitats, and bird and fish species.

Software:

- ArcGIS Desktop Pro by ESRI
- HEC-RAS - free software developed by the US Army Corps of Engineers, Hydrologic Engineering Center.

#### Methods:

- Create a current state DEM using data provided by the partner,
- Create a post-construction DEM including proposed river regulation structures based on the technical drawings of the proposed structures and current-state DEM using ArcGIS Raster Algebra,
- Perform calibration and validation of the model (this involves setting up appropriate Manning's roughness coefficient) on the current state model,
- Perform two-dimensional unsteady flow modelling using HEC-RAS software based on two characteristic water levels (Average water level and Lowest navigable water level) on both DEMs,
- Assessment of changes in flow dynamics (change in the distribution of velocities) based on the results of flow calculations. The results from HEC-RAS will be imported and visualized in ArcGIS, and changes (current VS proposed) will be identified using Raster Algebra functions, and
- Discussion of ecological implications of proposed regulation structures, with an emphasis on the environmental friendliness of regulation structures, by assessing changes in flow dynamics and morphological changes in the riverbed to identify potential destruction of habitats and creation of new habitats for river fauna.

### 1.5 Statement of Objectives

This research aims to assess the impacts of the construction of river regulation structures on the flow dynamics and ecology of the river. These impacts can be negative, positive, and neutral. It's in the best interest to preserve the ecological values of the region to construct river regulation structures that can have a positive impact, or at least be neutral.

This aim is to be achieved through the following set of objectives:

- mathematical modelling of the current state and post-construction state of the river channel,
- identification of changes in output parameters using GIS tools,
- Overall assessment of the effectiveness of the proposed technical solution,
- Assessment of changes in flow dynamics, and
- Assessment of ecological implications.

### 1.6 Thesis Structure

The structure of this research is as outlined below:

- Chapter 1: Introduction
- Chapter 2: Methodology
- Chapter 3: Results and Analysis
- Chapter 4: Discussion
- Chapter 5: Conclusion

### 1.7 Limitations of Research

The main limitation of the research is the fact that modelling is a simplified version of reality. DEMs are based on finite elements and represent the closest representation of the real terrain. Therefore, all the research is based on the best approximation of reality.

The second important limitation of this research is the lack of sediment data for the area. The mathematical modelling is based solely on water transport and movement equations. This is unfortunate as sediment transport is an important factor in the modelling of changes within the river systems.

The bathymetric survey and hydrologic data analysis (water flow and water surface elevation) date back to 2018. Rivers are dynamic systems, and some changes may have occurred in the meantime. However, the hypothesis is trying to define the impact of regulation structures at a given point in time and this limitation would not have an impact on the outcomes and validity of this research.

## 1.8 Context and Risks

As this is an ongoing project, the results of this research could be used in further stages of this project including the Environmental Impact Assessment.

The following is the overview of identified risks, their probability, effects, and mitigation measures.

- RISK 1:**            **There is a possibility that the provided data will be insufficient for modelling.**  
PROBABILITY:    Medium  
EFFECTS:            High  
MITIGATION:      Request additional data from authorities or the partner. Another alternative would be to interpolate missing data.
- RISK 2:**            **The model might not function or provide the desired results due to various software issues.**  
PROBABILITY:    Low  
EFFECTS:            High  
MITIGATION:      Look for alternative software solutions that could fit the research hypothesis.
- RISK 3:**            **The computing power available at the time of writing this research might be insufficient and prolonged computing times might cause major delays in writing the thesis.**  
PROBABILITY:    Mid  
EFFECTS:            Mid  
MITIGATION:      Look for online sources of computing power or upgrade the existing machine.
- RISK 4:**            **Various software and data-related problems such as geographical projection issues, differences in raster data extents and resolutions, and regional settings as HEC-RAS uses both Metric and Imperial systems but only works with USA data and time format.**  
PROBABILITY:    Mid  
EFFECTS:            High  
MITIGATION:      Special attention has to be paid to those details and if there are any cases of inconsistencies within results, problems have to be identified and procedures repeated until the outputs provide satisfactory results.

## 1.9 Outlook

Mathematical modelling using software packages such as HEC-RAS has been used successfully in the past on similar projects, with HEC-RAS generally being accepted as a good modelling tool. This research aims to use modelling to quantify the impacts of river regulation structures on river flow dynamics and ecology. Based on the outputs of the proposed model, it is expected to provide sufficient evidence to answer the research question.

This research is an example of a conflict of interest between nature conservation and river navigation. The methodology of this research can be used in future projects to aid the decision-making process and help find the best solution for both environmental protection and inland navigation.

## 2. Methodology

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### 2.1 Introduction

The basic idea behind the methodology for this research is to make a hydrological model of the river Drava in its current state and calibrate the model to represent the real-world flow as realistic as possible. Once the current state model is validated and provides the same output data as in reality, the model is then run with the post-construction terrain, which incorporates the proposed regulation structures. The difference between the two sets of outputs would provide insight into the impact of the construction of river regulation structures on the flow dynamics.

The methodology for this research is aided by using ArcGIS Pro and HEC-RAS software packages. ArcGIS Pro is used to prepare terrain and other input layers such as flow area, while HEC-RAS is used for hydrologic modelling and creation of outputs. ArcGIS Pro was used at the end to process and compare the outputs from HEC-RAS. The coordinate system used was “HTRS96/TM Croatia” (EPSG: 3765) which is the official coordinate system of the Republic of Croatia.

### 2.2 Current State DEM

The current state DEM has been provided by the Partner Company “Hidroing Ltd. for Design and Engineering, Osijek/Croatia”. According to the description provided in the Study (Hidroing, 2019), the Digital Terrain Model was compiled by merging the bathymetric survey for the riverbed and the official state geodetic survey for banks and floodplains. The bathymetric survey was completed using a small vessel and depth recording device (single beam echo sounder “Reson NaviSound 110”). The final DEM has been provided in Triangulated Irregular Network format (TIN).

For this research, the selected digital terrain model format is a TIFF raster file as this format is readable by HEC-RAS software. Conversion from TIN to TIFF raster has been carried out using ArcGIS’s 3D Analyst Tool and the raster resolution has been set to 10 cm. The resulting raster file was cropped to the high banks of the river channel as the focus of this research is on the riverbed only.

The following figures show the digital terrain model of the river Drava in its current state.

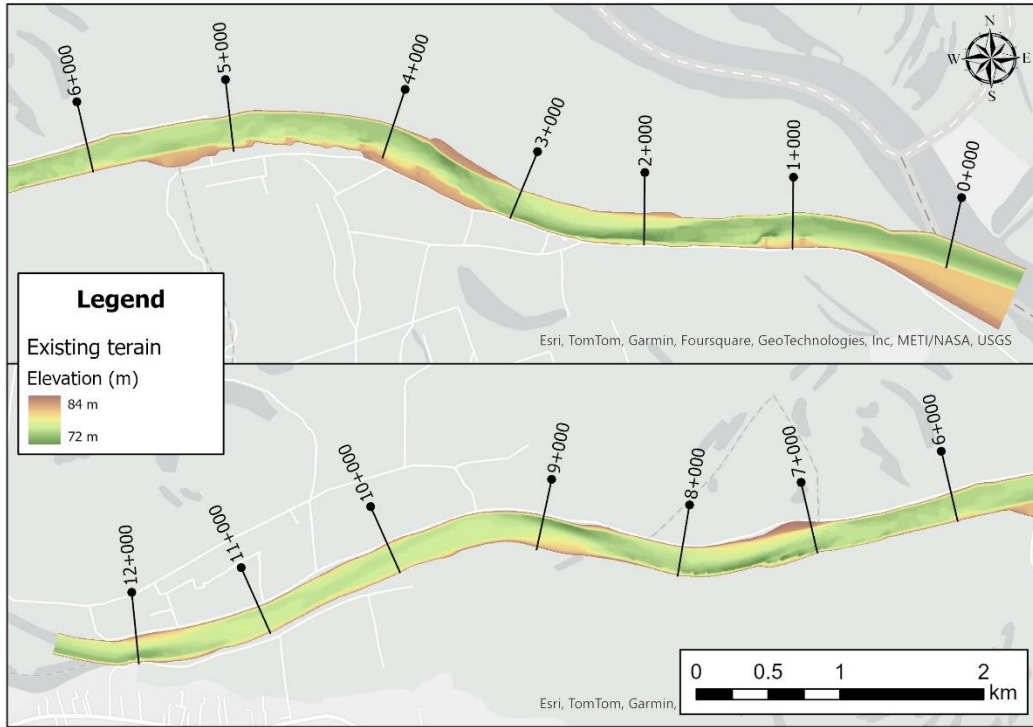


Figure 16 Digital terrain model of the river Drava in its current state

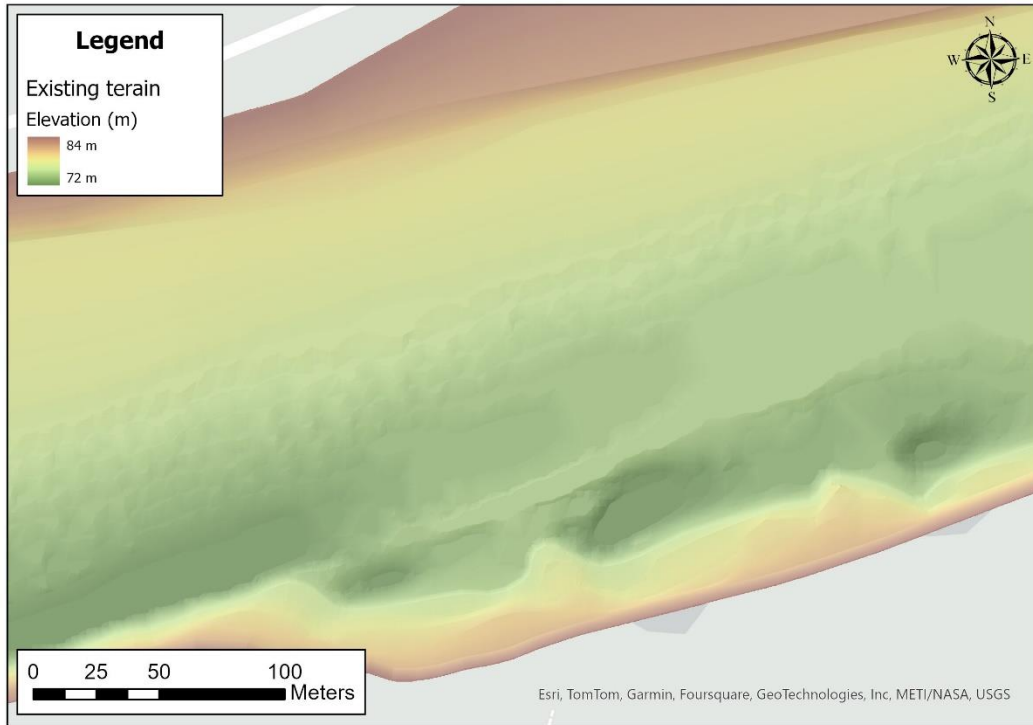


Figure 17 Digital terrain model of the river Drava in its current state – detail between river kilometres 7 and 8

### 2.3 Post-Construction DEM

The results of the Study proposed the construction of five Declinant Groynes and six Chevrons on the stretch of river Drava between 0 and 12<sup>th</sup> river kilometre. River regulation structures are made of crushed stone to fit into the natural environment. These structures are located in three separate sections:

- One Declinant Groyne was proposed at the mouth of river Drava into the Danube (0+000 river km) along the right bank,
- Six Chevrons were proposed on the stretch between 4+700 and 6+300 river km along the right bank of river Drava, and
- Four Declinant Groynes were proposed on the stretch between 9+000 and 10+500 river km along the right bank of river Drava.

The creation of post-construction DEM employed technical drawings and data of regulation structures provided by the Partner. Those technical details are presented in the following table.

Table 1 Technical details of the proposed river regulation structures

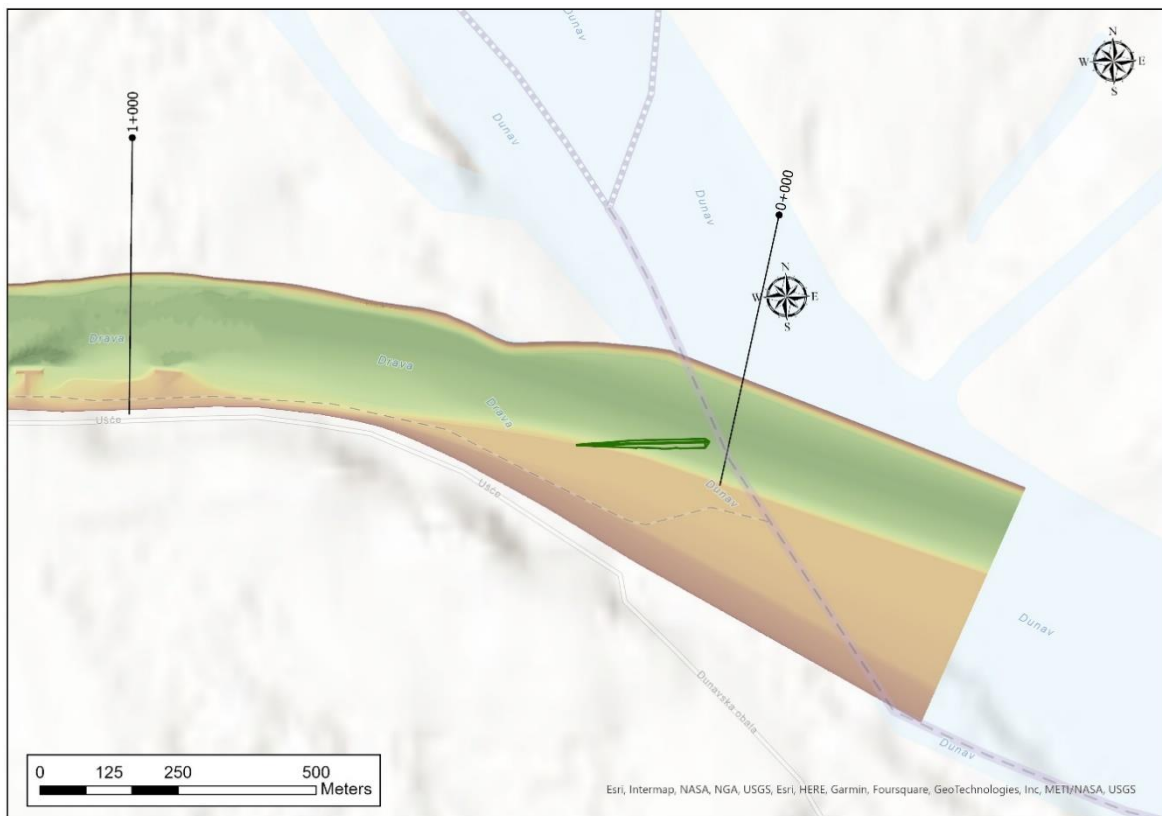
#### One Declinant Groyne at 0+000 river km

Top width = 1.0 m

Top elevation = 80.68 m asl.\*

Top length = 230.0 m

Slopes = 1:1 upstream and 1:2 downstream



### Six Chevrons at 4+700 - 6+300 river km

Top width = 1.0 m

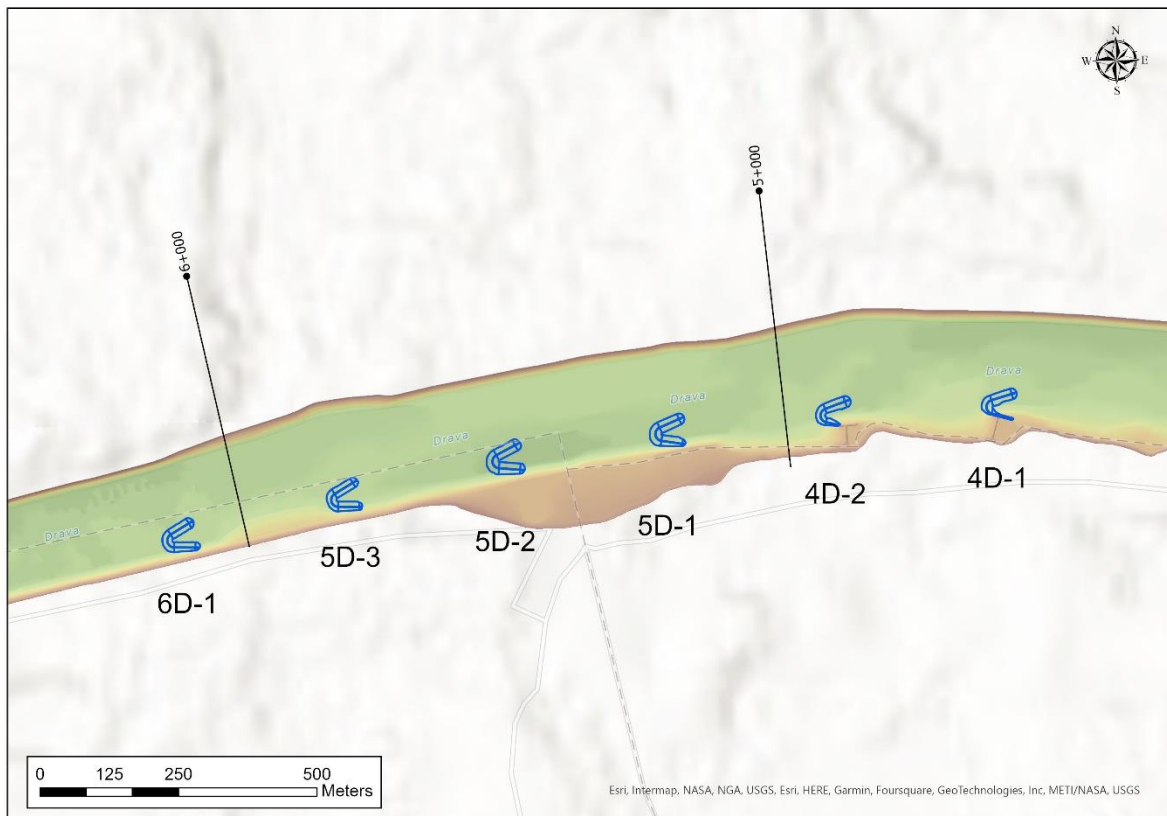
Top elevation = 80.88 m asl.\*

Top length = 110.0 m

Slopes = 1:2

Exact locations:

- Chevron 4D-1 = 4+646.30
- Chevron 4D-2 = 4+918.50
- Chevron 5D-1 = 5+216.00
- Chevron 5D-2 = 5+517.00
- Chevron 5D-3 = 5+817.50
- Chevron 6D-1 = 6+121.60



### Four Declinant Groynes at 9+000 - 10+500

Top width = 1.0 m

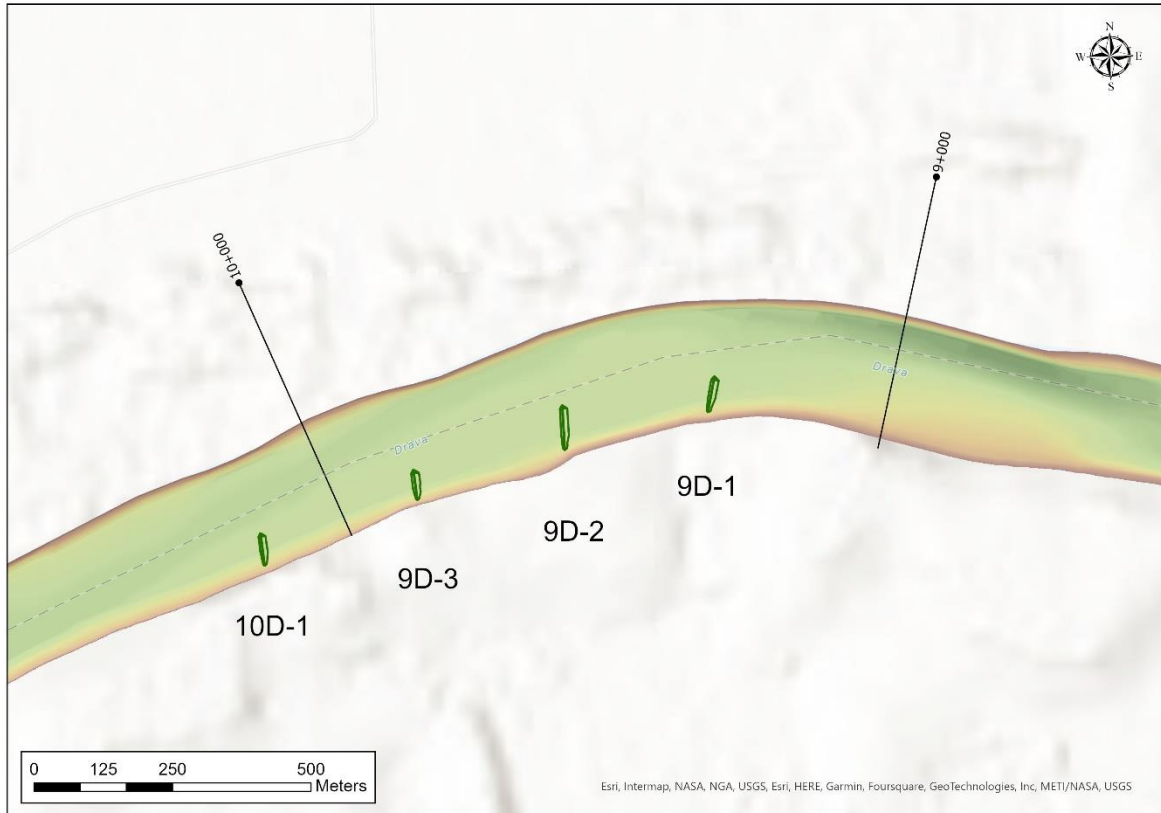
Top elevation = 81.08 m asl.\*

Top length = 57.0 m (DP9D-1); 72.0 m (DP9D-2); 47.0 m (DP9D-3); 51.0 m (DP10D-1)

Slopes = 1:1 upstream and 1:2 downstream

Exact locations:

- Declinant Groyne 9D-1 = 9+325.10
- Declinant Groyne 9D-2 = 9+599.70
- Declinant Groyne 9D-3 = 9+873.00
- Declinant Groyne 10D-1 = 10+166.00



*\*m asl. – meters above sea level.*

*Croatia uses sea level reference of the Adriatic Sea – gauging station in the Port of Trieste.*

The regulation structures were modelled in ArcGIS using their location, top width, length, and elevation information. The top contour was drawn as a 3D polyline. Respecting their slope properties, subsequent buffers were made, and appropriate elevation data was entered for each polyline. The regulation structures were modelled to have a total height of 10 meters (which is exaggerated) to ensure they would intercept with the existing terrain. The following example shows how the Declinant Groyne 9D-1 was modelled. Note that the left side of the structure on the picture (upstream facing) has a slope of 1:1, while the right side (downstream facing) has a slope of 1:2. In the case of chevrons, they have slopes of 1:2 on both sides.

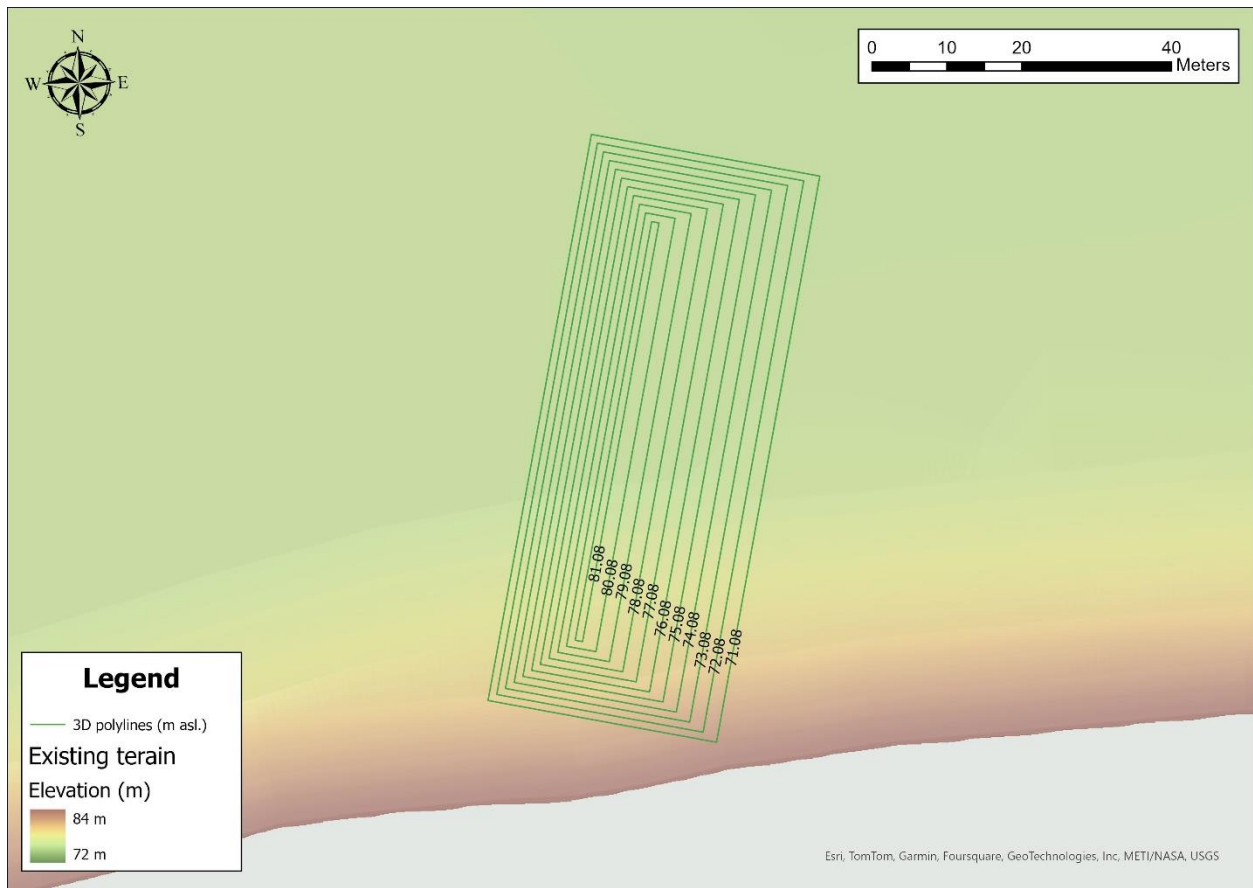


Figure 18 Modelling of Declinant Groyne 9D-1

The flow chart provided below illustrates how the polylines representing the regulation structures were incorporated into the existing terrain. On the following pages, the entire process is explained in more detail using Declinant Groyne 9D-1 as an example.

