POLITECNICO DI TORINO

Master's Degree in Environmental and Land Engineering

Master's Degree Thesis

Hydrodynamics of the river Hiitolanjoki in Finland under dam removal process

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Summary

The re-naturalization of rivers and the removal of dams is at the center of world's attention: in fact, it is a practice that is becoming more and more important in the United States, and Europe is following the American example. The most important project currently present in our continent is "Dam Removal Europe": about 101 dams were removed in 2020, and it is estimated that by 2030 about 25,000 km of rivers will be restored. Obviously, only the dams that are no longer used for energy production and that over time have become obsolete are considered, because in these cases the maintenance costs are exceeding the earnings. This thesis focuses on the removal of the three dams along the Hiitolanjoki River in Finland. This river is an important fish route: it is the main breeding river for Ladoga Salmons. The removal of the three dams began in 2021, with the disruption of the one in correspondence of the Kangaskoski rapid; the removal of the other two dams is planned for 2022 and 2023. In this work, the flow velocity data that were sampled in the area of the Kangaskoski rapid were analyzed. The data were collected in two different periods: during Spring 2021, before the removal of the dam, and during Autumn 2021, immediately after the removal of the dam. The purpose of the work is to analyze the short-term impact of dam removal, in particular the hydrodynamic variations, differences in the erosive potential and river depth. The data were collected using an Acoustic Doppler Current Profiler coupled with a GPS in such a way as to have precise and well localized data; surface velocity, near bed

velocity and mean speed, were interpolated using the Inverse Distance Weighted and Kriging methods. Using the velocity interpolations, it is possible to see how the velocity, after the removal of the dam, has generally decreased, causing the sediment to be easily settled. This could also be the one of the reasons why the river depth has decreased after the dam removal. The changes in flow velocities and water depth could represent an obstacle for the re-naturalization of the river, because they can affect the water quality and the fish nesting. While the velocities have decreased on average, changes have been heterogeneous in space and increases have been recorded in different locations. The differences in the erosion potential were established using a hotspot analysis, with which the speed clusters (both high and low velocity) were highlighted. The analysis shows that some areas, in particular the stretches of river close to the infrastructures (Houses and Bed and Breakfasts), after the removal of the dam, begin to be affected by erosion. For this reason, it is necessary to proceed with further researches in order to plan mitigation interventions for the protection of the surroundings.

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Chapter 1

Introduction

This thesis follows the removal of a dam on the Hiitolanjoki river, in particular of the dam in correspondence of the Kangaskoski rapid. The dam removal project has been carried out by the South Karelia Recreation Area Foundation which, over the years, has acquired all the rights of the three power plants located on the Hiitolanjoki river (Lahnasenkoski, Ritakoski and Kangaskoski). This project is funded by different associations, such as WWF, Lassi Leppinen Foundation, the South Karelian Savings Bank Foundation, OP Simpele, Lähi-Tapiola and the municipality of Rautjärvi which are the largest financiers [1].

Aalto University, together with Natural Resources Institute Finland, has been involved in this project to monitor the long term variations in the river hydrodynamics after the dam removal.

This thesis will focus on the comparative analysis of the water velocities before and after the removal of one of the dams within the Hiitolanjoki river.

This study is important because, despite the increase in dam removal projects, there is still little research on the very short-term hydrodynamic consequences that can occur. It can be very useful to predict how the future dam removal in Ritakoski and Lahnasenkoski (planned in 2022 and 2023) will evolve considering

that they belong to the same river: in particular, this work shows how this type of dam removal affects the spatial variation of the velocities of the flow and their impact on the erosion potential.
This study will therefore give a new perspective on the very short-term variations in the river hydrodynamics, erosion forces and river depth.

1.1 General Background

Rivers are one of the most important water resources present on the planet earth: together with lakes, they are one of the largest sources of fresh water in the world, they host habitats of all kinds and that is why it is very important to monitor them. In fact, water is at the basis of human activities of all kinds and rivers are an easily accessible resource for water supply: they are in fact used as a primary source of water for the irrigation of cultivated fields, a source of water that will then be made drinkable, for the transport and, last but not least, for the production of electricity through the construction of hydroelectric dams.
The restoration of the rivers and dams removal are new practices that will affect many rivers in the immediate future: in fact, the dams, despite having been built with the intention of producing "cleaner" energy, if not maintained in the correct way, can be harmful to the environment and contribute to climate change. According to the Earth Law Center, the dams release greenhouse gasses, deprive ecosystems of nutrients and destroy habitats [2].
Considering that one of the reasons why the dams on Hiitolanjoki river are planned to be removed is because of Ladoga salmons, it is then important to evaluate the short-term consequences of a dam removal to see if the "new" river environment will be hostile to the salmons rise. For example, a study published in May 2013 made by Ming-Chih Chiu, Chao-Hsien Yeh, Yuan-Hsun Sun & Mei-Hwa Kuo [3] shows the short-term effects of a dam removal on macroinvertebrates in a Taiwan

steam. This study explains how the transport and increasing of sediments caused by the removal of the dam (which is a sediment trap) brought to the decrease in the macroinvertebrate population. This is a problem because macroinvertebrates are one of the principal food source for fish (salmon included).

Moreover, erosion monitoring is very important because it can represent a threat both for the environment and for the society. Erosion, if not taken under control, can cause the topsoil to no longer be able to hold nutrients and it could be a threat to the regulation of the water flow. This means that erosion increases the spreading of pollutant and the flood risk.

Concerning the water quality of the river, during the last decade, the amount of Biochemical Oxygen Demand, suspended solids and phosphorus have been substantially reduced in the Finnish territory, causing the water quality to increase a lot. The only thing that is remained at the same level is the nitrogen discharge but apart from it, the water quality of Finnish water bodies is constantly improving. More specifically, the water quality on the Finnish side of the Hiitolanjoki river is considered to be good/moderate. This means that Hiitolanjoki river could be the perfect environment for the rising of Ladoga Salmons after the dam removal: the problem that follows the dam removal is due to the erosion and to the nutrient leaching. Sedimentation is in fact one of the major problem that affect salmon survival [4] because their eggs, in order to survive, need a particularly oxygenated water: this is why a gravelly environment is perfect, because it allows oxygen to pass through the interstices of the gravel. If, on the other hand, the gravel is blocked by fine sediments, as a result of erosion, the salmon eggs can be smothered, and, when it is time for the eggs to hatch, the fish can remain trapped.

Moreover, the presence of dams in a river might be a problem in some cases because they makes it segmented and discontinuous, being a threat to the marine ecosystem: fish, in fact, if special infrastructures are not built to allow them to pass through, are trapped. Furthermore, a dam can cause the water quality to diminish because it is a sediment and nutrient trap: if sediments and nutrients are trapped upstream, down steam the so-called "clear water condition" can develop .

The area on which this thesis focuses is the region of South Karelia. Hiitolanjoki is a 62 km long river which for most of its length crosses Russia and it crosses the Finnish region only for its last 8 km. This is a very important river because of the Ladoga Salmons stock that lives in it: it works as a fish route and it is crossed by salmon that go up the river from lake Laatokka (Russia) to Finland to get to the lake Simpelejärvi.
The main problem with this fish route is that it is interrupted by the presence of dams which over the years have been built to stock the water into basins with the aim of creating an hydraulic jump to produce electricity. The river, on the Finnish side, is characterized by the presence of 4 rapids each of which was used for the production of electricity after the construction of dams and the installation of power plants. The rapids are Juvankoski, Ritakoski, Lahnasenkoski and Kangaskoski and right now all the power plants have been shut down. Even though these power plants have been part of the electricity grid for over 100 years, the energy production and the maintenance of the dam were not worth the money and this is another reason why the dam removal was planned and it is happening.
In September 2021, the dam in Kangaskoski was removed as planned, officially starting the river restoring process.
While on the Russian side the dams have been completely removed, on the Finnish side there are still two dams that are going to be removed respectively in 2022 and 2023. This is indeed the biggest dam removal that is ever happened in Finland because of the dimensions of the dams and their historical importance.

1.2 Aims of the work and Research Questions

This thesis deals with flow velocity data collected on the Hiitolanjoki river, in particular in the Kangaskoski area, to evaluate what are the changes in the hydrodynamic conditions of the river before and after the the dam removal.

Figure 1.1: Kangaskoski Rapid in March 2022, 5 months after the dam removal

The data were collected in May 2021 and September 2021, immediately before and after the dam removal. In particular, the variation of surface velocity, mean speed and near bed velocity that the river undergoes with the removal of the dam have been compared. The aim of this study is to analyse the hydrodynamic differences that arise right after the dam removal and to identify possible clusters and hotspots in the water velocity datasets, in order to to highlight a possible spatial variation of the erosion forces.

Research Questions

A What are the short-term hydrodynamic differences consequent to the dam removal?

B How the erosion potential, river channel and depths have spatially changed with the removal of the dam?

In the following chapters the theoretical aspects concerning the dynamics of a river, the construction and removal of a dam with the consequent restoration of the river, are described in depth; thereafter, the methodologies and analyses that led to the final results will be described in the methods chapter.
The results are examined and argued in the discussion section, where different scenarios are taken in consideration.
Finally, the research questions will be answered in the conclusions chapter.

Chapter 2

Theoretical Background

2.1 Hydrodynamics of a river: generalities

The hydrodynamic of a river can be studied by implementing the fluid-dynamic theory to the open channel flow case [5]. Fluid-dynamics has a very ancient history because it has always been at the center of attention: Archimedes was one of the first scientists that discovered and was able to exploit the principles of hydrostatic. However, even if Greeks with Archimedes made very important discoveries, the Romans were the first to master the knowledge about fluids flow and therefore about open channel flows: they are in fact well known for the construction of an advanced water supply systems (e.g., aqueducts). Anyway, nothing was mathematically described yet, making discoveries hardly usable and adaptable in different environments.

The first scientist who tried to analytically describe the movement of water was Leonardo da Vinci in the book *"Del moto e misura dell'acqua"*, where he tried to theorize a mathematical formula that linked width, depth, the slope and roughness of the river in the so-called “fluid continuity law".

The Naiver-Stock equations are currently the most important equations when talking about fluid dynamics, as well as one of the seven ever unsolved mathematical problems: in fact, an analytical solution in closed form to these differential equations has not been found yet. This set of equations describes the behavior of a viscous fluid at the microscopic level. It is possible to derive from the Naiver-Stock equations a set of equations that are valid at a macroscopic level, but this can be done only by making some assumptions about the open-channel flow (i.e., the density of the water is constant because it is considered as an incompressible fluid, the vertical pressure distribution is considered hydrostatic, the bed slope is negligible...). The results are the so-called "Saint-Venant equations".

The description of the fluid movement is only a small part of what concerns the characterization of a river: it is a complex system composed by not only water, but also by vegetation and sediments, whose movement leads to the continuous change of the river shape. The river bed is in fact defined as "mobile" because sediments are continuously transported by the water and, depending on the speed of the water, they can settle (deposition) if the speed of the water is too low, or can be dragged (entertainment) into space if the speed of the water is sufficiently high; this causes a local variation of the river depth and this variation leads to a variation in the water flow itself: it is a dynamic system.
The study of this complex system is called morphodynamics. Also in this case Leonardo da Vinci studied this phenomenon in an empirical way, evaluating the relationship between the erosion of different river beds and the deposition of sediments generated by the water flow, taking into consideration all the obstacles present within a river (e.g., channel constrictions, river bends). Subsequently, many experts have tried to analytically describe this phenomenon. However, the morphology of a river is not only characterized by the flow of water and the consequent transport of sediments, but also by the presence of flora and fauna. Many experiments have been carried out studies on riparian vegetation which show that vegetation

is very important both for the development and for the stabilization of a river. Furthermore, the same experiments show how the distribution of vegetation greatly influences the role of vegetation in the fluvial environment [6].

2.2 Spatial Variation of the Water Flow

A river, during the course of a year, is subjected to variations of the streamflow caused by the seasonal variation of the meteorological conditions. For this reason, it is normal that the water level is not constant throughout the year, but rather changes: in particular, it is necessary to consider the differences in precipitation during the seasons, the melting of the snowpack that formed during the winter and also the ground infiltration capacity. The last characteristic is important because it defines the amount of water that will infiltrate into the soil, becoming part of groundwater, and the amount of water that will transform instead into runoff going into surface water bodies such as rivers. These are the so called short-term variations that a river can experience during a year. Concerning the long-term variations, they can be caused by human activities such as the construction or the removal of a dam, the water usage for agricultural purposes, channelization, alterations of the natural stream channel and climate change. [7].
The removal of a dam and the restoration of a river can constitute a major disturbance for the watercourse since, following the construction of the dam, it has "got used" to the presence of the obstacle and has therefore evolved accordingly: it is an upheaval in the steady state condition of the river. Moreover, the disruption of a dam could lead to various spatial variations, including for example the displacement of the river bed. In 2018, a study on a large dam removal on the Carmel River (California, USA) was published: this study shows how the displacement of the river within the first year after the dam removal is about 1 meter and so very small and almost irrelevant, while already after two years the river has a lateral shift of

45m [8]. This study proves how the removal of a dam, if not studied in detail, can be very dangerous for the infrastructures that are close to the river.

2.3 Sediment Erosion and Deposition

First of all, sediments are agglomerates of organic and inorganic material that can be transported by various atmospheric agents (snow, wind, water...). They can be classified according to their size (British Standards and MIT):

- Pebbles: elements with a dimension between 60 mm and 200 mm
- Gravel: particles with a dimension between 2 mm and 60 mm
- Sand: particles with a dimension between 0.06 mm and 2 mm
- Silt: particles with a dimension between 60 µm and 0.06 mm
- Clay: particles with a dimension less then 2 µm

The sediments in the river, depending on different conditions, can be eroded, transported and deposited.

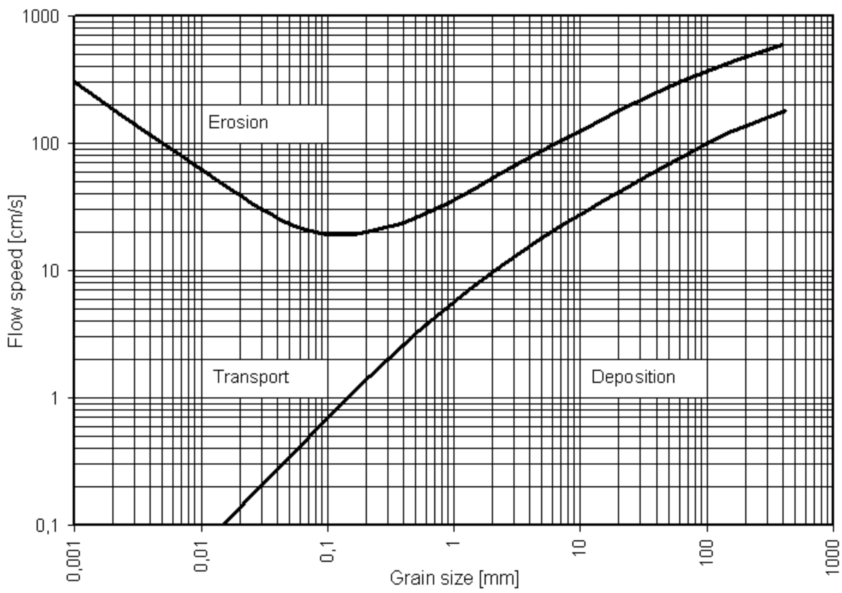


Figure 2.1: Hjulströms Diagram, source Wikipedia. The diagram shows how, depending on the grain size and the flow speed, the sediments behave in contact with water.

The Hjulströms diagram [9] is a double logarithmic diagram which, knowing the size of the sediment grains and the speed of the water flow, it is capable to predict the fate of the sediments. According to the sediments classification made before, the water flow needs to be very fast in order to erode pebbles and gravel: it has to be higher than 0.55 m/s in order to start eroding the smallest gravel sediments, while it has to be very high (> 3 m/s) to start eroding pebbles. The same goes for very small sediments (clay), which are transported very easily by the water flow even at very low speeds, but if they are too fine, the water velocity needs to be higher than 3 m/s to erode them. Anyway, it is possible to state that the smaller the sediments are (< 0.01mm), the easier is for them to be transported by the

water rather than being eroded or deposited; on the other hand, the bigger the sediments are, the easier is for them to be deposited rather than being transported or eroded by the water.
Silts and Sands, that are in the middle of the sediment classification, can be easily eroded, transported and deposited.

2.4 Dams and Hydro-power Plants

A dam is a permanent artificial structure (fixed or mobile) whose main objective is to regulate the water flux or to create an artificial basin that will be used by a hydropower plant [10].
Dams are a fundamental tool in the production of renewable energy from water: the flowing water in a river releases potential energy in the form of kinetic energy due to the gravity force. However, since the potential energy is necessary to produce hydroelectric energy because it is needed for the rotation of the turbine to happen, it is necessary to use a stratagem to block the water and then to store potential energy to be able to use it at the most suitable moments. This is where dams come into play: their role is in fact to accumulate water in a basin in order to "block" the release of kinetic energy that would occur naturally [11].
The altitude (head H) difference between the water, that it is stored in the upstream basin, and the downstream hydropower plant, is exploited through the transformation of the potential energy of the water into mechanical energy of rotation of the turbine, which is in turn converted into electricity through a generator. The “Three Gorges Dam” is the biggest dam in the world in terms of installed capacity (22.5 GW) [12] and electricity production since 2012; it is situated in China, on the Yangtze River.
China (global leader in renewable energy installation) is the largest producer of hydropower, followed by Brazil and Canada [13].

Looking at the topic a little more closely, Europe is also a major user of hydroelectric energy: in 2020, the production of electricity deriving from renewable resources exceeded 30%, of which almost 20% is provided by hydropower.

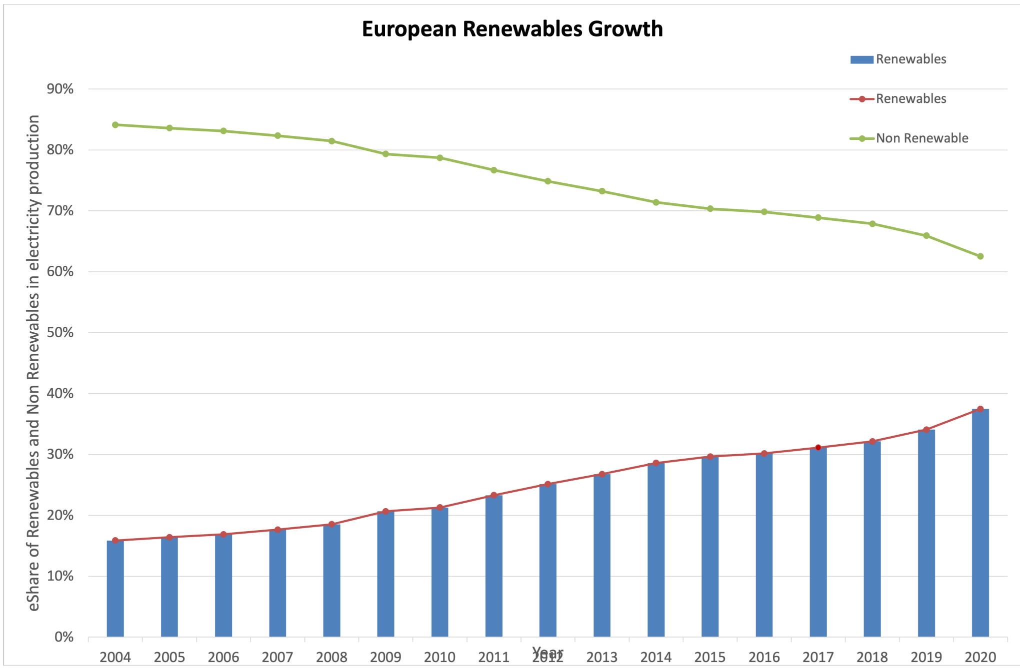


Figure 2.2: Renewables mix in Europe (Based on Eurostat 2020 data [14])

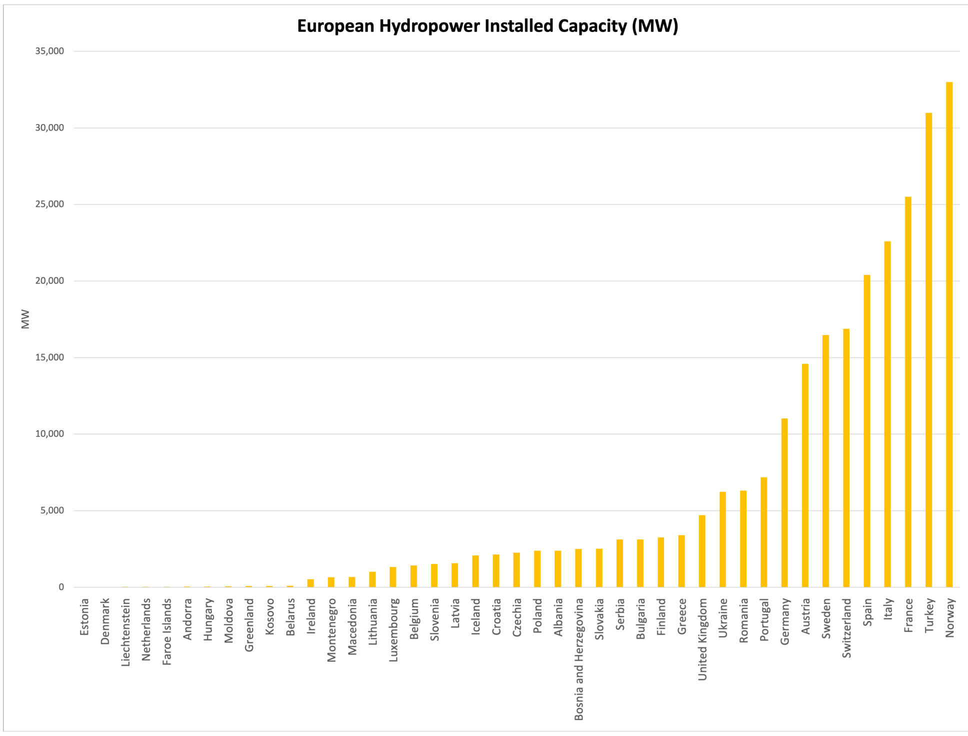


Figure 2.3: 2020 Hydropower installed capacity in Europe (Based on The International Hydropower Association [15])

As it is possible to see from figure 2.3, Norway is the country in which the hydropower installed capacity is the highest: here, hydropower is not only the most used type of renewable energy in the production of electricity, but it is the main source of energy (90% of the annual Norwegian electricity consumption) [16] .
Hydroelectric energy is one of the most important types of energy today because it is essentially a zero-emission energy, but above all it is part of the branch of renewable energy that constitute the future of the planet.
Why renewable energy? Renewable is defined as a resource that is able to regenerate itself over time and also becomes sustainable if its regeneration rate is higher than its consumption rate, thus resulting almost "infinite". Hydroelectric energy is therefore part of this category since it uses water as the principal "raw material" for the production of energy.

Furthermore, hydroelectric energy is very important since it is the only renewable energy to be dispatchable [17]. A dispatchable generation refers to sources of energy that can be used on demand and dispatched at the request of operators, according to the market needs [18]. The only types of renewable energy that are dispatchable are large hydroelectric plants with a reservoir, biomass and geothermal energy. Looking at the 2021 global electricity demand and generation mix, hydropower is currently the most used renewable energy in the mix

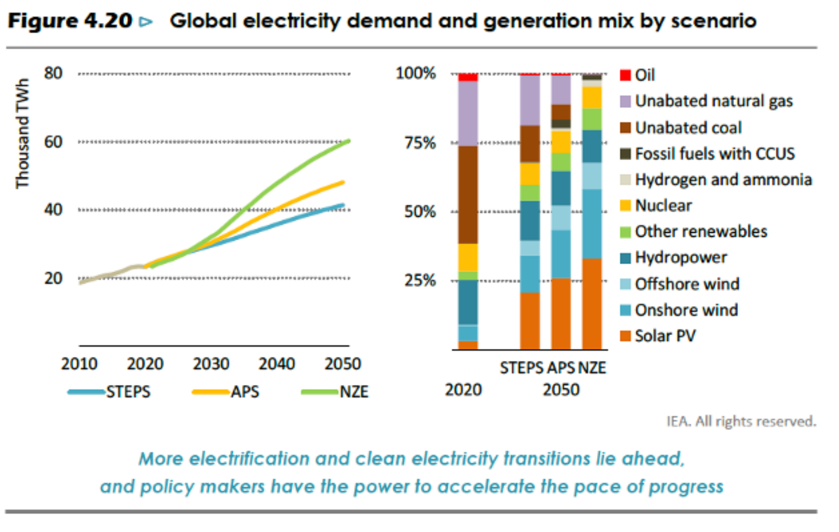


Figure 2.4: Energy mix in Europe, source: World Energy Outlook 2021 [19]

The main problem is that over the years, with technological advancement, much more performing hydroelectric plants with larger dams have been built: this brought small hydroelectric to be closed because they were not more convenient than larger plants from an economic point of view. Therefore, the dams in correspondence of these small hydroelectric plants are only an obstacle to the normal flow of the river. These infrastructures are gradually being dismantled also for environmental reasons, as they are an obstacle not only to the normal water flow, but they are an obstacle for the fish that cannot move inside the river: according to the proceedings of the

"Fish Passage Conference” held in 2021, in the last 50 years, the European fish stock has decreased by 94%. Furthermore, the dams "trap" the sediments carried by the river, causing the formation of stagnant conditions with an increase in the temperature of the water and consequently a decrease in the dissolution of oxygen.

This is one of reasons why associations such ad Dam Removal Europe started a campaign to remove all the unnecessary dams present on the European rivers. For example, it has been estimated that in 2020 alone, 101 dams were removed in Europe (37 of which in Sweden [20]). The aim of the “Dam Removal Europe” project is to restore 25000 km of rivers by 2030 [21]. Obviously, the dams that are taken into account in the decision-making process are dams that no longer satisfy the reason why they were built or that were even abandoned. This objective is numerically achievable considering that the total number of dams in Europe has been estimated as 1.2 million and about 15% of these dams are obsolete (amounting to about 200 thousand) [22]. Currently, Finland counts a total of 221 hydropower stations, 164 of which are either small or micro plants. This means that the contribution of these plants to the total Finnish electricity production is not very effective: as it is possible to see from figure 2.5, ¾ of the plants contribute only to the 9% of the total hydropower production and only to the 2% of the total electricity production in Finland (in comparison, a modern windmill has a power capacity of 10 MW).

