Master's thesis

NTNU
Norwegian University of Science and Technology
Faculty of Engineering
Department of Civil and Environmental Engineering

Mahlet Kinfe Gebreegziabher

Modelling weir adjustments in the Lærdal river

Master's thesis in Hydropower Development
Supervisor: Professor Knut Alfredsen
Co-supervisor: Dr. Behnam Balouchi
December 2023

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M.Sc. THESIS IN

HYDROPOWER DEVELOPMENT

Candidate: **Mahlet Kinfe Gebreegziabher**

Title: **Modelling weir adjustments in the Lærdal river.**

1 BACKGROUND

Weirs were a common mitigation measure in regulated rivers in the past to alleviate the effect of reduced water flow after regulation. Different purposes led to weir construction, among them to improve the habitat for fish, to keep up water level and for aesthetic purposes. The knowledge of the effect of weirs has increased over the years and today the tradition weirs with their weir basins are not considered a useful environmental measure, and in several cases, weirs have been removed or replaced with other structures with better environmental performance. The Lærdal river in western Norway was first developed for hydropower in 1974, and following the regulation numerous weirs were built, mainly to keep up water levels, to prevent ice erosion on the river bottom and to improve sport fishing for Atlantic salmon. Today there is ongoing work to see if the weirs can be removed or modified to improve the habitat for Atlantic salmon.

The objective of this thesis is to investigate methods of weir modifications and to use numerical modelling to evaluate the proposed modifications. Selected key weirs will be chosen and alternative modifications will be applied and modelled to present information on how the modification influences the flow pattern and key hydraulic variables. Further, an evaluation of the erosion potential and how to protect the new structure from damages will be evaluated.

2 MAIN QUESTIONS FOR THE THESIS

The thesis shall cover, though not necessarily be limited to the main tasks listed below.

The following main steps will be carried out during the thesis work:

1. A brief literature overview of the current status of weir adjustment and removal from national and international sources. This section should also include a short overview of what has been done regarding weir adjustment work in Lærdal based on the work done by Alfredsen and Awadallah (2022).

2. Prepare geometry and set up HEC-RAS 2D for some selected weirs in Lærdal. Perform simulations of the weirs for known discharges and calibrate the model against observed water levels.

3. Decide on a method to modify the existing weirs to improve the conditions for Atlantic salmon and sea trout in the area around the weir. This could be by creating openings in the existing weir, replacing the existing weir with distributed rocks or any other good idea that may come up in the project. Based on the method selected, recreate the geometry from 2) with the new weir solution in place.

4. Run simulations with the new weir from 3) for different discharges. Present the results of the new weir in the form of maps and graphs showing the distribution of key variables like depth, velocity, and shear stress.

5. Do simulations for high flows and estimate the potential for erosion around the new weir and use this to look into if we need erosion protection and the necessary stone size for the improved weir.

3 SUPERVISION, DATA, AND INFORMATION INPUT

Professor Knut Alfredsen will be the main supervisor of the thesis work, co-supervisor will be Dr. Behnam Balouchi. Discussion with and input from colleagues and other research or engineering staff at NTNU, SINTEF, power companies or consultants are recommended. Significant inputs from others shall, however, be referenced in a convenient manner.

The research and engineering work carried out by the candidate in connection with this thesis shall remain within an educational context. The candidate and the supervisors are therefore free to introduce assumptions and limitations, which may be considered unrealistic or inappropriate in contract research or a professional engineering context.

4 REPORT FORMAT AND REFERENCE STATEMENT

The thesis report shall be in the format A4. It shall be typed by a word processor and figures, tables, photos etc. shall be of good report quality. The report shall include a summary, a table of content, a list of literature formatted according to a common standard and other relevant references. A signed statement where the candidate states that the presented work is his own and that significant outside input is identified should be included.

The report shall have a professional structure, assuming professional senior engineers (not in teaching or research) and decision makers as the main target group.

All data and model setups should be compiled, documented, and submitted with the thesis.

The thesis shall be submitted no later than 12th of June 2023.

Trondheim 11th of January 2023

____

Knut Alfredsen

Professor

Statement Of Authorship

I, Mahlet Kinfe Gebreegziabher, declare that I am the exclusive author of the thesis entitled "Modeling Weir Adjustments in the Lærdal River."

This thesis was submitted to the Norwegian University of Science and Technology (NTNU) on the 20th of December 2023, as part of the fulfillment requirements for the M.Sc. degree in Hydropower Development.

I have appropriately acknowledged the contributions of any other sources, adhering to standard referencing practices.

Abstract

In the context of regulated river management, weirs have historically been employed to counteract the consequences of reduced water flow resulting from river regulation interventions. The Laerdal River in western Norway, initially developed for hydropower in 1974, saw the construction of multiple weirs to fulfill diverse objectives, encompassing the maintenance of water levels, prevention of ice erosion, and the creation of a conducive habitat for Atlantic salmon. However, contemporary environmental awareness has sparked ongoing efforts to reassess the viability of these weirs, exploring potential removal or modification to further enhance the habitat for Atlantic salmon.

This thesis embarks on an exploration of weir modification methods, utilizing numerical modeling through Hec-Ras 2D to assess proposed alterations. Initial stages involve the preparation of 1.2 km geometry for selected four weirs in Lærdal, followed by the establishment of Hec-Ras 2D simulations calibrated against observed water levels. Subsequently, the focus shifts to the selection of a modification method aimed at improving conditions for Atlantic salmon and sea trout. This encompasses various strategies, including creating openings, replacing the weir with distributed rocks, and other innovative solutions.

Upon determining the modification method, the geometry is recalibrated with the new weir solution. Simulations encompassing different discharges yield results showcased through maps and graphs, revealing the impact of modifications on flow patterns and key hydraulic variables such as depth, velocity, and bed changes. Expanding the study to simulate high flows, the research estimates potential erosion and deposition around the modified weirs. The overarching goal of this thesis is to adapt the weir to enhance fish migration, whether focusing solely on improving fish migration or concurrently enhancing fish migration and mitigating sediment accumulation in the weir pool located upstream of the Øye.

The research findings inform an exploration into the significance of weir removal, particularly concerning the removal of fine sediments in the upstream portion of the pool at Øye. This investigation is integral for comprehending the potential impact of weir removal on sediment transport dynamics. Simultaneously, the study addresses the necessity for erosion protection measures and endeavors to determine the optimal stone size for securing the new structure. These considerations are crucial for crafting a recirculating, ecologically favorable habitat for

Atlantic salmon, striking the right balance between depths and velocities among the rocks. Ultimately, this research aims to contribute valuable insights to the ongoing dialogue surrounding sustainable weir modifications and the coexistence of hydropower development with ecological preservation.

Keywords

Lærdal river – Artificial Rocks – Boulder arrangement – Hec-Ras - Hydropower – Atlantic Salmon – Weir Removal – Arc-GIS Pro

Acknowledgements

I would like to express my sincere gratitude to my supervisor, Professor Knut Tore Alfredsen and co-supervisor Dr. Behnam Balouchi, for their invaluable technical support, engaging discussions, and constructive feedback throughout this research journey. Your guidance has been instrumental in shaping the trajectory of this master's thesis.

I am also grateful for the opportunity to visit Lærdal, which provided a firsthand understanding of the study area, insights into fieldwork methodologies, and a profound awareness of the local community's concerns related to the thesis topic.

Heartfelt thanks to my husband Germawi Teklit for his unwavering support, love, and belief in my abilities. Your encouragement has been my pillar of strength, and I am grateful for the journey we have undertaken together. Special thanks to my families in Ethiopia for their continuous support and encouragement, which has been a source of inspiration throughout.

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Nomenclature

ALB - Airborne Laser Bathymetry

CMS – Cubic meters per second

DEM - Digital Elevation Model

DSM - Digital Surface Model

DTM - Digital Terrain Model

DWE - Diffusion Wave Equations

GIS - Geographic Information System

GPS - Global Positioning System

GSD - Grain size distribution

EIA - Environmental Impact Assessment.

Hec-Ras - Hydrologic Engineering Center’s River Analysis System

LiDAR - Light Detection and Ranging/ 3D Laser Scanning

NTNU - Norwegian University of Science and Technology

NVE - Norges Vassdrags og Energidirektorat

NEVINA - Rainfall Field-Water Flow-Index-Analysis

SfM - Structure-from-Motion

SWE/ELM - Shallow Wave Equations Eulerian-Lagrangian Method

TIF - Tagged Image File

TIN - Triangular Irregular Network

USACE - United States Army Corps of Engineers

WSE - Water Surface Elevation

XS - Cross Section

1 Introduction

The Lærdal River, nestled in western Norway, underwent substantial regulation for hydropower development, the initial stage of development concluded in 1974, and the second phase was completed in 1988. Over the years, a network of weirs has been meticulously constructed along its course, serving various purposes. The primary rationale behind the construction of these weirs was to maintain water levels post-regulation. Beyond this fundamental function, the purposes for creation of these weirs were combating bottom erosion resulting from excessive ice formation and trying to improve sites for salmon fishing. River owners also played a role in their construction, with an overarching goal of enhancing salmon fishing.

The weirs exhibit diverse structures, including straight thresholds and counter-current designs featuring various openings (Syvde weirs), Comprising stone structures that impede the river's flow, these weirs have been integral to the landscape for numerous years. Field measurements indicate their enduring presence, even amid past flood events, leading to an uncertain amount of sediment transport to the river.

Recent considerations about the effect of weirs on various conditions in the river including habitat, sediment, and fishing, challenge the perceived utility of these weirs, particularly as envisioned in the late 1970s. Latest examinations involve recognizing the changes in this river, which is crucial for understanding the broader impacts on river health, sediment transport, and habitat dynamics. A shift in perspective prompted the exploration of weir removal as a potential solution, with practical implementations beginning three years ago. This endeavor aimed to assess the ramifications of weir removal on the river ecosystem.

In the wake of this groundwork, our focus turns to the present, where we engage in hydraulic modeling tasks. The objective is to modify individual weirs and discern the consequential changes, specifically in terms of depth, velocities behind the weirs, and sediment potential within the weir basins. By undertaking this comprehensive analysis, we seek to identify thresholds where modification may prove beneficial, thereby adding to our detailed understanding of the river's hydraulics and sediment, making it more suitable for the fish habitat within the weirs.

Based on Alfredsen and Awadallah's (2022) extensive work in Lærdal, a two-dimensional hydraulic model was initially configured for simulating the water-covered region in the Lærdal River. This aimed to replicate the impact of adjusting thresholds. A technique was devised to eliminate these thresholds, substituting them with a flat riverbed. Simulations were then conducted with a new geometry to observe the threshold effects. Additionally, for Øye, Grønnebank, and Molde thresholds, a more detailed model was created to explore alternative adjustment methods.

Their study revealed that removing thresholds resulted in decreased water depth and increased water velocity upstream of the threshold, particularly greatest changes during low water flows. These changes diminished as water flow increased. Surprisingly, no significant alterations were observed in the water-covered area after removing the thresholds, distinguishing it from past threshold adjustment projects. This difference was believed to be linked to the river's profile. Their simulations were extended to average and 20-year floods, using Shield's formula to estimate potential changes in mobilizing sediment. Results indicated minimal differences in erosion potential during floods between a river with thresholds and one without.

Alfredsen and Awadallah's (2022) weir adjustment project in Lærdal aimed to employ a hydraulic model. Their focus was on assessing the effects of removing or altering thresholds, specifically on water coverage, depth, and speed. The project aimed to generate valuable information for planning threshold adjustments and enhancements. Additionally, they sought to create a tool for evaluating the impact of various changes on hydraulic conditions in the river.

In this study, we explored different ways to change the existing weirs. We built upon the work done in Lærdal by Alfredsen and Awadallah (2022), taking it a step further. Our focus was on replacing the existing weir with distributed boulders, with the aim of creating an artificial habitat to enhance conditions for Atlantic salmon and sea trout in the weir area.

To achieve this, we first completely removed the weir, resulting in a leveled river bottom. We then applied an advanced weir removal method, which involved creating openings in the existing weir. This process was designed to not only modify the weir but also establish a habitat that is favorable for fish. The goal is to improve the environment for Atlantic salmon and sea trout in the surrounding area of the weir. This aligns with the overall goal of our project, which is to demonstrate the tested approaches and provide an understanding of what these scenarios might entail, taking into account an assessment of how thresholds impact the habitat for salmon.

1.1 Objectives

The primary aim of this study is to conduct a comprehensive comparison between the effects of a weir, a condition without a weir, and the incorporation of artificial habitat in the form of randomly placed rocks. This comparative analysis will focus on evaluating the performance of these configurations concerning fish habitat under low-flow, conditions. Subsequently, the study will extend its investigation to assess sediment dynamics when subjected to higher flow conditions. The objective is to gain insights into the hydraulic and ecological implications of different river configurations, considering both low and high flow scenarios, In the context of Lærdal river which undergoes regulation, considering sediment and environmental perspectives.

1.2 Outline

This study is designed as follows. It starts with an introduction, providing insights into the present scenario of weir adjustments and removals based on comprehensive weir removal work done by Alfredsen and Awadallah's (2022). The study's objectives are clearly articulated in this section. Progressing to the second section, a thorough literature review guides us through previous weir adjustment initiatives in Lærdal and other locations.

In the third section, the groundwork is laid by presenting the background and theory behind weir adjustments and removals. Transitioning to the fourth section, a detailed exploration of a method employed for adjusting existing weirs is undertaken. The primary objective is to enhance conditions for Atlantic salmon and sea trout around the weir. This section also provides valuable insights into data extraction techniques, with a focus on modeling modifications using different approaches.

Advancing to the fifth section, the paper discloses the results. Maps and graphs are presented, showcasing crucial variables such as depth, water speed, bed changes, and an estimation of potential erosion and deposition around the new weir is provided.

Section six, the discussion, mirrors a thoughtful conversation about the findings. It thoroughly assesses the model's performance, addresses uncertainties, and outlines future work plans. Notably, it includes a comparative analysis with outcomes from previous studies.

The conclusive section, section seven, summarizes the findings, providing readers with a clear and concise conclusion.

2. Literature Review

This section starts by sharing the latest information on weir adjustment and removal from national sources. It covers the work done in Lærdal, building upon Alfredsen and Awadallah's (2022) research, and explains the deposit patterns in Lærdal. Furthermore, this section includes a concise overview of weir removal projects sourced from international studies.

2.2 Erosion patterns in Lærdal

Aurland tunnel in Tynjadalen was washed out in the 2014 flood and transported into the river through Kyuvelda river. This study was done as part of one of the projects, Lærdal commune has a project from the Norwegian Water Resources Directorate to undertake fine sediments removal and do some weir adjustments.

The flood event, with flow rates ranging from $400m^3/s$ to $500m^3/s$, caused significant changes in the area. The weir's structure was affected, with rocks dislodging and falling during the flood, raising concerns about its stability. This prompts a closer look into how the flood affected the local fish and their homes. Understanding these changes is crucial, as they involve complex interactions between water forces and the environment during extreme floods in Lærdal.

Figure 2. 1 weir at øye

2.3 Prior Hydraulic Impact Assessment of Thresholds in Lærdalselva: Insights and Findings

The research that has been done by Alfredsen and Awadallah 2022 regarding the weir adjustment work in Lærdal river by means of hydraulic model had broadly investigated the effect of removing or changing the weirs and how this affects the area covered by the water, depth, and speed.

According to the paper there has been generated important information that can be useful when planning adjustments or improvements to weirs and create a tool that can be used to assess the effects of the various changes on hydraulic conditions in the river. The conclusion made on this weir adjustment and removal investigation was that when the weir is taken away it resulted in the changes of the hydraulic conditions in the river: Those were changes in the Water covered area, water Depth and Velocity. It has been shown that the water gets shallower and faster. Nevertheless, there had not much change in the water covered area. Despite the changes in the weir crest if we remove the weirs (Alfredsen and Awadallah, 2022).

Shields formula had been implemented using the velocity and shear stress to investigate the size of sediment size that could mobilize the river. This outcome has shown little difference before and after the weirs are taken away (Alfredsen and Awadallah, 2022).

2.4 Weir removal work done in relation to its influence on salmonoid habitat in a Norwegian river

In the late 1970s, the construction of weirs in Norwegian regulated river systems was a common practice driven by aesthetic considerations. However, contemporary river restoration efforts prioritize enhancing biological functionality and biodiversity. The study conducted by Fjeldstad et al., (2012) focuses on the removal of two weirs originally built to maintain a stable water level in a Norwegian regulated river. The removal aimed at restoring river connectivity and re-establishing the local population of Atlantic salmon. The removal process was informed by hydraulic modeling, and biological monitoring was conducted before and after weir removal to assess the biological response.

Results indicate that the removal of the weirs led to the recreation of salmon spawning sites in the old bed substratum. These sites were quickly occupied in the first season after removal when water velocities became more favorable to spawning. Consequently, the mortality of Atlantic salmon eggs decreased, and the densities of juvenile salmon exhibited a significant increase post-removal. Conversely, pike and cyprinids, present in the reach before weir removal, were absent in samples taken after removal, indicating a successful shift in the fish community in response to habitat alteration.

Additionally, the enumeration of migrating adult salmon at an upstream fishway revealed that, on average, the migration peak occurred 1 month earlier in the three years post-removal compared to the five years pre-removal. The study underscores the utility of hydraulic modeling for designing physical habitat adjustments and assessing their impact on fish biology. Furthermore, the model results supported an efficient and expedited process in the planning and execution of construction works related to weir removal (Fjeldstad et al., 2012).

2.5 Unveiling the Vital Connection: Weir Removal and Creating Favourable Conditions for Fish Habitat

The study by Stranzl et al. (2020) focused on modeling a weir removal scenario in Lærdalselva to demonstrate practical applications in concrete measures. The comparison of cross-section, Structure-from-Motion (SfM), and Airborne Laser Bathymetry (ALB) base data was undertaken, emphasizing ecological assessments and implications. Examining weir removal as a common measure in Norwegian streams, the authors utilized datasets to reveal that, particularly at higher discharges, changes in water depth and flow velocity were negligible, and substrate stability remained unchanged. Real weir removal experiences were consistent with these findings, highlighting the stability of sediments in basins above weirs. The study emphasized the benefits of weir removals under mean flow conditions, revealing increased flow velocities up- and downstream of the removed weir. This led to expanded spawning areas and heightened juvenile salmonid densities. The paper underscored the importance of considering low flow conditions and utilizing high quality bathymetric data for assessing stranding risks. The iterative adaptation of weir scenarios using ALB data was highlighted as a valuable planning tool for improving habitat conditions while minimizing stranding risks, particularly in the context of climate change.

In line with the findings of Einum and Nislow (2011) the environment where salmon live is determined by the material on the riverbed. The substrate on the riverbed has an impact on the types and abundance of invertebrates in the stream. It has also been proved that the substrate on the river stretch is largely dominated by stone (51% degree of coverage of the total area) and gravel (25%). There is a significant amount of sand between the gravel and stones in the riverbed (10%). Traces of silt were mainly observed in most study area segments. The substrate composition along the studied river stretch is indicative of mesohabitat and gradient conditions, with gravel and stones ranging from small to cabbage head-sized dominating the recorded landscape. Notably, threshold basins exhibit a substantial deposit of fines, which does not undergo the same level of washout observed in natural river stretches. Cover measurements conducted in 199 transects, totaling 597 cover measurements from Voll bridge to the brackish water zone, reveal that approximately 67% of the mapped river area provides limited shelter for young fish, while only 5% offers sufficient hiding spaces. Despite the dominance of stone (51%) and gravel (25%) as substrates, the concealment typically associated with such materials is compromised by the prevalence of sand and silt. The riverbed configuration also includes blocks (12%) along the riverbank and near sills, present in all river segments. Notably, in 9 segments, where aeration and bottom mass extraction measures were implemented, demonstrated reduced fine matter deposition, and improved concealment, likely attributed to a significant drop and higher water velocity in this stretch. Additional concealment was observed in 5 segments and parts of 2 different segments, likely linked to the presence of rapids and faster-flowing water facilitating the transport of fines. (Einum & Nislow 2011)

A watercourse's potential for salmon production is profoundly shaped by the physical habitat conditions and the effective utilization of the area's carrying capacity for juvenile fish production. Einum and Nislow (2011) highlight the distribution of habitat resources across various life stages within the watercourse. The growth of fish reaching the smolt stage depends on the quality of the rearing habitat. Spawning areas represent a limiting resource, serving as a bottleneck for fish production. This book also delves into the heightened significance of providing shelter for fish habitats in the river.

Access to shelter is considered a crucial limiting resource for salmon fry pairs, and the habitat bottleneck for the survival of young fish is contingent on stocking density. In instances where the number of fish exceeds a certain threshold, an ideal salmon river exhibits well-distributed spawning areas with good access to resources. This strategy minimizes the potential reduction in growth, survival, and resource access, ensuring that the stock size aligns with the carrying capacity. This phenomenon is described as the population passing through a density-dependent bottleneck.

Given the limited hiding areas for salmon fry near the spawning grounds, the ability (or motivation) to spread becomes pivotal. The amount and distribution of spawning habitat play a decisive role in determining the recruitment of fry to a specific area. If the available spawning habitat is restricted, watercourse regulation can significantly impact physical conditions in the river, affecting water flow and temperature. Changes in water flow, such as reducing spring floods, can increase the distance to the nearest spawning area. Consequently, the amount of fry supplied to an area may fall below the watercourse's production potential for juvenile fish, illustrating the importance of access to spawning areas as a limiting resource and bottleneck for fish production. The survival of fry to the smolt stage further hinges on the quality of the rearing habitat. In essence, an ideal salmon river is characterized by well-distributed spawning areas within the river and provides ample access to hiding areas near the spawning grounds (Kennedy et al., 2008).

Figure 2. 2 Substrate (EIA TTM5171 Water resources modelling, 2022)

The substrate on the river stretch is largely dominated by sand and silt (48% coverage of the total area) and stone (27%). The reason for this is the large area in the Borgundfjord with low water velocity and sedimentation of fine matter. Gravel makes up 16% of the total area and block 9%. Cover was measured in a total of 154 transects (a total of 462 cover measures) and the results from the cover measurements show that approximately 66% of the river area has been mapped stretch has little to very little shelter for young fish. 18% of the area has medium cover and 14% has a lot of cover (Fjeldstad et al.,2019).

Figure 2. 3 Upstream part of Øye, located in the upper section of the weir, a shallow river area where a significant number of fine materials is accumulated.

This segment in figure 3 is characterized by a long, slow-flowing nature, presently acting as the main storage for fine materials. Diverse features, including rapids, pools, and smooth currents, define the landscape, with sand, gravel, and stone dominating the riverbed.

A notable modification involves the replacement of the old weir with a constructed arrangement of distributed rocks. This shift aims to improve both ecological and hydraulic aspects of the river stretch, providing a contemporary alternative to traditional weir structures.

Understanding the implications of this alteration is vital for comprehending broader impacts on river health, sediment dynamics, and habitat conditions. The transition from a conventional weir to distributed rocks signifies a commitment to adaptive and environmentally sustainable river management practices.

The Eri-Voll weir is situated on the north side approximately 500 meters downstream from where the E-16 crosses the river. Recent adjustments have been made to this weir, that include the innovative replacement of the weir with scattered stones. This reflects a contemporary perspective on river management and introduces a notable shift in the traditional approach.

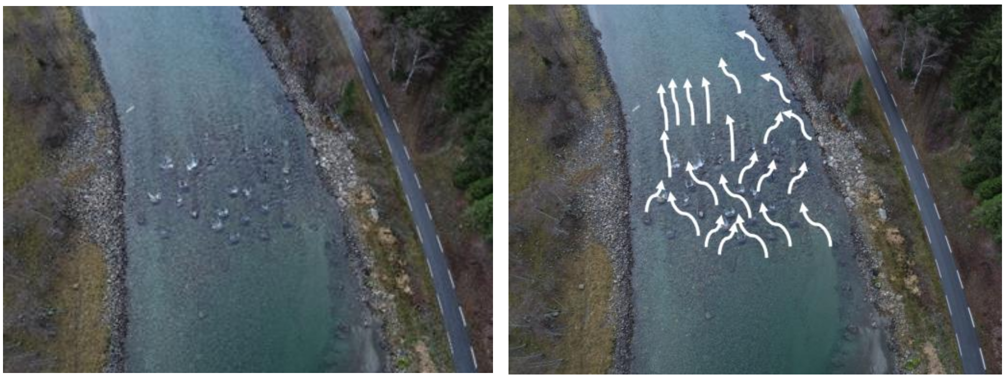


Figure 2. 4 Image of the Eri-Voll (Norce-LFI)

Figure 2. 5 The weir at Eri-Voll and blue arrows show the river flow.

2.6 Ecological Transformation Following Weir Removal in Gongneung River, Korea

The study conducted in the Gongneung River Basin, Korea, delves into the consequences of artificial hydraulic river structures, with a specific focus on dams and weirs. As the removal of such structures gains momentum in Korea to restore natural river dynamics, this research zeroes in on the changes observed post the removal of Gongneung Weir-2 on April 4, 2006. Utilizing a combination of field surveys and numerical simulations, the study investigates alterations in local river flow, channel morphology, and fish habitat (Im et al., 2011).

The removal of the weir, located in a river with fine-sand-to-fine-gravel bed material, triggered swift upstream erosion and downstream sedimentation, even under low-flow conditions. Predicted water elevation aligned closely with measured data, showcasing a decrease of 0.5-1.3 m in the upstream reach. The emergence of new bed zones, including a sand island and a marshy area, contributed to diversified water-level and velocity ranges, enhancing wildlife habitat in the river (Im et al., 2011).

However, despite the positive ecological changes, the shift in bed material and flow velocity had adverse effects on A. rivularis, the dominant species before weir removal, A. rivularis favoured slower flow velocities and a riverbed of sand and clay. Post-removal, R. brunneus became more prominent, favouring coarser bed material. Z. platypus (Pirami) also exhibited a slight increase in numbers after weir removal, becoming the target fish species for assessing the impact on physical habitat (Im et al., 2011).

The computed habitat suitability for Pirami indicated no significant impact downstream but revealed substantial improvements upstream of the weir. Discontinuity in habitat suitability caused by the weir was effectively mitigated post-removal. Simulated results demonstrated increased Water Use Area (WUA) values by about 32.3–53.4% for all life stages, accompanied by enhanced Overall Suitability Index (OSI) and Habitat Suitability Percentage (HSP) values. These qualitative and quantitative findings underscore that weir removal substantially improved the river environment, creating a more favourable habitat for Pirami (Im et al., 2011).

3 Background and Theory

3.1 The Study Area

Flowing into the Sognefjord at Lærdalsøyri, the river encompasses a catchment area of 1183 km^2. Regulated by the Borgund and Stuvane power plants since 1974 and 1988, respectively, Lærdalselva is renowned as the most significant salmon river in Sogn og Fjordane. The lower segment of the river features alternating hills, fast currents, rapids, and is characterized by forebuildings and thresholds (Alfredsen et al., 2019). This designation entails special protection against activities within the watercourse and nearby fjord areas that could adversely impact the salmon population (Fjeldstad et al., 2019).

It has a population of 1120 inhabitants and 161 historic buildings that represent one of the best preserved original old wooden house communities in Norway. Lærdal has experienced historical large flood events. Flooding of the Lærdal river results in flooding of the village of Lærdalsøyri, located at the mouth of the river on a large floodplain. Flood risk mitigation measures are therefore considered potential threats to the river ecosystem, and environmental perspectives are particularly important. Conventional flood risk mitigation measures should be challenged. Lærdal is an 81 km long river with an average flow of 36 m^3/s; the peak discharge for the 200-year flood is 920 m^3/s. The river reach analyzed in this study is a 2.2 km reach including the upper slow flowing pool part of the Lærdal river where most of fine material is accumulated, that includes four small weirs and fish antenna constructed.

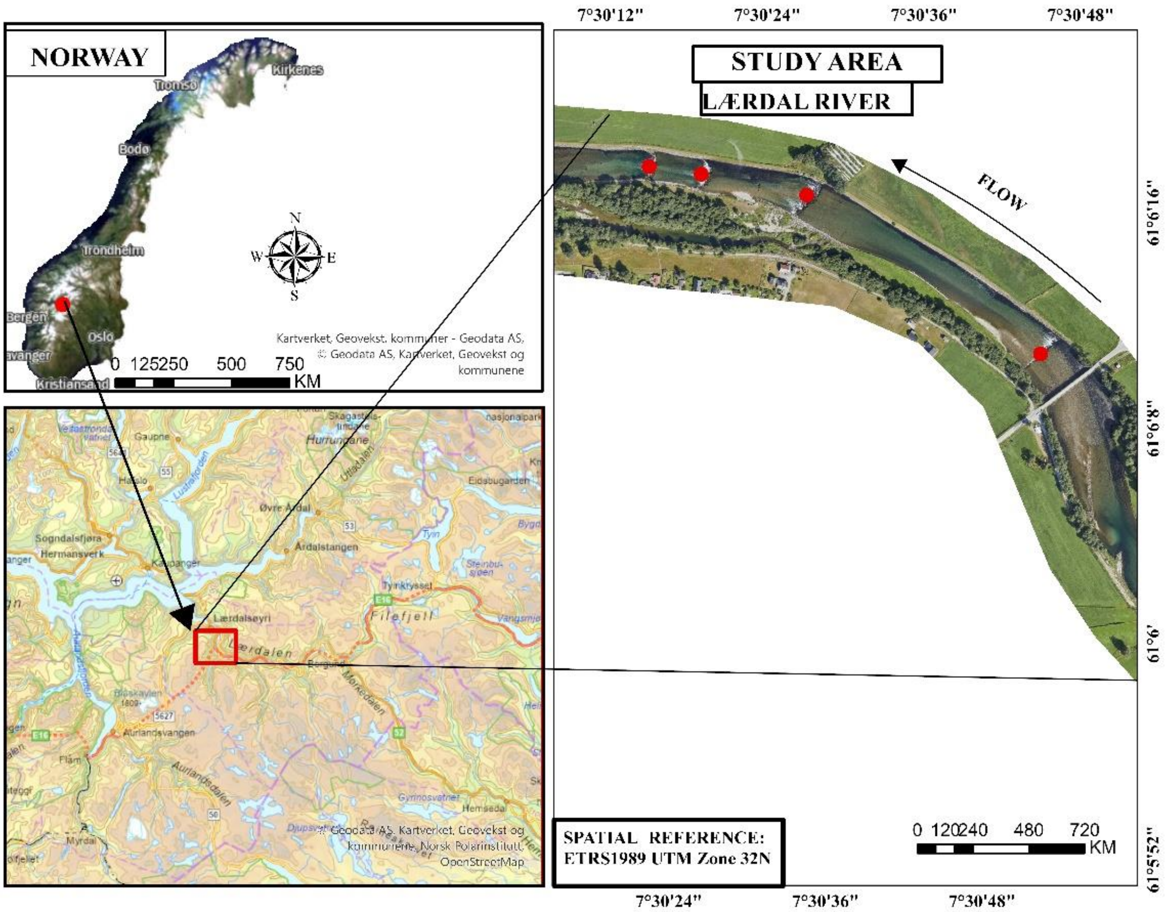


Figure 3. 1 Study site, red points indicating the locations of weirs in the study domain.

3.2 Weir Removal

The most effective approach to enhance up-migration is the removal of thresholds, as emphasized by (Fjeldstad, Pulg, and Forseth, 2018). This restoration method has demonstrated success in river stretches with minimal water flow. According to (Forseth & Harby, 2013), considering threshold removal is paramount, especially when it leads to suboptimal spawning and rearing conditions. This restoration measure aims to return the river to a more natural state.

Thresholds can disrupt water speeds and depths in the river, negatively impacting the fish's requirements for spawning habitat (Forseth and Harby, 2013). Trout, for instance, favor deep areas with moderate to low water velocities and rocky substrate (Heggenes, 1996). Successful trout spawning requires suitable substrate types and minimum flow water velocities (Bjølstad et al., 2014). Threshold removal, as demonstrated by Fjeldstad et al. (2012) in a regulated river in southern Norway, resulted in the utilization of old spawning areas by salmon during the first spawning season after removal, leading to improved water velocity conditions. The removal also contributed to reduced fish egg mortality and an increased number of young fish.

The composition of fish, such as pike and carp, in threshold pools changed in the desired direction after threshold removal, suggesting a positive impact. Thresholds contribute to sediment deposition in the basin, reducing shelter and creating poorer spawning grounds for fish (Pulg et al., 2018). Removing thresholds facilitates the reintroduction of natural sediment transport, transporting sediments further out of the basin. Additionally, riverbed cleaning during floods is reinstated, providing more hiding spots. While threshold removal enhances hydraulic capacity, it induces significant changes in the watercourse's shape and surface, which may be unfavorable. The potential reduction in deep areas post-removal could adversely affect larger fish preferring deeper habitats (Heggenes, 1996). This removal may also impact the overwintering conditions for fish, as deep areas in threshold basins are crucial for this purpose (Fergus, Hoseth, and Sæterbø, 2010).

3.3 Artificial Rocks Habitat

The primary modification post complete weir removal involved creating openings in the existing structure and substituting it with a distributed rock arrangement. Those artificial rocks help it to raise the bottom, securing the bottom riverbed and creating artificial fish habitat. To create favorable conditions for fish like this, ensuring low fields and shelters with a good substrate, we adopt a methodical approach. Subsequently, we replace the weirs in various sections with alternative solutions. This involves removing the weirs and introducing rocks of different sizes, randomly distributed throughout the area.

The implementation of a distributed rock setup emerged as the logical progression following the removal of weirs, presenting a viable alternative to sustain river stability. Ensuring the stability of these artificially distributed rocks involves meticulous dimensioning, anchoring and advocate selecting of stone sizes based on the specific morphology of the river stretch.

In practical terms, the Watercourse Handbook suggests a stone size of 1-2 meters for cell thresholds (Fergus, Hoseth, and Sæterbø, 2010), while Forseth and Harby (2013) propose stones of 0.4-0.6 meters for weirs, including larger stones for foundational support, with some potentially protruding above the water surface.

The introduction of these artificial rocks not only contributes to stabilizing the riverbed but also creates an artificial fish habitat by elevating the river bottom. To optimize conditions for fish, including low fields and shelters with suitable substrate, a systematic approach is adopted. This entails the removal of weirs in various sections, to be replaced with rocks of varying sizes, randomly distributed throughout the designated area. This strategic replacement aims to enhance the overall ecological environment and mitigate potential adverse impacts caused by the original weirs.

Figure 3. 2 Rocks in Lærdal, Photo captured during the field trip

3.4 Submerged Weir

One method of stabilizing the riverbed post-weir removal involves the incorporation of a weir crest, consisting of solid rocks, to anchor the riverbed securely and prevent displacement. While an alternative approach of filling the deepest part was considered, its implications are beyond the scope and warrant further study. A submerged weir crest structure emerges as a viable option to maintain river stability, addressing concerns outlined in the rock stability section 5. The potential risk of erosion, leading to a sudden reduction in water levels, is a critical consideration when placing a submerged weir, removing the weir, and replacing it with distributed rocks. To minimize this risk, the rock stability section 5 briefly outlines a solution.

In the replacement of a 40m-50m span weir, the proposed structure, whether built from stone or concrete, envisions a river bottom with a slight elevation approximately 30-40 cm higher. This design ensures a continuous flow without disruptions, illustrated by a submerged crest example at shallower stations. This involves creating a 30 cm high structure that spans the removed weir section and is 10m wide. Additional rocks, randomly distributed, are strategically placed upstream and downstream of the structure.

This approach serves the dual purpose of securing the bottom through the implemented structure and allows for a detailed investigation by incorporating rocks across the area to observe its impact. Given that one of the original functions of the weir was to prevent ice formation from eroding the bottom, reinforcing the riverbed becomes crucial. In essence, the construction of a submerged weir not only ensures bottom stability but also serves as a protective measure against potential ice-related erosion, aligning with the original purpose of the weirs.

3.4 Reducing the Crest of the Tall Weir

Another tested alternative involves replacing the tall weir with a reduced one while preserving the deeper section in the lower part. Additionally, randomly distributed rocks are introduced upstream of the weir to influence the flow dynamics. The resulting flow pattern exhibits a continuous water surface, with a noticeable effect observed at the end, characterized by a small jump. This modification is complemented by the strategic placement of upstream rocks to examine their impact on flow and depth. A key focus is achieving a smooth transition around the steep part of the weir, where adjustments have been made to mitigate sediment-related challenges. This comprehensive approach aims to address the issues associated with sediments by optimizing both the weir structure and the introduction of rocks upstream.

3.5 Hydraulic Modelling

3.5.1 Hec-Ras 2D

In the realm of water resource management, hydraulic modeling stands as a pivotal tool, unraveling the complex intricacies of fluid dynamics and providing invaluable insights for effective decision-making. Hydraulic modeling, a sophisticated technique in water engineering, involves the computational simulation of fluid flow behavior, offering crucial insights for effective water resource management and infrastructure design. (Pulg et al., 2018)

Hec-Ras (Hydraulic Engineering Center's River Analysis System) is a powerful software tool extensively utilized for hydraulic modeling, enabling comprehensive analysis and simulation of river and water flow dynamics. The software, created by the US Army Corps of Engineers, is employed for computing 1D steady flow, 1D and 2D non-steady flow, sediment transport, and for simulating water temperature or quality (Brunner, 2016). For this task, Hec-Ras version 6.3.1 is utilized.

3.5.2 ArcGIS Pro

ArcGIS Pro is a powerful computer program made by Esri. It helps people work with maps on their computers. It helps to explore data, make 2D maps, and even create 3D scenes. In this study, we use ArcGIS Pro to change raster data, working together with Hec-Ras. We also use it to make nice-looking maps and create shapefiles with different features. Essentially, ArcGIS Pro plays a crucial role starting from creating DEM file of the study area to modifying and making maps for our investigation.

3.6 Activities Conducted During the Project Assignment

3.6.1 Field Survey

In late April 2023, during the field trip to the Lærdal River, the flow recorded was around 19-20 m^3, providing favorable conditions for our work in collecting sediment samples and obtaining the necessary data for sediment analysis.

Specifically, in the bridge pool area, we gathered sediment samples and conducted sieve analyses in the lab. Additionally, we employed the pebble count method to understand the sediment composition in the basin—an essential input for Hec-Ras, where sediment distribution curves play a crucial role. It's worth noting that there was no snowfall during the end of April.

To streamline our sediment collection process, we utilized 10-liter buckets equipped with lids. After shoveling several buckets at each site, we marked them with corresponding lids, specifying the site and location. The depths of the areas we sampled ranged from 0.5m to 11m, with a particular focus on a location deeper than 1m. Safety precautions were paramount, and we ensured that our team had life vests and all the necessary equipment.

Despite the increased flow, hindering a comprehensive investigation of the weir, we were still able to observe the location and inspect both the existing weir and the one constructed with distributed stones. The journey itself took more than three hours.

Our activities included measuring the existing rock layout using a digital caliper and assessing naturally occurring rocks in the river. We also used RTK GPS to measure the water level during our visit.

We took the opportunity to observe the weirs already constructed with distributed rocks and surveyed the surrounding areas. The bridge pool became an intriguing site for sediment calculations. For Hec-Ras, we introduced a sediment curve derived from a comparison of different curves representing the average sizes of rocks found across the river.

3.6.2 Some Uncertainties in Grain Size Collection

The accuracy of sediment measurements depends on the individual collecting the samples and their approach to thinking about and measuring sediment. Achieving precise results is challenging, as sediment analysis involves multiple parameters that may require calibration. In cases of erosion at a specific location, adjusting these parameters becomes crucial for accurate calibration. While this aspect is not explored in-depth in this master's thesis, it is a critical consideration that merits attention in future studies. The ongoing evolution of calibration methods and understanding the impact of individual perspectives on sediment measurements would significantly contribute to the robustness of sediment analyses in future research endeavors.

4. Method and Data

4.1 Modification of Existing Weirs

In this study we have used Hec-Ras and GIS to modify the geometry and remove completely. For this we had worked on Point cloud, DEM (DTM) and estimation of uncertainty with interpolation. (Stickler et al, 2022)

The basis for the model is created by Using the Bathymetric Lidar data from hoydedata.no, the latest available data has been used which is year 2021. The point cloud data from 2021 was then downloaded as LAZ file. We aim to interpolate the lidar data of 2021 to integrate bathymetry into the topographic lidar, creating comprehensive valley-wide data. This is crucial for assessing potential erosion in our geometry during specific discharge scenarios. If the discharge surpasses the coverage of the green lidar, merging it with the topographic lidar becomes necessary to encompass the entire valley.

Bathymetric LiDAR (Light detection and ranging/3D Laser Scanning) is a laser instrument with a wavelength that penetrates the water surface and can thus measure reflections from the bottom of the river so that data about the underwater topography can be collected. The method has limitations related to depth, turbidity, and surface turbulence, but in the right circumstances it is a very effective method for collecting detailed data on the bathymetry of a river. This is data that can then be used in various forms of analysis, for example as a basis for hydraulic modelling, dimensioning, monitoring and evaluation of various interventions and measures in watercourses. (Alfredsen, 2022)

The main part of the results in this report will deal with data collected by the company Airborne Hydro Mapping, AHM, from Austria. Data is from a Riegl LiDAR mounted in a small plane that did all the collecting the point cloud in these waterways. (Alfredsen, 2022)

There are different types of LIDAR depending on the platform used, physical process or scattering process. Based on the platform used we find 3 types of LiDAR. Ground based LiDAR, AiRborne LiDAR and spaceborne LiDAR. We have used airborne LiDAR. (Juarez,2020)

4.2 Data Preparation Lidar Data

LAS TOOLS had been used to transform LiDAR Data into LAS format and using ARC GIS PRO to transform it into raster. LAS TOOL is an open-source software suite and not user-friendly. It is a collection of highly efficient, batch-scriptable, multicore command line tools. Tools to classify, tile, convert, filter, raster, triangulate, contour, clip, and polygonise LiDAR data/just a few functions (Rapidlasso.com).

LAZ FORMAT --- LAS TOOLS --- LAS FORMAT ---- ArcGIS --- RASTER

First, the Lidar data/point cloud (LAZ) is acquired from hoydedata.no. Following this, the data undergoes conversion to the LAS file format utilizing LAS Tools. The coordinate system (ETRS1989 UTM Zone 32N (XY coordinate system) and NN2000 (Z coordinate system) is implemented when creating the intermediate Las dataset file and further works.

Subsequently, ArcGIS is employed for the purpose of interpolating an integrated terrain model. This model effectively encompasses both the valley floor and the bathymetry of the river. The interpolation is performed with a grid cell size of 0.25 x 0.25 meters terrain model, a resolution that facilitates the clear delineation of thresholds within the river. This high resolution proves particularly advantageous for visualizing subtle features.

Finally, the derived Digital Elevation Model (DEM) is employed for experiments conducted on Hec-Ras. The DEM serves as the foundational model for these experiments, providing a comprehensive representation of the topography and bathymetry. The chosen grid cell size of 0.25 x 0.25 meters ensures a detailed and accurate depiction of the terrain, supporting the precision required for the Hec-Ras simulations.