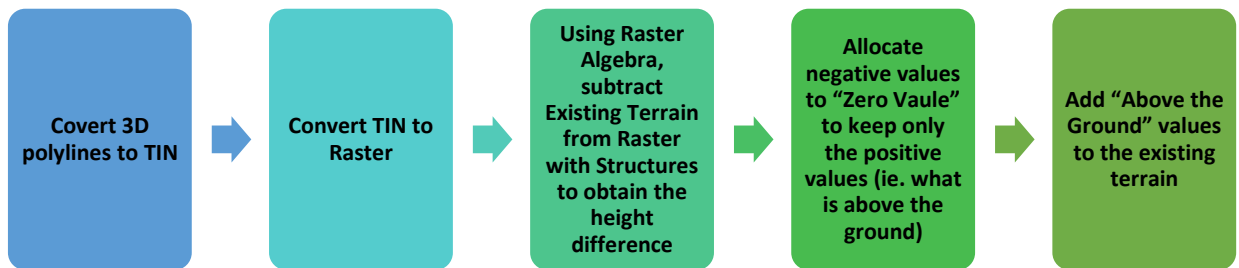
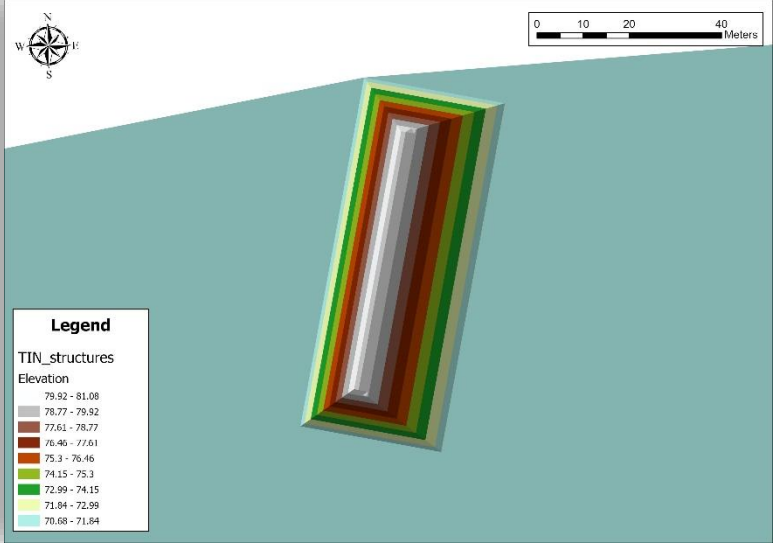
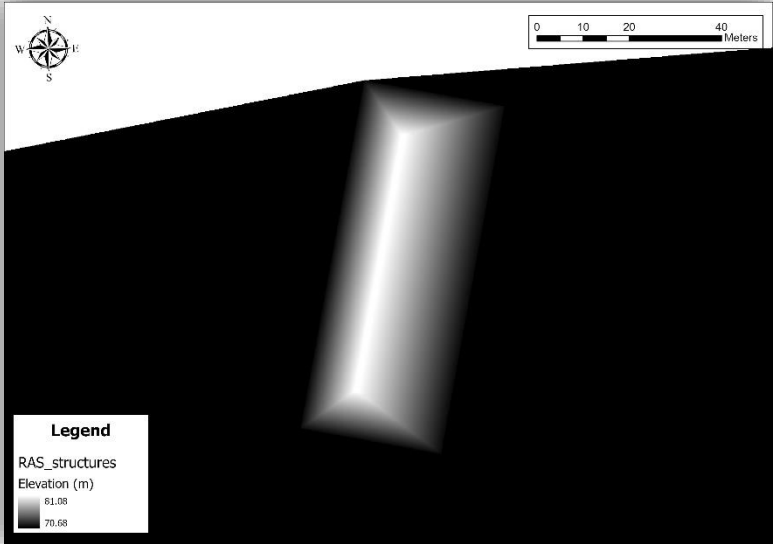


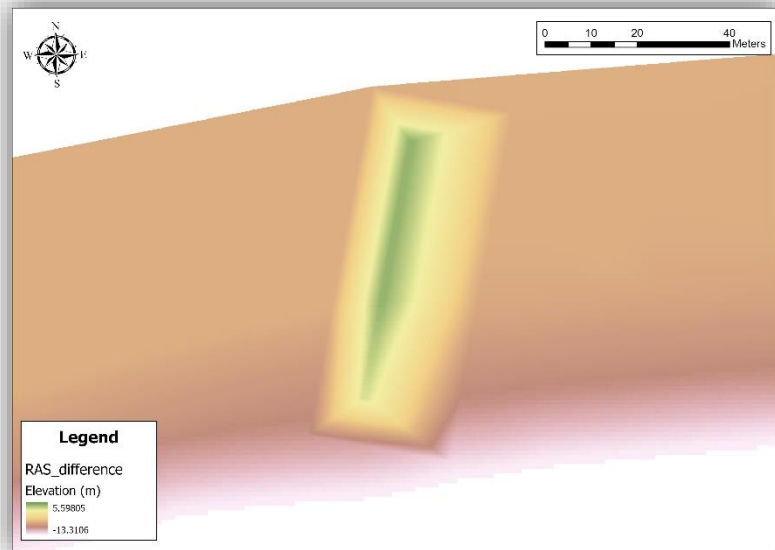
Figure 19 Regulation structures modelling workflow

Table 2 Detailed description of how regulation structures were modelled into the existing terrain with examples on Declinant Groyne 9D-1

STEP	Example
<p><b>STEP 1:</b> <b>Covert 3D polylines to TIN</b></p>	 <p>The image shows a 3D perspective view of a terrain surface (TIN) with a rectangular groyne structure. The terrain is colored in shades of green and blue, representing different elevation levels. The groyne structure is a raised rectangular platform. A legend titled 'Legend' is located in the bottom-left corner of the image, showing 'TIN_structures Elevation' with seven color-coded elevation ranges: 79.92 - 81.08 (grey), 78.77 - 79.92 (light green), 77.61 - 78.77 (medium green), 76.46 - 77.61 (dark green), 75.3 - 76.46 (light blue), 74.15 - 75.3 (medium blue), 72.99 - 74.15 (dark blue), 71.84 - 72.99 (very dark blue), and 70.68 - 71.84 (black). A scale bar (0, 10, 20, 40 Meters) and a north arrow are also present in the top-left and top-right corners of the image.</p>
<p><b>STEP 2:</b> <b>Convert TIN to Raster</b></p>	 <p>The image shows a 3D perspective view of the same terrain surface and groyne structure, but now rendered as a raster. The terrain is represented by a grid of black and grey pixels, with the groyne structure appearing as a raised rectangular platform. A legend titled 'Legend' is located in the bottom-left corner of the image, showing 'RAS_structures Elevation (m)' with two grayscale values: 81.08 (white) and 70.68 (black). A scale bar (0, 10, 20, 40 Meters) and a north arrow are also present in the top-left and top-right corners of the image.</p>

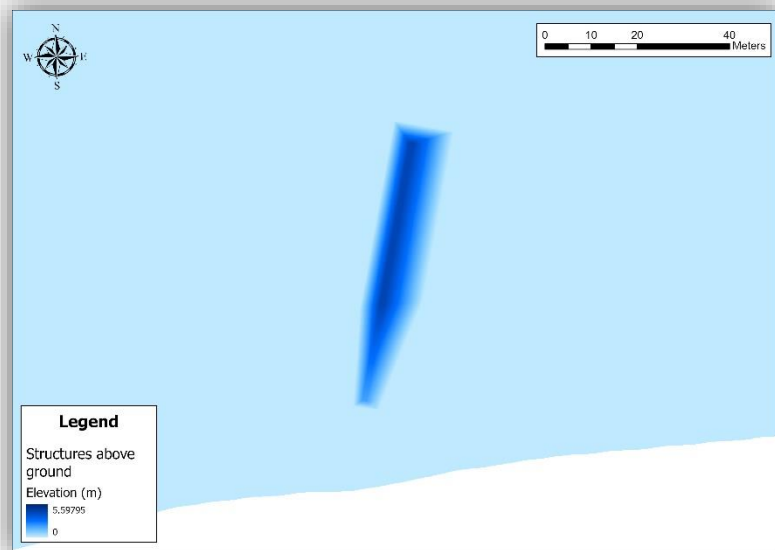
**STEP 3:**

Using Raster Algebra, subtract Existing Terrain from Raster with Structures to obtain the height difference – this raster gives the height of structures relative to the existing terrain



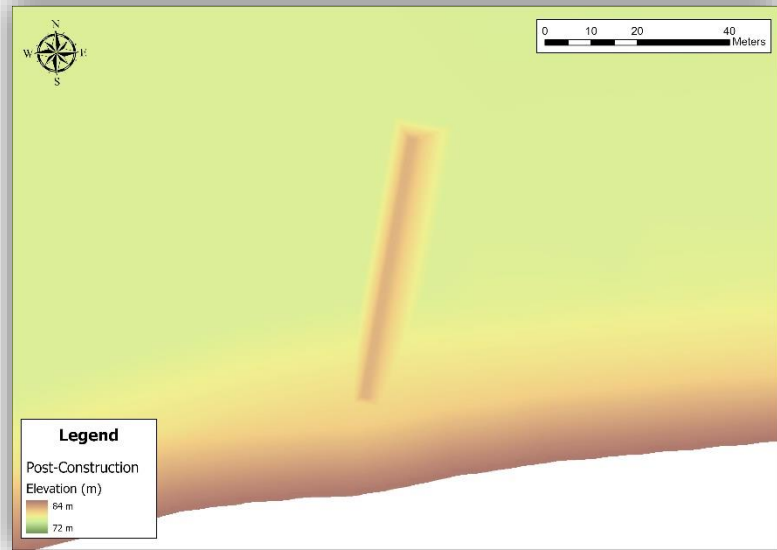
**STEP 4:**

Allocate negative values to "Zero Value" to keep only the positive values (ie. what is above the ground)



**STEP 5:**

**Add "Above the Ground"  
values to the existing  
terrain**



Since we used current-state terrain as a basis for adding the proposed regulation structures, both current-state and post-construction terrain models have the same extent and resolution. Terrains also include a slightly longer river stretch on both the downstream and upstream sides. However, for the modelling, the exact stretch of 12 kilometres was used. The following figures show the digital terrain model of the river Drava in the post-construction state.

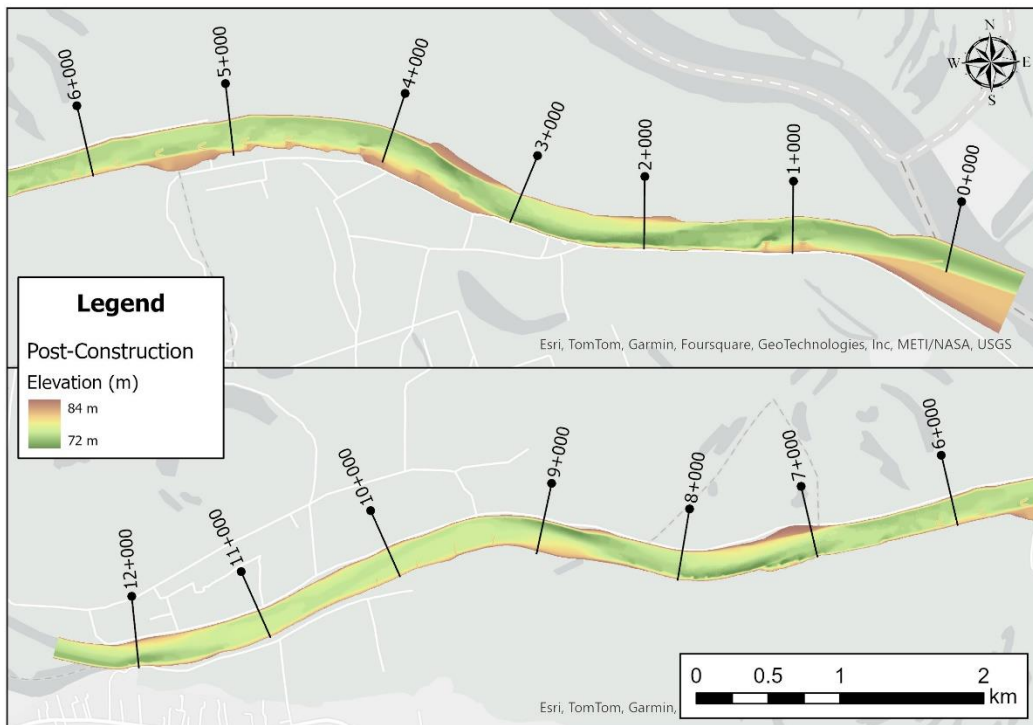


Figure 20 Digital terrain model of the river Drava in the post-construction state



Figure 21 Digital terrain model of the river Drava in the post-construction state – detail around river kilometre 6 showing chevrons 5D-3 and 6D-1

Terrains in both current and post-construction states have a range of values between 72 and 84 meters above sea level with 72 meters representing the deepest parts of the river and 84 being the high banks. Proposed regulation structures are between 5 and 6 meters in height.

## 2.4 Hydrological Data

In the wider area of the research, there are four river gauge stations, two on the river Drava and two on the Danube (as shown in Figure 22). The Croatian Water Management Authority provided the official data from those four gauge stations and the Study received from the Partner includes a very detailed analysis of hydrologic data.

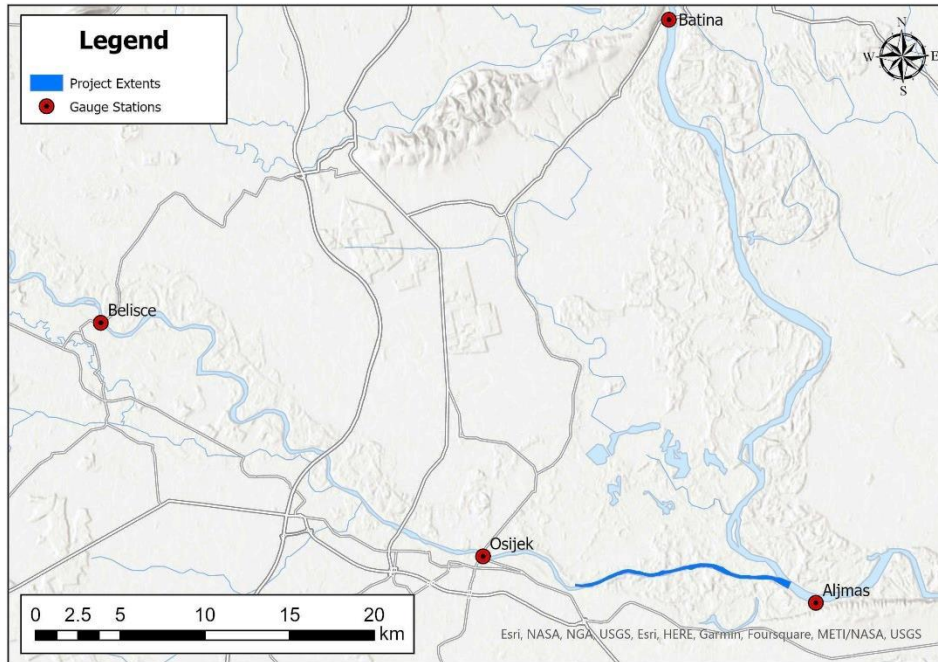


Figure 22 Location of river gauge stations on the Danube and Drava

The following table provides some basic information on those four gauge stations.

Table 3 Basic information on gauge stations

River	Gauge Station	Location (river km)	Operational since	Water flow Q (m <sup>3</sup> /s)	Water station H (m asl.)
<b>DRAVA</b>	BELIŠĆE	53+800	1691	1962 -	1962 -
<b>DRAVA</b>	OSIJEK	18+960	1827	n/a	1900 -
<b>DANUBE</b>	BATINA	1424+840	2001	2006 -	2001 -
<b>DANUBE</b>	ALJMAŠ	1381+500	1909	2006 -	1923 -

Based on the data pool available in the Study, the research focuses on the following:

- two characteristic water level conditions:
  - o Lowest navigable water level, and
  - o Average water level.
- water flow (Q) and water surface level (h) information for those two conditions.

The Lowest navigable water level as defined in the previous chapter, is relevant for this research as it forms the basis for defining safe navigation depths. The other relevant water level is the Average water level, which as its name implies, “is the average water level measured at a water gauge over a specific time period (ViaDonau, 2023)”. The average water level also gives a more common representation of river flow dynamics contrary to the Lowest navigable water level which represents the lower end of the river dynamics spectrum. Average water level is an additional important factor in navigation as it was used to determine the height of river regulation structures (Hidroing, 2019). Lastly, for the validity of the results of this research, it was important to include more than one water level condition.

Data required for modelling in HEC-RAS should at least include water flow and water surface elevation information. Therefore, water flow (Q – m<sup>3</sup>/s) and water surface level (h – m asl.) for those two water level conditions are required as input data for modelling.

Water flow is uniform throughout the research area as there are no major tributaries to river Drava in this region. On the other hand, water surface elevation is gradually decreasing throughout the stretch of 12 kilometres, and the data for water surface elevation is needed for both upstream and downstream ends of the project extent.

As a part of the hydrologic analysis in the Study, a 1-D HEC-RAS model was created to feed all the raw data and to obtain the exact measurements of water flow and water surface elevation in the project area. The 1-D model was provided by the Partner and data readings were taken exactly at 0 and 12 river kilometres. The following table shows the data extracted from the 1-D HEC-RAS model that was used for further analysis. This data represents the real-world data which was used for the current state model.

*Table 4 Hydrologic input data for HEC-RAS modelling*

Condition	Water flow (Q)	water surface level (h)	
		12+000 r. km	0+000 r. km
<b>AWL (Average water level)</b>	522 m <sup>3</sup> /s	81.13 m	80.52 m
<b>LNWL (Lowest navigable water level)</b>	290 m <sup>3</sup> /s	79.54 m	78.45 m

## 2.5 Creating 2-D Model

To create a 2-D unsteady flow model in HEC-RAS the following basic steps were performed:

- Importing of digital terrain models
- Creating Geometry
  - o Establish 2D Flow Area,
  - o Create mesh over the flow area using the digital terrain model, and
  - o Define boundary conditions – upstream and downstream boundaries.
- Creating Unsteady Flow Data

These steps are further elaborated in the following text.

### ➤ *Importing of digital terrain models*

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Prepared digital terrain models were imported in HEC-RAS using the RAS Mapper interface. RAS Mapper is a graphical interface of HEC-RAS used for editing various spatial data as well as viewing modelling results. For the successful implementation of multiple analyses, it is important to associate terrain models with corresponding geometries and unsteady flow data. This step is done in RAS Mapper too and it ensures that analyses and outputs are based on a correct set of input data.

For this research, there will be a total of 4 analysis combinations performed:

- Lowest navigable water level flow based on current state terrain,
- Average water level flow on current-state terrain,
- Lowest navigable water level flow based on post-construction terrain, and
- Average water level flow on post-construction terrain.

### ➤ *Creating Geometry*

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The Geometric Data editor in HEC-RAS provides multiple options for entering river reaches and cross sections (1-D models), 2D flow areas (2-D models) and different river engineering features such as storage areas, lateral structures, bridges, etc. For this research, a Geometric Data Editor was used to define a basic 2D Flow Area, ie. the area of flow calculations.

- o Establish 2D Flow Area

The 2D flow area was prepared in ArcGIS and has been entered in the Geometric Data editor via point coordinates. The flow area includes the entire riverbed up to the high banks to ensure that water in the model always stays within the riverbed, ie. there are no losses within the model. The flow area stretches exactly from 0 to 12 river kilometres. The 2D flow area is the same for all four analyses.

- o Create mesh over the flow area using the digital terrain model

For the defined Flow Area, HEC-RAS creates a computational mesh which is the basis for all flow calculations. Regardless of the terrain resolution, the computational mesh can be generated at different resolutions.

After some trial and error, the computational mesh for this research was defined at 2 x 2 meters resolution. The higher the mesh resolution, the greater the calculation times and the greater the output files are. On the other hand, it is desirable to have resolution as high as possible to provide the most accurate modelling results as possible. The resolution of 2 x 2 meters proved to be a perfect balance.

One feature that HEC-RAS offers which was useful for this research was the creation of breaklines. Breaklines are lines representing features within the riverbed, so the computational mesh accounts for these features in the best possible way. In the project area, there are several existing river regulation structures which were traced using the breaklines feature. Also, all the proposed regulation structures in the post-construction terrain model were outlined using breaklines.

Current-state and post-construction meshes contain a total of 678.062 cells each.

- Define boundary conditions – upstream and downstream boundaries

Once the meshes for two different terrain models were created, the next step was to define upstream and downstream boundaries. Boundaries are simple lines drawn along the edges of the 2D flow area to the far upstream and downstream edges respectively.

Figure 23 shows a part of the current-state digital terrain model with computational mesh, breaklines over the existing regulation structures and downstream boundary in the Geometric Data editor.

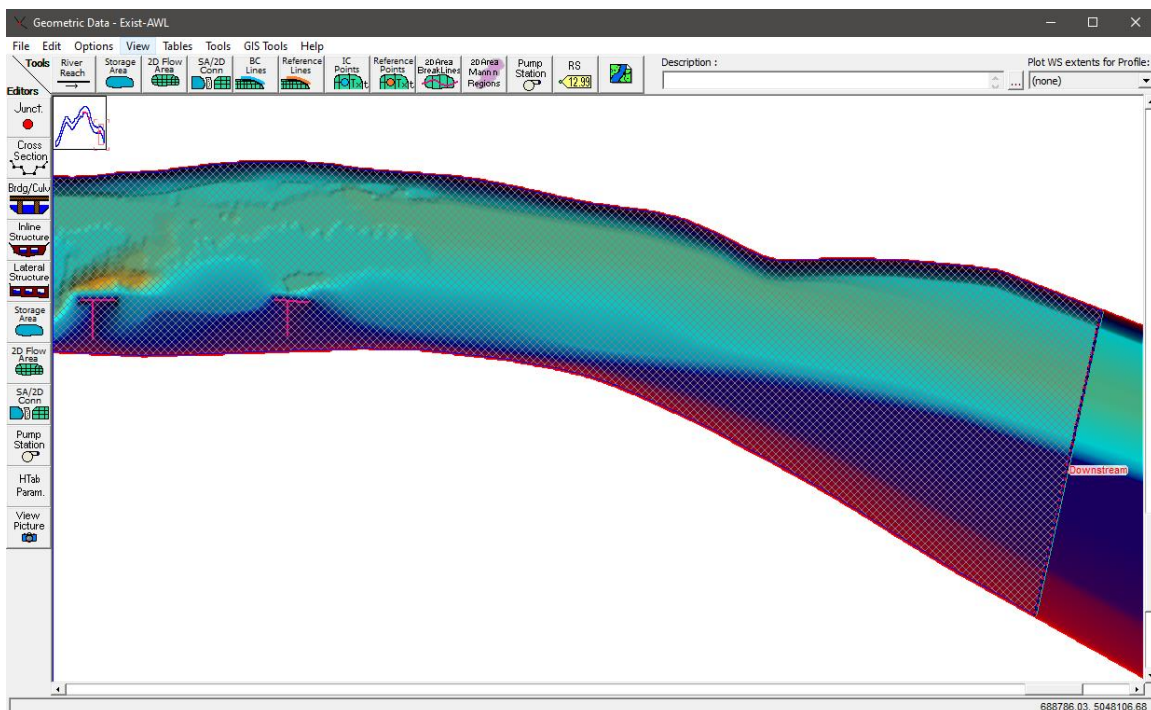


Figure 23 Geometric Data editor with features required for computational model

### ➤ **Creating Unsteady Flow Data**

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As previously mentioned, data for modelling in HEC-RAS should at least include water flow and water surface elevation information. This is half true as the model only needs water flow value to run, but the water surface elevation values on the upstream and downstream ends are required for calibration of the model.

Water flow data for two water level conditions (Average water level – AWL and Lowest navigable water level – LNWL) is entered in the Unsteady Flow Data editor and stored as two separate input files. Water flow data is entered for the location of the Upstream boundary.

## 2.6 Model Calibration

Once the data required for the model to be processed is entered, the next step is the calibration of the model. Calibration is performed only for the current-state terrain for both Average water level and Lowest navigable water level conditions. The aim is to have the output of HEC-RAS flow calculations match upstream and downstream water surface elevation values as provided in Table 4.

Calibration can be done by adjusting two variables that are part of the flow calculation equations, namely:

- **Manning's n value or Manning's roughness coefficient** – the loss of energy due to roughness or friction in open channels (Ye, et al, 2018) and one of the most important parameters in hydrological calculations, and
- **Friction slope** - the slope of the energy grade line (US Army Corps of Engineers, 2023a).

According to the HEC-RAS Manual (US Army Corps of Engineers, 2023a), the n value range is between 0.025 and 0.05 for open-water areas, ie. natural streams on mild to moderate slopes. Manning's n value was assumed to be uniform across the entire 2D Flow Area as the research concerns only average and low water levels, ie. when the water is flowing within the riverbed.

In terms of Friction slope, again according to the HEC-RAS Manual (US Army Corps of Engineers, 2023a), this value can be based on the land slope over the extent of the model or the slope of the water surface if the friction slope is unknown.

An interesting fact is that the river Drava is under the significant influence of the Danube. Water flow in Average water level conditions on Danube can be 5 times as much as on Drava (Hidroing, 2019) and depending on the coincidence of different conditions of those two rivers, the Danube can even cause backflow of river Drava in this section. Having this in mind, Friction slope value can vary greatly in different conditions.

Manning's n and Friction slope values were adjusted using recommendations from the HEC-RAS manual and considering the above-mentioned phenomena to get the real-world values on the project area as defined in Table 4. of Chapter 2.4 Hydrological Data. Manning's n is accounted as a part of mesh attributes while Friction slope is defined as a part of Unsteady Flow Data.

The final values of these two variables that provided real-world values for the current state model are given in Table 5.

Table 5 Final Manning's n and Friction slope values

Condition	Manning's n value	Friction slope
AWL	0.0287	0.0000327
LNWL	0.029	0.0000575

Once the current state model was calibrated, the same values were used for the post-construction terrain.

## 2.7 Running the Model

HEC-RAS performs flow calculations in time steps. For the model to run, it is necessary to specify the time range for the simulation, the time interval within that time range at which calculations are performed and the time interval at which the snapshots of our results are taken. Following the HEC-RAS manual suggestions along with a trial-and-error approach, the following computational setting was selected for all the simulations:

- Simulation time: 24 hours
- Computational Interval: 1 minute
- Mapping output interval: 5 minutes

A 2D Diffusion Wave equation has been used for simulations. On average, one run of Unsteady 2D-Flow analysis took around 15 minutes to complete.

Figure 24 shows the dialogue box displayed at the end of the simulation process.

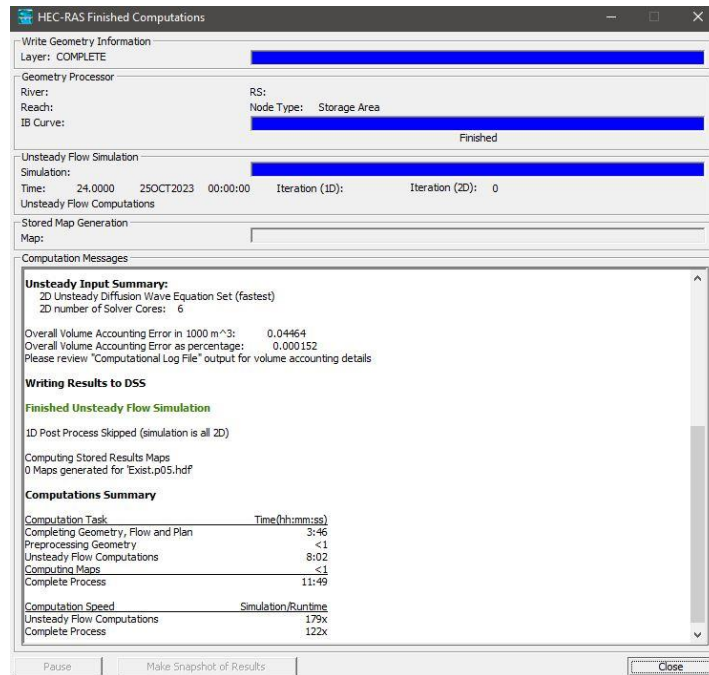


Figure 24 HEC-RAS computation summary

It is important to mention that the simulation starts completely dry, and the water takes time to fill in the terrain. After about 12 hours, the river channel is filled and there are no further variations in water levels. Therefore, it can be assumed that the model is stable after 12 hours and that the simulation time of 24 hours provides sufficiently accurate results for a single water flow (Q) value.

## 2.8 Outputs

Following the outlined approach, a total of 4 analysis combinations were performed. As a result of the HEC-RAS simulation, the following default variables/outputs are provided in the form of raster files:

- Water surface elevation (m asl.)
- Depth (m)
- Velocity (m/s)

Apart from these defaults, HEC-RAS provides the option to perform further calculations and provide additional results parameters. Having in mind the research question, the additional two parameters were selected as a part of the analysis output:

- Shear Stress (Pa)
- Stream Power (N/ms)

Per Wang (2015), the formula for Shear Stress is the following:

$$\tau = \gamma R s$$

where:

$\tau$  = shear stress

$\gamma$  = specific weight of water

R = hydraulic radius

s = riverbed slope / energy slope

Stream Power equals the average Velocity times the average Shear Stress (HEC-RAS Mapper User's Manual, 2023).

Per Wang (2015), Stream Power can be also calculated as follows:

$$P = \gamma Q s / P = v \tau$$

where:

P = stream power

$\gamma$  = specific weight of water

Q = discharge

s = riverbed slope / energy slope

These two additional variables are important for the outcomes of this research. Velocity, Shear Stress, and Stream Power are the main drivers of geomorphic processes including erosion, sediment transport, and sediment deposition (Wang, 2015). Also, it should be noted that the concentration of flow into narrower

channel area and intensified shear stress can lead to continuous incision of the riverbed which is one of the biggest problems related to the construction of regulation structures (ICPDR, 2010).

These outputs can be viewed together with other spatial data in the RAS Mapper but can also be exported in TIFF raster format for use in other GIS software. The output of the modelling consists of five raster datasets for each of the four simulations, which gives a total of twenty raster files.

The summary of the modelling process in HEC-RAS is summarized in Figure 25.

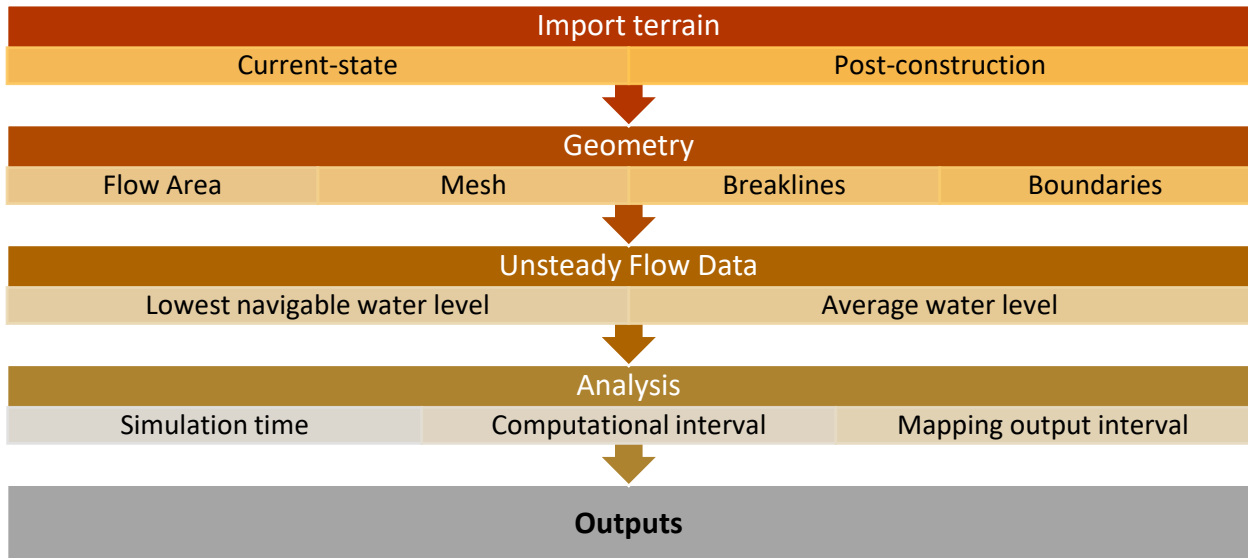


Figure 25 HEC-RAS modelling process

### 3. Results and Analysis

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This chapter provides an in-depth look into results obtained by hydrologic modelling in HEC-RAS. The results are grouped according to 4 different analysis combinations defined in the previous chapter. For each of those analyses, 5 different datasets are presented and analysed.

It should be noted that all exports are made from the final Mapping output timestep of the calculation, ie. the 24<sup>th</sup> hour of the simulation. As mentioned in the previous chapter, it is assumed that the model is stable at this point and that this timestep gives the best representation of the real-world situation.

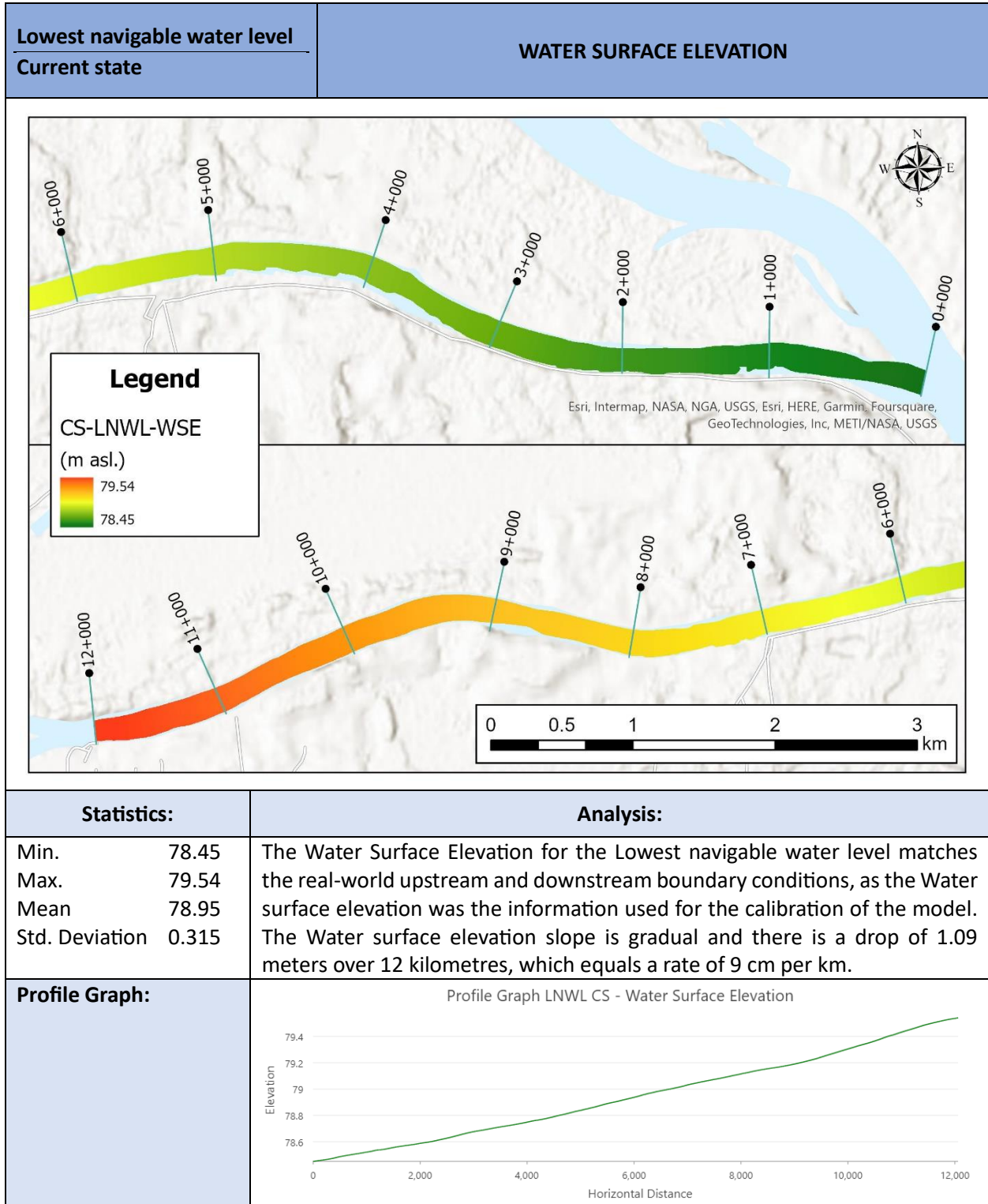
After the analysis of the outputs of HEC-RAS modelling, the comparison of current-state and post-construction results was performed for each variable. For the comparison, the Raster Calculator from ArcGIS Image Analyst Tools was used.