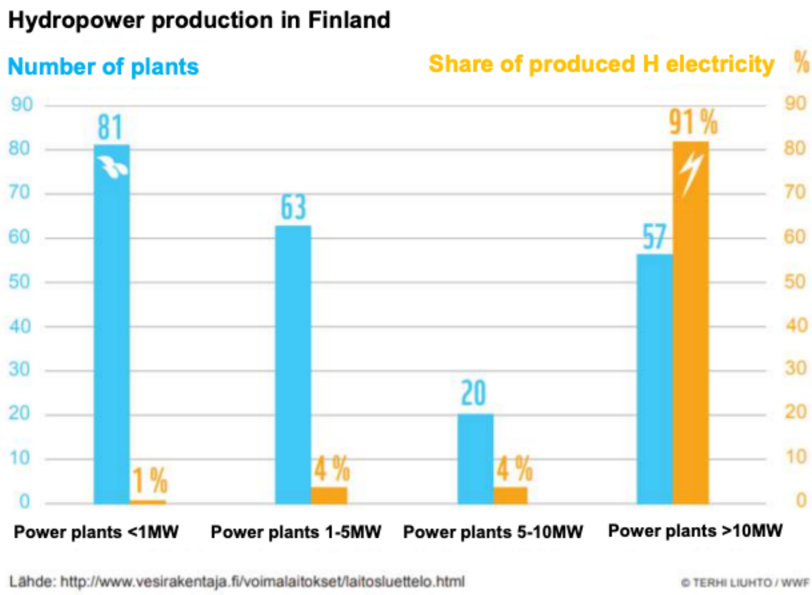


Figure 2.5: Hydropower production in Finland, source: Etelä-Karjalan Litto [23]

For this purpose, a poll within citizen has been made to decide whether to keep or to remove the hydropower dams that are insignificant for energy production to improve migratory fish stocking. 71% of the population voted in favor of the removal.

2.5 Generalities of river restoration

River restoration is a practice that in recent years is becoming increasingly important with the increase in awareness towards environmental issues. With "river restoration" it is meant the reshape operation of a river and the consequent removal of artificial modifications in order to bring it back to conditions that are as close as possible to the original conditions. Water is a precious good and rivers have been exploited a lot through years, especially since the beginning of the first industrial revolution.

The main problem is due to the fact that the human intervention in this natural

environment has promoted the loss of biodiversity, which has heavily damaged the ecosystem.
The positive side of river restoration is that the benefits derived from it on an environmental level also affect society: from water purification to the increase of freshwater supply with the addition of improved human health.

In Europe, the 5 countries that have removed the highest number of dams are Spain, UK, Sweden, Finland and France (figure 2.6).

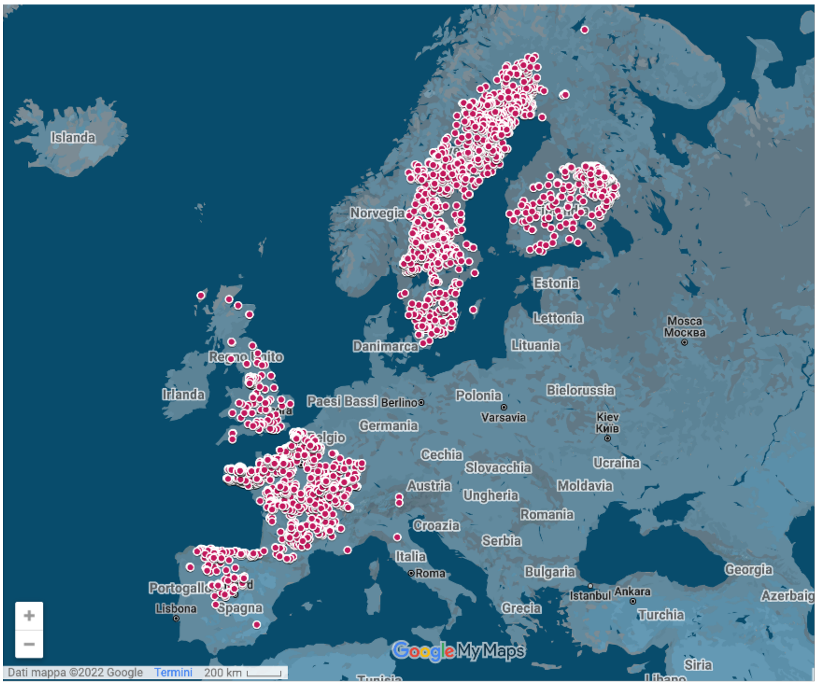


Figure 2.6: Dams Currently Removed in Europe by the project "Dam Removal Europe", source: Dam Removal Europe [24]

2.6 Finland

Finland has an area of 338,440 km^2 [25]: this is the “greenest” country in the entire Europe because 73% of the land area is covered by forests [26]. For what concerns the water present in the area, there are more than 57,000 lakes and more or less

130,000 km of rivers/rills [27]. According to the Finnish Environment Institute (2019), 87% of Finnish lakes and 68% of rivers are in a high or good ecological status (figure 2.7):

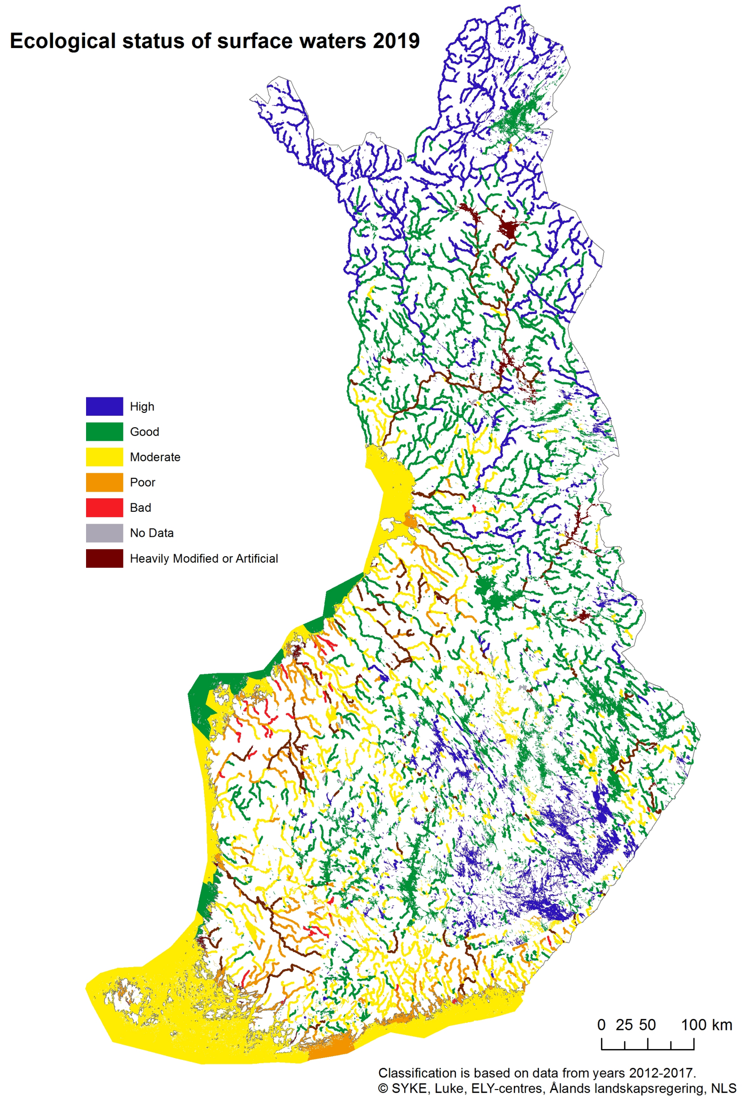


Figure 2.7: Ecological status of surface waters in Finland (2019), source: SYKE [28]

Nevertheless, the habitat situation is not as good: as stated by the Red List of habitat types (Kontula & Raunio, 2019), 44% of streams and rivers are listed as threatened. Furthermore, since it is a particularly watery land, many mires and wetlands were precluding the possibility of forestry: for this reason, a network of underground channels has been created for their drainage. This channels network has inevitably damaged the environment as it can be an obstacle to the migration of fish. In this regard, there are directives that serve to regulate the use of these channels and to ensure that they are not too harmful to the ecosystem: for example, the Water Act (587/2011) argues that an obstacle to migration must not cause important changes to the natural environment in which it is inserted in such a way as not to compromise the functioning of the ecosystem. Even though culverts do not properly meet the requirements of this act, there is no legal obligation that requires to notify them, even when they are built in official and registered water bodies. For this reason, a research work was conducted by Mr.Anssi Eloranta and Antti Eloranta which have mapped all the underground channels in the area: the result is surprising as 90,000 to 95,000 culverts have been found throughout Finland, of which about 1/3 constitute an obstacle to migration. Culverts are not the only obstacle to migration, but other 25,000 obstacles have been found during the research. WWF Finland has therefore joined the campaign to remove the harmful obstacles, starting with a project focused on culverts and then moving to the dams as well. So far, more than 500 [29] dams have been removed in Finland. It must be considered that many dams, especially the very old ones, were floating dams built to temporarily increase the discharge during spring; the dam removal project started from these old dams: between 2015 and 2019, 9M euros were spent by the Finnish government for dam removals and by-pass solutions [23]. In 2019, the dam removal project was explicitly mentioned in the national program and the intention of the Finnish government is to spend 18M euros between 2019 and 2023 for dam removals and by-pass solutions. Anyway, the dam removal is not impact free: as the construction of a dam has consequences on the environment, the removal of a dams, if not carefully monitored and studied before being implemented, can have catastrophic consequences.

2.6.1 Impact of a dam

Before talking about the possible consequences of a dam removal, it is important to study the impacts that a dam has on the environment [30].
First of all, it is necessary to consider that the river is a dynamic and complex system with a turbulent flow pattern characterized by a certain natural temperature and turbidity conditions to which the habitat of that river has adapted over time. When a dam is built, the system changes completely: considering that the intent of a dam is to create a basin of water in order to manage the water release according to the necessities, close to the dam the water no longer has a turbulent flow pattern, but can be defined as static [30]. For this reason, the water in the basin tends to stratify, causing its temperature and quality to change. The increase in temperature leads to an increase in the amount of water that evaporates. Furthermore, by changing the temperature and quality of the water upstream of the dam, there will inevitably be changes in the quality of the water and in the temperature downstream of the dam.
As the water temperature increases, the level of dissolved oxygen decreases, resulting in an increase in algae blooms which cause the quality of the water to decrease both upstream and downstream of the dam [30]. Moreover, the dam blocks debris, nutrients, and sediments: this results in an accumulation of sediments and nutrients upstream and a shortage downstream. This brings to the so-called “clear water condition”: the river, in order to balance the absence of sediments that are blocked upstream, starts “eating away” the river bed and the river banks [30].
Lastly, dams block the movement of aquatic organism.

The maintenance of a dam is also very important and complicated: considering that the river is a dynamic system, if it is "blocked", it will continuously fight back the dam. This means that the river will continuously change over time in order to try to adapt to the presence of the obstacle, and that is why the maintenance strategy of the dam has to change over time.
In addition to the maintenance, an important aspect that needs to be considered while building a dam is the risk. There are some areas called dam break inundation zones that need to be mapped in order to prevent catastrophes: they are downstream areas characterized by a high flooding risk in case of a dam failure.

2.6.2 Impact of dam removal

Installing a dam is not the only process to cause impact to the surrounding environment, but the dam removal itself is another process that, if not correctly planned and monitored, can be dangerous. One of the biggest problems to deal with when removing a dam is associated to the geomorphic stability of the river [31]: considering that a dam blocks debris and sediments, taking the dam out would mean mobilize them, changing inevitably the morphology of the system. This is not the only problem related to the sediments: before releasing all the sediments, it is necessary to evaluate the quality and the quantity of sediments that are going to be released, to make sure that will not damage the downstream environment.
Another big impact that a dam removal can have is related to the infrastructures [31]: some of them have been built after the construction of the dam and so it is very important to consider carefully what the consequences of the removal would be, to be sure that the river, while finding a new balance, will not put them at risk. Furthermore, a dam has to be constructed for a proper reason, that can be anything from water supply, flood control, recreational use; it is important to make sure that by removing the dam, its main function does not fail and that, if

necessary, it is replaced by other means. That it is why a dam removal must be properly planned. There are 4 main steps [31] to follow to be sure that a dam removal is made in a proper way.

STEP 1: planning and feasibility phase

First thing first is to select the project and its goals: a lot of projects are selected opportunistically (e.g., is a dam is abandoned and there will be benefits in removing it). Once selected the project, it is important to search for some funding, necessary to sustain the expenses. The third thing is to identify the key issues of the project:

- sediment
- infrastructure
- current use (and economic value of the dam)
- geomorphic equilibrium
- public health and safety
- flooding and hydrologic impacts
- historic/archeological importance
- cost and funding availability

...

After having identified the key issues of the project, it's necessary to collect as many data as possible: there are a lot of online databases from which search for information: threaten and endangered species database, infrastructure and utilities at risk, historic and archaeological issues... this research is necessary to evaluate the pros and cons of the dam removal, to see if it's both economically feasible and to see if the benefits overcome the risks. During these initial stages of the project, stakeholders play an important role as well because their opinion is important. Considering that in a lot of countries rivers are privately owned (in Finland, rivers are privately owned as most of the lands and lakes), it is necessary to have their approval before proceeding with the project. Another important step is the geomorphic assessment: this steps comprehend the sediment investigation, that is the analysis of the physical characteristics of the sediment (coarse, fine grain, cohesive or non-cohesive), the quantity of the sediment and the configuration of the sediment. This is needed for the development of the sediment management plan:

- passive release by letting the sediments go down on their own in the river; this procedure can be done only if the downstream ecosystem can handle it (quantitatively talking) and only if the sediment has a similar quality as the background level or lower (qualitative talking).
- staged release
- excavation of the sediment with the consequent relocation of the sediment on-site or off-site

STEP 2: Design and permitting phase During this phase, the first thing to do is to delineate the protected resources, such as wetlands, sensitive flora and fauna... Then, a survey needs to be conducted (topographic, bathymetric, profile, cross-section). Based on the survey information, the sediment management plan can be refined. Furthermore, a hydrologic and hydraulic analysis is needed to determine if there is any attenuation associated with the dam, any increase in flooding downstream, how the elevation of the water surface will change, and which stresses the river system and infrastructures will be subjected to. Further steps are design plans and report, construction cost estimate, stakeholder and public meeting and permitting with regulatory consultation.

STEP 3: construction phase Once obtained the permit, the construction phase can begin. This is the phase where the construction/demolition phase takes place. During this process, there is a regulatory sign-off to make sure that everything in the permits was completed.

STEP 4: monitoring and adapted management This is a long-term phase, in which the river has to be monitored both during the demolition phase and also after, to make sure that everything goes as planned. This phase is very important because during a dam removal there is always the unknown component, something that can happen without having been planned. Regarding the monitoring part, there is a good guideline called “stream barrier removal monitoring guide” specifically for dam removal.

Chapter 3

Study Site: Hiitolanjoki

Site and General info

Hiitolanjoki is a 62 km long river.

As it is possible to see from figure 3.1, this river crosses two nations: Finland (Suomi) and Russia (Venäjä).

On the Finnish side, the river flows in the region of South Karelia (municipality of Simpele) for 8 km, while on the Russian side it flows in the Lakhdenpokhsky District (Republic of Karelia) for 54 km. The river crosses the border between Finland and Russia right in the Kangaskoski area, where one of the three Finnish dams that are going to be disrupted are situated. This river has 2 different springs: Simpelejärvi (south Karelia) and Kivijarvi in Simpele. The outlet is in lake Ladoga, which is the largest lake in Europe with an area of 17,900 km^2 (it is situated between Leningrad region and the Republic of Karelia)

Figure 3.1: Hiitolanjoki position map, source: Illusia Sarvas / Yle [32]. This is a Finnish map where Finland is referred to as "Suomi" and Russia is referred to as "Venäjä".

Ecosystem of the river

This river is a very important fish route, in particular of the lake salmons called "Ladoga salmons". Because of the dam, fish could not go up the river any further than Kangaskoski and this started to be a problem, mostly because this river is the most important breeding river for Ladoga Salmons.

The restoration of the river's natural state would double the production of salmons in the Hiitolanjoki river [33] and this will be a very good advantage both from an economic and from an environmental point of view. Furthermore, as it is already been done in Russia, also on the Finnish side, during the next years, there will be the re-naturalization and the restoration of the coastal areas of the river that will be used for recreational purposed. For example, a lot of swamps are being restored in the region of South Karelia but also in South Savo and Kymenlaakso. Moreover, the river itself is going to be treated with the installation of new infrastructures such as biofilters to capture and store carbon dioxide but also to sustain new and old habitats [34]. The biofilters are made with a new method that is being tested in Hiitolanjoki: they are made with wood that is dumped in the water and on which algae, bacteria and fungi start to grow on, creating a filter that cleans the water from impurities and metals. For this purpose there is a two years project that started on the 1st of April 2020 and that is coordinated by the Finnish Association for Nature Conservation in collaboration with Hiitolanjoki Association from Finland and the NGO Neo Eco Project from Finland and Russia, the municipality of Käkisalmi, the Komarov Botanical Institute and the Directorate of Nature Reserves in the Leningrad Region. The restoration of the river Hiitolanjoki is part of a 10 years nature management program established and funded by Metsä Group, which is a company operating in the forest industry. The goal of such program is to improve the biodiversity and the waterways state, investing part of their business profit into the improvement of the Finnish natural state [35].

Water quality

In general, the river's water quality has always been good: it has been monitored since before the war years and then after 1993 as a joint monitoring of the Rautjärvi municipality and the Simpele mills. The monitoring program was then updated in 2012, by increasing the amount of water sampling and sampling sites (5 sampling sites 6 times a year).

The water coming from Kivijärvi has always had an excellent quality for a lot of years, but lately, due to the increase in turbidity and solid content caused by heavy

rainfalls, it has been reduced. Furthermore, discharges from various industries have reduced the nutrient concentration. The river is in fact polluted by the treated wastewater from Metsä Board Oyj's Simpele mills and the Simpele agglomeration in the municipality of Rautjärvi [36].
In the Uudensillankoski sampling point, the water quality has improved. The problem is that in Simpele there is an agglomeration treatment plant which discharges have reduced the hygienic quality of the water and the nitrogen content at the Ritakoski sampling point. Anyway, thanks to a better river plant, now the water quality is good enough for fish.
Ultimately, Kangaskoski is the last sampling point on the Finnish side: here, the river is subjected to diffuse loads caused by heavy rains. Moreover, the phosphorous content is particularly high in this area; anyway, the water quality has always been between good and satisfactory.

Tourism

Hiitolanjoki river, as already said before, housed 3 hydroelectric power plants that were built at the beginning of the 20th century and that were providing electricity until not very long ago. Studies, anyway, showed that the electricity production made by these three plants is not worth the money, but activities like fishing, hiking and kayaking are both more sustainable and have more value from a touristic point of view.
The fishing tourism, both on the Finnish and Russian side, has been financed by INTERREG and TACIS (from the EU) [37]. Furthermore, this river environment is a very beautiful destination for hikers but it's also an interesting destination for fishermen, even though it is prohibited to take the Ladoga Salmons from the river if not properly licensed.
Tourism in these areas is not only for sports, but a recreational possibility is also given by the history of the river itself and by the emotional value that the

population of South Karelia (and not only) has towards the dams and the power plants themselves. For this reason the plants will not be completely dismantled, but rather museums are being built to be able to remember them. For this purpose, a new project was approved not very long ago [38]: at the beginning of the 20th century, Kangaskoski area housed pulp, cardboard and paper mill factory that were working thanks to the hydroelectric energy produced by the rapids and turbine; this new project has the aim of recreating the factory scenario using advanced virtual reality in order to "rebuild" it and let future visitors familiarise and remember what was going on in the area when the dam was built and for which reasons.

Power plants

On the Finnish side, there are four rapids (Juvankoski, Ritakoski, Lahnasenkoski and Kangaskoski) that were used for electricity generation and paper production. One of the first paper mills was built in correspondence of the Juvankoski rapid: this paper mill was operating using the power generated using the 8 meters natural jump of the rapid at the beginning of the 19th century. Unfortunately the paper mill was destroyed in 1902 following a fire. After the paper mill, a small hydropower plant was built and completed in in 1948 but it had a short life because it was shut down in 1970 [39].

Figure 3.2: Juvankoski Rapid, source: Suomen Vesiputoukset [39]

The second power plant is the Lahnasenkoski power plant, which was completed in 1911 (it's the oldest wooden power plant in Finland): it has a drop height of 8 m and an annual electricity generation of 4500 MWh (Capacity 0.8 MW) [40]. It is the highest waterfall of the river. This was the first power station to generate and provide electricity on the Hiitolanjoki river. This power plant is still working and it is still providing energy until July 2022, after which the dam will be dismantled.

Figure 3.3: Lahnasenkoski Dam

The third power plant is the Ritakoski one, built in 1920; it has a drop height of 6 m and annual electricity generation of 2200 MWh. This will be the last power plant to be shut down because its dam is the last one that is going to be dismantled.

Figure 3.4: Ritakoski Power Plant, source: Apila A. [41]

The fourth and the last power plant is the one built in correspondence of Kangaskoski rapid: at the beginning of 20th century, this rapid was bought and prepared for power production. The hydropower plant was completed in 1925. It is the first Finnish power plant using a Kaplan turbine. It has a hydraulic jump of 4 m and an average annual electricity generation of 3300 MWh. The turbine was shut down in July and the dam was the first one to be dismantled, in September 2021.

Figure 3.5: Kangaskoski Dam before being dismantled, source: Hiitolanjoki Website

What brought to the Demolition of the Dams?

High head hydropower plants are characterized by a dam with a reservoir. Thanks to the reservoir it is possible to move water into a penstock (a pipe) to the turbine (in case of a high heads, it usually a Pelton turbine). The turbine uses the kinetic energy of the water to generate electricity. The transformer then module the energy from medium to high voltage. In figure 3.6, it is possible to see a comparison in the daily electricity production of the principal power generation plants:

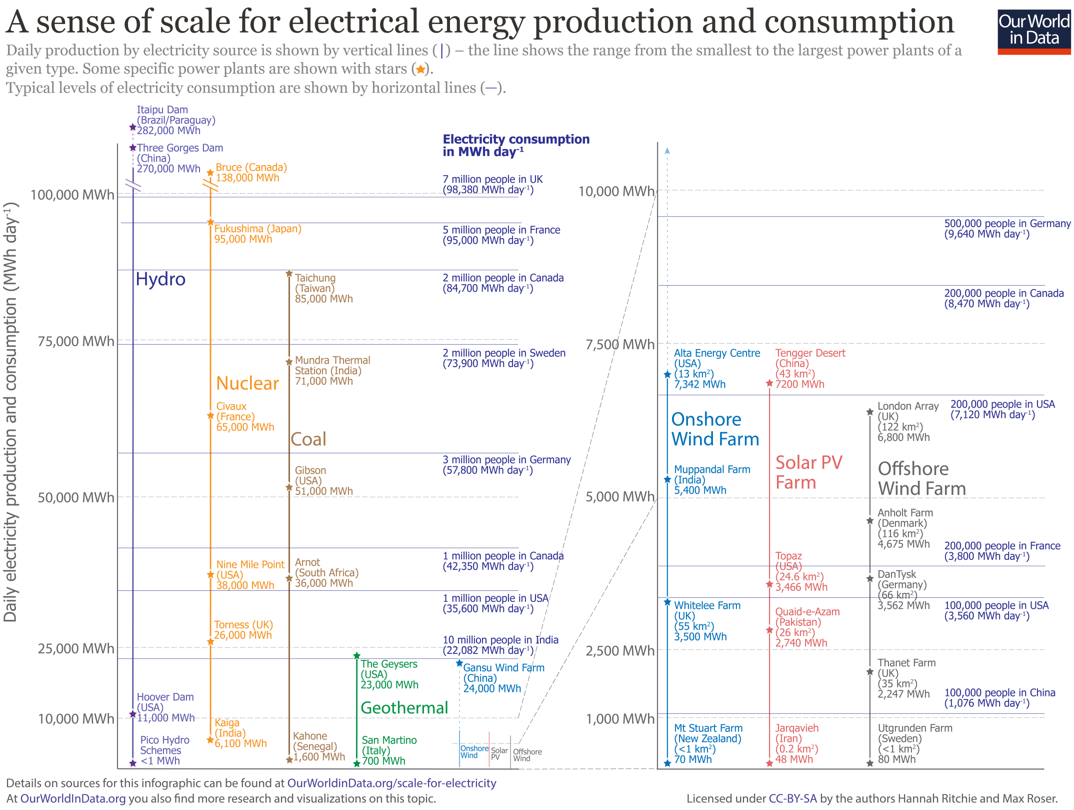


Figure 3.6: Daily electricity production and consumption, source: Our World in Data [42]

Focusing on the amount of electricity that is produced with small hydropower plants (< 5000 MWh), it is easy to say that the average annual production of these power plants is way smaller than the daily power production provided by big plants. Finland yearly energy consumption per capita is 12,175 kWh, for a total of 60,875,000 MWh (considering 5 millions of inhabitants). This means that the Hiitolanjoki hydropower plants are very small: in a year, they produce less energy than the energy produced in a day by the Hoover Dam. this means that the power plant in Hiitolanjoki have no practical significance for Finnish energy production (in general, Finnish Hydropower energy provide only for the 0.2% of the country's annual electricity production). Since these mini hydropower plants are not necessary for the energy production, it is better to get rid of them because they are also harmful to the aquatic environment.

Dams' demolition – restoration of the rivers' natural state

The first association which started to fight for the dismantling of unnecessary dams is WWF: they started a campaign 20 years ago for the demolition of the underwater structure in the border zone (they were also economically involved because they were funding the demolition). Furthermore, in 2019 they become involved also in the demolition of Hiitolanjoki dam campaign, promoting the rise of the Ladoga salmon. WWF is currently financially contributing to the dams' removal [43].

In 2019 the South Karelia Regional Recreation Foundation signed an agreement to redeem the Ritakoski and Kangaskoski power plants while Lahnasenkoski was already property of the foundation. The foundation planned to shut down the power plants and to dismantle the three dams by 2023.

This is a very big project because Hiitolanjoki is the first Finnish large river to be completely freed from hydropower dams: this is why the restoration of this river is the first of its kind in Finland and it can become an example on how to deal with these changes in both an economic, administrative, and environmental way [44].

KANGASKOSKI: this is the lowest rapid of the river and finds itself very close to the Russian border (1 km). The power plant in Kangaskoski used a Kaplan turbine. Since the construction of the dam and the power plant, the original riverbed in correspondence of Kangaskoski´s basin has been a bypass channel: this means that this riverbed section was dry, but the water it's projected to re-fill the original riverbed forming a natural rapids: in this way, salmons (and other valuable species of fish) will not have any obstacles and will be able to rise upstream. The dam was dismantled in August 2021: to prevent the water level from rising too quickly in the channel following the shutdown of the turbine, the dam regulation hatches were opened so that the water was released into the bypass channel (main riverbed) .