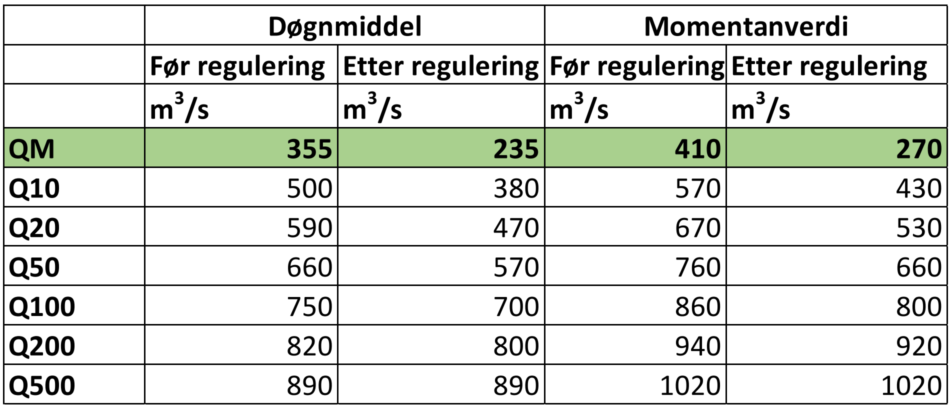
4.3 Water Flow

The Lærdal watercourse originates from the confluence of Mørkedøla and Smedøla, flowing into the fjord at Lærdalsøyri with a minimum required water flow of $10m^3/s$. During the collection of the satellite image used in this study, the water flow in the study area was $20m^3/s$, serving as the calibration point for the model. This value is also considered the effective minimum water flow in the river. The watercourse underwent regulation starting in the 1970s with the construction of reservoirs for hydropower, totaling 3 power plants and 7 reservoirs with a combined volume of 274 million m^3. Following regulation, the average annual flow decreased by 20%. Monthly average water flow measurements were recorded at Skjærsbrui before and after regulation, spanning 1964 to 1970 and 1988 to 1998, respectively. Measurements in the latter period were taken at Stuvane and later adjusted due to the destruction of the Skjærsbrui station during the 1971 floods (Holmqvist, 2000).

4.3.1 Flood Data

Table 4.1 displays the flow rates for various recurrence intervals in this river section, utilizing data from the pre-existing Skjærsbrui gauge station. The Norwegian Water Resources and Energy Directorate (NVE) derived these values through frequency analyses based on flood data from Lærdal and neighboring watercourses. It's crucial to acknowledge the potential impact of regulatory changes on higher flood values and consider a minimum 20% uncertainty in these values (Holmqvist, 2000).

Table 4. 1 Illustrates the flood values within the study region both prior to and following regulation (NVE and Holmqvist, 2000).



	Døgnmiddel		**Momentanverdi**	
	Før regulering	**Etter regulering**	**Før regulering**	**Etter regulering**
	m^3/s	**m^3/s**	**m^3/s**	**m^3/s**
QM	**355**	**235**	**410**	**270**
Q10	500	380	570	430
Q20	590	470	670	530
Q50	660	570	760	660
Q100	750	700	860	800
Q200	820	800	940	920
Q500	890	890	1020	1020

This project specifically focuses on analyzing the sediment simulation values associated with a (Mean Flood) QM flood occurrence.

4.4 Setup in Hec-Ras

4.4.1 Calculation of Grid

The topography generated during preprocessing was incorporated into Hec-Ras through RAS Mapper. The initial step in constructing the geometry involved delineating the 2D flow area and choosing the mesh's cell size. The grid covers a condensed domain that includes the specified weirs and the upstream river pool. The cell size is set at 3 x 3m, with a 1 x 1m refinement in the weir regions. It is crucial to strike a balance with the cell size, ensuring it is small enough for stable computations and accurate results yet large enough for efficient processing.

Numerous break lines were strategically inserted to align the grid with the terrain. Break lines act as guides for cell generation and are often placed along or across significant structures. In this case, break lines were positioned in the middle of the river, encircling the island and modelled boulders to ensure proper integration into the grid. Break lines serve a dual purpose: firstly, they help identify areas where water might escape the river, preventing overflow before complete submersion, and secondly, they align cell faces with the highest points to prevent premature overflow.

Initially, we created a 2D flow area that extended downstream to cover the island and a bit upstream, with refinement details around the individual weir region. This setup was used for various simulations: hydraulic simulations with minimum and medium flows, calibration of the Manning number, comparison of sediment simulations (examining bed changes for two turbulence models), and several other experiments at the start of the project. However, as we delved into sediment studies, we realized that these simulations were time-consuming. Due to the time constraints, efficient planning and execution were essential to meet the study's objectives within the allocated timeframe, we decided to shorten the grid and set up a slightly smaller 2D flow area, focusing on the four weirs and aiming to complete both sediment and hydraulic simulations thereby we were able to save a significant amount of time.

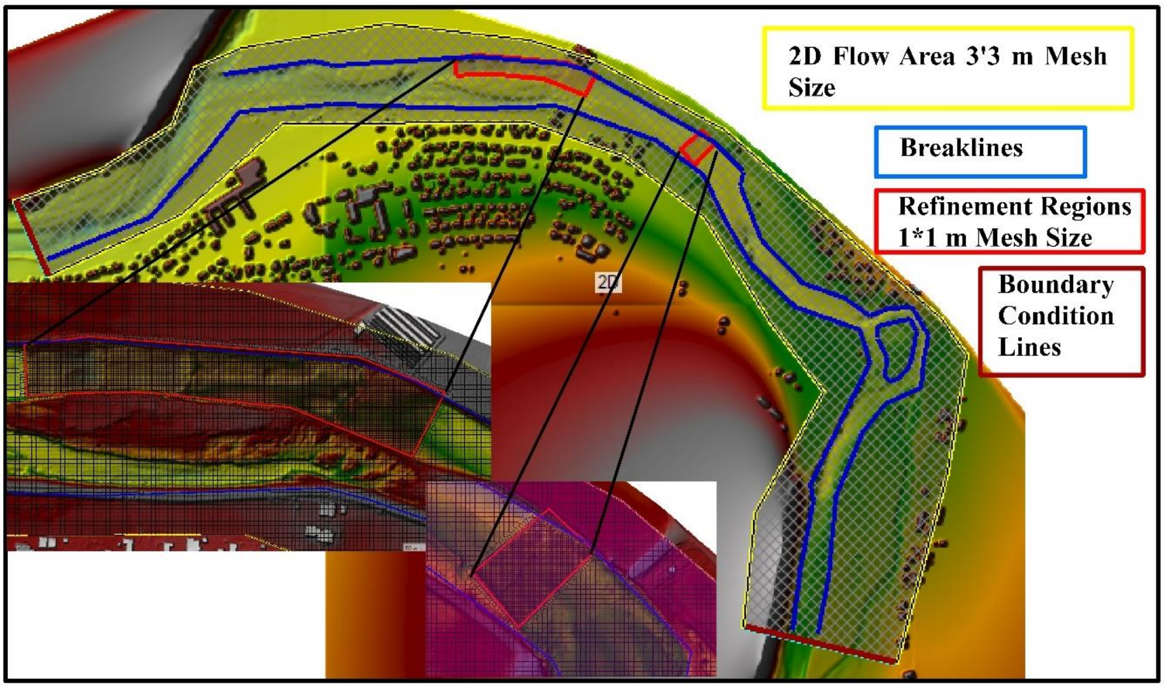


Figure 4. 1 Initial grid setup featuring extended coverage, including the island, with a 3x3 m mesh cell size and refinements specific to the intended weirs.

The second grid set up used for further simulations is shown in the figure 4.2.

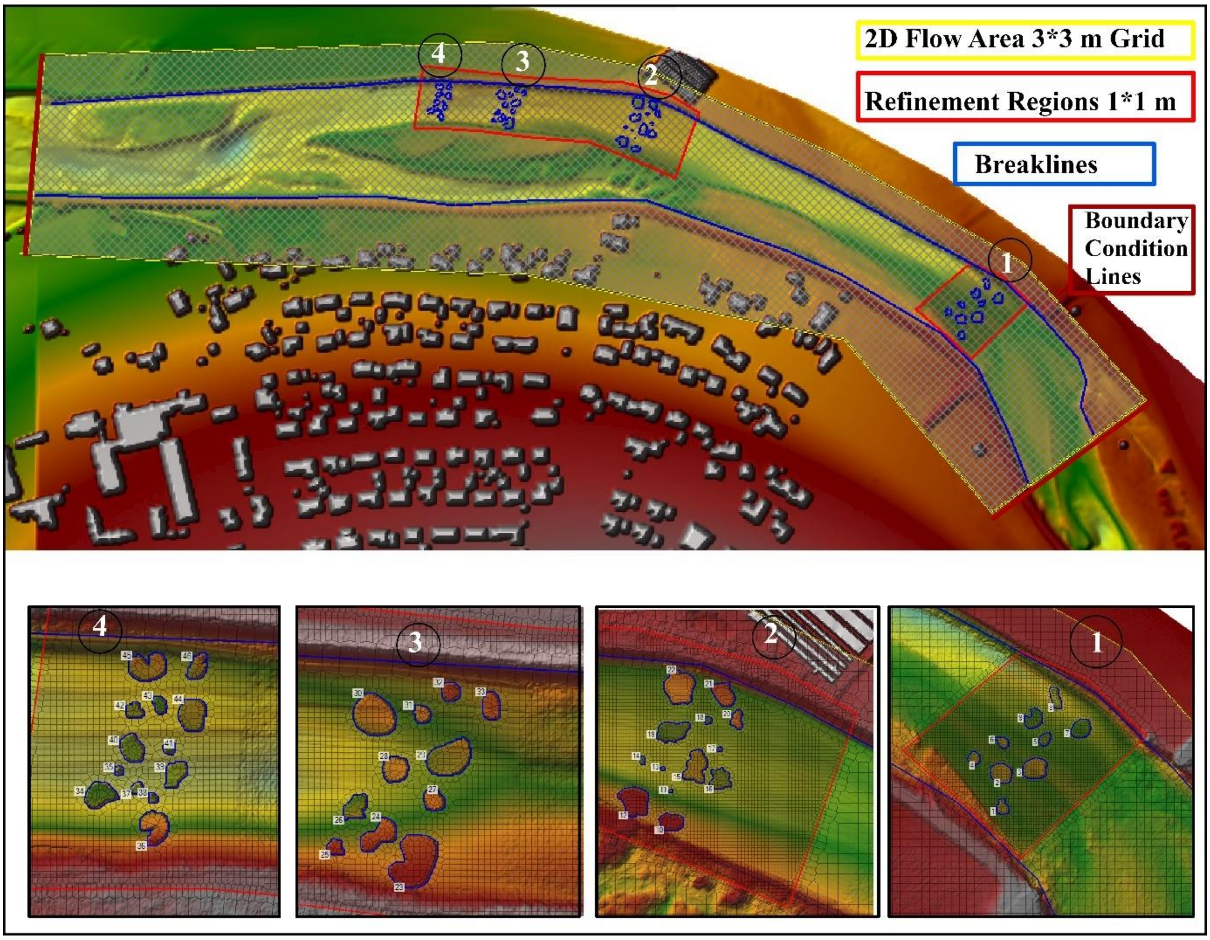


Figure 4. 2 The terrain with boulder arrangement is used to show the grid and the breaklines.

Additional break lines along the riverbank and above the thresholds were incorporated to maintain grid alignment with the riverbank and current direction. Despite these efforts, some areas still had overly large calculation cells. To address this, computational points were manually added to refine and divide the large cells.

In summary, the grid setup involved in running simulations first with the initial weir using break lines and controlled refinement, Subsequent steps included modifying the weir, running new simulations without the weir, and comparing the results. Various terrain modifications, such as artificial rocks, submerged weirs, and lowered weir crests, were tested using the same grid setup with sediment and without sediment, and the results were thoroughly analyzed.

4.4.2 Time Steps

The Courant criterion plays a crucial role in determining the appropriate time step relative to cell size. For the diffusion wave equations utilized in these simulations, a Courant number below 2 is maintained. Despite the model's capability to operate with a Courant number up to 4, a conservative approach is taken by identifying areas with elevated water velocity. Subsequently, the water velocity and cell size in those areas are determined, and the necessary time step is calculated, following the methodology outlined by Brunner (2016). The Courant number, computed based on a grid resolution of 1 x 1 m, is set at 2, ensuring consistency in simulations conducted with and without sediment.

The adjustment of the Courant number inherently increases the computational step and stability of unsteady flow. It is feasible to visualize the Courant number across the grid and identify potential areas of concern. By plotting the Courant number, any instances where the set limit is exceeded can be identified, allowing for a targeted investigation and potential resolution. RAS Mapper aids in this process by generating a map that highlights problematic cells during simulation, enabling further examination and necessary adjustments.

4.4.3 Boundary Conditions

Establishing effective boundary conditions is essential for determining the ingress and egress of water within the specified area. The upstream boundary is positioned on the right, just outside the 2D study area, mirroring the arrangement of the downstream boundary on the left. For the upper boundary, a constant 24-hour flow hydrograph is implemented, providing a predefined water flow. The distribution of water flow across the boundary cross-section is computed using the energy slope, as outlined by Brunner (2016). In contrast, the lower boundary adheres to normal depth, where Manning's formula utilizes the bottom slope of the boundary cross-section to calculate the normal depth. The energy slope is approximated by determining the average slope of the river in proximity to the boundary cross-section (Brunner, 2016).

For the lower boundary condition, a uniform slope of 0.01, corresponding to the normal depth, is consistently applied throughout all simulations within the study domain. Regarding the Hydraulic Warm-Up or Initial Conditions time, it is determined by running an initial simulation to observe the hours required for the river model to reach full capacity. In our case, the diffusion wave model is employed, commencing with a dry riverbed that gradually fills during the simulation. The optimal duration for hydraulic warm-up is determined to be 2 hours for a one-day hydrograph, striking a balance between convergence and efficiency. This approach is adopted for subsequent simulations, ensuring the grid is adequately filled before the commencement of each simulation.

To optimize computer performance for faster computations, a specific number of cores, namely 4, have been employed. This choice aligns with the Hec-Ras 6.3.1 manual recommendation, indicating that more cores are not always advantageous. It has been observed that for smaller 2D areas, such as those with fewer than 10,000 cells, using 8 cores may result in slower performance compared to 4 or 6 cores. This phenomenon is attributed to the computing overhead required for data transfer between cores. Fortunately, Hec-Ras offers the flexibility to adjust the number of cores in the Computation Options and Tolerances window, accessible through the unsteady flow analysis window by navigating to Options, then Calculation Options and Tolerances, and finally, the 2D Flow Options tab.

4.4.4 Equation Sets and Other Calculation Options

In this study, we have a crucial decision to make regarding equation sets, offering two options. The default choice is Diffusion Wave, and the other alternative considered is Full Momentum Equation/ELM, also known as Shallow Water Equations or 2D St. Venant Equations. Diffusion Wave simplifies the Full Momentum Equation, focusing on gravity and friction terms for flow conditions while neglecting other terms (Brunner, 2016).

Although Diffusion Wave is faster and more stable, Full Momentum may be more accurate, especially for tasks like sediment simulations and tidal waves. The recommended approach is to run both equation sets and compare their results. (Brunner, 2016)

In our study, we initially ran the model with both Diffusion Wave and ELM/Full Momentum equations, comparing their outcomes. We observed that, despite a small average difference in computed geometrical area using both equations, there was a substantial difference in simulation time. ELM equations took significantly longer. As a result, we chose to use Diffusion Wave for running hydraulic simulations because it saves time and ensures proper model functionality. Subsequently, we employed Full Momentum (ELM/original) specifically for sediment calculations. This approach optimizes both time efficiency and model accuracy.

4.5 Grain Sizes

The grain size distribution (GSD) study is an important part of rivers study in order to analyses sedimentary impact on bed and riverbanks. Indeed, grains statistics are required to provide bed features, describe habitats, and analyze bed changes due to the floods. This work requires to go on field and collect data. It can easily be realized by hand thanks to a substrate sample, but it becomes much more time consuming as the field is large and as you want to provide the most precise work. A common way to provide a GSD are the sieve methods. But an alternative way is to use pebble count method and using frame sampling of grains and gravels on the field, and analyze the samples by counting individual grains and create graphs from the data using Excel or specialized software/code.

In this study, two grain size distributions were generated employing distinct methods. Initially, a 10-meter measurement tape was utilized, and samples were collected from all rocks in direct contact with the tape. Subsequently, the pebble count frame method was employed, ensuring a uniform sampling process. Lastly, the frame was placed, and samples were collected within its boundaries by shoveling materials into a designated 10 liters bucket.

4.5.1 Measurement Tapes 10meters Length

The concept involves laying down a measurement tape or rope on the ground, and then collecting all sediment particles that come into contact with it. This approach poses a slight challenge when working underwater. Random sampling, although easier in terms of capturing visible rocks, may not be as comprehensive. Therefore, opting for systematic digging ensures a more thorough collection, allowing us to capture a more representative sample of the sediment environment. The challenge with this equipment lies in its tendency to omit the finer sediment fractions, resulting in a coarser outcome.

Figure 4. 3 sample collection using a tape.

4.5.2 Pebble Count- A Frame for The Sediments

The pebble count procedure involves measuring 100 randomly selected stones from a homogeneous population on a riverbed or bar, providing reproducible size distribution curves for surficial deposits of gravel and cobbles. Widely used in geomorphology and increasingly in river engineering, this method characterizes surficial grain size distributions without the need for impractical bulk samples for gravels. Sampling coarse bed material should be gynomorphically stratified based on the natural sorting of grain sizes into distinct channel features. For a composite grain size, different bed areas occupied by distinct populations can be mapped, pebble counts conducted on each, and a weighted average distribution computed (Wolman, 1954).

However, a challenge we faced was the insufficiently low water flow during the data collection. As we approached a period when the water flow was expected to increase, conducting a pebble count at that moment was a cold and challenging experience, especially if performed underwater.

Figure 4. 4 sample collection using a total frame.

4.5.3 Shoveling

We utilized a shovel to gather substrate samples and filled two buckets with sediment. These samples were then brought to the laboratory for processing. Initially, the collected samples were placed in an oven to facilitate drying. Following the drying process, the samples underwent further preparation by being shaken using a machine. This meticulous preparation ensured that the samples were adequately primed for subsequent detailed analysis.

We employed both methods, comparing the outcomes of each to discern subtle differences. In instances where necessary, we incorporated small fractions of samples only substrates derived from both approaches. However, a notable challenge with the shoveling method is its preference for execution outside the water. Shoveling underwater can result in the loss of fine materials during the digging process. Therefore, it is advisable to conduct shoveling activities at the water's edge, along the embankments, to optimize material retention and accuracy in sampling. At that moment the samples were taken the depth varies from 0.5m-11m and discharge was around 19 m3, gravel bars became evident, particularly in the Bridge Pool area on Øya. In this location, we were able to conveniently collect sediment samples from the water and proceed to weigh the larger stones before depositing them into the designated area.

The first bucket contains fine material, while the second bucket holds undisturbed material collected by placing a frame then shovel samples inside this frame into bucket at location upstream of the weir near the river. The frame also provided the advantage of retaining some substrate for subsequent sieving. This collection includes both large and small particles, as well as fine and coarse materials. Both samples underwent separate sieving processes in the lab, and sediment simulation was conducted based on the undisturbed sample, which comprises both fine and coarser materials. As we shovel the initial 10 cm or 15 cm and place them in the bucket, we inadvertently included these minute fractions as well.

Figure 4. 5 Undisturbed Sample Bucket 1 (Left) & Substrate Sample Bucket 2 (Right)

4.5.4 Mechanical Sieve Analysis

The grain size analysis test serves to ascertain the percentage of each grain size within a given sample, allowing the generation of a grain size distribution curve. This data proves instrumental in sediment classification and predicting its behavior. Employing the sieve analysis method, the grain size distribution of sand and gravel is determined using a series of mechanical sieves. (Dr. MD Sahadat Hossain et al., 2020)

The sieves utilized in this process are RETSCH woven wire mesh sieves, characterized by a solid stainless steel sieve frame with square openings. specific details on the sieve sizes along with their corresponding weights, are provided in Table 4.2 below.

Table 4. 2 Specifications of Used Sieves and Corresponding Measured Weights.

Size Openings (mm)	Weight of sieves (kg)
63	1.595
31.5	1.755
16	1.845
8	1.605
4	1.545
2	1.32
1	1.145
0.5	1.075
0.25	0.985
0.125	0.905
0.1	0.925
0.063	0.924

This test method plays a crucial role in grading sediment samples obtained from Lærdal, with the results serving as essential input for sediment simulation in Hec-Ras.

The equipment used in this process includes a stack of sieves with a cover, a balance, an oven, a mechanical sieve shaker, and a brush. ASTM D6913: Standard Test Methods for Particle-Size Distribution (Gradation) of Soils Using Sieve Analysis served as the reference standard.

The procedural steps are as follows:

Obtain a representative oven-dried soil sample, dried for 4 hours at 110 degrees Celsius. It was crucial to clean the sieves before the test using a brush.

Record the weight of each equipment, the pan, and the dry sediment sample separately.

Stack the sieves, placing those with larger openings above those with smaller openings. Position a pan under the finest sieve (0.063mm opening size in this case) to collect the sediments passing through.

Pour the soil into the stack of sieves from above, cover it, and place the stack in the sieve shaker. Affix the clamps, set a timer for 10 minutes, and initiate the shaker.

Stop the sieve shaker and measure the mass of each sieve along with the retained soil.

Figure 4. 6 Composition of Substrate Analyzed in Laboratory

A cumulative particle size distribution was then developed from these measurements as shown in Figure 4.7.

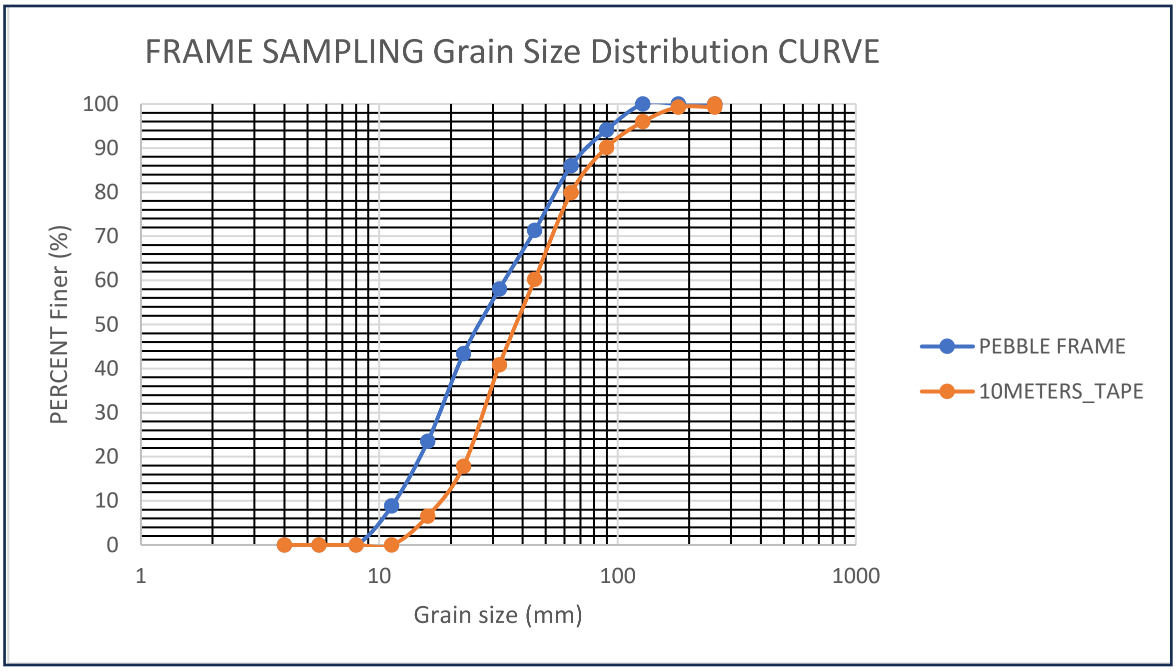


Figure 4. 7 Cumulative particle size distribution developed from Pebble Count substrate measurements and 10 Meters long TAPE and 10 meters long TAPE.

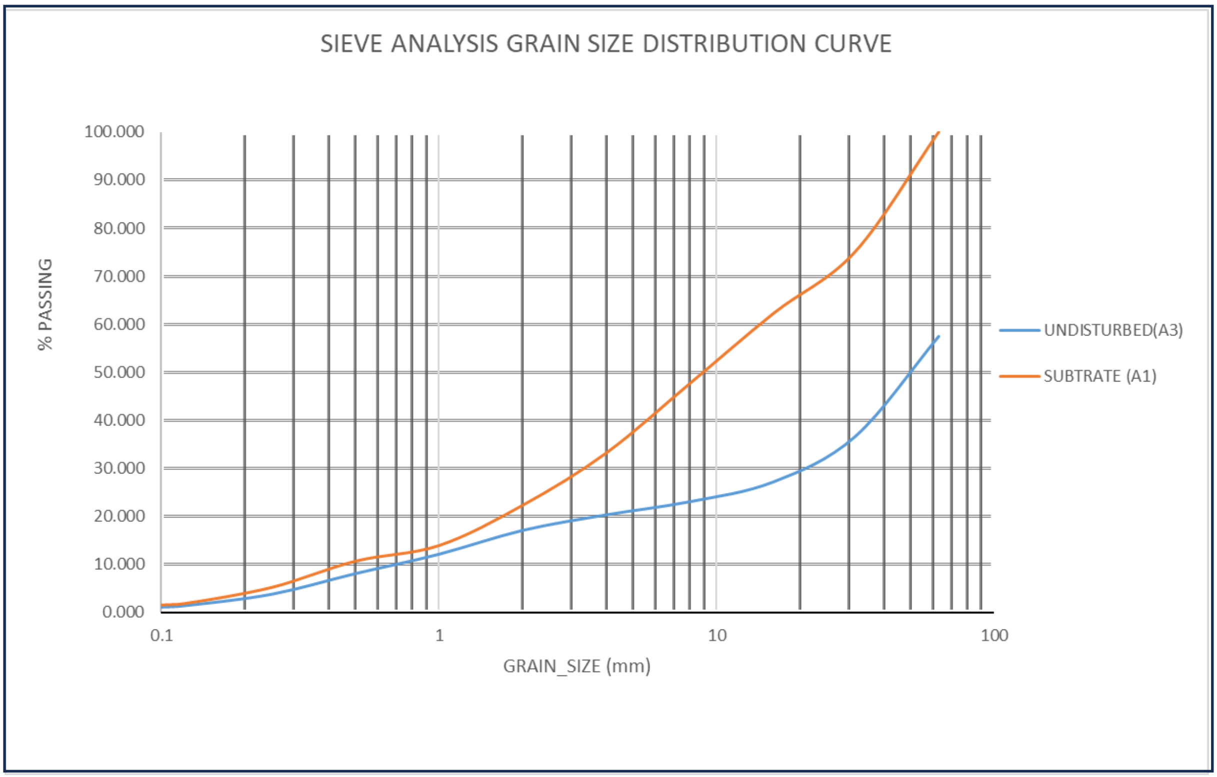


Figure 4. 8 Cumulative particle size distribution developed from Sieve Analysis Test Conducted in the laboratory.

4.6 Roughness Characterization

A measure of channel roughness was necessary to depict flow behavior using the hydraulic models. Roughness was primarily characterized using the sieve analysis grain size distribution technique. The samples were collected at the Near Bridge pool location, specifically chosen due to its proximity to fine or exposed materials submerged within the 10m-20m depth range. This site was selected because it represents an area with a significant presence of fine materials, making it particularly interesting for further investigation.

The particle size in millimeters that 50% of the samples were equal to or smaller than (D_{50}) was estimated. The Strickler equation was employed to determine a Manning's n roughness coefficient from the particle size data: (Tupen, 2020)

$$\boldsymbol{n=0.0132D50}$$

By using a median size of the bed material 27 mm the Strickler equation above gives a manning value of 0.0356 as a starting value for further calibration of the observed data with the satellite image.

Additionally, our calculated D_{50}, representing the median grain size, aligns with the reported median grain sizes for nursing and spawning habitats of Atlantic salmon and brown trout, as documented in Table 5.1 and 5.2 by Armstrong et al. (2003). The calculated D_{50} falls within the established range for both species, indicating a noteworthy concordance with the reported habitat preferences. This finding underscores the ecological relevance of the grain size parameter in the context of spawning and nursing activities for Atlantic salmon and brown trout in our studied area. The alignment with established habitat preferences suggests that the calculated D_{50} holds significance in understanding and potentially managing the populations of these key fish species, emphasizing the importance of considering grain size in habitat conservation and restoration efforts.

Moreover, D_{50} is a helpful value that plays a crucial role in subsequent hydraulic calculations. The study of grain size enables the execution of sediment simulations using Hec-Ras, presenting a notable challenge related to the arrangement of boulders. The following section will investigate into a comprehensive discussion regarding the overall effectiveness of this solution and the various challenges associated with it. The conclusion regarding the efficiency of the boulder arrangement as a solution is a pivotal aspect of our study. This involves evaluating how well the chosen approach addresses the identified issues and meets the desired objectives. Additionally, an in-depth exploration of the challenges encountered during the implementation of the boulder arrangement is essential. Understanding these challenges is crucial for refining the solution and ensuring its successful application in real-world scenarios. The upcoming discussion will provide a nuanced analysis, emphasizing on both the positive outcomes and the challenges in adopting this approach to ecosystem and fish habitat.

4.7 Calibration of Model

Calibrating our model is crucial because it helps ensure that our simulation reflects reality accurately. Calibration builds confidence in our results, particularly when replicating real-world conditions. In this case, we focused on correcting the Manning roughness value considering uncertainties in the waterline. The calibration process is thorough, involving various data sources, topographic changes, and understanding the river's complex geometry to achieve precise simulations.

To make our calibration comparisons more accurate and sensible, we used pictures from satellites. This choice made us look at the data from satellite images to set the roughness in the best way.

Historically, calibration involved using drone images, aerial photographs, water lines, and other parameters in the previous Hec-Ras model. Experience suggests minor adjustments to the Manning value (between 0.03 to 0.04) typically yield accurate results for rivers with precise geometry. The water edge line was also used for the calibration of the model. To achieve this, we compared different Manning values in the riverbed, calculating the error using a method outlined in previous studies. After careful consideration, a final Manning number of 0.035 was chosen. (Juárez et al., 2021).

Ensuring precise measurements, we utilized an aerial photograph from Norge i bilder 2021 for comparison. Our analysis revealed consistency in the topography year and the year of the satellite image on Norge i bilder, both being 2021. With precise date and time data, along with a discharge hydrograph of 20 m^3/s corresponding to that specific date, we validated our model. Extracting the water-covered area for this discharge and overlaying it onto the image allowed us to assess accuracy and make necessary adjustments to Manning numbers for improved precision.

The Manning value of 0.035 was confirmed as correct and verified, providing an optimal fit. A comparison of the aerial image encompassing fields, forests, islands, and gravel with the model simulation demonstrated near-perfect alignment. The model effectively captured the water edge, confirming its reliability.

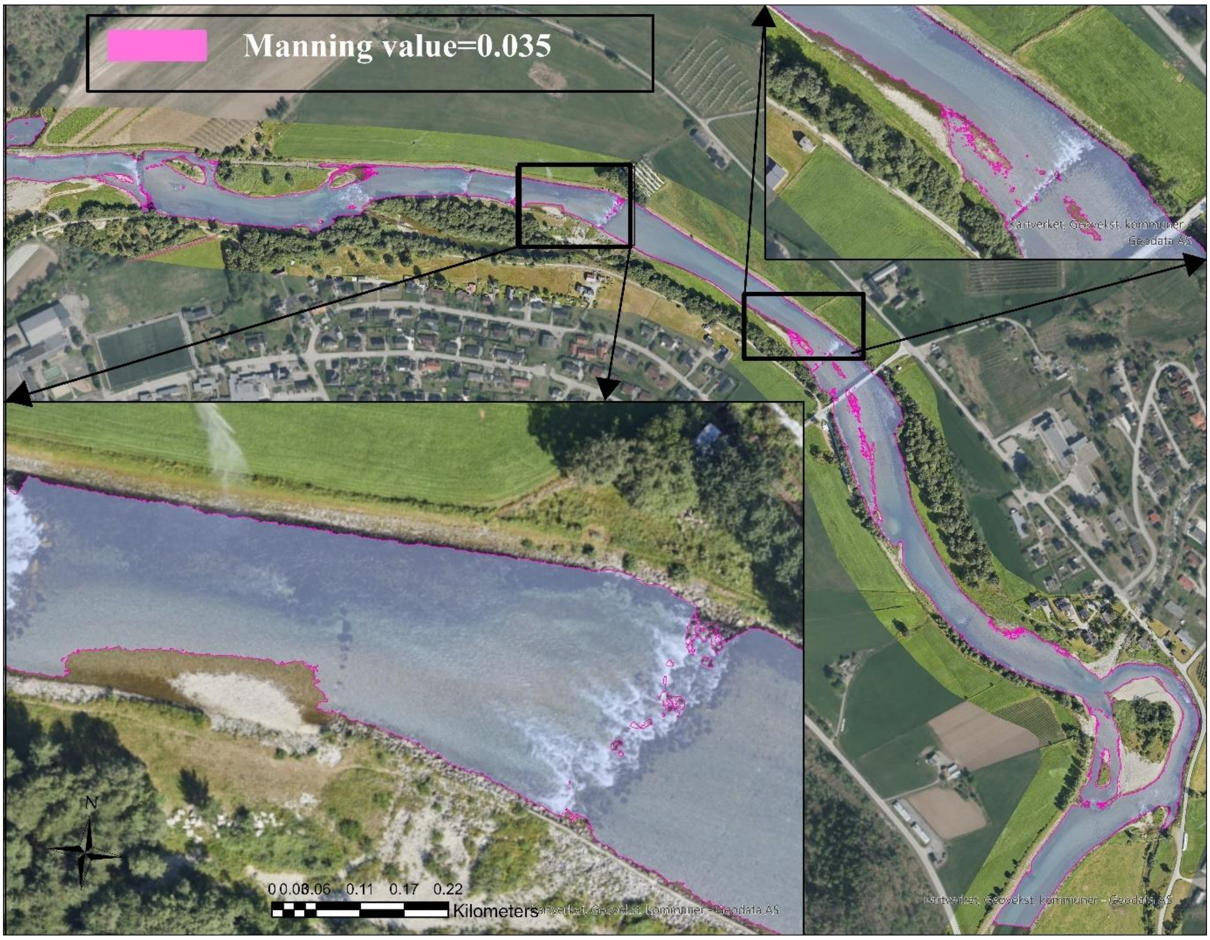


Figure 4. 9 Inundation Boundary Simulated for a 20 m^3/s Discharge Overlayed on the Satellite Image.

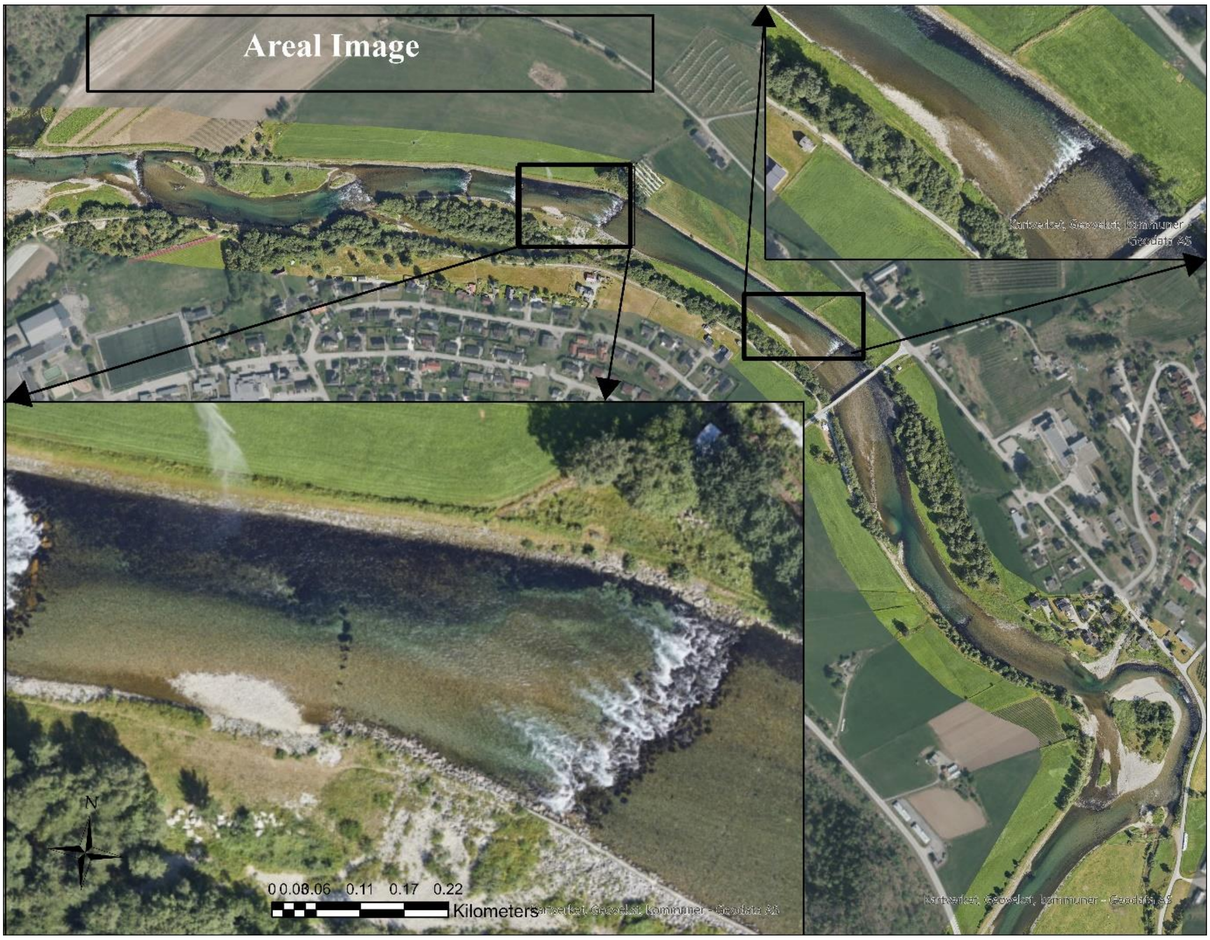


Figure 4. 10 An aerial photograph from Norge i bilder 2021, used for comparison with the simulated inundation boundary, water flow when image was taken was 20 m^3/s.

The only discrepancy lies in a slight overestimation of the dry area downstream of a small gravel bar, which represents a shallower region. The model interprets a very small water-covered area as dry, contrary to the image that correctly depicts water presence in that specific location.

Moreover, we conducted a survey to assess forecast errors using various criteria, including Median Absolute Error (MdAE), Mean Square Error (MSE), Root Mean Square Error (RMSE), and Mean Absolute Error (MAE). These measurements are crucial for evaluating the quality of forecasting. Forecast error measures play a pivotal role in addressing practical problems effectively. (Shcherbakov M.V et al., 2013).

Table 4. 3 Types of error indexes calculated for each roughness value (n)

n	MAE	MDAE	MSE	RMSE
0.03	0.0075	0.008	0.0000875	0.0093541
0.035	0.005	0.005	0.0000375	0.0061237
0.045	0.0075	0.008	0.0000875	0.0093541

As mentioned by Shcherbakov M.V et al. in 2013, the optimal value for achieving the lowest error is considered the best. The image above demonstrates that a roughness value of 0.035 yields the lowest error indexes, affirming its high quality.

4.8 Modification of The Existing Weirs and Comprehensive Weir Modelling

We explored various ways to change the existing weir, and what we did was create different scenarios to demonstrate examples of what has been done and what could be done in future projects. We aim to provide ideas based on our work for suggesting new arrangements of the rocks. These methods are explained more briefly in the sections below.

Using the chosen methods, we reconstructed the geometry by adjusting the terrain, which now includes the newly added weir solution. Our decision focused on modifying four weirs and conducting sediment simulations. Considering the costs involved, we went ahead with modeling and testing the removal or alteration of these four weirs, making necessary changes. We then assessed how they looked after the modifications. Following this evaluation, sediment samples were introduced, and simulations were carried out before weir removal, after removal, and after creating an artificial habitat.

We evaluated each weir under different flow conditions, including minimum flow, low flows, and medium flows. The current goal is to examine weir configurations that can create a more interesting flow pattern rather than opting for complete removal. This approach allows us to consider both environmental impact and cost-effectiveness in weir modifications.

4.8.1 Weir Removal

A theoretical weir removal in river Lærdal was modelled and analyzed based on the AHM ALB data to demonstrate application for restoration and quick adjustments to the base data. (Stranzl et al.,2020). The riverbed was interpolated based on bed elevations upstream and downstream of the weir, employing Hec-Ras and ArcGIS Pro. In Hec-Ras, two cross-sections one at the lower and one at the upper part of the weir were inserted, and interpolation was done between them. Subsequently, the interpolated DEM was overlaid onto the original DEM using the "mosaic to new raster" tool in ArcGIS to achieve a flattened result.

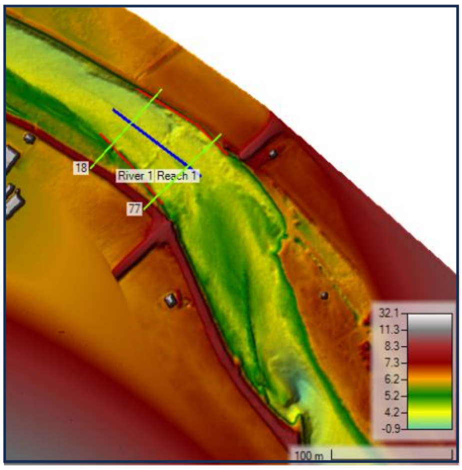


Figure 4. 11 Showing designed geometry for bed interpolation in Hec-Ras, Where Blue (river line), green (cross-sections lines), and red (bank lines).

When removing the threshold, a transverse profile upstream of the weir and a transverse profile downstream of the weir served as the starting points. Between these profiles, a consistently sloping riverbed was interpolated, removing both the threshold crown and the deep area often found directly downstream of the crown in Lærdalselva's thresholds. The assumption was made that the model had the same roughness in the new area as in the surrounding area (Alfredsen and Awadallah, 2022).

Adjusting weirs followed a similar method, involving the removal of parts of the aimed weirs in the study domain only, while the rest of the threshold remained in the terrain model. The engineering aspects of threshold removal were not explored in-depth. While the Lærdal River is regulated, with potential for large flood discharges, the dimensioning of the adjusted threshold or the new riverbed to handle flood situations would be necessary. The assumption during removal was that this process would be done without detailed consideration of the engineering specifics (Alfredsen and Awadallah, 2022).