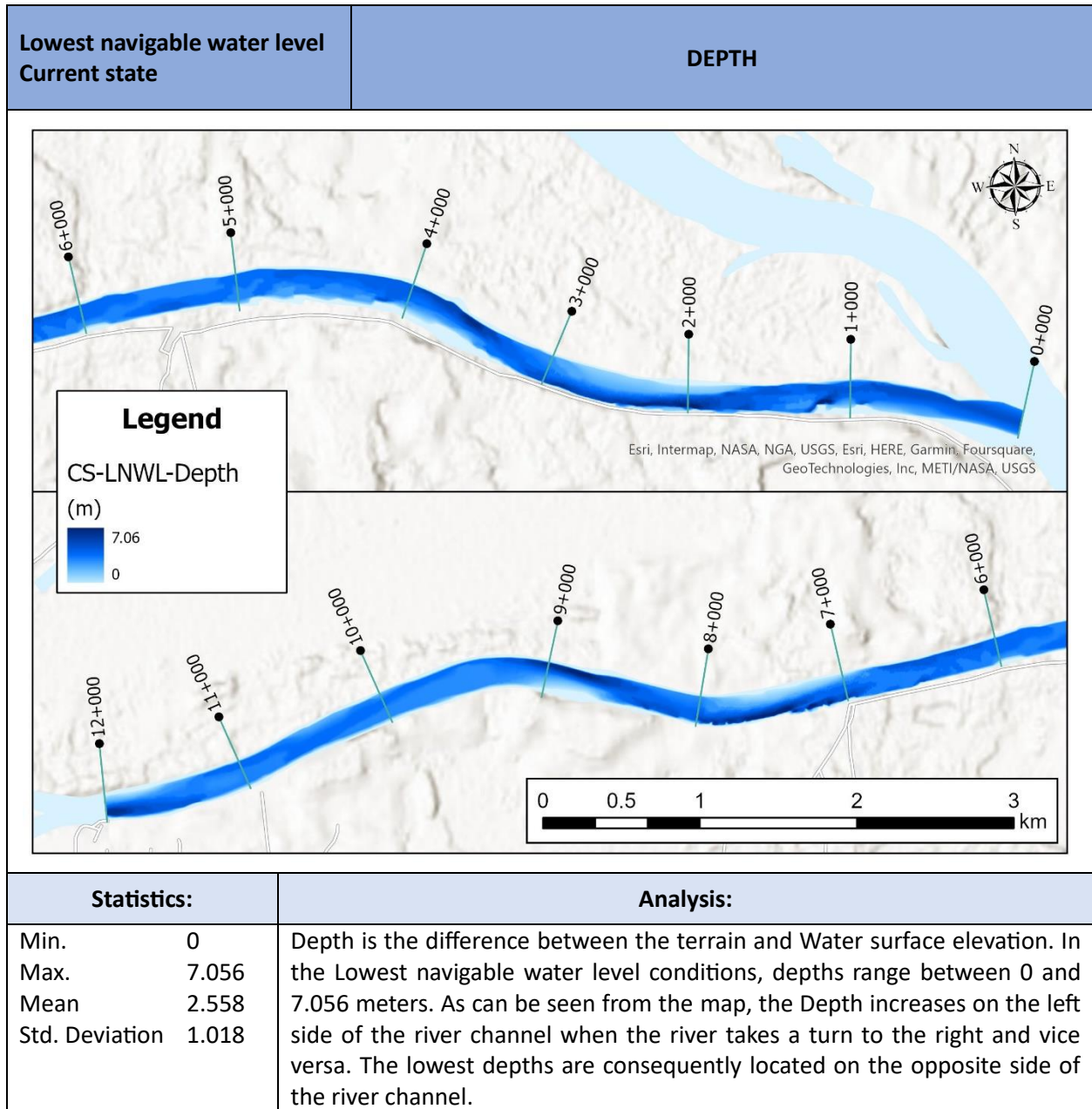
Simple Raster Calculator formula:

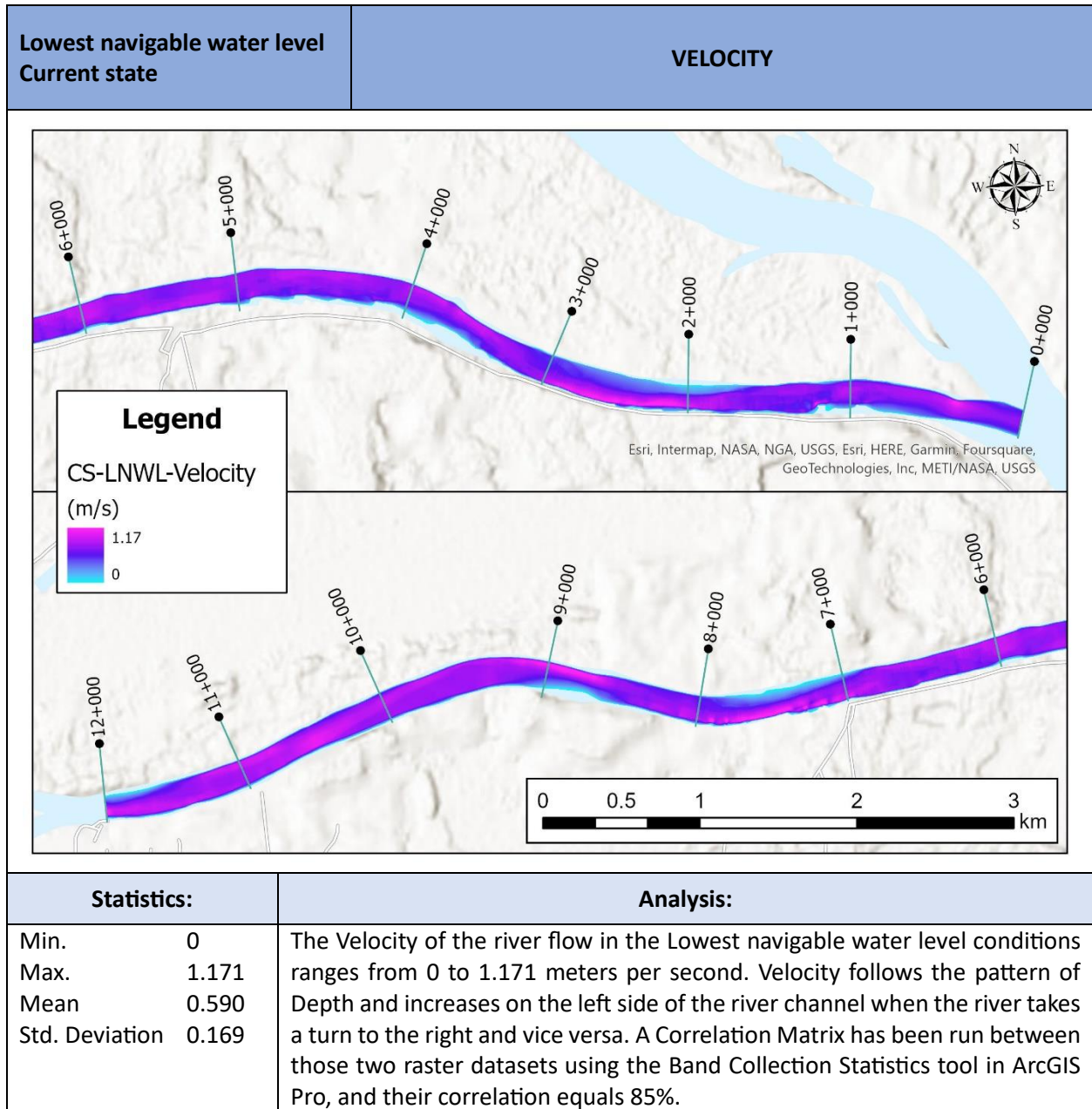
***post-construction datasets – current-state datasets = difference (comparison datasets)***

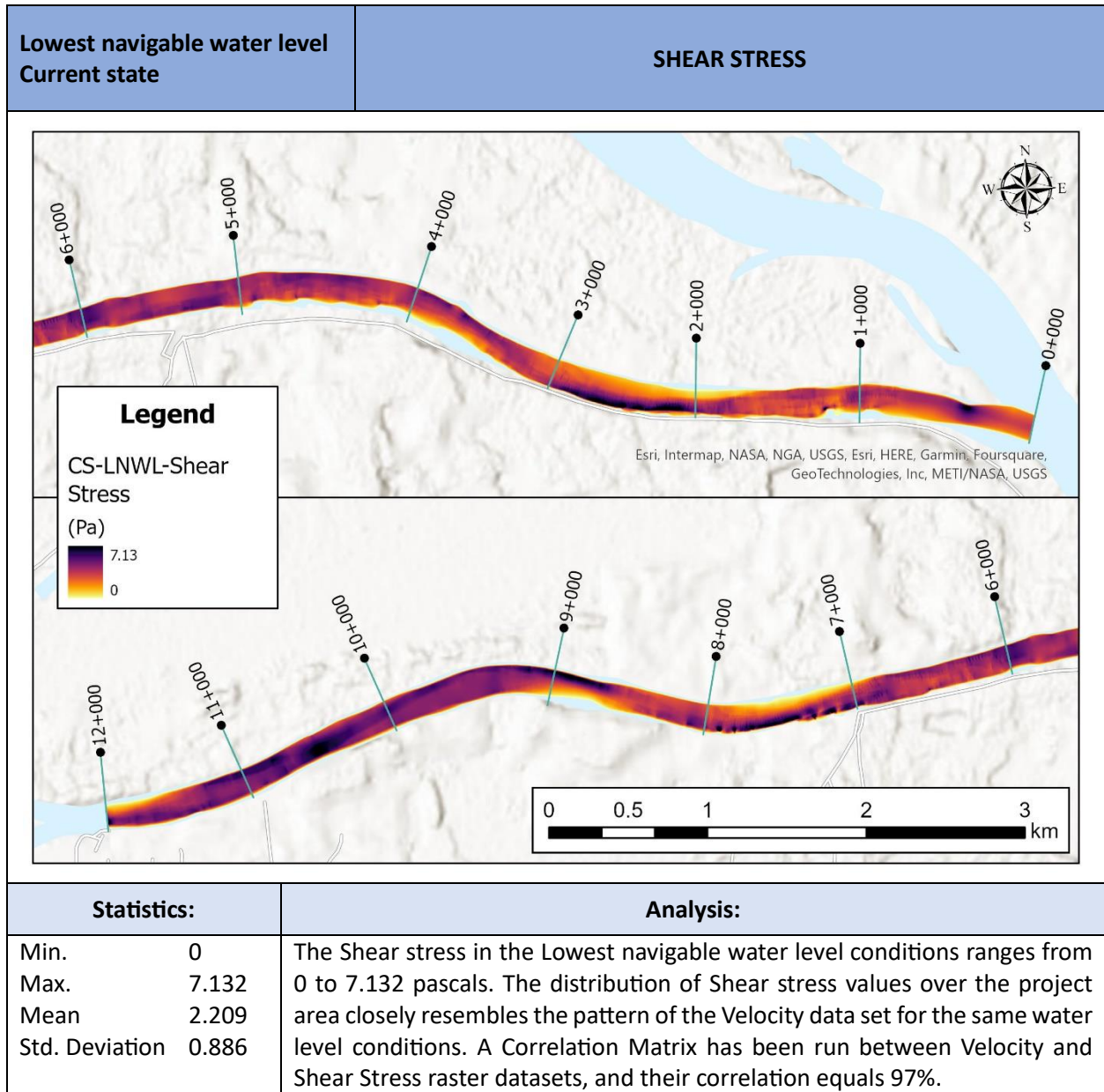
### 3.1 HEC-RAS Outputs

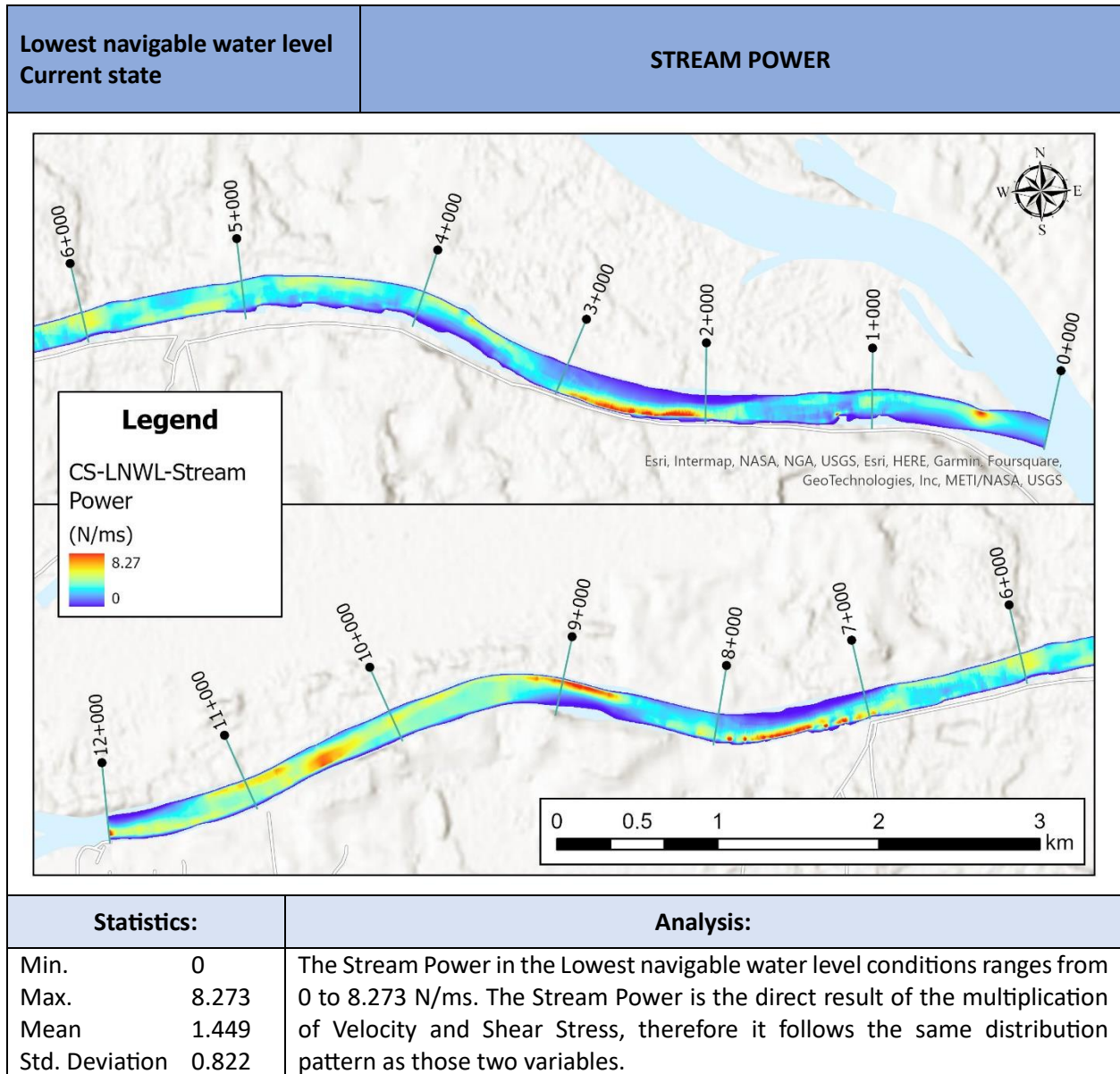
#### 3.1.1 Lowest Navigable Water Level- Current State