Workflow:

1. Rocks were brought to the dam to shape the top of the rapid (simulating the dam)

2. When the upper part of the river is ready to maintain the level of the water surface above the dam, the hatches were opened and the water began to fall from the dam and the upper channel began to dry out.

3. A tributary was excavated

The work was done during the summer months since the water level is the lowest throughout the year, so as to allow the machines to move inside the riverbed.

In the following figure (figure 3.7), it is possible to see how the Kangaskoski section looks without the dam:

Figure 3.7: Kangaskoski after dam removal

LAHNASENKOSKI: going upstream, after Kangaskoski there is Lahnasenkoski, that is the rapid with the highest waterfall (8 m). The dam that has been constructed here will be dismantled in 2022. There are currently 4 Waterpumps Oy turbines operating on the river (these types of turbines are designed for small plants with low heads).

RITAKOSKI: the dismantling of the dam in Ritakoski will be the last one and it will be done in 2023. This power plant was built to diminish the firewood consumption for the electricity production and to so increase the amount of wood in the forests: as a result of the building of the power plant, the amount of wood production doubled. Originally, the power plant worked with 2 Francis turbines with a vertical axis.

Financing

The dam removal project is now financed by:

- Government
- Regional council and municipality
- Foundations
- Private donors

The largest financiers of this project are WWF, the Lassi Leppinen Foundation, the South Karelian Savings Bank Foundation, OP Simpele, Lähi-Tapiola and the municipality of Rautjärvi [45].

3.1 Kangaskoski

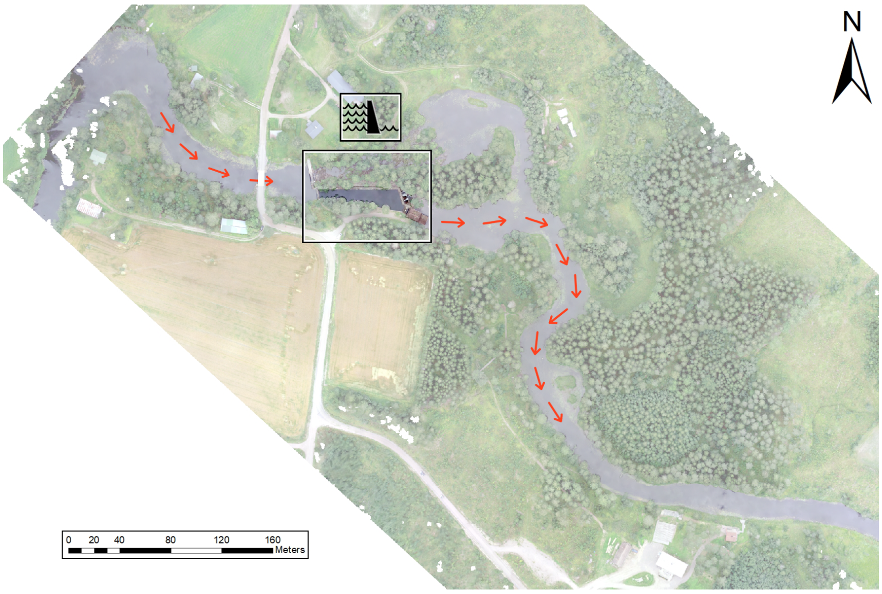


Figure 3.8: Kangaskoski Before the Dam Removal (photographer: Pasi Korpelainen)

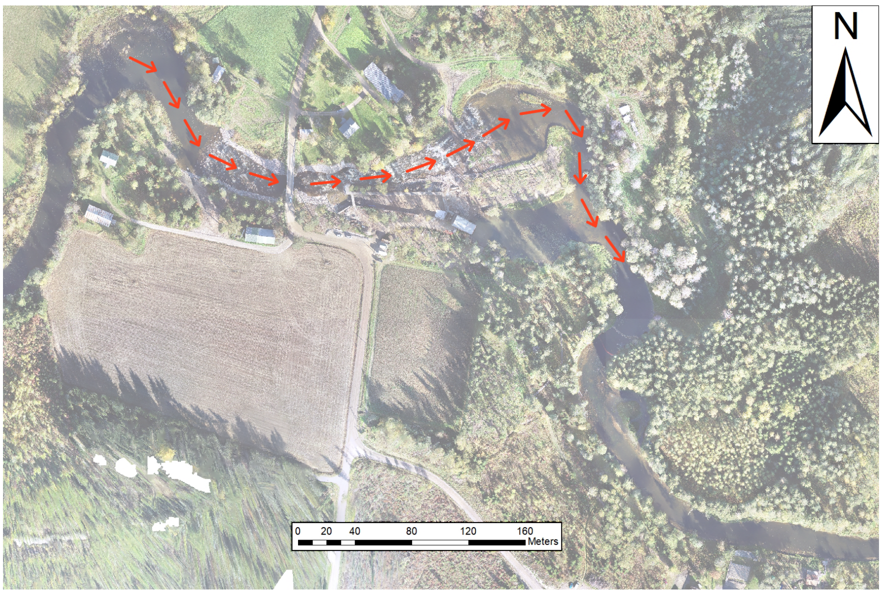


Figure 3.9: Kangaskoski After the Dam Removal (photographer: Anton Kuzmin, University of Eastern Finland)

In figure 3.8 and 3.9, it is possible to appreciate how the river path has changed before and after the dam removal: in figure 3.8 the basin is visible and it is possible to see that the path of the river is different from the path after the dam removal. This is due to the fact that after the construction of the dam, the river was deviated and a segment of the "real" river channel has been used as a bypass channel. After the removal of the dam, the bypass channel became again the main river channel and the basin is now empty.

Chapter 4

Methods

4.1 Data collection

The data sets that are used for the purpose of this analysis are primary data (directly collected from the source by researchers and not yet analysed) collected in two different periods of the year: Spring 2021 (figure 4.2) and Autumn 2021 (figure 4.3), in particular on the 7^{th} of May 2021 and on the 24^{th} of September 2021. The Spring 2021 ADCP data were collected by Eliisa Lotsari and Marko Kärkkäinen, while the Autumn 2021 ones were collected by Eliisa Lotsari, Marko Kärkkäinen and Tuure Takala.

The aim of the thesis is to analyze the impact of a dam before and after its removal: that is why the data were collected in these two periods.

The point data were collected using an Acoustic Doppler Current Profiler (ADCP). ADCP is a device that uses sound waves to measure the velocity of the water. It is indeed called Acoustic Doppler Current Profiler because it uses the Doppler's effect to measure the velocity: the device emits sound waves with an ultrasonic frequency (not perceptible by the human ear); considering that inside the water are present suspended particles that are transported by the water flow, the sound wave

reflects on them, returning to the device with a different frequency. The ADCP collects the sound waves that have been reflected by the particles and, based on the frequency and time taken to return back, it is able to determine the water speed and depth at which this speed was measured. In order to have a three-dimensional reconstruction of the water velocity, the ADCP must send at least 3 beams, which deviate from the vertical by 20-30 degrees [46]. This is why the instrument has tilted transducers that emit waves with a specific frequency that depends on the instrument. Once the measurements are obtained, the ADCP averages the values to obtain a single value of velocity and flow direction.
The ADCP was mounted on a boat and during the campaign, the data were collected in two different ways: zig-zag data and cross-sectional data.

Figure 4.1: ADCP used for the collection of the data, source: Eliisa Lotsari

The ADCP has an internal GPS, but in order to have more accurate data, it was coupled with a Real-time kinematic positioning system (RTK).
In figures 4.2 and 4.3, the data collection is shown:

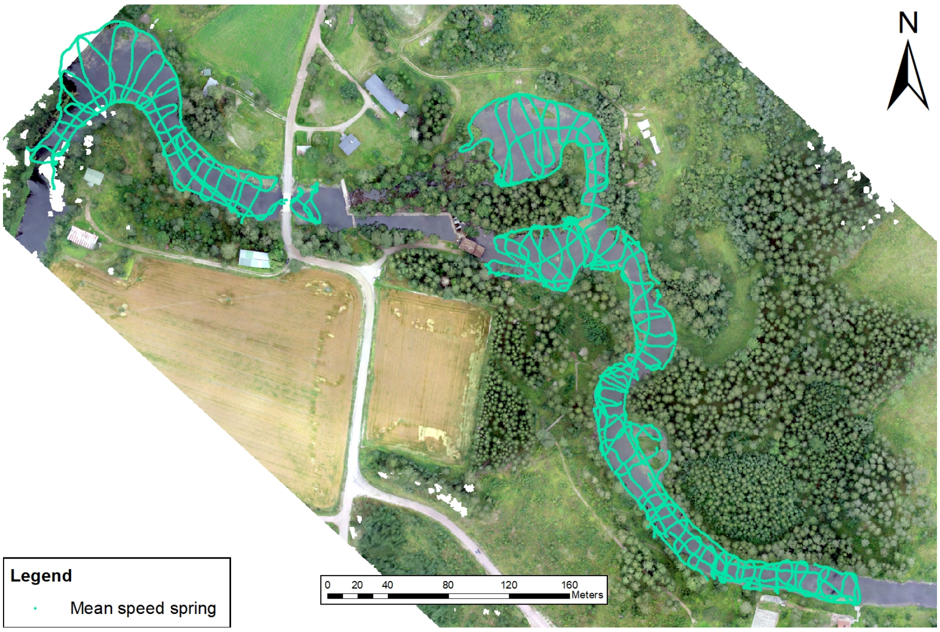


Figure 4.2: Data Visualization in ArcGIS (Spring 2021)

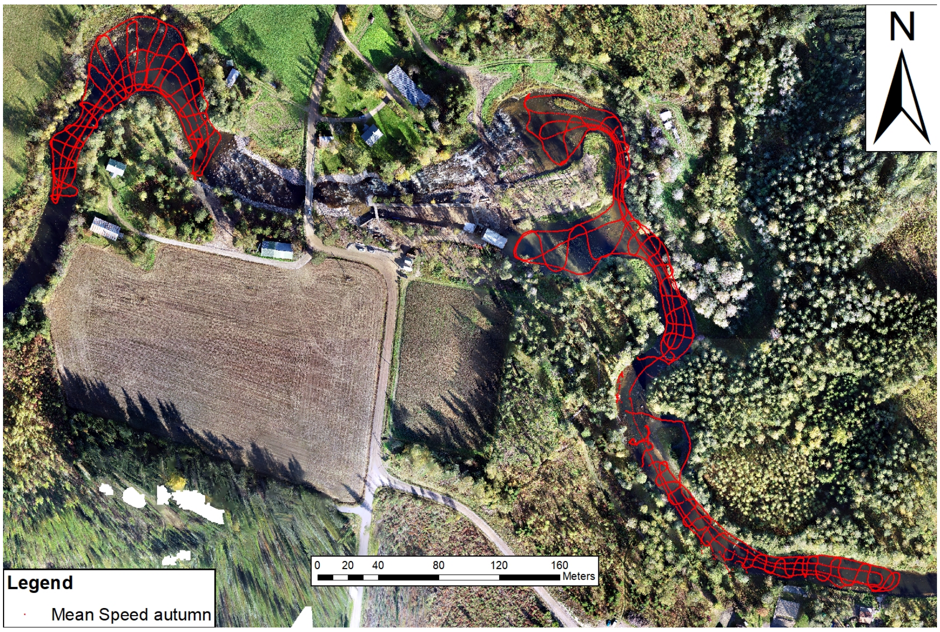


Figure 4.3: Data Visualization in ArcGIS (Autumn 2021)

The ADCP measures the velocity by firstly dividing the section into water columns, then dividing each water column into cells and then calculating the average velocity for each cell.

4.2 Used Software

For the purpose of the thesis, three software were mainly used. The ADCP data were firstly analysed with River Surveyor Live, which is a program that is used both in the data sampling phase and in the post-processing phase. In this case, it was used during the post-processing phase, in particular for the extraction of the collected data in a ASCII format. The ASCII format is easy to import in excel, where it can be manipulated (useless data were deleted) and then it can be imported into R.

R is the second software that is used for the data extraction. The ADCP data in fact are not of immediately usable, as it is not possible to directly obtain the surface speeds and the near bad velocities, contrarily to the vertical average speed which is instead already given in the summary file. Therefore, in order to obtain such data, it is necessary to write a simple code loop in order to extract them from the velocity file, which contains the velocities of each cell (the depth of the river is divided into cells in such a way that each cell contains the velocity value of that portion of the river). Once that the surface velocities and the near bed velocities are extracted, it is possible to proceed with the analysis by using QGIS and ArcGIS. These software are very useful because they can perform the data interpolation that is necessary to have an overview on the velocities of the whole river to better identify clusters and hotspots. The interpolation that are executed are Inverse Distance Weighted and Kriging.

4.3 Data Structure

The data collection of an ADCP campaign can be operated using a particular software called "River Surveyor Live". This software can be in fact used both during the data collection and also during the post-processing phase of the data [47] .

Data Post Processing

In order to open the collected data into the software, they have to be stored as .riv files. By opening a file into the software, the datasets can be explored: it is possible to notice that the dataset is subdivided into start edge, transect and end edge. This is due to the sampling method that was used: basically, after completing the pre-measurement tests phase, the data collection begins with the positioning of the device at the "Start Edge" of the transect. It is therefore necessary to keep the device very still and collect at least 10 samples, so that, during the post processing phase, it is very certain when the actual data collection begins. After that, it is possible to start with the actual collection of the transect data. At the end of the transect, it is necessary, as it was done at the beginning, to keep the device very still so that it can collect the data of the so-called "End Edge" in order to be sure where the data collection ends. For this reasons, the "Start Edge" data and the "End Edge" data were not considered in the analysis.

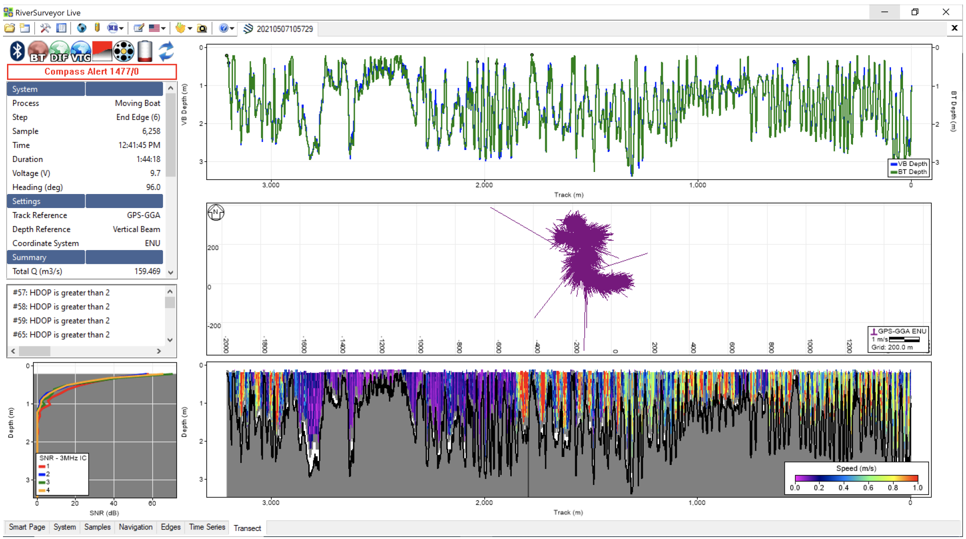


Figure 4.4: River Surveyor Live: in the panel are shown two graphs representing the depth variation of one of the river segments that was sampled (top and bottom graphs). In particular, in the upper chart, the depth measured by the vertical beam is shown, while in the bottom chart the velocity measured in each water column is added to the graph (the color gradient refers to different velocities intensity). The graph in the middle, shows the GPS data.

The data that have been exported from River Surveyor Live and that have been used in this analysis are:

- Step: this column shows if the sample that is being considered is belonging to the "start edge" phase, to the "Transect" phase or to the "End Edge" phase.
- Track and DMG
- Depth: this is the depth of the river at the sample point.
- Mean Speed: this is the average of the different velocities values that are

collected in one point (depth average speed).

- Vertical velocities: file containing the velocities in each cell of the vertical column.
- UTM X and UTM Y: UTM stands for Universal Transverse Mercator and it is the coordinate system. These two values are the coordinates of each sample point.

River Surveyor Live is an important post-processing software because it gives the possibility to export the data in two different formats: matlab and ASCII format. In this case, it was chosen the ASCII format. Once the ASCII files are downloaded, three different files are obtained: the vertical velocity file, the summary file and a file containing the "signal to noise ratio" (SNR) for every measured cell. Every ASCII file can be opened with excel, but while the SNR file is just containing information about the quality of the measurements, the other two files contain the measurements themselves: in particular the vertical velocity file contains all the measurement, cell by cell (in the vertical direction), of each sample, while the summary file contains the data previously listed.
Concerning the vertical velocity file, it contains:

- Ve = east velocity
- Vn = north velocity
- Vu = up velocity
- Vd = down velocity
- Vspd = total averaged velocity

For the purpose of this thesis, the Vspd velocities were used. Furthermore, cell number 1 is the most superficial one, while going forward with the cell number, the sample is taken at a greater depth until the ADCP beam reaches the river bed. Everything is then valid for each sample point.

Regarding the signal to noise ratio, since noise tends to be predominant on measurements only at very high depths (about 70 meters [48]) and considering that the Hiitolanjoki river does not exceed 5 m, it is possible to conclude that in this case it is not necessary to apply a filter to "clean" the dataset.

4.4 Extraction of the Near Bed Velocity and Surface Velocity from the vertical velocity file

By importing the vertical velocity dataset into R, it is possible to extrapolate the Near Bed Velocity and the Surface Velocity. The datasets are in form of an excel table and so to import them into R, the library "readxl" was used. The surface velocity is easy to extract because it is simply the velocity in the first cell of every sample. Considering that the dimension of the vertical cells is not fixed during the survey, but varies for each water column between 0.02m, 0.06m and 0.1m, the surface velocity location is not the same for each measurement, but varies between 0.01m, 0.03m and 0.05m below the water surface. In general, the dimension of the cell can be manually defined, but in this case, the researchers decided to let the sensor "decide".
The Near bed velocity is instead extracted as the last numeric value in a cell before encountering an invalid value (NaN). As before, considering that each vertical cells do not have the same dimension (but varies between 0.02m, 0.06m and 0.1m), the near bed velocity location varies always, based on the depth of the river. The ADCP can not directly measure the stream surface velocity and the near bed velocity because of the draft of the instrument and the required blanking distance (which is the distance that corresponds to the electronic and transducer recovery

time) and also because of the side-lobe interference, caused by the reflection of a vertical side lobe from the stream bed [49]
The two new vectors were then exported from R studio in an excel file (using the library "writexl") which was subsequently saved as a "Comma-Separated Values" (.csv) file in such a way that it can be more easily imported into a GIS software (as a "delimited text layer"). Once obtained the surface velocity and the near bed velocity, all the different spring and autumn datasets were imported into two different QGIS files as layers. The layers with the different data segments for Near Bed Velocity and Surface Velocity were merged to form two different layers containing the total Near bed velocity and Surface Velocity in the Kangaskoski area. The same procedure was followed for the Mean Speed, with the only difference that this dataset was easily extrapolated from the summary file exported from River Surveyor Live.

4.5 Data overview and Outliers detection

Now, it is possible to export the attribute table of every layer as "Comma-Separated Values" (.csv) file in order to import the data once again in R studio for the Data overview and Outliers detection. One of the methods to find the Outliers of a dataset is to use the boxplot. The boxplot is a graphical representation that is used to show the distribution of a dataset based on some statistical values [50]:

- Median: this is the value that is exactly in the middle of the dataset and divide the data in half, meaning that 50% of the data lied below the median and 50% lies above it.

- First quantile (Q1): it can be defined also as the 25th percentile and its the value which is midway between the smallest value in the dataset and the median value [51].

- Third quantile (Q3): it can also be defined as the 75th percentile and its the value which is midway between the biggest value in the dataset and the median value

- Minimum: this value is defined as Q1 - 1.5*IQR, where Q3 is the third quantile and IQR is the "Interquantile Range" and so the "distance" between the two quantiles.

- Maximum: this value is defined as Q3 + 1.5*IQR, where Q3 is the third quantile and IQR is the "Interquantile Range" and so the "distance" between the two quantiles.

A clear representation of the different parts of a Boxplot is shown in figure 4.5

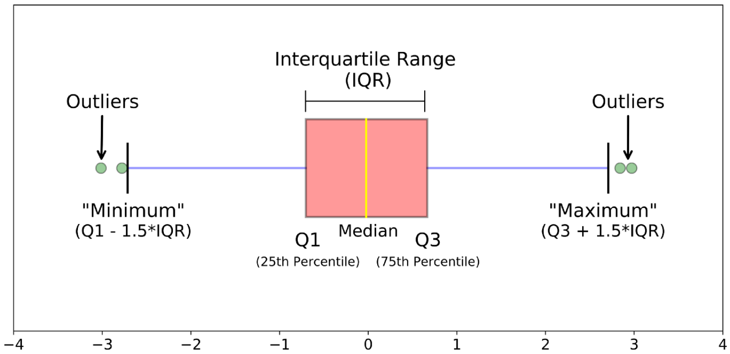


Figure 4.5: Different parts of a Boxplot, source: Towards Data Science [50]. This representation shows how the data can be distributed: the Interquantile range represents the group of most frequent data value in a given dataset (25th and 75th percentile). If a data value is not included in this range, and moreover it is outside of the minumum and maximum range, they are outliers.

4.6 Interpolations techniques and GIS

In general, interpolation is a numerical analysis that uses mathematical methods to generate new data points from other known data points. The interpolation allows us to perform a reconstruction of data starting from known information. From a spatial point of view, the measurements that have been collected in specific points need to be “managed” in order to move from a discrete representation to a continuous representation: the idea is to create a continuum surface that guarantee the continuity of the information content. It’s useful, because it can reveal patterns, trends, or anomalies in our data: we can use this tool to predict and verify if the prediction was made in a proper way.

4.6.1 Inverse Distance Weighting

Inverse distance weighting is a deterministic interpolation method that uses mathematical functions, meaning that no randomness is included in this method. The value at each unsampled point is obtained using the weighted average of the nearby points: this means that this interpolation method gives a lot of importance to the values that are closer and less importance to the ones that are distant (this interpolation uses a simple algorithm based on distance). This method is one of the easiest ones because it allows very fast calculation to have a fist overview on the final result. The issue with IDW is that it is not very precise and one of the main problem that this interpolation gives is the so-called "bull’s eye effect": this is a characteristic artifact of the inverse distance weighting interpolation that results in concentric areas around the measured point and a non-smooth prediction map (figure 4.6. This is due to the fact that this type of interpolation does not let the unsampled values to have an higher value than the sampled ones and so the maximum and the minimum values can occur only at the measured points.

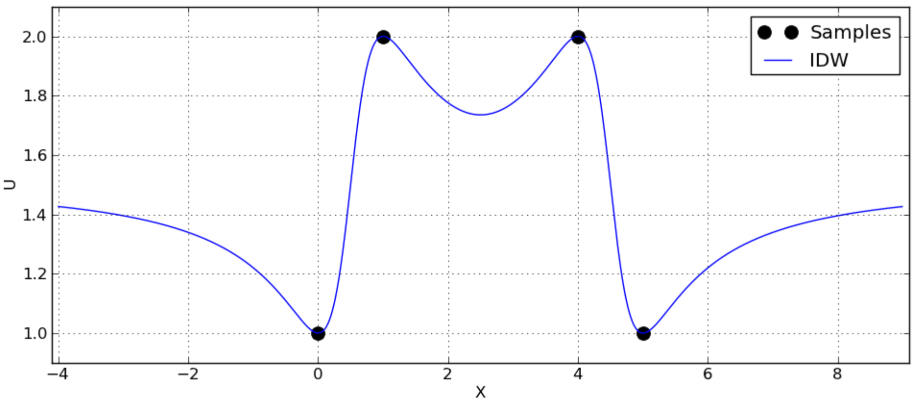


Figure 4.6: Graphical representation of how the inverse distance weighting interpolation works. Source: Wikipedia [52]. As it is noticeable from the map, this type of interpolation gives a lot of importance to the measured points, causing the Bull's eye effect and resulting in a non-smooth prediction map

4.6.2 Kriging

Kriging is an advanced geostatistical procedure that uses mathematical and statistical functions to generates a prediction surface starting from scatter points. The positive side of this type of interpolation is that it does not only create a prediction surface, but it also provides a measure of the uncertainty of the predictions.

This type of spatial interpolation is based on the spatial autocorrelation of the data, thus on the relative position of two points (and not on their absolute position). The spatial autocorrelation of the data can be evaluated in different ways, but a convenient tool that kriging uses for these purposes is the semivariogram (also known as the variogram). The variogram is a graph that shows the relationship between the semi-variance of the data (which is half of the variance) and the lag distance i.e. the distance between a pair of points which is arbitrarily chosen by whoever is constructing the graph in such a way as to include a number of significant points within each lag.

Kriging is a three step approach [53]:

1. Understanding the best lag distance with which starting the construction of the variogram.
   If the lag distance is too low, there is the chance to have too many couples in every step, ending up in an incorrect variogram. On the other hand, if the distance is too high, there are not a lot of couples in every step meaning that the variogram would not be very detailed but it will be very smooth. Anyway, there are some general rules that should be followed: the lag distance should not be lower than the minimum distance between two points and not bigger than the maximum distance between two points. A rule of thumb could also be that the product between the chosen lag size and the consequent number of lags should be half of the maximum distance between two point.

2. Creation of the experimental variogram.
   After having defined the lag distance, it is possible to build the experimental variogram by calculating the semi-variance. This step will result in a point distribution.

3. Fitting of the experimental variogram with a theoretical variogram (linear, spherical, circular, exponential, gaussian) and use it to do the predictions.
   The last step, is the choice of the theoretical variogram that better fits the experimental one:

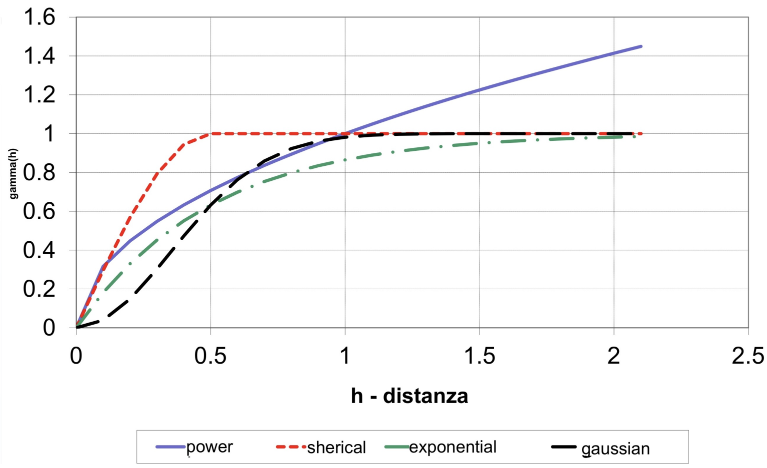


Figure 4.7: Theoretical Variograms: on the x-axis is represented the lag distance, on the y-axis is reported the semivariance.