The method employed aimed not to entirely flatten the weir but to leave a lowered elevation to maintain the water level over the end. This was done to ensure water availability for fish, addressing landowners' concerns. Additionally, the method partly reproduced natural formations in the terrain, following the direction of the current. During any physical threshold removal, measures would likely be taken to imitate the natural state rather than making the threshold area flat across the river (Alfredsen and Awadallah, 2022).

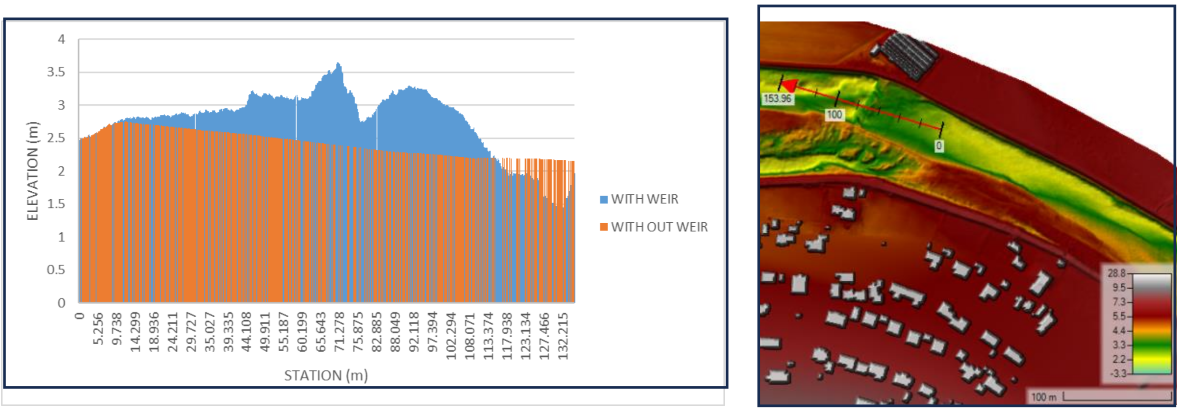


Figure 4. 12 Blue Line (With weir) is how it was before any changes, and the orange line (With out weir) shows the new shape of the river after modification in the specified section.

The interpolation process was carefully executed, prioritizing the lengthwise direction over transverse, with additional points placed strategically along the edges to avoid smoothing the banks. This decision ensured that high banks did not unduly influence the interpolated area. The interpolation specifically targeted the riverbed, excluding the banks to prevent their impact on elevation. Subsequently, a 2D geometry grid was created, extending slightly to the embankments, allowing an exploration of the potential erosion impact on the new construction during high-flow discharges. The focus is on evaluating the feasibility of channel formation under these conditions.

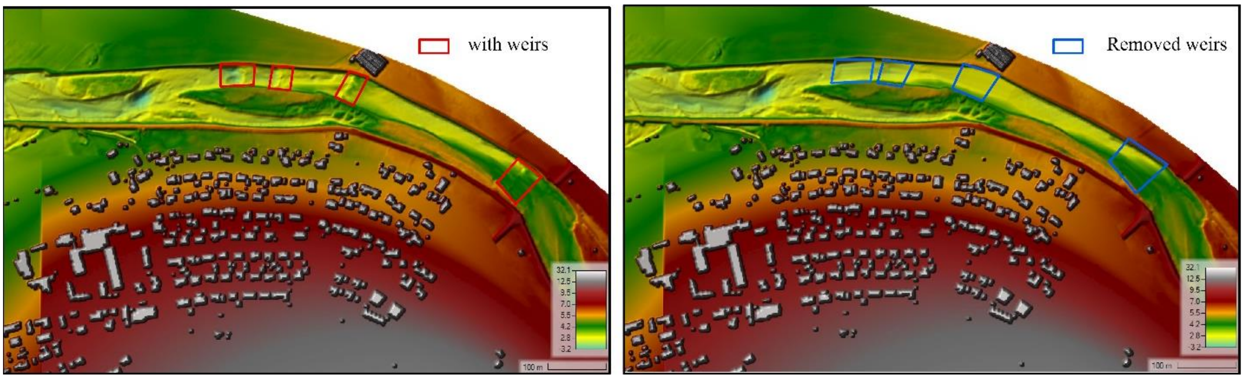


Figure 4. 13 The weirs where adjustments are made, before (left) and after (right) the levelling.

In summary, the removal of the weirs involved the use of Hec-Ras to insert cross-sections and interpolate between them. Numerous cross-sections were interpolated to create a geometry, and the terrain was modified by replacing the geometry between the cross-sections, resulting in a flattened appearance. The observation of the modified terrain revealed the appearance of flat stripes, confirming the success of the interpolation process.

4.8.2 Artificial Habitat

We investigated several modifications to the current weirs in this study. We expanded on and enhanced the work that Alfredsen and Awadallah (2022) had done in Laerdal. We aimed to improve conditions for Atlantic salmon and sea trout in the weir area by replacing the current weir with scattered boulders, thus establishing an artificial habitat.

In order to accomplish this, the river bottom was flattened after the weir was entirely removed. Next, we employed an advanced weir adjustment technique that comprised making openings in the already-existing weir. The intention behind this process was to create a fish-friendly environment in addition to modifying the weir. The purpose is to enhance the habitat around the weir for Atlantic salmon.

4.8.3 Boulders Configuration

We figured out the sizes of boulders for our Hec-Ras model by measuring real rocks in Lærdal during a site visit. This data was essential for deciding how to arrange rocks in our model. The distribution of these rocks is randomly placed corresponding to the rocks found in nature.

To do this, we used both ArcGIS Pro and Hec-Ras. Initially, we started with the removed weir DEM, replacing it by strategically placing boulders of mixed sizes in the river. We created shapefiles for these rocks using ArcGIS Pro, clipping the shape files using the flattened terrain. The GIS system was then used to transform them into 3D models by elevating their heights through a raster calculator in ArcGIS. After observing the real boulders in Lærdal, we assigned elevations of 0.5 to 1.3 based on observation data and reasonable original elevation.

These rocks have a random size distribution, helping create a flow path that addresses various environmental erosion concerns in addition to improving fish potential.

Figure 4. 14 Random boulder arrangement: ArcGIS Pro

4.8.4 Modelling of Artificial Rocks

As highlighted earlier, to incorporate rocks into our model, we primarily utilized ArcGIS. We drew rock shapes, created a shapefile, and clipped it with the flattened weir DEM. Using the mosaic to new raster tool, we merged the clipped rocks with the DEM. ArcGIS then adjusted the rocks heights using the raster calculator tool, setting some at 1m, 1.23m, and 0.5m. Practical measurements of rock sizes were taken using a Digital Caliper.

Establishing a boundary with accurate coordinates (ETRS 1989 UTM Zone 32N), we created a new shapefile named rocks. We drew polygons of various randomly sized shapes and imported them into the terrain. Random drawing proved more effective than using cylinders, hexagons, or triangles. Although Hec-Ras also has a similar capability, it caused issues with the virtual terrain in Hec-Ras 6.1 (Alfredsen and Awadallah, 2022). Further testing demonstrated that in Hec-Ras 6.3.1, the simulation worked more effectively.

Our experimentation involved combining high and low stones to assess density and observe flow differences. This approach led to the inclusion of stones with various sizes and shapes.

We calculated the surface area of the modeled artificial rocks using ArcGIS. By adjusting their heights, we determined the volume of a typical rock, as detailed in table 5.6.

In the process of replacing the weir cross section with stones, the flow moves between the rocks, resulting in a flat bottom, as depicted in the area below.

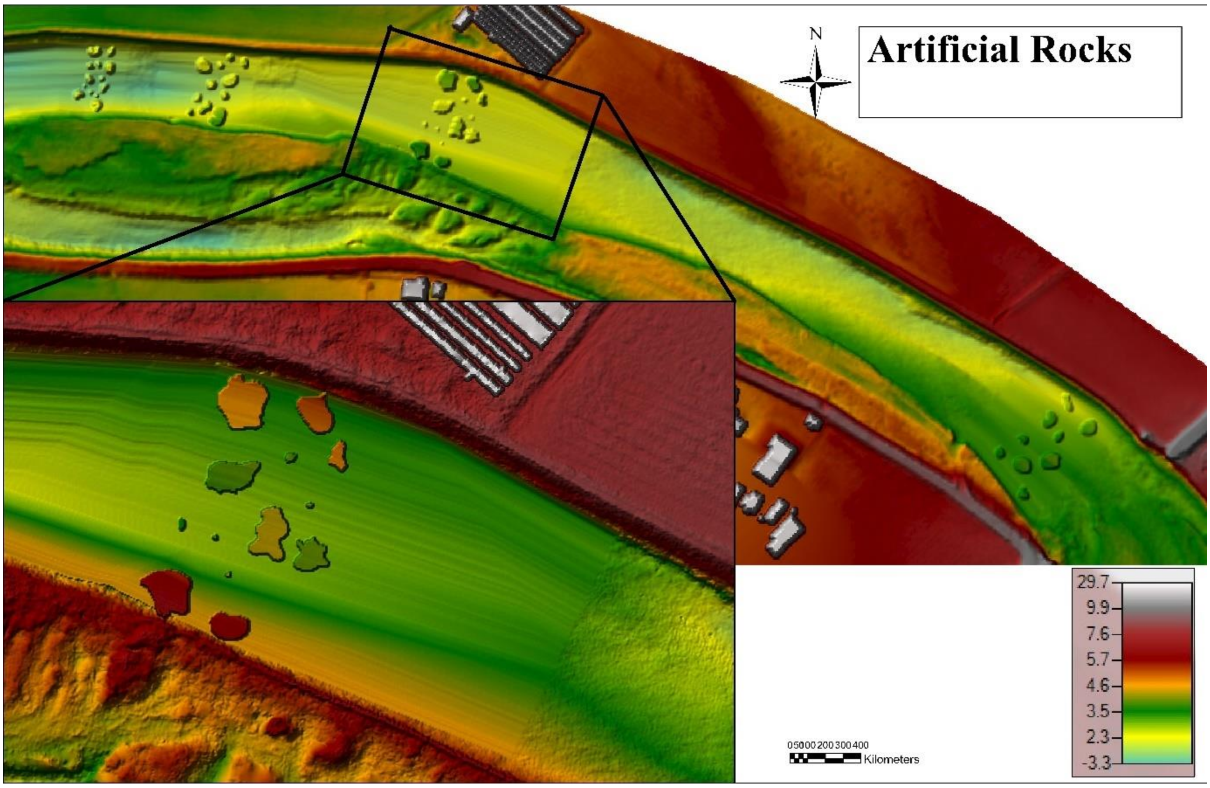


Figure 4. 15 The rocks distributed in place of weir after taking out the weir in Hec-Ras 6.3.1

4.8.5 Submerged Weir

Some other ideas of existing weir modifications around the weir Øye that come up in the project also tested out. One of those things we looked at here is we make a submerged weir at the specified locations on the shallower part of the weir which is near to the downstream end of the weir. Surrounding with randomly placed rocks upstream and downstream of the weir.

When we flattened out the weir, it became deeper, and we needed to secure the bottom. One solution we considered was creating a submerged weir in the middle of the cross-section. This submerged weir, 30 cm high and 10 m wide, serves as an even barrier across the river. We surrounded it by placing large rocks at the bottom. This option was explored in the project.

We have evaluated the modification of weirs, for the selected weirs. Each weir is individually assessed, and we used ArcGIS Pro as a raster editor for all modifications to the weirs.

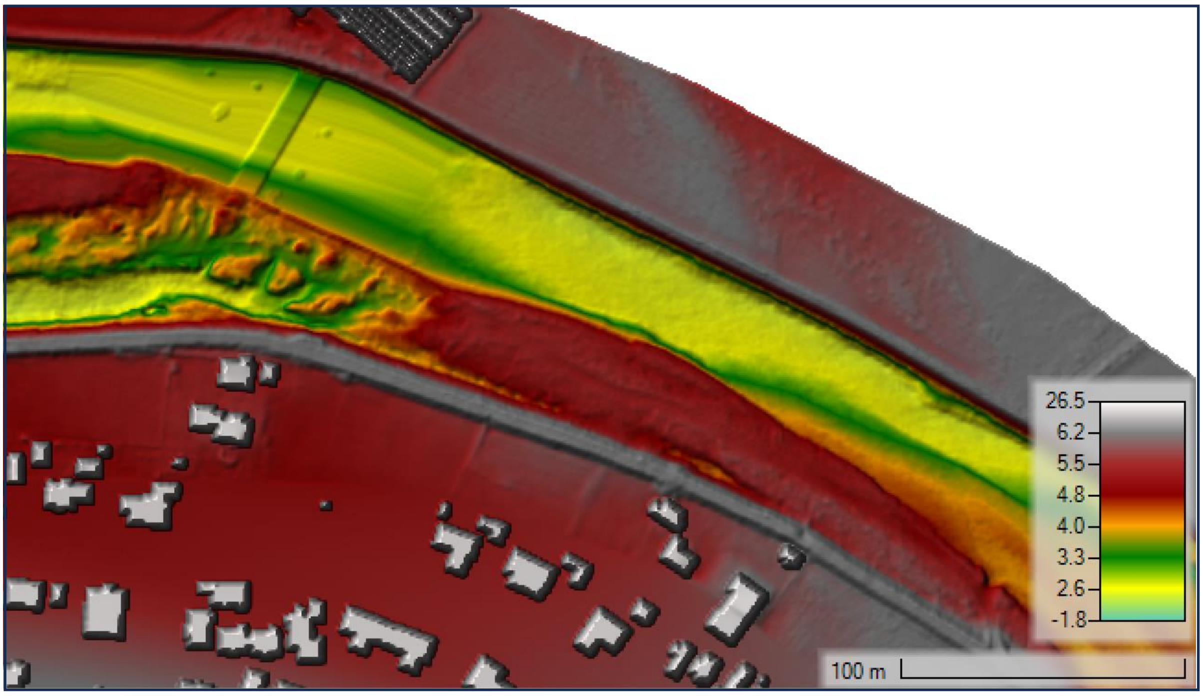


Figure 4. 16 terrain with Submerged weir, shows weir at øye.

Various endeavors are underway to mitigate the need for the power company to increase the minimum flow. Investing in activities such as dredging, weir removal, and rock placement is a more cost-effective approach compared to raising the water level and minimum flow, which would significantly impact production costs.

The implementation of a Hec-Ras 2D model was essential for comprehensive planning, especially when considering scenarios like a 100 m^3/s flow rate, which would result in water accumulation behind the island further downstream. In assessing the local weir, simulations of low flows were conducted to establish a baseline for further analysis both upstream and downstream.

4.8.4 Reducing the Height of The Weir Crest

Another option explored here involves lowering the bottom from the upper profile to the lower profile, maintaining the deeper part in the lower section. This is achieved by adding randomly distributed rocks upstream of the weir. The goal is to increase the drop through the current weir area and remove fines from the region near the threshold crown. The choice of method required adaptation for each weir, and for this assessment, the solution depicted in the figure below illustrates what was tested for the Øye weir.

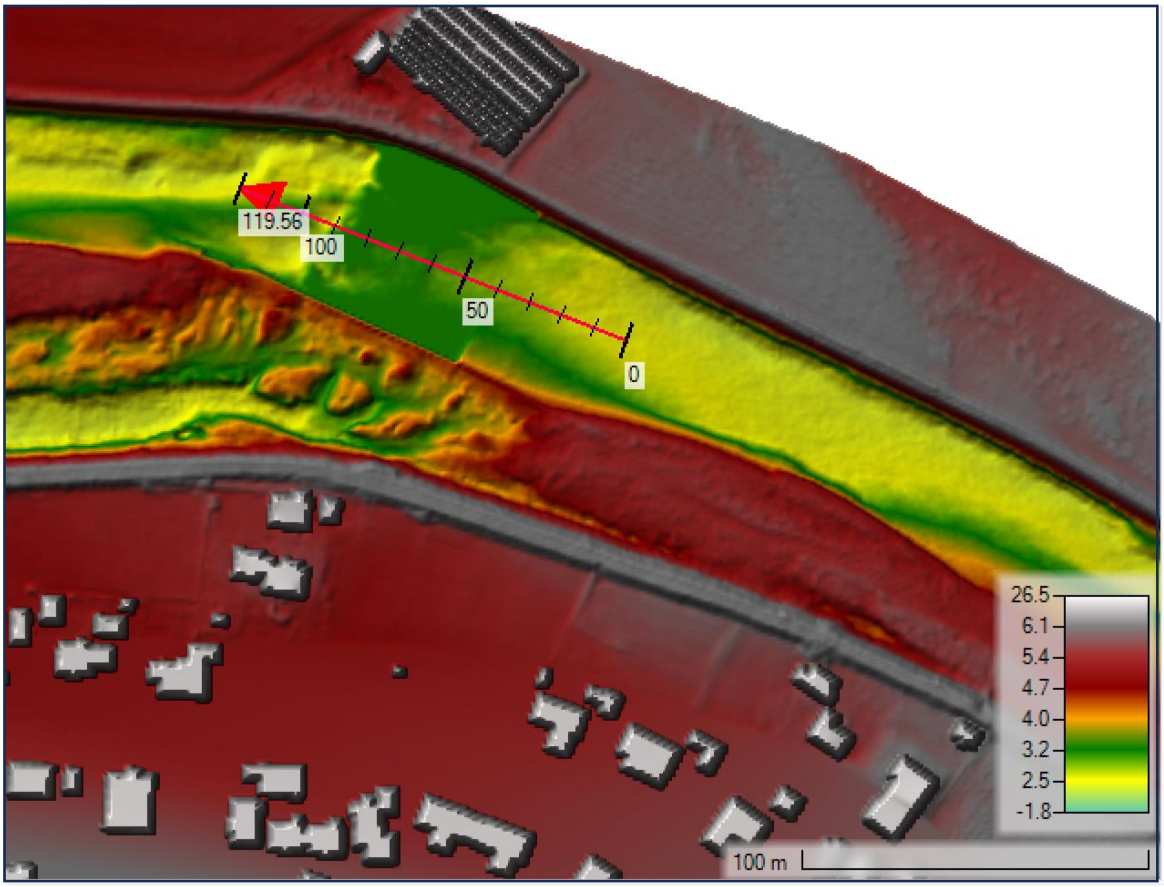


Figure 4. 17 terrain with reduced weir crest, shows weir at øye.

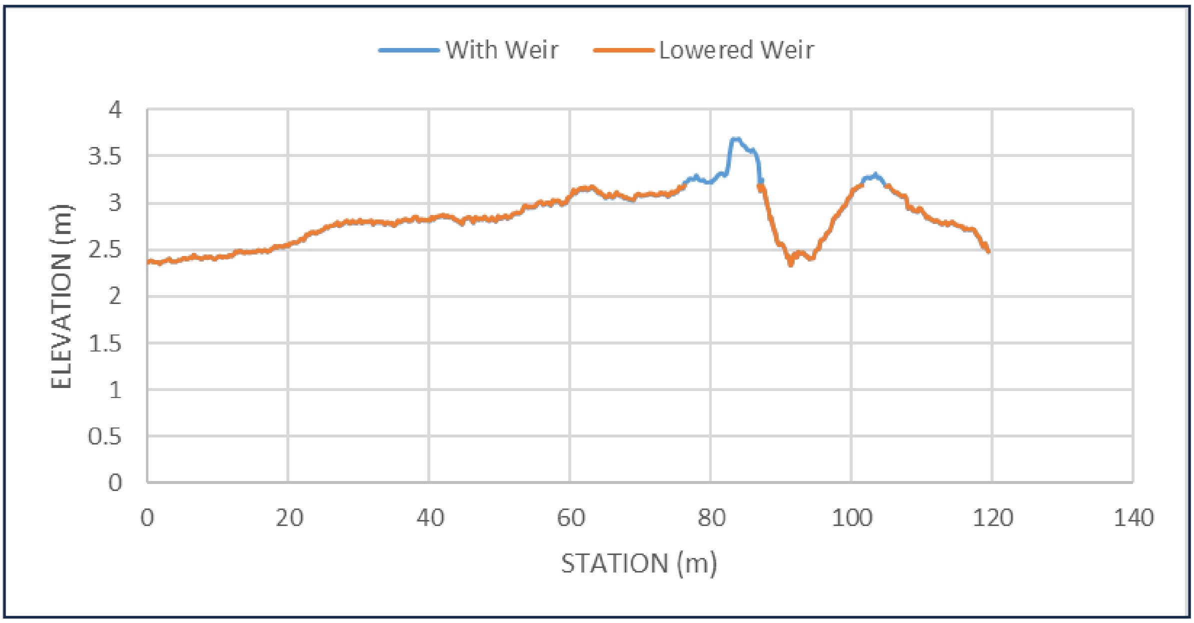


Figure 4. 18 Terrain Plot for the profile line shown in figure 4.17.

4.9 Defining Sediment Layer

Sediment transport potential is assessed based on grain size fractions, enabling the simulation of hydraulic sorting and armoring. The model offers features like modeling a complete stream network, channel dredging, various levee and encroachment alternatives, and utilizing different equations for sediment transport computation. Its primary purpose is to simulate long-term trends of scour and deposition resulting from changes in water discharge, stage frequency and duration, or channel geometry modifications. This system finds applications in evaluating deposition in reservoirs, designing channel contractions for navigation depth maintenance, predicting dredging impact on deposition rates, estimating maximum scour during floods, and assessing sedimentation in fixed channels (Brunner, 1995).

In the Sediment Bed Material Layer in RAS Mapper, Sediment Bed Material Types are defined as polygons. These polygons can overlap to override regions and are drawn separately for each element, such as the initial weir, new modeled boulders, concrete wall, and riverbed. Bed Layer Groups, associated with Bed Gradation Templates or Non-erodible Surfaces, are defined within the 2D Bed Gradations (Beta) tab of the Sediment Data editor. Non-erodible surfaces, like bedrock or structures, are specified within a Bed Layer Group and associated with Sediment Bed Material. These surfaces are not enforced at computational faces and are specified at computational cells (Stanford Gibson, 2023).

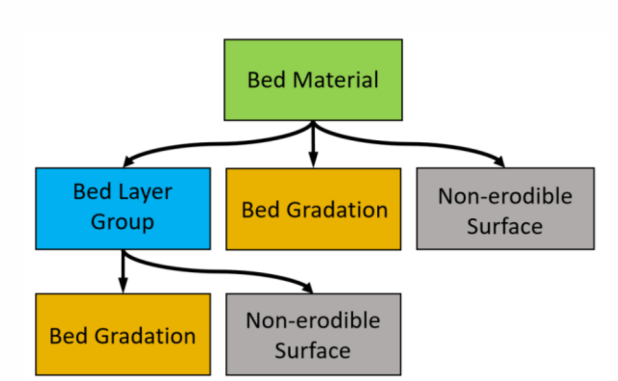


Figure 4. 19 Bed Gradation Template Editor (Hec-Ras 2D sediment user manual)

Bed gradations are specified through the Define/Edit Bed Gradation button, representing sediment grain class sizes from project bed samples. They serve as a database of different sediment types; we defined the sample with the % Finer form. % Finer outlines the sample using a cumulative bed gradation curve with percent finer based on the upper bound of each grain class.

The Initial Conditions and Transport Parameters, defined in the Sediment Data editor, specify the transport function, sorting method, and fall velocity method for the entire model. For this study, an equilibrium load was chosen as a boundary condition. The Equilibrium Load boundary condition computes the inflow sediment load as the equilibrium sediment load, assuming a zero-gradient concentration normal to the boundary (Gibson S, 2023). The detailed settings and related assumptions are provided in the Appendix F.

In our case, sediment boundary conditions were considered for different elements such as boulders, concrete walls, and bed material. Bed material, erodible with laboratory-tested grain size distributions, was contrasted with non-erodible boulders and concrete walls. Different sediment curves were defined accordingly.

The river reach featured a sediment curve with fine material like gravel, while large boulders around the weir were considered non-movable by the flow, designated as non-erodible. To differentiate between erodible and non-erodible surfaces, rocks, and a concrete wall were defined as non-erodible surfaces in Hec-Ras. Sediment distribution curves were established for different reaches.

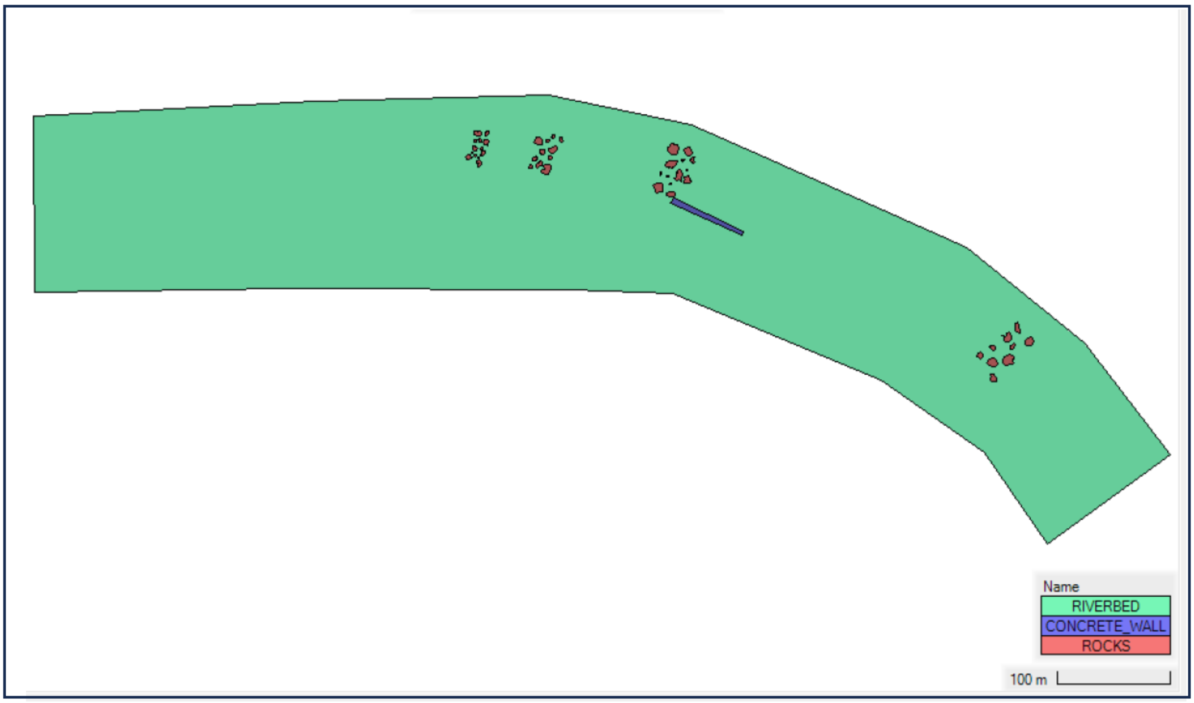


Figure 4. 20 Scenario-Modeled Boulders, Classification Polygons in Ras Mapper

Sediment calculations were executed, incorporating initial grain size distributions for the sites. This facilitated the assessment of scour and erosion scenarios with and without the weir, and with modeled artificial rocks, revealing significant differences.

For realistic sediment simulations, a hydrograph of floods (240 m^3/s) was employed, evaluating variations with the weir, without the weir, and with artificial rocks. These simulations aimed to understand differences in sediment transport.

During a site visit to Lærdal, insights into the sediments were gained, allowing realistic calculations on the potential effects of weir removal on erosion in the weir basin. The focus was on understanding the sediments mobilized during flood discharge, both with and without the weir.

4.9.1 Concrete Wall Around Weir Øye (non-erodible)

To maintain continuity in the model, we ensured that the water flows over the concrete wall and into the side channel. Defining the concrete wall as a non-erodible surface was crucial because, without this designation, it could impact the flow pattern, potentially causing water to flow out of the grid. This observation is evident in the aerial image, and it's important to preserve the concrete wall without erosion or disappearance. Based on the narrower width observed in the aerial image from Norgeibilder.no, we created a concrete wall with a defined non-erodible surface when setting up the sediment bed material layer in Hec-Ras.

Figure 4. 21 concrete wall defined as non-erodible surface, Norge i bilder

5. Results and Discussion

Building upon previous efforts to create an artificial fish habitat (Alfredsen and Awadallah, 2019), we focused on comparing scenarios with a weir, without a weir, and with distributed rocks. The subsequent plots provide insights into water depth, velocity patterns, and recirculation patterns. It's important to note that the flood condition used for these assessments was 240 m^3/s, aligning with the mean flood in Lærdal.

We then compared variation of shear stress and bed changes for three conditions: the current state of the weir, without the weir, and the presence of an artificially distributed rocks habitat. These comparisons were made across a mean flood scenario after conducting the sediment calculations.

5. Analysis of Flow

Following the modifications, simulations were carried out to observe resulting flow patterns. Thes following simulations covered various discharge scenarios, providing insights into the fish population and sites behaviour under conditions of low, medium, and mean flood scenario. Our analysis includes a detailed assessment of the anticipated changes in the movement of fine materials in the area upon weir removal, based on comprehensive sediment simulations.