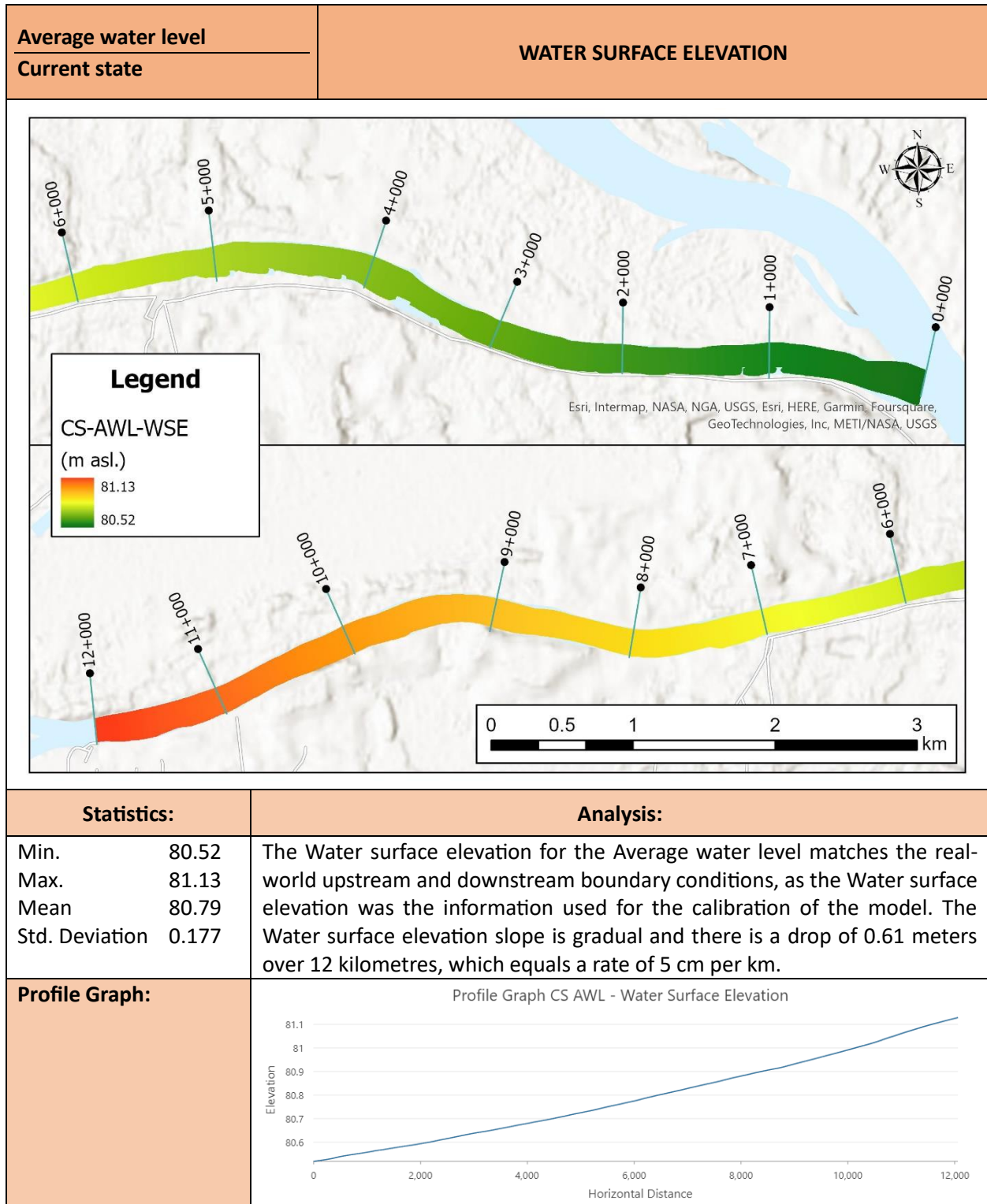


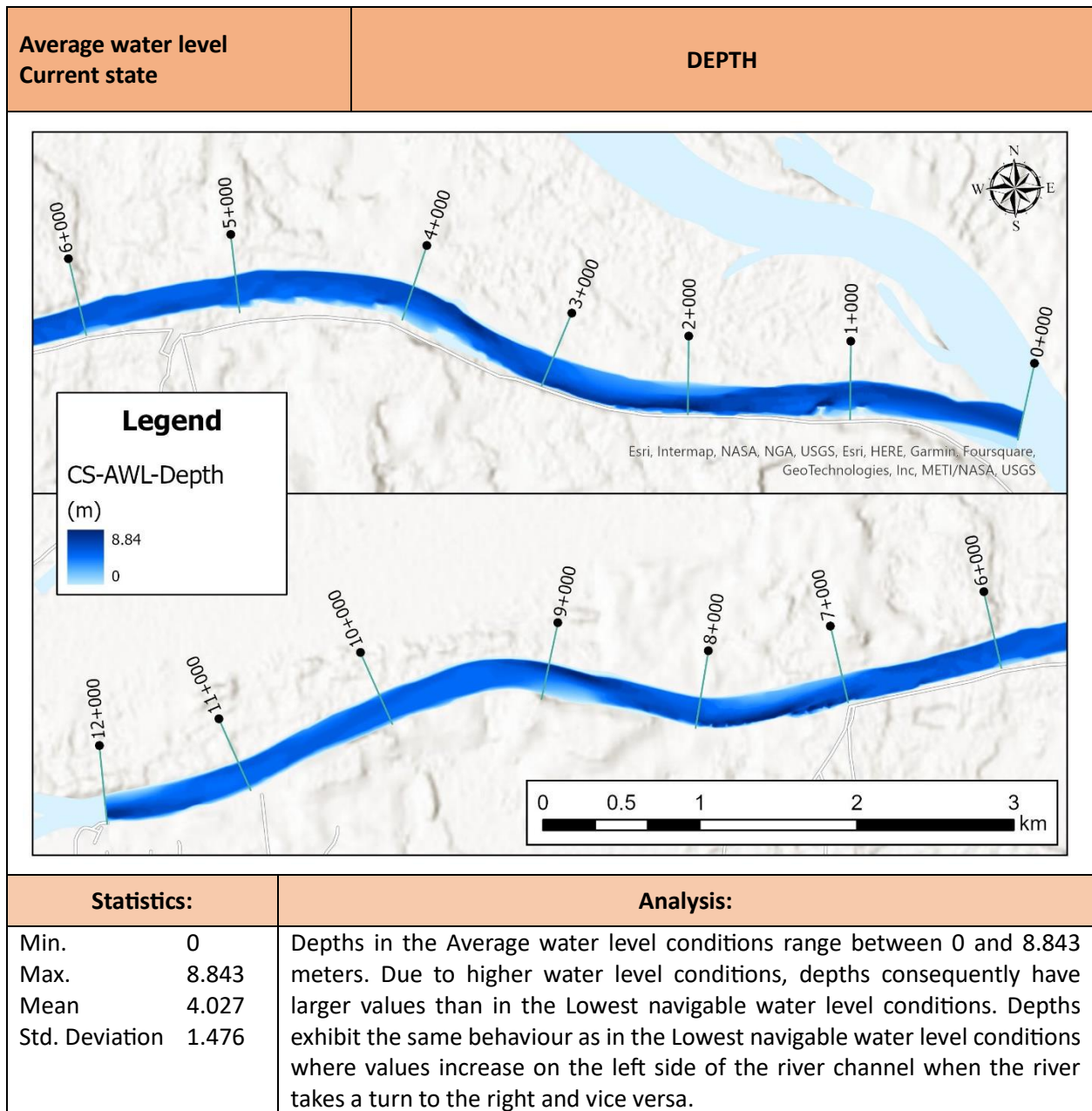


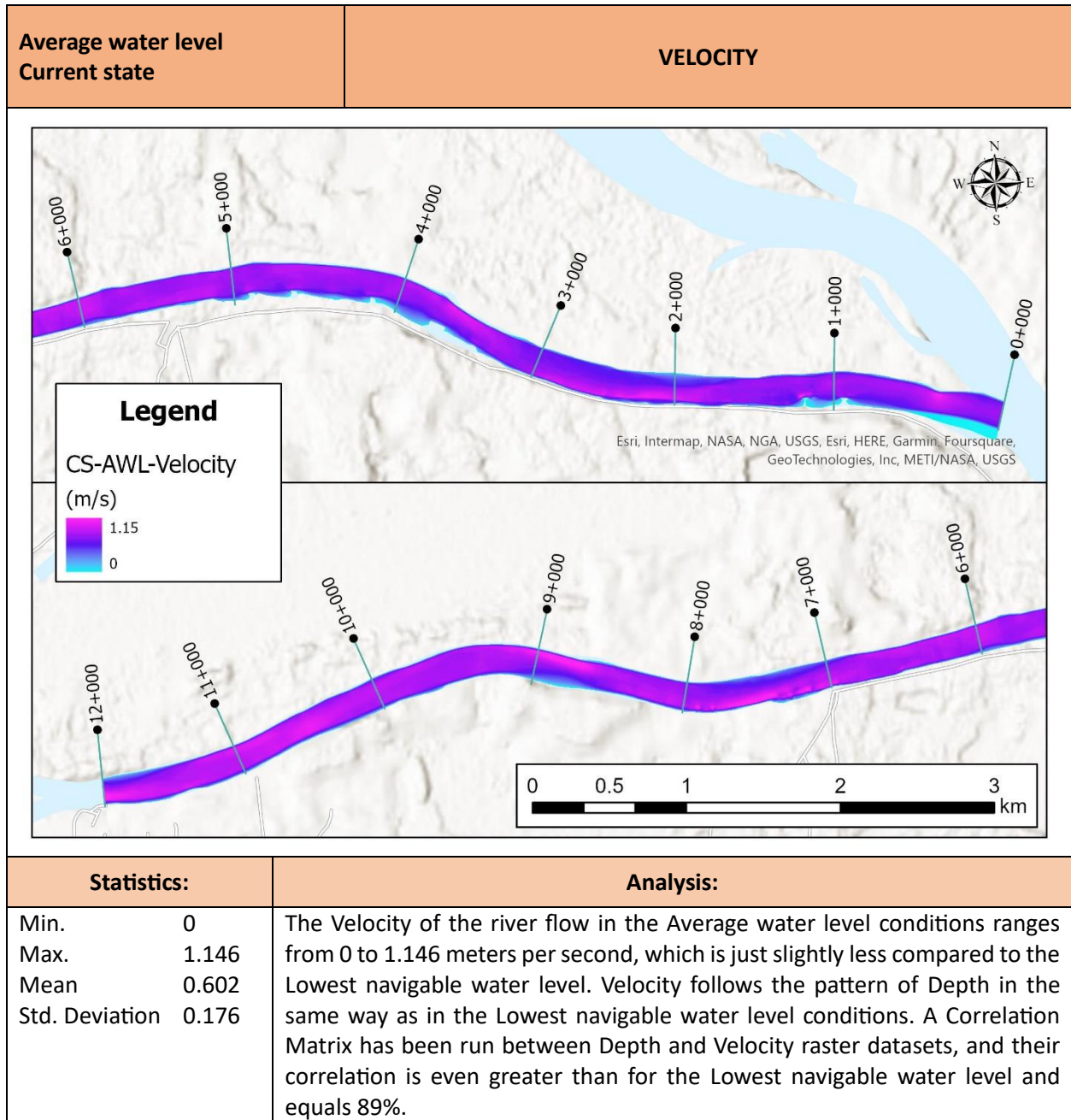


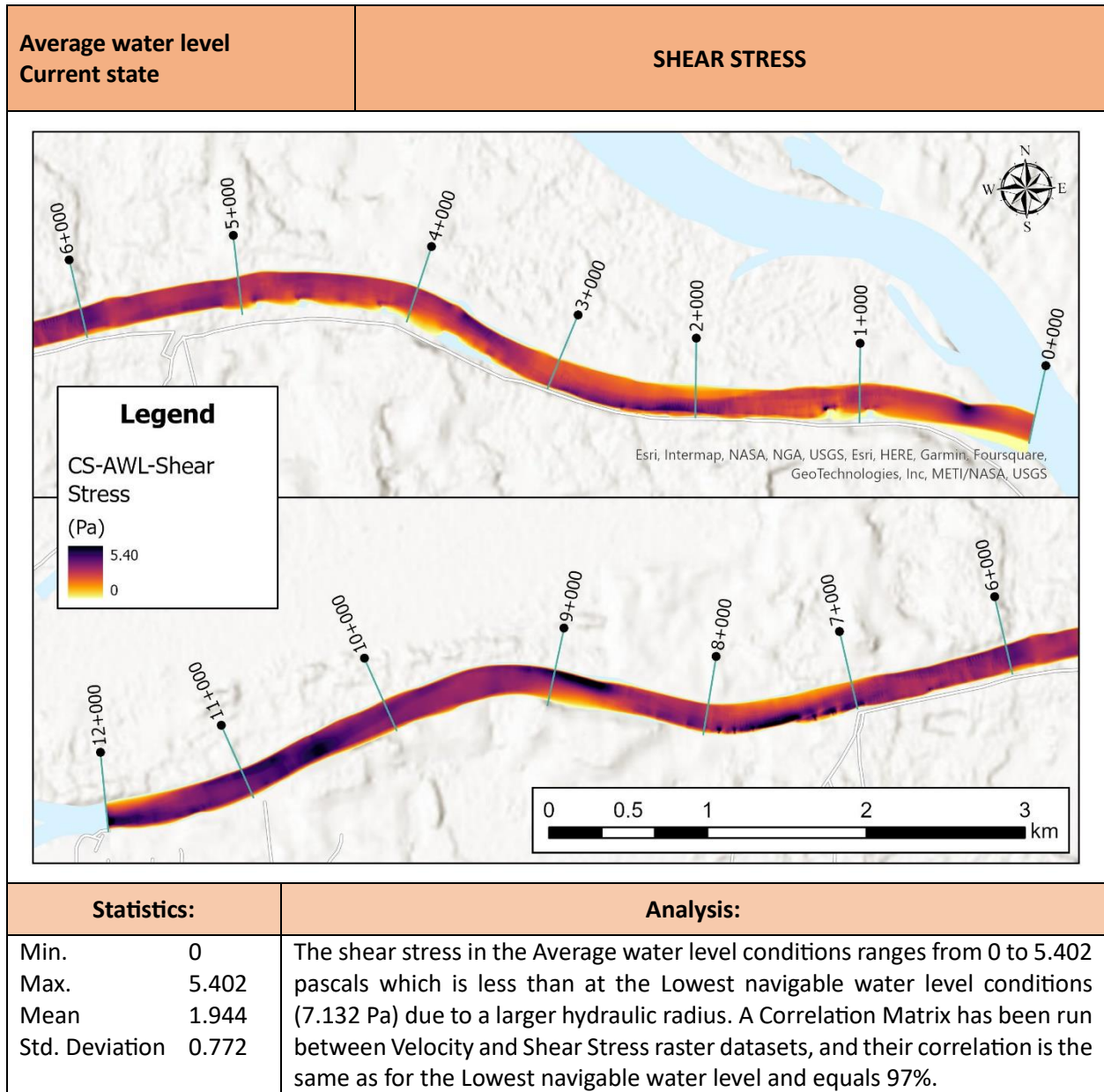


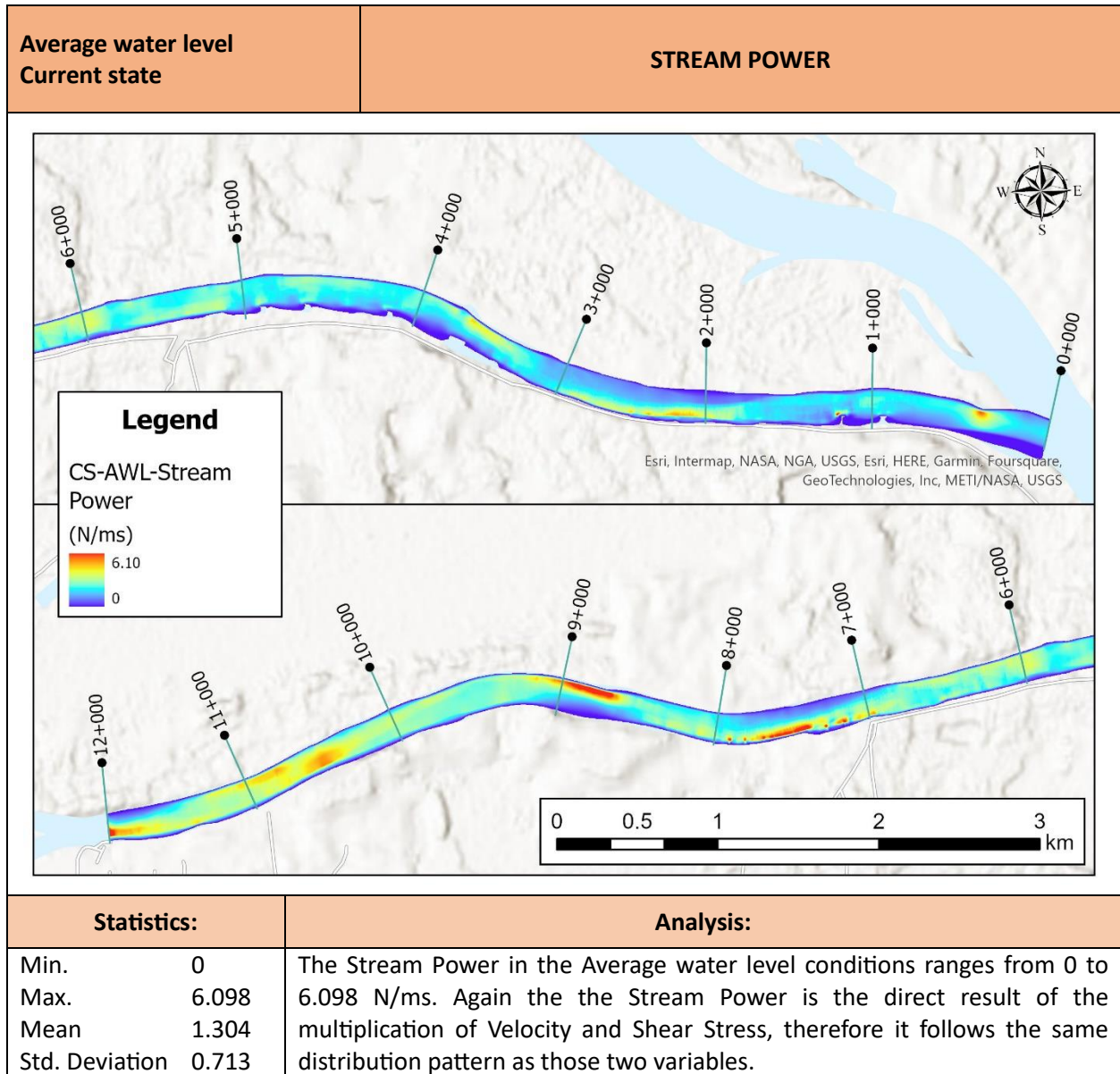
3.1.2 Average Water Level - Current State



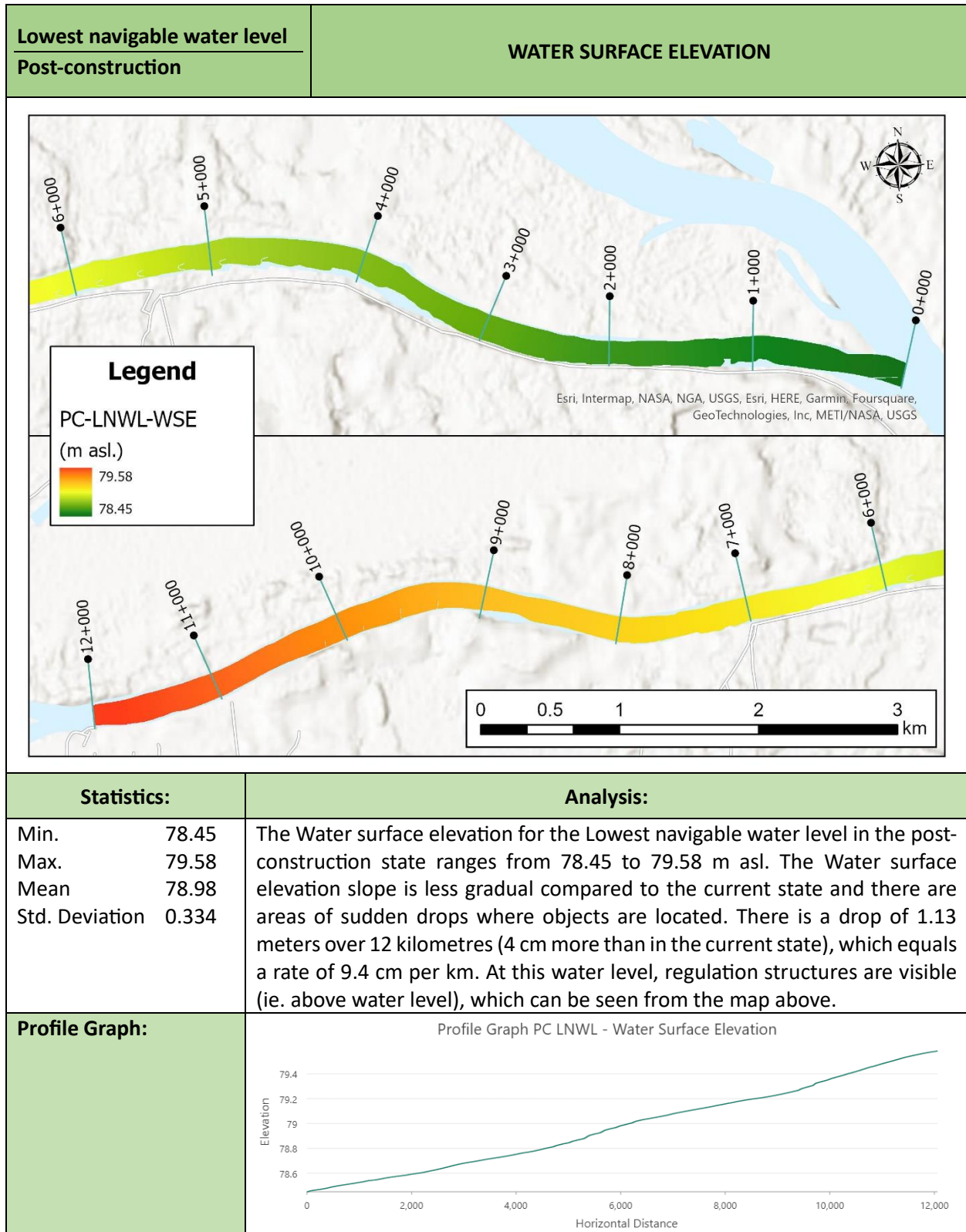


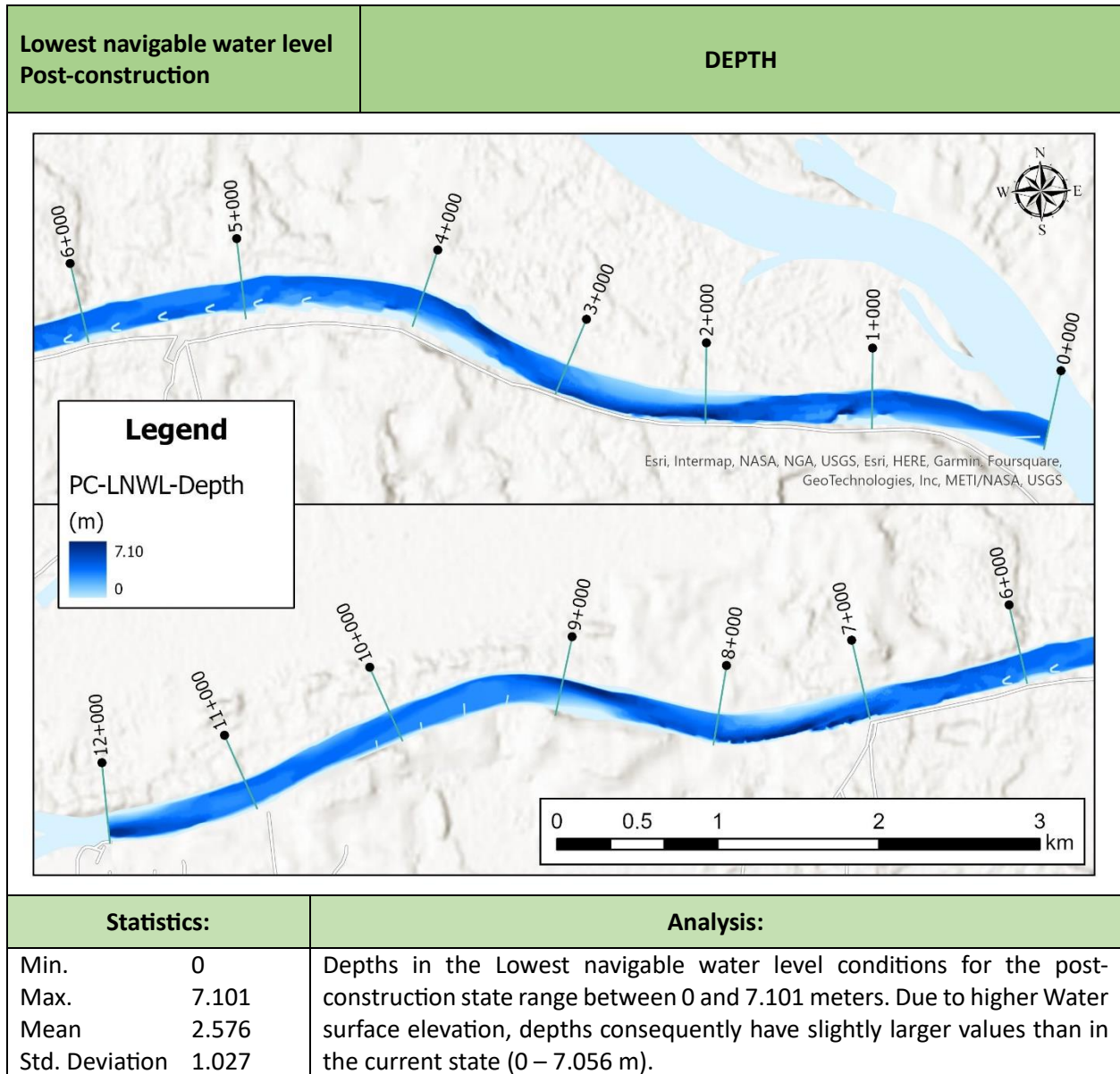


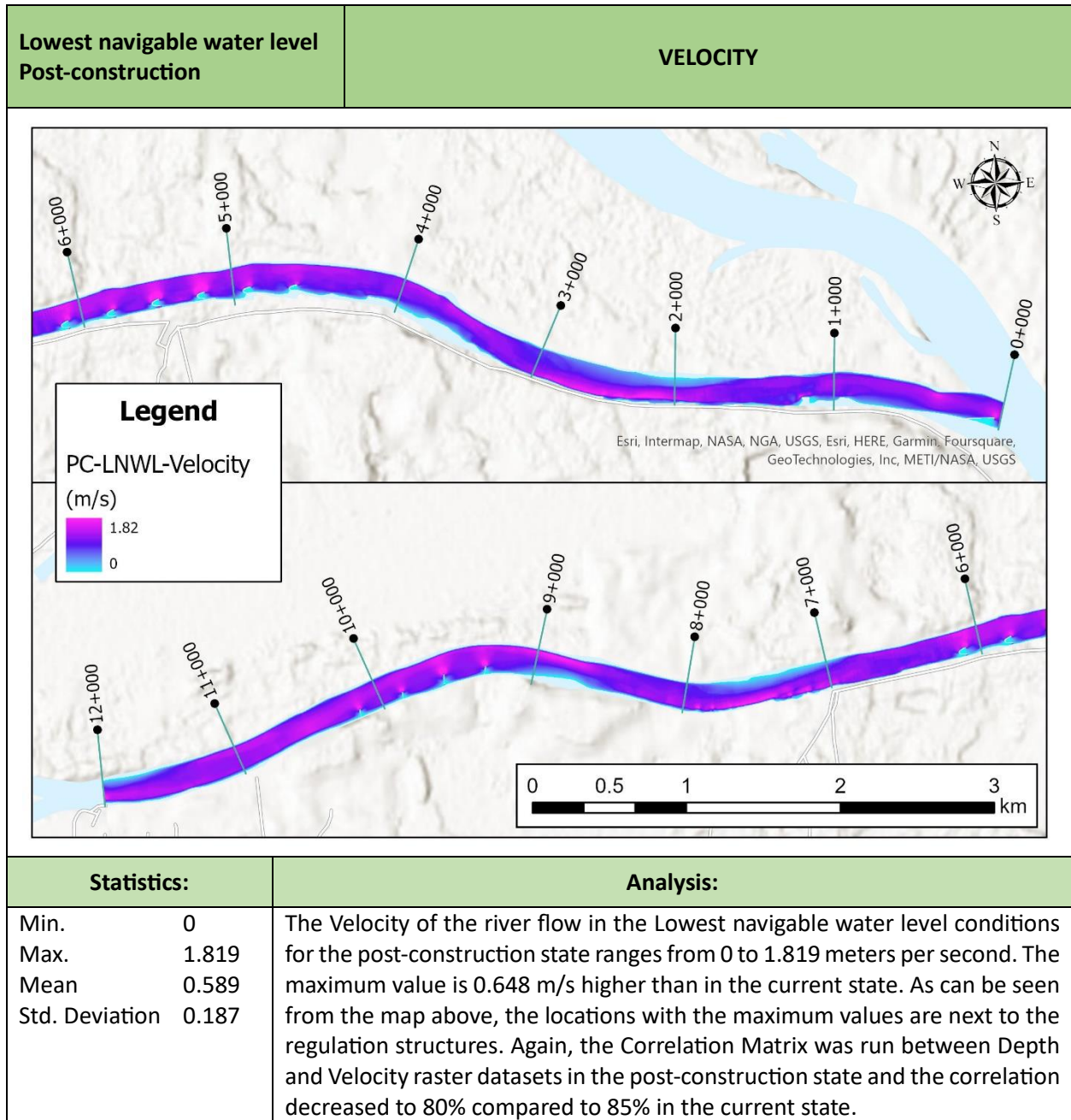


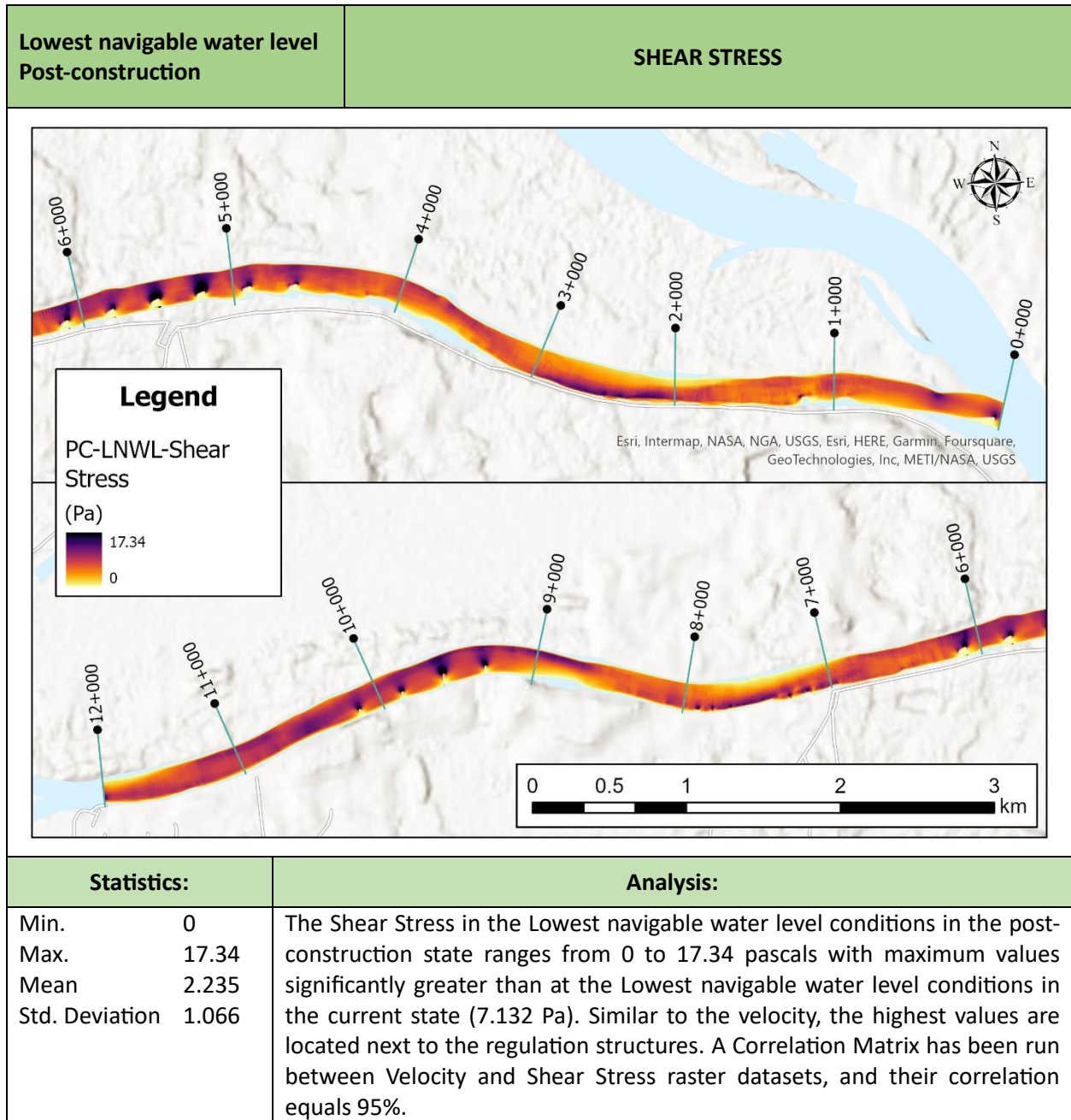


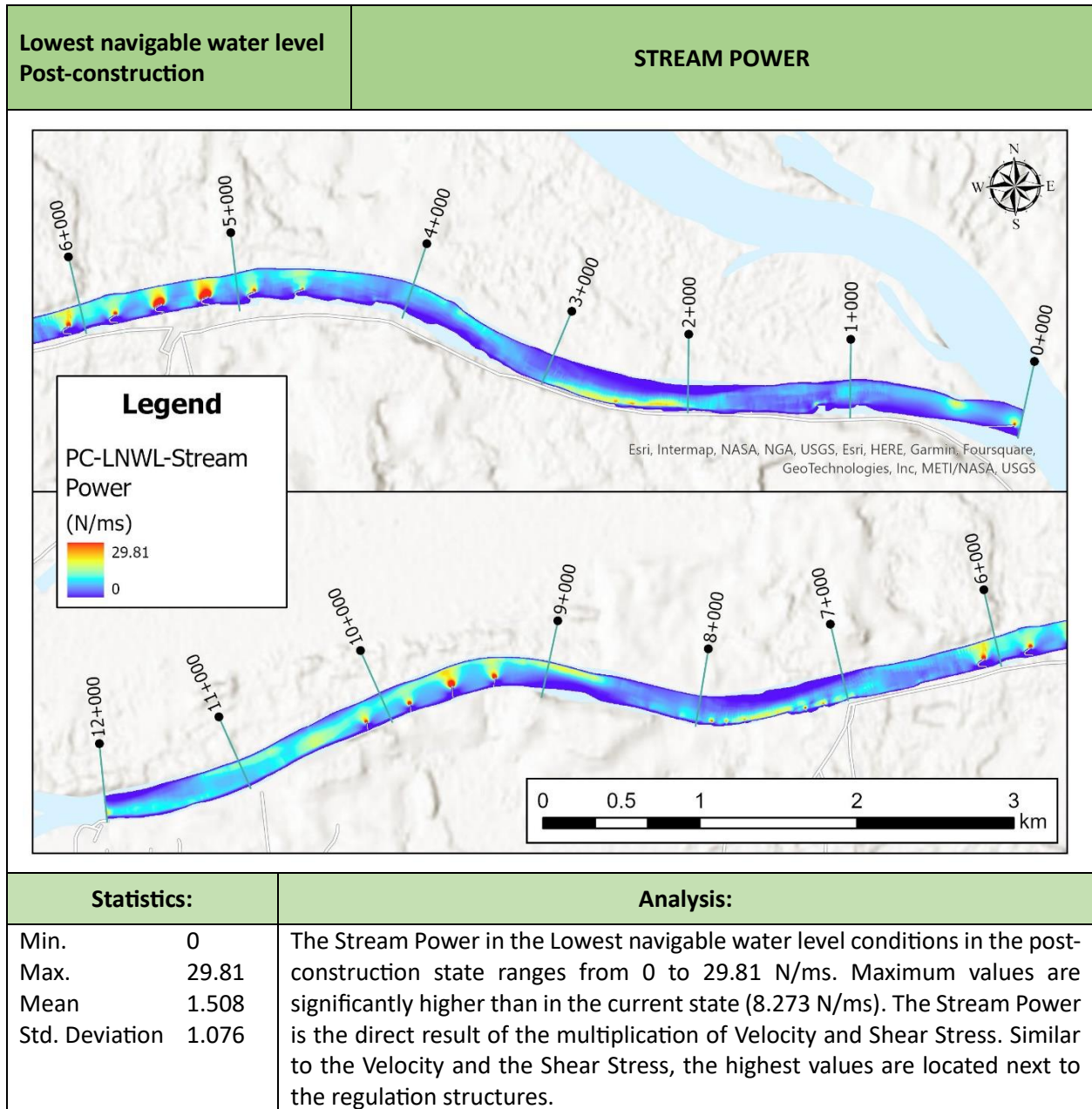
3.1.3 Lowest Navigable Water Level- Post-Construction