As it is possible to see from the figure, different models show a different behaviour in the points correlation:

- Power model: the correlation increases with the distance between points.
- Spherical model: progressive decrease of spatial autocorrelation (increase of semi-variance). This model is the most used in software.
- Exponential model: in this model, the growth towards the sill is very smooth and not rapid.
- Gaussian model: this model has an horizontal tangent in correspondence of the origin of the variogram.

The parameters that are estimated from the variogram are:

- Range, that is maximum distance where there is still spatial correlation (i.e. it's the distance on the x-axis where the model starts to be flat)
- Sill, which describes the level of spatial variability: it is the semi-variance value correspondent to the range.

- Nugget describes the level of random variability; it can be assimilated to a measurement error. It corresponds to the intercept of the variogram: this happens when there is a sudden change in the value of two close samples, and so the distance between these two points is almost null but the variance difference is high.

These parameters are fundamental to fully describe the model.

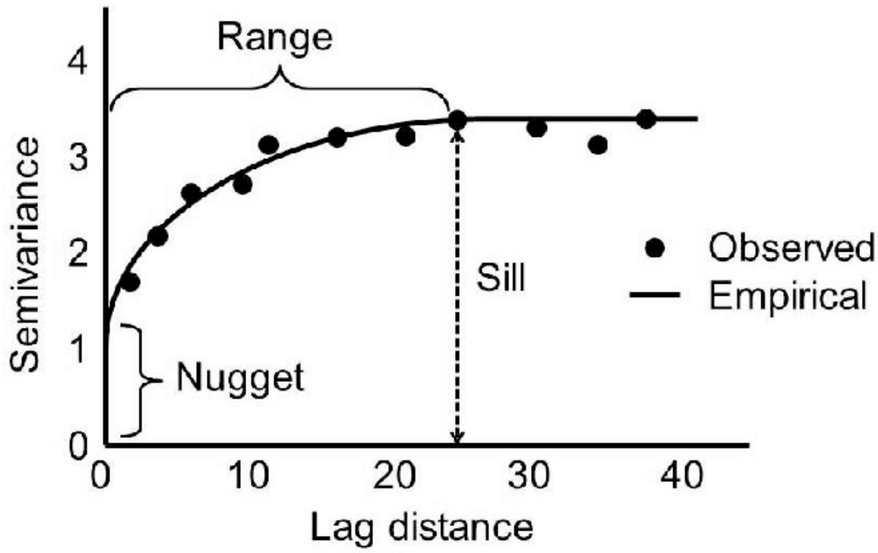


Figure 4.8: Representation of Nugget, Sill and Range in a variogram, source: Huriel Reichel and Tony Vinicius Sampaio [54]

The important thing in kriging is the shape of the variogram close to the origin because the closest the points are, the higher their weight (and so their importance) in the final interpolation.

After having defined all these parameters, it is possible to start with the interpolation and prediction of the values.

It is important to precise that there are different versions of kriging that are more or less sophisticated and that are used in different occasions:

- Simple kriging: the mean of the sample is known. As the name says, this is the easiest type of kriging, but it is also the least accurate type of kriging

- Ordinary kriging: the mean of the sample is unknown, but it is constant. This is the most used kriging method.
- Universal kriging: this type of kriging assumes that the dataset has a trend (e.g., prevailing wind). With this type of kriging, the trend is subtracted from the dataset and the autocorrelation is modeled with the remaining data without the trend. Once the model is calculated, the trend is added back to have meaningful predictions.

Considering that the following study is the analysis of spatial data and not temporal data, trends have not been considered: hence, for the purpose of this thesis, the ordinary kriging has been used.

4.6.3 Kriging with Geostatistical Wizard

The kriging interpolation was performed using the Geostatistical Wizard in ArcGIS, which can be found in the Geostatistical Analyst toolbar.
Geostatistical Wizard is a tool that guides the "construction" phase of the interpolation: it helps in finding the best parameters to obtain the interpolation that describes at is best the reality. It includes the exploratory statistical analysis of the data, variogram modeling, surface creation and measurement of the certainty of the predictions.
This tool is not only used for kriging interpolation, but it provides a wide variety of interpolation methods: Deterministic Methods such as Inverse Distance Weighting, Global Polynomial Interpolation and Local polynomial Interpolation, Geostatistical Methods such as Kriging and Co-kriging and also Interpolation with barriers such as the Kernel Smoothing.
For what concerns Kriging, as already mentioned before, there are different types

of it and the geostatistical wizard has almost every kind. It is also possible to choose the output that we want between Prediction Map, Quantile, Probability and Prediction standard Error. In this case, the Ordinary Kriging and Prediction Map were chosen. The next step is the creation of the semivariogram: this is created by splitting the measured points into bins (or lags) and the geostatistical wizard is able to determine a good lag distance to group the points. The semivariogram creation is a fundamental step because it helps revealing if there is and which kind of spatial correlation there is between the measurements, depending on their distribution in the graph (figure 4.7).
The last step is the cross-validation: it gives the possibility to evaluate how well the model will predict the values. During this phase, it is possible to visually evaluate through graphs the relationship between the predicted values and the measured ones, the error and the standardized error.
Finally, the outcome of the analysis is rectangle which coincide with the rectangular extent of the study zone. To obtain the interpolation only in the river area, a mask is required.

4.6.4 Mask creation to clip the interpolations

In order to set the borders of the interpolation, there is the need for the creation of a "mask". In order to do that, a shapefile of the water area was created using the orthomosaics. Orthomosaics are aerial images that have been orthorectified in order to remove any sort of sensor error, satellite/aircraft motion and geometric distortions related to the shape of the earth. After having been orthorectified, the images were also georeferenced in order to have a continuity in the coordinate system of the data and of the image.
Since the orthomosaics have a very good position accuracy and high resolution, it was possible to easily distinguish water and land areas. This new shapefile was

then used to filter the interpolation by clipping the interpolation layer with the mask that was created.

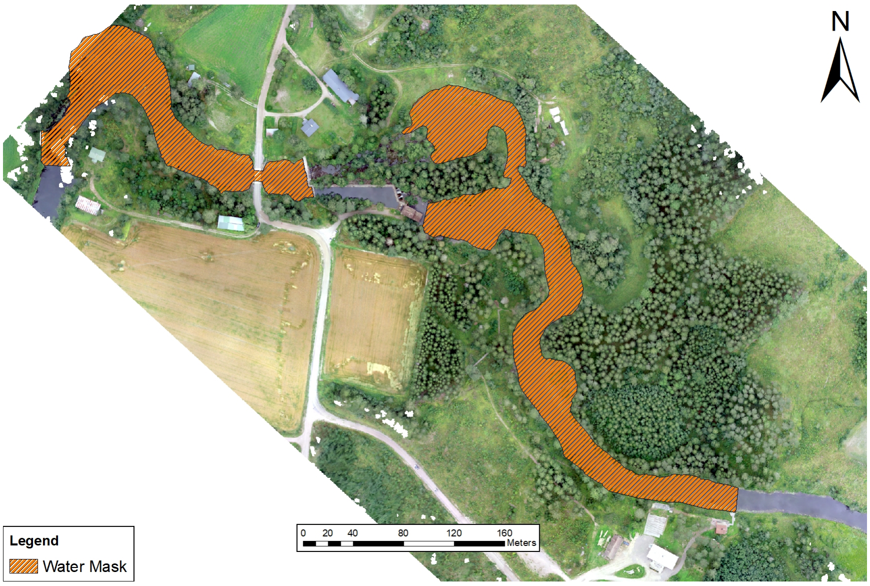


Figure 4.9: Water Mask Spring

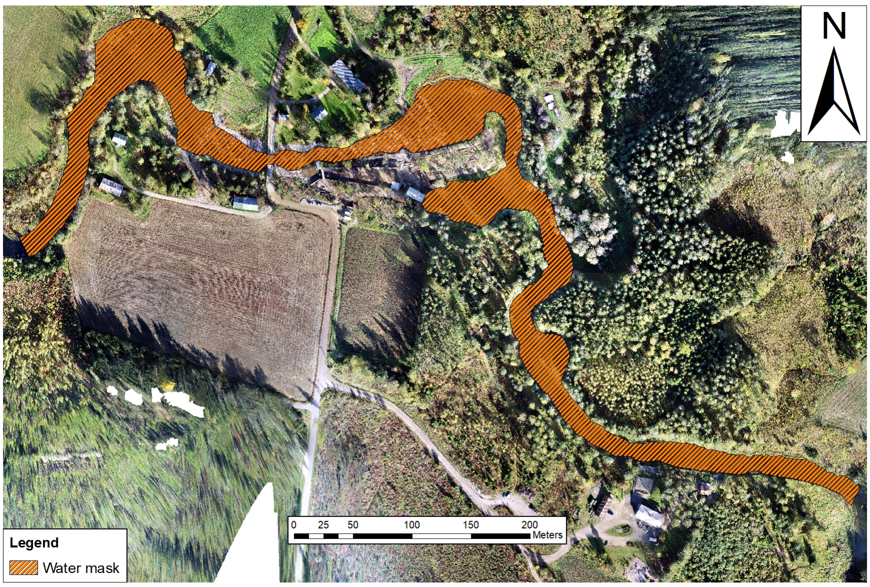


Figure 4.10: Water Mask Autumn

4.7 Hotspot Analysis

The Hotspot Analysis is a type of data exploration that is used to study the concentration of certain values in the dataset in order to distinguish the areas where the concentration is higher and areas where the concentration is lower.

This type of analysis is a statistic test that is used to determine if the point of a dataset belongs to a cluster. The Hotspot analysis is a statistical test that tries to test the null hypothesis for which there is no spatial correlation between two data. If this hypothesis is verified, the two data that are taken into account do not affect each other. On the contrary, if the null hypothesis is rejected, there is spatial correlation between the data.

The result of an Hotspot Analysis is a "P-value" and a "z-score": the P-value is defined as the probability that the dataset that is being analyzed is created by a random processes; z-score measures the relationship between one value of the dataset and the mean of the entire dataset [55]. This value is defined in terms of "standard deviations from the mean". Negative values of the z-score are given to values that are below the mean, while positive values are given to values above the mean.

z-score	p-value	Confidence
$<$ -1.65 or $>$ +1.65	$<$ 0.10	90%
$<$ -1.96 or $>$ +1.96	$<$ 0.05	95%
$<$ -2.58 or $>$ +2.58	$<$ 0.01	99%

The smaller the p-value, the lower the possibility of randomness. The negative values of the z-score indicate cold points, while the positive values indicate hot points. In figure 4.11 there is a visual representation of how does a statistic test work, with a focus on z-scores and P-values:

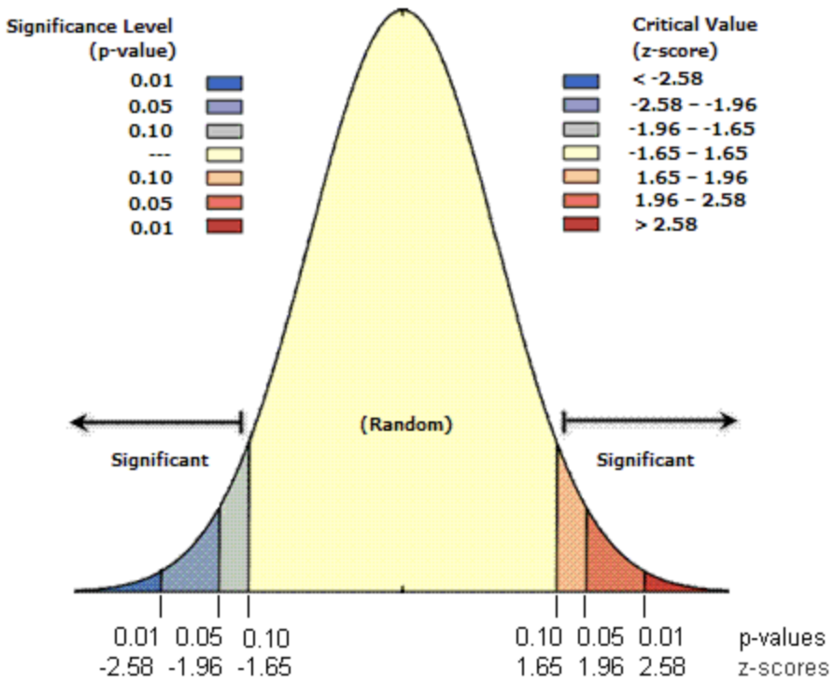


Figure 4.11: Hotspot Analysis, source: Demetris Demetriou

In this specific case, cold spots represent points where the water velocity is particularly low, while hotspots represent points where the water velocity is high compared to the average velocity of the river. Anyway, not every point with very high velocity or very low velocity are considered: in fact, isolated high or low velocity data are not detected as significant hot/cold spots because they are not neighbouring other points with high/low values. Hence, the hotspot analysis is very important because it permits to find clusters in the velocity datasets (Surface Velocity and Near Bed Velocity particularly) that can reveal possible erosion and accumulations of sediments.

The tool that is used in this study to perform the Hotspot analysis is the "Hotspot Analysis (Getis-Ord Gi*)" tool present in ArcGIS. This tool has a very easy interface (figure 4.12: it asks for the input feature class and the input field, which are respectively the layer and the field on which the hotspot analysis will be performed. The conceptualization of the spatial relationship that is used by this tool is a "fixed distance band", meaning that the features that are considered will influence each other only within a certain distance and anything that is outside of the distance threshold does not have any influence.

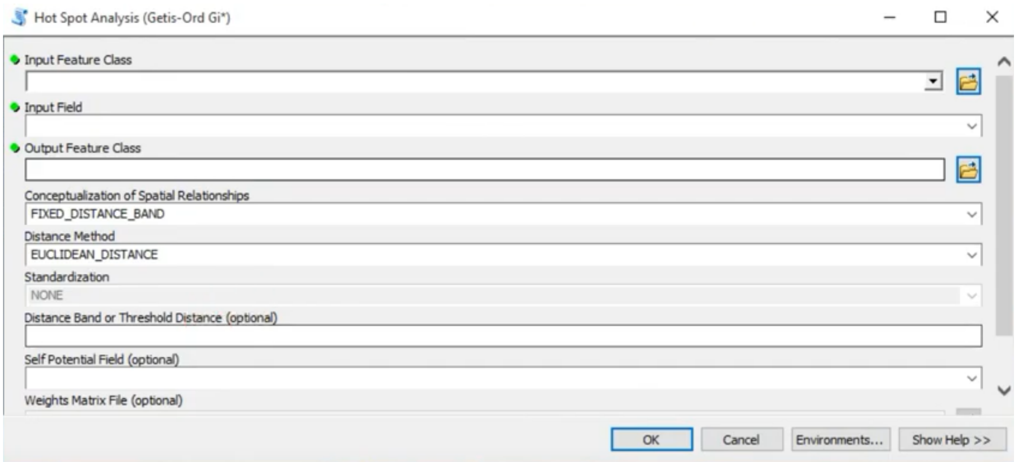


Figure 4.12: Hotspot Analysis (Getis-Ord Gi*) tool in ArcGIS. This is the interface for the hotspot analysis given by ArcGIS: it is necessary to provide a dataset (Feature Class) on which the hotspot analysis will be performed. To perform the analysis on a specific point of a dataset, not every measurement is considered, but only a limited number included in a specific distance range (fixed distance band).

Chapter 5

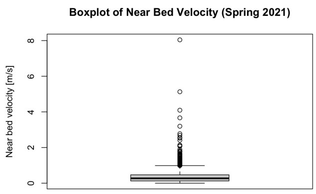
Results

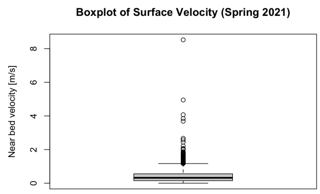
First of all, the datasets representing the Surface velocity, the Near Bed Velocity and the Mean velocity before and after the dam removal have been plotted.
This is necessary to have a first overview on what are the most evident differences between the datasets but also to understand if there are any speed values outside the normal condition that could be possible outliers and should be therefore eliminated.
The analysis continues with the verification and with the removal of the measurements errors (outliers).
In order to have a clearer explanation, the analysis is from now on subdivided into Spring 2021 (before dam removal conditions) and Autumn 2021 (after dam removal conditions).

5.1 Spring 2021

5.1.1 Boxplots and Outliers removal

As explained in the methods section, the boxplots are one of the tool that are used to visualize and recognise possible outliers in the data.
In the following figures, the boxplots for the three spring datasets are shown:





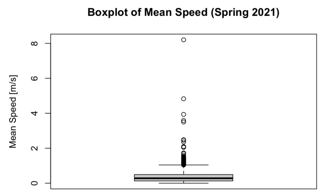


Figure 5.1: Boxplot of the Near Bed Velocity dataset in Spring 2021

Figure 5.2: Boxplot of the Surface Velocity dataset in Spring 2021

Figure 5.3: Boxplot of the Mean Speed dataset in Spring 2021

As it is possible to see from figures 5.1, 5.2 and 5.3, there are some values that exceed the "Maximum" of the boxplot, but in particular there are 5 values which are very distant from the point cloud that is instead very close to the Maximum. Anyway, there is the possibility that these points are situated in proximity of the turbine or into the rapid and this can be a possible explanation of why the velocity is so high. In order to confirm if these values are real outliers or not, the location was checked:

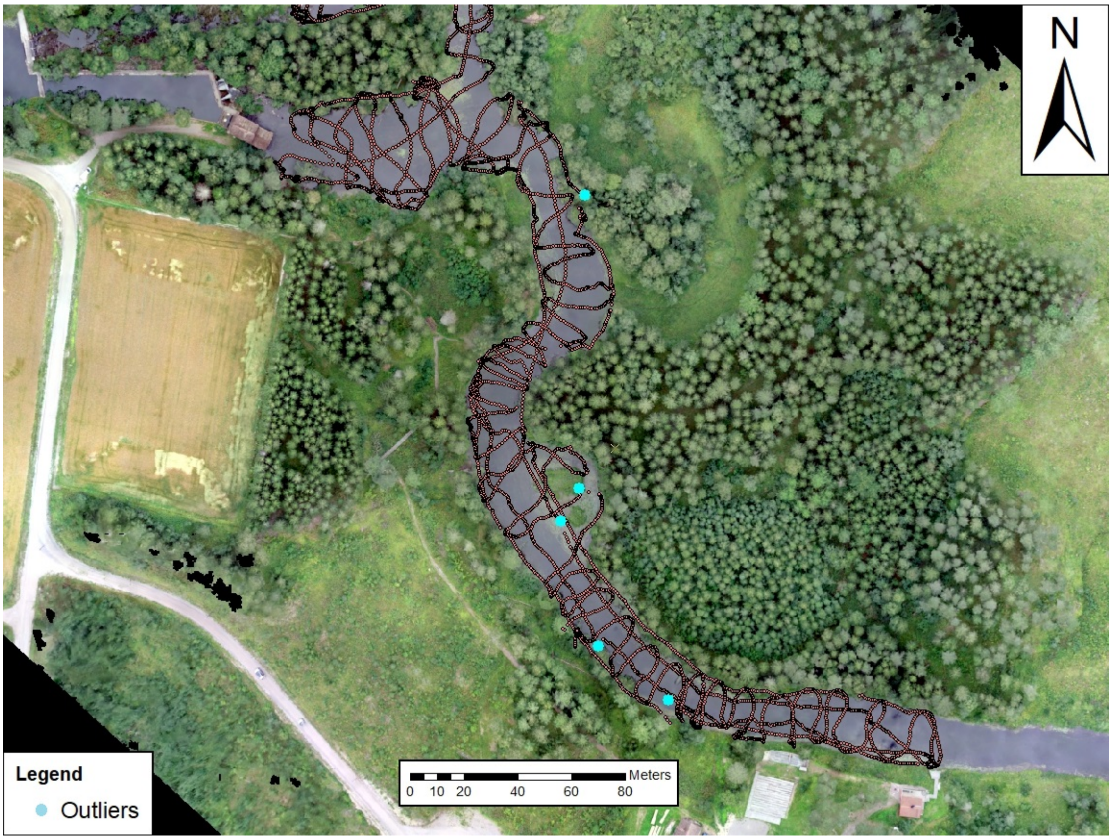


Figure 5.4: Outliers (Spring)

It is observable from the figure 5.4 that these values are not in proximity of the turbine or the rapids, hence they are outliers that have to be cut from the datasets.

5.1.2 Interpolations

As already explained in the previous section, the data interpolations were made using the Geostatistical Wizard tool present in the ArcGIS software and coupled with a "mask" which was built to be able to isolate and clip the prediction map only in correspondence to the river region.

IDW interpolation

Below (figure 5.5, 5.6, 5.7) are shown the inverse distance weighted interpolations for the measured Mean Speed, Near Bed Velocity and Surface Velocity in the Kangaskoski river segment for the spring dataset:

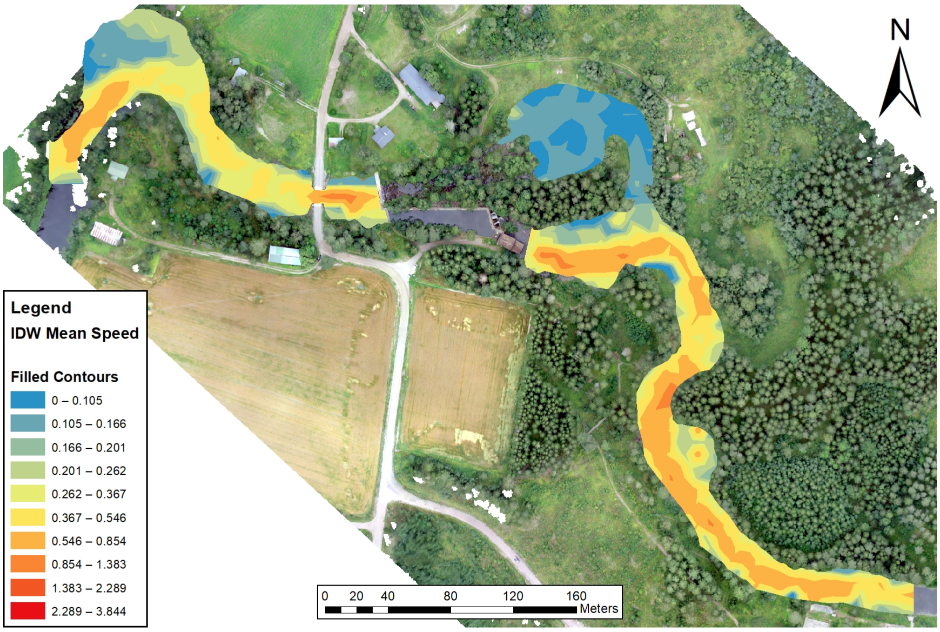


Figure 5.5: IDW Mean Speed [m/s] (Spring)

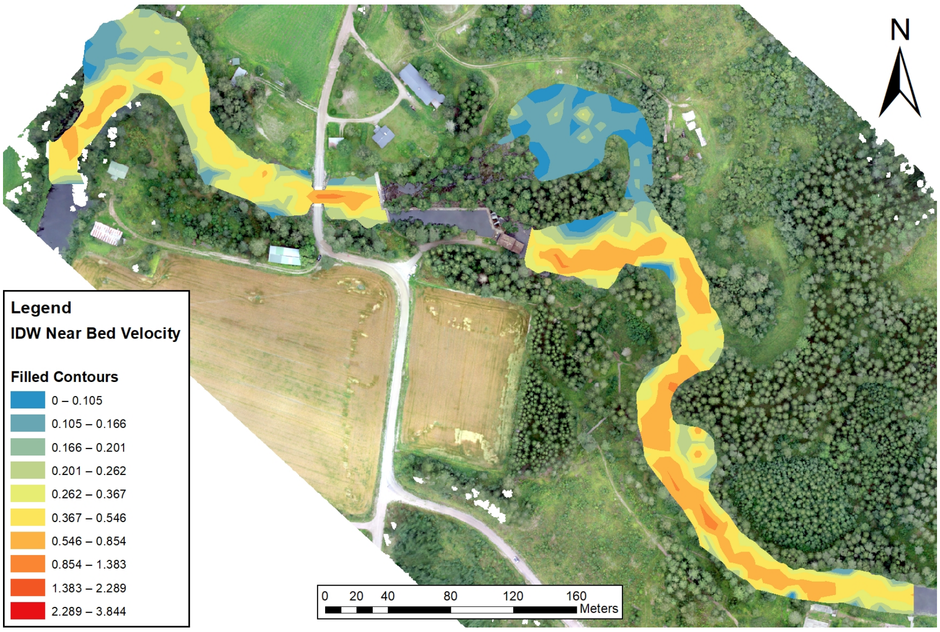


Figure 5.6: IDW Near Bed Velocity [m/s] (Spring)

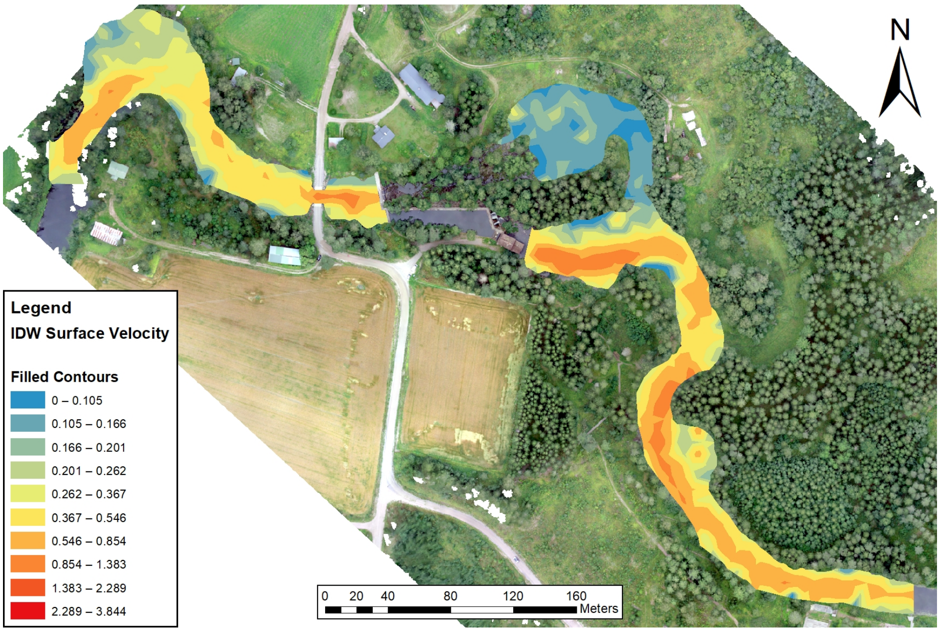


Figure 5.7: IDW Surface Velocity [m/s] (Spring)

This was the first interpolation that was made in order to have a first impression

on how the different velocities are distributed along the segment.
As already said before, the IDW interpolation is not the best kind of interpolation for this purpose because it makes the assumption that the closest elements have similar values. It is in fact called "weighted" because the unsampled points are given a value that depends on the distance with the sampled points and this can cause the so called "Bull's eye effect" that was previously explained. Moreover, the maximum and minimum values can occur only in correspondence of the measured values and therefore, this is not the best interpolation method.
For these reasons, the kriging interpolation was performed as well in order to compare it with the IDW interpolation.