5.1The current condition with Initial Weir

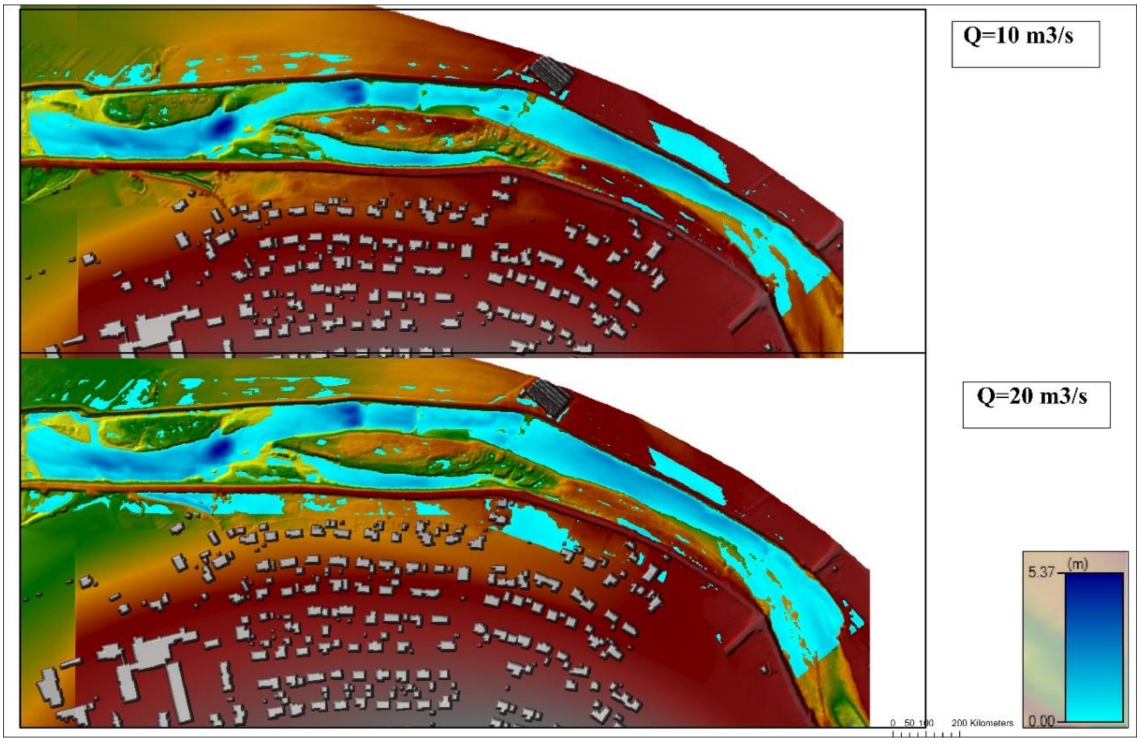


Figure 5. 1 Water Depth with initial weir for Q= 10 m^3/s and 20 m^3/s

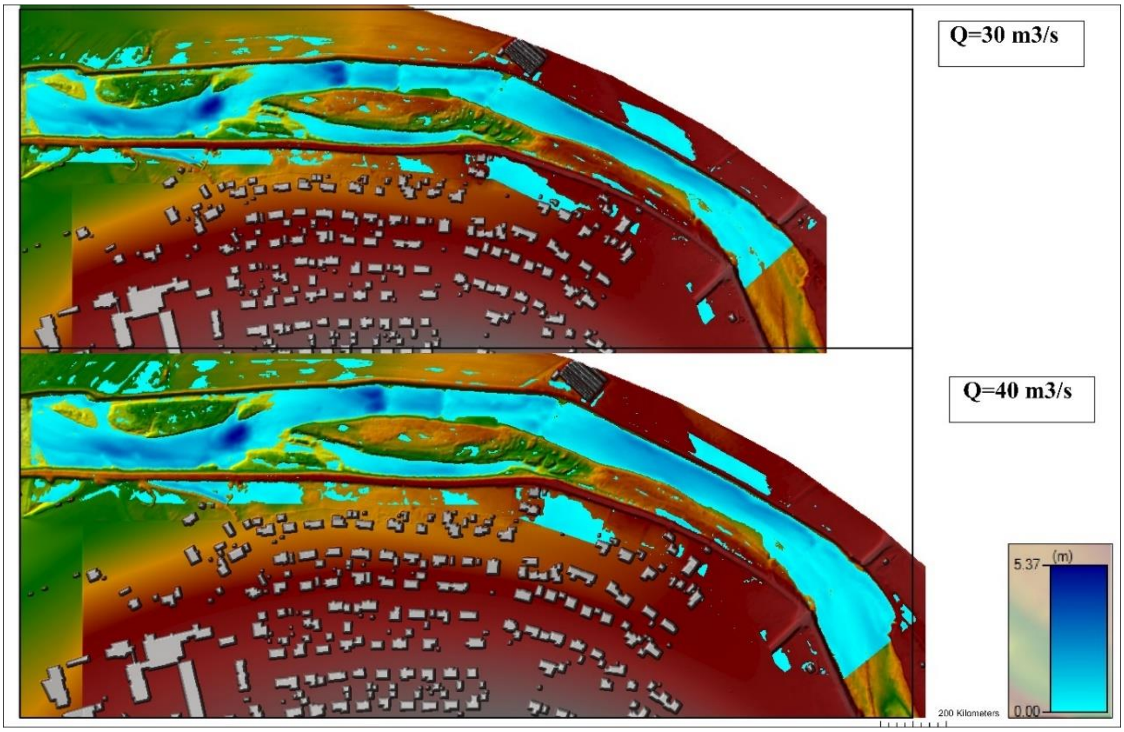


Figure 5. 2 Water Depth with initial weir for Q= 30 m^3/s and 40 m^3/s

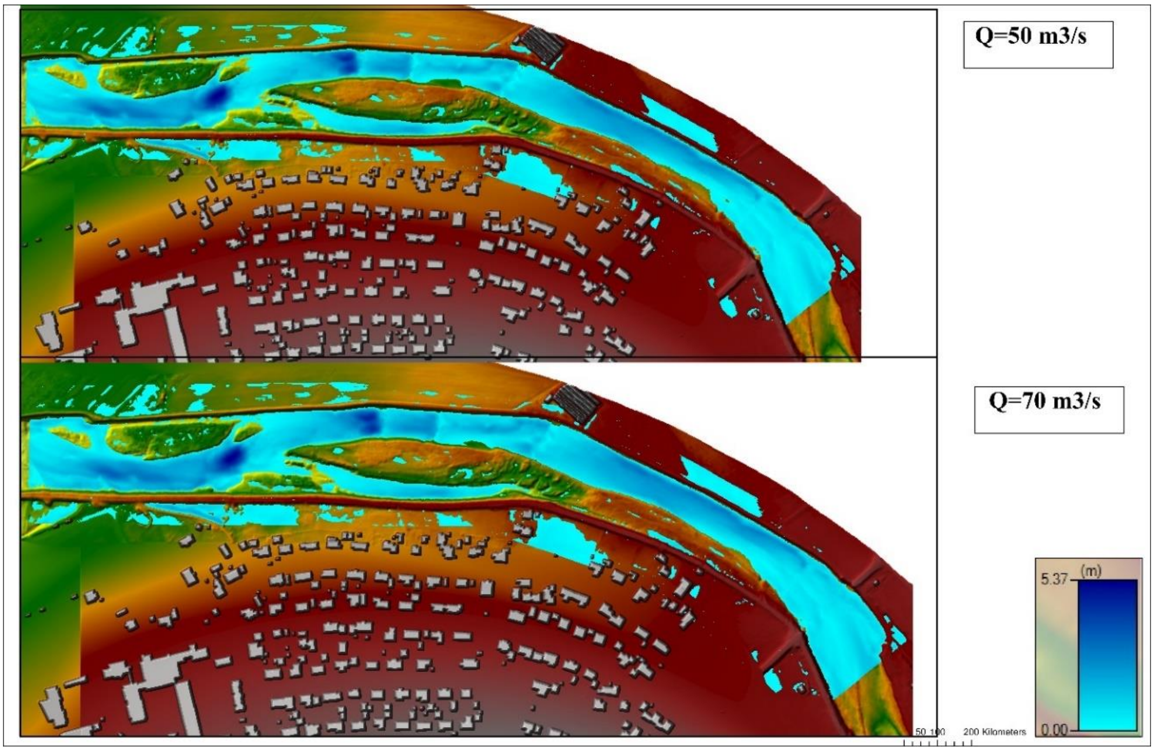


Figure 5. 3 Water Depth with initial weir for Q= 50 m^3/s and 70 m^3/s

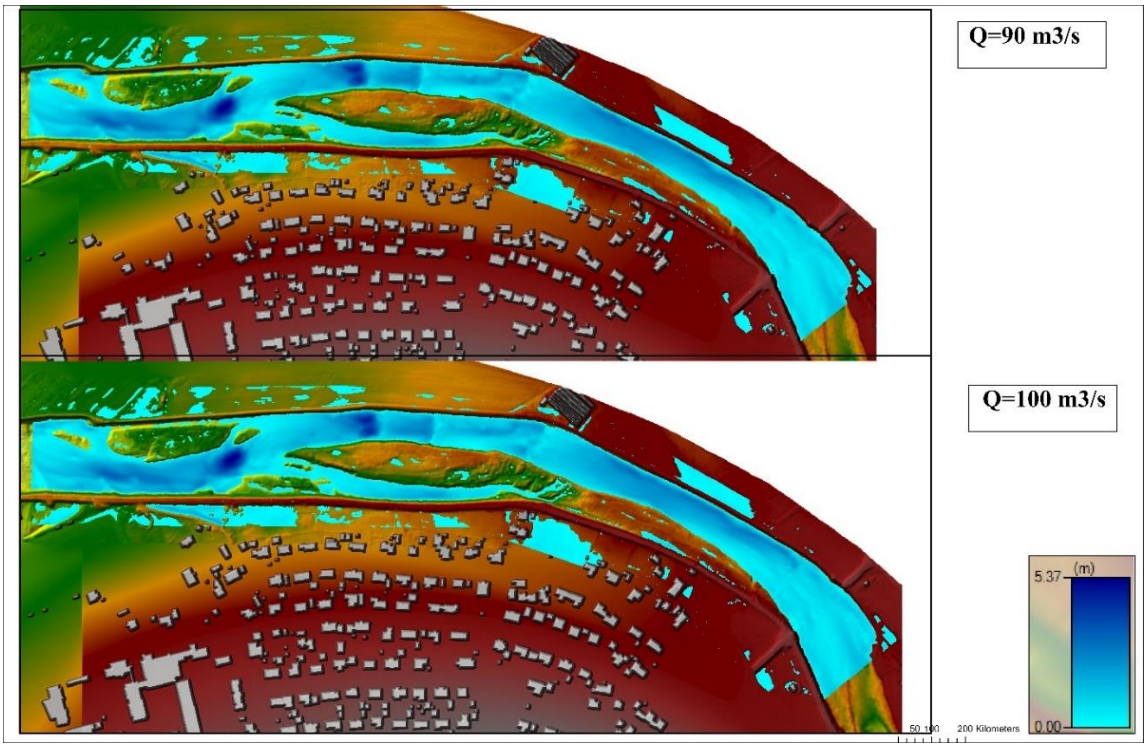


Figure 5. 4 Water Depth with initial weir for Q= 90 m^3/s and 100 m^3/s

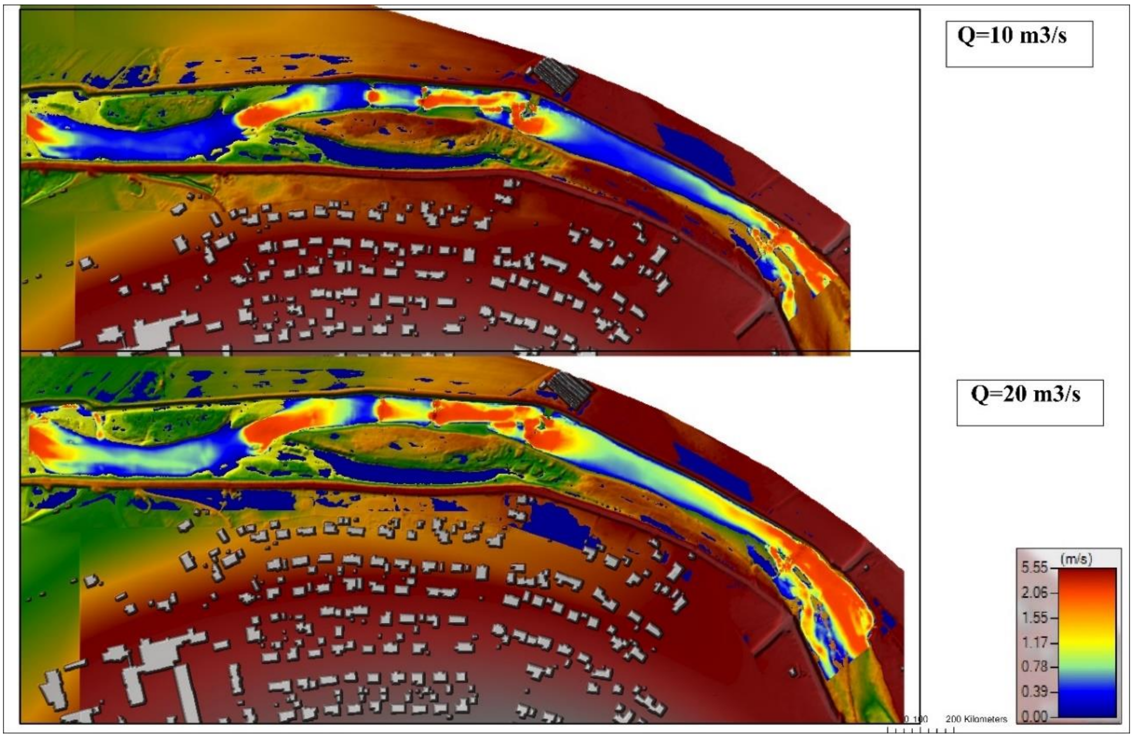


Figure 5. 5 velocity pattern with initial weir for Q= 10 m^3/s and 20 m^3/s

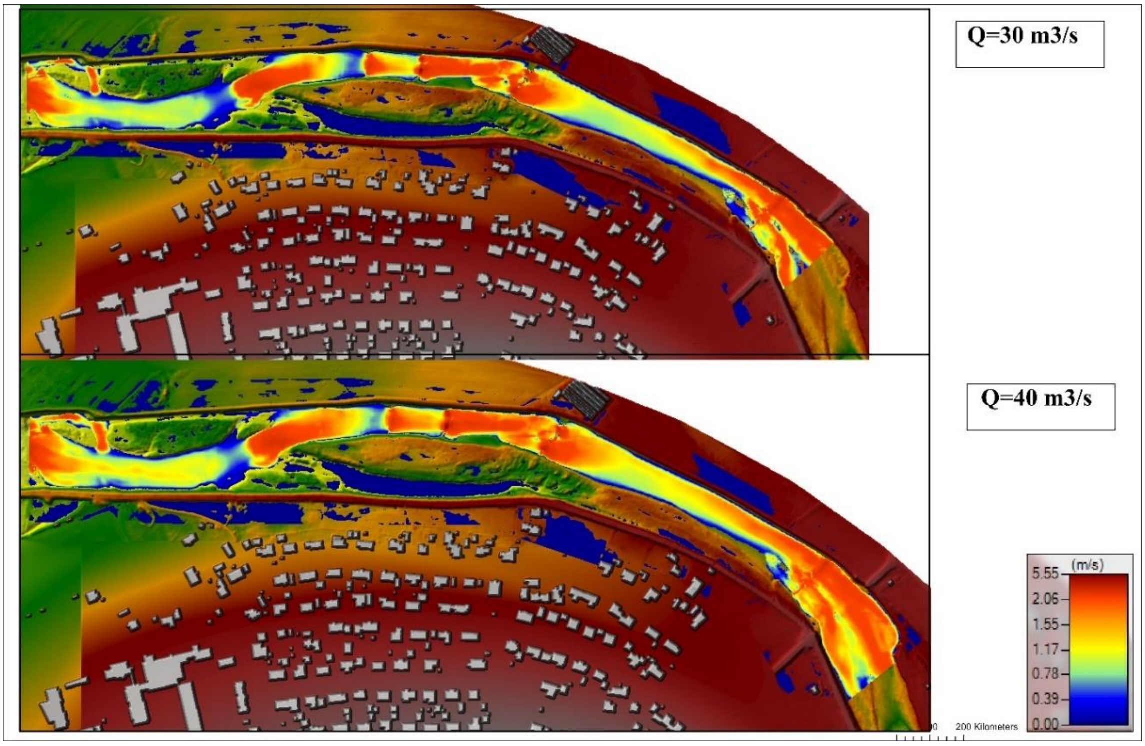


Figure 5. 6 velocity pattern with initial weir for Q= 30 m^3/s and 40 m^3/s

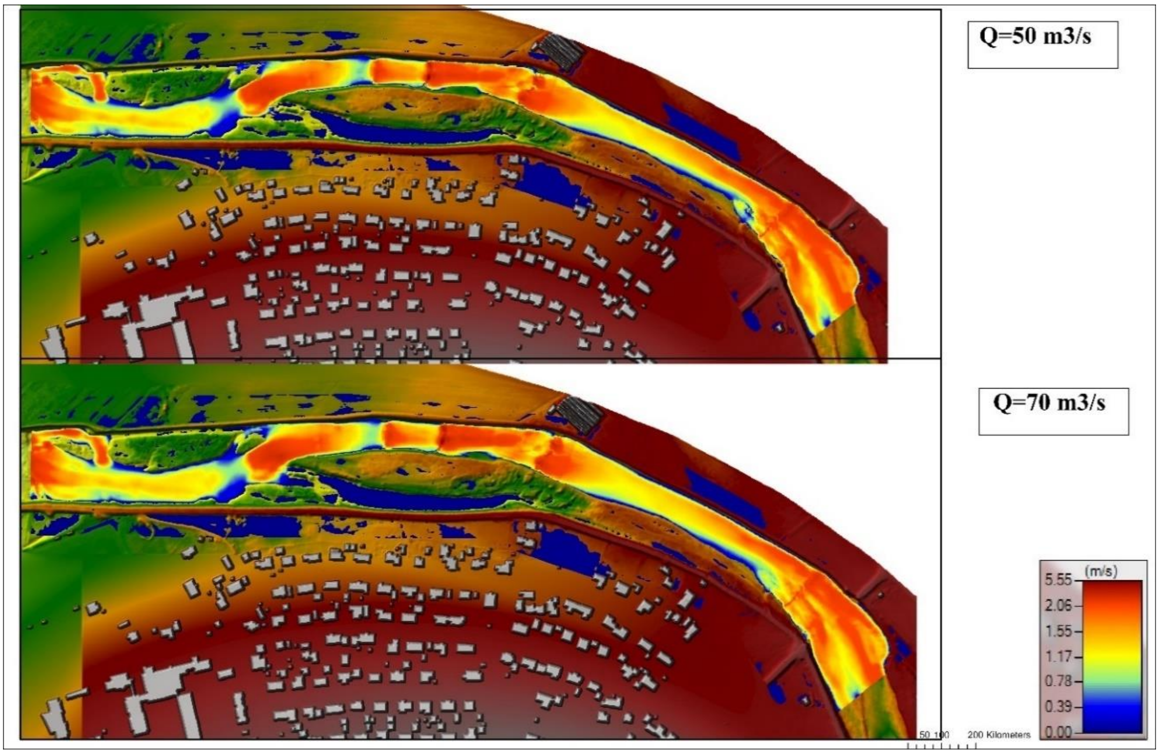


Figure 5. 7 velocity pattern with initial weir for Q= 50 m^3/s and 70 m^3/s

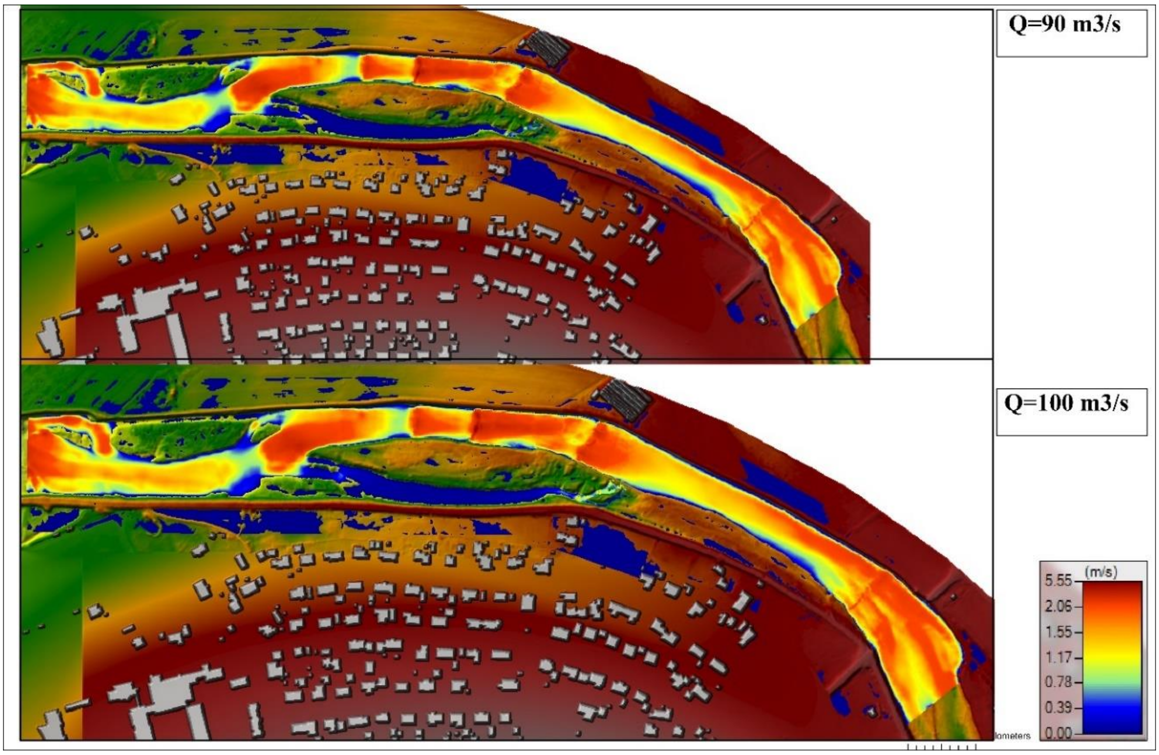


Figure 5. 8 velocity pattern with initial weir for Q= 90 m^3/s and 100 m^3/s

5.1 Removed Weirs

Fish are sensitive to sudden changes in their environment, such as shifts in temperature, water depth, velocity, or flow patterns. The maps clearly shows that the flow intensifies immediately behind the weirs in this configuration. The primary concern is that the existing terrain acts as an obstacle to ecological continuity, hindering fish from migrating upstream in the river. To address this issue, it becomes essential to examine the terrain without the weir and explore potential modifications that can enhance the fish habitat and allow for smoother upstream movement.

5.1.1 Analysis of Depth Maps on Removed Weir

If we decide to take out the weir, the flow won't be controlled anymore, and there's a higher risk of flooding, especially during higher floods. The simulations after removing the weir show that in the middle of the weirs, the depth profile indicates a slight shallowness in the lower part of the structure. After several attempts, we managed to make the upstream area relatively flat and aesthetically pleasing, adjusting the deepest channels and holes accordingly. The water speed increases after the weir removal. Additionally, during periods of high-water flow, the water level becomes too high, posing a risk of flooding to the floodplain.

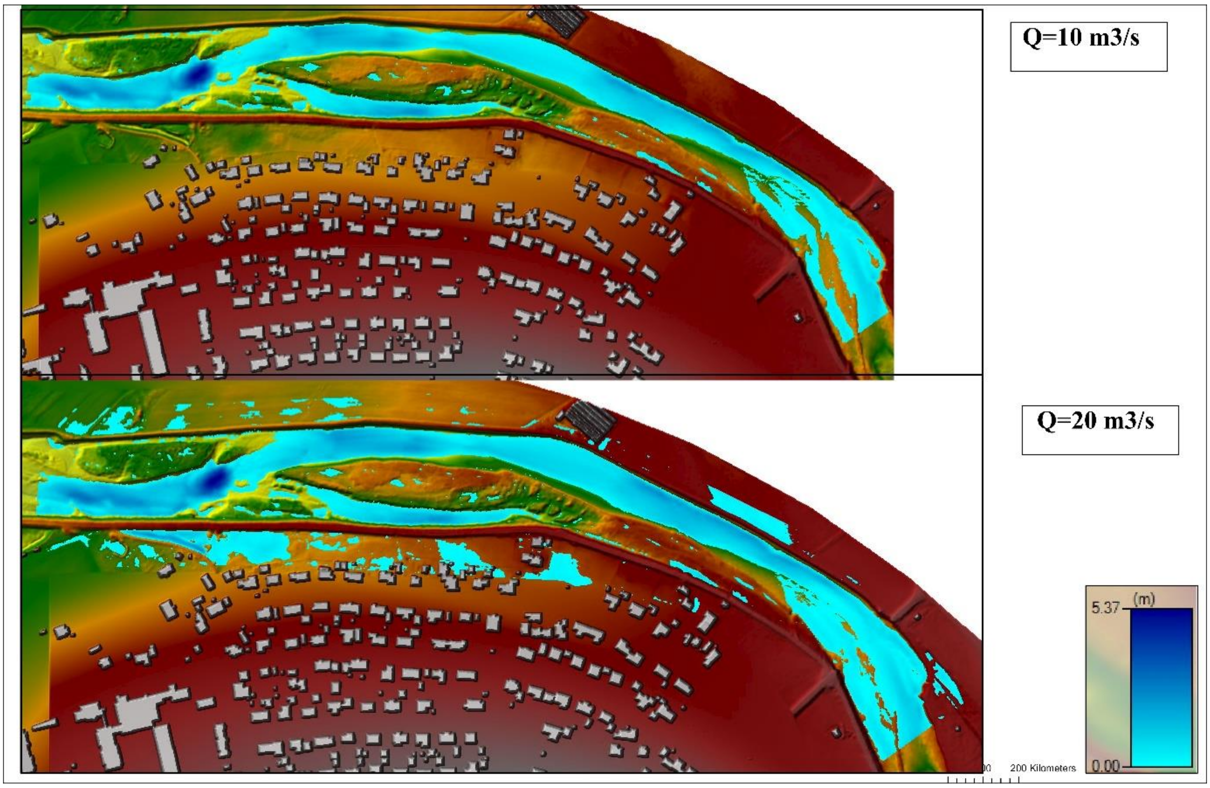


Figure 5. 9 Water Depth after the weir is removed for Q= 10 m^3/s and 20 m^3/s

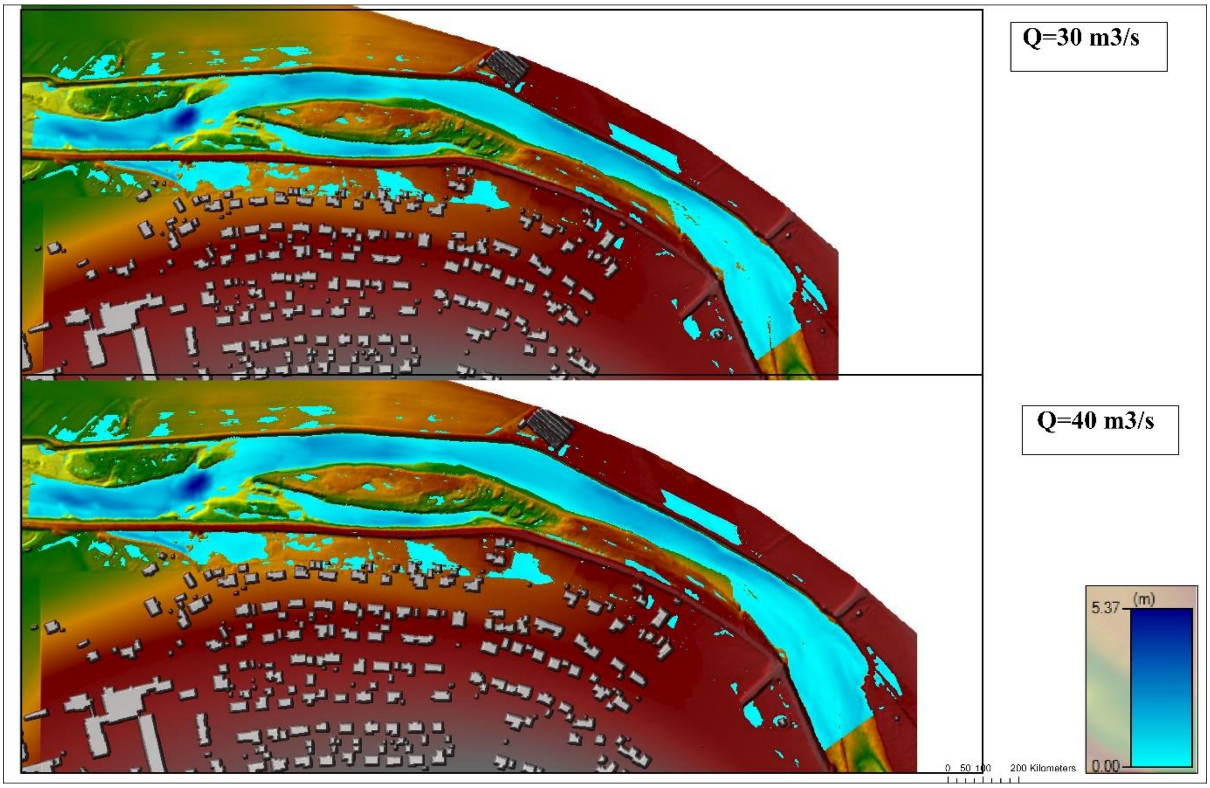


Figure 5. 10 Water Depth after the weir is removed for Q= 30 m^3/s and 40 m^3/s

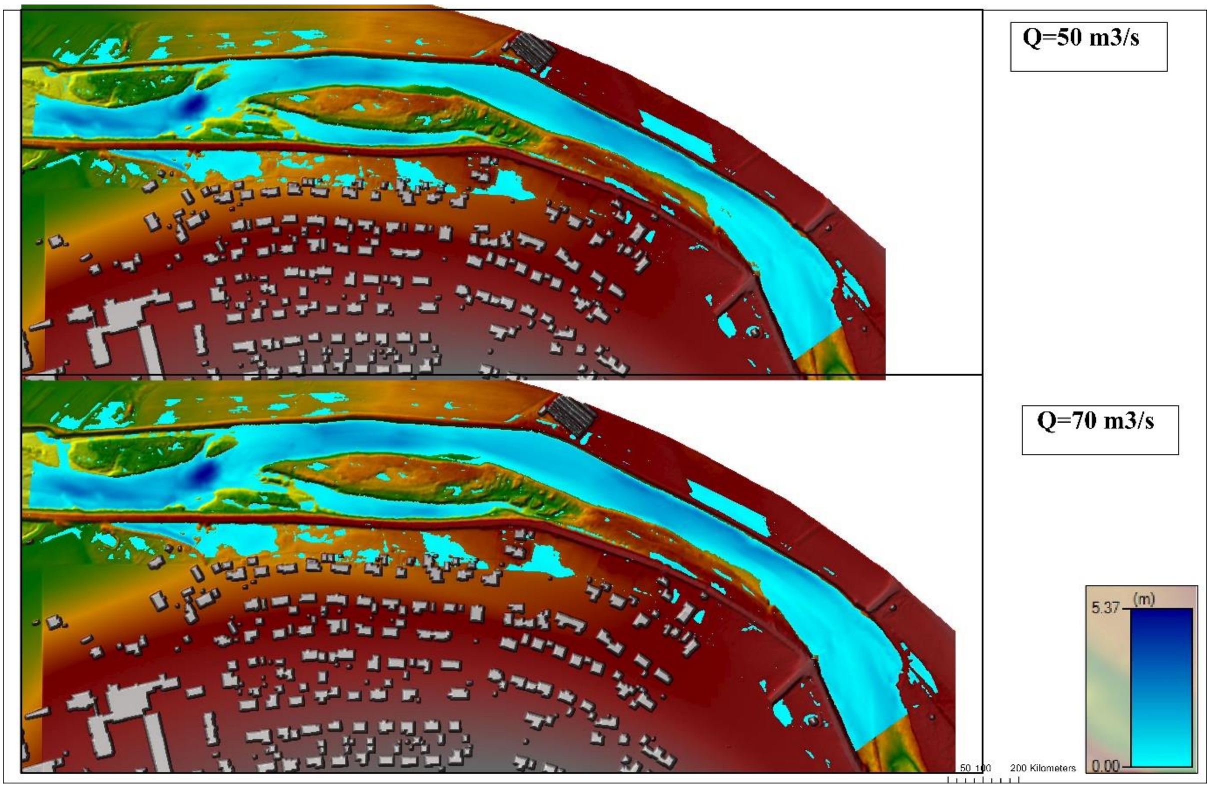


Figure 5. 11 Water Depth after the weir is removed for Q= 50 m^3/s and 70 m^3/s

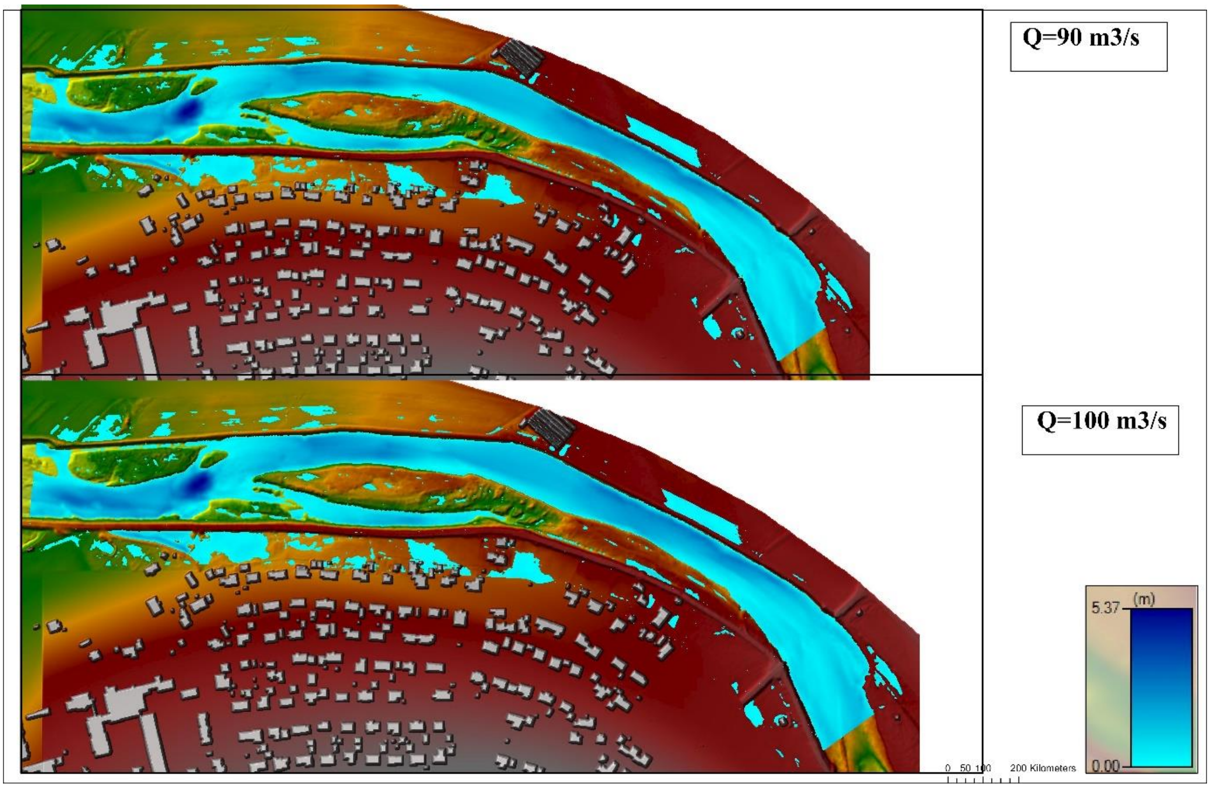


Figure 5. 12 Water Depth after the weir is removed for Q= 90 m^3/s and 100 m^3/s

Even though salmonids can now move upstream, they have unfortunately lost some of their essential habitats and hiding spots, making them more vulnerable to predators and exposure to light. The ultimate remedy involves strategically placing boulders in the riverbed to restore these critical shelters, all while maintaining a controlled flow.

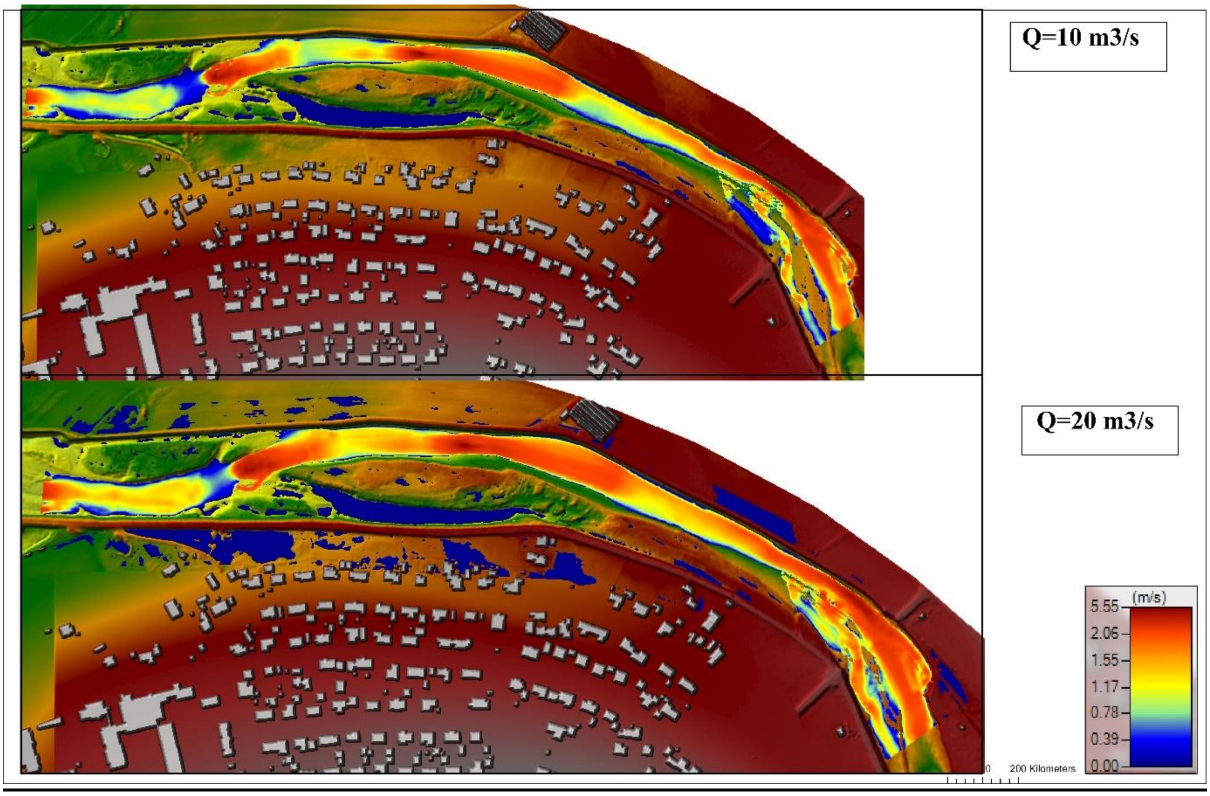


Figure 5. 13 Velocity pattern after the weir is removed for Q= 10 m^3/s and 20 m^3/s

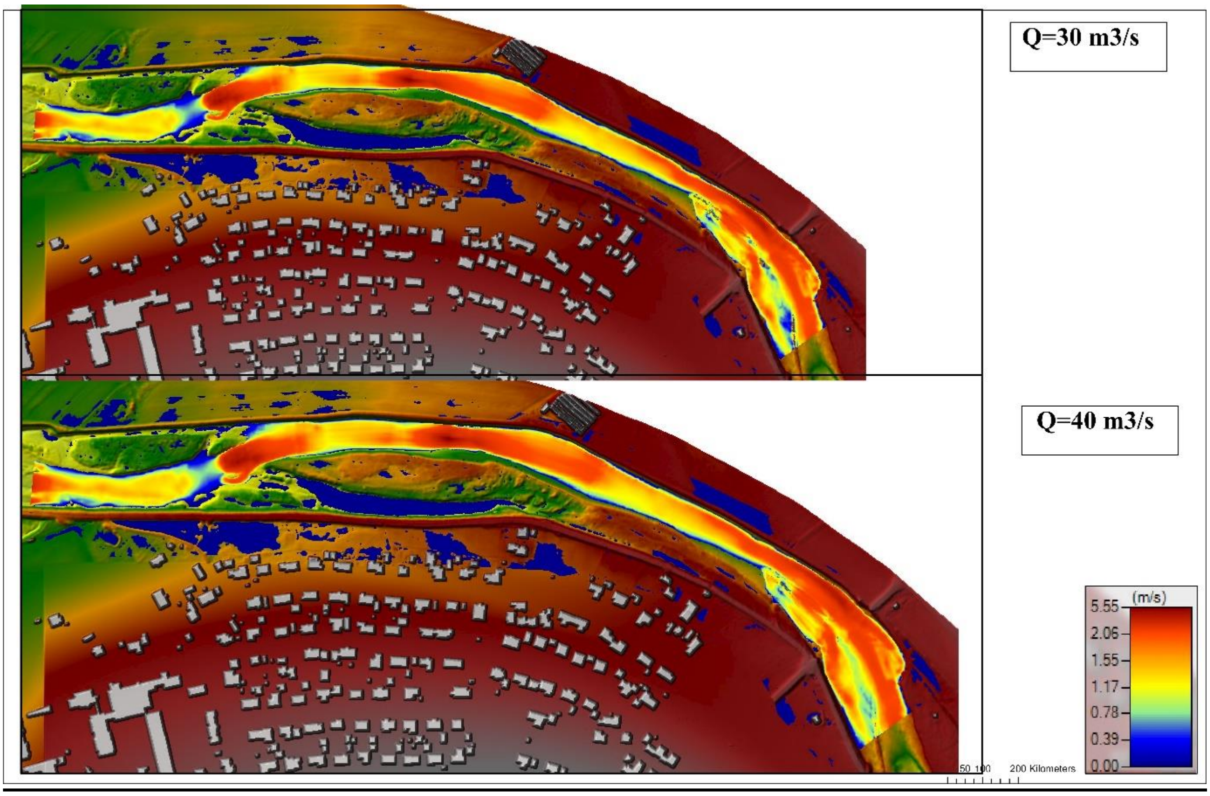


Figure 5. 14 Velocity pattern after the weir is removed for Q= 30 m^3/s and 40 m^3/s

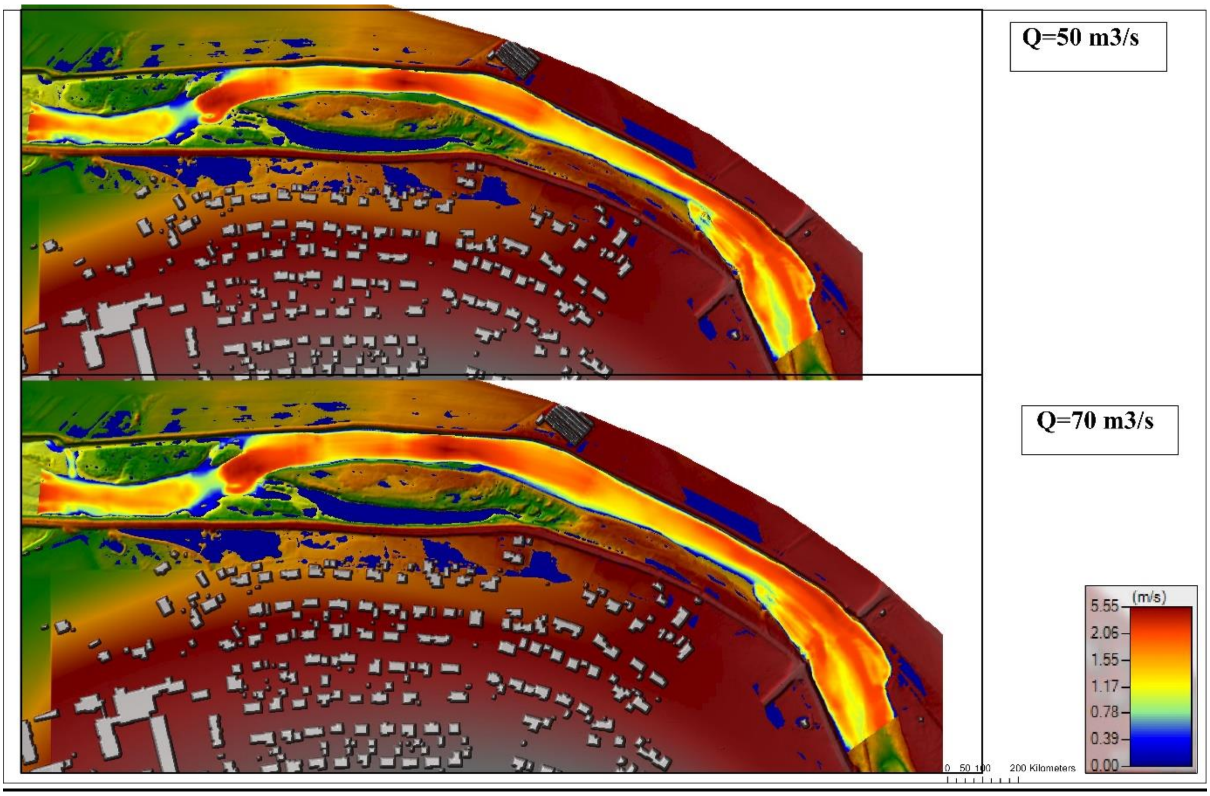


Figure 5. 15 Velocity pattern after the weir is removed for Q= 50 m^3/s and 70 m^3/s

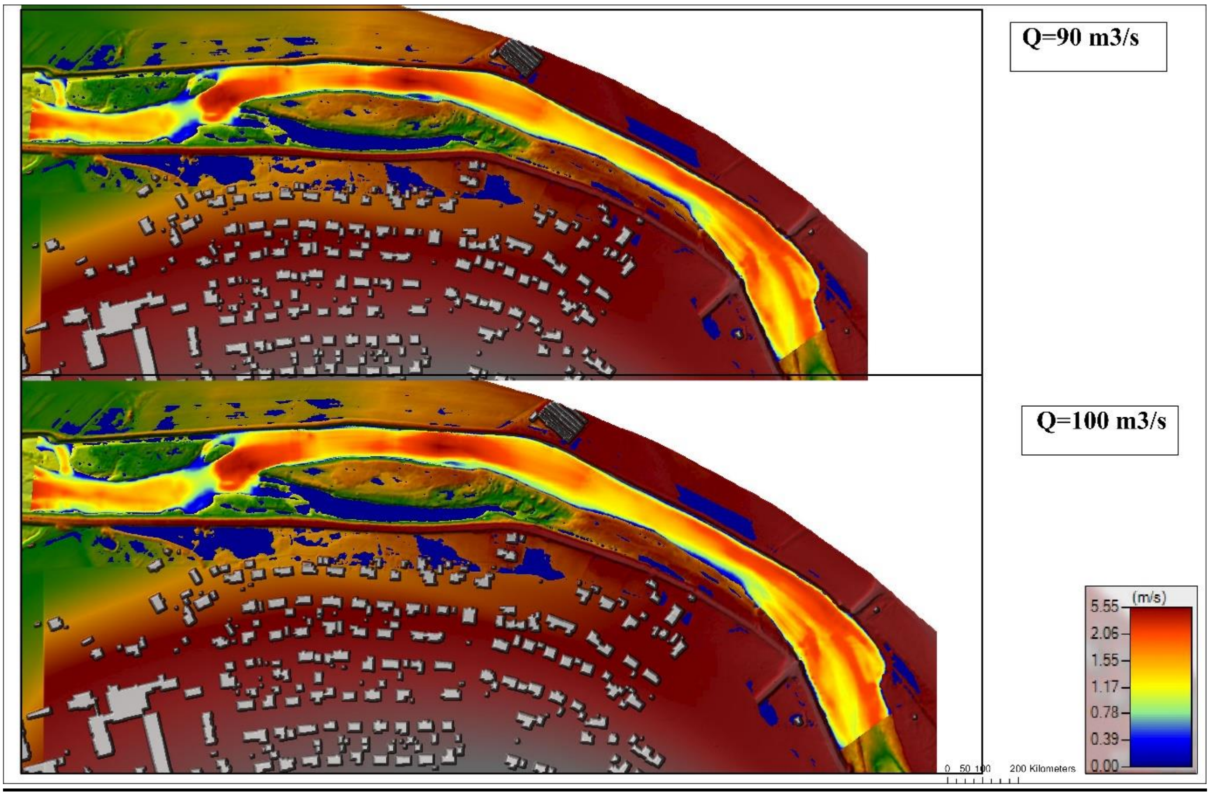


Figure 5. 16 Velocity pattern after the weir is removed for Q= 90 m^3/s and 100 m^3/s

5.2 Distributed Rocks

We designed the rocks to impact the flow, which is their intended purpose. Instead of having a completely even and flat flow over the removed weir area, we strategically placed rocks to create a habitat. In practical terms, when implementing this, it's crucial to place rocks to protect the river from erosion during the excavation process. This is necessary because we will be affecting the layer of rocks in the original river.

In an engineering perspective, the goal is to stabilize the river and prevent excessive erosion when modifying the site by removing the weir and placing stones. The idea is to use rocks or something similar, like sunken stones, to anchor the river in place. This ensures that the changes we make, such as digging and removing the weir, don't turn the site into a highly erodible area.

This study focuses on hydraulic effects, rather than considering issues like ice formation at the bottom moving rocks when placing weirs. The hydraulic effects are essential for creating a habitat and sustaining fish populations. From an engineering standpoint, it's crucial to ensure the stability of the construction. Therefore, the rocks should be securely set into the river. In some cases, drilling holes through rocks is done to prevent them from moving or sliding away. (Fleldstad, 2011) The potential motion of these boulders during a mean flood is assessed in below sections.

5.2.1 Analysis of Flow on Modelled Artificial Rocks

With a minimum discharge of 10 m^3/s, some rocks will be submerged while others stick out. Simulations were conducted for low flows/flat discharges, as well as medium flows. The resulting maps and comparisons are presented below.

Looking at the cross-section of stones, we varied the cross-section height of boulders from 0.5m to 1.23m height. Smaller-sized finer gravel was combined when analyzing the sedimentary transport, and larger ones of the same size as boulders were added in the place of the weir. With this rock setup, we by design created eddies. Some rocks will be submerged, and others will protrude from the water.

The random arrangement of boulders looks more natural and might not look exactly engineered, and that was intended. The mixing of different sizes was done deliberately to observe the flow going in between the rocks and the formation of eddies.

To assess the performance of the rocks, simulations were conducted for various normal discharges, ranging from 10 m^3/s to 100 m^3/s. The resulting depth and velocity maps provide a comprehensive understanding and are displayed below.

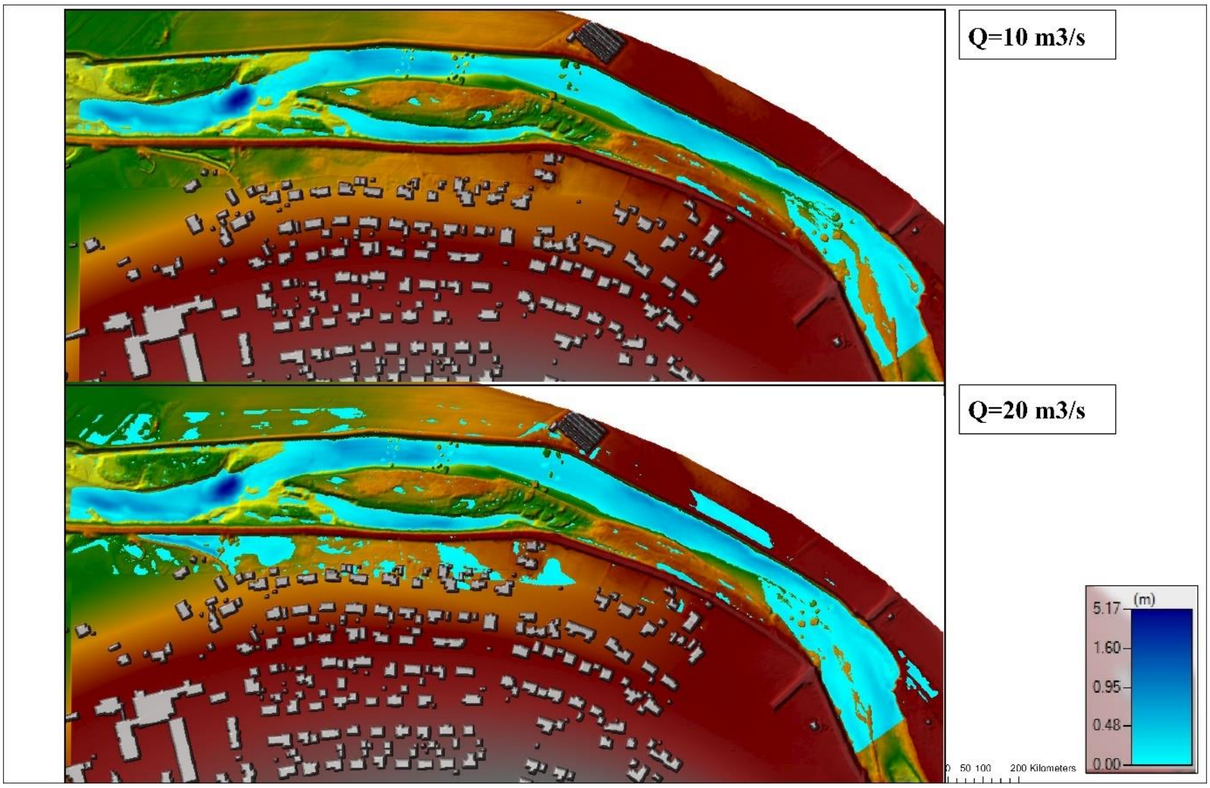


Figure 5. 17 Water Depth maps with artificial weirs for Q= 10 m^3/s and 20 m^3/s.

The low flows at 10 m^3/s, 20 m^3/s, and 30 m^3/s are critical for weir functionality, and in assessing the fish habitat's effectiveness for studying ecosystem development in unfavorable conditions. We conducted a flood simulation at 240 m^3/s to evaluate the potential impact on these rocks, testing their stability and susceptibility to erosion.

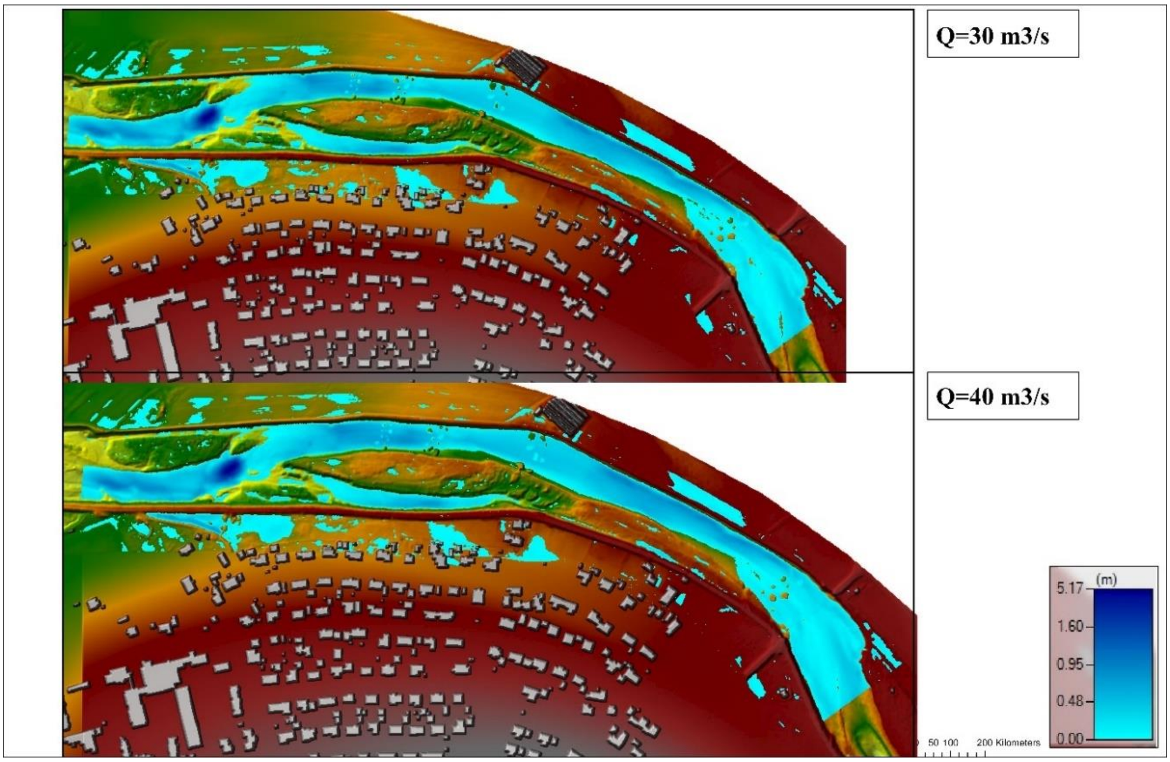


Figure 5. 18 Water Depth maps with artificial weirs for Q= 30 m^3/s and 40 m^3/s.