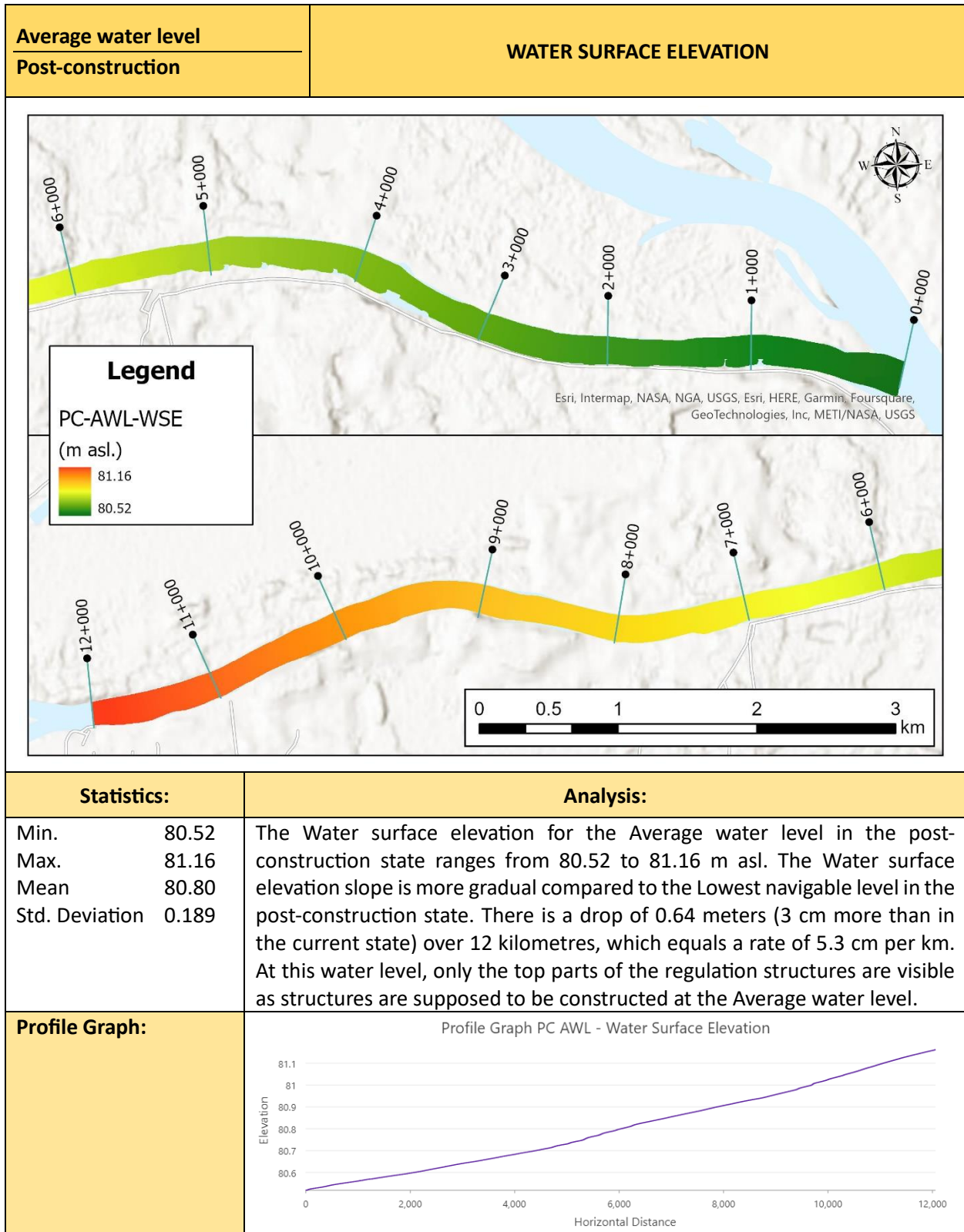


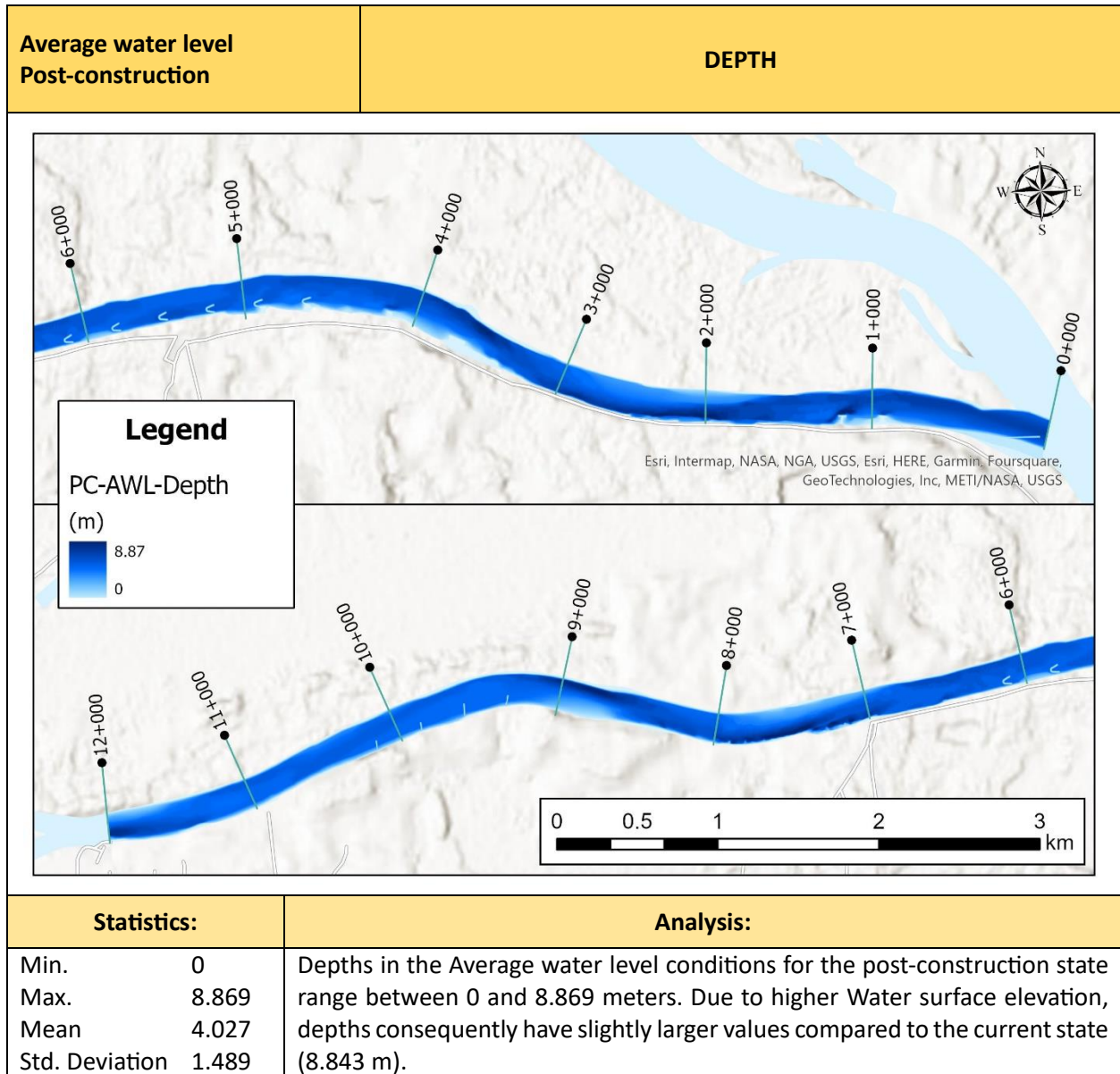


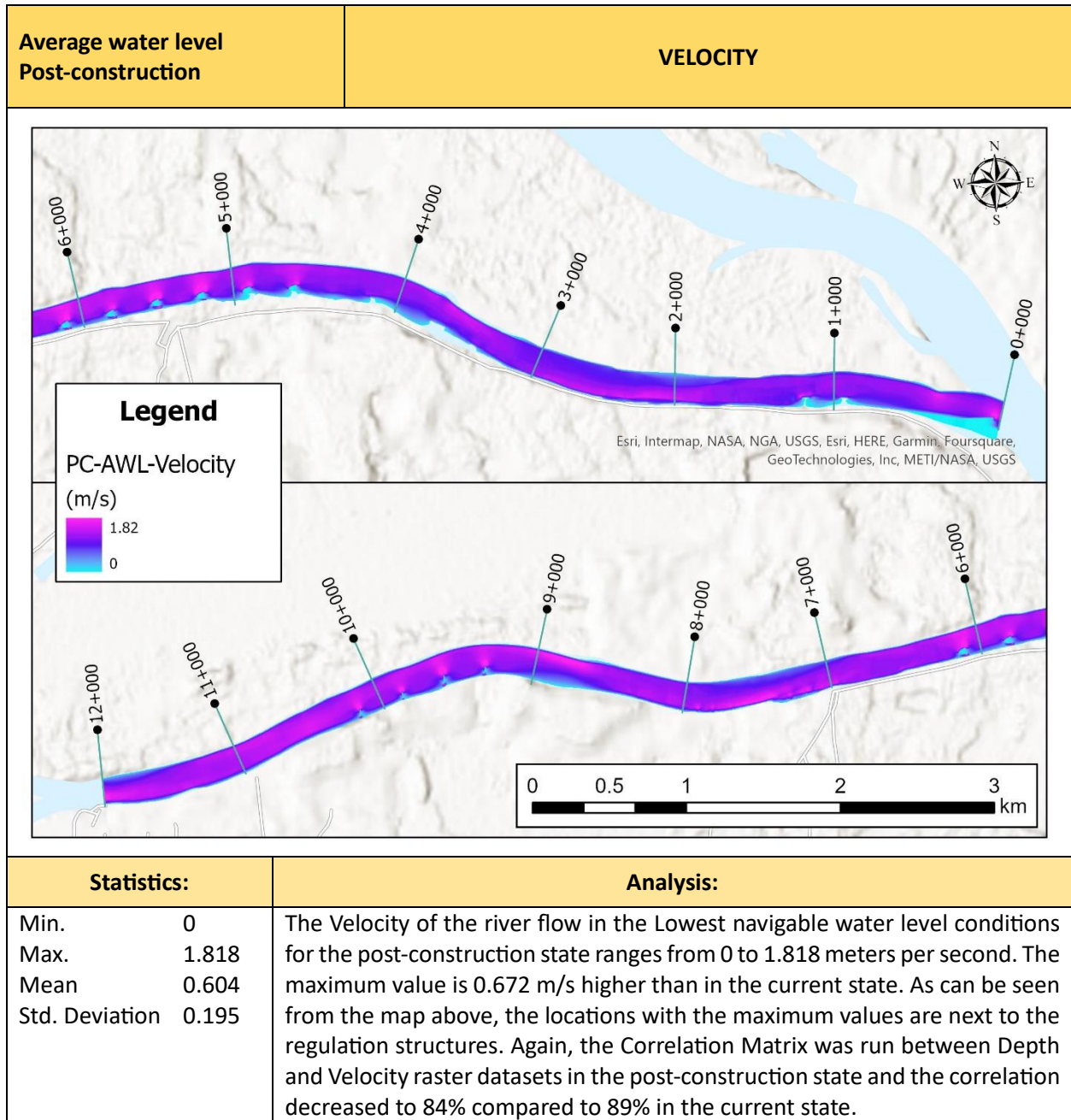


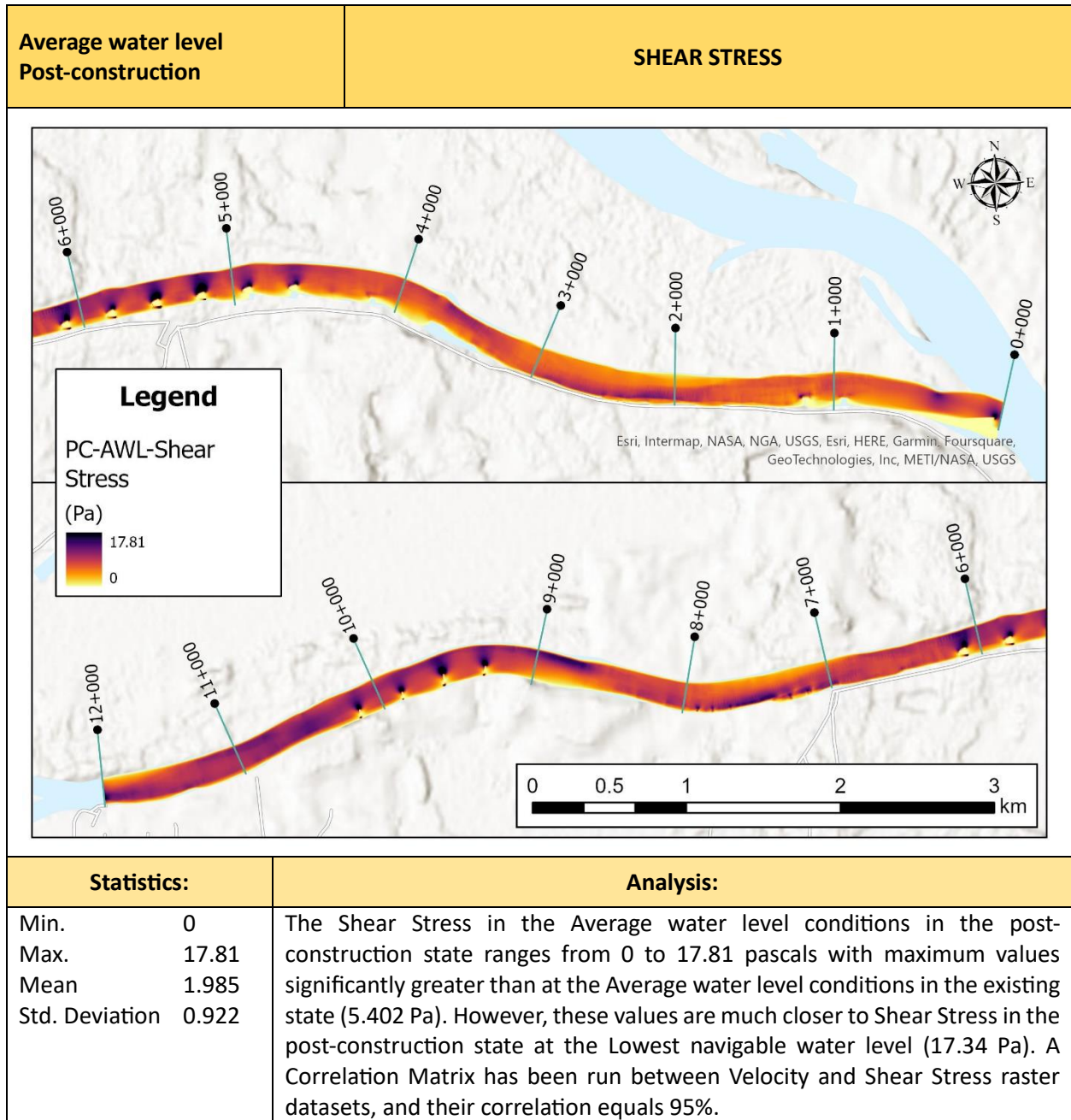


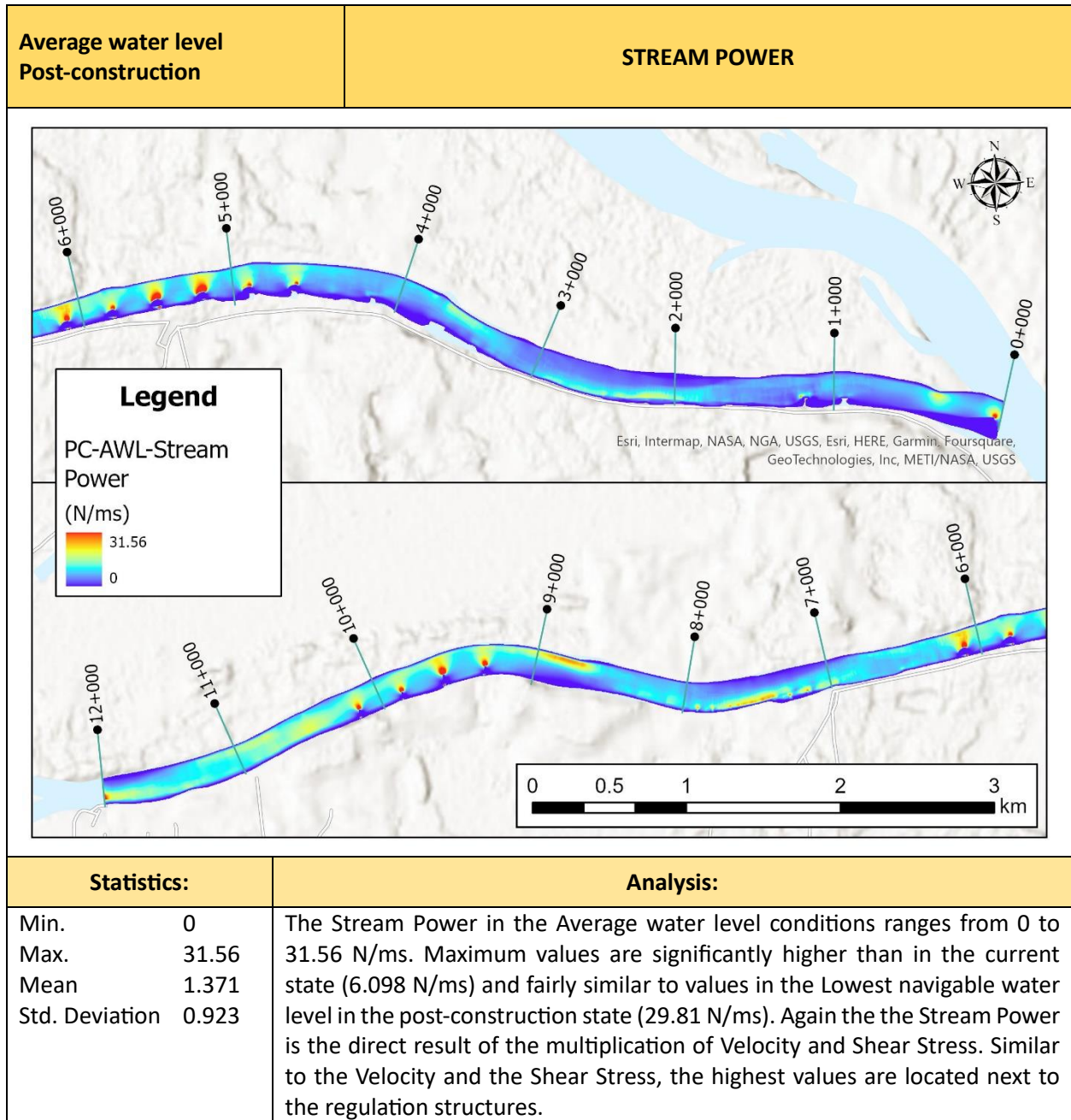
3.1.4 Average Water Level- Post-Construction





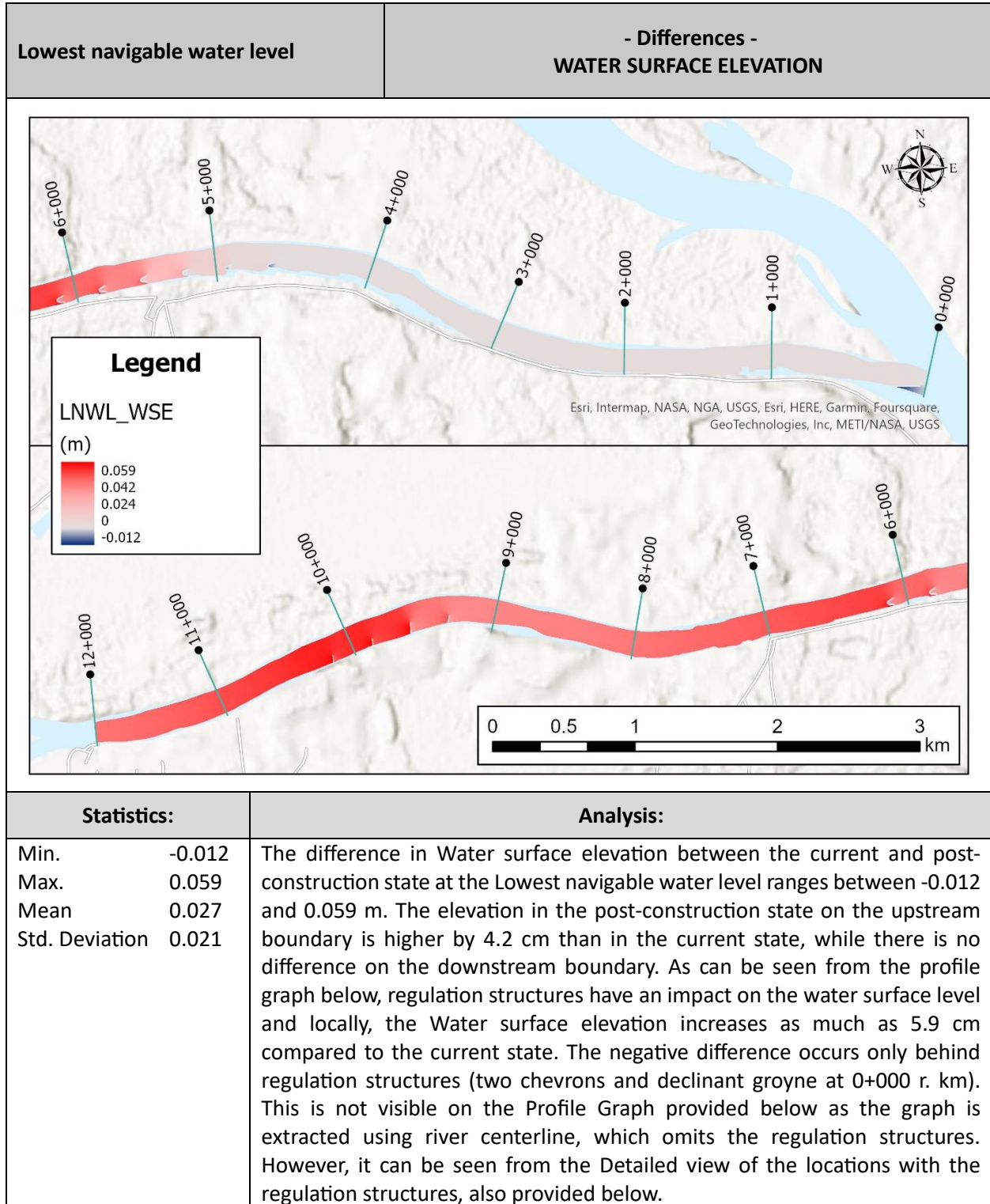




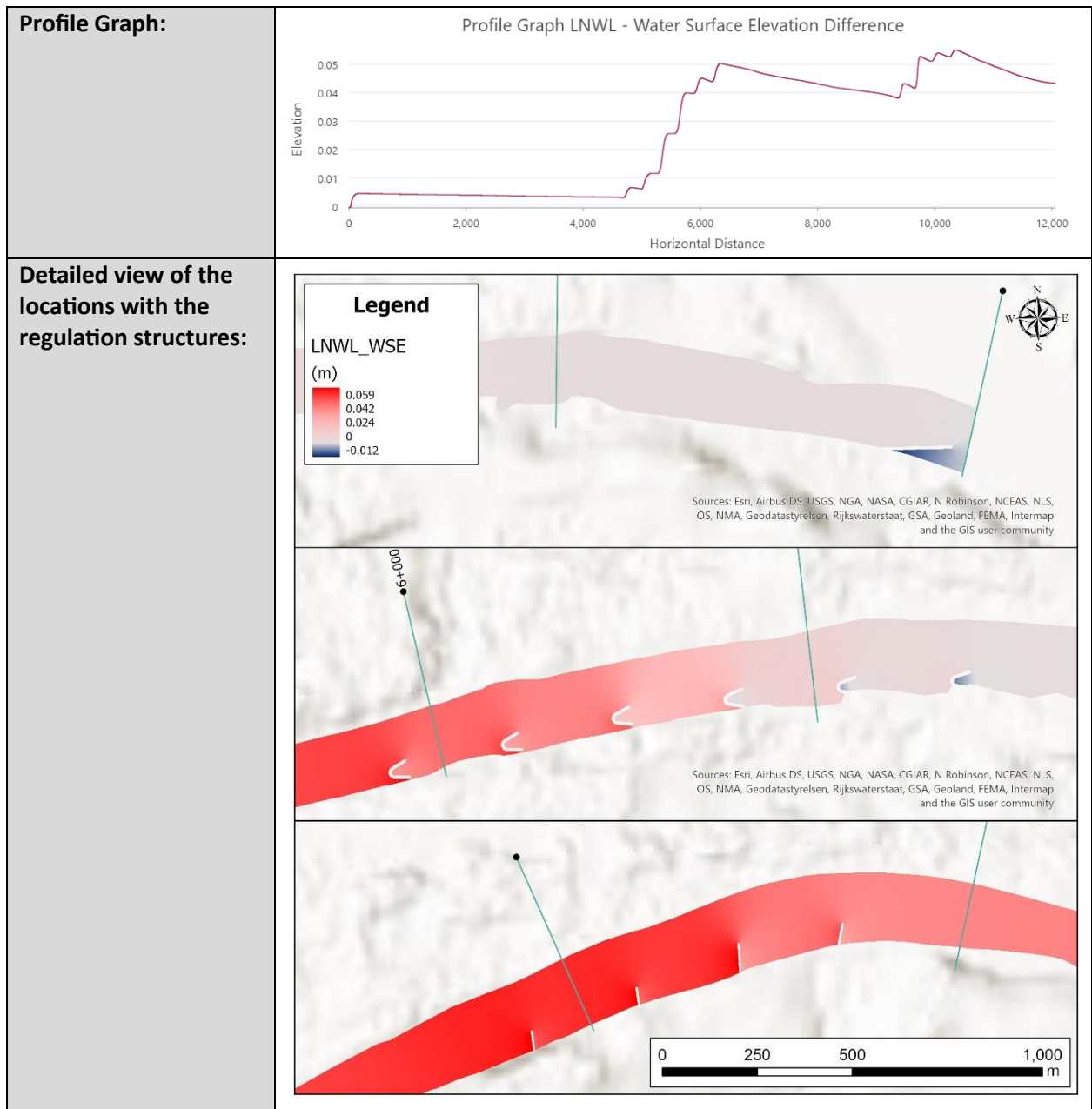


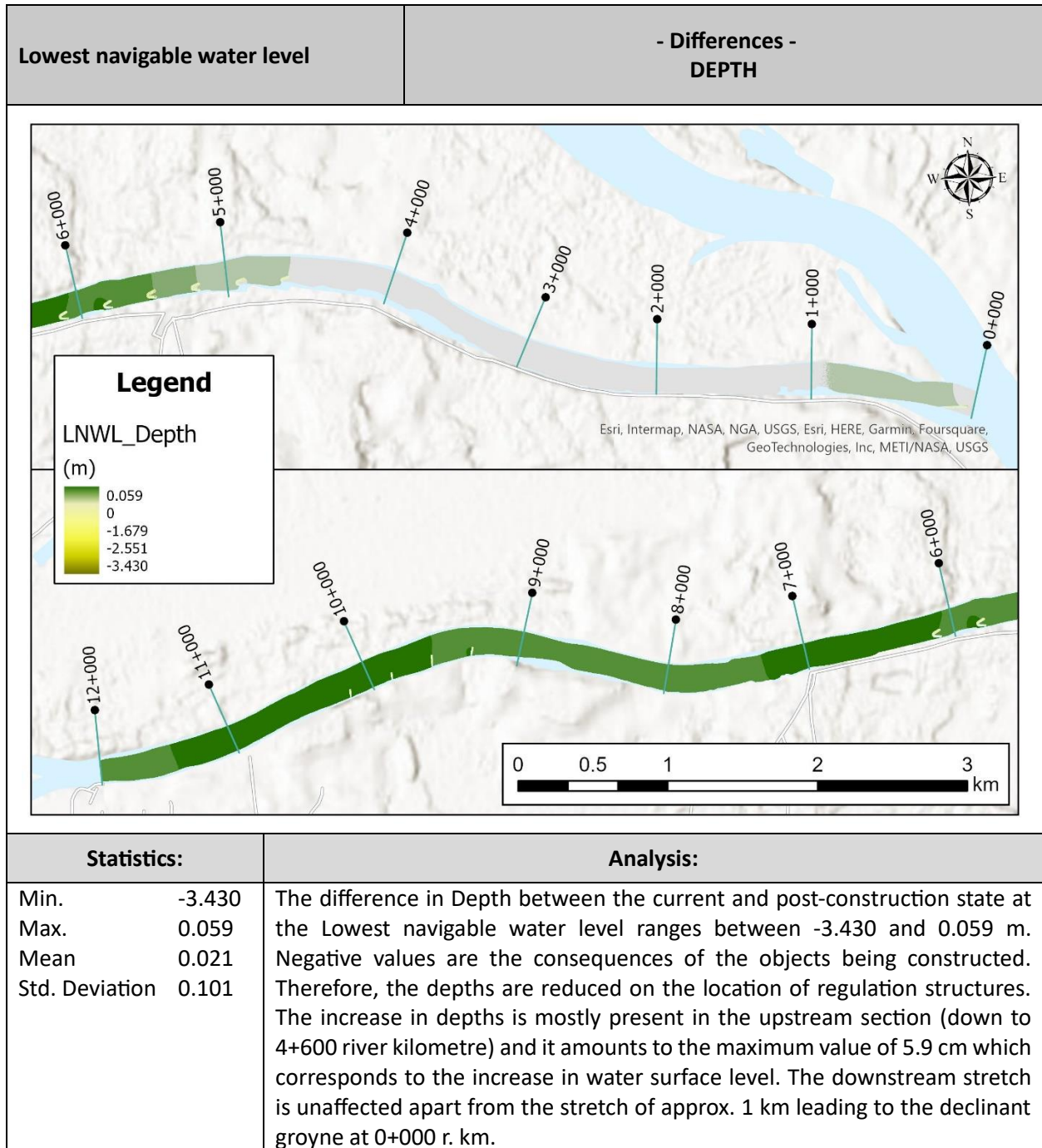
### 3.2 Comparison of Current-and Post-Construction State Results

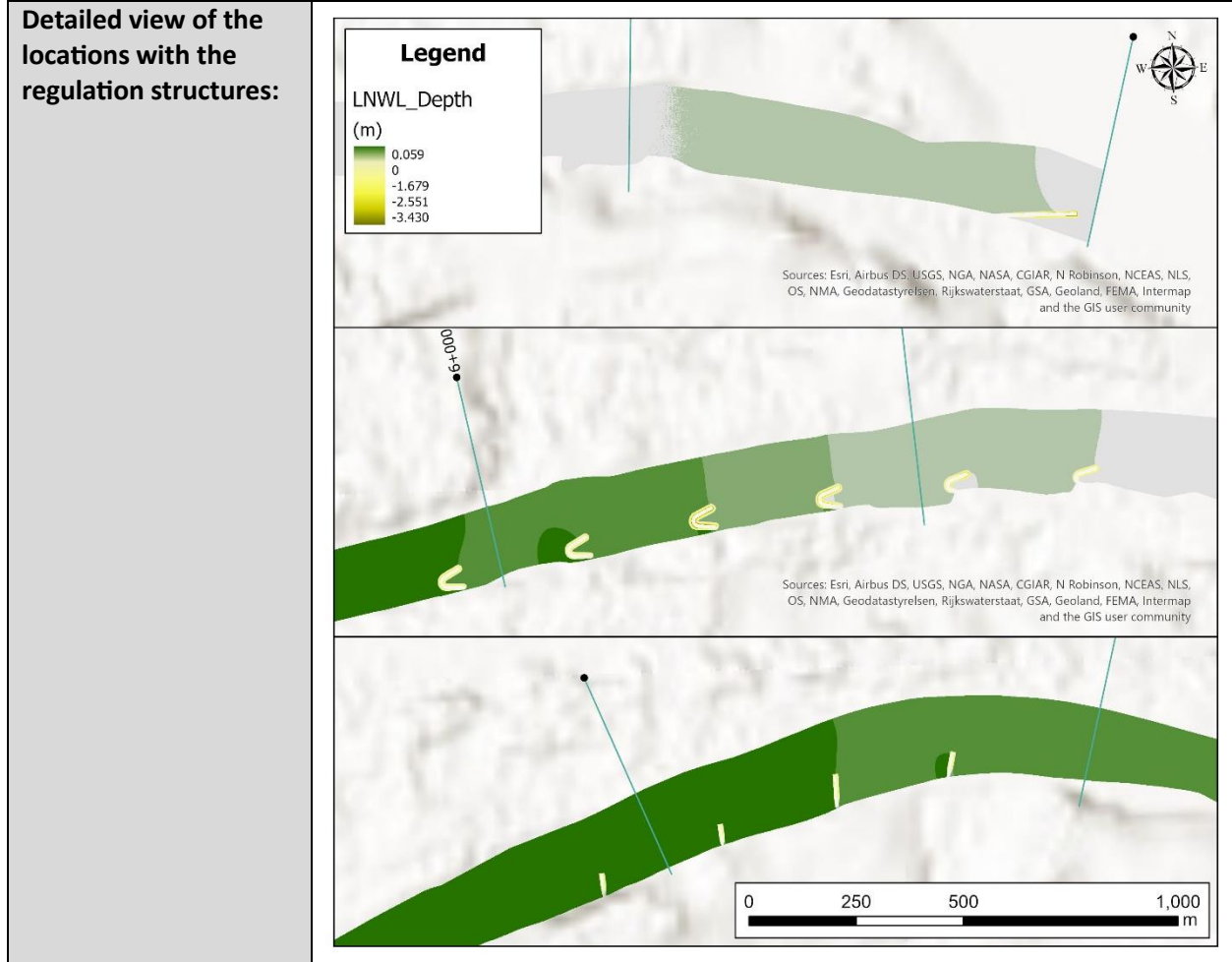
#### 3.2.1 Lowest Navigable Water Level

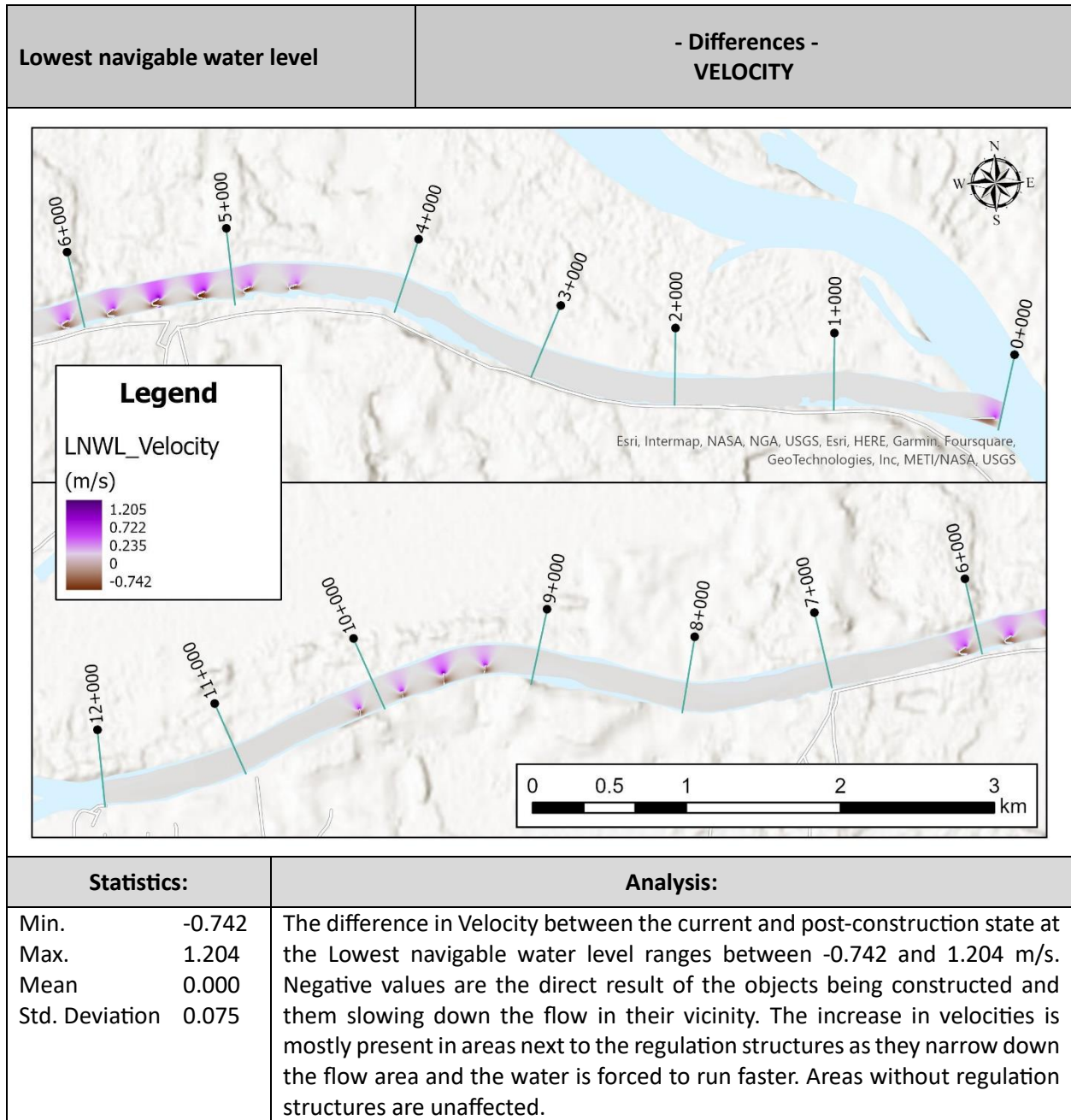


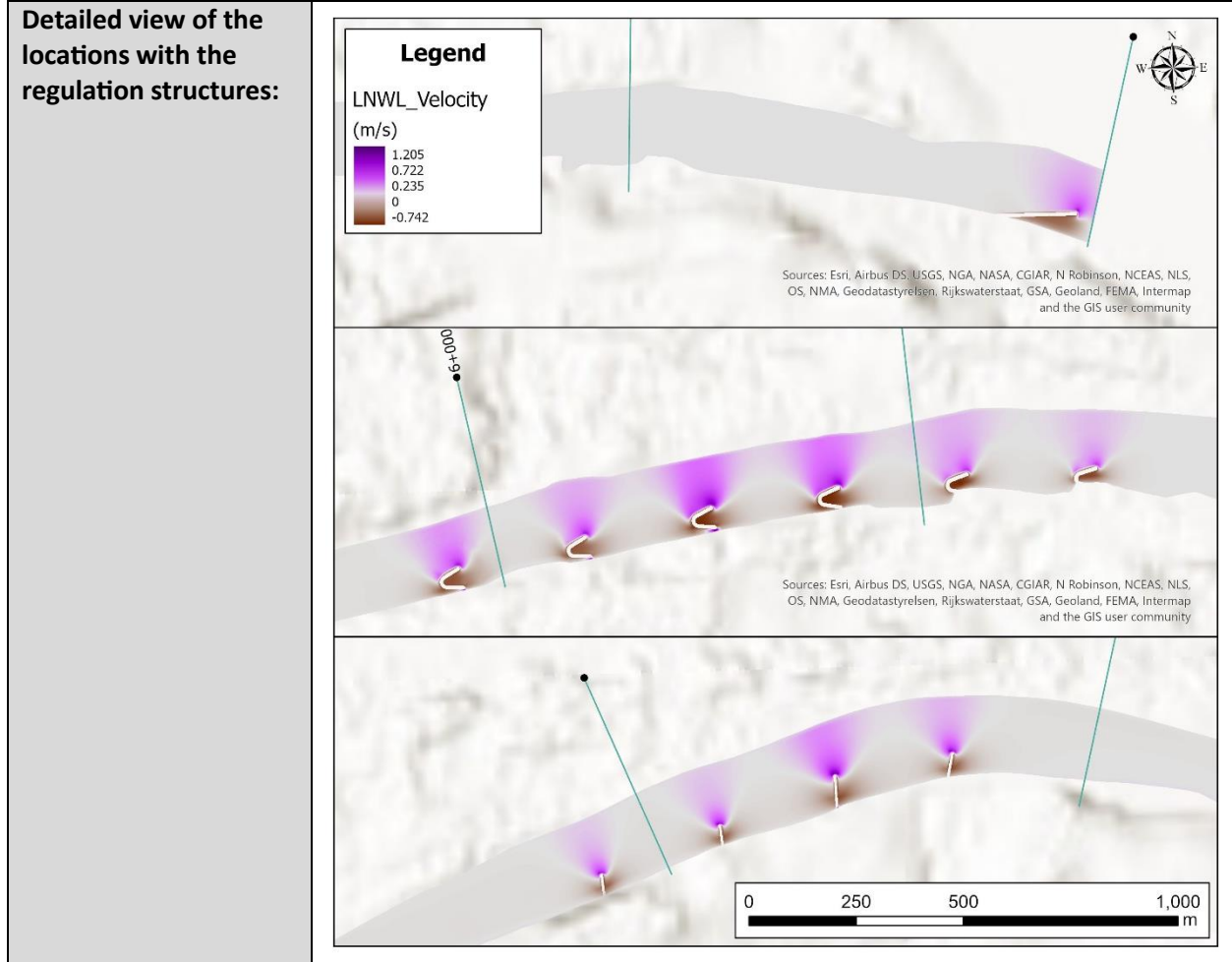
Assessing the Impacts of River Regulation Structures on Flow Dynamics and Ecological Systems:  
A Case Study of the Drava River