Kriging interpolation

The first fundamental phase of this type of interpolation is the evaluation of the mathematical model to be used. As already said before, this type of spatial interpolation is based on the spatial autocorrelation of the data. Similarly to the IDW interpolation, the interpolated values are calculated starting from the distance from the sampled datasets. However, in this case the weights that are used to calculate the new values are evaluated using the semivariogram (also known as the variogram). The variogram is a mathematical function that can be of various types and that is used to calculate the values during the interpolation phase. It is therefore important to choose the analytical model that is closest as possible to the empirical distribution of the data.
The sampled data are then divided into classes (lags) and the experimental variogram is calculated and plotted. After this passage, the sampled data are interpolated using a curve: the tool present in ArcGIS is able to automatically find the function that best approaches the distribution of the sampled data. Once the function is found, this will be used to calculate the data value at the points that

have not been measured.

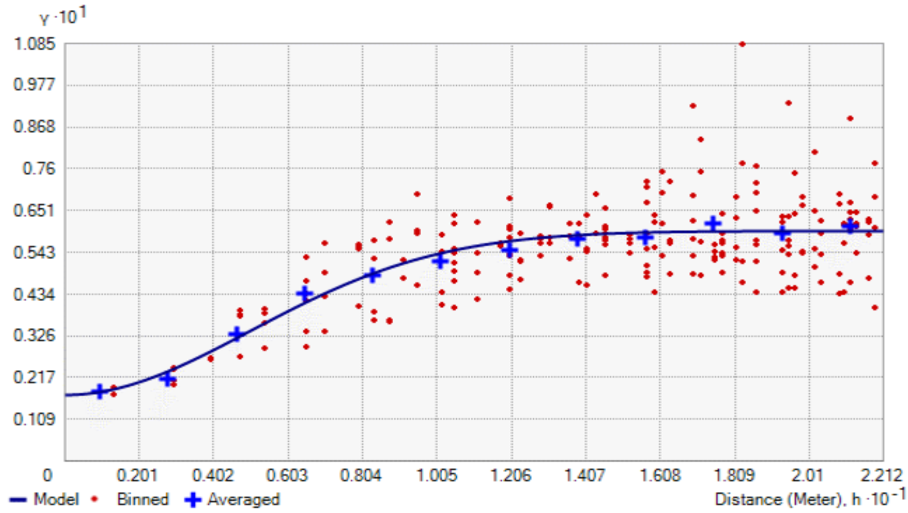


Figure 5.8: Semivariogram Mean Speed (Spring)

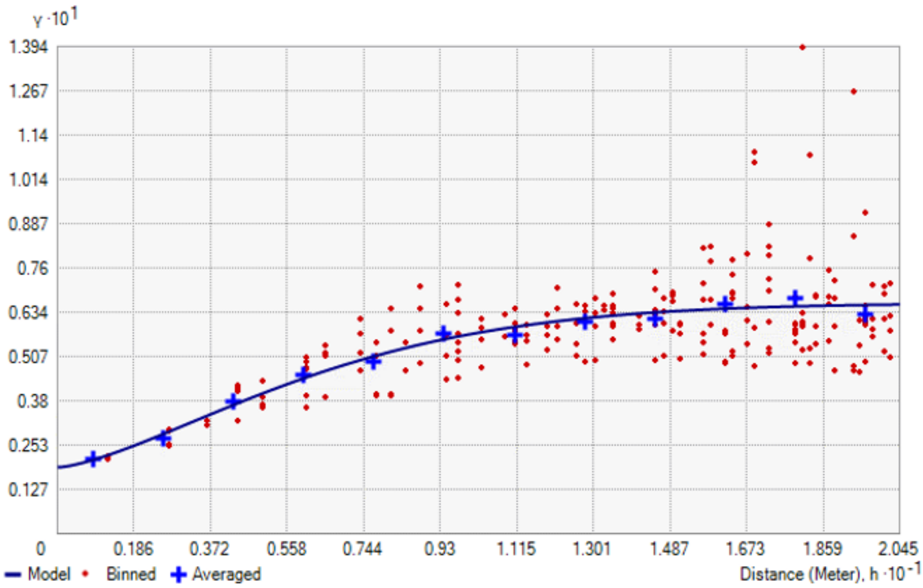


Figure 5.9: Semivariogram Near Bed Velocity (Spring)

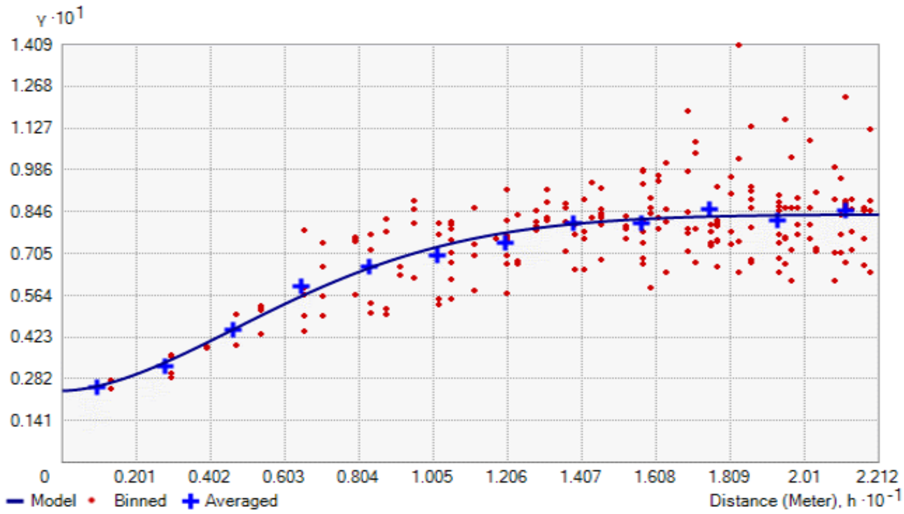


Figure 5.10: Semivariogram Surface Velocity (Spring)

It can be seen that in all three cases, the theoretical variogram that best approximates the experimental variogram is the Gaussian model. In fact, the curve representing the variogram has a horizontal tangent at the origin. Furthermore, the variograms have a pretty evident nugget, which means that the datasets are affected by some kind of noise. This is understandable considering that this are raw data. The equation of this curve that will be used by the tool to calculate the interpolated values is the following:

$$\gamma(h) = b + \omega \cdot \left[1 - e^{\frac{h^2}{\alpha^2}}\right] \tag{5.1}$$

where γ is the semivariogram, b is the nugget, h is the lag and α is the correlation length.

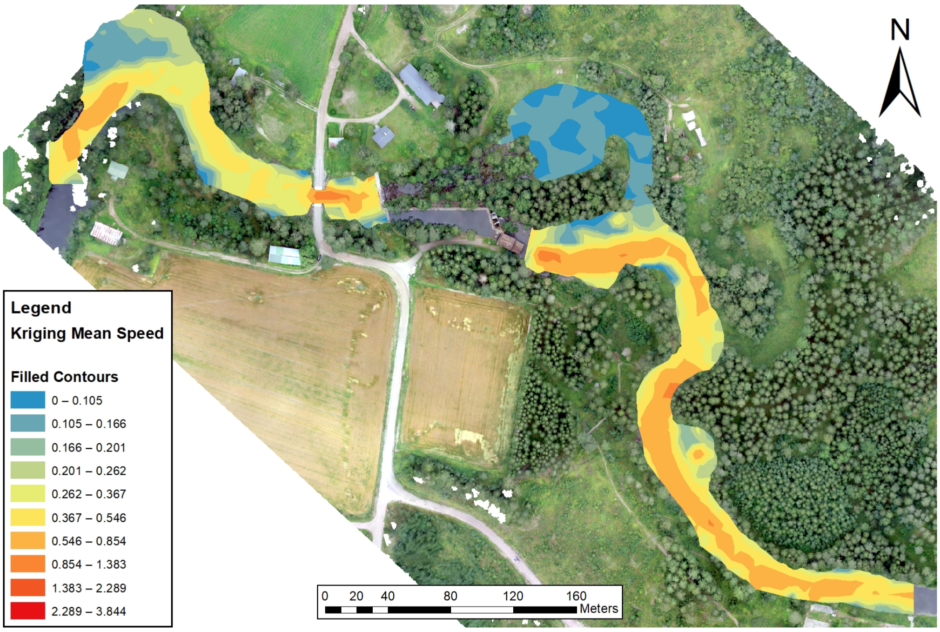


Figure 5.11: Kriging Mean Speed [m/s] (Spring)

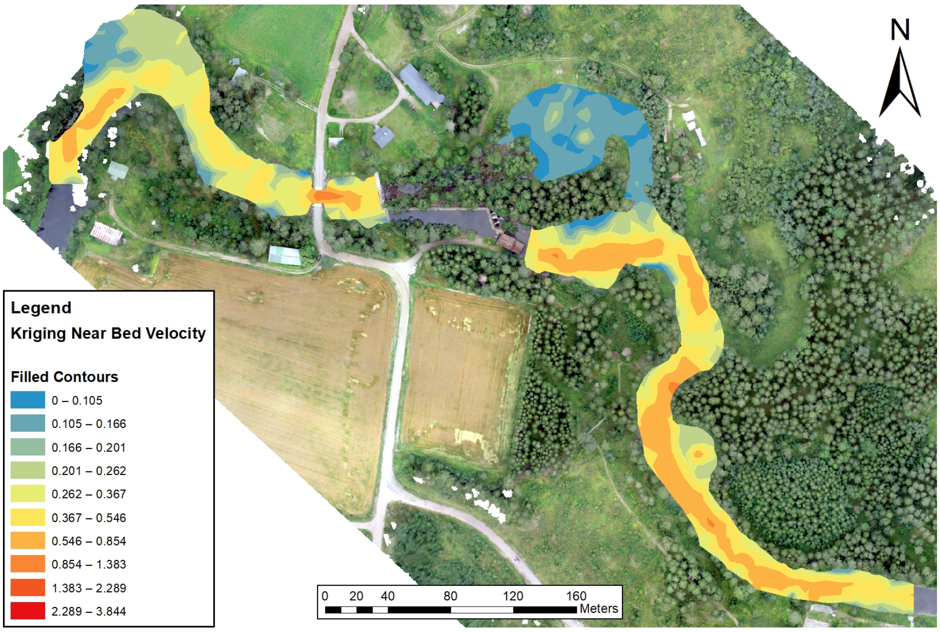


Figure 5.12: Kriging Near Bed Velocity [m/s] (Spring)

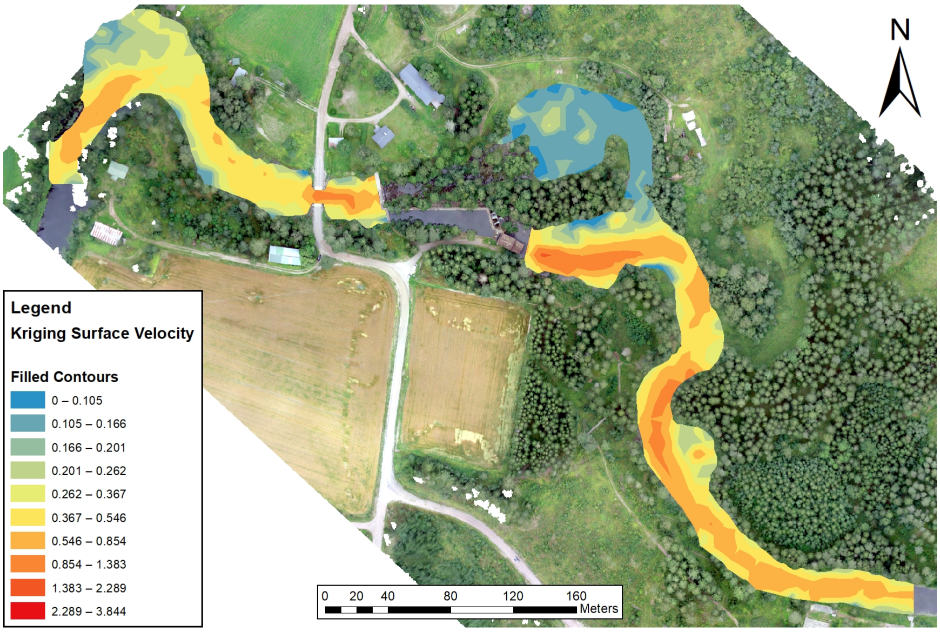


Figure 5.13: Kriging Surface Velocity [m/s] (Spring)

It is difficult to understand from these plot the real differences between the velocities in the different layers, but it is evident that the water velocity is higher in correspondence of the bridge and right after the power plant, certainly due to the hydraulic jump. Moreover, after the power plant, the water velocity is higher in the middle of the river and slows down approaching the river banks. On the other hand, the water velocity in correspondence of the "old" river segment is very low in every layer. Furthermore, the first river band is characterized by an area where the velocity is very slow and a neighboring area where the velocity is particularly fast. In correspondence of the bridge, water velocity is particularly high: this is caused by the fact that its presence brings to a narrowing of the watercourse due to the bridge abutment (figure 5.14).

Figure 5.14: Bridge in Kangaskoski

The narrowing of the watercourse leads inevitably to an increase in the water speed since, with the same discharge, if the area crossed by the water is smaller, its speed must necessarily increase.

The same considerations are visible in the hotspot analysis plots, where the red points indicate clusters of very high velocities and blue points indicate clusters of low velocities.

5.1.3 Hotspot Analysis

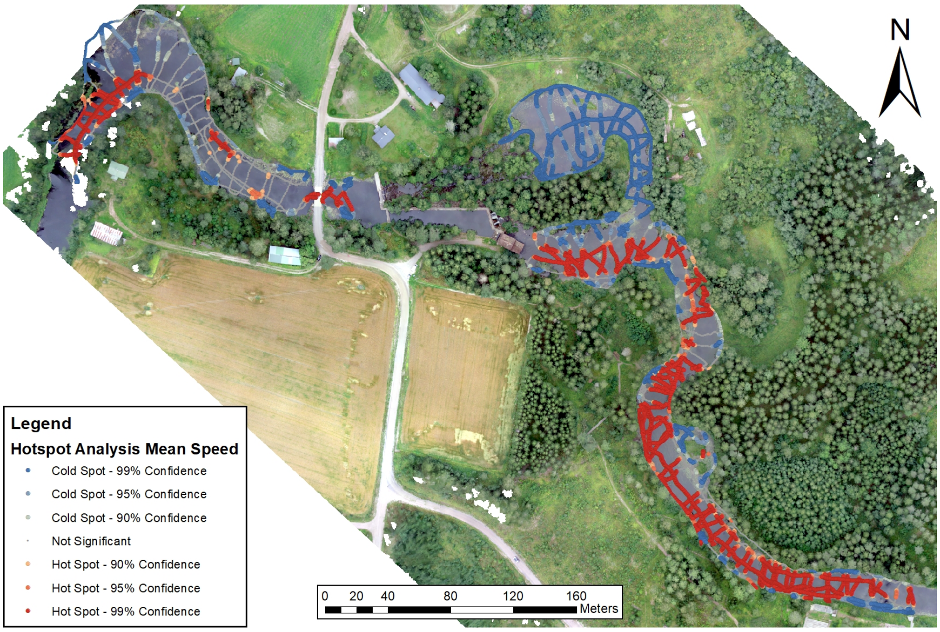


Figure 5.15: Hotspot Analysis Mean Speed (Spring)

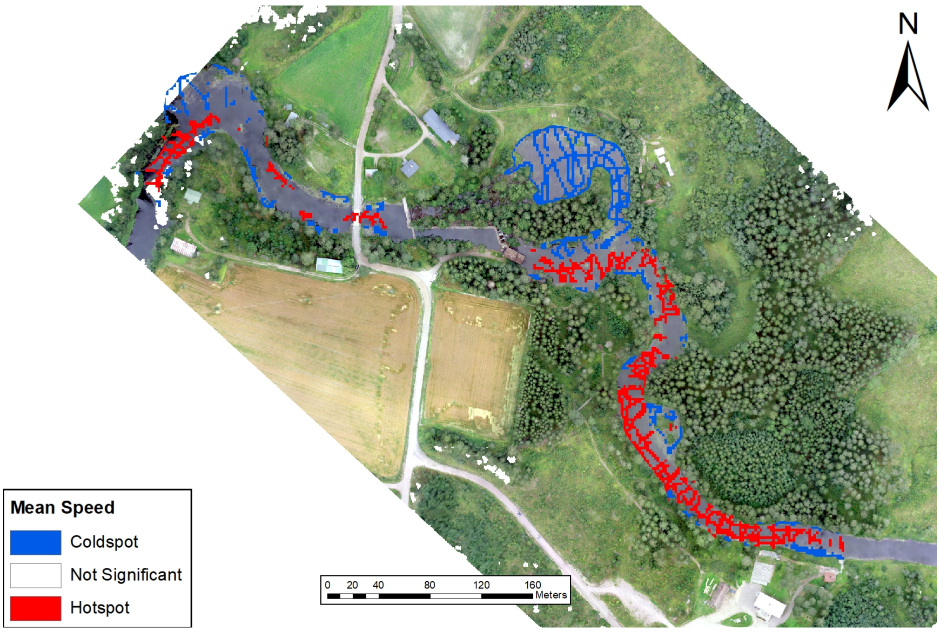


Figure 5.16: Raster Hotspot Analysis Mean Speed (Spring)

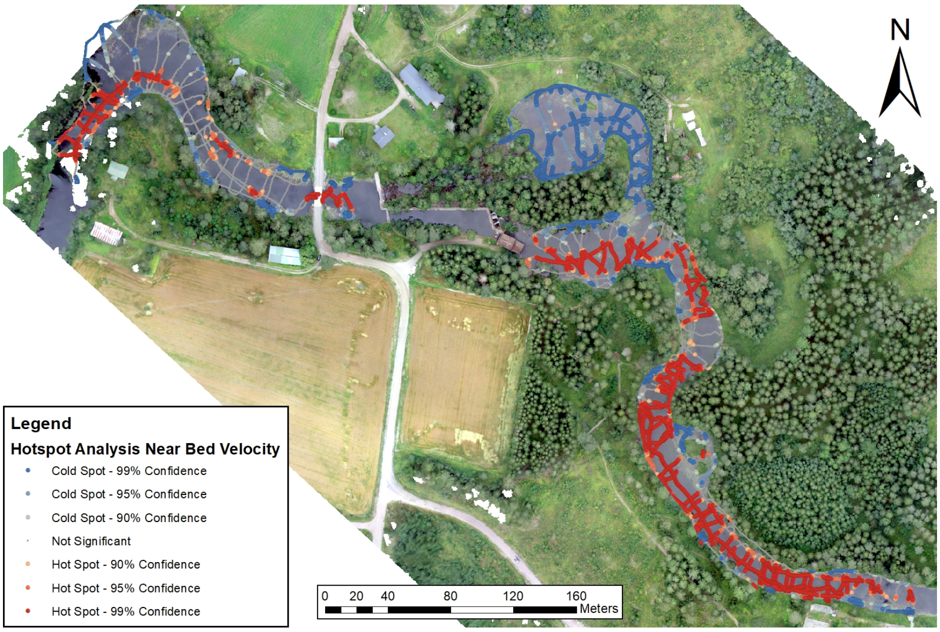


Figure 5.17: Hotspot Analysis Near Bed Velocity (Spring)

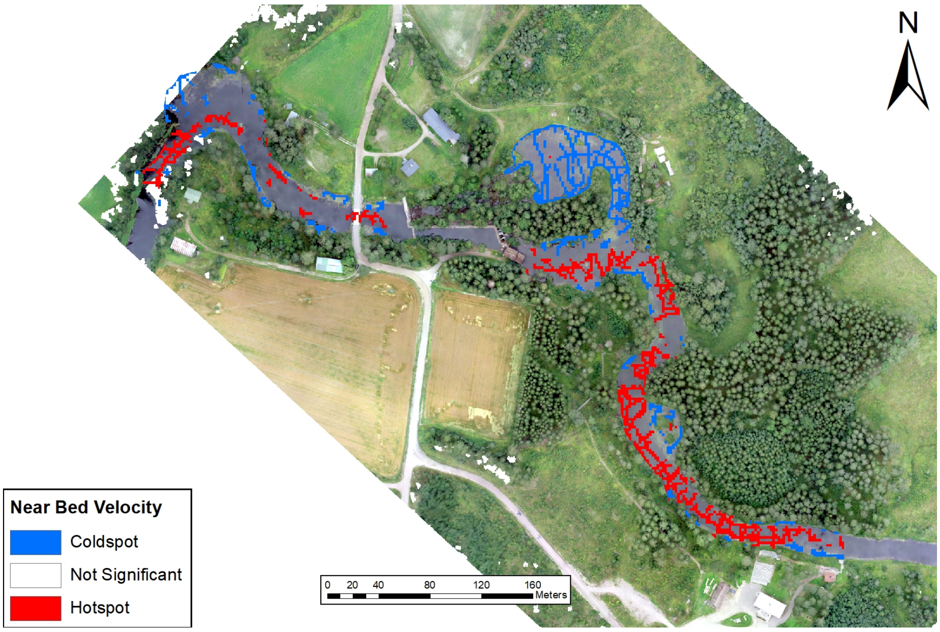


Figure 5.18: Raster Hotspot Analysis Near Bed Velocity (Spring)

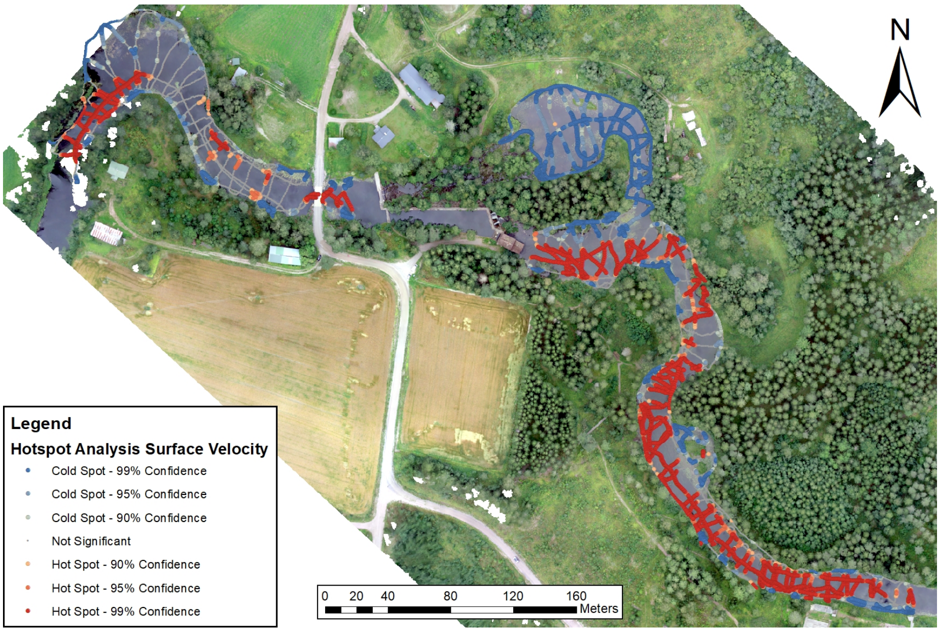


Figure 5.19: Hotspot Analysis Surface Velocity (Spring)

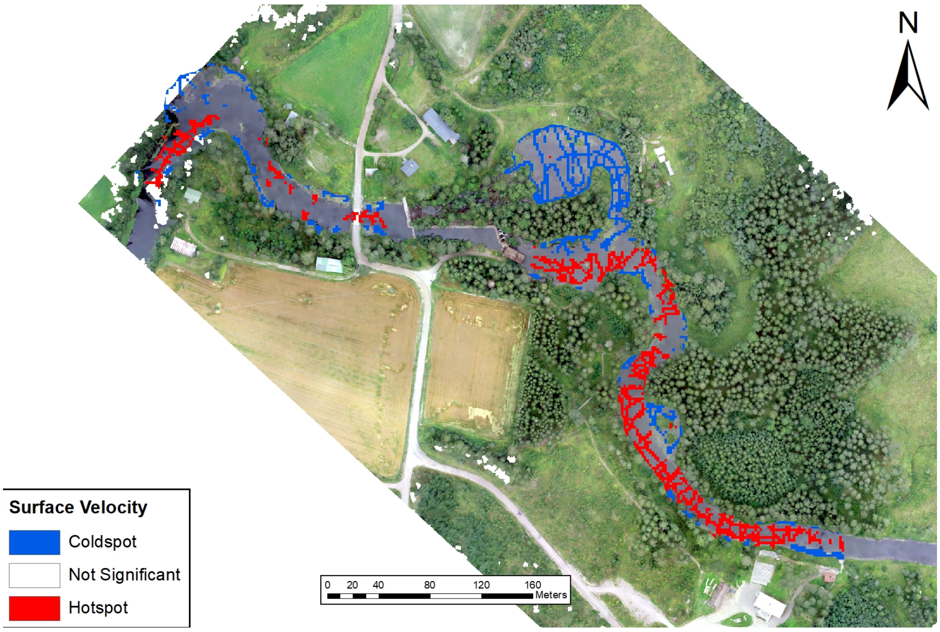


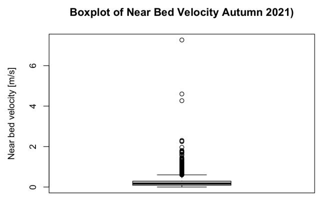
Figure 5.20: Raster Hotspot Analysis Surface Velocity (Spring)

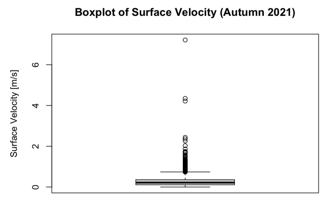
The Hotspot analysis was performed using the "Hotspot Analysis (Getis-Ord Gi*)" tool in ArcGIS. Also in this case, the hotspot analysis was performed on Surface Velocity, Near Bed Velocity and Mean Speed. The output of this analysis is a map where the measurement point can have different colors depending on their statistical significance: in general, the points that have a blue-ish colour indicate coldspots (low velocity clusters), while points that have a red-ish colour indicate hotspots (high velocity clusters). In order to have a better overview on where the clusters are, coldspots and hotspots with different statistical significance were put together in a raster map. Contrarily to the interpolations, that have the purpose to give an overview on the velocity distribution through the river channel, the hotspot analysis can provide a better idea whether the measured velocities are spatially correlated and consequently if clusters are evident. As a result, it is possible to state that hotspots are pretty evident in correspondence of the first bend, in correspondence of the bridge and after the power plant. On the other hand, coldspots are really evident only in the "old" river segment, while in the rest of the river it is possible to see that there are clusters of low velocities nearby the river banks.