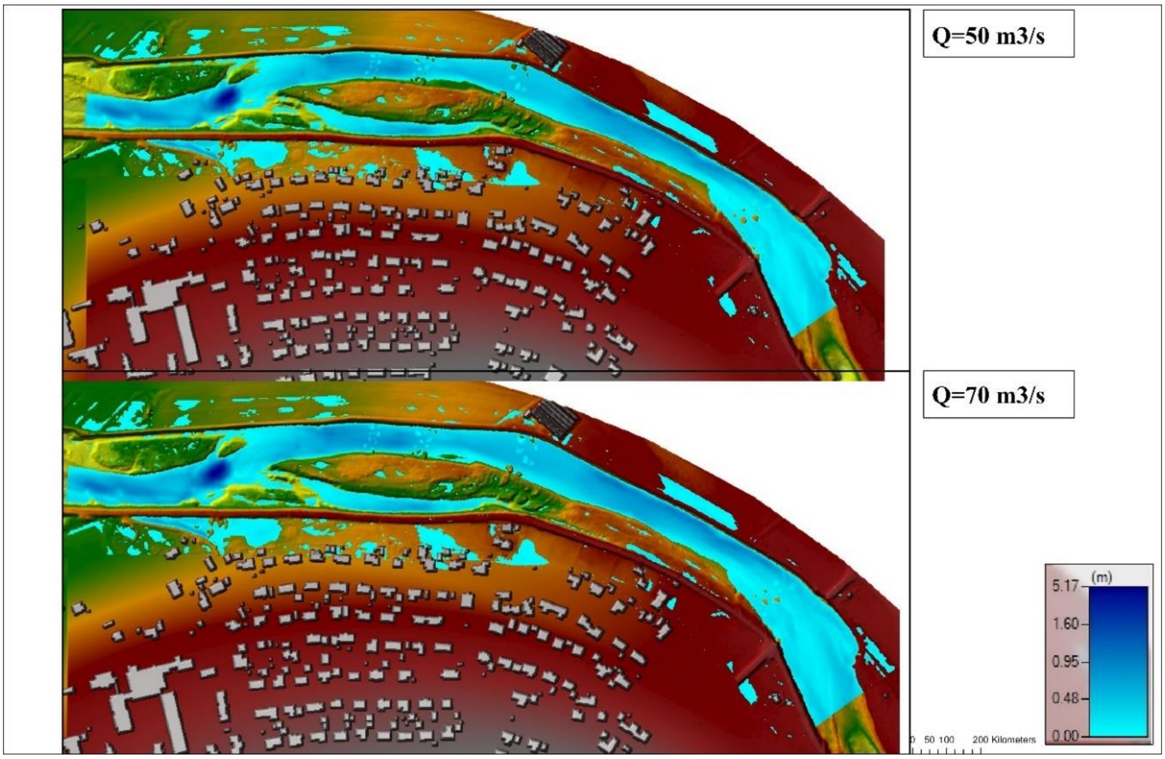


Figure 5. 19 Water Depth maps with artificial weirs for Q= 50 m^3/s and 70 m^3/s.

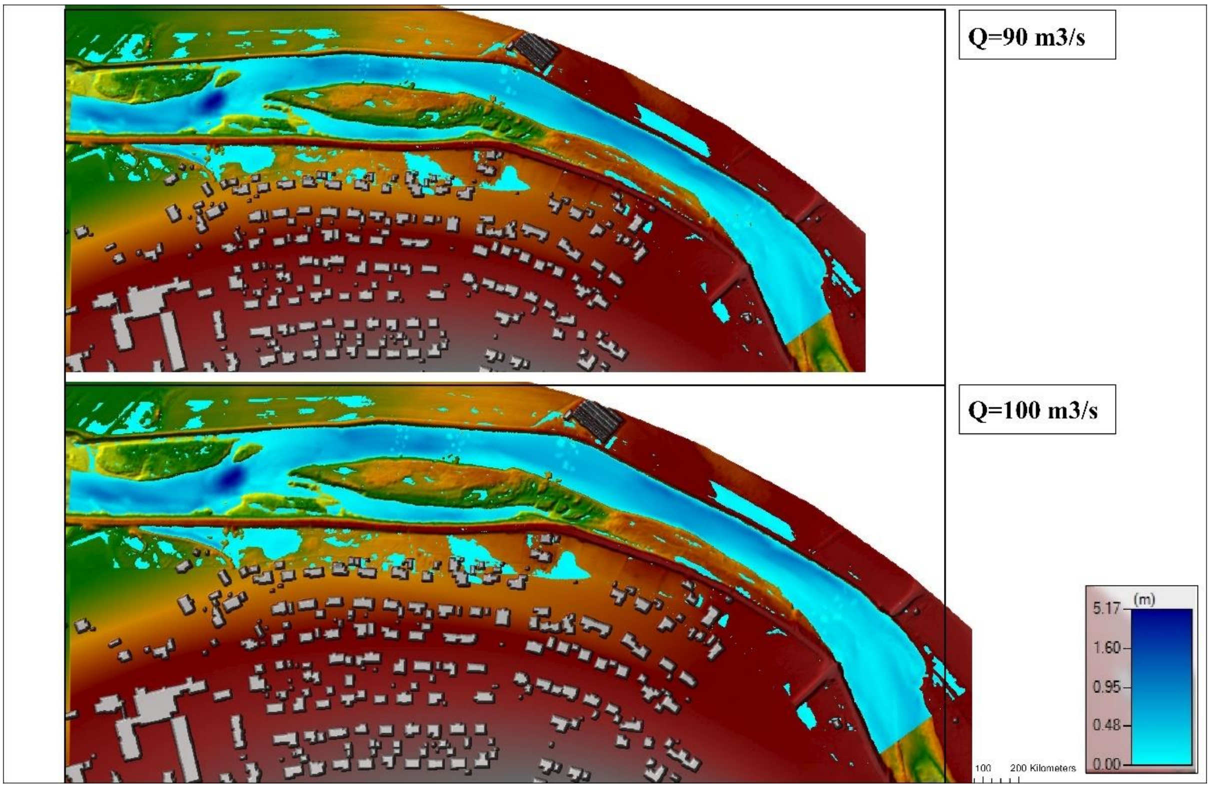


Figure 5. 20 Water Depth maps with artificial weirs for Q= 90 m^3/s and 100 m^3/s.

The maps offer insights of the river hydraulic response. We observe smoother changes in water depth compared to the scenario with the initial weir. Additionally, the water covered area is reduced, prompting a closer examination of potential features to maintain a suitable habitat for fish.

Ensuring that the current arrangement is optimal and effectively addresses the challenges faced in Lærdal requires a careful comparison of its relevant features using different tools provided by Hec-Ras. This step is crucial in evaluating whether the existing setup aligns with the desired objectives and provides the most efficient solution. Considering this we aim to assess how well the arrangement meets the specific needs and requirements of the area.

In order to carry out this comparison effectively, we will delve into a detailed analysis of the depth using minimum flow Q=10 m^3/s as shown in section 5.2.3. It will enable us to identify any discrepancies, assess the overall effectiveness of the arrangement, and make informed decisions on potential enhancements or modifications. By leveraging these analytical tools, we can ensure that the arrangement is not only optimal but also tailored to effectively address the unique challenges of salmon habitat in the area.

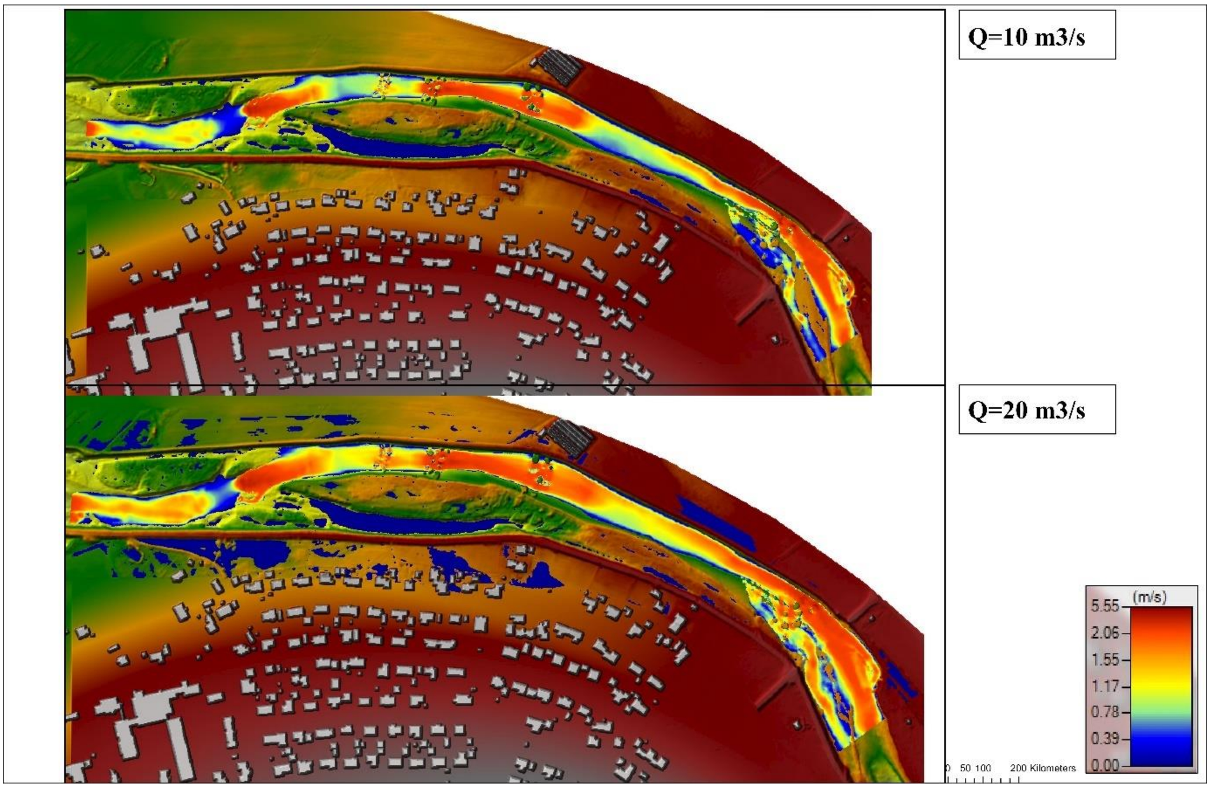


Figure 5. 21 Velocity Pattern with artificial weirs for Q= 10 m^3/s and 20 m^3/s.

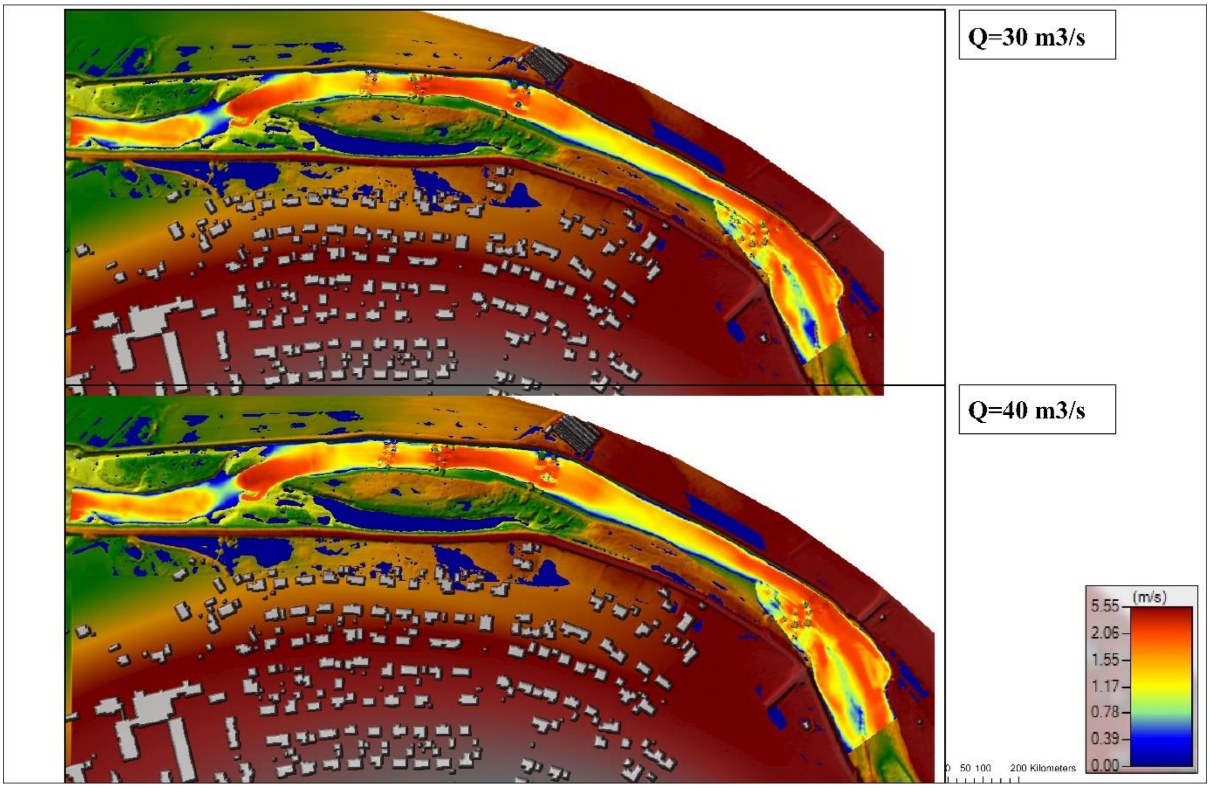


Figure 5. 22 Velocity pattern with artificial weirs for Q= 30 m^3/s and 40 m^3/s.

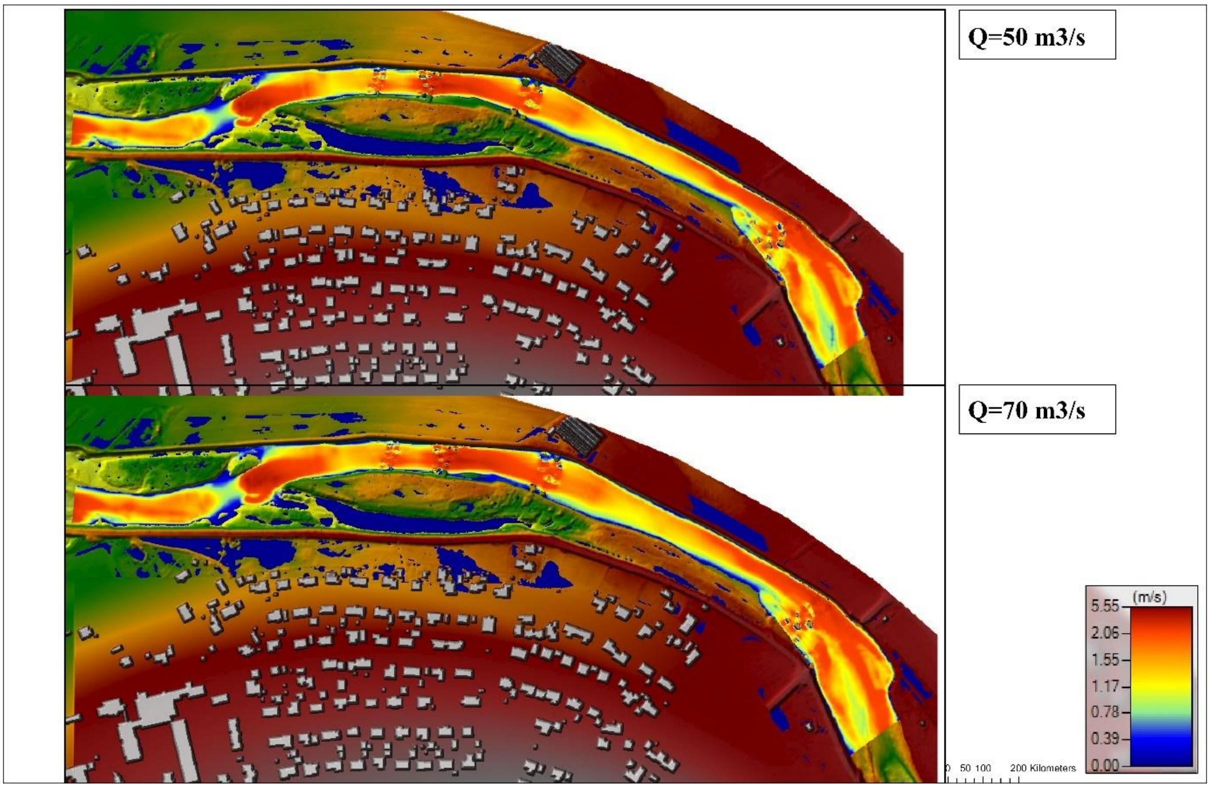


Figure 5. 23 Velocity pattern with artificial weirs for Q= 50 m^3/s and 70 m^3/s.

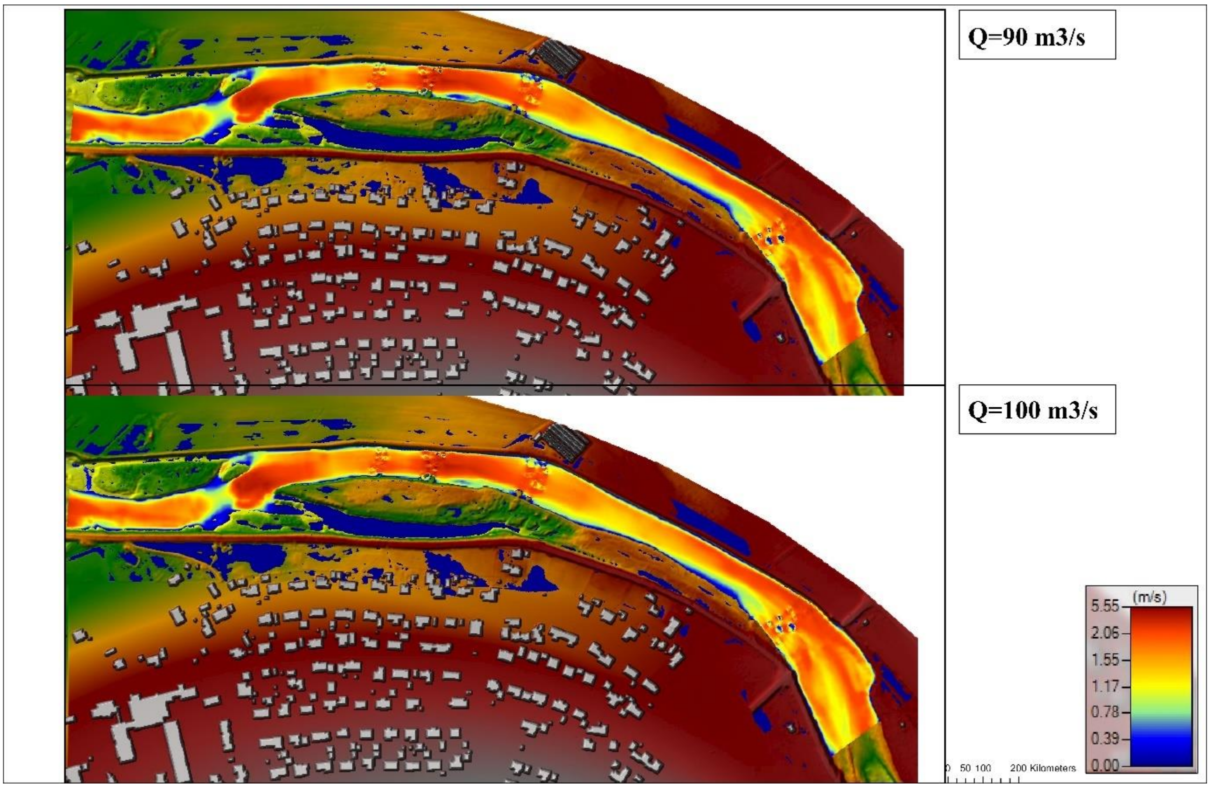


Figure 5. 24 Velocity pattern with artificial weirs for Q= 90 m^3/s and 100 m^3/s.

5.2.2 Streamlines on Artificial Rocks

Turbulence plays a vital role in the ecology of salt and freshwater environments. Large swirling water movements, known as eddies, can span vast oceans and lakes. Surprisingly, fish seem unaffected by these large gyres, treating them much like steady or still water, using them as pathways for migration. Eddies, identified through streamlines, contribute to variations in fish populations. However, not all eddies impact fish (Brett, 1995).

Even small eddies may not affect swimming performance significantly. While it might be expected that small eddies induce turbulence, potentially increasing energy losses and reducing performance, studies suggest that boundary layer energy losses are a small part of the overall energy losses. The boundary layer may already be turbulent over much of the fish body. Research in low-volume water tunnels introduced micro-turbulence to create rectilinear flow profiles, further exploring fish performance in turbulent flows (Liao et al., 2004).

As current speed increases, fish exhibit rheotaxis, orienting themselves to the flow, reducing drag, and promoting station holding. The ability to navigate in turbulent flows is crucial for survival, influencing feeding opportunities and energy conservation, especially during periods of inactivity (Elder J. et al., 2015).

Appropriate eddy structures may enhance swimming performance, although specific data from controlled experiments are currently lacking. Observations suggest that fish may improve speed and endurance or reduce transit times by exploiting flow variations (Webb et al., 2010).

In simulations with a minimum flow of 20 m^3/s, particles are randomly dropped into the flow, and some rocks are submerged. The streamlines illustrated in the simulated image show the movement of particles in the flow, tracking their path over submerged rocks. Some particles drop onto rocks but don't move much due to lower flow. Streamlines go up, over the rocks, then down, flowing in between them. This simulation considers the submergence of rocks and how streamlines interact with them.

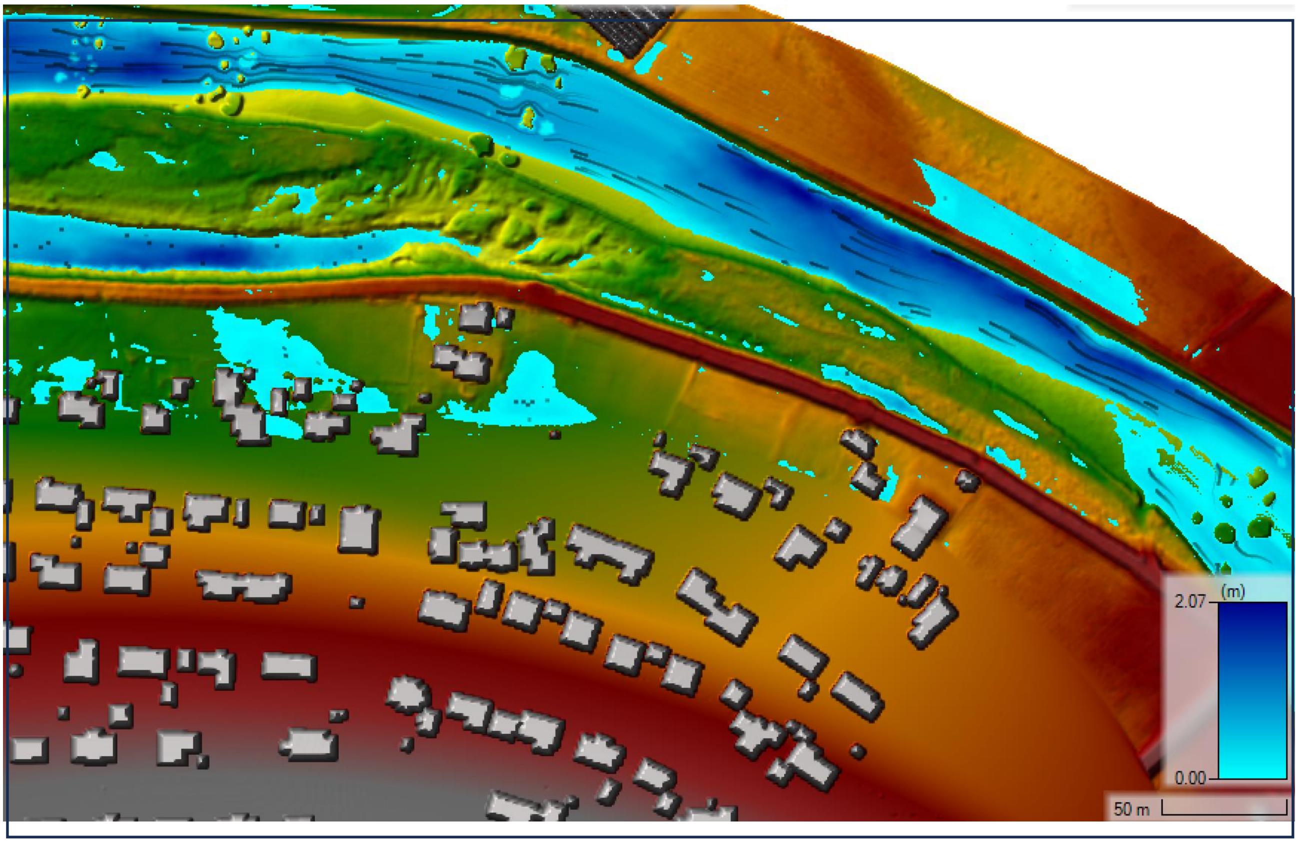


Figure 5. 25 Streamlines on depth map results with Q=20 m^3/s, after placing the boulders.

5.2.3 The Optimal Biological Characteristics for Atlantic Salmon

Changes in water flow not only led to temporary shifts in available habitats but also influence the behavior of fish. The speed of water, its depth, and the type of riverbed have a significant impact on the habitat of fish, affecting populations of brown trout and Atlantic salmon. Laerdal, a salmon river at the national level, forms a substantial part of the river ecosystem. This emphasizes the need for restoration projects to prevent the extinction of salmon species, as highlighted by (Heggenes et al., 1996).

To ensure the well-being of salmon, it is crucial to monitor the ideal living conditions at various stages of their lives, including spawning, nursing, and rearing. Concerning water speed, salmon prefer faster currents as they grow, while slower speeds in feeding areas allow them to concentrate their energy on eating. In terms of depth, salmon favor shallow waters for nursery, even when water flow is low. The mean values of the three variables under the study, as presented by Armstrong et al. (2003), are included in the following tables.

Table 5. 1 Reported habitats used by spawning Atlantic salmon and brown trout (Armstrong et al., 2003)

Species	Habitat Variable	Measure	Values
Atlantic Salmon	Water Velocity (cm/s)	Range	35-80
	Water depth (cm)	Range	17-26
	Substrate size (mm)	Median grain size (Combined for several species)	22
Brown trout	Water Velocity (cm/s)	Range	15-75
	Water depth (cm)	Range	6--82
	Substrate size (mm)	Median grain size (Combined for several species)	8-128

Table 5. 2 Reported nursery habitat used by Atlantic salmon and brown trout (Armstrong et al., 2003).

Species	Habitat Variable	Measure	Values
Atlantic Salmon	Water Velocity (cm/s)	Range	10--30
	Water depth (cm)	Range	20-40
	Substrate size (mm)	Median grain size (Combined for several species)	16-256
Brown trout	Water Velocity (cm/s)	Range	0-50
	Water depth (cm)	Range	0--30
	Substrate size (mm)	Median grain size (Combined for several species)	10--90

Table 5. 3 Reported rearing habitat used by Atlantic salmon and brown trout (Armstrong et al., 2003).

Species	Habitat Variable	Measure	Values
Atlantic Salmon	Water Velocity (cm/s)	Range	10--50
	Water depth (cm)	Range	20-70
	Substrate size (mm)	Median grain size (Combined for several species)	64-512
Brown trout	Water Velocity (cm/s)	Range	0-20
	Water depth (cm)	Range	40--75
	Substrate size (mm)	Median grain size (Combined for several species)	8--128

The data in the table helps us assess whether arranging the boulders will lead to an increase in the density of salmonids in the Laerdal River. To better understand this, we present graphs illustrating water velocity and water depth, comparing them with the information obtained from Hec-Ras simulations.

First, let's analyze three different situations by examining the longitudinal profile of the river. We kept the discharge constant (Q=10 m^3/s) for all three cases: the first scenario involves the original weirs, the second has no weirs, and the third features randomly placed boulders. The water levels for these scenarios are illustrated in the longitudinal profile, which includes the four weirs within the study domain. The substrate size is focused by conducting sedimentary simulations.

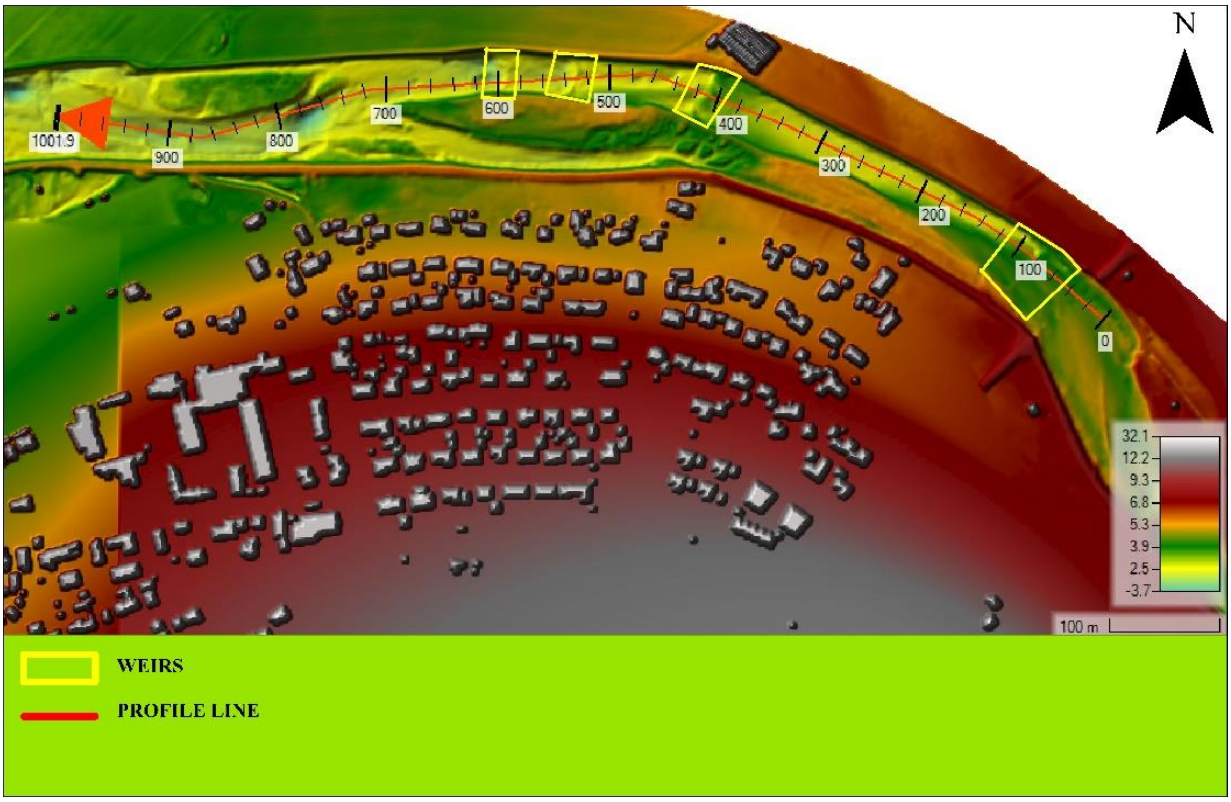


Figure 5. 26 Longitudinal Profile Line starting from station “0” upstream of the river.

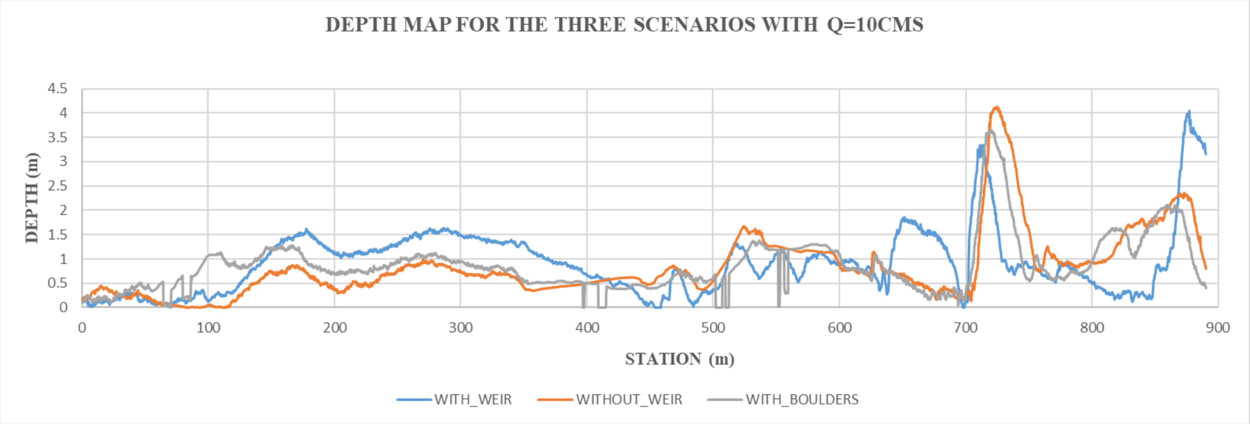


Figure 5. 27 Depth map with Q=10 m^3/s for three scenarios.

The depth graphs show promising results following the arrangement of boulders. Unlike the weir, which restricts the feeding and nursery capacity of the area, the placement of boulders achieves optimal depth values. The optimal depth value of boulder arrangement on first profile crossing the weir, situated between stations 80m and 90m, exhibits a maximum depth of approximately 62.2 cm. The second, located between stations 400m and 420m, reaches a depth of 49.4 cm. The third, positioned between stations 520m and 540m, maintains a depth of 80 cm. Lastly, the fourth location, found between stations 590m and 610m, records a depth of 89 cm. Importantly, all these values fall reasonably within the desired range for all four artificial rocks arrangement, the initial weir restricts feed and nursery while the distributed rocks improves the result and give ideal depth value with a maximum that doesn’t seem to be higher than 90cm.

Based on water velocities, the two maps in the figure 5.28 show the preferred environment. With Q=10 m^3/s, this illustrates the conditions both before and after the weirs were modified. The accompanying color ramp values make it simple to determine the optimum compromise regions for fish by concentrating on the weir area, where changes were performed. This guarantees that in times of low flow, they will always have a pathway that is less than 4 m/s. Higher velocities are produced in simulations with fewer or more boulders, despite the fact that this solution might not seem ideal. Furthermore, the presence of boulders improves the preferred habitat of fish by allowing them to experience reduced water velocities while they remain near the rocks.

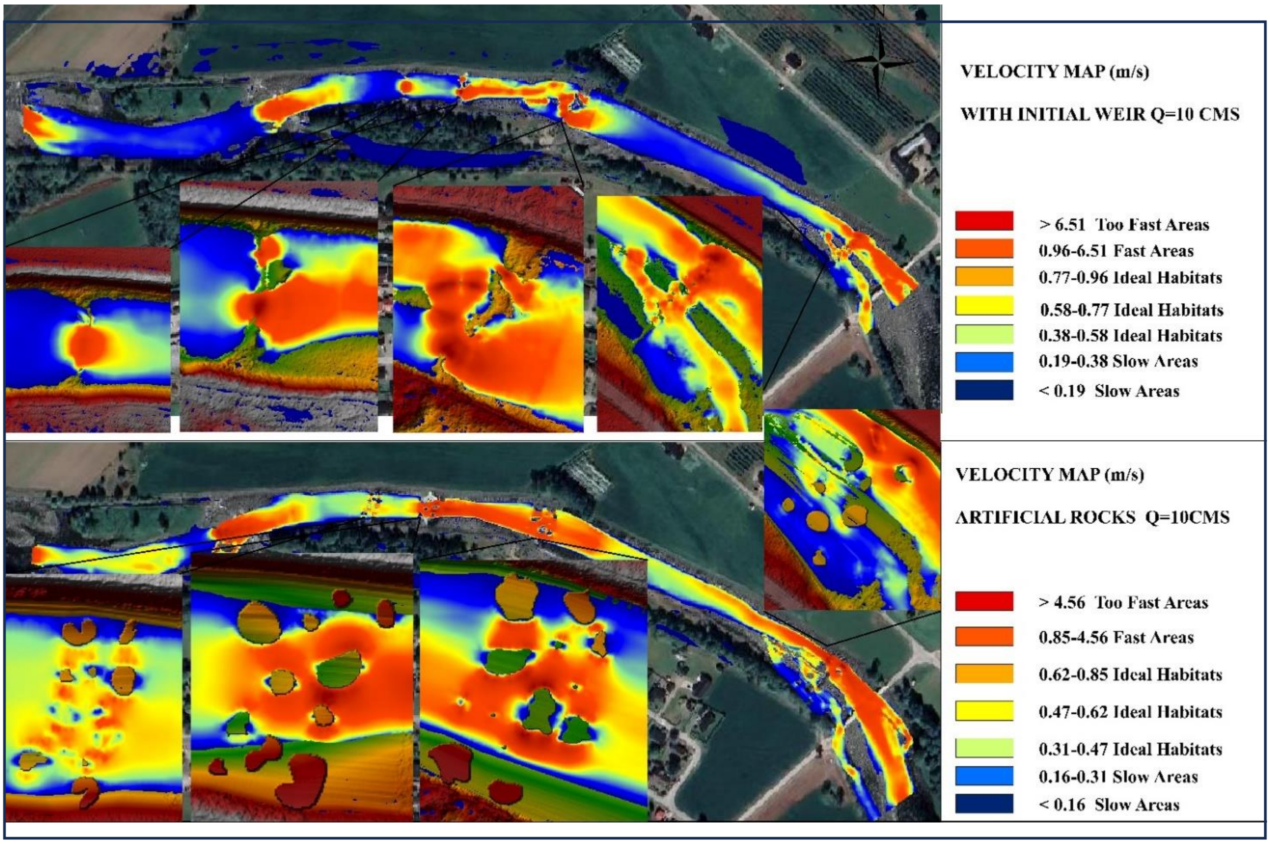


Figure 5. 28 Ideal spawning habitats areas for Atlantic Salmon habitats based on flow velocity after weir modifications.

The picture above is analyzed using information from Table 5.1, which shows the habitats preferred by spawning Atlantic salmon and brown trout (Armstrong et al., 2003). To sum it up, the ideal habitats can be explained as follows.

Table 5. 4 Ideal Velocity used for spawning by Atlantic salmon, (Armstrong et al., 2003)

water velocity range (m/s)			
	Spawning	**Nursering**	**Rearing**
Atlantic Salmon	0.35-0.7	0.1-0.3	0.1-0.5
Brown Trout	0.15-0.75	0-0.5	0-0.2

5.3 Submerged Weirs

What has done with the model was that making a combination of more rocks and a submerged weir in the middle, and accordingly a presentation of the weirs that shows the potential, like it’s very abrupt change in depth across the river with the simulation of submerged weir with minimum flow discharges. It was observed also that it overflows the side.

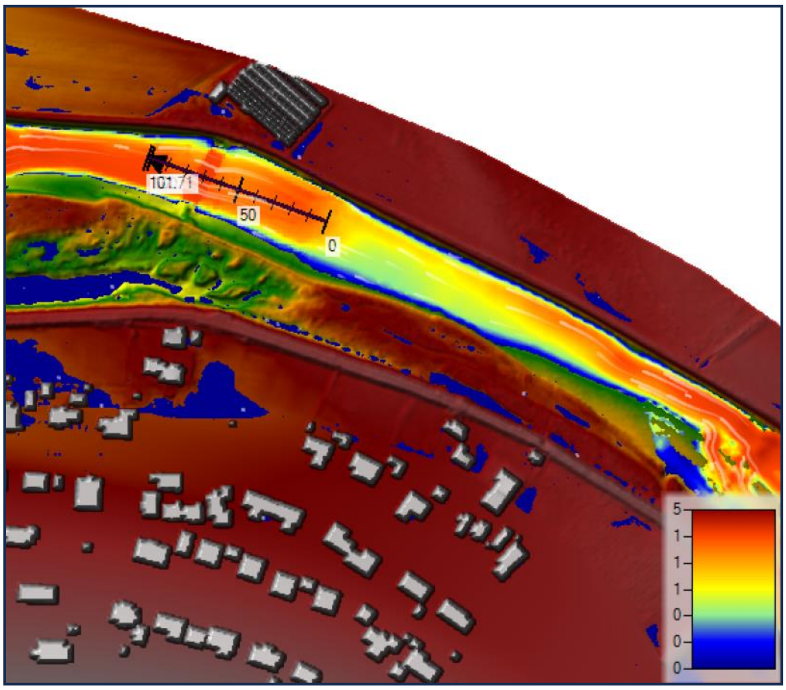


Figure 5. 29 Velocity Pattern with Q= 20 m^3/s, showing Profile Line 1, weir øye

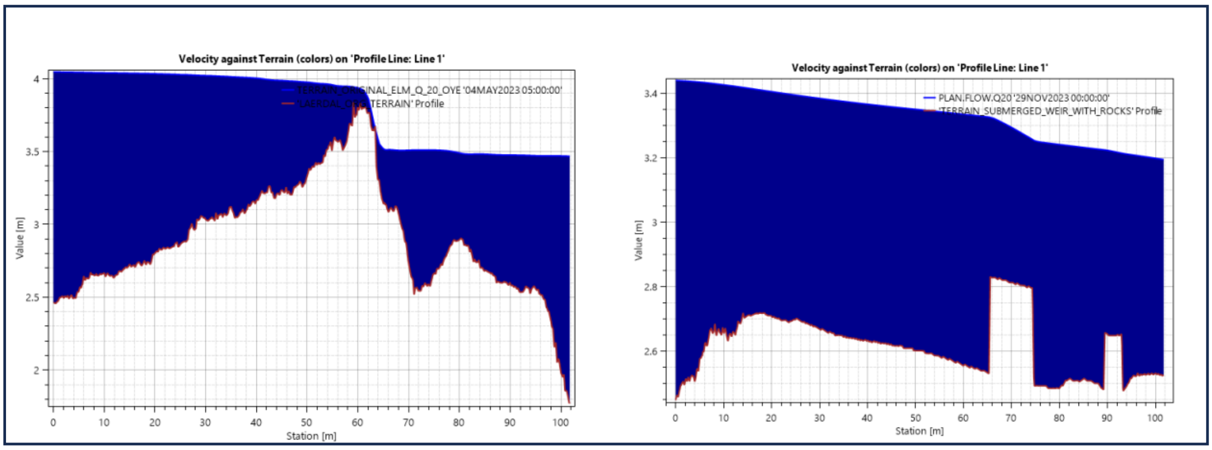


Figure 5. 30 Velocity against terrain at profile Line 1 with Q=20 m^3/s, before (Left) and after (Right) the submerged weir is made.