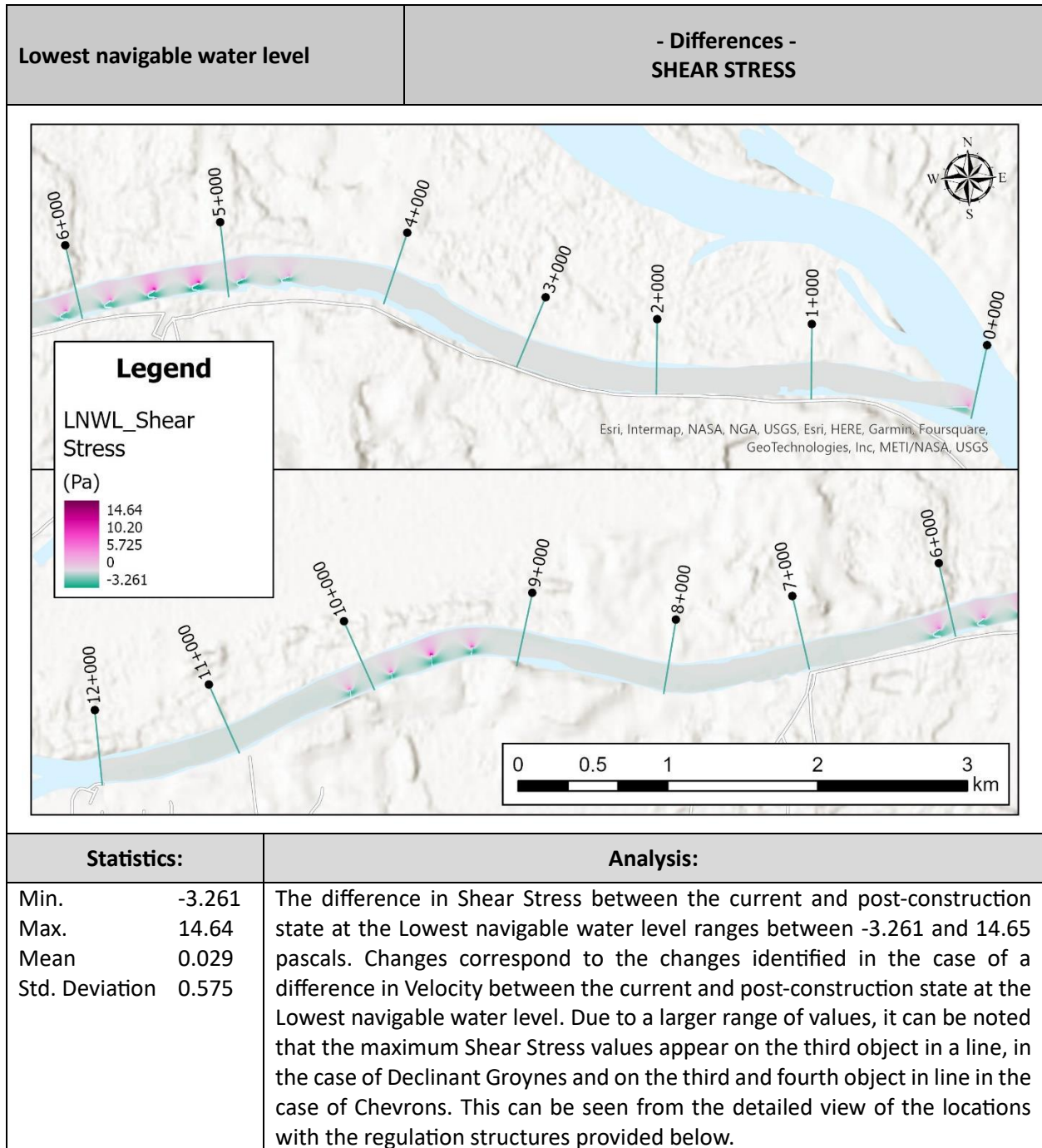


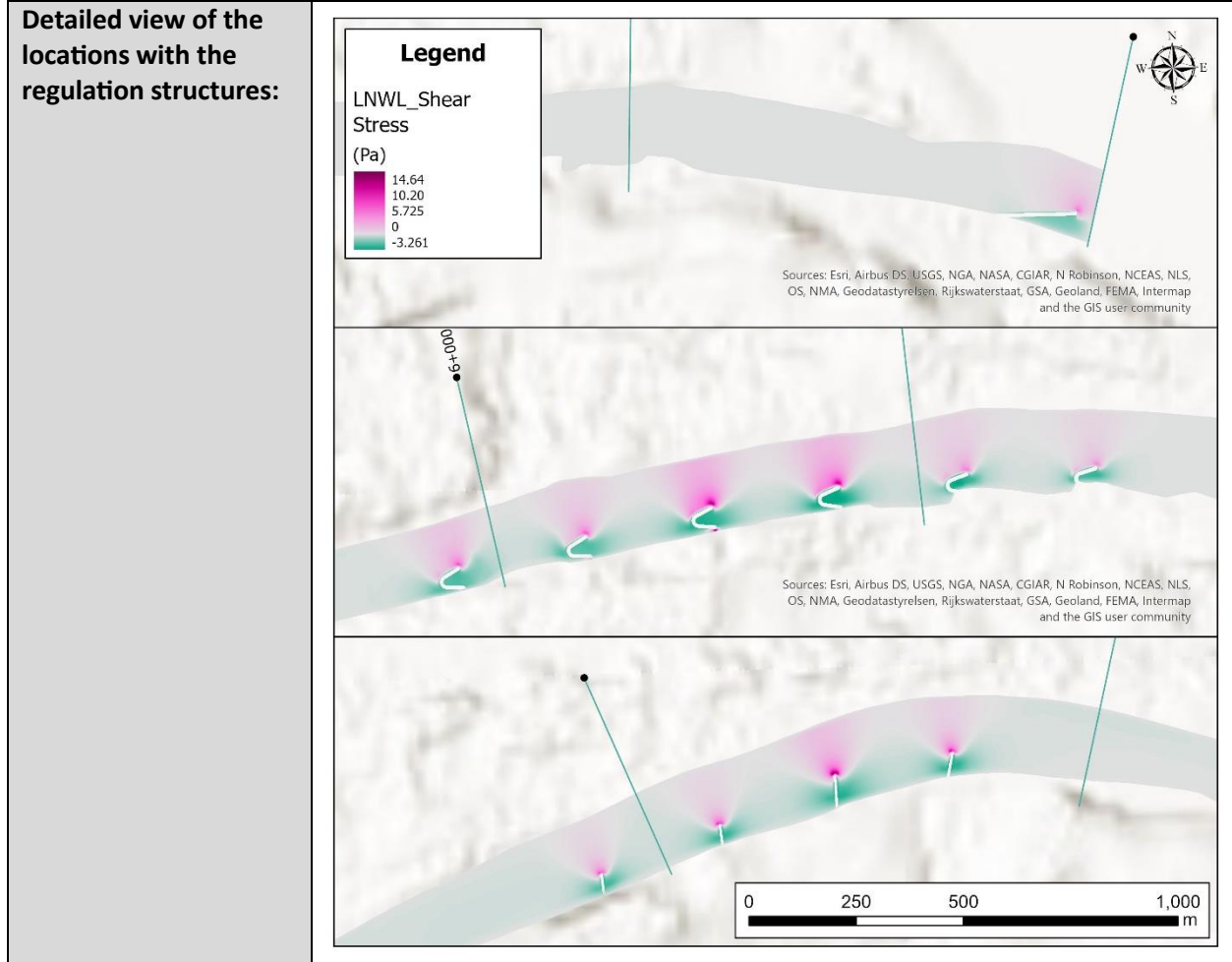


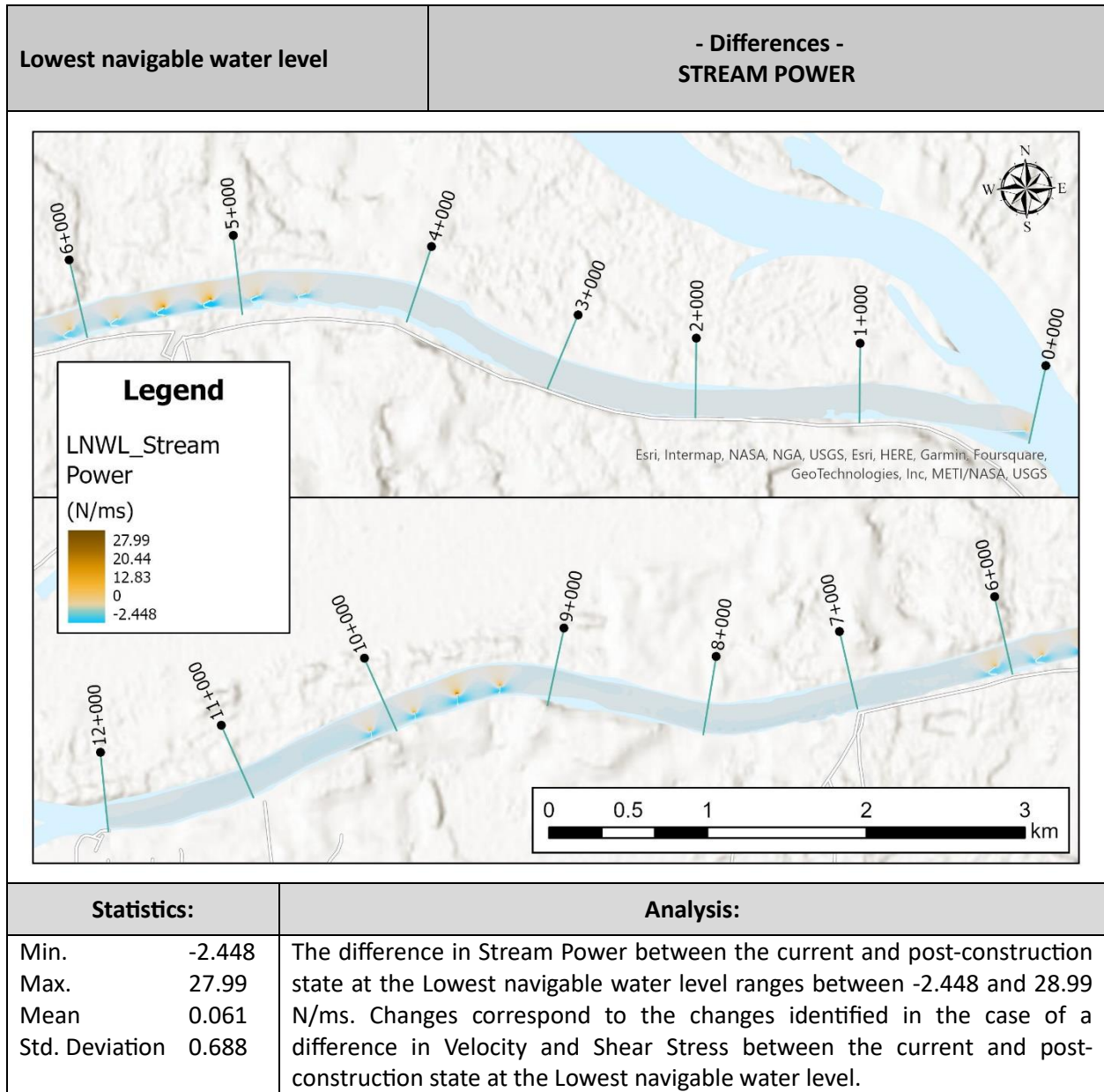


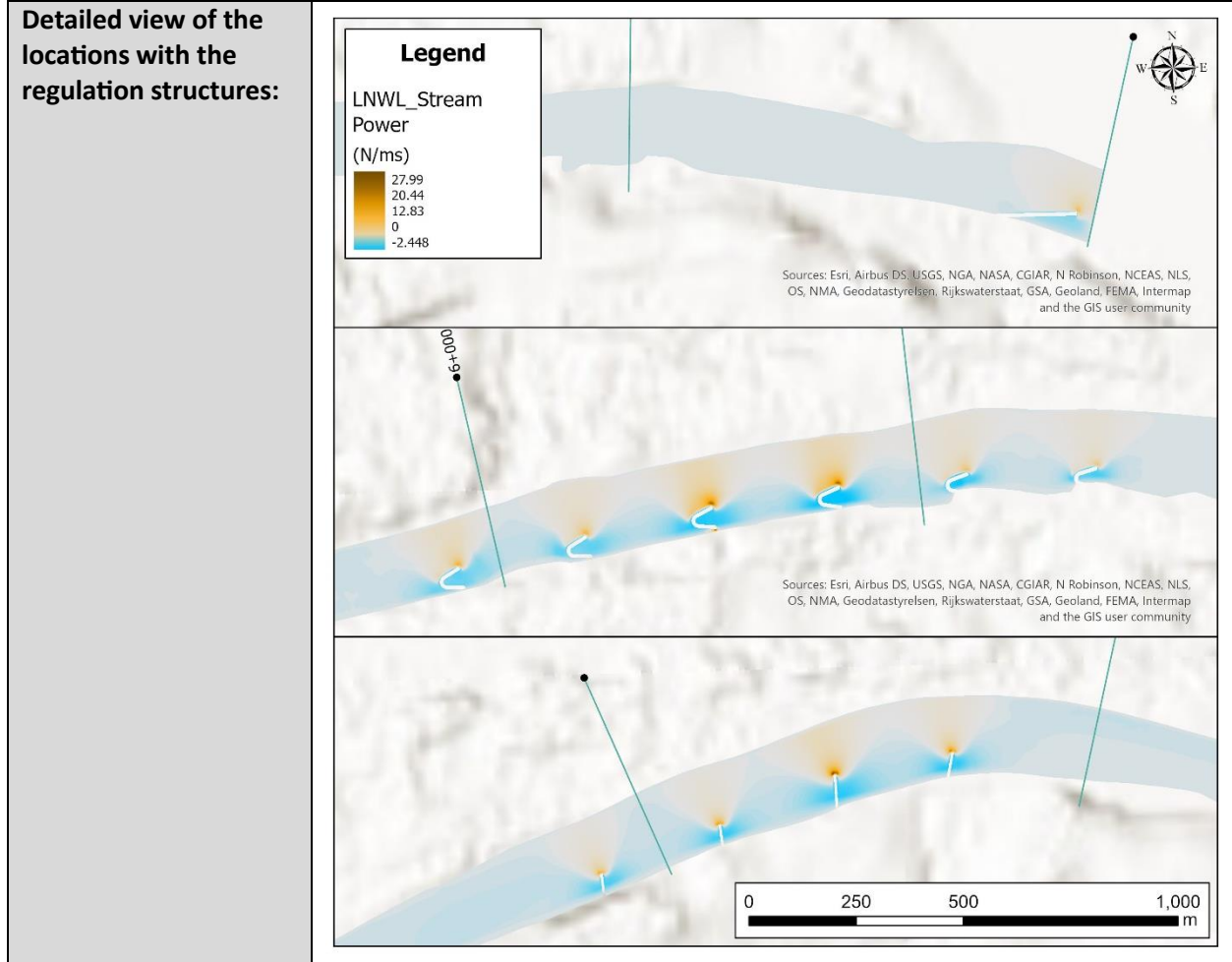




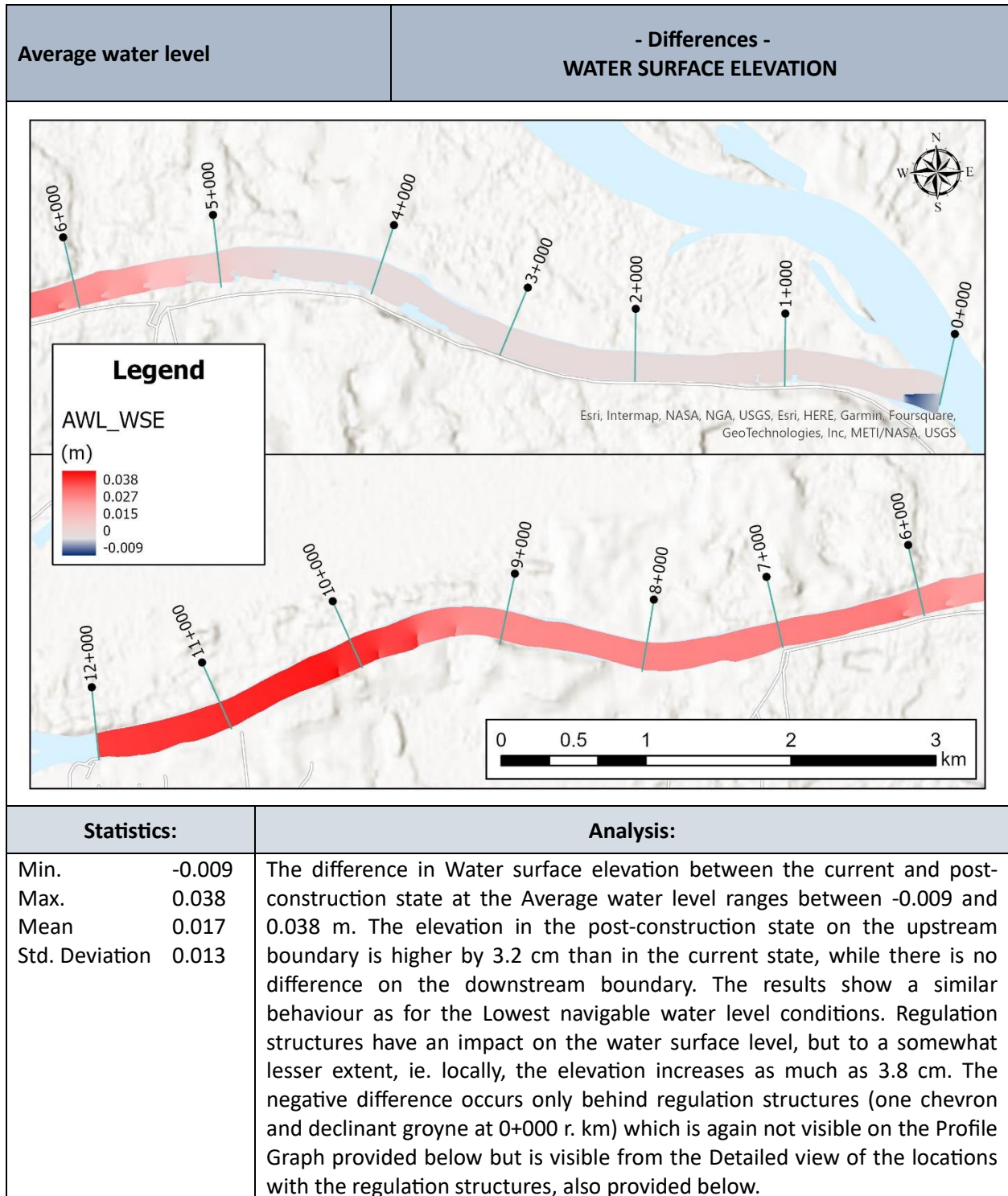




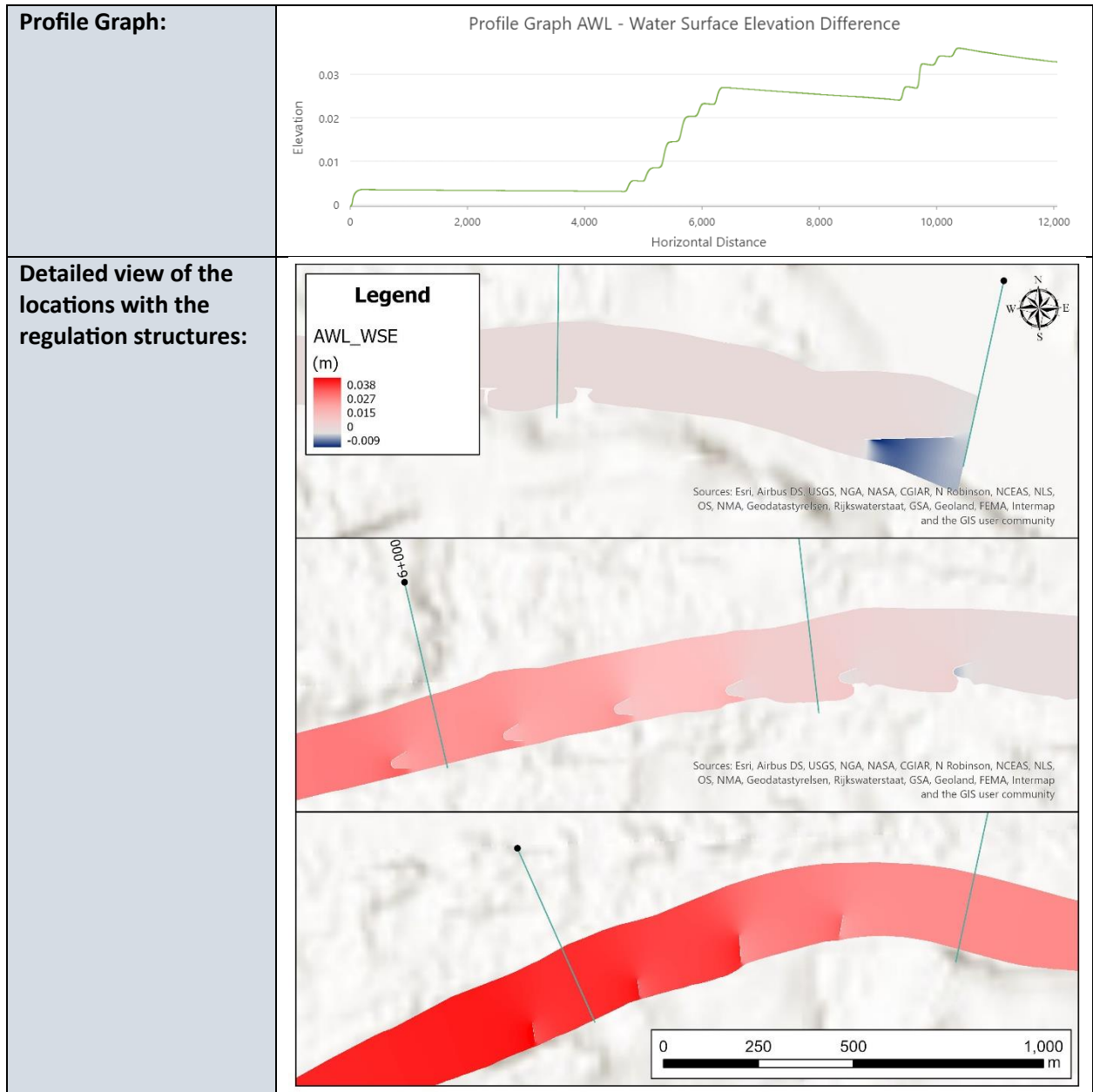


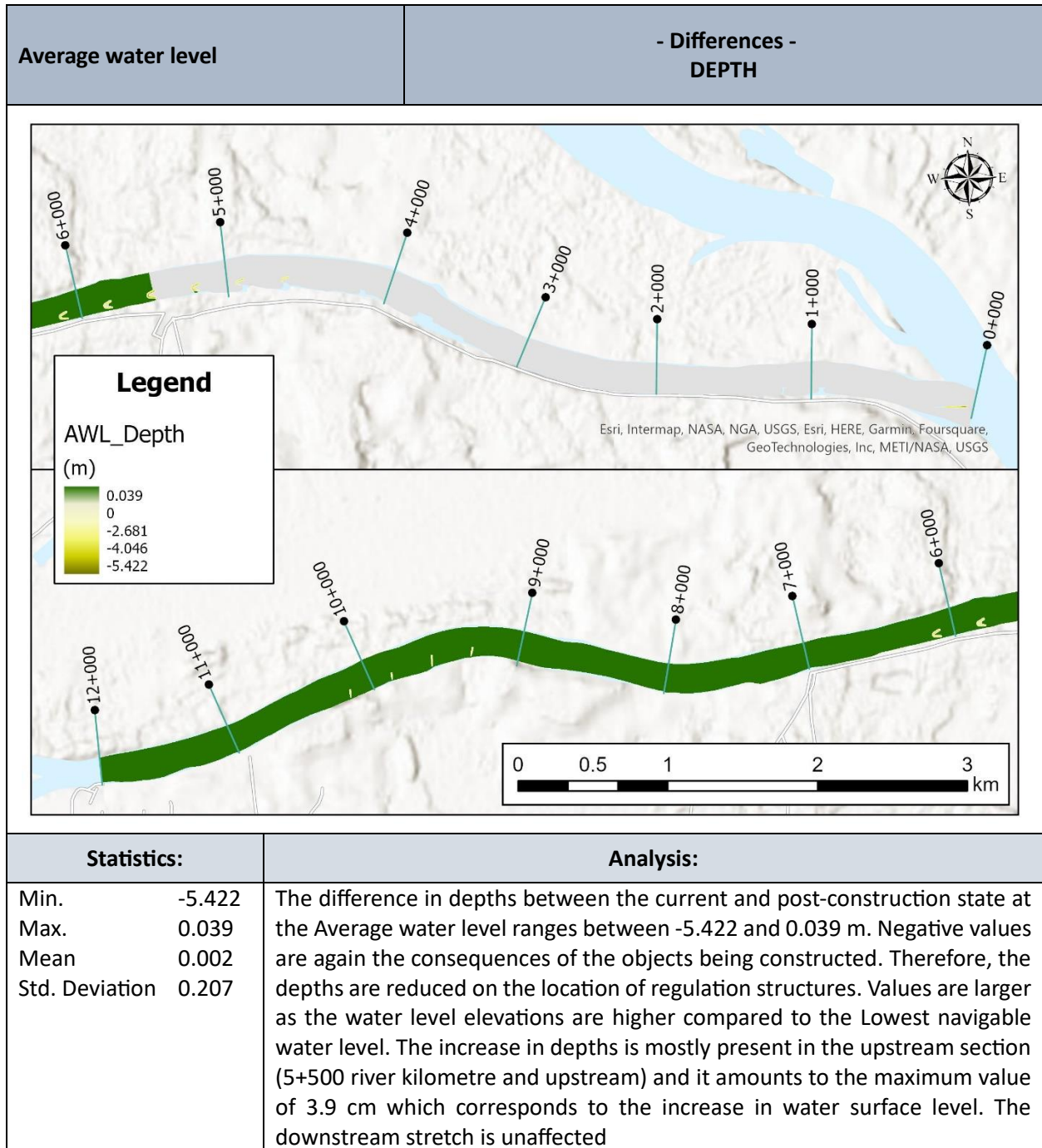


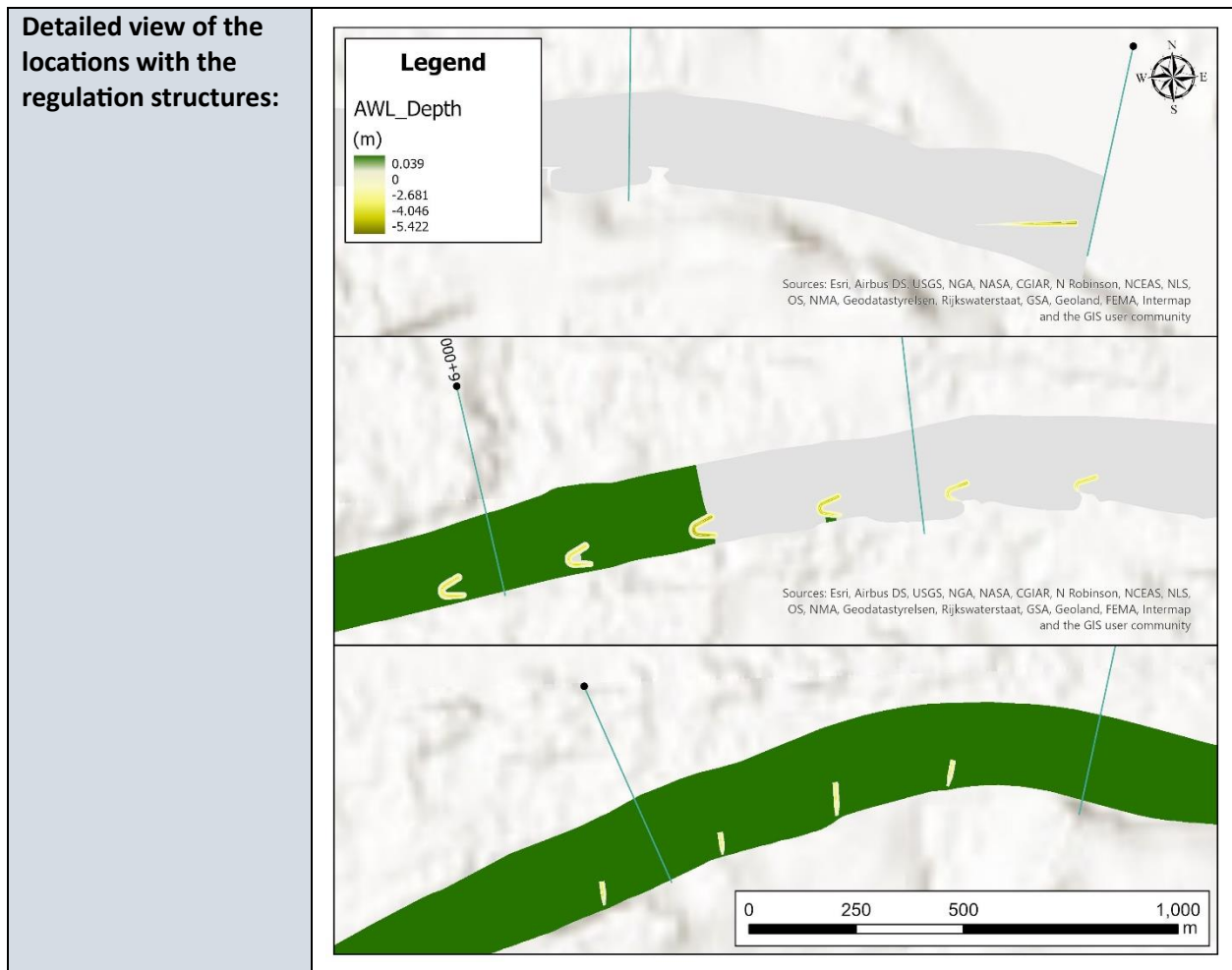
3.2.2 Average Water Level

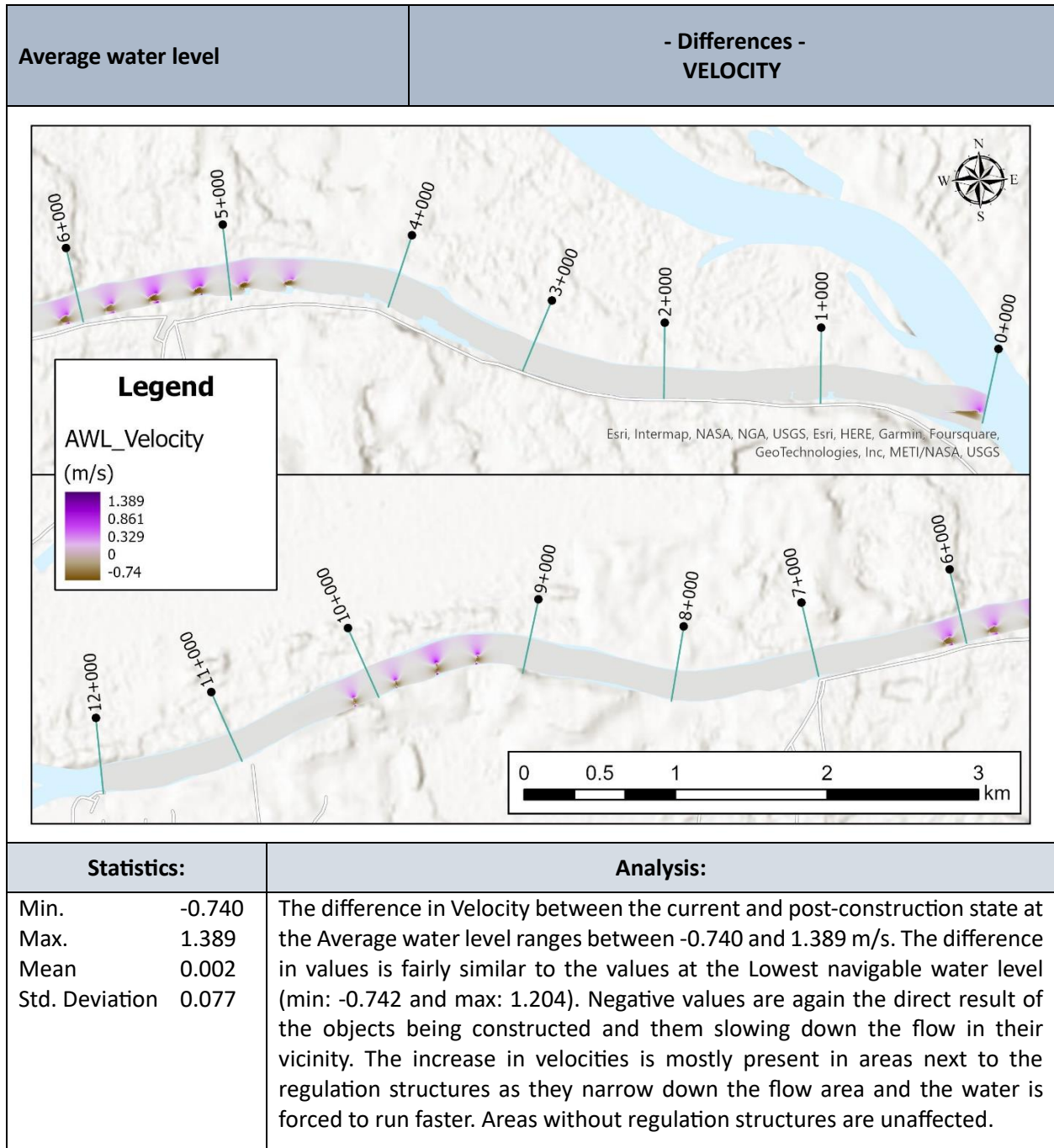


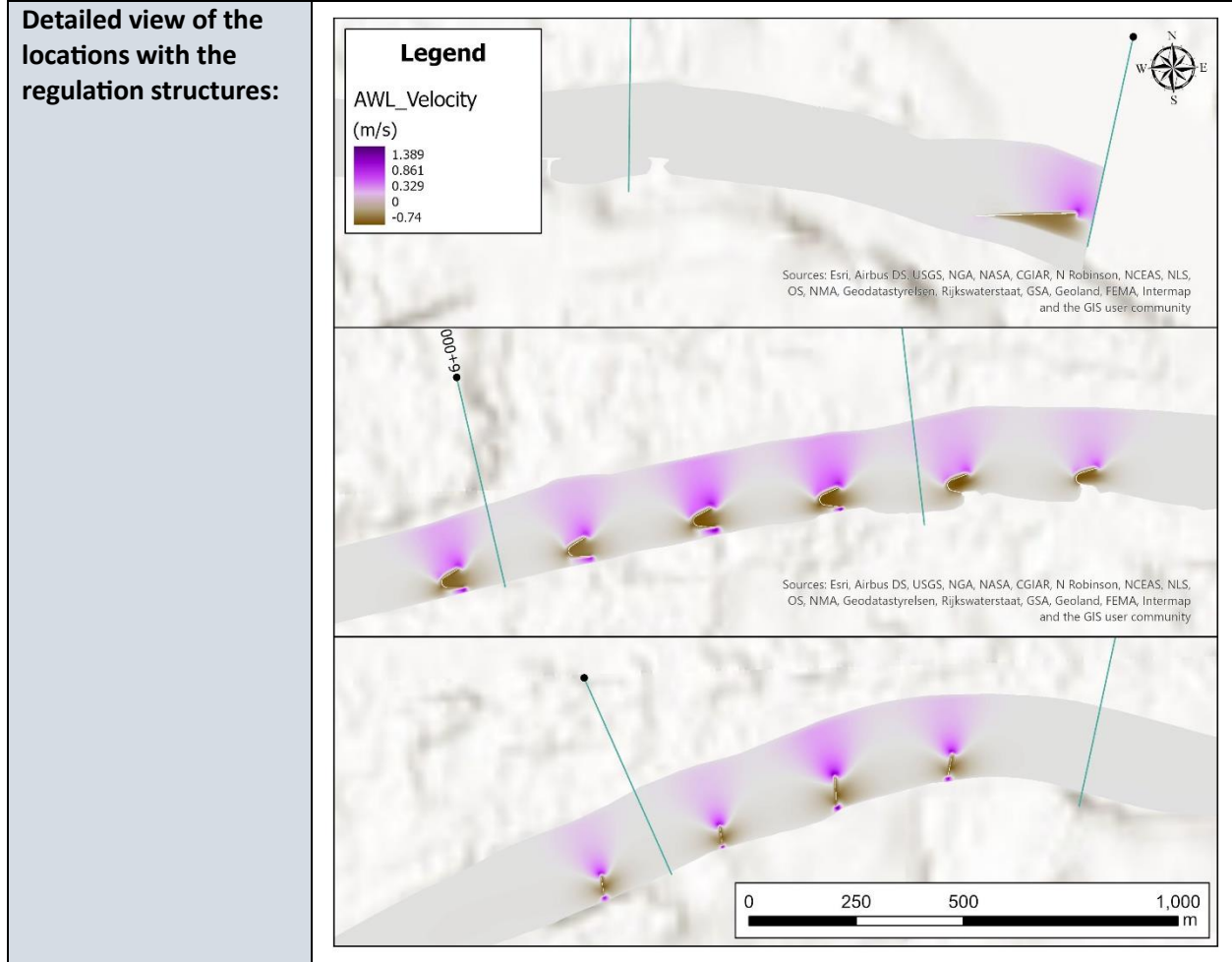
Assessing the Impacts of River Regulation Structures on Flow Dynamics and Ecological Systems:  
A Case Study of the Drava River

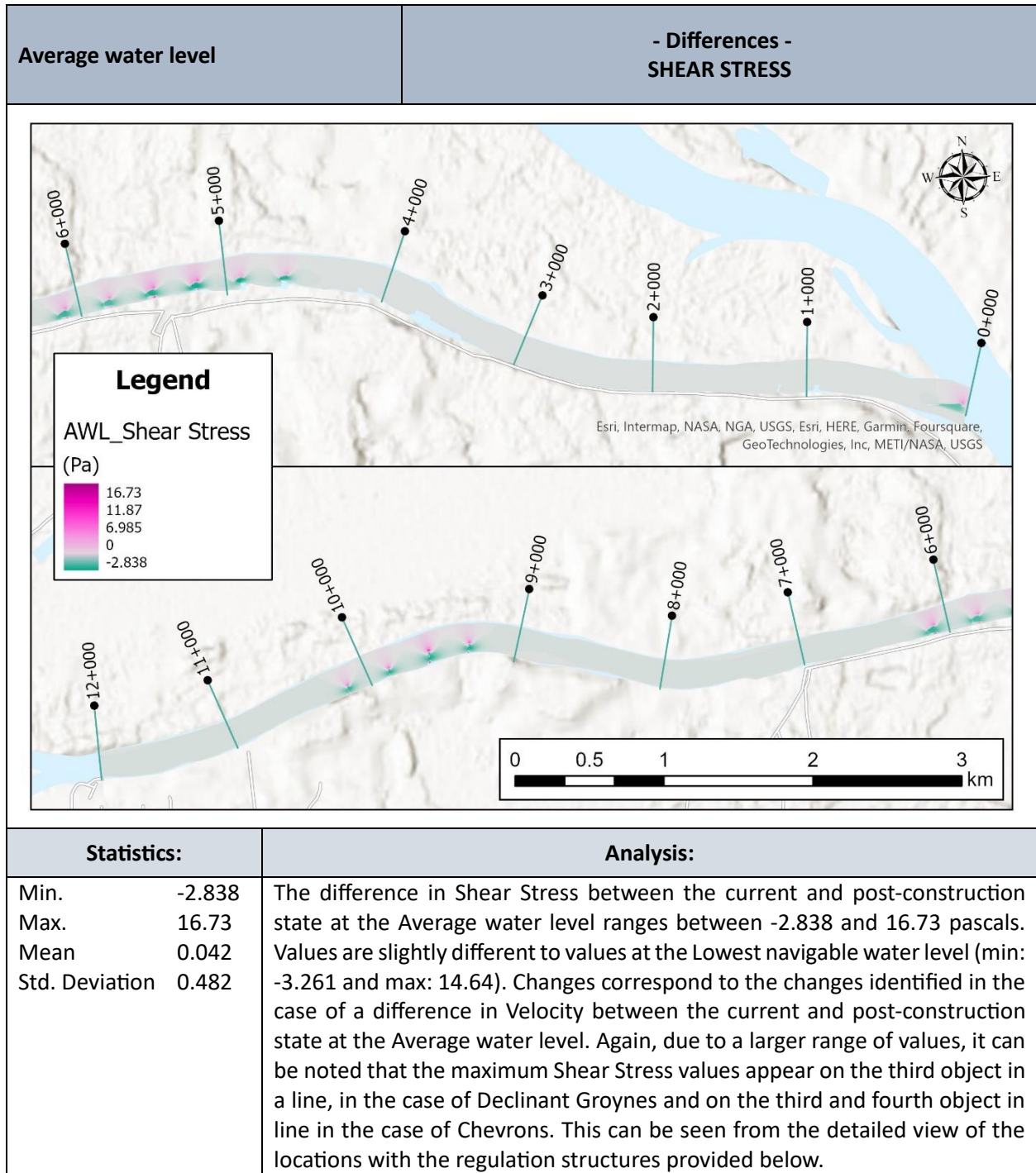


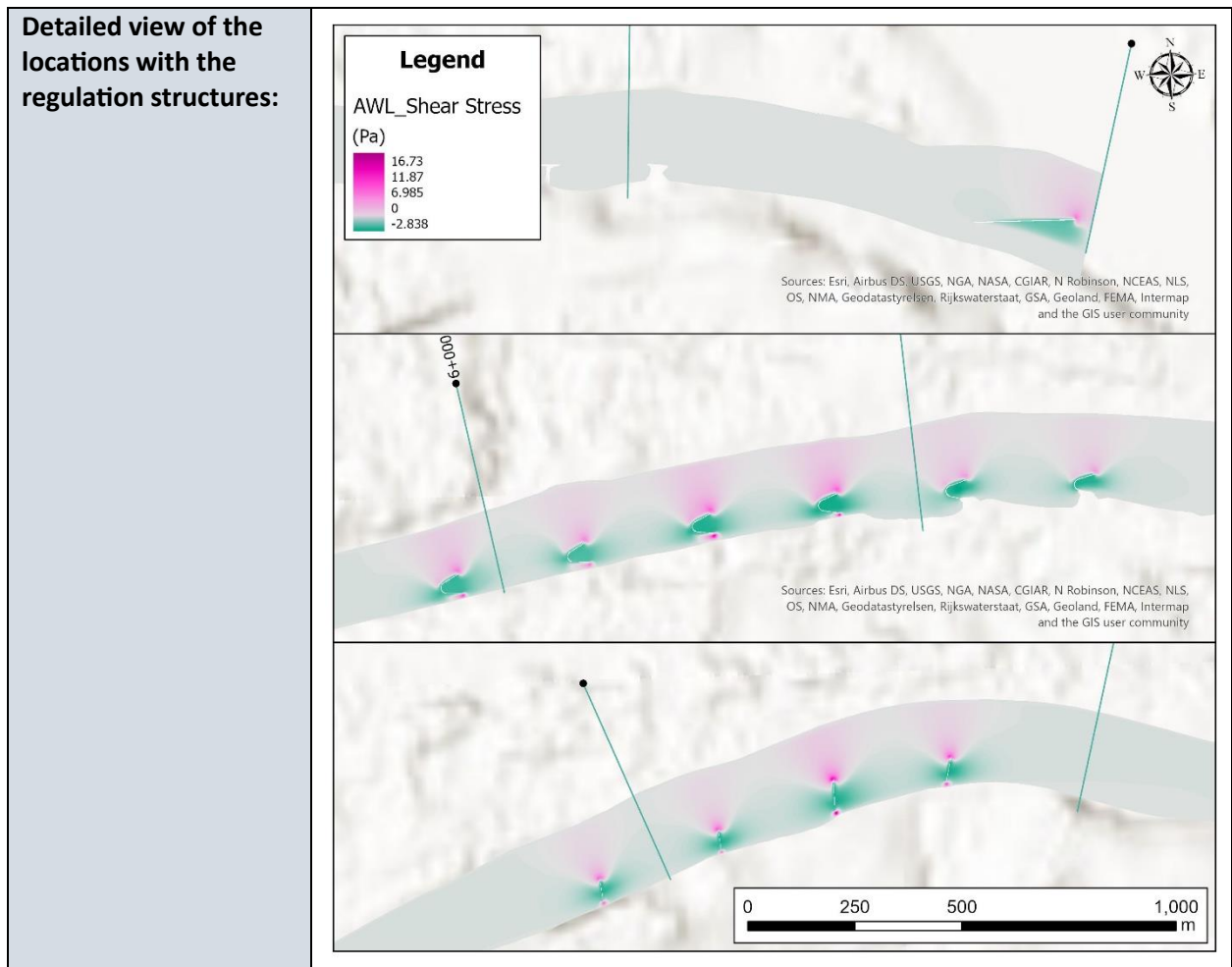


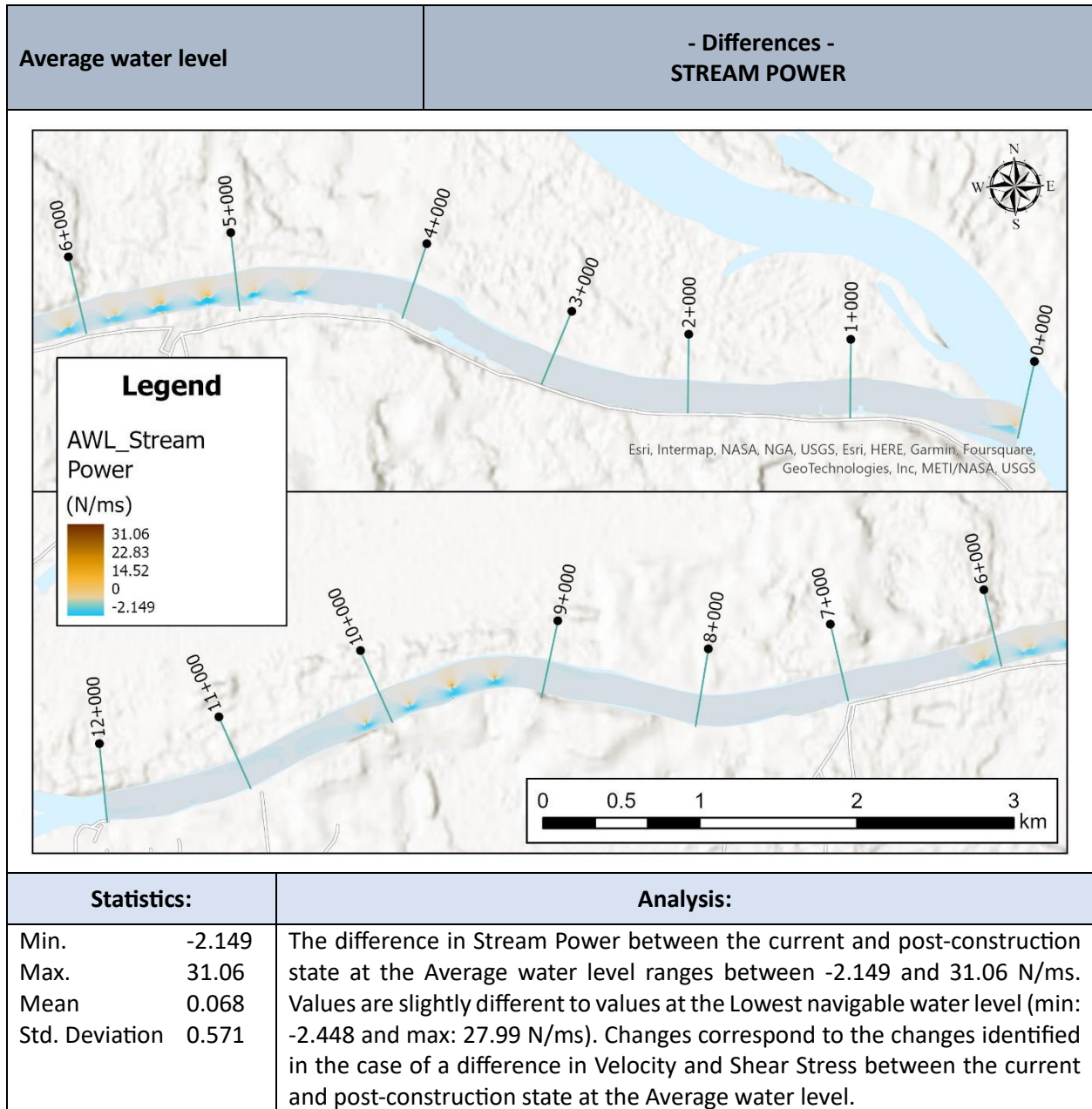


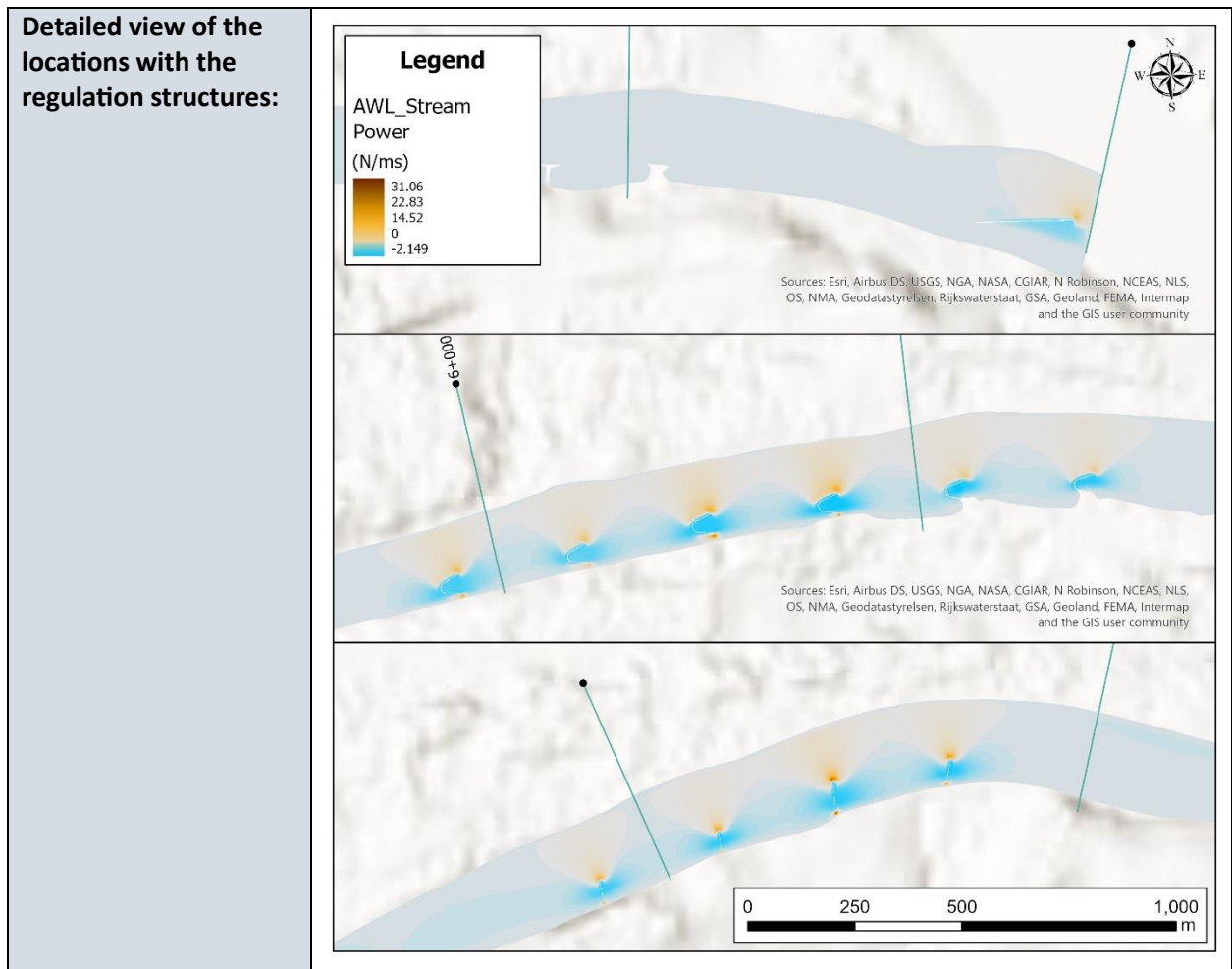












## 4. Discussion

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This chapter provides a summary of findings from the analysis undertaken as a part of this research. The key points are based on the comparison of results obtained by hydrologic modelling between the current and the post-construction state.

Results are discussed in terms of differences between specific variables that are analysed, and whether these differences will incur significant changes in riverbed morphology and river dynamics. Furthermore, the implications of those changes are assessed in terms of research objectives, namely:

- Overall assessment of the effectiveness of the proposed technical solution
- Assessment of changes in flow dynamics
- Assessment of ecological implications

The chapter concludes with an overview of limitations, additional considerations, and a quick comparison to other similar projects.

### 4.1 Results

Results obtained from the hydrological modelling could be split into two groups. The first group is based on the water surface gradient and includes Water Surface Elevation and the resulting Depth. The second group includes Velocity, Shear Stress and Stream Power, variables more related to the flow dynamics and energy of the river.

#### 4.1.1 Water Surface Gradient

At the Lowest navigable water level, Water surface elevation shows a difference of -0.012 to 0.059 m, while at the Average water level, this difference ranges between -0.009 and 0.038 m. As the research examines average and low water levels, this increase would only wet the area that is within the riverbed. This difference is insignificant as the maximum increase of 5.9 cm will not have any adverse effects on the surroundings. Such a difference could have an effect at high water levels in the form of flooding. But considering that the difference decreases as the water levels go up, at least in the case of two analysed water levels, and that the regulation structures are constructed at the Average water level height, this difference would be smaller and therefore less significant at high water levels. Analysis of the impacts of river regulation structures at high water levels could be an interesting topic for similar research.

In terms of depth, except where the difference is obvious in the location of constructed structures, the results show the same pattern and are directly a variable of Water surface elevation changes.