5.2 Autumn 2021

5.2.1 Boxplots and Outliers Removal

In the following figures, the boxplots for the three autumn datasets are shown:





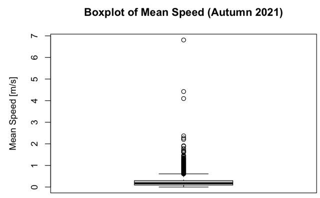


Figure 5.21: Boxplot of the Near Bed Velocity dataset in Autumn 2021

Figure 5.22: Boxplot of the Surface Velocity dataset in Autumn 2021

Figure 5.23: Boxplot of the Mean Speed dataset in Autumn 2021

As already seen in the case of spring 2021, the boxplot analysis reveals that there are some values that exceed the "Maximum": in particular there are 3 values which are very distant from the point cloud that is very close to the Maximum. There is the possibility that these points are situated into the rapid and this can be a possible explanation of why the velocity is so high. In order to control if these values are real outliers or not, the location was checked:

Figure 5.24: Outliers (Autumn)

As before, these values are not situated into the rapids, therefore they might be outliers, hence they have been cut from the dataset.

5.2.2 Interpolations

As already explained in the previous section, the data interpolations were made using the Geostatistical Wizard tool present in the ArcGIS software coupled with a "mask" which was built to be able to isolate and clip the prediction map only in correspondence of the river region.

IDW interpolation

Below (figure 5.25, 5.26, 5.27) are shown the inverse distance weighted interpolations for the measured Mean Speed, Near Bed Velocity and Surface Velocity in the Kangaskoski river segment for the autumn dataset:

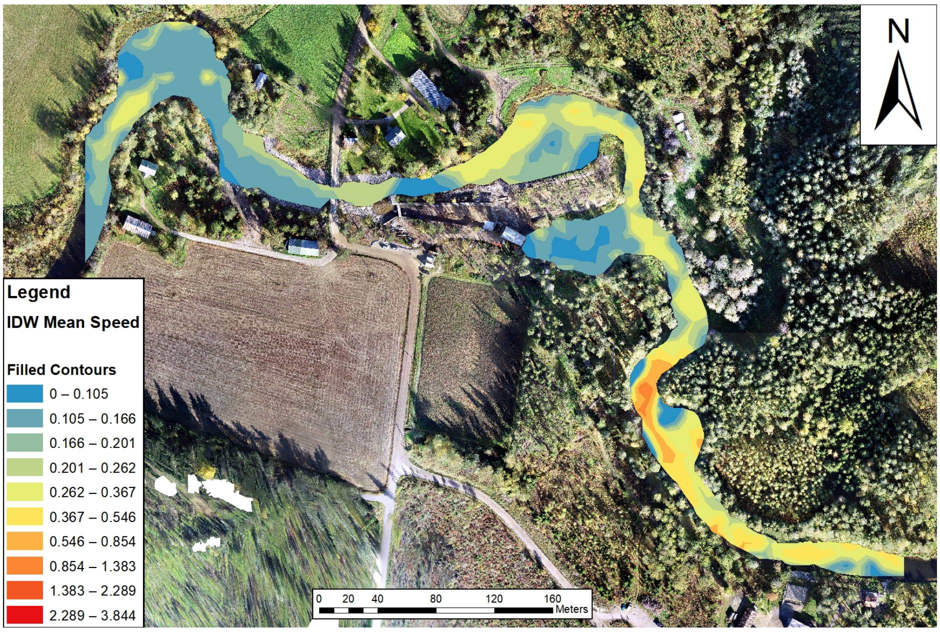


Figure 5.25: IDW Mean Speed [m/s] (Autumn)

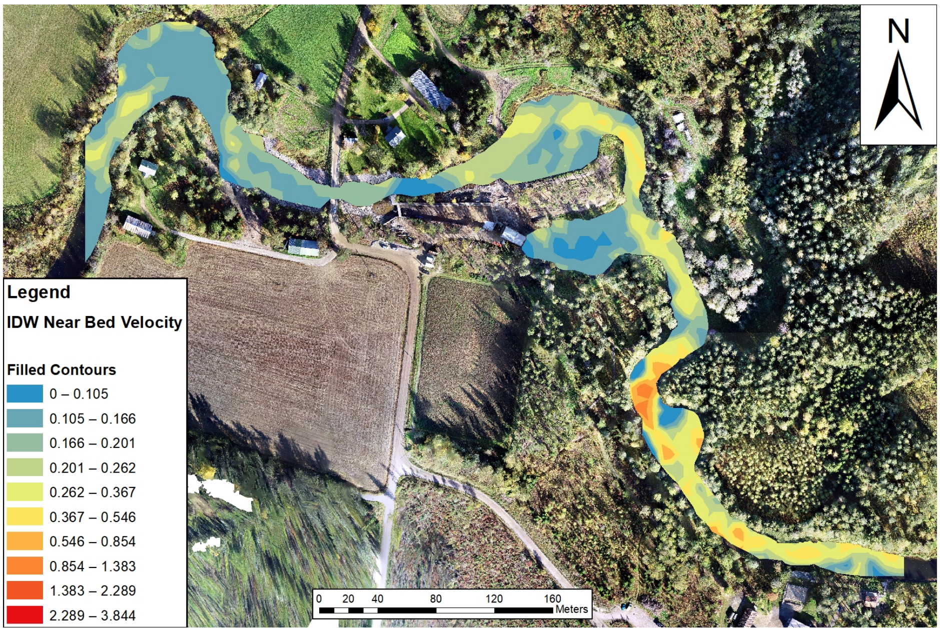


Figure 5.26: IDW Near Bed Velocity [m/s] (Autumn)

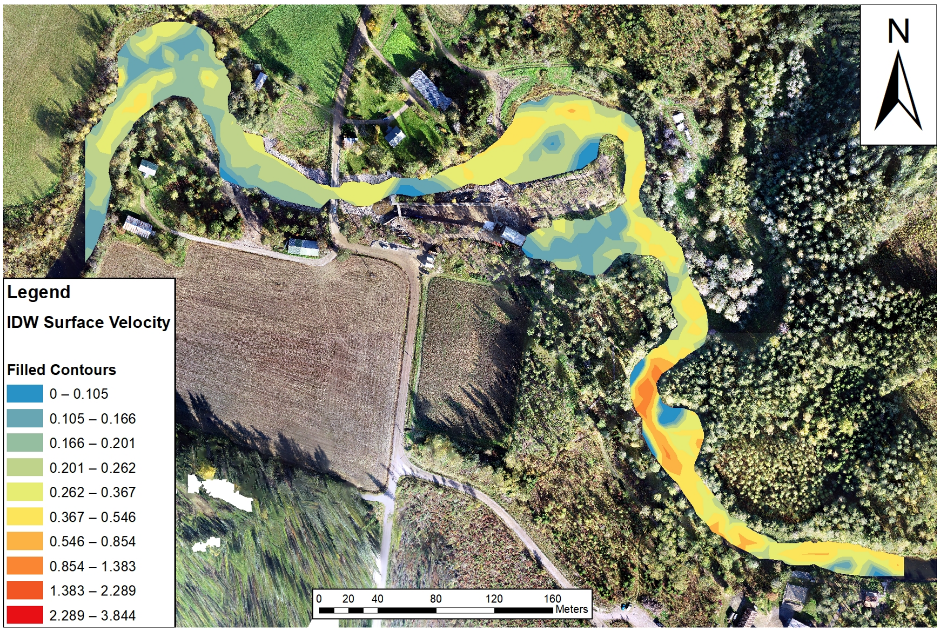


Figure 5.27: IDW Surface Velocity [m/s] (Autumn)

As for the spring, IDW interpolation is not the best type of interpolation, but it

was done to have a initial overview on the velocity distribution. Here, more than before, is evident how the bull´s eye effect is affecting the interpolation: especially in correspondence of the first river bend, there are some points surrounded by circular concentric areas.
Also in this case, kriging was performed.

Kriging interpolation

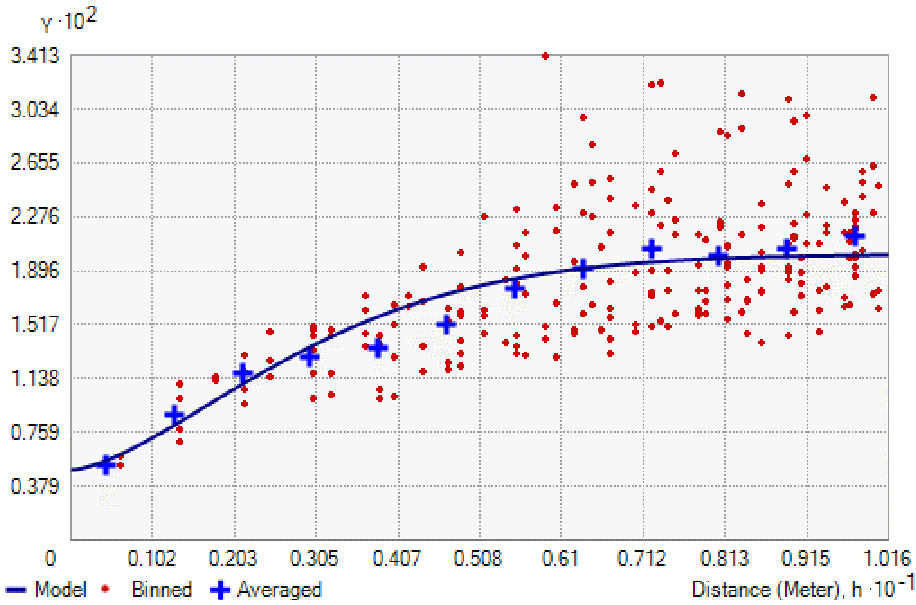


Figure 5.28: Semivariogram Mean Speed (Autumn)

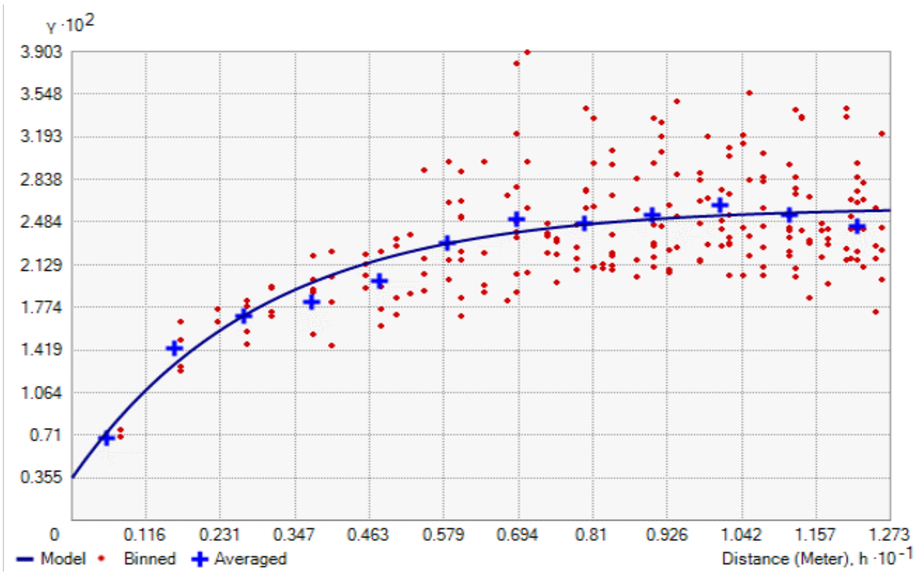


Figure 5.29: Semivariogram Near Bed Velocity (Autumn)

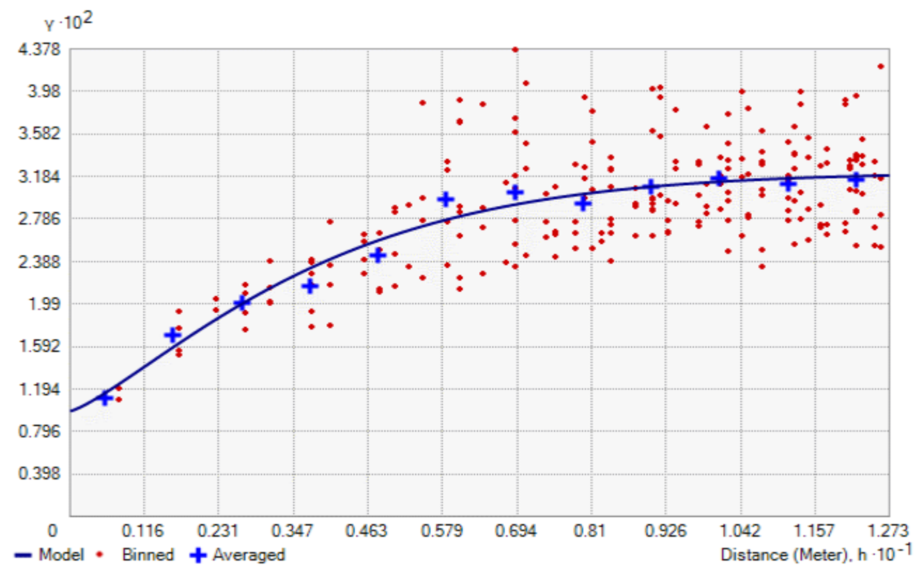


Figure 5.30: Semivariogram Surface Velocity (Autumn)

Contrarily to before, in this case the theoretical variogram are different and not approximable with the same model. For what concerns the near bed velocity, the exponential variogram is the one that best approximate the experimental variogram;

regarding the variograms of the surface velocity and the mean speed, it is instead visible a horizontal tangent close to the origin: for this reason, the best theoretical variogram that fits the experimental variograms is the Gaussian model.

Furthermore, the variograms have a pretty evident nugget, which means that the datasets are affected by some kind of noise. This is understandable considering that these are raw data.

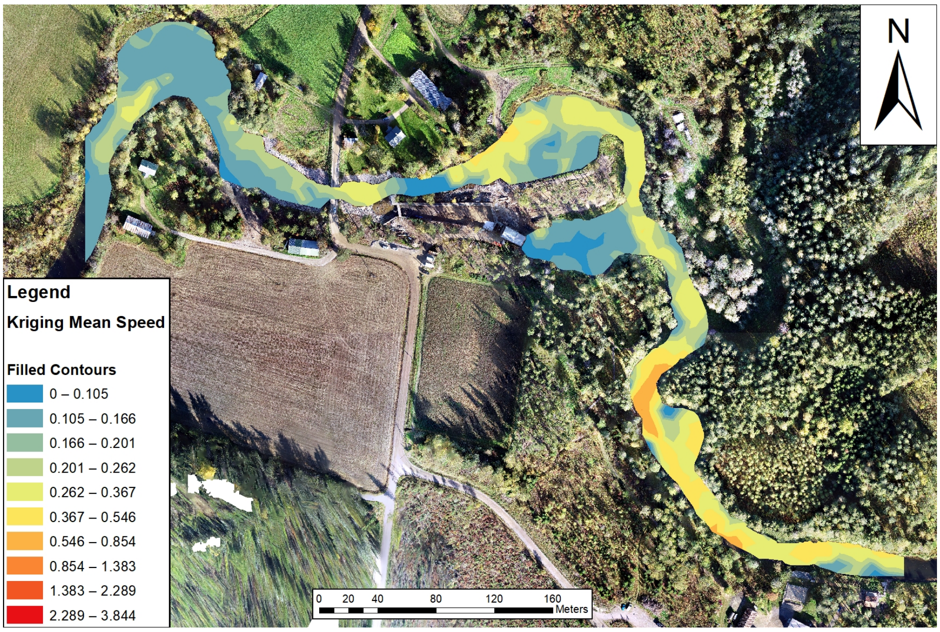


Figure 5.31: Kriging Mean Speed [m/s] (Autumn)

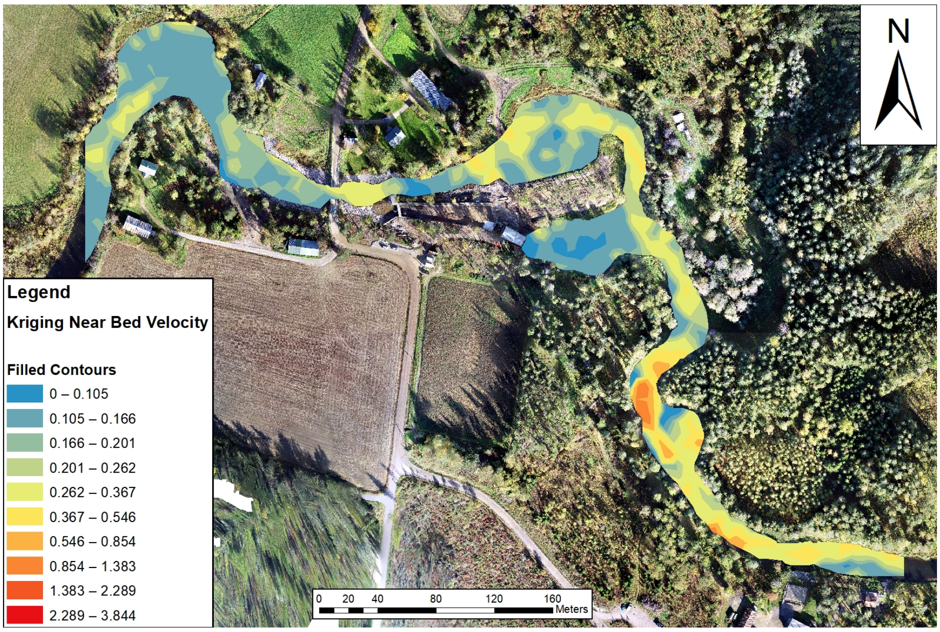


Figure 5.32: Kriging Near Bed Velocity [m/s] (Autumn)

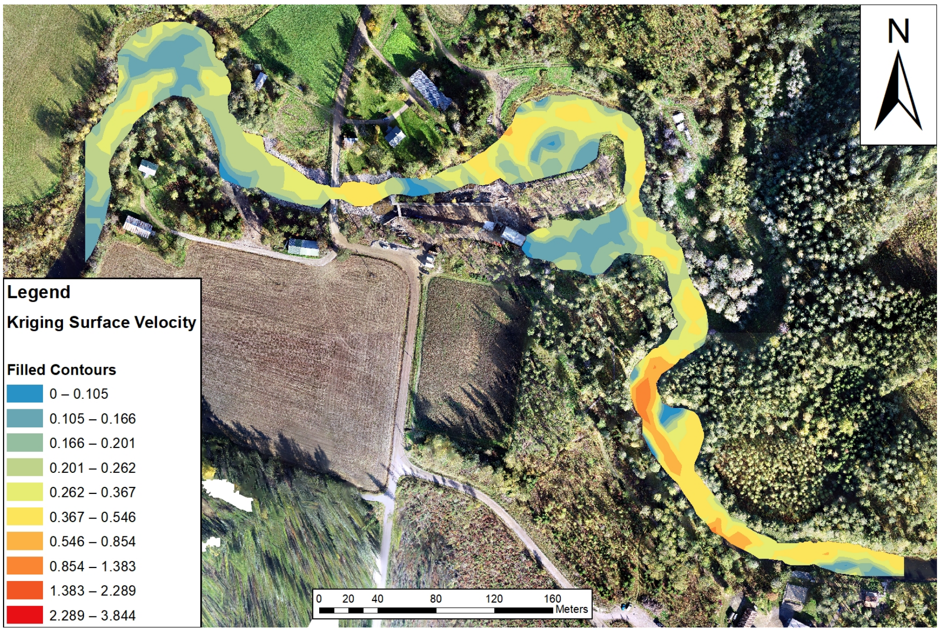


Figure 5.33: Kriging Surface Velocity [m/s] (Autumn)

At a first glance, it is very visible that, compared to spring, the river velocity in every layer is abundantly decreased. In fact, if in the spring dataset there were velocity values over 3 m/s, the maximum velocity visible in the autumn interpolation does not overcome 1.4 m/s.

As a consequence of the dismantling of the dam and of the turbine shutdown, the water velocity right after the dam area is now very low, almost static in some points. This is due to the fact that the "old" river segment that was used as a bypass channel has become again the principal channel. To dissipate the water energy coming from upstream, some stones were positioned before and after the bridge (figure 5.34):

Figure 5.34: Stones Positioned before the bridge in Kangaskoski

As a result, the velocity in correspondence of the bridge is diminished compared to the velocity in the spring dataset.

In general, the velocity distribution through the channel segment has completely changed: after the dam removal the water velocity seems to be at its highest in correspondence of the fourth bend.

The velocity in the second bend, right after the zone where the stones were placed, is not the highest but still high compared to the rest.

5.2.3 Hotspot Analysis

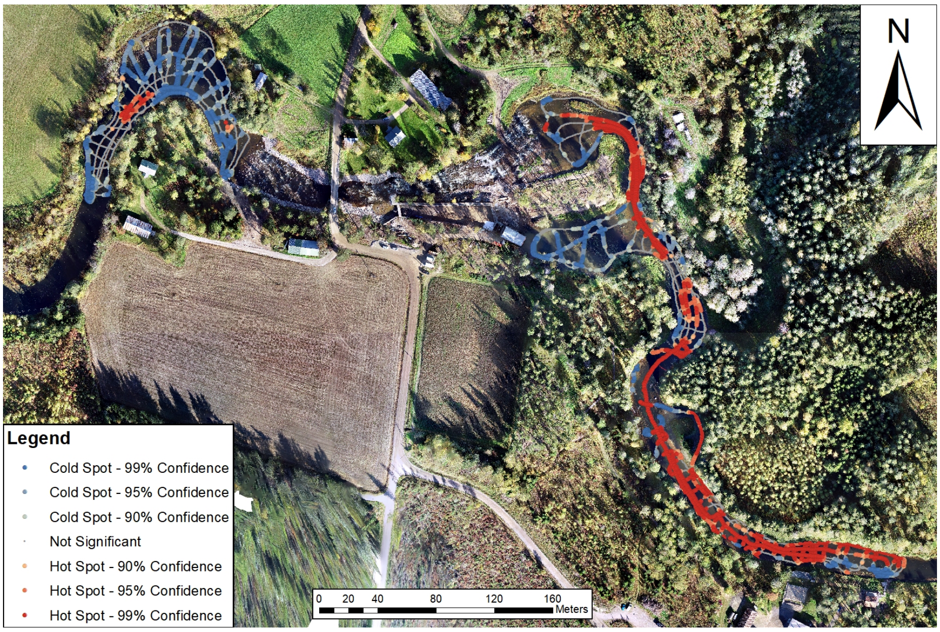


Figure 5.35: Hotspot Analysis Mean Speed (Autumn)

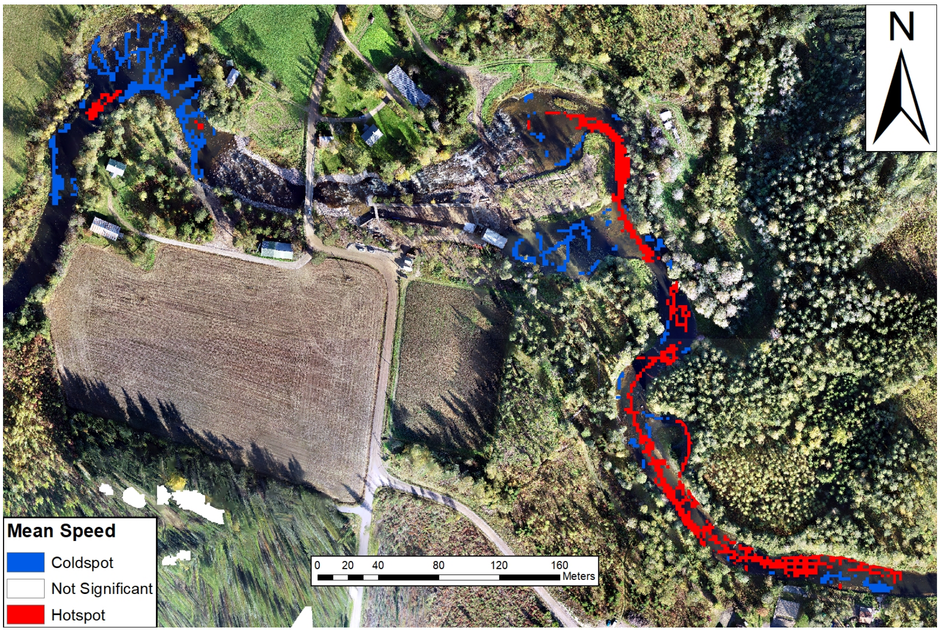


Figure 5.36: Raster Hotspot Analysis Mean Speed (Autumn)

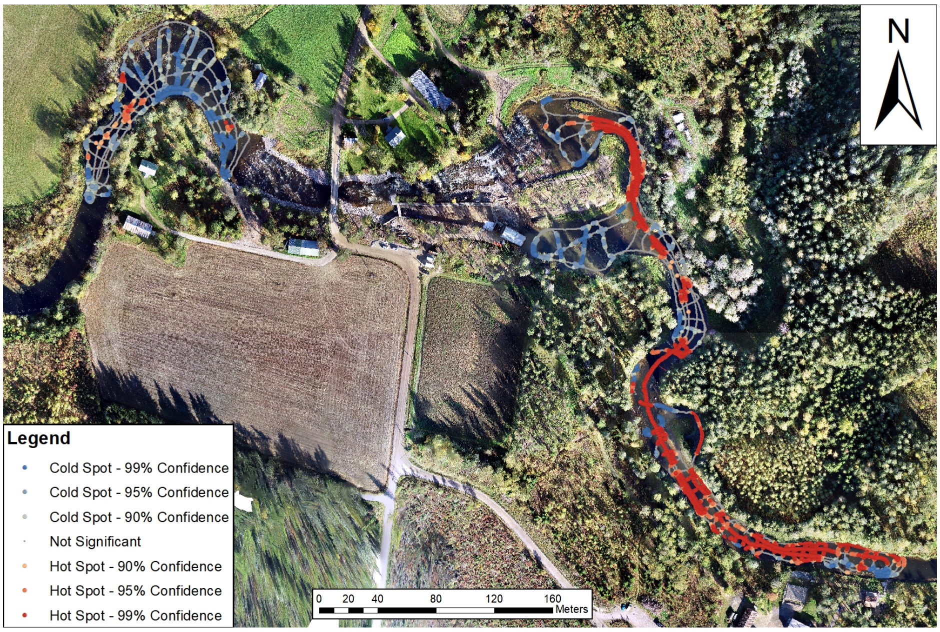


Figure 5.37: Hotspot Analysis Near Bed Velocity (Autumn)