5.4 Consistent Water Surface on The Lowered Weir Crest

We conducted a simulation, mapping the velocity against the terrain at minimum flows with intervals of 10m^3/s discharge. In this simulation, we lowered the weir elevation by approximately 0.5 meters. The outcome revealed that the weir is fully submerged at these minimum flows, yet it remains in place, allowing for overflow. Additionally, we introduced randomly placed rocks upstream to observe their impact on flow and depth. A key focus was achieving a gradual transition for stations near the steep part of the weir, where adjustments were made to mitigate sediment-related issues.

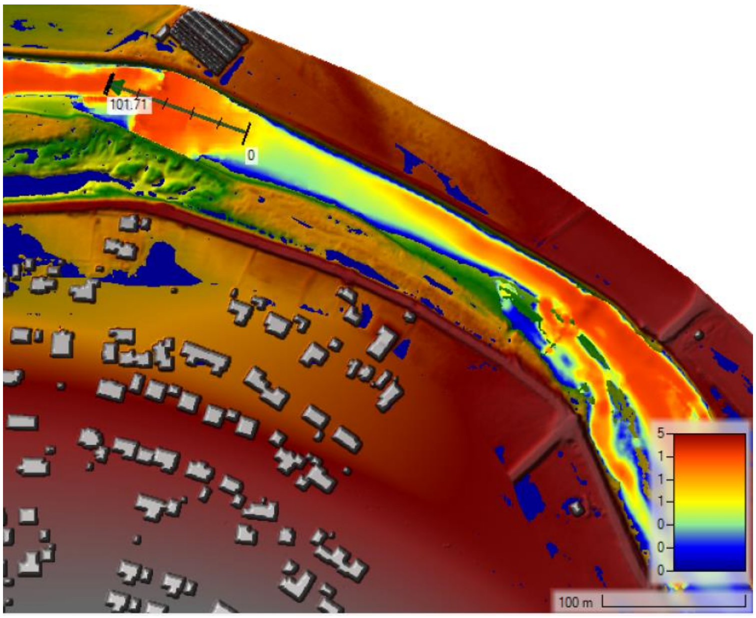


Figure 5. 31 Velocity Pattern with Q= 20 m^3/s, showing Profile Line 2, weir øye

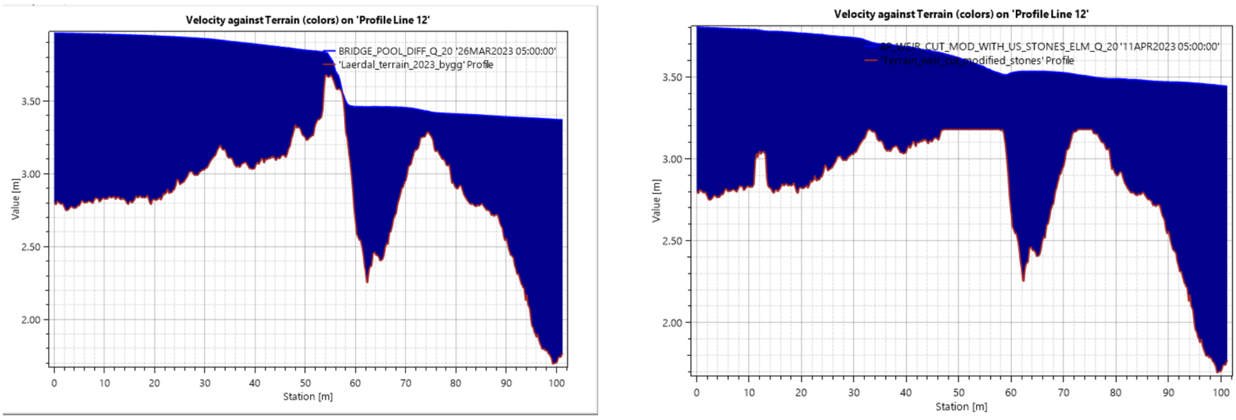


Figure 5. 32 Velocity against terrain at profile Line 2 with Q=20 m^3/s, before (Left) and after (Right) the weir crest is lowered.

Here's a comparison between the current weir design and the modified version, specifically focusing on the taller section of the weir. The image demonstrates the expected appearance of the water drop over the weir after our adjustments.

A noticeable standing wave forms when there are changes in the depth of water flow around the modified weir area. These alterations in flow, depth, and velocity carry significant importance in securing the river bottom. They help in reducing the energy of water while managing the discharge effectively. This adjustment is crucial to maintain stable velocities and ensure the stability of the riverbed.

5.5 Sediment Modelling

In all our hydraulic simulations, we utilized Diffusive Wave equations to set up the model. When it came to sediment simulations, we opted for SWE/ELM equations after completing the hydraulic model. This choice was driven by our need for flow patterns that create eddies, for which ELM/full momentum is well-suited for sediment simulations (Brunner, 2016).

As highlighted earlier to conduct sediment simulations, we took samples from Lærdal, specifically in the weir basin. This goes beyond previous practices that solely used Shields formula. Our simulation also considered changes in the bed which are the changes in topography by scouring and depositions past using this sampling.

In our current sedimentary analysis, we focused on coarse materials, treating them as an armor layer to prevent scouring, while minimizing the impact of less fine materials. using a flood scenario of 240 m^3/s, considering it as a suitable flood to model compared to extreme events like the 200-year floods (940 m^3/s) that would flood the city.

The chosen duration for flood simulations was one day (24 hours), following the standard hydrograph procedure. In Lærdal, high discharges typically occur in spring. However, a flood frequency analysis (Engeland, 2022), revealed a significant reduction in floods due to dam effects.

We assessed the impact on today's geometry in Lærdal under various discharges, including the current 240 m^3/s flood and hydraulic simulations with bankfull discharges which appear more frequently like 90 m^3/s and 100 m^3/s in the flow pattern (Copeland et al., 2001). The removal of smaller floods, now rare, which are caused by regulation has allowed sediment to settle and transformed former rocky banks into soil. This change in river dynamics influences erosion and deposition, also affects the overall flow characteristics. Subject to idea taking away of the weir in Lærdal triggers erosion of fine sediments, deepening the river and altering the depth profile.

For the sediment simulation, we used a 3m x 3m cell size resolution. In the weir area, and where we had modeled rocks, we employed a fine mesh of 1m x 1m to capture the rocks' effects. The simulation covered two different sediment curves and three adjusted terrain scenarios to observe sedimentation and erosion.

Addressing a common belief in Laerdal that removing weirs would make fine sediments disappear, our results showed otherwise. When we removed the weirs, we also eliminated floods, leading to increased velocity. Without the weirs, erosion rates significantly rose compared to situations with weirs. The sediment area extended nearly up to the bridge to cover the entire pool, considering that a substantial amount of sediment travels into the deeper water upstream. Removing the weirs endorsed this expectation.

We observed effects around the old weir and additional impacts after adjustments. We examined how these changes affected areas 50, 100, and 150 meters upstream of the weirs. This insight aligns with the background of the weir removal project, suggesting that by removing weirs, we could enhance the existing habitat, transitioning from fine to coarser material, providing more shelter for fish. However, our simulations indicated this was not the case, and needs added modifications, which is similar results from the study by Alfredsen and Awadallah in 2022, where detailed assessments were conducted, highlighting these simulations contribute valuable insights to the project.

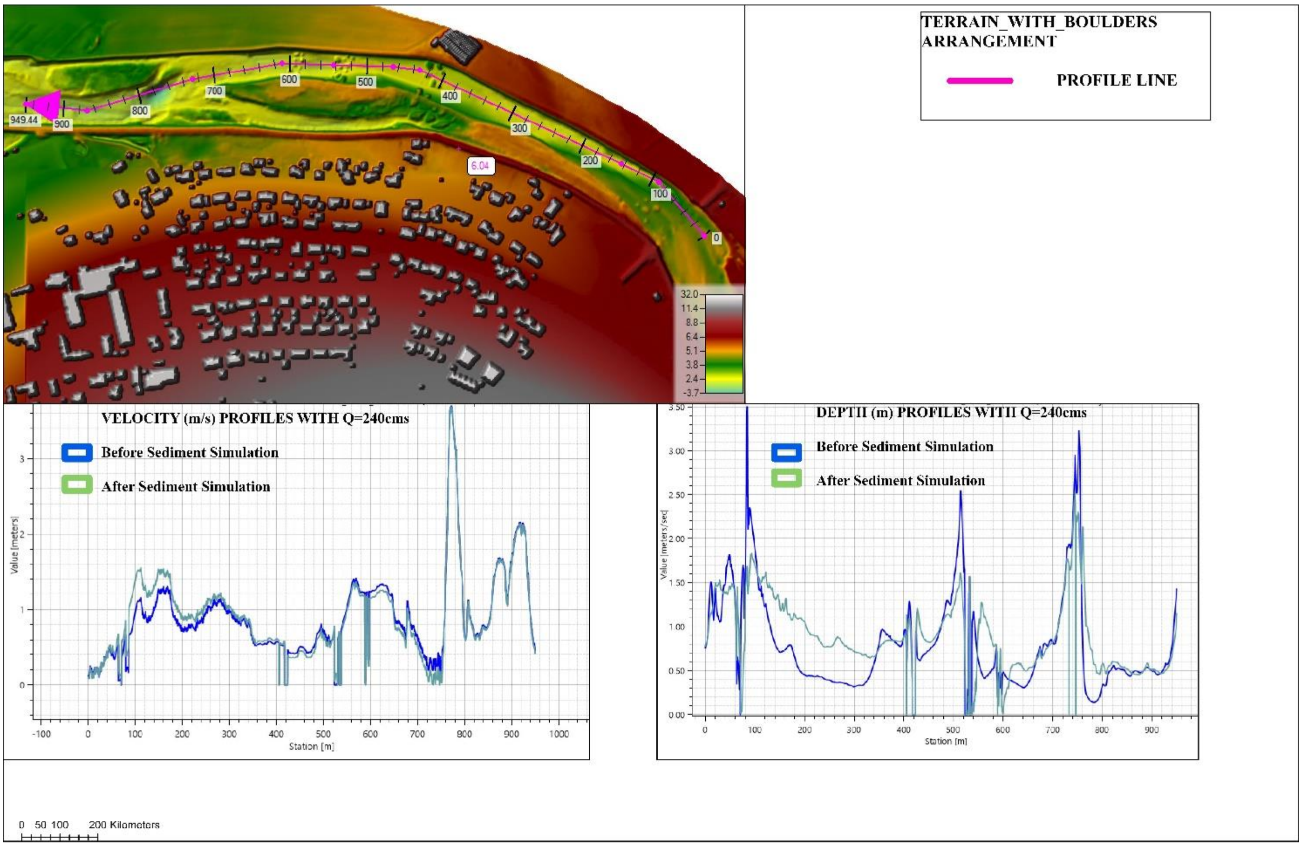


Figure 5. 33 Water Depth and Velocity Pattern before and after the Sediment simulation, Q=240 m^3/s.

Figure 5.33 shows effect of sedimentary modelling on the pattern in Hec-Ras, after calculating erosion and deposition, automatically updates the terrain. After analyzing the deposited and scoured areas, we verified these changes by creating modified profiles in ArcGIS. As expected, the primary current over the deposited area and the same water flow also experienced alterations, on the depth and velocity.

5.6 Comparison of The Fine and Coarser Sediment Curves

We examined the impact of altering the sediment curve while keeping all other factors constant. The sediment routines were adjusted based on grain size distribution near the riverbank, and we considered sediment down to the finer details.

In Lærdal, there is a significant presence of fine materials in the deep part due to its overall depth, leading to the accumulation of finer sediment. While it's known that samples from this deep part are essential, we decided to include sand and fine sediments in the calculations, as we took into account all considerations down to the smallest details.

By referencing Figure 5.34, when comparing the two sediment curves in the presence of the weir, we observed no deposition in the upper part of the pool in the coarser curve, unlike the fine curve. The fine curve exhibited more fine sediments compared to the coarser curve, and there was noticeable erosion, especially in the finer curves.

Moving to the weir downstream, we observed erosion and deposition occurring at the same location for both situations. During a flood, sediment is carried away from the upstream part of the weir and deposited into the deeper area behind the weir. The detailed maps of results are shown in below sections.

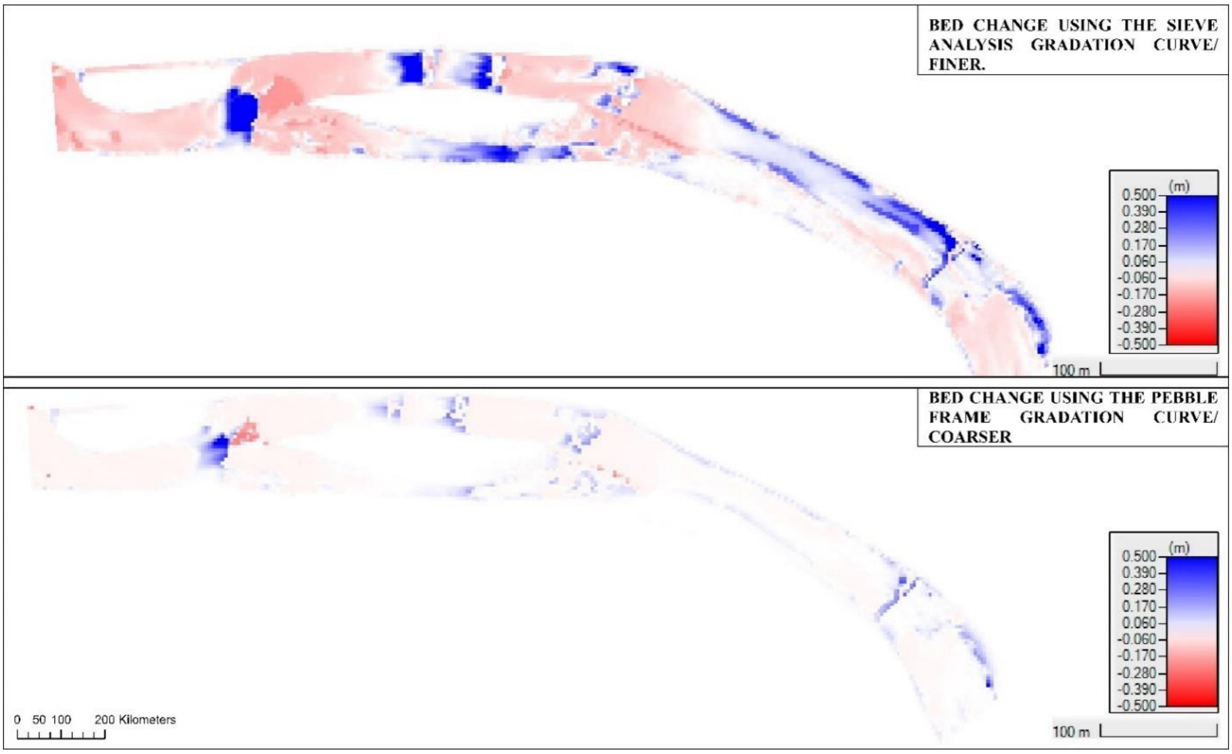


Figure 5. 34 Bed changes, with 240 m^3/s Flood: Finer vs. Coarser Curves using the initial weir set up, Positive value of change indicates a deposition, and the negative value of change shows scouring.

In the figure 5.34, we present the bed changes which are the changes in topography by scouring and depositions, observed during a 240 m^3/s flood, considering two sediment curves. The finer curve, represented by a mechanically sieved gradation curve, is compared to the coarser curve, which follows a pebble frame-sampled sediment distribution curve. Scouring areas are depicted in red, while deposition areas are highlighted in blue.

In studying sediment transport in a river using 2D modeling with Hec-Ras, we observe two different grain size distributions. Notably, both scenarios exhibit visible deposition behind the weir and scouring at the upper part of the weirs.

5.6.1 Pebble Frame Curve (Coarser Curve) Simulation

When simulating sediment using the pebble frame method as in figure 5.34, representing a gravel bed river, we notice that discharges up to -0.8 m induce erosion, showcasing the scouring effect of sediment.

5.6.2 Sieve Distribution Curve (Finer Curve) Simulation

Referencing same figure 5.34, by changing the sediment curve to the sieve distribution curve and adjusting the class size, we notice more scouring, bringing in finer materials compared to a coarser curve. This happens in a sediment model that spans 1.055 km for both scenarios. In the case of the sieve sediment curve, there's minimal scouring in the main part of the pool, with logical depositions on the edges. Notably, there's scouring in front of the weir, occurring 70 meters upstream, involving fine materials and an increase in velocity near the shallows. While the two lower sections experience scouring, the big deep pools do not. Increased fine sediments correlate with more erosion. It is reasonable that we get one meter sand deposition, occurred in some areas after the 2015 flood, particularly from a tributary with a high flood that washed out a significant amount of material. The regulated river flow results in low main river flow during non-high flood periods. The flood frequency change after regulation contributes to the accumulation of fine material, transforming a once clean gravel bar from the 1970s into a grassy flat.

5.6.3 Analysis of The Results

During initial shield calculation testing, its discovered that removing the weir results in the inability to mobilize sediments in the deep areas, even when there is a considerably high flow. Whether the weir is present or not, erosion in the deep parts remains the same. This insight, supported by Alfredsen and Awadallah in 2022, highlights the limited impact of the weir on sediment dynamics in these deeper regions. This evaluation was initially conducted using shear stress calculations and, in this report, it has been further validated through detailed assessments with a fine curve. Importantly, this aligns seamlessly with our overall research findings. It's noteworthy that, throughout all our sediment simulations, we consistently utilized a finer curve or a sieve grain size sediment distribution curve. This standardized approach enhances the accuracy and reliability of our results across various scenarios.

5.6.4 Challenges in Sediment Simulation

The inclusion of sediment transport calculations in Hec-Ras models presents challenges. Sediment simulations contribute to slower computational performance due to the software accounting for sediment movement and changes in bed elevations. This additional complexity is noted to significantly increase computational load, especially during high floods, limiting the time frame (Brunner, 2023).

5.7 Bed Change Comparing the Difference Between the New Condition And The Main Topography

We utilize the Bed Change function in Hec-Ras to compare variations in bed topography. This function generates a map produced in Hec-Ras, illustrating alterations in each cell and bed features. The comparison involves three scenarios: the original bed elevation, the bed without the weir, and the bed with artificial rocks. This allows us to discern differences and similarities among these scenarios. It's crucial to establish a benchmark with the original terrain to gauge changes accurately, especially post-scouring or sediment simulation.

Once the setup is complete, considering the presence of non-erodible elements like concrete walls, boulders, and initial rocks, we simulate three scenarios with the same configuration for meaningful comparisons. Specifically, we compare deposition and scouring areas with weir, without weirs and with artificial rocks. The resulting maps, illustrating these comparisons, are presented below for a clearer understanding of the bed dynamics.

5.7.1 Scenarios 1 With Initial Weir (Keeping the Current Weir)

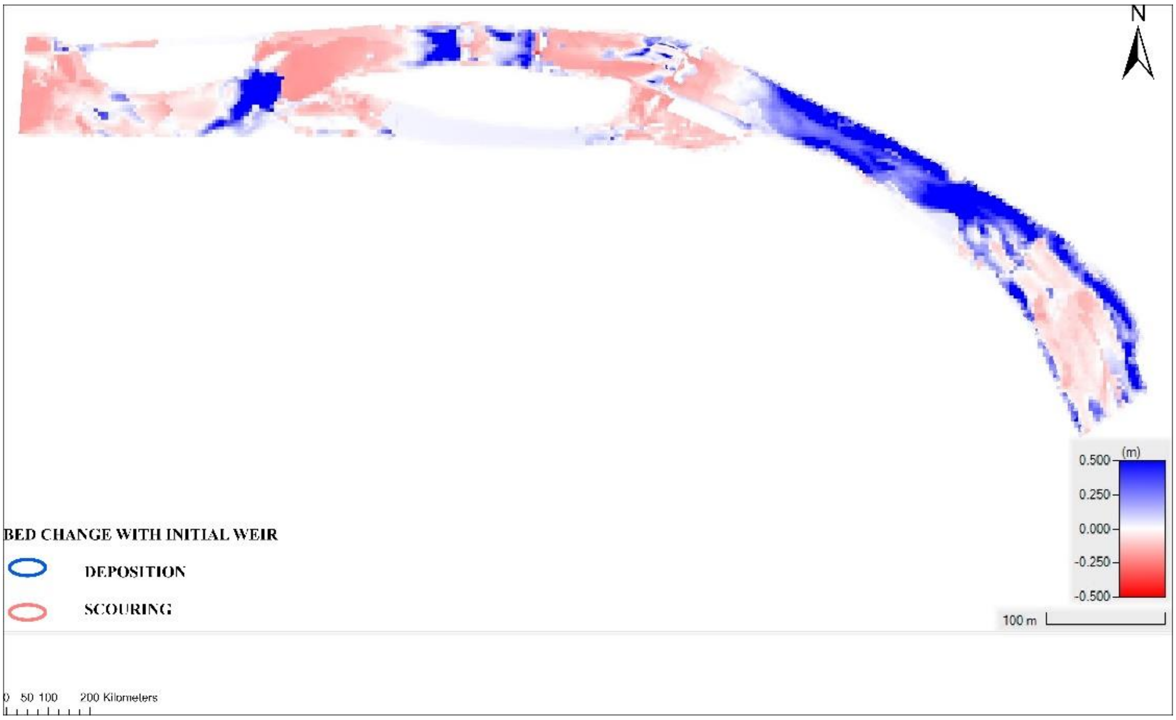


Figure 5. 35 Bed change using the initial weir set up, Q=240 m^3/s.

This is done by Create polygons around the initial rocks of each of the four weirs, designating them as non-erodible boulders. Maintain the existing configuration for the rest of the main river reach. Utilize a 3m*3m grid, refining the mesh with a finer 1m*1m cell size around the weir areas. Extend the study model to observe sediment dynamics slightly further upstream and downstream. Apply the non-erodible attribute to all weirs in the domain, including fixing the upstream area of øye weir as a non-erodible concrete wall. Employ the same unsteady flow conditions. In Hec-Ras, we specify areas as non-erodible; otherwise, it has been confirmed that they erode. The resulting map illustrates erosion in red locations and deposition in blue locations, providing a comprehensive view of sediment behavior in the study area.

5.7.2 Analysis of Results from First Simulation Scenario 1

In the front part of the weir, we observe erosion, while sediment settles in the deeper upstream of the pool, resulting in deposition at the upper pool, which is the slow flowing part of the weir. Additionally, there are some depositions in the deep part, and erosion occurs in the second weir. In this scenario, the water flows through the holes in the weir, indicating that the overlaying structure works effectively in this setup. Notably, we observe erosion and deposition occurring between the rocks, aligning with our expectations for this study.

5.7.2 Scenarios 2 With out Weir (After Taking Away the Weir Completely)

In the second scenario, the entire study area is considered non-erodible. We maintained the same setup as before. In this configuration, when the weir is removed, sediment deposits in the pool, and there is a slight erosion along the weir. This observation helps us understand how the changes in the model, specifically the removal of the weir, impact sediment behavior in the pool area.

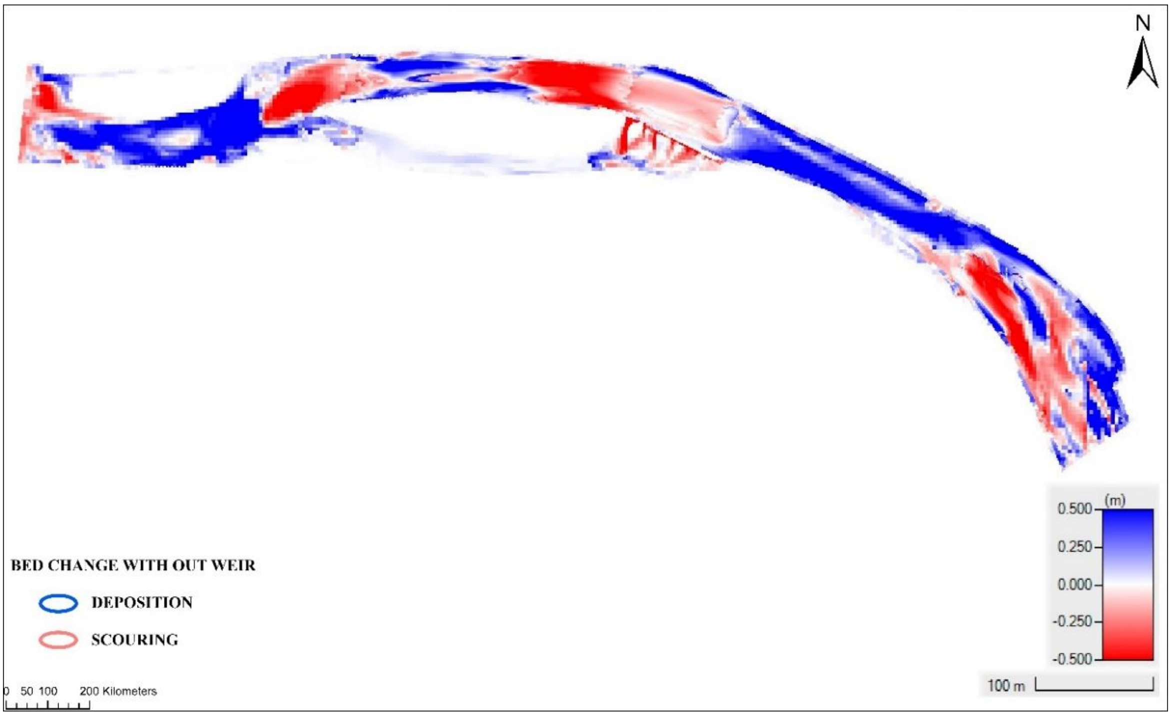


Figure 5. 36 bed change after the weir is removed, using Q=240 m^3/s.

Based on Alfredsen and Awadallah, 2022 a weir was removed and simulated mean flows of 270 m^3/s. Then, by extracting shear stress data from Hec-Ras and applied the Shields formula to calculate the sediment size it could mobilize. The intention was to see if removing these weirs could resolve the issue of fine sediment accumulation in Lærdal. However, the calculations indicate that the impact of removing the weirs on sediment dynamics is not as significant as it hoped.

5.7.3 Scenarios 3 With Artificial Rocks Set Up

Firstly, we outlined each rock with a polygon, designating them as non-erodible, while the rest is considered erodible. In the testing, we observed scouring upstream of the weir and deposition behind it. There's minimal scouring in the upstream part of the pool, with some deposition and scouring in the non-erodible section. The boundaries of the non-erodible surface show slight scouring and deposition in a few cells, but overall, the setup appears to be effective. The logic behind the deposition is that sediment from other areas falls into the deep hole behind the weir, and due to the high flow situation, it's realistic to expect some erosion in front of the weir, leading to the accumulation of fine materials.

Expanding our study both upstream and downstream, we examined the main parts of the pools to understand the broader effects. Surprisingly, our findings indicate that there isn't a significant impact on the pool upstream of the weir.

In the third scenario, where we introduced Distributed Rocks (boulders), creating a conducive habitat for fish, we set up an erodible bed with non-erodible rocks overlaid on top. This configuration adds complexity to the model and provides insights into how the interaction between erodible beds and non-erodible rocks influences sediment dynamics.

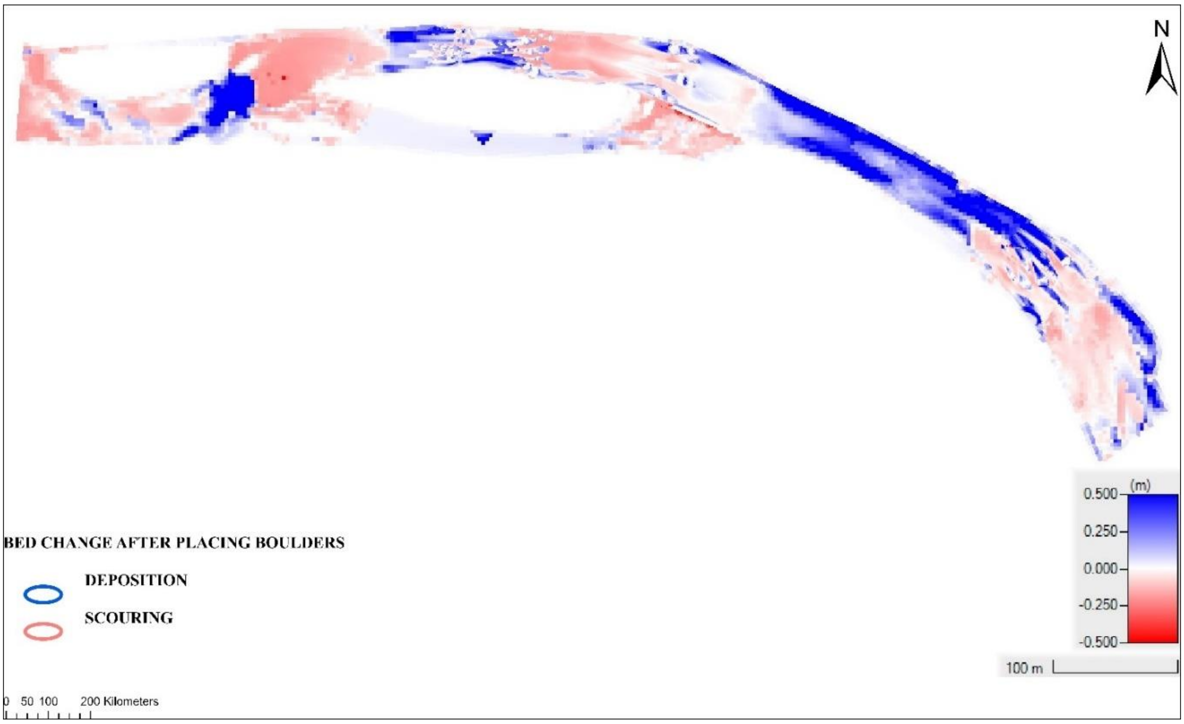


Figure 5. 37 bed change after the arrangement of boulders, Q=240 m^3/s.

5.7.4 Analysis of Artificial Rocks Sediment Simulations

In our study, we utilized a less dense rock setup, conducting simulations and employing particle tracing to achieve visually compelling results. These simulations revealed scouring at the bottom in the curvature behind the rock, indicating a scenario where, if the area is excavated deeply enough, the rock might dislodge a phenomenon similar to what could happen with a weir.
It indicates also expected ice scouring in the area below the weir, leading to the disappearance of some rocks in the weir and the creation of a hole in the river, particularly on the left side of the øye weir area. It's essential to note that the study did not cover the effects of ice in detail.

In our approach, we set up Hec-Ras specifically for the targeted weirs, running sediment calculations to determine sediment transport upstream and downstream. Subsequently, we ran calculations to boulder motion in Laerdal, we used two ways to analyze the impacts: First the comparison of the shear stress before and after weir changes on Hec-Ras after computing a sediment scenario, second with a theorical approach on forces applying on the boulders during flash floods. This comprehensive methodology provided insights into the dynamic behavior of the river and how it could be related to the fish population under various conditions.

5.8 Sedimentary Transport

5.8.1 Analysis of Possible Mobilization of Sediment by Comparing of variation of shear stress

The size of particles is super important for salmon to grow. Sediments are like building blocks for where salmon live, and having big rocks is crucial for salmon to be there. The study by (Armstrong et al.,2003) checked the size of these particles, and our comparison showed that the sediments are just right for salmon. But when floods happen, these sediments can move and mess up the riverbed, causing problems for the ecosystem.

Now, let's delve into a comprehensive research endeavor. Alfredsen and Awadallah, (2022) conducted a study where they removed a weir and made it flat. Then, they simulated floods and checked how sediments would move with and without the weir. They found small changes, mostly around the weir. Our study goes a step further. We used real sediment samples and calculated where sediments would build up or erode in more detail. We found that this happens in specific places near the weir and in the shallower parts of the river. Our study has finer details and a more thorough approach.

To figure out how sediments might erode, we compared the total bed shear stress before and after changes to the weir using Hec-Ras. We also used a map showing the flow velocity and bed change after considering different sediment scenarios. By using a average flood scenario as Alfredsen and Awadallah (2022), We then compared the results to see what differences we could find.

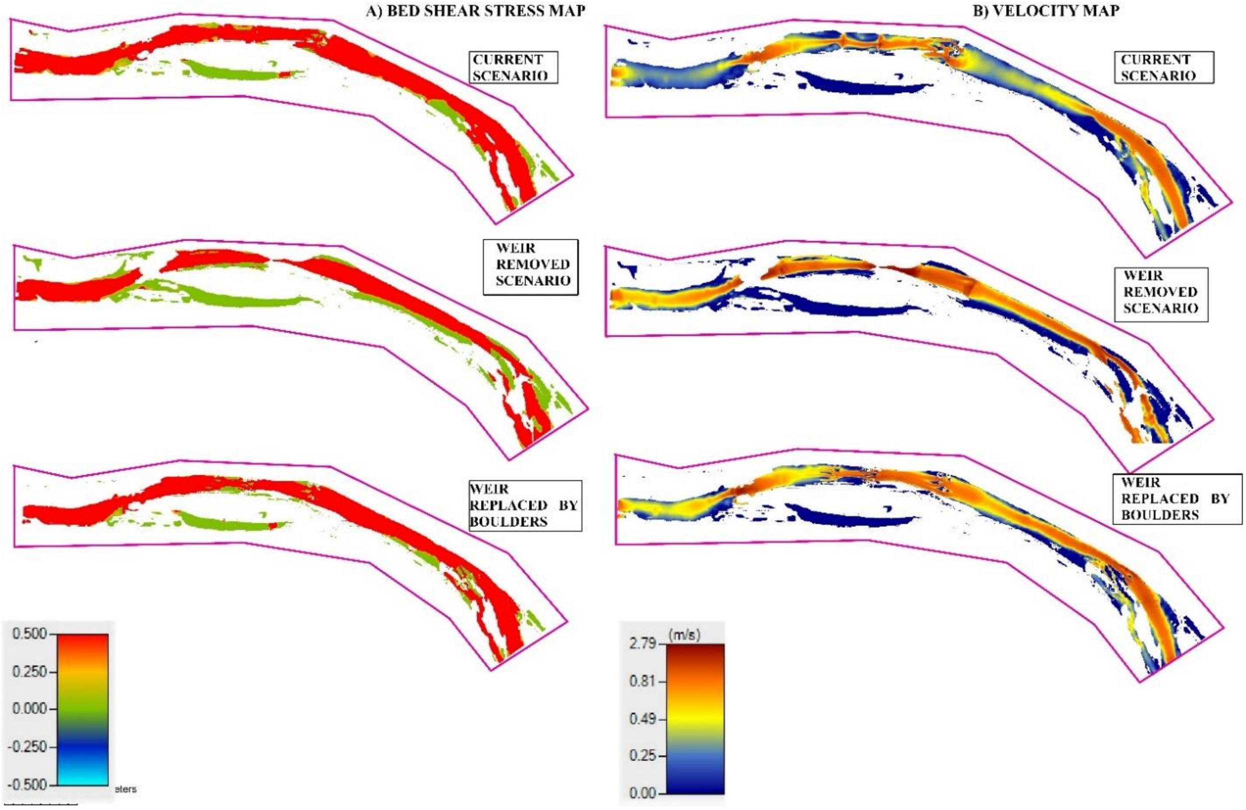


Figure 5. 38 variation of bed shear stress and velocity pattern, with initial weir, after weir removal and with artificial habitat. Left and right figures depict bed shear stress and velocity, respectively, Q=240 m^3/s.

This figure addresses about the possible movement of sediment in a stretch of the river. We used Hec-Ras to simulate what might happen during a medium flood of 240 m^3/s. The Hec-Ras calculations didn't show big changes before and after we made changes to the weir. We looked at shear stress values, which tell us how strong the water flow is and if it can carry sediment or erode the riverbed. The values stayed quite similar.

The clustered map below illustrates a summary of bed changes across scenarios based on the topography, this map supports the idea that there isn't a lot of movement happening. Considering it would be intriguing to evaluate potential outcomes associated with various bankfull discharges in future studies.

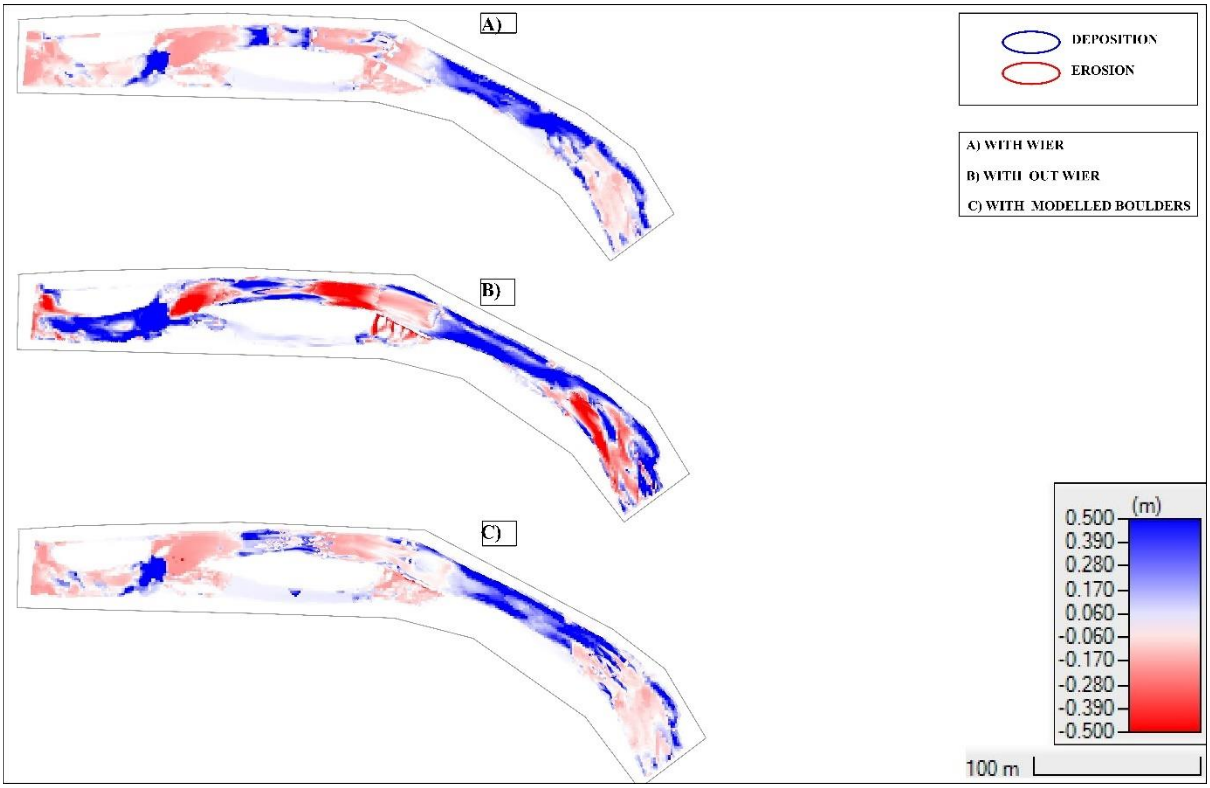


Figure 5. 39 Clustered map of bed change for three scenarios, Q= 240 m^3/s.

As brought up before sediment simulations based on samples from Lærdal, both in the weir basin and upstream, indicate no significant impact on sediment removal. Sediment mobilization occurs in the weir area, but not in the main part of the pool. This means it suggest that the outcome of removing the weir there isn't a noticeable impact on the pool itself. Any effects observed seem to be limited to sediment deposition in the upper pool. However, there are positive effects around the weir area.

The underlying idea behind removing the weir was to induce erosion in the upstream pool. The expectation was that by eliminating the weir, water velocities would increase, leading to erosion. Surprisingly, this isn't affecting the fine sediments we're interested in. Instead, we're witnessing increased erosion in the weir region, but minimal erosion in the main upstream area, contrary to expectations. This finding is significant for fish habitat.

Around the rocks we placed, there's some erosion and sedimentation, suggesting a good chance they'll stay clean. The sediments among the rocks create a favorable habitat for fish spawning. Sediments settle behind the rocks, but erosion between them keeps embeddedness low and spacing high.

During floods, fish might move away to gravels, and the rocks could be cleaned. At low flows, the fish return, using this area as their primary site. Simulations with modeled boulders align with expectations, showing erosion around the rocks and deposition behind them. Aligning the regulation of the river, which reduced floods, is identified as one of the reasons for the abundance of fine sediments.

In order to compare (Alfredsen and Awadallah, 2022) findings with ours we looked at simulations with similar floods example is the average flood and there it predicted erosion, of some rocks up to 0.1 and 0.05. subsequently, these zones correspond with our most of simulations results shown above.

We have used bed change and the shear stress map and compared it to the previous work made in using standard formulas and standard methods which looked the type of sediments that would be lifted/activated with and without the weir with the same discharge (Alfredsen and Awadallah, 2022).

In their study they had been proved that for the normal range of discharges that we have taking out the weir will not have a very big effect when using the shields formula because of the main reason that the increase in velocity was not enough to change or move any sediments from the upstream part of the pool where most of fine sediments are accumulated. This is what we showed in more detail in the model from the results of sediment simulation illustrated above.

No matter what, floods will change how sediment is spread out. The biggest impact is likely to be boulders moving around after the accumulation of a lot of sediment. Armstrong et al. (2003). In real life, things might happen a bit differently, but when we calculate sediment movement, we assumed the boulders wouldn't move in our simulation. Still, it's good to think about how this works in actual situations.

5.9 Rock Stability

In Hec-Ras, when we want to make sure rocks stay put, our only choice is to label them as non-erodible in the 2D bed gradations (beta) window.

When we talk about the sediment simulation, we model rocks and notice erosion happening between them, it's an indication that we need to secure those rocks in those areas in real life.

Another uncertainty from a biologist in Lærdal concerning removing the weir entirely, if we do that, we need to figure out what kind of protection to put in place to prevent the riverbed from eroding during big floods. This is important because floods can wash away the protective layer and cost a lot of money to fix this armor layer. To handle this more safely, we modeled larger rocks to make sure they stay in place during floods. This setup was seen as an improvement over completely removing the weir (Alfredsen and Awadallah, 2022). But, when we do this, we also think about preventing erosion at the bottom for added security.

5.9.1 Eventual Motion of Boulders During Floods

Understanding how boulders move is a big part of our discussion. When boulders move, they can carry other rocks and sediments along with them, and this can have serious effects on floods, how the river reacts, and the balance of sediments (Guo, 2002). Boulder movement is mostly caused by flash floods, so we need to do some math checks to make sure the boulders stay in place.