The results also show that the difference in water level elevation changes at the locations of regulation structures. Profile graphs of Water surface elevation difference, for both water levels, indicate areas where the water level changes to compensate for the reduced flow area caused by the structures.

#### 4.1.2 Flow Dynamics and Energy

Considering the second group of outputs, Velocity, Shear Stress and Stream Power, there is a difference in all three variables in the post-construction state for both water levels. These differences are mostly obvious in the close vicinity of the regulation structures, while other areas are relatively unaffected.

Maximum Velocity at the Lowest navigable water level is increased by 55.34%, while this increase equals 58.64% at the Average water level. Maximum Shear Stress at the Lowest navigable water level is increased by 143.13% in the post-construction state and by 229.69% at Average water levels. A similar pattern is present for the Stream Power variable, with maximum values increased by 260.33% at the Lowest navigable water level and by 417.55%.

The difference in values for all three variables is higher in the Average Water Level (Velocity (m/s): -0.740 - 1.389 for AWL VS -0.742 - 1.204 for LNWL, Shear Stress (Pa): -2.838 - 16.73 for AWL VS -3.261 - 14.65 for LNWL and Stream Power (N/ms): -2.149 - 31.06 for AWL VS -2.448 - 28.99 for LNWL). Increased values result from the fact that greater water flow carries more energy (Water Flow: 522 m<sup>3</sup>/s for AWL VS 290 m<sup>3</sup>/s for LNWL).

All three variables relate to each other, therefore they show the same spatial distribution of differences between the current and post-construction states. Velocity and Shear Stress have shown a positive correlation in the current state of 97% at both the Lowest navigable water level and Average water level. Stream Power is a direct result of the multiplication of Velocity and Shear Stress.

Results also show that the Depth variable is related to the Velocity variable. This can be seen from the Correlation Matrix run between these two variables in the current state (correlation of 85% at LNWL and 89% at AWL). In the post-construction state, the correlation is lower (80% at LNWL and 84% at AWL) which indicates the future tendency of the river to increase depths in locations of increased velocities. Within a certain period after the construction of regulation structures, the correlation would match the numbers in the current state.

Velocity, Shear Stress, and Stream Power are the driving force of morphological changes within the river and are responsible for erosion, sediment transport and sediment deposition (Wang, 2015). Therefore, it may be concluded that these differences in all three variables will cause significant changes in riverbed morphology and river dynamics. However, these changes will only have a considerable effect on the stretches where regulation structures are to be constructed.

## 4.1 Implications

### 4.1.1 Overall Assessment of the Effectiveness of the Proposed Technical Solution

The proposed technical solutions appear to be adequate in terms of reaching safe navigation depths. By overlaying the Stream Power variable at the Average water level in the post-construction state with areas where depths currently do not meet safe navigation requirements, it can be concluded that regulation structures are targeting the right areas.