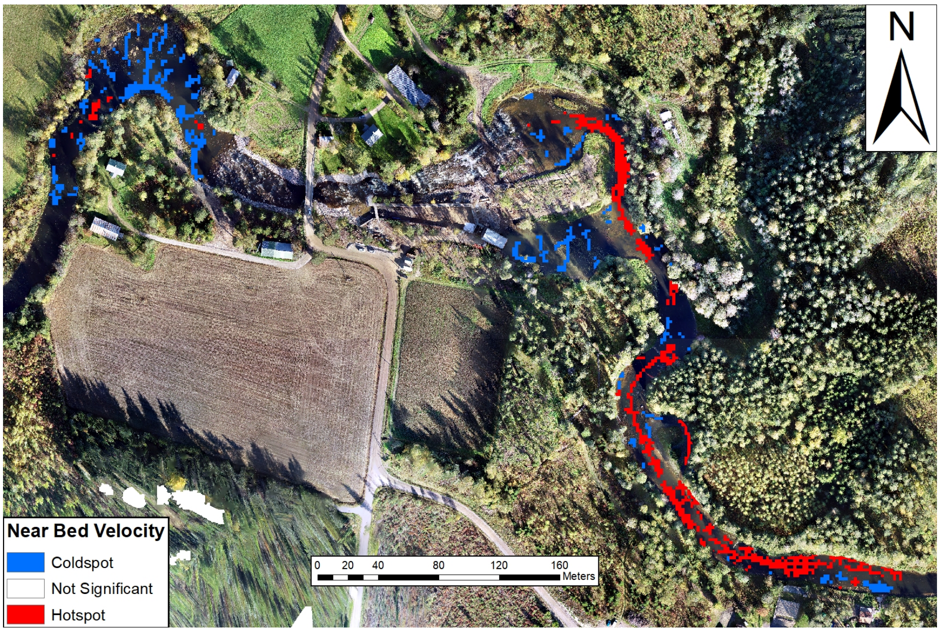


Figure 5.38: Raster Hotspot Analysis Near Bed Velocity (Autumn)

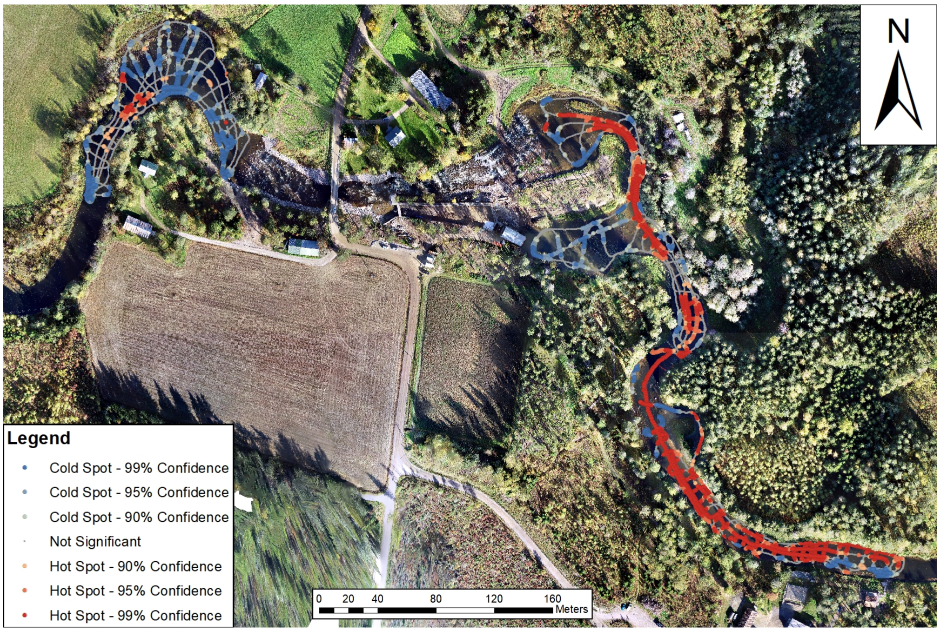


Figure 5.39: Hotspot Analysis Surface Velocity (Autumn)

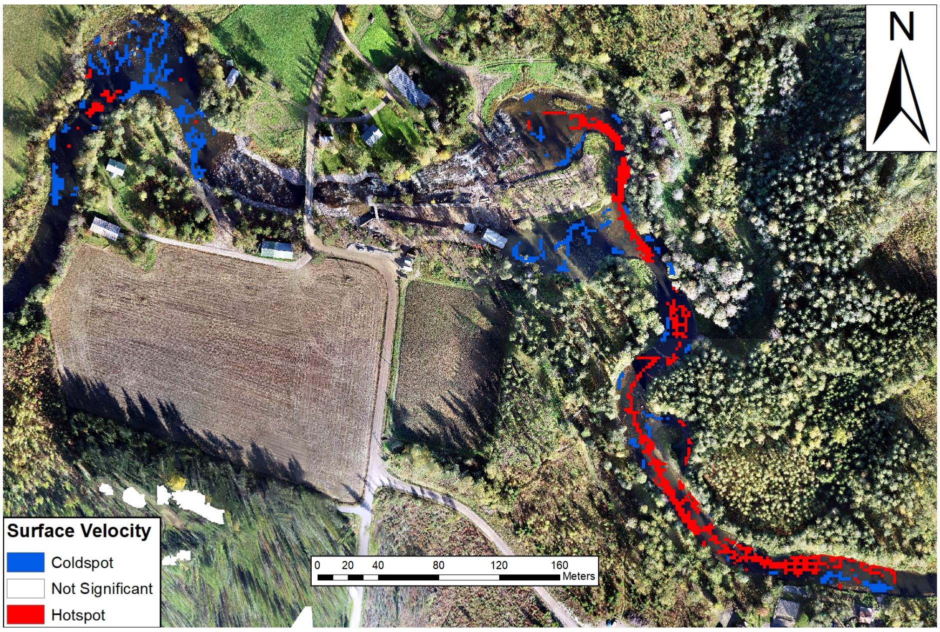


Figure 5.40: Raster Hotspot Analysis Surface Velocity (Autumn)

The Hotspot analysis was performed using the "Hotspot Analysis (Getis-Ord Gi*)" tool in ArcGIS. Also in this case, the hotspot analysis was performed on Surface Velocity, Near Bed Velocity and Mean Speed. The output of this analysis is a map where the measurement points can have different colors depending on their statistical significance: in general, the points that have a blue-ish colour indicate coldspots (low velocity clusters), while points that have a red-ish colour indicate hotspots (high velocity clusters).
In order to have a better overview on where the clusters are, coldspots and hotspots with different statistical significance were put together in a raster map.

After the dam removal, there has been an evident variation in the spatial distribution of velocity clusters: in correspondence of the former bypass channel, now the water is not still but it is flowing causing a new accumulation of hotspots.
On the contrary, in correspondence of the former turbines, now the water is not flowing anymore, but it is rather stagnant, causing an accumulation of coldspots.

5.3 Velocities Differences

5.3.1 Difference between Surface and Near Bed Velocity

In figure 5.41 and 5.42 are shown the differences between the surface velocity and the near bed velocity before the dam removal (Spring) and after the dam removal (Autumn). These maps were realized to show how the dynamics between the surface velocity and the near bed velocity have changed with the dam removal and to check if some anomalies between the two dataset can explain a change in the erosion potential and sediment transportation.
These maps where realized firstly exporting the kriging prediction maps of the Surface Velocity and Near Bed Velocity into rasters. Then, the tool "Raster Calculator" was used to perform the difference between the two raster maps.

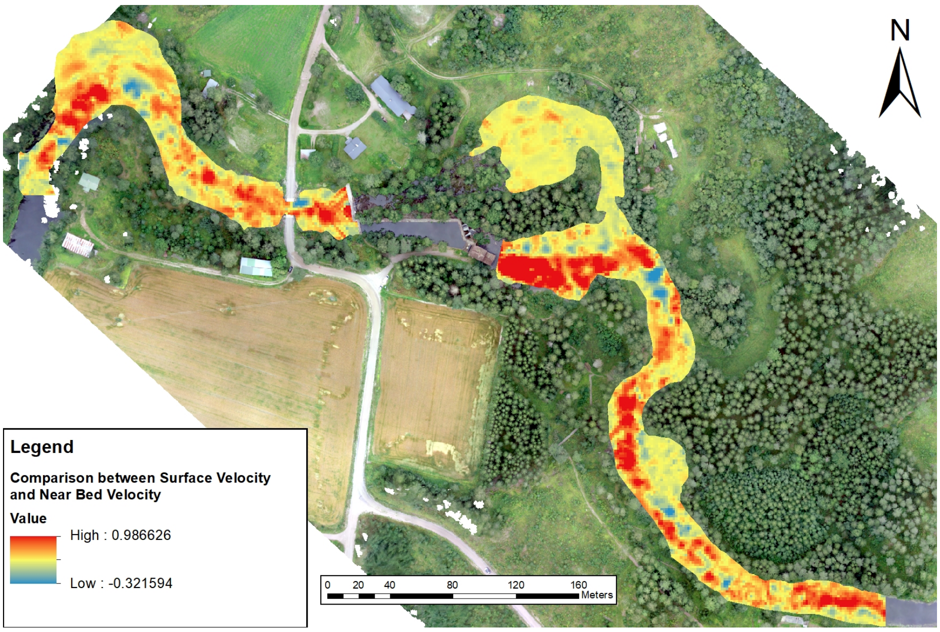


Figure 5.41: Difference between Surface Velocity and Near Bed velocity (Spring)

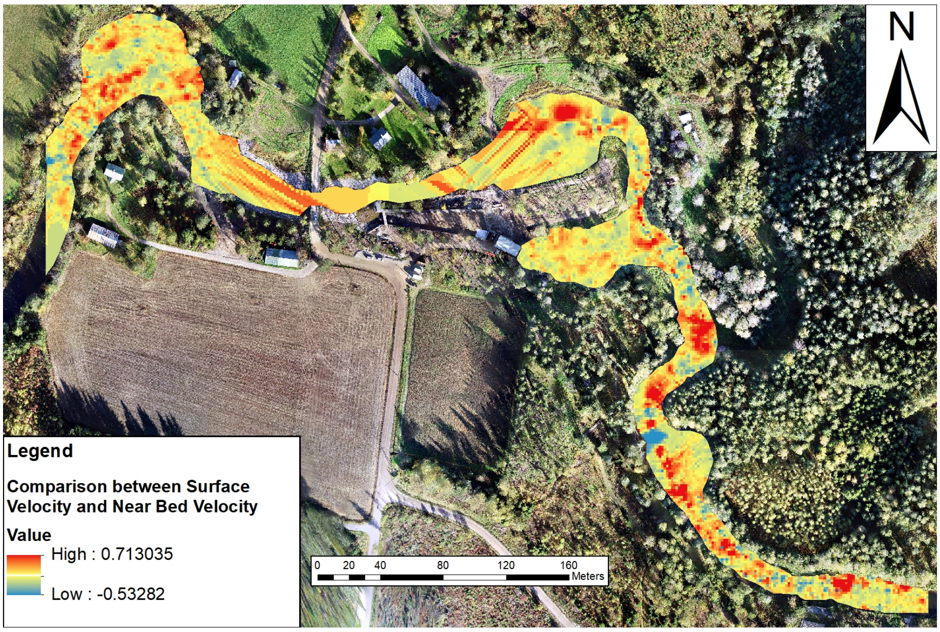


Figure 5.42: Difference between Surface Velocity and Near Bed Velocity (Autumn)

Looking at the legend, it is possible to state that the red-ish point indicate areas where the surface velocity is very high compared to the near bed velocity, while blu-ish points indicate areas where the near bed velocity is higher than the surface velocity. Yellow-ish points indicate areas where the difference between surface velocity and near bed velocity is null. In figure 5.42, it is possible to notice that the interpolation, in correspondence of the bridge, has some strange segments artifact: this is due to the fact that in that portion of the river, no data were collected because of the presence of stones in the watercourse (as visible in figure 5.34).

The cases in which the velocity in the lower layers of water is greater than the surface velocity, can be explained by the possible presence of anomalies.
For this reason, the directions of the water flows measured in contact with the river bed and on the surface were analyzed in two areas to reveal the possible causes of these irregularities.

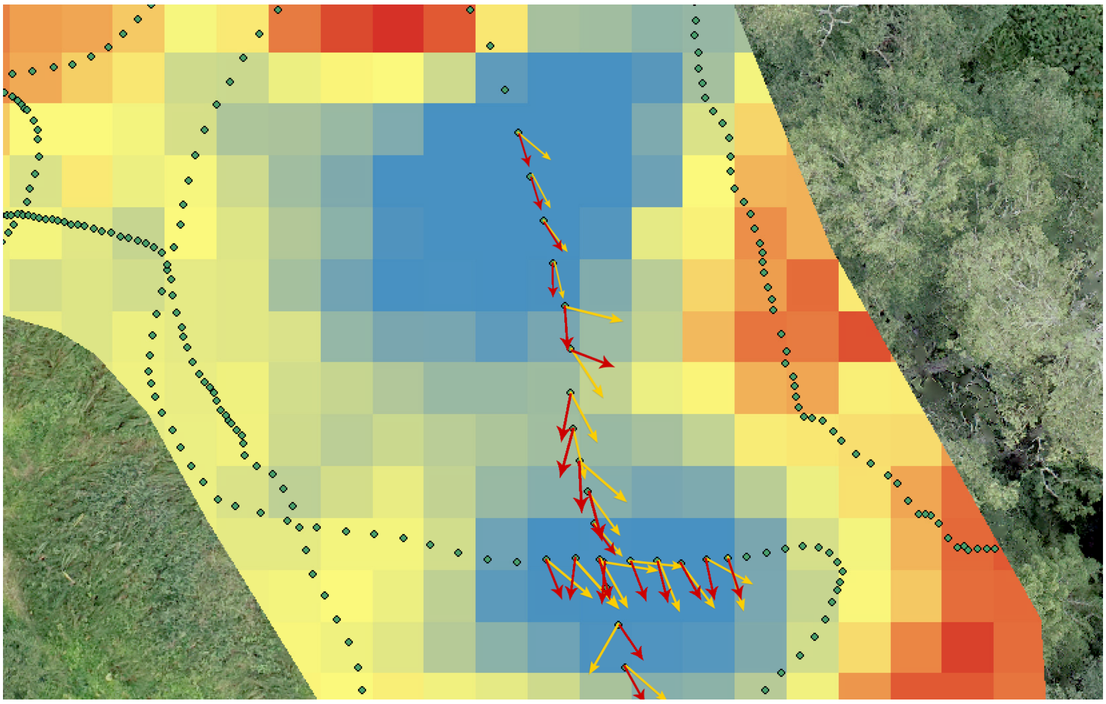


Figure 5.43: Direction of the Flow before the dam removal: with the red arrows is indicated the direction of the Near Bed Velocity, while with the yellow arrows is indicated the direction of the Surface Velocity

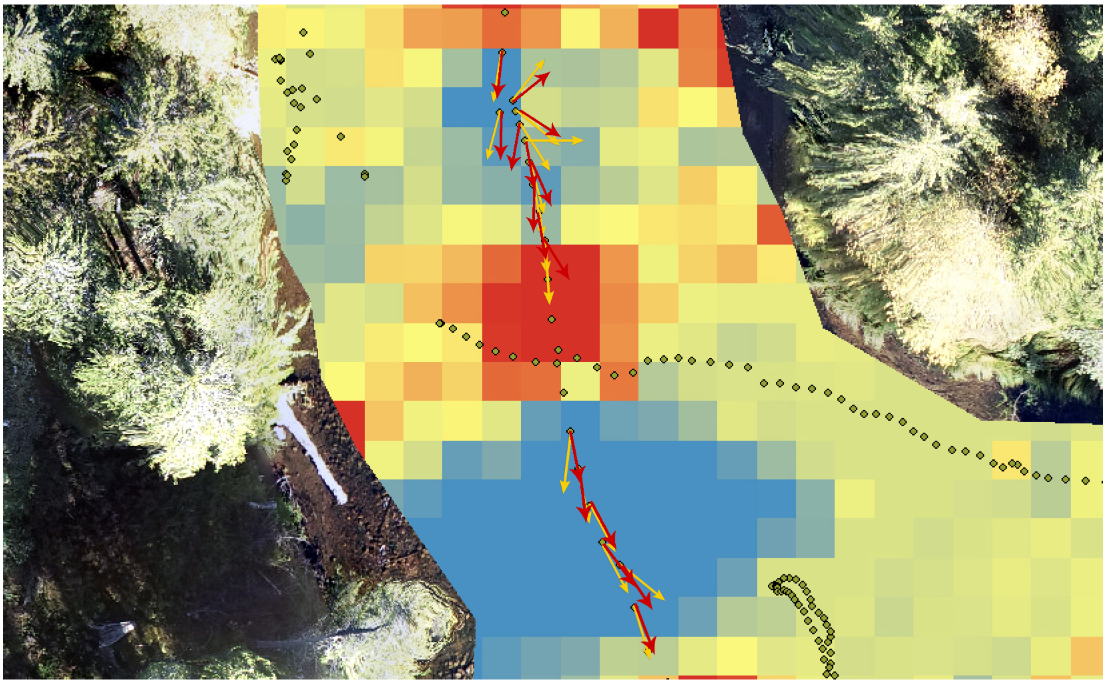


Figure 5.44: Direction of the Flow after the dam removal: with the red arrows is indicated the direction of the Near Bed Velocity, while with the yellow arrows is indicated the direction of the Surface Velocity

It is possible to notice from figure 5.43 that, in certain measurement points, there is a discrepancy between the direction of the surface velocity and the near bed velocity: this phenomenon could explain the reason why in this river segment the near bed velocity is higher than the surface velocity. In figure 5.44 it is possible to see that in some measurement points, in the upper part of the map, the direction of the flow is going in the opposite direction as it should go.

Both situations can be caused by anomalies such as vortexes, that are very common in meandering rivers. The vortexes can have a horizontal axes or a vertical axes: the horizontal ones are generated by the flow of water that comes back after beating against the river banks; on the other hand, the vertical ones are caused by the angular forces that are created by the curvature of the river. Therefore, the anomaly visible before the dam removal, can be a vortex with a horizontal axis, while the

one after the dam removal can be a vortex with a vertical axis.
Vortexes can interfere with sediments, that are brought into suspension. This dynamics can bring to a change in the river morphology. This is just an hypothesis that can be confirmed only by doing an in-depth analysis about vortex in this river segment.

5.3.2 Difference between the velocities Before and After the Dam Removal

The following maps were made to show how the river speed in the different layers (Surface, Near Bed and Mean Speed) evolved from a condition of "stability" before the dam removal to a "new unstable condition" that was created after the dam removal.

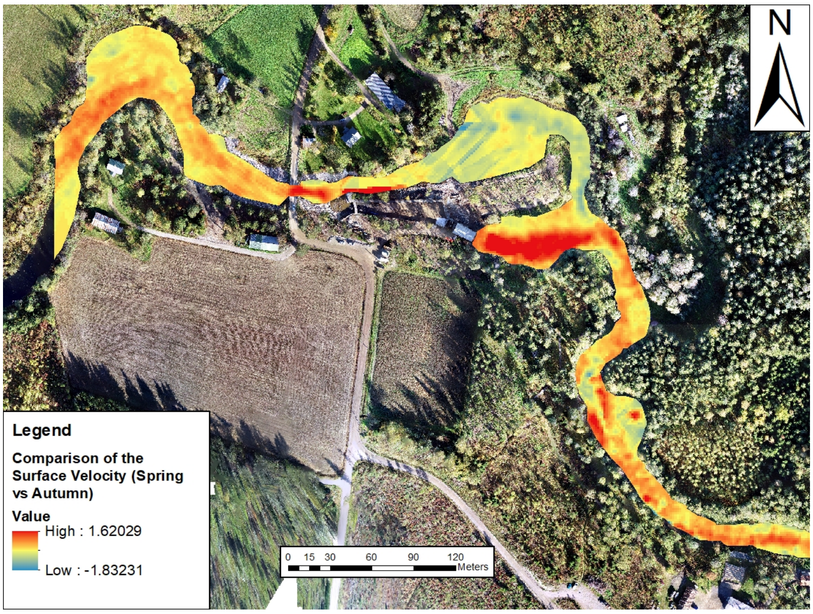


Figure 5.45: Comparison of Surface Velocity Before and After the Dam Removal

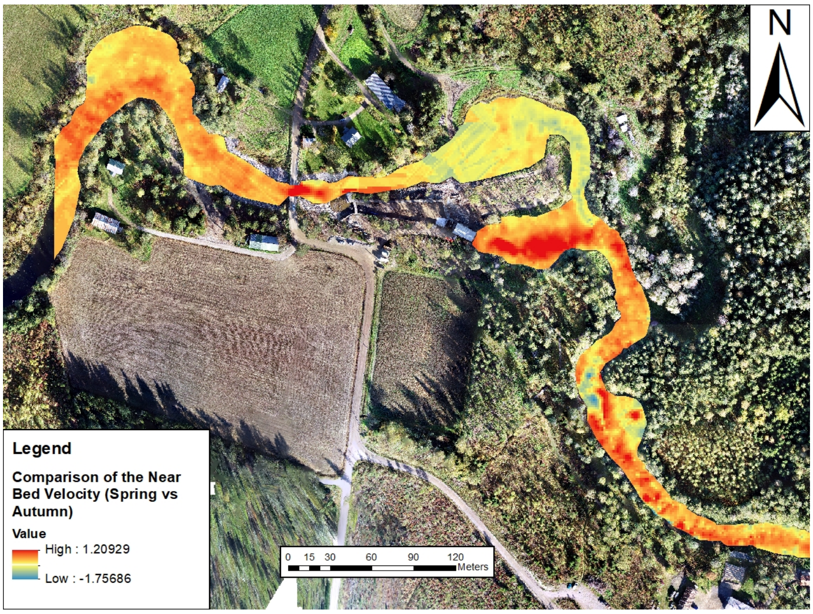


Figure 5.46: Comparison of Near Bed Velocity Before and After the Dam Removal

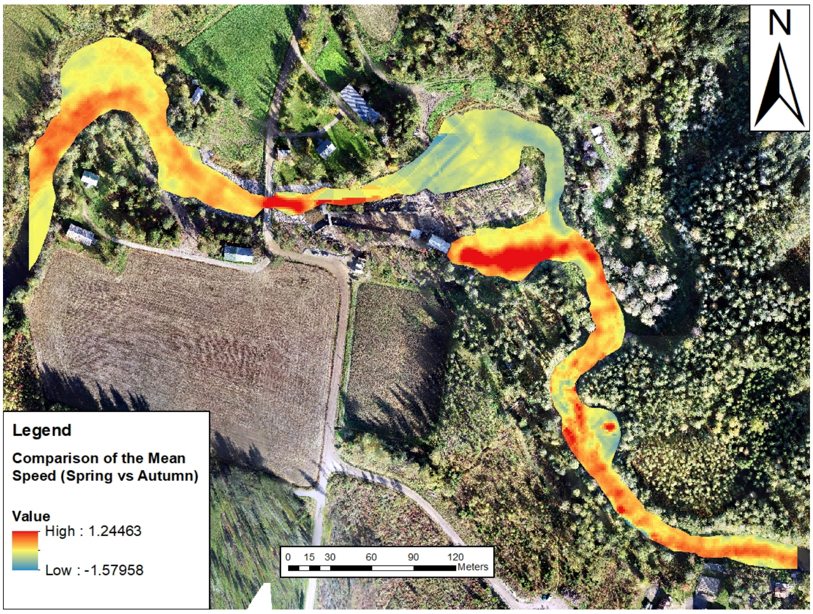


Figure 5.47: Comparison of Mean Speed Before and After the Dam Removal

In this case, red-ish points indicate areas where the velocity decreased with the dam removal, blu-ish points instead indicate areas where the velocity increased after the dam removal and, lastly, yellow-ish points indicate area where the velocity did not change with the dam removal.

There is an evident pattern in all three cases: the velocity in every layer is decreased in correspondence of the bridge and in correspondence of the area where the turbines were positioned. On the other hand, it is possible to notice how the velocity, after the dam removal, increased in the segment of the river that was used as a bypass channel while the power plant was still working: considering that in this river section the water was almost stagnant before the dam removal, while after the dam removal the river channel is working again, the reason why the water velocity increased is obvious

5.3.3 Focus on the Differences in the Hotspot Analysis before and after the dam removal

In the following figures are reported the areas where the most visible changes in the distribution of velocity clusters are spotted.