A paper by Jan Alexander in 2016 gives us a theoretical view of the forces on boulders during flash floods. It talks about the different forces that act on a boulder that's not moving on the riverbed during a flash flood. This paper develops a theory for the initiation of boulder movement due to the additional impulsive force generated by unsteady flow, and discusses the implications which is more suited for our methods. The goal is to figure out how fast the water needs to be to start moving the boulders. Flash floods are the main reason boulders move, but they are challenging to study because the flow is so unpredictable. We also looked into a theory about how stable rocks are. We used formulas, both simple ones and more complicated stability calculations, to see the balance between the rock tilting or sliding and the opposing forces of weight and friction on the other side.

As mentioned earlier, we carefully considered the sizes of boulders we should use based on the realities. We used data guiding us on the types of rocks we want to place to create a good environment. By arranging them randomly, it appears more natural and is suitable for fish spawning. We believe this should be implemented in a more precise manner in real world applications. In addition, this is crucial to safeguard the protective armor layer. We think this approach is a significant improvement for the fish habitat compared to the previous work.

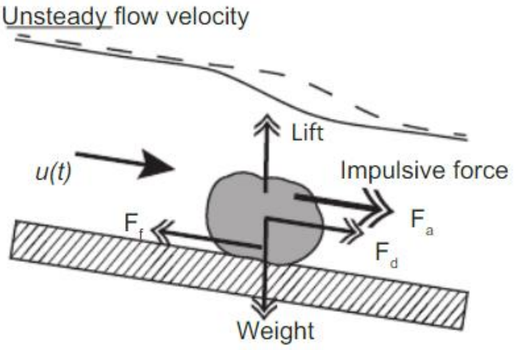


Figure 5. 40 The forces applying on the boulder in a flow resting on a flat bed (Alexander J, 2016).

According to the book and based on Newton's second law the size conditions for boulders is obtained. This law considers three forces: drag force (F_d), frictional force (F_f), and impulsive force (F_a) acting on the boulder. To make the calculations simpler, we make some assumptions because the equation to solve isn't straightforward.

We assume the Froude number is one during a flash flood, and acceleration comes from the difference in velocities over a specific time interval given by Hec-Ras simulation results, during a simulation with a flow of 240 m^3/s. The equations developed from this give us the condition needed for the length of our boulders as shown in the formula below, where Length (L in m), Water depth (h in m), Froude number (Fr), density of boulders (ρ_s in kg/m^3), density of fluid (ρ_f in kg/m^3), coefficient of friction (λ_{max}), dimensionless constant that depends on the shape of the boulder (k),acceleration (a in m/s^2), gravity (g in m/s^2).

The range of sizes of boulders that are moved, as a function of fluid acceleration is shown in the following inequality,

$$0 \leq \mathrm{L} \leq \frac{\mathrm{hFr}}{2\left(\left(\frac{\rho \mathrm{s}}{\rho \mathrm{f}}-1\right) \lambda_{max}-\mathrm{k}\frac{\mathrm{a}}{\mathrm{g}}\right)}$$

We denoted this condition expression F. By proving F, we can show that the boulders in our arrangement on all the weirs found along the study river stretch will not move. The detailed calculations on the stability of the boulders are summarized in table 5.6.

5.9.3 Forces Applying on The Boulders During Flash Floods

Table 5. 5 representation of the data on the boundary conditions along with their respective magnitudes

Boundary Conditions Data		
Dimension less constant (Sphere)	K	0.5
Boulders Density	ps (kg/m^3)	2500
Drag Coefficient/For a blunt body	Cd	1
Lambda max (coefficient of friction)	ʎmax	1
Flow Density (Water Density)	p f (kg/m^3)	1000
Gravity	g (m/s^2)	9.81
Froude/Flash floods	Fr	1
Acceleration (According to velocity Pattern from Hec-Ras)	a (m/s^2)	7.05776E-06

The three forces are denoted as follows: where Drag Force (F_d), Impulsive Force (F_a), Friction force between bed and boulder (F_f).

$$\mathrm{F_d} = \frac{1}{2}\, \mathrm{C_d}\, \mathrm{A}\, \rho_\mathrm{f}\, (\mathrm{u_0} - \mathrm{u_s})^2$$

$$\mathrm{F_a} = \mathrm{k}\, \rho_\mathrm{f}\, \mathrm{V}\, \mathrm{a(t)}$$

$$\mathrm{F_f} = \lambda\, (\rho_\mathrm{s} - \rho_\mathrm{f})\, \mathrm{Vg}$$

The criterion where boulders start to move, is shown on the formula below, Let's name the right side of this inequality as F, making it easier to demonstrate that the boulders in the final arrangement will remain immobile.

$$F = F_d + F_a + F_f$$

By using the mathematical expression above which illustrates the range of sizes of boulders that are moved, as a function of fluid acceleration, the following detailed calculations is made.

Table 5. 6 Information about the data pertaining to each boulder and outcomes related to their movement.

Name	Id	Area(m^2)	Height(m)	Volume m^3(A*H)	Added Mass Ma (kg)	Estimated Diameter d (m)	Cross-section A(m)	Length (m)	Depth water h (m)	Force F	Motion
WEIR_1	1	53	1.2	63.6	79500	8.217	1.2	5.477871589	0.000292308	9.7436E-05	NO
	2	31	1.23	38.13	47662.5	6.284	1.23	4.189428275	0	0	NO
	3	64	1	64	80000	9.029	1	6.019548245	0.00568	0.00189333	NO
	4	26	0.9	23.4	29250	5.755	0.9	3.836724246	0.00568	0.00189333	NO
	5	26	0.7	18.2	22750	5.755	0.7	3.836724246	0.009548387	0.0031828	NO
	6	40	0.65	26	32500	7.138	0.65	4.758870735	0.006480769	0.00216026	NO
	7	11	1.17	12.87	16087.5	3.743	1.17	2.495572867	0.006827586	0.00227586	NO
	8	43	1	43	53750	7.401	1	4.934102195	0.001659091	0.00055303	NO
	9	3	0.75	2.25	2812.5	1.955	0.75	1.303270425	0.007466667	0.00248889	NO
	10	5	0.5	2.5	3125	2.524	0.5	1.682514884	0.060685714	0.02022858	NO
WEIR_2	11	53	0.5	26.5	33125	8.217	0.5	5.477871589	0.209477108	0.06982572	NO
	12	14	0.5	7	8750	4.223	0.5	2.815385895	0.293821809	0.09794063	NO
	13	62	0.5	31	38750	8.887	0.5	5.924746285	0.248022346	0.08267414	NO
	14	37	0.5	18.5	23125	6.865	0.5	4.576935314	0.213419847	0.07113997	NO
	15	16	0.5	8	10000	4.515	0.5	3.009774123	0.236887574	0.07896254	NO
	16	21	0.5	10.5	13125	5.172	0.5	3.448129435	0.147373171	0.0491244	NO
	17	19	0.5	9.5	11875	4.920	0.5	3.279825311	0.23673253	0.07891086	NO
	18	45	0.5	22.5	28125	7.571	0.5	5.047544651	0.252232804	0.08407762	NO
	19	25	0.5	12.5	15625	5.643	0.5	3.762217653	0.089909091	0.0299697	NO
WEIR_3	20	48	1	48	60000	7.820	1	5.2130817	0.004416667	0.00147222	NO
	21	36	1	36	45000	6.772	1	4.514661184	0.004416667	0.00147222	NO
	22	10	1	10	12500	3.569	1	2.379435367	0.004416667	0.00147222	NO
	23	33	0.75	24.75	30937.5	6.484	0.75	4.322459	0.053742424	0.01791415	NO
	24	11	0.75	8.25	10312.5	3.743	0.75	2.495572867	0.053742424	0.01791415	NO
	25	5	0.75	3.75	4687.5	2.524	0.75	1.682514884	0.053742424	0.01791415	NO
	26	18	1.25	22.5	28125	4.789	1.25	3.192347538	0.002734043	0.00091135	NO
	27	14	1.25	17.5	21875	4.223	1.25	2.815385895	0.002734043	0.00091135	NO
	28	6	1.25	7.5	9375	2.765	1.25	1.84310271	0.002734043	0.00091135	NO
	29	5	1.25	6.25	7812.5	2.524	1.25	1.682514884	0.002734043	0.00091135	NO
	30	8	1.25	10	12500	3.192	1.25	2.128231692	0.002734043	0.00091135	NO
WEIR_4	31	16	1.17	18.72	23400	4.515	1.17	3.009774123	0.024169643	0.00805655	NO
	32	13	1.17	15.21	19012.5	4.069	1.17	2.712973732	0.024169643	0.00805655	NO
	33	18	1.17	21.06	26325	4.789	1.17	3.192347538	0.024169643	0.00805655	NO
	34	2	1.17	2.34	2925	1.596	1.17	1.064115846	0.024169643	0.00805655	NO
	35	8	0.9	7.2	9000	3.192	0.9	2.128231692	0.255773196	0.08525775	NO
	36	11	0.9	9.9	12375	3.743	0.9	2.495572867	0.255773196	0.08525775	NO
	37	10	0.9	9	11250	3.569	0.9	2.379435367	0.255773196	0.08525775	NO
	38	4	0.9	3.6	4500	2.257	0.9	1.504887061	0.255773196	0.08525775	NO
	39	2	0.9	1.8	2250	1.596	0.9	1.064115846	0.255773196	0.08525775	NO
	40	17	1.23	20.91	26137.5	4.654	1.23	3.102404154	0.06585	0.02195001	NO
	41	5	1.23	6.15	7687.5	2.524	1.23	1.682514884	0.06585	0.02195001	NO
	42	1	1.23	1.23	1537.5	1.129	1.23	0.752443531	0.06585	0.02195001	NO
	43	1	1.23	1.23	1537.5	1.129	1.23	0.752443531	0.06585	0.02195001	NO

Even though the boulders are not expected to be dragged in the river, they might get stuck in jams, and the river flow may not be strong enough to clean itself. We need to consider this aspect when planning and determining the time of exploitation (Alexander J, 2016).

5.9.2 Ensuring Riverbed Stability and Creating a Fish-Friendly Habitat

To make sure rocks stay in place, we use the force of the water on them. This force causes drag and tilting, but the weight of the rock's counters it. We create a front area on the rocks that turns them, and when we build it, the tilting helps drill a hole through the rock. We then secure the bottom by placing steel rods into these holes. (Olsen, 2017)

In practice, there's usually a rock layer beneath the rocks, but for a good fish habitat, we need to remove smaller stones and cobbles to create spaces.

Our calculations show that the modeled rocks don't move in flood scenarios but to make things clear and smooth, let's talk about putting boulders in a river. When deciding where to place them, we need to think carefully. Should we simply drop them on the surface, or should we dig a hole and put a big rock in, trying to anchor it securely. This choice matters because moving boulders can be costly, especially when it comes to altering the eddy flow of water in the river.

anchoring them properly increases stability in real life. Two ways to anchor rocks could be, by drilling a hole in the rock and driving an iron anchor into the bottom to prevent it from moving downstream during a big flood. Second If we have a riverbed and rocks modeled to be similar in size to the boulders we've used in our simulation, we can excavate down to the gravel layer and incorporate these rocks to create stability.

In chapter three, examples of this artificial habitat in Lærdal were presented, but they disappeared after the first flood. This emphasizes the importance of careful calculations before actual work. Rocks might move or roll, so it's crucial to determine their size to stay in place. A little movement settling down is acceptable, but avoiding big shifts is essential.

5.9.3 Utilizing Submerged Weirs for Riverbed Protection

When it comes to ensuring the stability of riverbed, we explore two key approaches. Firstly, one effective method involves calculating the stability of the rocks illustrated above. The second method involves constructing a submerged weir at the river's bottom, replacing the traditional Lærdal weirs that protrude.

The focus on the submerged weir revolves around its construction, particularly the use of cement, which lacks clear evidence of intent and impact. The primary objective is to remove the existing weir and replace it with a submerged one, surrounded with random placed rocks, preventing the river from initiating digging.

Considering the river's stability and the interest in fishing, maintaining the weir's current location and the small elevation where the old weir rocks are positioned is desired. Originally, the Lærdal River experienced low flow in winter, freezing over completely. Regulation changed this, releasing water from the reservoir to the turbine, resulting in raise the water temperature at the outlet of the powerplant enough to prevent the ice formation. Some weirs were constructed for ice protection since this ice started to erode sediments and moved rocks, while others were built for fishing and creating habitats for salmon. While there are claims of additional purposes, the primary goal was to facilitate salmon habitation and fishing (Fjeldstad et al., 2019).

Although detailed coverage of the ice effect is not within the scope of this thesis, maintaining a submerged weir is essential to control the tail end of long pools. This means that during low flow, the submerged weir would be completely underwater, allowing the random placement of rocks around it. This approach serves as a practical solution to address the complexities involved.

5.9.4 The Impact of Weir Adjustments on Upstream Embankment

Another crucial point to highlight is that when we made modifications to the weir, lowering the water level, we took into account the potential exposure of the undersides of the embankments upstream. This consideration was factored in while analyzing the outcomes from bed change maps after conducting the sediment simulation using average flood discharges. We extended our 2D flow areas in Hec-Ras 2D to include this aspect in our analysis. The concern was that lowering the water level might lead to more erosion beneath the embankments, risking their failure on the sides. Fortunately, in our case, we did not observe such results.

6 Discussions

6.1 Removed Weirs

In summary, the process began by importing the original terrain data with buildings. Next, interpolation was carried out by selecting optimal locations without protruding rocks or unusual structures this is vital, and a straight river line without bends is preferred. The interpolated geometry was then combined with the original terrain in ArcGIS Pro, and the terrain was reconstructed in Hec-Ras. Various simulations were conducted with different terrain modifications.

It's crucial to carefully assess the weir's depth, as it plays a role in determining the size of the rocks. The modified weir's depth provides valuable information for designing rock dimensions and deciding on the appropriate height. This approach ensures that the rocks remain submerged while avoiding the placement of unrealistically tall rocks across the weir crest.

6.2 Sediment Simulation

Due to their hindering function, larger rocks are more crucial than finer materials in our considerations. However, understanding the behavior of fine materials is important, especially in the context of removing the weir.

To investigate this, we simulated sediment movement in the model, focusing on four weirs. We assessed specific local areas for erosion and deposition. Comparing this to a more general analysis using shields as done by Alfredsen and Awadallah, (2022), we observed similar patterns. Their study involved removing a weir and calculating sediment sizes based on shear stress from Hec-Ras, using the shields formula. Our work offers more detailed insights into the potential outcomes under high discharge conditions.

Corresponding to Alfredsen and Awadallah, (2022), the model was tested for minimum floods like the 20-year and 50-year flood scenarios. The comparison of velocity distribution and application of the shield formula indicated that weirs have no significant impact on potential sediment areas.

When considering sediments for fish spawning in the distribution of artificial rocks, we placed bottom sediment samples between the rocks to create suitable spawning conditions. Analyzing bed changes revealed the accumulation of fine sediments behind the rocks. We also examined the depth and velocity around these rocks.

The sediment simulation conducted here provides a sufficient response to concerns raised in Lærdal regarding removing weirs. Their expectation was that removing weirs would increase velocity in the lower part and move more fine material. However, our simulations did not show a significant difference in the situation with or without weirs, providing fewer convincing grounds for removing them.

6.3 Sedimentation and Weir Impact

In our sediment simulation, it's evident that there isn't much erosion in the primary pool area, with erosion and deposition concentrated around the weir. To recapitulate the core idea behind the weir removal project is to remove not only the weir but also to see the effect of bed change throughout the entire upstream reach. However, both the shields calculation in the study by Alfredsen and Awadallah (2022) and our simulations suggest that this might not be the case.

Our simulations indicate erosion mainly in the weir region. Yet, when we move 100 to 200 meters upstream of the weir øye, there seems to be minimal erosion. The critical question lies in understanding what happens in this long, slow-flowing section, where most of the fine materials are currently stored. While erosion and deposition occur on both sides of the weir (at the front and back), there is no significant erosion in this stretch. This insight is crucial for the project because it suggests that removing the weir alone may not be sufficient to flush out fine materials from the lower part of the river.

In our study, we made the other four weirs in the domain non-erodible and subjected them to large floods. While exploring sediment behavior in low flows would be interesting, we had to consider the constraints of time, the project's timeframe, and the simulation duration.

6.4 Artificial Rocks for Stability and Habitat for Fish

In practical terms, when we replace the weir with modeled stones, we considered the need to be sizable enough to endure floods up to a certain level. If they weren't, we'd have to replace and restructure them after each flood. The material between these rocks consists of fine particles, essential for providing suitable spawning grounds for fish.

The bottom, where we've placed boulders partly dug in with machinery, contains a mix of fine materials like sand, silt, and gravel. The analysis of erosion and deposition results helps us understand where these sediments might transport, erode (clean), or impact the entire habitat. Once we've assessed how long these sediments persist based on simulated flood return periods, we could decide on methods to remove them safely.

When placing rocks, such as 1.23 meter high boulders and considered how they'll withstand floods, the key is also to ensure they provide shelter for fish. These rocks act as significant elements, slowing down and breaking up the current to create a natural flow pattern, while the sediment on the bottom consists of traditional river sediments more cobbles and gravel providing spaces for fish to hide.

Flattening out the weir would not mobilize the old sediment that has accumulated over time. Additionally, increasing velocity due to weir removal would not contribute to preventing sediment buildup in the main part of the river. According to the study by Alfredsen and Awadallah (2022), taking out the weir doesn't significantly increase movable sediment. The key rocks should remain after a flood, serving as engineered artificial habitats. Smaller rocks between them create a more natural riverbed.

Modelled boulders are nearly the same volume as in real life. If they were smaller and unstable, anchoring them to the bottom would be suggested. To keep them in place, plastering might be also necessary, but the potential for digging in the lower part or sliding into the river is not detailed.

To track their movement, one suggestion was using GPS to locate these rocks, while mapping through drones and aerial photography is another option. Conducting sediment samples upstream, downstream, and in the rock area, and monitoring them over the years, would provide valuable insights in the next works. Considering construction only when the flow is lower is advisable for using machinery in the river. Since primary goal of placing these rocks is to create favorable conditions for fish and establish recirculation areas. This is an important aspect of our study to enhance conditions for fish in these specific areas.

6.5 Sedimentation Impact

6.5.1 Assessing the Long-Term Effects on Modeled River Habitat for Fish

We could use this data to make predictions. For instance, if we are going to remove a weir in Lærdal and set up distributed rocks to create hiding spaces for fish, knowing how long such a setup lasts are vital. By using the flood frequencies, we might estimate how often such events are likely to happen. We need to consider potential drawbacks, such as the rocks getting filled with sand within a year, making this approach expensive. Utilizing the simulation helps us identify suitable locations for placing rocks avoiding risk areas with significant depositions and selecting spots where erosion is likely to keep the area clean. There are intriguing interpretations to explore based on this simulation.

6.5.2 Some Uncertainties in The Sediment Work

In our results, we observe significant scouring and deposition, possibly due to the armor layer, whether we mix it or use the default. It's crucial to test if this is too rough, especially the fine material beneath the rocks, which requires further investigation in the next works.

Concerning the modeled rocks, we need to understand if natural processes, like floods, are sufficient for the desired changes or if manual intervention is necessary. Additionally, other suggested solutions, such as using suction dredge devices or specialized excavators designed to remove fine material without heavy machinery, and dredging methods to extract accumulated sand, were suggested during the study. However, their implications go beyond the current scope and need detailed examination.

It's essential to note that in regions without a defined sediment domain, Hec-Ras indicates scouring. Therefore, it's important to specify non-movable regions as non-erodible.

For future endeavors, exploring erosion and sedimentation under common low-flow conditions in the river would be interesting, although this is constrained by the study's time frame.

6.5.3 Assumptions Made in Sediment Simulation

We assume that the bed material in Hec-Ras reflects the input grain size distributions. It's important to note that this study didn't delve into detailed investigations on the impact of altering some of the bed mixing settings in Hec-Ras.

Appendix (F) contains a record of all the assumptions made in the sediment formulas. However, it's essential to explore the potential consequences and how these assumptions might impact the results in future studies. A valuable avenue for further investigation would involve an in-depth sediment study on regulated streams, incorporating extensive fieldwork and measuring numerous samples to enhance our understanding of these processes.

6.5.4 Bed Mixing Options

This aspect defines the amount of sediment available for erosion. Ideally, we would have conducted measurements both before and after our intervention, using parameters like sediment volume for calibration. In the bed change analysis, it relies on the material within the results, allowing us to quantify the movement of coarse sediment. However, understanding the underlying principles and whether the results are accurate can be a bit challenging. Further clarification on the accuracy and correctness of these findings may be necessary (Brunner, 2023).

6.5.5 Understanding Hiding Functions and Bed Roughness Dynamics in Sediment Movement

In sediment beds with uneven sizes, the interaction between particles varies. Smaller particles find shelter behind larger ones, shielded from the flow, while larger particles are exposed and move more freely. The hiding function, introduced by Gibson (2023), calculates corrections to factors like shear stress or velocity, considering the concealment and exposure of particles.

Examining the dynamics of bed roughness and sediment movement, as proposed by Van Rijn, involves activating features like dunes to observe sediment motion. The method employed in this study is the minimal one available, suitable for scenarios where sediment movement occurs.

This study utilizes the default hiding function, representing only a portion of the movement, yet adjustments can be made manually to increase or decrease its influence. The research focuses on a brief stretch of the river, featuring two distinct sediment curves for a more in-depth investigation.

6.6.6 Clarifying Turbulent Models In Sediment Equations

In this study, we conducted two separate runs using the same hydrograph, terrain, and sediment file. The only distinction between the two runs was the turbulence term one with conservative settings and the other with none. Due to computational constraints, the simulations were conducted at different times, which, in our specific case, did not yield noticeable differences.

Upon comparing and exporting the datasets, we plotted them together and observed no significant disparities. However, the absence of calibration data makes it challenging to determine which model is more accurate. Future studies should explore the impact of running simulations at the same time to further evaluate these turbulent models.

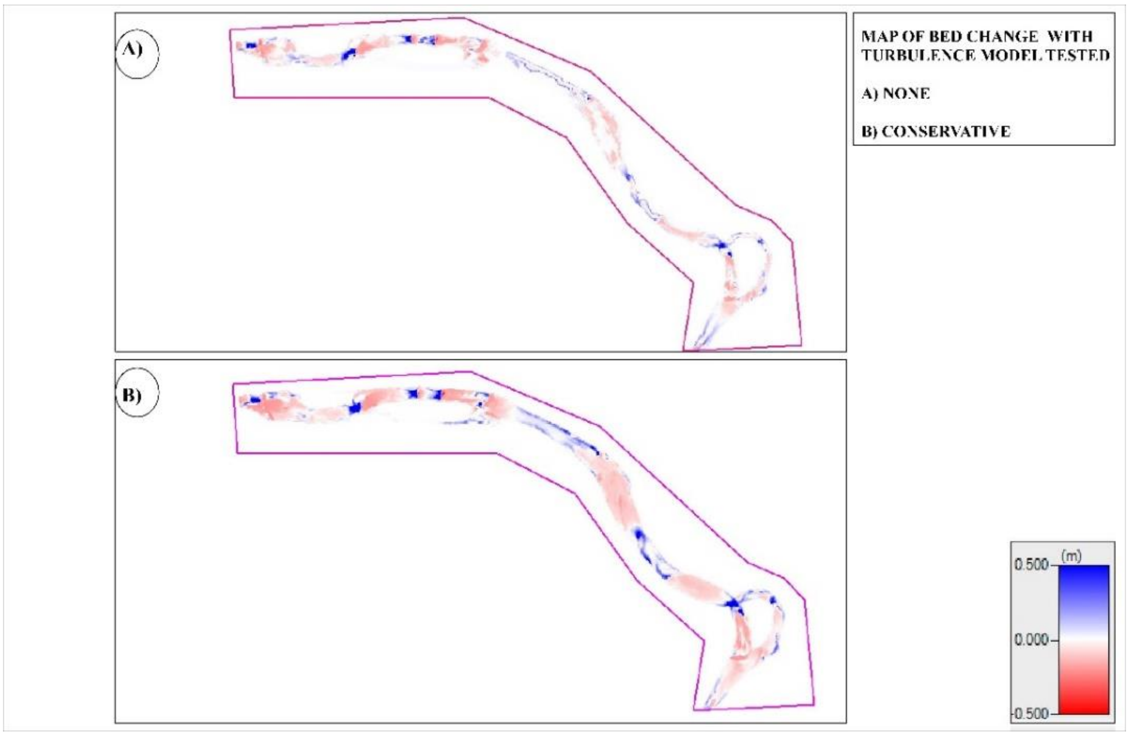


Figure 6. 1 Bed changes for two different turbulence models, A) NONE and B) Conservative with Q= 240 m^3/s, a terrain with initial weir is utilized for comparison.

7. Conclusions

The simulations revealed intriguing insights into the dynamics of sedimentation and the potential impact of weir removal. Contrary to expectations, removing weirs did not significantly affect the accumulation of fine sediments in the upstream pool. The focus was primarily on deposition in the upper pool, with minimal erosion observed in the main upstream area. This challenges the theory that weir removal would induce erosion upstream due to increased water velocities.

Artificial rocks introduced for habitat creation showcased erosion around the rocks and sediment deposition behind them, aligning with expectations. These rocks serve multiple functions, including creating recirculation, maintaining proper depths and velocities between them, and securing the riverbed.

Deep pools in the lower river exhibited minimal erosion and deposition, prompting reconsideration of the notion that weir removal is the solution for eliminating fine sediments. However, limited data on the riverbed and armor layer in deep pools hinder a comprehensive understanding of erosion patterns.

This study contributes significantly to Lærdal sediment research for environmental purposes, addressing a current gap in literature and data. Future research should validate these findings, exploring the sensitivity of model configurations and assessing the potential impact of high floods on river communities.

While weir removal may not be warranted in the near future in Lærdal, considerations for its effects on fish and other aquatic life, alongside alternative methods like plastering and anchoring, warrant further examination. This research challenges prevailing arguments, providing evidence against the assumption that weir removal would automatically lead to sediment washout. The study calls for a more distinct evaluation of rock characteristics and placement to effectively stabilize the riverbed, addressing the complexities associated with floods and sediment mobilization.

References

Alexander, J., & Cooker, M. J. (2016). Moving boulders in flash floods and estimating flow conditions using boulders in ancient deposits. Sedimentology, 63(6), 1582-1595.

Alfredsen, K., & Awadallah,M,O., (2022). Assessment of the hydraulic effect of thresholds in Lærdalselva.

Armstrong, J. D., Kemp, P. S., Kennedy, G. J. A., Ladle, M., & Milner, N. J. (2003). Habitat requirements of Atlantic salmon and brown trout in rivers and streams. Fisheries research.

Atwood, E., Duffy-Anderson, J. T., Horne, J. K., & Ladd, C. (2010). Influence of mesoscale eddies on ichthyoplankton assemblages in the Gulf of Alaska. Fisheries Oceanography.

Awadallah, M. O. M., Malmquist, C., Stickler, M., & Alfredsen, K. (2023). Quantitative Evaluation of Bathymetric lidar Sensors and Acquisition Approaches in Lærdal River in Norway. Remote Sensing, 15(1), 263.

Blake, R.W. 1979. The energetics of hovering in the mandarin fish (Synchropus picturatus).Journal of Experimental Biology 82: 25–33.

Blazka, P., M. Volf and M. Cepala. 1960. A new type of respirometer for the determinationof the metabolism of fish in an active state. Physiologia Bohemoslovenica 9: 553–558

Brett, J.R. 1995. Energetics. In: Physiological-Ecology of Pacific Salmon, J. R. Brett and C.Clark (Eds.). Gov. Canada, Dept. Fish. Oceans, Ottawa, Ontario.

Brunner, G.W. (2023). Hec-Ras 2D User's Manual Version 6.3.1. U.S. Army Corps of Engineers. https://www.hec.usace.army.mil/confluence/rasdocs/rasum/latest

Casas, A., Benito, G., Thorndycraft, V. R., & Rico, M. (2006). The topographic data source of digital terrain models as a key element in the accuracy of hydraulic flood modelling. Earth Surface Processes and Landforms: The Journal of the British Geomorphological Research Group, 31(4), 444-456.

Copeland, R. R., mccomas, D. N., Thorne, C. R., Soar, P. J., Jonas, M. M., and Fripp, J. B. (2001). Hydraulic Design of Stream Restoration Projects. Technical Report ERDC/CHL TR-01-28, U.S. Army Corps of Engineers: Engineer Research and Development Center; Vicksburg.

Einum, S., & Nislow, K. H. (2011). Variation in population size through time and space: theory and recent empirical advances from Atlantic salmon. Atlantic salmon ecology, 277-298.

Elder, John; Coombs, Sheryl (21 May 2015). "The influence of turbulence on the sensory basis of rheotaxis". Journal of Comparative Physiology A. 201 (7): 667–680.

Engeland, K., Aano, A., Steffensen, I., Støren, E., & Paasche, Ø. (2020). New flood frequency estimates for the largest river in Norway based on the combination of short and long time series. Hydrology and Earth System Sciences, 24(11), 5595-5619.

Fergus, T., Hoseth, K. A., & Sæterbø, E. (2010). Vassdragshåndboka: håndbok i vassdragsteknikk. Ny rev. Utg. Trondheim: Tapir akademisk forl.

Fjeldstad, H. P., Barlaup, B. T., Stickler, M., Gabrielsen, S. E., & Alfredsen, K. (2012). Removal of weirs and the influence on physical habitat for salmonids in a Norwegian river. River research and applications, 28(6), 753-763.

Fjeldstad, H.P., Gabrielsen, S.E., Robertsen, G., & Skår, B., (2019). Environmental design in Lærdalselva.

Fjeldstad, H. P., Pulg, U., & Forseth, T. (2018). Safe two-way migration for salmonids and eel past hydropower structures in Europe: a review and recommendations for best-practice solutions. Marine and Freshwater Research, 69(12), 1834-1847.

Foldvik, A., Holthe, E., Bremset, G., & Solem, Ø. (2022). Effects of Episodic Exposure to High-ph Water on Survival of Atlantic Salmon Eggs and Juveniles: Results from Laboratory and Field Studies. Environmental Toxicology and Chemistry, 41(3), 771-780.

Forseth, T., Harby, A., Ugedal, O., Pulg, U., Fjeldstad, H. P., Robertsen, G., ... & Arnekleiv, J. V. (2014). Handbook for environmental design in regulated salmon rivers.

Guo, J., & Julien, P. Y. (2002). Boundary shear stress in smooth rectangular open channels. In Advances in Hydraulics and Water Engineering: Volumes I & II (pp. 76-86).

Heggenes, J., Saltveit, S. J., & Lingaas, O. (1996). Predicting fish habitat use to changes in water flow: modelling critical minimum flows for Atlantic salmon, Salmo salar, and brown trout, S. Trutta. Regulated Rivers: Research & Management, 12(2-3), 331-344.

Holmqvist, E. (2000). Flomberegning for Lærdalsvassdraget. NVE: Oslo, Norway.

Im, D., Kang, H., Kim, K. H., & Choi, S. U. (2011). Changes of river morphology and physical fish habitat following weir removal. Ecological Engineering, 37(6), 883-892.

John E. Brittain (2003) Weirs as a Mitigation Measure in Regulated Rivers—The Norwegian Experience , Canadian Water Resources Journal / Revue canadienne des ressources hydriques, 28:2, 217-229, DOI: 10.4296/cwrj2802217.

Juárez, A.; Alfredsen, K.; Stickler, M.; Adeva-Bustos, A.; Suárez, R.; Seguín-García, S.; Hansen, B. A Conflict between Traditional Flood Measures and Maintaining River Ecosystems? A Case Study Based upon the River Lærdal, Norway. Water 2021, 13 1884. Https://doi.org/10.3390/w13141884.

Kennedy, B. P., Nislow, K. H., & Folt, C. L. (2008). Habitat-mediated foraging limitations drive survival bottlenecks for juvenile salmon. Ecology, 89(9), 2529-2541.

Liao, J.C. 2004. Neuromuscular control of trout swimming in a vortex street: implicationsfor energy economy during the Kármán gait. Journal of Experimental Biology 207:3495–3506.

Md sahadat hossain., ph.d., p.e., md azijul islam., faria fahim badhon., & tanvir imtiaz. (2020). Properties and behavior of soil - online lab manual.

Norge i bilder, retrieved from, https://norgeibilder.no/?x=525000&y=7175000&level=5&utm=33&projects=&layers=&plannedOmlop=0&plannedGeovekst=0.

Olsen, N.R. (2017). Numerical modelling and Hydraulics. Department of hydraulic and environmental engineering, the Norwegian university of science and technology.

Pavlov, D.S., A.I. Lupandin and M.A. Skorobogatov. 2000. The effects of flow turbulenceon the behavior and distribution of fish. Journal of Ichthyology 40, (Supplement 2).S232–S261

Pulg, U., Vollset, K. W., & Lennox, R. J. (2019). Linking habitat to density-dependent population regulation: How spawning gravel availability affects abundance of juvenile salmonids (Salmo trutta and Salmo salar) in small streams. Hydrobiologia, 841(1), 13-29.

Shcherbakov, M. V., Brebels, A., Shcherbakova, N. L., Tyukov, A. P., Janovsky, T. A., & Kamaev, V. A. E. (2013). A survey of forecast error measures. World applied sciences journal, 24(24), 171-176.

Stranzl, S., Pulg, U., Postler, C., Hauer, C., Floedl, P., (2022). Application of airborne lidar bathymetry in Norway.

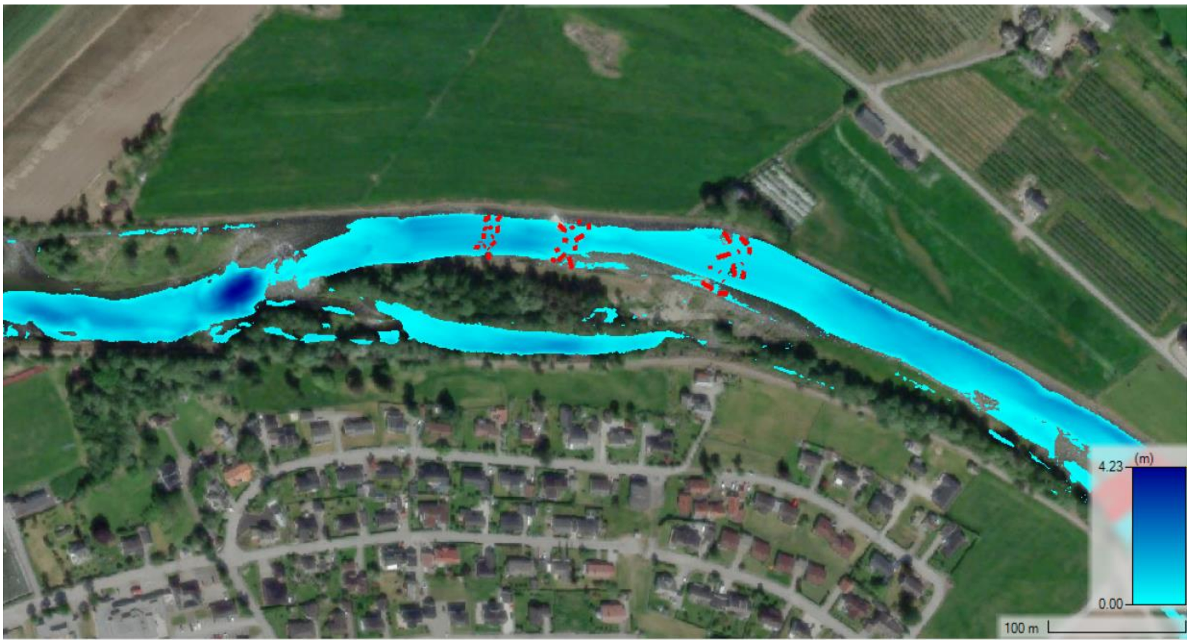
Tupen,H.N., (2020). Hydraulics, hydrology, and resulting fish passage at the Huntley diversionnature-likebypass.Retrievedfrom https://scholarworks.montana.edu/xmlui/handle/1/15982

Webb, P.W. 2002. Control of posture, depth, and swimming trajectories of fishes. Integrative and Comparative Biology 42: 94–101.

Webb, P. W., Cotel, A., & Meadows, L. A. (2010). Waves and eddies: effects on fish behavior and habitat distribution. In Fish Locomotion (pp. 1-39). CRC Press.

Wolman, M.G., (December 1954). A method of sampling coarse river-bed material, Transactions, American Geophysical Union.

Appendix (A): profile lines drawn to find the water depth utilized for calculating eventual movement of each boulder depending on their location.



Appendix (B): Granulometry Using Sieve Analysis.

EMPTY_WEIGHT_OF_SIEVES		(Wieght of sieve + Retained Soil) kg		Weight of Retained soil		Accumulative Weight of Retained soil		%Retained		%Finer (%Passing)	
Openings (mm)	Weight of sieves (kg)	SEDIMENT(A3)	SUBTRATE(A1)	SEDIMENT(A3)	SUBTRATE(A1)	SEDIMENT(A3)	SUBTRATE(A1)	SEDIMENT(A3)	SUBTRATE(A1)	SEDIMENT(A3)	SUBTRATE(A1)
63	1.595	8.259	1.595	6.664	0	6.664	0	42.4	0.0	57.554	100.000
31.5	1.755	5.035	2.9	3.28	1.145	9.944	1.145	63.3	24.9	36.662	75.087
16	1.845	3.33	2.435	1.485	0.59	11.429	1.735	72.8	37.8	27.204	62.250
8	1.605	2.255	2.275	0.65	0.67	12.079	2.405	76.9	52.3	23.064	47.672
4	1.545	1.975	2.21	0.43	0.665	12.509	3.07	79.7	66.8	20.325	33.203
2	1.32	1.83	1.82	0.51	0.5	13.019	3.57	82.9	77.7	17.076	22.324
1	1.145	1.925	1.53	0.78	0.385	13.799	3.955	87.9	86.1	12.108	13.947
0.5	1.075	1.71	1.225	0.635	0.15	14.434	4.105	91.9	89.3	8.064	10.683
0.25	0.985	1.66	1.235	0.675	0.25	15.109	4.355	96.2	94.8	3.764	5.244
0.125	0.905	1.27	1.055	0.365	0.15	15.474	4.505	98.6	98.0	1.439	1.980
0.1	0.925	0.985	0.945	0.06	0.02	15.534	4.525	98.9	98.5	1.057	1.545
0.063	0.924	0.995	0.955	0.071	0.031	15.605	4.556	99.4	99.1	0.605	0.870
	4.925	5.02	4.965	0.095	0.04	15.7	4.596	100.0	100.0	0.000	0.000
			SUM	**15.7**	**4.596**						

Appendix (C): Granulometry Using Total Frame.