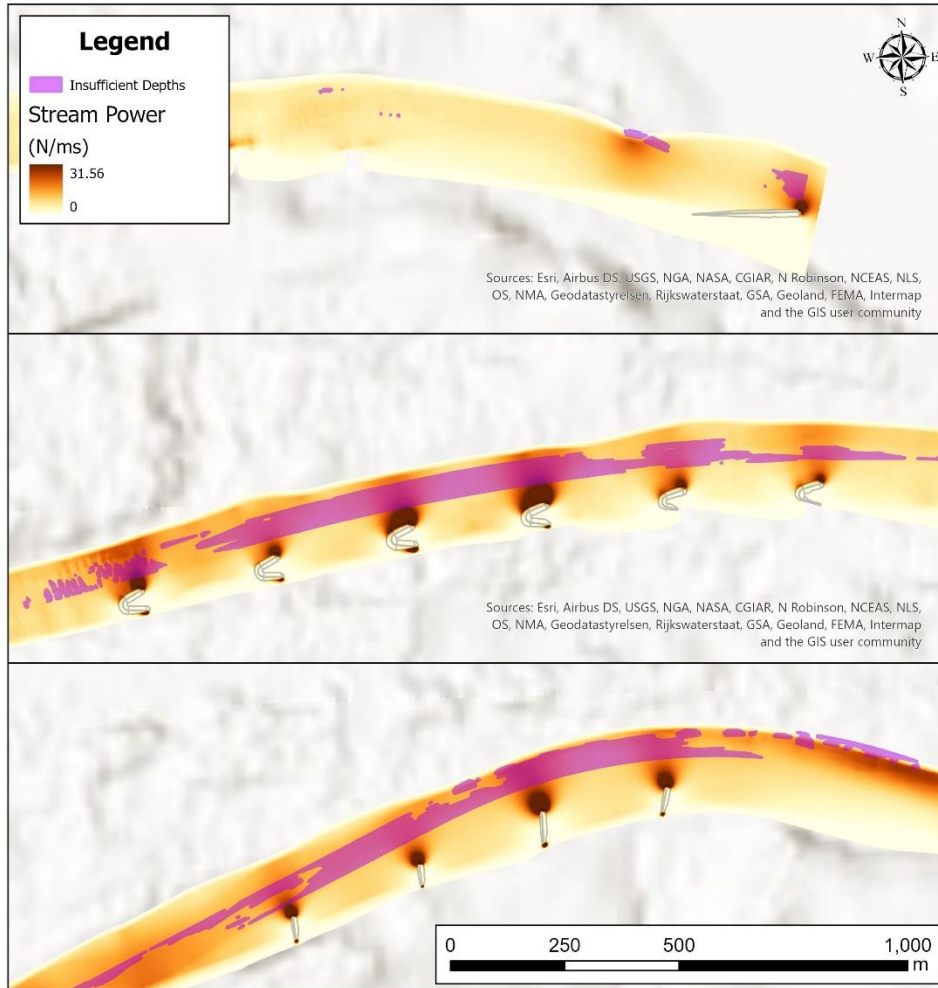


Figure 26 Areas of insufficient depths and Stream Power variable at the Average water level in the post-construction state

#### 4.1.2 Assessment of Changes in Flow Dynamics

The changes in Velocities, Shear Stress and Stream Power indicate that the flow dynamics of the river will be substantially changed after the construction of regulation structures. These changes would be limited to the exact bottleneck areas. The greatest impacts will be during the low water levels which was the purpose of such undertaking.

In terms of the effects of regulation structures on overall river flow dynamics, the Manual on Good Practices in Sustainable Waterway Planning (2010) identified several key areas. These are summarised for each type of structure as proposed by this project in the following tables.

Table 6 Effects of Chevron on the overall river flow dynamics. Source: (ICPDR, 2010)

<b>CHEVRONS</b>			
<i>L - low influence</i> <i>M - medium influence</i> <i>H - high influence</i>		Technical effects	
Hydrodynamics	Water flow	H	increased water depth at low discharges
	Flow velocity	H	increased flow velocity at low flow
	Shear stress	H	higher shear stress and therefore erosion
Sediment transport	Transport capacity	M	increase of transport capacity
River morphology		M	reduction of side-arm morphodynamics

In terms of hydrodynamics, chevrons have a high influence in all three areas. An increase in water depth is the purpose of their construction, ie. to ensure safe navigation depths. Increased Flow Velocity and higher Shear Stress are the negative sides of chevron construction and have an adverse impact on the river flow dynamics. In this area, they have the same impacts as traditional regulation structures, such as regular groynes and T-groynes.

Since the idea behind the chevrons is to be disconnected from the riverbank, there are added benefits in comparison to traditional structures in terms of preservation of morphodynamics and restoration of floodplains and river side-arms. Additionally, chevrons provide an advantage compared to traditional structures concerning sediment transport capacity. Effects of chevrons are therefore assessed with medium impacts in these two areas.

Table 7 Effects of Declinant Groynes on the overall river flow dynamics. Source: (ICPDR, 2010)

<b>DECLINANT GROYNES</b>			
<i>L - low influence</i> <i>M - medium influence</i> <i>H - high influence</i>		Technical effects	
Hydrodynamics	Water flow	H	water level increase at low flows
	Flow velocity	H	increased flow velocity
	Shear stress	H	higher shear stress
Sediment transport	Transport capacity	M	increase of transport capacity
River morphology		M	degradation in the main channel

Similar effects are identified in the case of declinant groynes. Water levels will increase at low flow providing more depth for the navigation. As an adverse effect of their construction, Velocity and Shear Stress will increase. Compared to the effects of chevrons, declinant groynes also ensure less degradation of the main river channel.

The side erosion along the banks could aid the restoration of natural riverbanks. Disconnection from the banks also ensures no sedimentation will occur as would be the case between a series of regular groynes connected to the banks. These effects will greatly depend on groyne height, orientation and spacing, which is why an approach like the one used in this research can greatly aid the final decision on these elements.

The following figure provides the results obtained as a part of this research indicating the beneficial effects of alternative regulation structures (ie. the flow is present along the riverbanks). The figures show water flow particles and velocities around the proposed regulation structures at the Average water level.

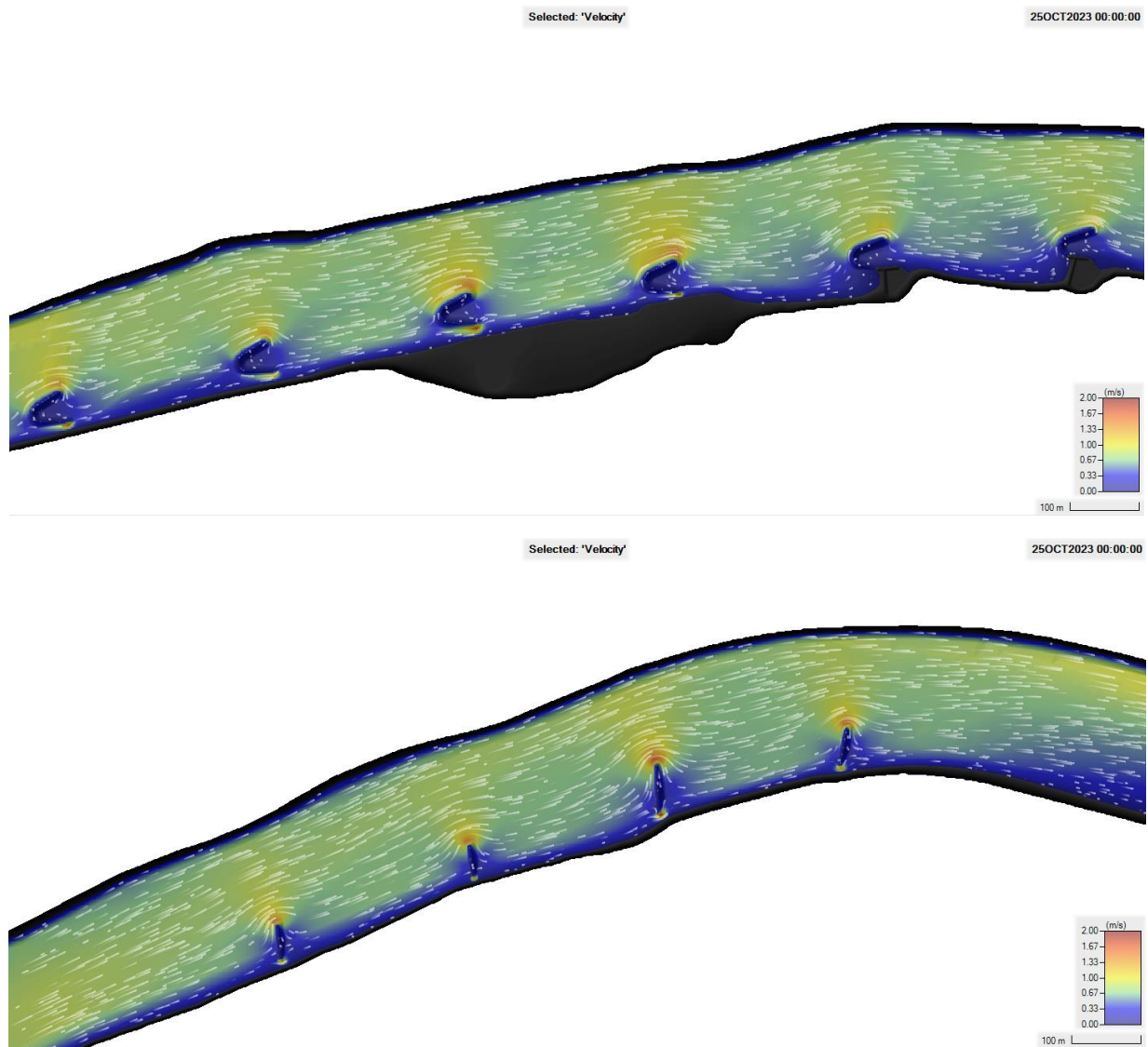


Figure 27 Flow particles and velocities around the proposed regulation structures Chevrons (top) and Declinant groynes (bottom)

#### 4.1.3 Assessment of Ecological Implications

The left bank of this stretch is the protected area of Kopacki Rit, and all the regulation structures proposed for this project are located along the right bank.

In terms of the ecology and environmental aspects of proposed engineering structures, there are different spatial and temporal scales at which potential impacts could be assessed. However, the environmental impact assessment for such a project could be a topic for whole new research. As this research is focused on the riverbed and low water levels, this chapter briefly outlines possible local impacts caused by the construction of regulation structures.

Basic aspects of environmental impacts can be classified in terms of impacts **during the construction** of the proposed structures (ie. by taking space in the environment and performing works) and terms of their impacts **after the construction** (ie. impacts resulting from the purpose/operation of the structures).

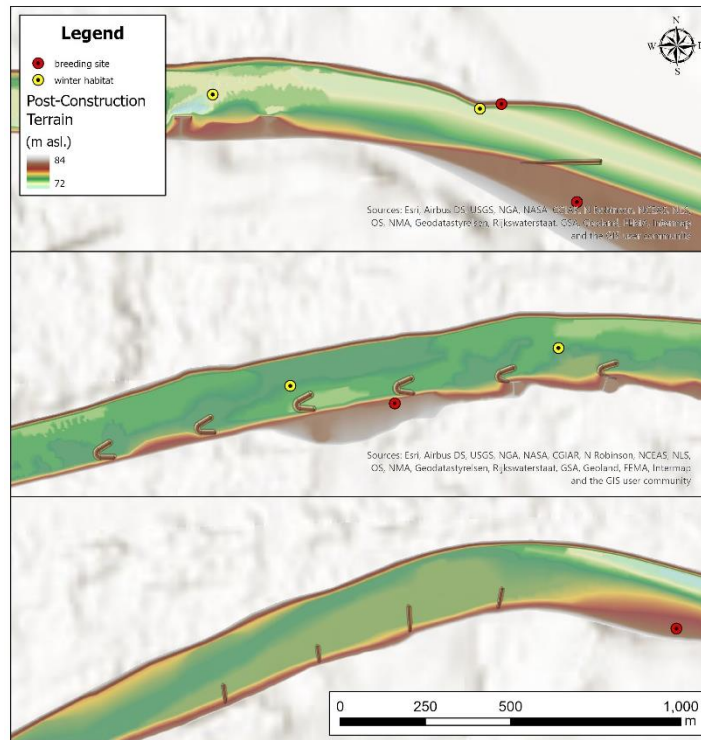
A biological and ecological study was performed in the wider project area including a survey of key habitats, as well as bird and fish species. This study was completed as a part of “Conceptual design for the improvement of navigation conditions on river Drava from the confluence - river km 0, to Port of Osijek - river km 12 (Hidroing Ltd. Osijek, 2016)” and therefore was provided by the partner.

This study identified important locations for fish species within the riverbed for breeding and as a winter habitat. On this stretch of the Drava river, breeding sites are mostly correlated with shallow water locations along the banks, while winter habitats usually represent deeper parts of the river channel (Geonatura, 2016). Also, the study defined several sites within the project area which are considered of high importance in terms of biodiversity preservation.

These two different variables are plotted against the location of regulation structures for the potential impacts **during the construction** and against the Stream Power variable at the Average Water Level in the post-construction state to assess the potential impacts **after the construction**. The Stream Power at the Average Water Level variable was selected as the most representative variable in terms of changes caused by the construction of regulation structures.

The following matrices give an overview of environmental impacts during and after the construction.

**Breeding sites/Winter habitats - Assessment of impacts during the construction**



**Breeding sites/Winter habitats - Assessment of impacts after the construction**

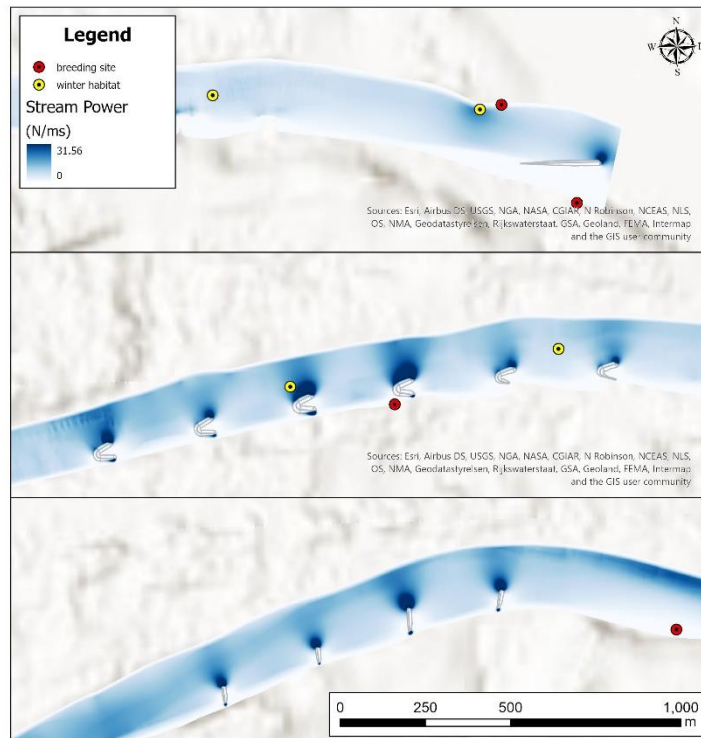
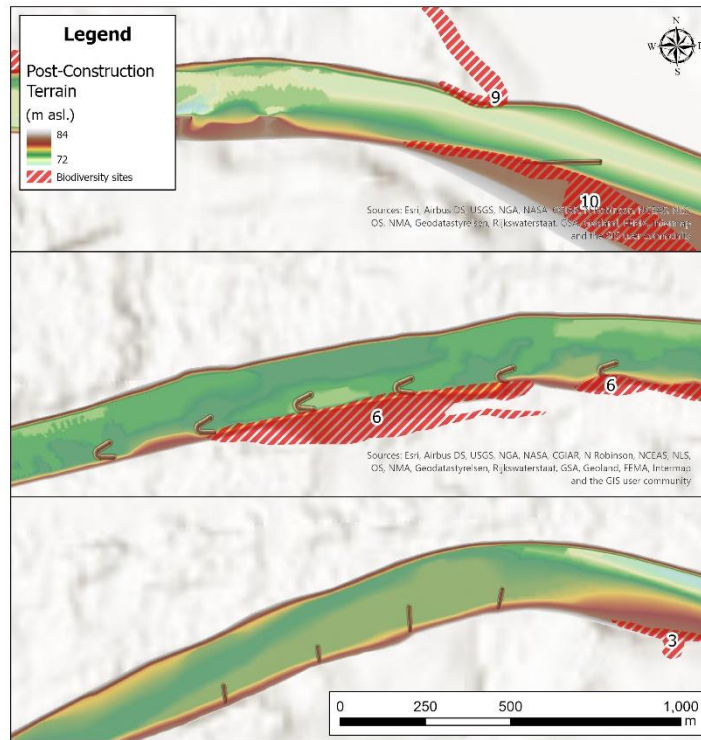


Figure 28 Environmental Impact Assessment Matrix – Visual Part 1

Sites of high biodiversity importance - Assessment of impacts during the construction



Sites of high biodiversity importance - Assessment of impacts after the construction

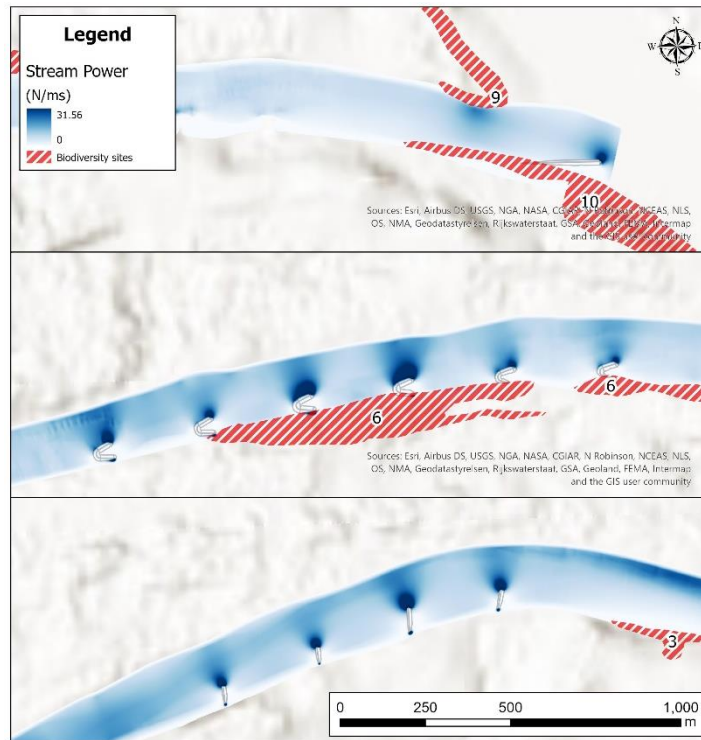


Figure 29 Environmental Impact Assessment Matrix – Visual Part 2

Sites of high biodiversity importance located within or in the vicinity of construction sites (as labelled on the figures above) include the following sites:

**6 - Existing embankment and t-groyne, connecting channel, willow forest and shallow river parts. This is a site suitable for aquatic, wetland, and floodplain habitats.**

Key elements for preservation:

Connectivity with the main flow, favourable regime of flooding and sedimentation.

**10 - Mouth of the river Drava into the Danube.**

Key elements for preservation:

Connection with the main river channel, favourable flooding, and sedimentation regime.

*Table 8 Environmental Impact Assessment Matrix*

<b>Breeding sites/Winter habitats</b> - Assessment of impacts during the construction	<b>Breeding sites/Winter habitats</b> - Assessment of impacts after the construction
<ul style="list-style-type: none"> <li>➤ No breeding sites or winter habitats are directly located on the site of construction of regulation structures.</li> <li>➤ One breeding site is located in the vicinity of Chevron 5D-1.</li> <li>➤ One winter habitat is located in the vicinity of Chevron 5D-2.</li> </ul>	<ul style="list-style-type: none"> <li>➤ One winter habitat location, near Chevron 5D-2, is under the direct influence of increased Stream Power after the construction of regulation structures.</li> <li>➤ There is another breeding site in front of Chevron 5D-1.</li> </ul>
<b>Sites of high biodiversity importance</b> - Assessment of impacts during the construction	<b>Sites of high biodiversity importance</b> - Assessment of impacts after the construction
<ul style="list-style-type: none"> <li>➤ Sites number 6 and 10 are under the direct impacts of the construction of regulation structures.</li> <li>➤ The impact concerns a group of chevrons and declinant groyne at 0+000 river kilometre.</li> <li>➤ There are no biodiversity sites identified on the location of the declinant groyne group.</li> </ul>	<ul style="list-style-type: none"> <li>➤ Sites number 6 and 10 will be under the direct impacts of the increased Stream Power after the construction of regulation structures.</li> <li>➤ The impact concerns a series of chevrons and declinant groyne at 0+000 river kilometre.</li> <li>➤ There are no biodiversity sites identified on the location of the declinant groyne group.</li> </ul>

The group of four declinant groynes is located outside any locations of ecological importance.

The potential impacts on breeding sites and winter habitats that are located in the vicinity of regulation structures could be mitigated by performing construction works outside of the breeding season and winter.

Winter habitat location, which is located near Chevron 5D-2, is under the direct influence of increased Stream Power after the construction of regulation structures and there are no foreseeable measures that could avoid this kind of impact other than not constructing this Chevron as proposed by the Study.

The breeding site, which is located in front of Chevron 5D-1, will not be impacted by the increased Stream Power as it's located close to the bank and there is no major increase of Stream Power in that specific location.

There could be potential impacts on sites of high biodiversity importance labelled with numbers 6 and 10 during the construction works. However, these impacts are expected to be short-term. The space taken by the regulation structures that fall within biodiversity areas is limited to a small footprint. A special caution needs to be taken during the construction to minimise disturbance to aquatic, wetland, and floodplain habitats.

After the construction, those two sites will be affected minimally as regulation structures are not connected to the riverbanks. There is a river flow along the bank which ensures connectivity with the main flow, and a favourable regime of flooding and sedimentation, all of which were identified as key elements for preservation in the Biological and ecological study performed by Geonatura (2016). This is where the application of guidelines outlined in the Manual on Good Practices in Sustainable Waterway Planning (ICPDR, 2010) and the Good Practice Manual on Inland Waterway Maintenance (ViaDonau, 2016) show the positive impacts of alternative regulation structures.

To summarise this chapter, it is evident that there will be some impacts on the ecological values of the project area. Some impacts might be mitigated by performing construction works in certain parts of the year and some by added protection measures while performing construction works. In the long term, the construction of regulation structures will have an impact on one winter habitat which cannot be mitigated in any way.

It is also important to note that the site identified as a site of high biodiversity number 6 is situated within the area with several regulation structures present. These are old regulation structures built a long time ago. They happen to provide favourable conditions for shallow water habitats and fish breeding sites.

Lastly, an assessment of the construction of chevron structures in the Middle Mississippi River, USA, suggests that chevron construction positively affected wintering habitats, shallow water habitats, and physical-aquatic-habitat diversity in the area (Remo et al., 2013). This research implies that the construction of chevrons in the project area could also bring positive effects on biodiversity.

#### 4.1 Limitations

There are multiple areas where the methodology of this research could be improved. As already stated, there are no data regarding the sediment in the project area. HEC-RAS provides superb modelling capabilities and can integrate sediment transport with unsteady flow calculations. The sediment transport modelling would provide more specific results regarding the change in the riverbed such as the exact location where deepening of the channel will occur.

The Digital Elevation Model could be further improved by using more advanced surveying techniques such as Lidar. DEM used for this research is based on transversal point surveying and is heavily interpolated, therefore might lack the essential details for modelling.

The choices used in this research regarding modelling variables such as mesh size, computational time, and interval, are subjective and there is always a shadow of doubt whether the results could be improved by using different modelling parameters. However, the outputs proved to be successful in terms of determining the changes in Water Surface Levels, Velocity and Shear Stress.

Despite all the limitations, the choice of methodology provides sufficient evidence to answer the research question.

#### 4.1 Additional Considerations

There are several T-groynes already present in the project area. To fully utilise the environmental potential of alternative structures such as chevrons, the existing structures should be removed. Similar actions were completed on the Danube as a part of Pilot Project Witzelsdorf, Austria (ICPDR, 2010). The following figure gives a closer look at the location where two chevrons are proposed in a way that they connect to existing T-groynes. This would result in limited connectivity of shallow water areas along the bank and affected sedimentation regime within the riverbed.

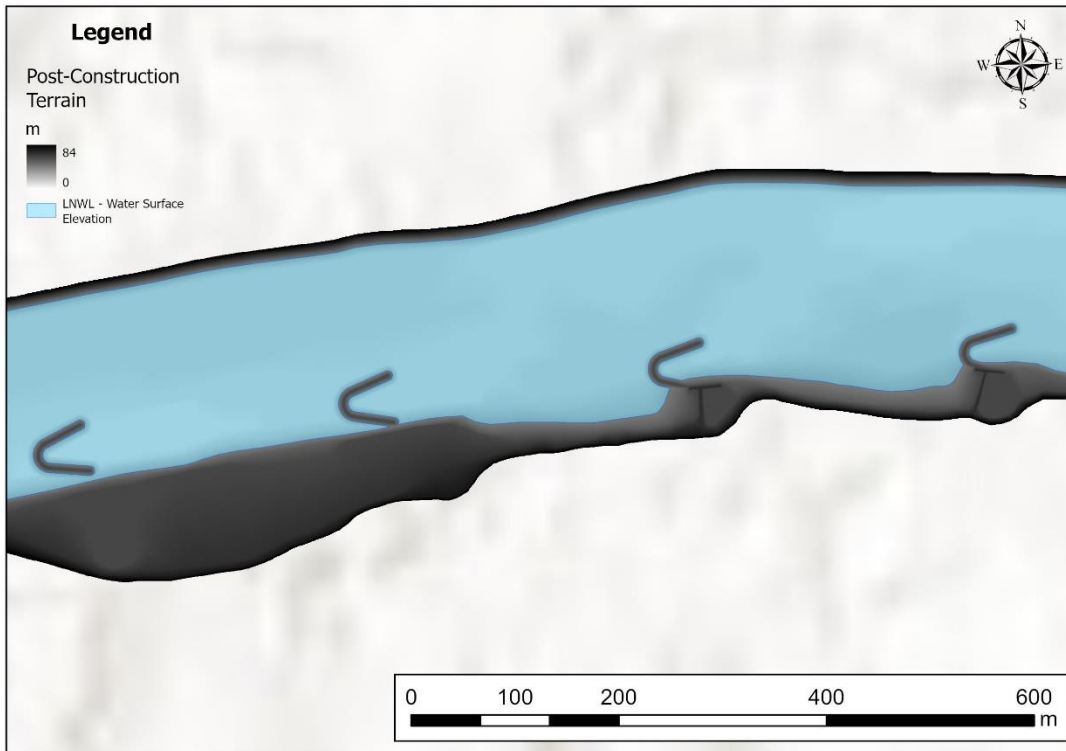


Figure 30 Closer view of the location where two Chevrons are connected to existing T-groynes

## 4.2 Comparison to Similar Projects

Jaafar et al. (2023) conducted the research on use of numerical models in river engineering studies. The research included 60 scientific papers on river regulation and the results suggest that 93% of researchers used HEC-RAS as a decision-making tool. The other popular software is MIKE by DHI, but HEC-RAS proved dominant in the river engineering sector covering areas such as sediment transport, training works, flood management and navigation.

A very similar study was conducted on the Dwarkeswar River in West Bengal, India by Malik and Chandra Pal (2019). However, in their example, a series of groynes is already constructed and they used old remote-sensing images to recreate the state without regulation structures. Their focus was channel morphology, sedimentology, and flow characteristics. This research concluded that there are considerable impacts of groynes with sedimentation behind the non-submerged groynes and channel degradation as the most serious concerns.

Another study performed in Villahermosa, Mexico by Rivera-Trejo and Hernández-Cruz (2020), used a 1-D HEC-RAS model to numerically simulate an arrangement of seven groynes oriented at a certain angle from the bank and partially submerged. The study used a similar approach to modelling regulation structures as physical barriers, stepped barriers and natural terrain (the approach used in this research). The objective was to perform a hydraulic analysis, but the research concluded that a 2-D model is necessary as a further step in this project.

When it comes to projects on the Danube River there are several examples of similar projects. One of them is a research paper by Horvat et al. (2020) where the authors used the HEC-RAS River Analysis System 2D Modeling to perform flow simulations on the old meander of the Danube River in Southern Hungary. The aim was to investigate the effects of different engineering works that would have a positive effect on the ongoing degradation of the meander. Similar to this research, the project area is located within the protected area, Duna-Drava National Park in Hungary. The employment of hydraulic models was deemed beneficial for the selection of engineering works. However, the lack of sediment data was also identified as a model shortcoming.

Several researches were completed on the river Drava too, which utilised mathematical modelling software. These include works such as Flood frequency modelling of the Kopački Rit Nature Park by Tadic et al. (2013) using HEC-RAS, and Sediment transport modelling of the Drava river confluence by Cikojevic et al. (2020) using MIKE by DHI.

## 5. Conclusion

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The final chapter concludes the research by providing the answer to the research question while also providing insight into the general aspects of river management. The chapter concludes with the outlook for future work on this topic and the possible application of research methodology for similar projects.

### 5.1 Major Findings

Every project that includes construction activities in nature will inevitably have some consequences. Regulation structures have been used on rivers for a long time and they have certainly caused some damage to the environment. At least, since their first uses, a lot has been learned about their impacts and how to make these structures more environmentally friendly.

The entire river Drava, including the research area, has been heavily modified in the past century. Despite all the regulation works, the project area still provides a unique habitat for a great diversity of plant and animal species. To preserve that natural richness and improve the biodiversity in this area, it is necessary to limit the engineering works but also to define and perform adequate conservation measures. Engineering measures could also be performed in an environmentally friendly manner and work in synergy with nature to counteract the damage done. The attitude must be shifted from “how to utilize rivers”, to “how to utilize rivers with minimal damage, and possibly even perform additional restoration measures”.

This or any other similar project concerning regulation structures could benefit from the approach used in this research to assess and propose the number and size of regulation structures with as little impact on the environment as possible. River regulation projects could also be used to maximize the opportunities in terms of restoration of natural habitats and enhancing the biodiversity within the area while still fulfilling the main purpose of ensuring safe navigation depths.

Yes, the construction of river regulation structures has an impact on the flow dynamics and ecology of the river system. At least there has been a substantial effort undertaken to make those impacts as minimal as possible with some added benefits.

Impacts on both flow dynamics and ecology of the river, looking from the perspective of this research have local character, but such undertakings also must be assessed from a broader perspective of the entire river system. River Drava already is under pressure from hydropower utilisation, irrigation, water supply, river regulation, and flood defences. In the end, the key is finding the balance between human needs and nature conservation.

River transportation is a significant part of the entire European transportation network and presents one of the cleanest means of transport especially in terms of combating climate change (Platina, 2010). From a general point of view, projects such as this one will contribute to the environment in a different form.

If river transportation is utilised where the conditions exist, it is necessary to take appropriate measures to ensure safe navigation depths and prevent potential disasters. Such disasters could result in severe pollution of the river and floodplain environments and degradation of aquatic ecosystems, but also in loss of life and significant financial consequences.

Lastly, it's also very important not only to look at all the components of the river and its uses but also to approach the river as a whole, including the entire watershed with all tributaries and catchment areas. The Drava is an international river and cooperation on an international level is necessary for successful river management and finding the balance between utilization and conservation goals.

### 5.1 Outlook for Future Work

The next step for projects like this one would be to improve the data used. Every model is as good as the data used. This relates mainly to better bathymetric surveying, but also to detailed habitat surveying and ecological monitoring. Also, it would be beneficial to assess the greater picture of the project area in terms of existing disturbances to the entire river system. Hydrological datasets could be further improved to include sediment data. Lastly, it would be beneficial to test the usage of various commercial software providing 3-D modelling options for even more detailed modelling of the system.

### 5.2 Project Application

The methodology used for this research could be applied to a wide variety of similar river engineering projects. Any structure that could be successfully modelled into the existing terrain could be assessed in terms of potential impacts on the hydrologic system. HEC-RAS or any other similar software could be successfully used for the assessment of potential changes in river dynamics before the actual construction of river engineering structures. Computer models give insight into river behaviour and can greatly aid decision-making on the exact locations, numbers, and dimensions of the proposed structures. Depending on the size of the project and the availability of computing power, these models can provide very precise results.

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