Figure 5.48: Comparison between Hotspot Analysis in Correspondence of the Bypass Channel and the Power Plant

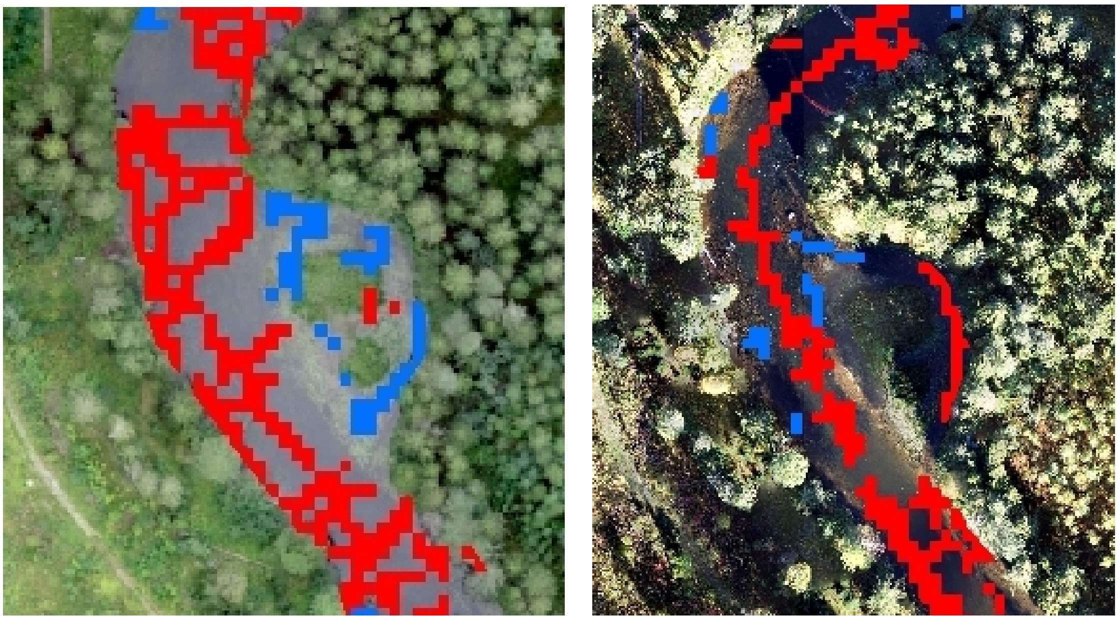


Figure 5.49: Comparison between Hotspot Analysis in Correspondence of the Obstacle

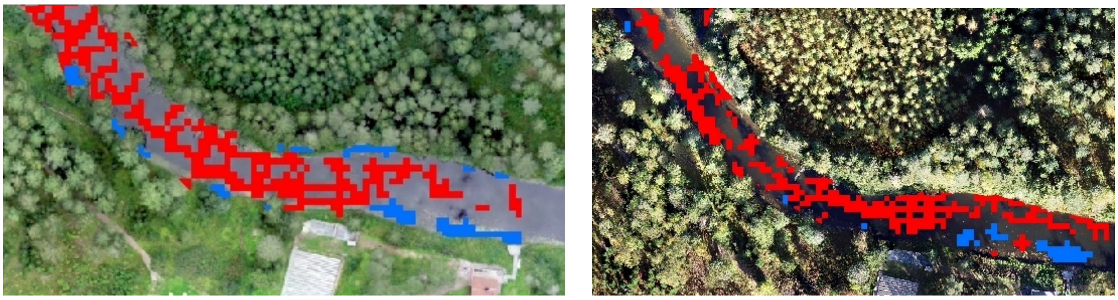


Figure 5.50: Comparison between Hotspot Analysis in Correspondence of the Bed & Breakfast

In figure 5.48, there as been an evident change in the velocity distribution: for example, the segment of the river that was used as a bypass channel, was mostly characterized by cold-points since the water in this part was stagnant; after the dam removal the water started to flow again causing a shift from cold-spots to hot-spots. Another minor change is shown in figure 5.49 and in figure 5.50, where the distribution pattern of cold and hot spots changed after the dam removal.

5.3.4 River Depth

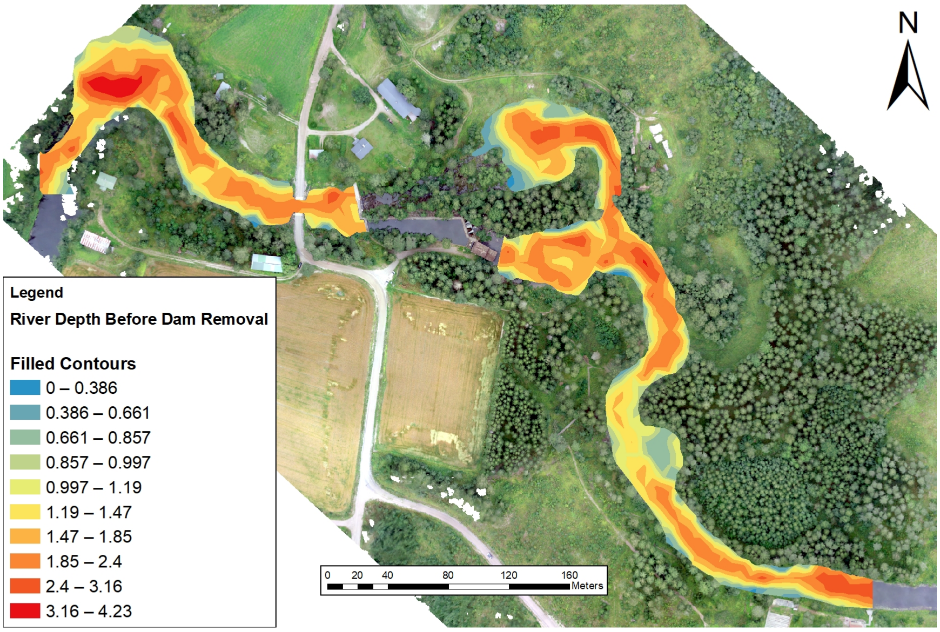


Figure 5.51: River Depth Before Dam Removal [m] (Spring)

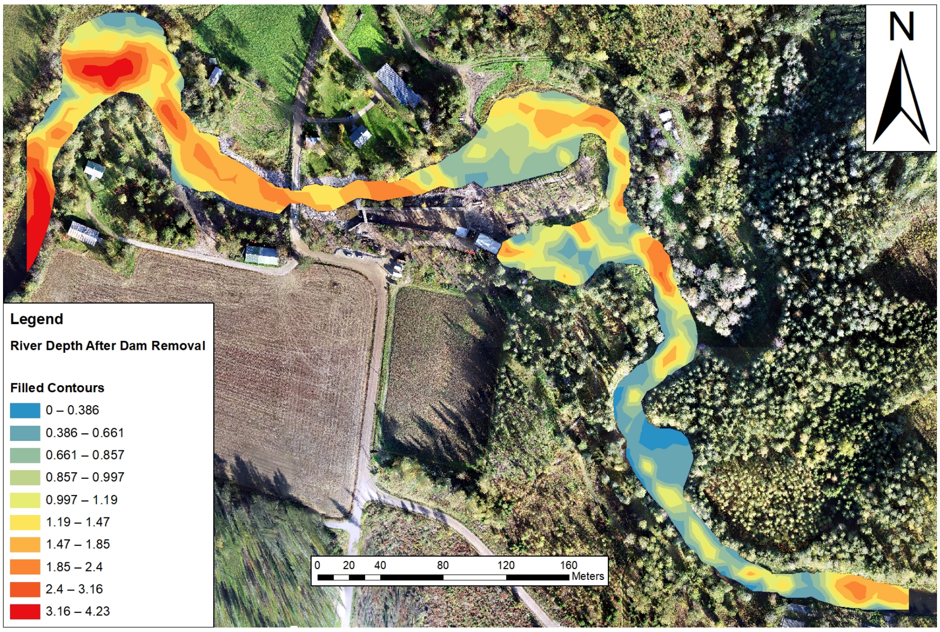


Figure 5.52: River Depth After Dam Removal [m] (Autumn)

The ADCP is able to measure also the water depth. Even though the accuracy of the measurement is not that high, the data are precise enough to have a general understanding on how the water level changed after the dam removal. The problem of the ADCP depth measurement is that the instrument finds problematic to distinguish the riverbed sediments and the suspended sediments that are very close to the stream bed: that is why the measurements are not very precise. In figure 5.51 and 5.52 it is possible to appreciate the huge difference in the water depth downstream of the dam: after the dam removal there has been an evident decrease of the water depth, that might have been caused by the fact that also the water velocity decreased a lot from spring to autumn. A decreasing in water depth is surely caused by an increasing in the sediment deposition. Another thing need to be also considered: the dam is a big sediment trap because it stores all the sediment coming from upstream.
The differences between the two situations is even more evident in figure 5.53:

Figure 5.53: Comparison of River Depth Before and After the Dam Removal

The red-ish the values indicate the points where the river depth was higher before the dam removal than after it, yellow-ish values means that the difference between the river depth before and after the removal is almost null, while blue-ish values indicate that the river depth is higher after the dam removal then before it.

Chapter 6

Discussion

In general, a dam removal is a great possibility to evaluate how the river reacts to big changes, both in the short and in the long term.

In this thesis, the short-term changes of the river have been studied: in particular, the analysis is focused on the changes in water speed, the spatial variation of the streambed erosion and changes in river depth.

As previously mentioned, this study can be used as an example for the dams that will be removed in 2022 and 2023 on the same river. The dams, in fact, have not been removed all together to allow the river and the ecosystem to stabilize little by little. The Kangaskoski dam was the first to be removed on the Finnish side of the Hiitolanjoki River, allowing the salmon to gradually ascend the river and re-colonize it.

Thus, the analysis that has been done for this thesis can be applied to the removal of the Ritakoski and Lahnasenkoski dams as they are on the same river and therefore the conditions might be the same.

6.1 Short-term Hydrodynamic Consequences of the Kangaskoski Dam Removal

The speed variation is the first thing that has been analysed. The results show that there has been a general decrease in both the downstream and upstream velocity: as it is possible to see in figure 5.47, where the mean speeds are compared, there are some spots where the difference is pretty evident, such as in correspondence of the bridge, where the water velocity has drastically decreased after the dam removal. It might have been caused by the fact that big boulders have been placed in the former bypass channel to decrease the power of water after the dam removal. By placing these big rocks, the channel roughness was increased and consequently, because of the increased friction, the water velocity decreased.
Before the dam removal, the water flow right after to the hydropower plant was very fast because of the artificial jump created so that the turbines could use the kinetic energy of the water to produce electricity. After the dam removal, it is possible to see that the water flow has been not only diverted and returned to the original river bed, but also that the stretch of river close to the turbines now has a very low water flow, almost stagnant because the water plant has been shut down.

The main consequence that a decrease in water velocity is causing is related to the sediment transportation: after the removal of the dam, a large amounts of sediment, that had been previously trapped by the dam, are released. If the water speed decreases, the sediment transportation decreases consequently.
When discussing about sediment transportation, it is also important to look at the near bed velocity (figure 5.46): as the mean speed, the near bed velocity has in general decreased, even if there are some spots in which it is increased. Anyway, the decrease in the near bed velocity causes the sediments that are carried by the water to settle more easily. This effect is visible if figure 5.52 and figure 5.53

are compared: the depth of the river has decreased a lot after the dam removal, probably due to the release of the sediments that were trapped in the basin created by the dam. In fact, the upstream stretch of the river has a lower variation in depth than that of the downstream portion of the river.
As a support to these statements, the Hjulström diagram can help: the areas where the near bed velocity is at its lowest do not exceed 0.1 m/s (10 cm/s), which translates into a preponderance in the transport of fine grain sediments (silt and clay) and in the deposition of coarse grain sediments (sand and gravel).
According to the Ministry of Agriculture and Forestry of Finland, "coarse mineral soils and organic soil types are common in Finland" [56]: this means that the Hiitolanjoki riverbed is very likely to be composed by coarse grain soil, and so the deposition of the sediments is plausible to happen.
On the other hand, where the near bed velocity is at its highest, it does not exceed 1.4 m/s (140 cm/s), meaning that the sediment erosion is preponderant for every type of soil: there are few spots where this velocity is that high and there the river depth is expected to increase in the long-run.

The sediment movement is a threat to the geomorphic stability of the river: this is a problem, because it is difficult to characterize the water flow in order to make predictions on how the river will develop in the long run [57]. Thus, it is necessary to go on with this study and monitor the river in order to follow its evolution and start making some predictions on how the river will look like when it will reach a stable state. Moreover, sedimentation might affect the fish nesting: as the gravel is blocked by fine sediments, as a result of erosion, this could cause the smothering of the salmon eggs, but it is also a problem when the eggs hatch and the fish remain trapped.
In addition, a large amount of sediments can affect the water quality: if a lot of sediments are suspended, they can increase water turbidity that blocks sunlight,

affecting the photosynthesis [58].
Monitoring is a fundamental part, because it means that some events can be predicted and managed before they turn into too large and unmanageable events. In this case it is even more important because the river, considering that it is continuously evolving, does not allow to make precise forecasts, in particular regarding floods risk. Furthermore, with the advent of climate change, extreme events are becoming more and more frequent and this could constitute an aggravating factor. It would be then necessary to further amplify the results of this work with numerical modelling approaches.
Without any doubt, the removal of a dam and the restoration of a river, ecologically speaking, has many positive sides: after the removal of these barriers, the river is no long divided into segments but returns to be a whole, improving the connectivity between the different parts. By improving the connectivity, animal and plant species are able to move and colonize the entire river from upstream to downstream, in a more or less uniform way; this means that there is a growth in the biodiversity of the ecosystem.
However, the removal of a dam changes the environments that formed upstream and downstream after its construction and which are very different from each other [59]: before the dam removal, the mean speed of the upstream water, apart from the specific case of the bridge, is lower than the downstream mean speed, because this is accelerated by the presence of the turbines of the hydroelectric plant. Because of this reason, different ecological conditions might develop. There are studies where the conditions of the ecosystems that may develop following a dam removal are studied; anyway, since data about the ecosystems are not given for this type of studies and considering that every system has different dynamics, it is difficult to make absolute predictions on the possible consequences.
In general, vegetation tends to develop where there are the best conditions to do

so. In this specific case, as it is possible to observe from the aerial photos used for the entire analysis, the area is surrounded by vegetation: in particular, the vegetation of the river is composed by marine flora (which in most cases consists of rushes) and also by a plants and flowers that develop on the riverbanks, such as globeflowers, hepatica and golden saxifrage [60]. For what concerns the fauna, Hiitolanjoki river hosts different species, but the most abundant are salmon, spined loach, bull head and asp [60].
The adaptive capacity is the ability of animal and plant species to adapt to changes within their habitat (regime shift). These changes can be natural or man-made. When talking about the adaptive capacity of species, it is easy to think about climate change and how species, despite living in very different conditions compared to 50 years ago, have managed to adapt to the new surrounding without changing their behavior. Of course, it is very important to take into consideration the fact that the adaptability of the species is not valid in all conditions: the species can in fact adapt to conditions that do not go outside certain ranges of tolerance. In optimal conditions (optimum tolerance range), the biological activity reaches its highest and therefore a condition where the population is increasing; however, when these conditions deviate from the optimum range, there is a variation in response: the conditions are no longer sufficient for the development of a population, but remains only sufficient for the single individual to survive: this means that the life of the population persists, but the specie does not grow. If the conditions diverge even further, the specie end up in a range in which the conditions are not sufficient even for the survival of a single individual, and so it faces a decay.
The problem with the removal of the dam at Kangaskoski is that the changes are sudden and it is difficult for species to adapt so quickly.
In the following figure (figure 6.1), there is a clear representation of the short-term and long-term ecosystem responses to the dam removal:

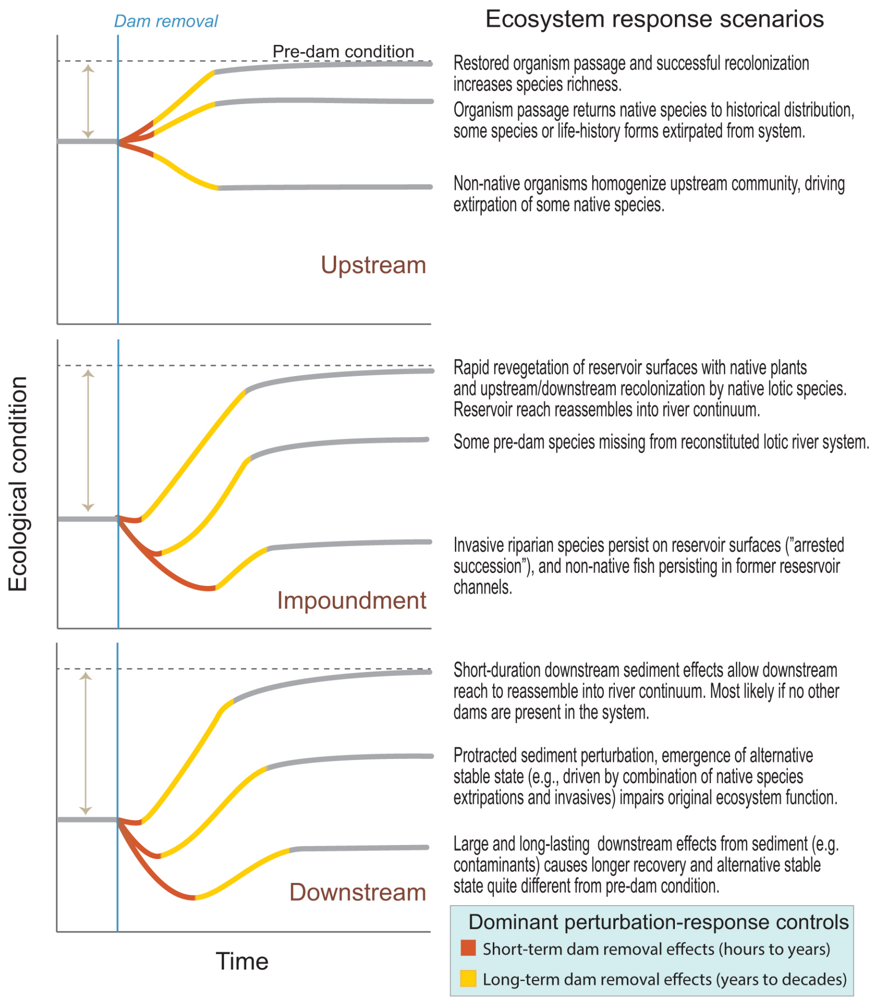


Figure 6.1: Ecosystem Response to Dam Removal, source: BioScience [59]

From these graphs it is possible to see that before the dam removal, the ecological condition are different and "worse" than the pre-dam conditions that are seen as the optimal conditions. The ecological conditions are also different in the different sections of the river: it can be seen that the upstream conditions are better than those of the basin and those downstream of the dam. Anyway, right after the dam removal (short-term), the ecological conditions in correspondence of the impoundment and downstream tend to decrease in every scenario, while upstream it increases in two out of three scenarios.

After the first years (long-term), the ecological conditions in the best scenarios upstream, downstream and in correspondence of the impoundment tend to increase and reach the pre-dam condition.
In the middle scenario, the ecological condition is increasing everywhere and is improving compared to the one that was characterizing the environment with the dam, but it will never reach the pre-dam conditions.
The worst scenario shows a situation in which the ecological conditions are not improving, indeed on the long-term they are even worse than the ones characterizing the environment with the dam.

Thus, this analysis is necessary to evaluate which dam removal scenario is more likely to develop in the Kangaskosi river stretch in order to act to restore the ecological condition to be very similar to that before the construction of the dam. Moreover, since a lot of impurities and pollution that might have been accumulated behind the dam are now free in the river, biofilters are necessary to capture and store carbon dioxide but also to sustain new and old habitats

6.2 Short-term Spatial Variation in Streambed Erosion Potential

River bed erosion is a phenomenon that occurs in a river due to disturbances which in most cases are of human origin. River erosion can for example be caused by an increase in the water velocity due to canal constrictions (e.g., bridges), increased discharge caused by an increase in urban runoff (or to an increase in precipitation), decrease in the sediments distribution due to an artificial obstacle that completely blocks their transport leading to the so-called clear-water condition.
In this case, the construction of the dam at Kangaskoski brought many sediments, in particular the most coarse ones, to be trapped by the dam, causing the clear-water

condition to form downstream of it. As already said in the theoretical background section, this condition is dangerous for the downstream stretch of river, because since sediments are not being transported from upstream, the river starts "eating" away its bed and the banks.

When the dam is removed, all the sediments that were trapped are released, causing the morphology of the river to change because of their deposition. If the morphology of the river changes, its hydrodynamic changes bringing to a spatial change in the riverbed erosion.

The spatial variation of the erosion is visible from the variations in the hotspot analysis. The hotspot analysis is useful because it is possible to see where the velocities clusters are situated. In the upstream part of the river stretch, since the channel is more stabilized, there are not many clusters other than a group of hotspots in the center of the channel at the first bend, and at the bridge, where there is a constriction of the channel which causes the increase in the water speed. On the other hand, downstream the dam, there is a clear high flow clusters in the middle of the channel, where the water velocity is higher, but also in correspondence of the external part of the bends.

Before the dam was removed, at the stretch of the river which was used as a bypass channel, only coldspots were present; when the dam has been removed, however, the speed in this stretch of river increased a lot and therefore it is possible to see an evident cluster of hotspots in the center of the canal (figure 5.48). Furthermore, prior to the dam removal, there was an accumulation of hotspots immediately after the dam, in the stretch of canal where water was returned to the river after passing through the turbines; after the dam has been removed, this stretch of river is almost stagnant, which is why there are only a few coldspots due to very low speed.

Another difference that can be seen between spring and autumn 2021 is that in

correspondence of the obstacle that deviates a part of the river for a short distance (figure 5.49), before the removal of the dam, there were no hotspots but only cold-spots, while after the removal of the dam in this section there is a cluster of hotspots, due to the fact that here the speed is increased.
The last spot in which it is necessary to analyze the differences in the hotspots is the one in correspondence with the Bed & Breakfast: as is is possible to see in figure 5.50, there are some differences on the right bank of the river, in particular concerning the fact that after the dam removal, the coldspots disappeared.
This variation in the position of the velocity clusters will result in a variation of points affected by river erosion: according to this analysis, since the clusters are positioned in the same way both in the surface velocity dataset and in the near bed velocity dataset, there will be a long-term lateral shift of the mentioned river bed segments. Riverbanks erosion can have a long term impact on human life because, if not controlled, it can cause an increasing in flood risk. This could be a serious problem considering that in this area there are different infrastructures such as a bridge, a bed and breakfast, hiking routes and in the future there will be museums to remember the power plants.

Figure 6.2: Satellite Image of the Kangaskoski Area, Source:Google Earth. In the picture, the infrastructures are circled, while the location of the potential erosion that may impact on the river banks is indicated with red arrows

In figure 6.2, two areas are circled: in one case there are houses, while in the other case it is a bed and breakfast. In the first case, considering that the result of the hotspot analysis predicts that the potential riverbed erosion is very accentuated on the left bank of the river, it could be a problem in the long run for the infrastructures as they are very close to the water. Concerning the Bed & Breakfast, it seems that the erosion is moving from the right bank to the left bank of the river, thus ensuring that the structures are not affected by any problem.

Infrastructures are not the only things that are threatened by the erosion: erosion can cause the topsoil to no longer be able to hold nutrients that are needed by the ecosystem of the river.

In order to protect the infrastructures ad the ecosystem from the riverbed erosion, there are some techniques to control its evolution such as soil erosion blankets: they are special biodegradable blankets that have to be placed on the riverbanks in order to support and stabilize them [61]. Moreover, since erosion modify the morphology of the river, it is necessary to update the flood risk maps to prevent catastrophes.

6.3 Climate Change Impact

There is no doubt that Climate Change is now underway and that action must be taken as soon as possible.
One of the consequences of Climate Change is the increase in climatic extremes, i.e. intense rainfall, long periods of drought, all those events that are unusual and unexpected as they happen infrequently, making the adaptation process way more difficult.
Focusing on Finland, according to the newest Finnish Climate Change Panel, heavy precipitations are projected to increase in the next 30 years [62]. The direct consequence of an increase in precipitation intensity is the increase in flood frequency and intensity. In July and August 2004, a sudden extreme precipitation caused a flood that brought not only to the death of fish populations and nutrients loss, but also to the threat of buildings and people, that were completely surrounded by water; this event might not be a consequence of climate change but it gives an idea on how things can evolve if this situation is not taken under control.
Although many dams have been built with the intention to try to mitigate the negative effects of floods, it is emerging from some new studies that in some cases, their presence could instead be negative [63]. The study conducted by the scientist Hongbo Ma has revealed that the fact that the sediments, upstream of the dam, are blocked by the barrier, means that the basin, as the time goes by, can no longer

contain all the water for which it was built, increasing the risk of floods. Moreover, dams are likely to aggravate the impacts of climate change, because they are an obstacle to sediments and to the nutrients, and they cause the increase of the water temperature.
The removal of small dams is therefore used as a tool to reduce the negative influence of humans on natural ecosystems, allowing them to readjust to the original conditions and increase their resilience. For this reason, many associations, including Dam Removal Europe, are actively engaging in trying to remove as many obsolete and unused dams as possible, to mitigate their impact on climate change. Finland is working really hard to reduce its impact on the climate: in their new national plan, the removal of all the unnecessary dams is a priority, starting from the three dams of the Hiitolanjoki river. The complete restoration of this river will give the possibility to the Ladoga Salmon to migrate again to their original spawning place.

Chapter 7

Conclusions

The restoration of rivers and the dam removal is becoming more and more important as the years go by. This is due both to the fact that the dams that were built years ago have become obsolete and are no longer necessary to perform the task for which they were constructed and also to the fact that the dams constitute an obstacle to the ecosystem of the river that is found stuck. Moreover, with the climate emergency, the role of ecosystems is fundamental in the regulation process: for this reason it is necessary to safeguard biodiversity, to mitigate and to slow down climate change.

The study of the flow velocity data it is very important in order to design a research plan aimed at decreasing the impact of river restoration on society because the removal of a dam, as well as its construction, leads to a change in the dynamics of the river.

Hiitolanjoki is the first Finnish large river to be completely freed from hydropower dams: this is why the restoration of this river is the first of its kind in Finland and it can become an example on how to deal with these changes in both an economic, administrative, and environmental point of view. The aim of this thesis was to analyse the flow velocity data in correspondence of the Kangaskoski rapid.

As a result, from a hydrodynamic point of view, the average speed of the river after the removal of the dam has decreased, both upstream and downstream of the basin. The decrease in the speed of the river can represent a problem in the transport of sediments, which, until the dismantling intervention, were trapped by the dam itself. An increase in the quantity of sediments in the river could be a problem for the re-naturalization of the river itself, but above all for the recolonization of the Ladoga Salmon. In addiction, considering that the most common type of soil in Finland is coarse and that the near bed velocity in some areas does not exceed 0.1 m/s, the sediments are led to deposition.
The depth of the river is also affected a lot by the removal of the dam: analysing the data, it is possible to see how the depth has decreased a lot, probably caused by the massive release of sediments that were trapped behind the dam.

Another outcome of this thesis concerns the erosive potential of the river. The analysis that was carried out is a hotspot analysis, that made the comparison of the water speed before and after the removal of the dam possible, using a statistical approach. Through this analysis it is in fact possible to highlight the areas in which high and/or low speed values accumulate, causing a potential erosion of the river bed or banks. The results show that there has been a shift in the areas that are potentially affected by erosion, in particular we are talking about the canal segment that in the past was used as a bypass channel and that with its removal was brought back to principal channel; this means that the situation changed from one in which there were only cold spots caused by the stationary water, to a one in which the water is in motion and is also particularly fast. In addition, a shift in the areas affected by erosion was detected in the proximity of the bed and breakfast, were the hot-spots moved toward the left bank of the river. Both of these areas are very close to human infrastructures, and this is why it is necessary to get to the root of the matter and continuously monitor these zones, in order to safeguard

the structures. Moreover, erosion can increase the flood risk that can have a high impact on human's lives because this area is characterized by hiking routes, a bridge and some other infrastructures.
The results of the analyses that have been performed on the flow velocity data that have been sampled in the Kangaskoski area, could be taken as an example for the evaluation of the short-term variations that will occur following the removal of the Ritakoski and Lahnasenkoski dams (both belonging to the Hiitolanjoki River) which will take place in 2022 and 2023 respectively.
Further analysis will be useful in the planning of adaptation measures, necessary to counteract the variation of the shape of the river that will necessarily occur as a consequence to the change in the hydrodynamic conditions of the river.

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