	COUNT		**FREQUENCY (%)**		**CUMULATIVE (%)**	
SIZE CLASS	**NUMBER Area_1**	**NUMBER Area_2**	**A1**	**A2**	**AREA_1 (Total FRAME)**	**AREA_2 (TAPE)**
<4	0	0	0	0	0	0
<5.6	0	0	0	0	0	0
<8	0	0	0	0	0	0
<11.3	12	0	8.8235294	0	8.823529412	0
<16	20	18	14.705882	6.56934307	23.52941176	6.569343066
<22.6	27	31	19.852941	11.3138686	43.38235294	17.88321168
<32	20	63	14.705882	22.9927007	58.08823529	40.87591241
<45	18	53	13.235294	19.3430657	71.32352941	60.2189781
<64	20	54	14.705882	19.7080292	86.02941176	79.9270073
<90	11	28	8.0882353	10.2189781	94.11764706	90.1459854
<128	8	16	5.8823529	5.83941606	100	95.98540146
<180	0	9	0	3.28467153	100	99.27007299
<256	0	0	0	0	100	99.27007299
>=256	0	2	0	0.72992701	100	100
TOTAL	136	274				

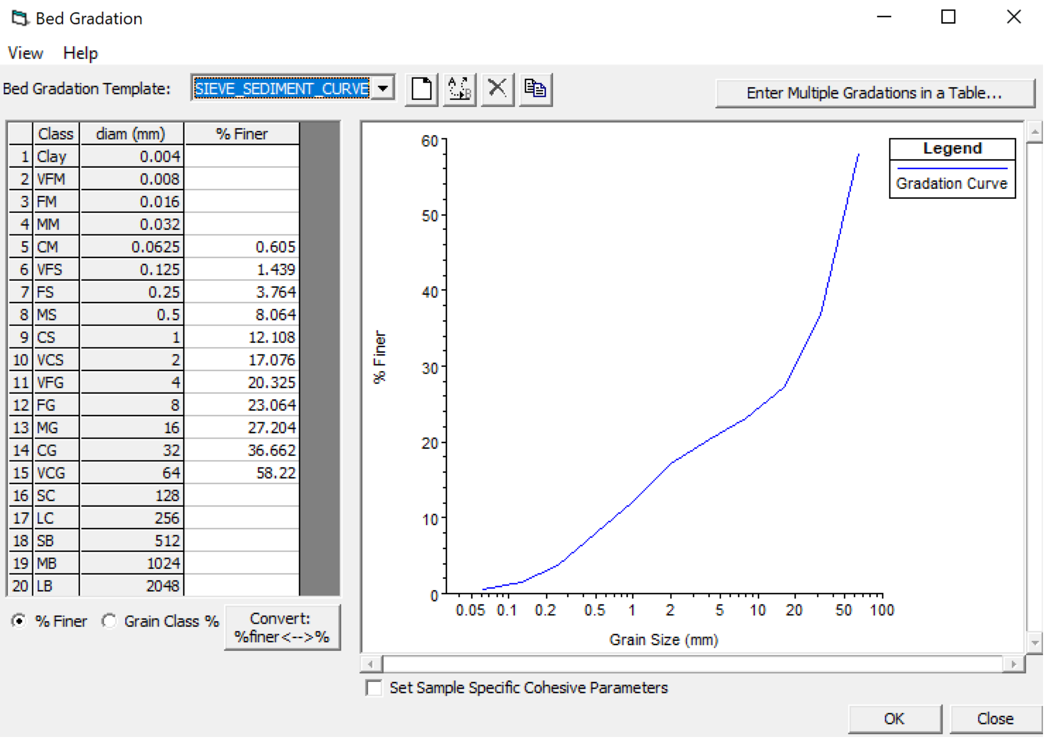
Appendix (D): Pictures from Field Trip In Lærdal (28-29 April 2023)

Figure D.1 Pictures of The Lærdal

Figure D.2 Some Views Of River, The Discharge During That Day Was 20 m^3/s

Figure D.3 GPS measurements near ØYE

Appendix (E): Bed Gradation's View In Hec-Ras



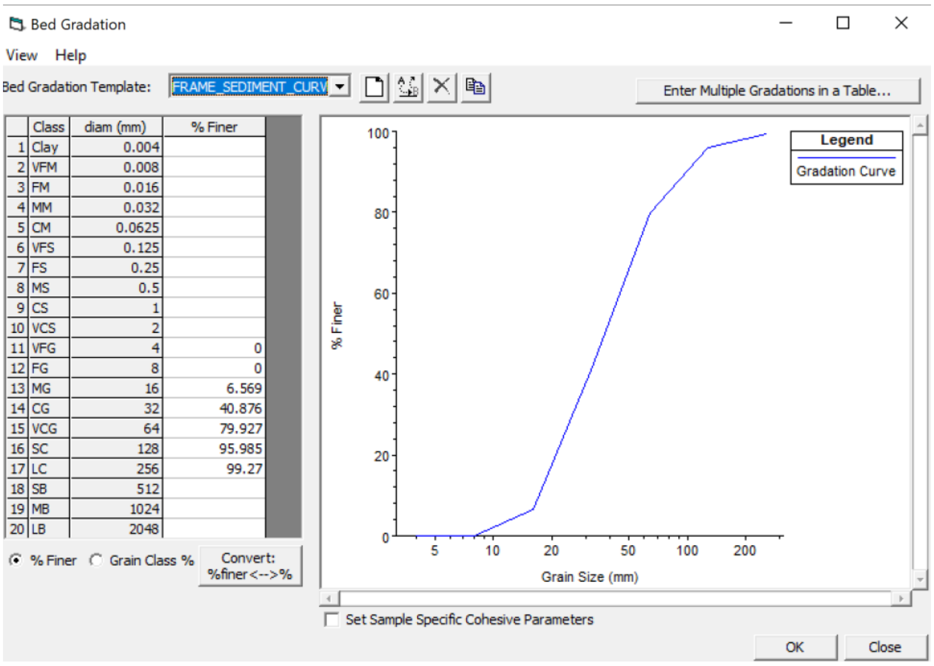
Bed Gradation Template: SIEVE_SEDIMENT_CURVE

	Class	diam (mm)	% Finer
1	Clay	0.004	
2	VFM	0.008	
3	FM	0.016	
4	MM	0.032	
5	CM	0.0625	0.605
6	VFS	0.125	1.439
7	FS	0.25	3.764
8	MS	0.5	8.064
9	CS	1	12.108
10	VCS	2	17.076
11	VFG	4	20.325
12	FG	8	23.064
13	MG	16	27.204
14	CG	32	36.662
15	VCG	64	58.22
16	SC	128	
17	LC	256	
18	SB	512	
19	MB	1024	
20	LB	2048	

● % Finer ○ Grain Class %

☐ Set Sample Specific Cohesive Parameters

Figure E.1 Sieve Gradation Curve



Bed Gradation Template: FRAME_SEDIMENT_CURV

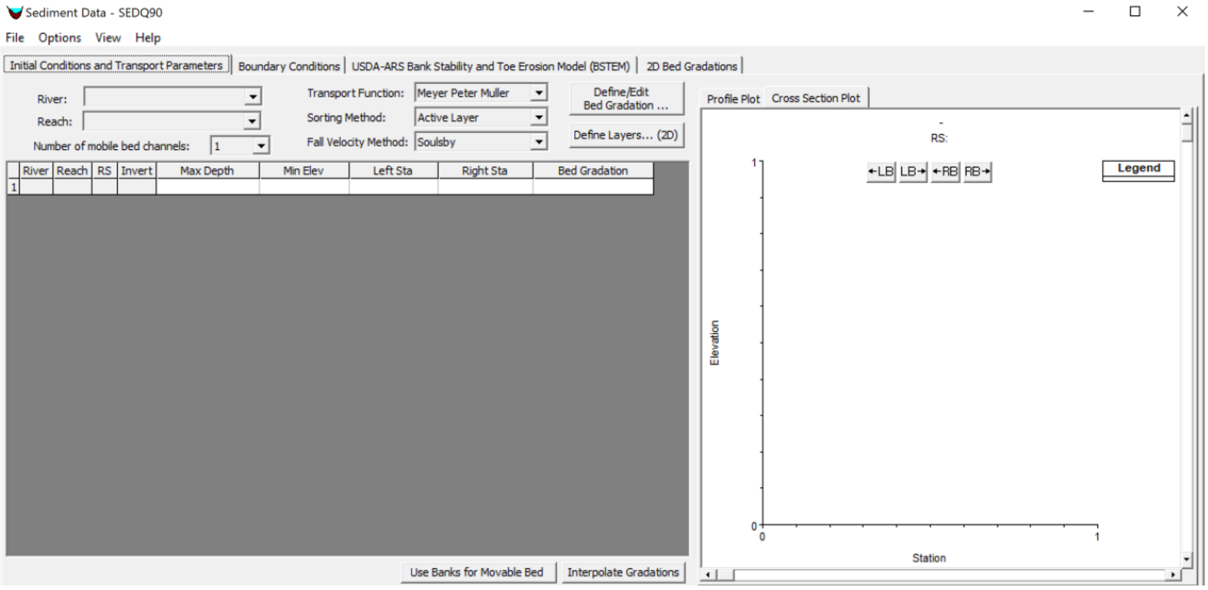
	Class	diam (mm)	% Finer
1	Clay	0.004	
2	VFM	0.008	
3	FM	0.016	
4	MM	0.032	
5	CM	0.0625	
6	VFS	0.125	
7	FS	0.25	
8	MS	0.5	
9	CS	1	
10	VCS	2	
11	VFG	4	0
12	FG	8	0
13	MG	16	6.569
14	CG	32	40.876
15	VCG	64	79.927
16	SC	128	95.985
17	LC	256	99.27
18	SB	512	
19	MB	1024	
20	LB	2048	

● % Finer ○ Grain Class % Convert: %finer<-->%

☐ Set Sample Specific Cohesive Parameters

Figure E.2 Pebble Frame Gradation Curve

Appendix (F): Assumptions from The Sediment Simulation



River:

Reach:

Number of mobile bed channels: 1

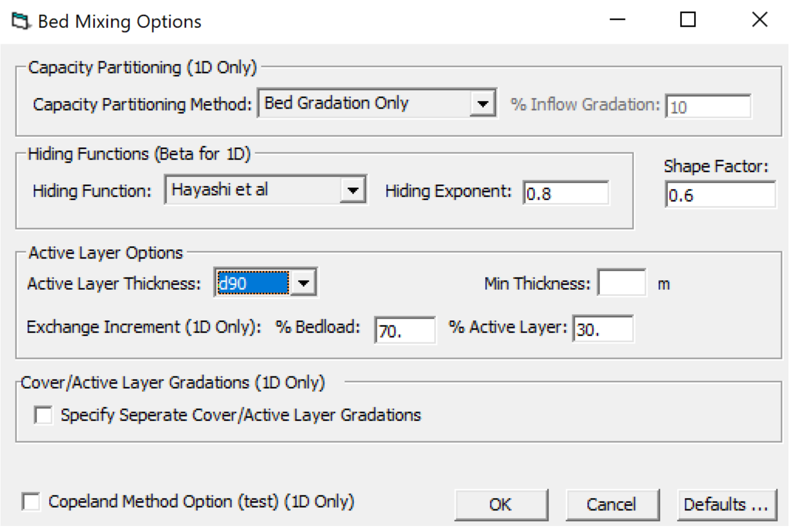
Transport Function: Meyer Peter Muller

Sorting Method: Active Layer

Fall Velocity Method: Soulsby

	River	Reach	RS	Invert	Max Depth	Min Elev	Left Sta	Right Sta	Bed Gradation
1									

Figure F.1 Initial Conditions and Transport Parameters



Capacity Partitioning Method: Bed Gradation Only

% Inflow Gradation: 10

Hiding Function: Hayashi et al

Hiding Exponent: 0.8

Shape Factor: 0.6

Active Layer Thickness: d90

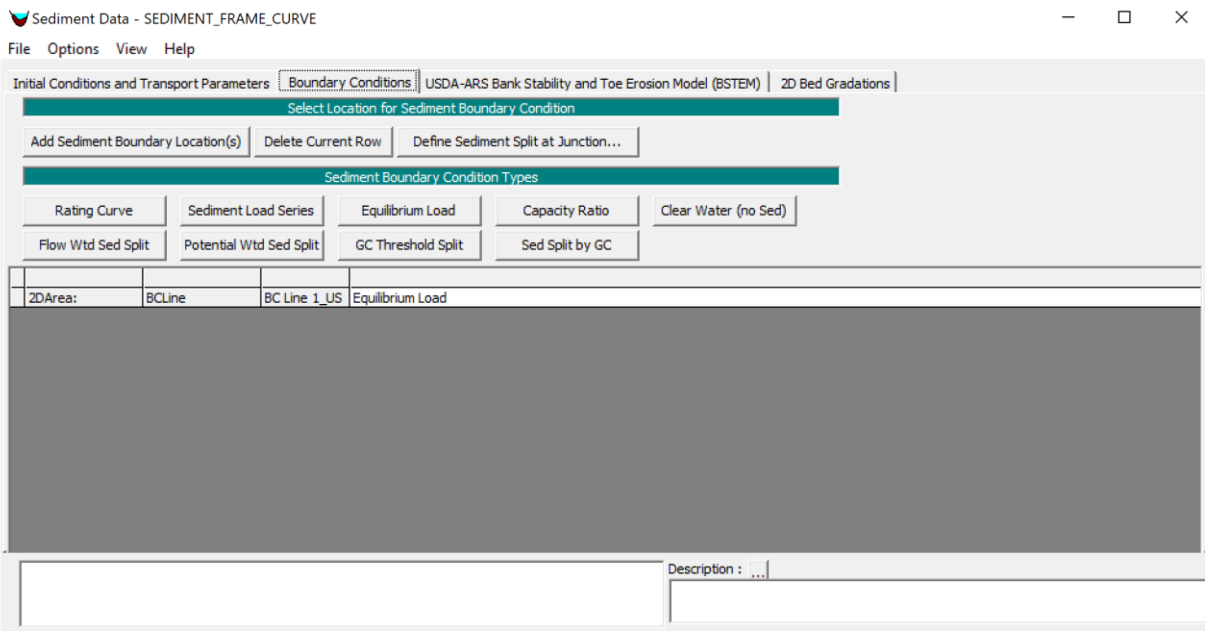
Min Thickness: m

Exchange Increment (1D Only): % Bedload: 70. % Active Layer: 30.

☐ Specify Seperate Cover/Active Layer Gradations

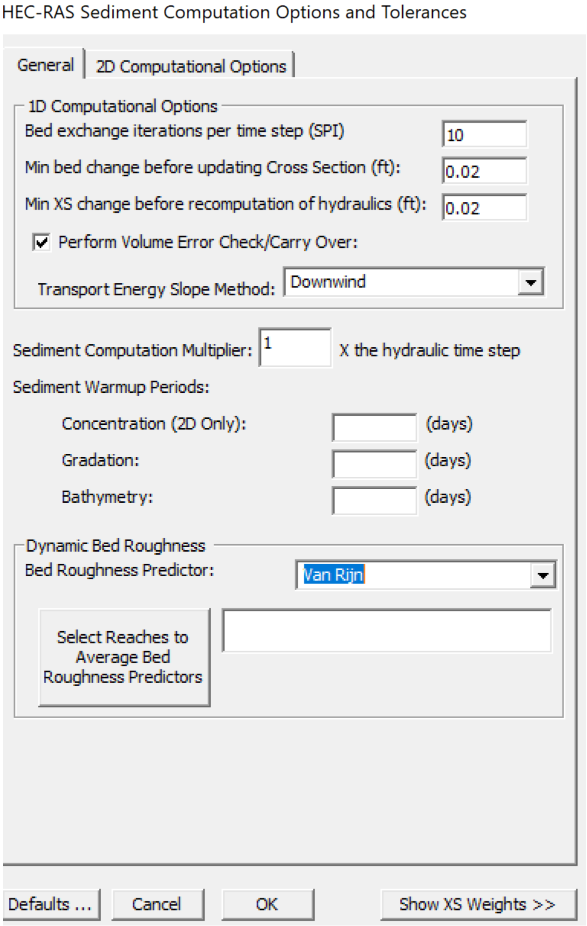
☐ Copeland Method Option (test) (1D Only)

Figure F.2 Bed Mixing Options



2DArea:	BCLine	BC Line 1_US	Equilibrium Load

Figure F.3 Boundary Conditions



1D Computational Options

Bed exchange iterations per time step (SPI): 10

Min bed change before updating Cross Section (ft): 0.02

Min XS change before recomputation of hydraulics (ft): 0.02

☑ Perform Volume Error Check/Carry Over:

Transport Energy Slope Method: Downwind

Sediment Computation Multiplier: 1 X the hydraulic time step

Sediment Warmup Periods:

Concentration (2D Only): (days)

Gradation: (days)

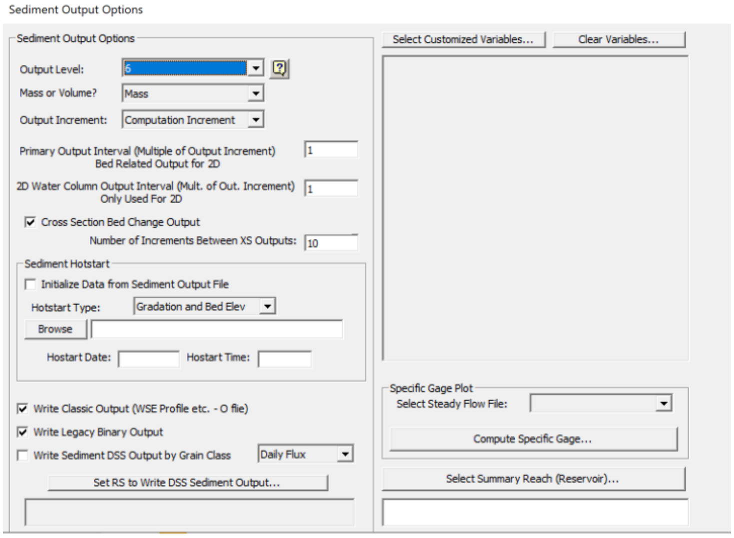
Bathymetry: (days)

Dynamic Bed Roughness

Bed Roughness Predictor: Van Rijn

Select Reaches to Average Bed Roughness Predictors

Figure F.4 Sediment Computation Options And Tolerances



Sediment Output Options

Output Level: 6

Mass or Volume? Mass

Output Increment: Computation Increment

Primary Output Interval (Multiple of Output Increment) Bed Related Output for 2D: 1

2D Water Column Output Interval (Mult. of Out. Increment) Only Used For 2D: 1

☑ Cross Section Bed Change Output

Number of Increments Between XS Outputs: 10

Sediment Hotstart

☐ Initialize Data from Sediment Output File

Hotstart Type: Gradation and Bed Elev

Hostart Date: Hostart Time:

☑ Write Classic Output (WSE Profile etc. - O fiie)

☑ Write Legacy Binary Output

☐ Write Sediment DSS Output by Grain Class Daily Flux

Specific Gage Plot

Select Steady Flow File:

Figure F.5 Sediment Output Options

Appendix (G): Simulation Results of Depth And Velocity Maps In Terrain With Artificial Rocks

Appendix (G.1) Water Depth Maps

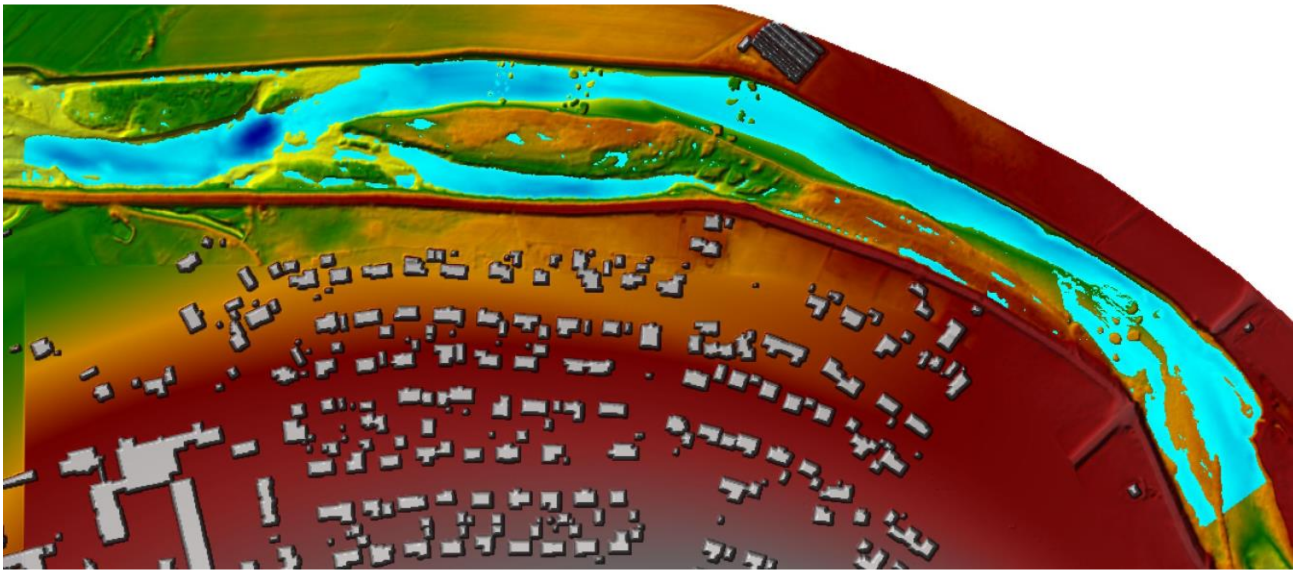


Figure: Water Depth, Q=10 m^3/s

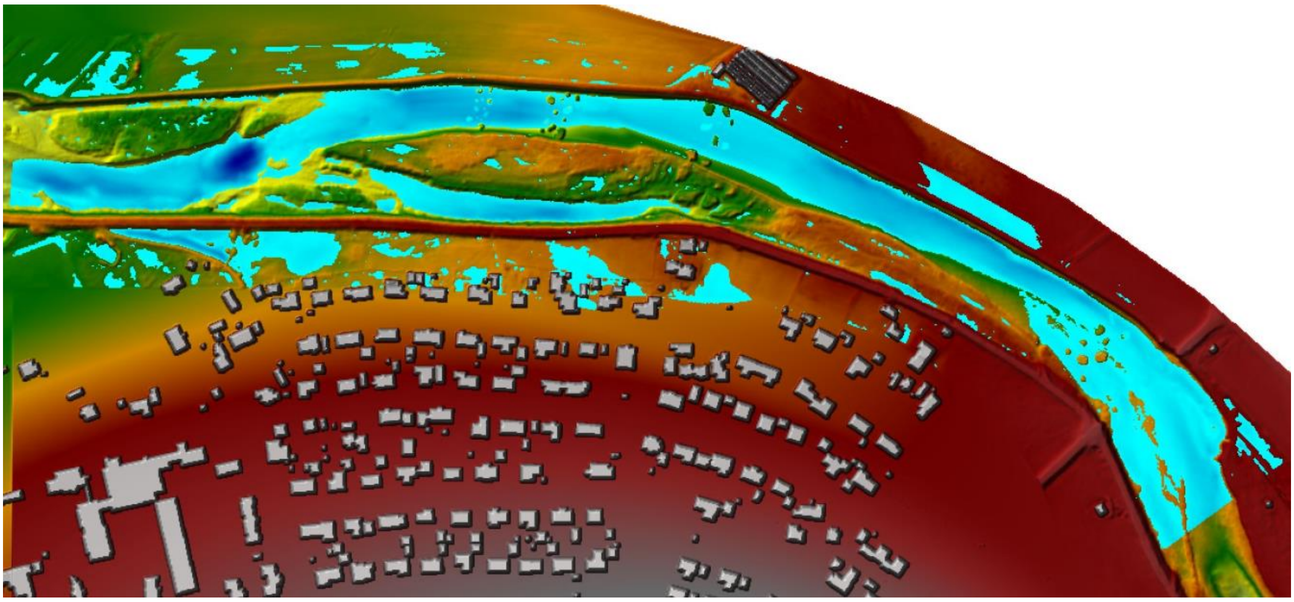


Figure: Water Depth, Q=20 m^3/s

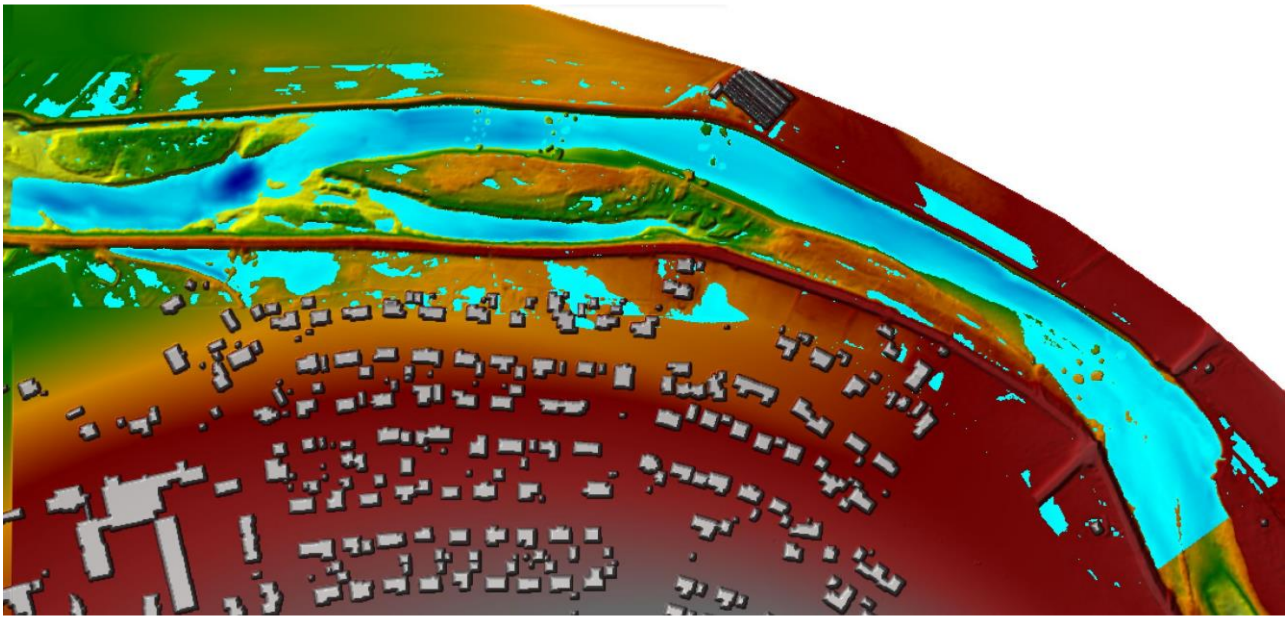


Figure: Water Depth, Q=30 m^3/s

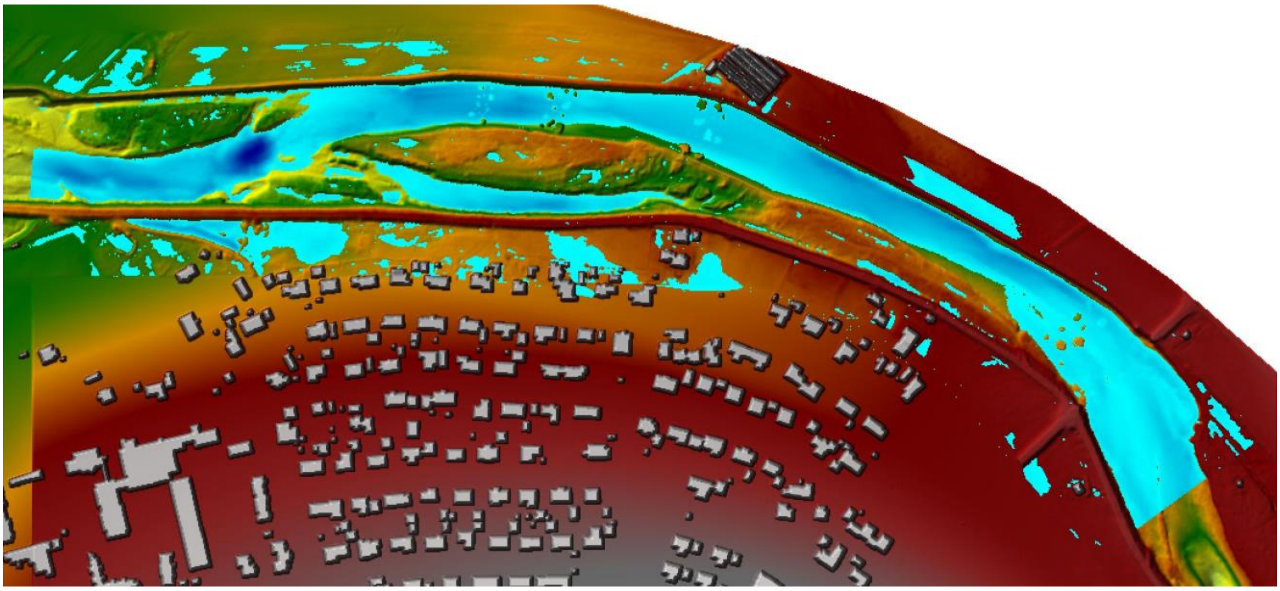


Figure: Water Depth, Q=40 m^3/s

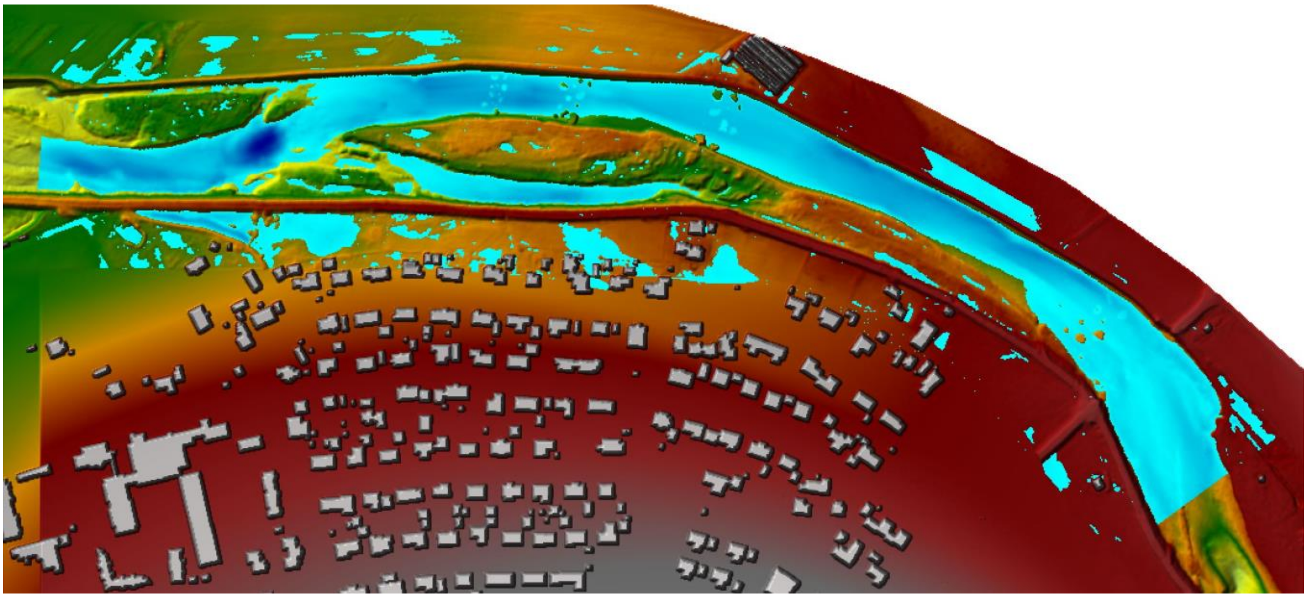


Figure: Water Depth, Q=50 m^3/s

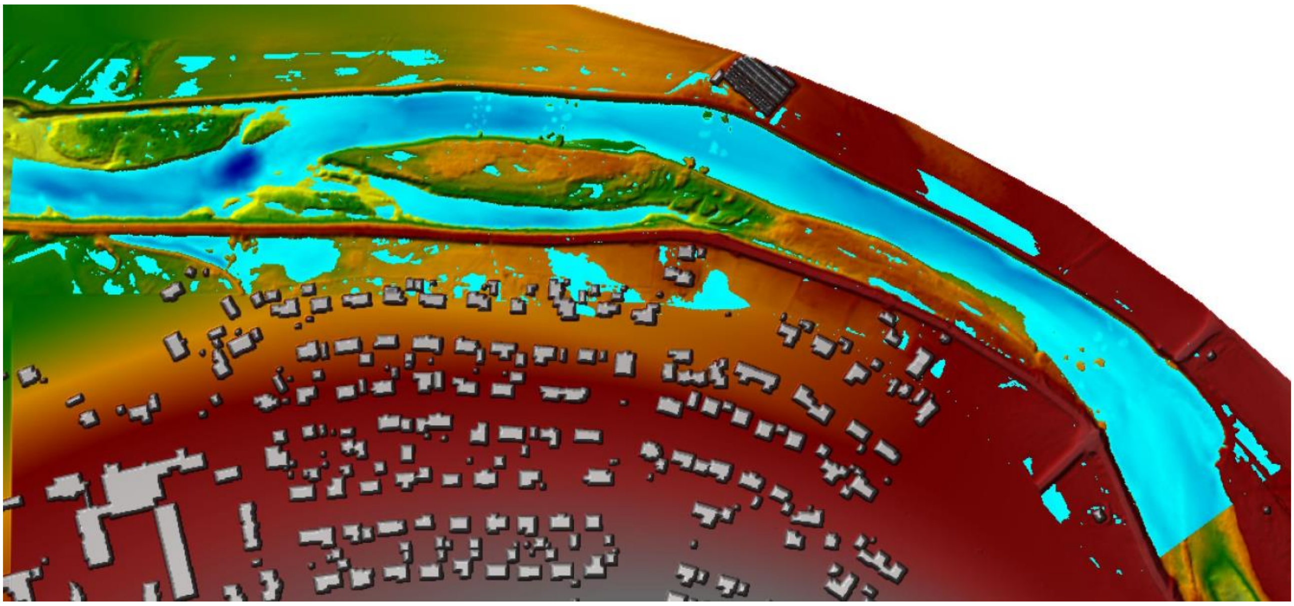


Figure: Water Depth, Q=60 m^3/s

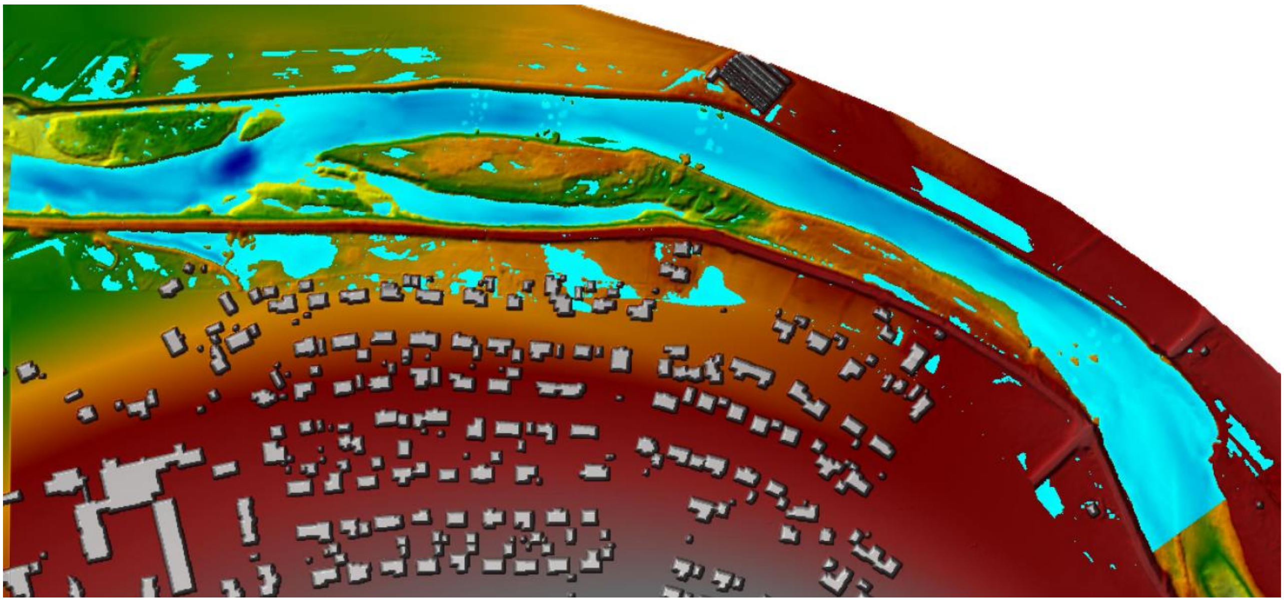


Figure: Water Depth, Q=70 m^3/s

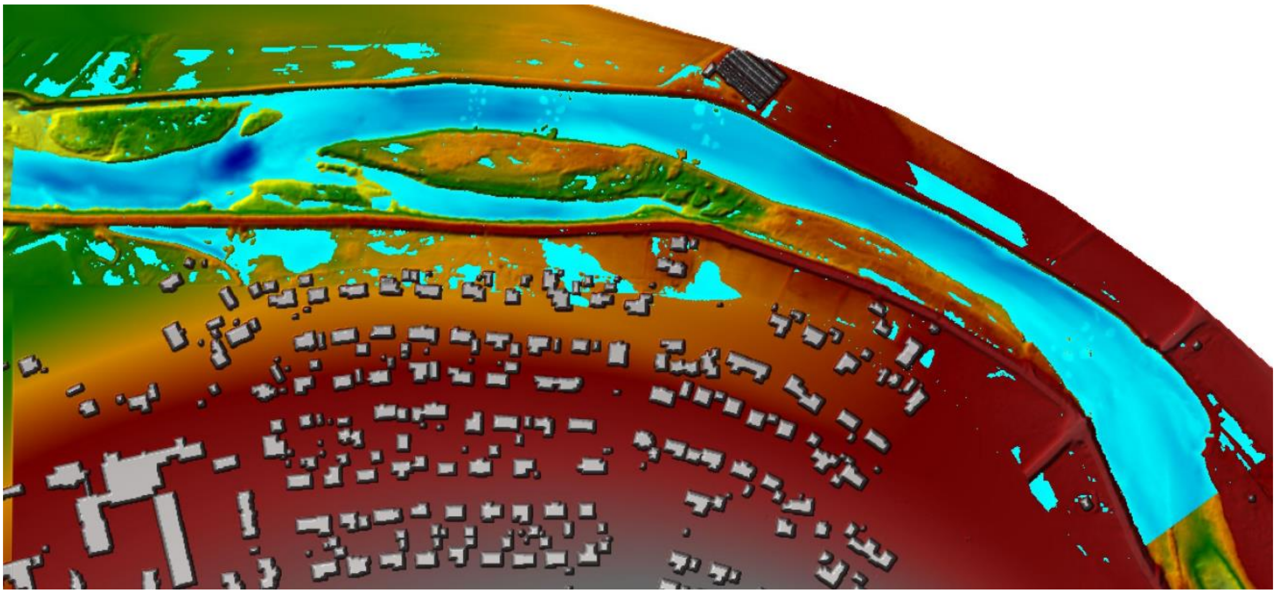


Figure: Water Depth, Q=90 m^3/s

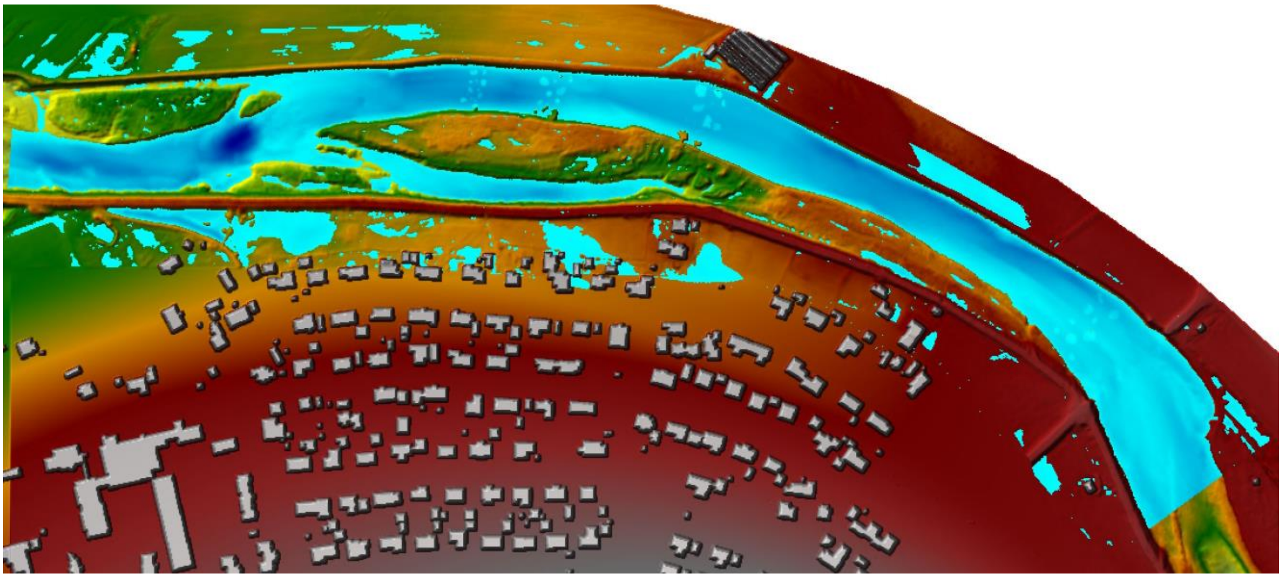


Figure: Water Depth, Q=100 m^3/s

Appendix (G.2) Velocity Pattern

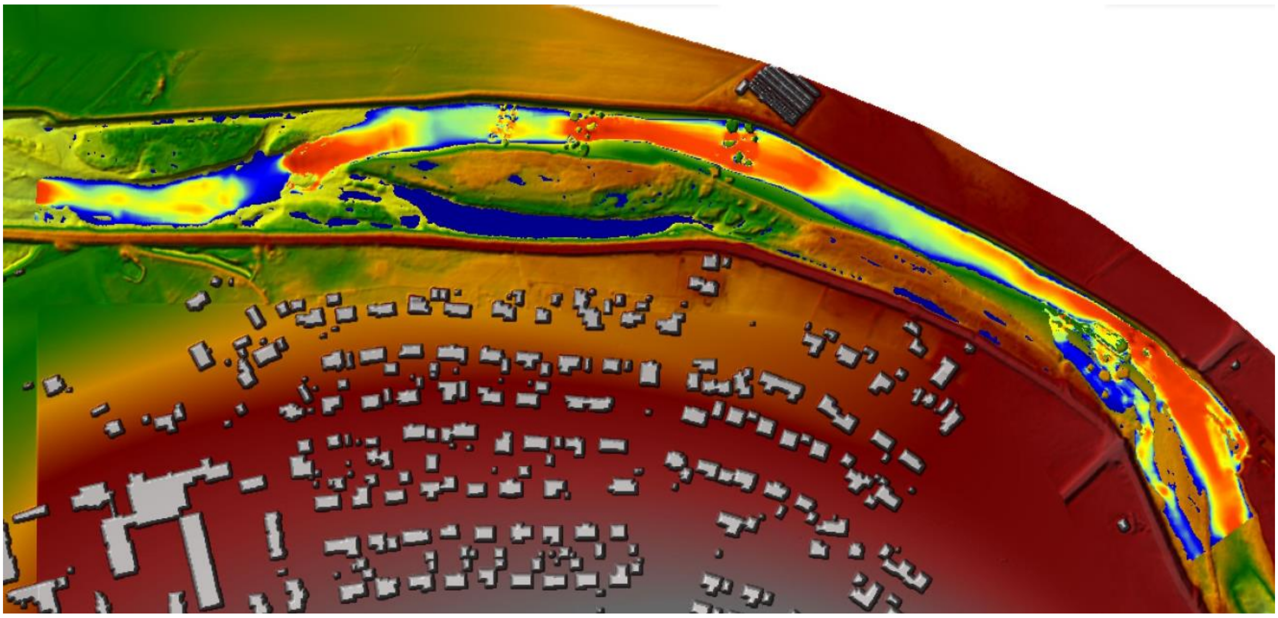


Figure: Velocity Pattern, Q=10 m^3/s

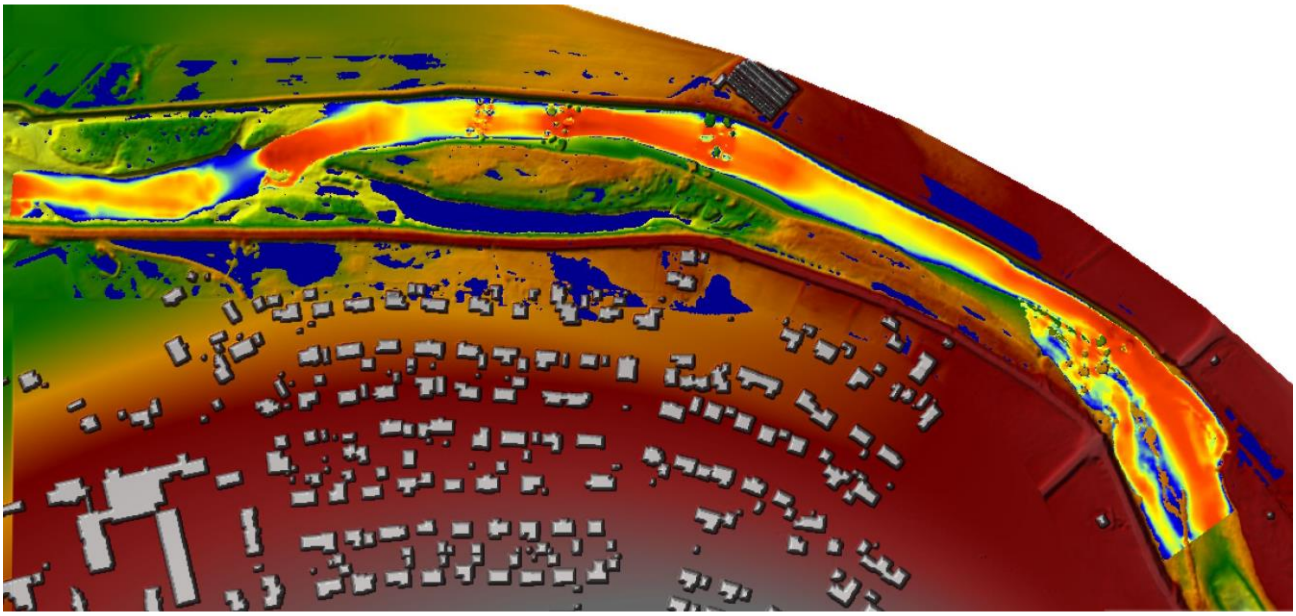


Figure: Velocity Pattern, Q=20 m^3/s

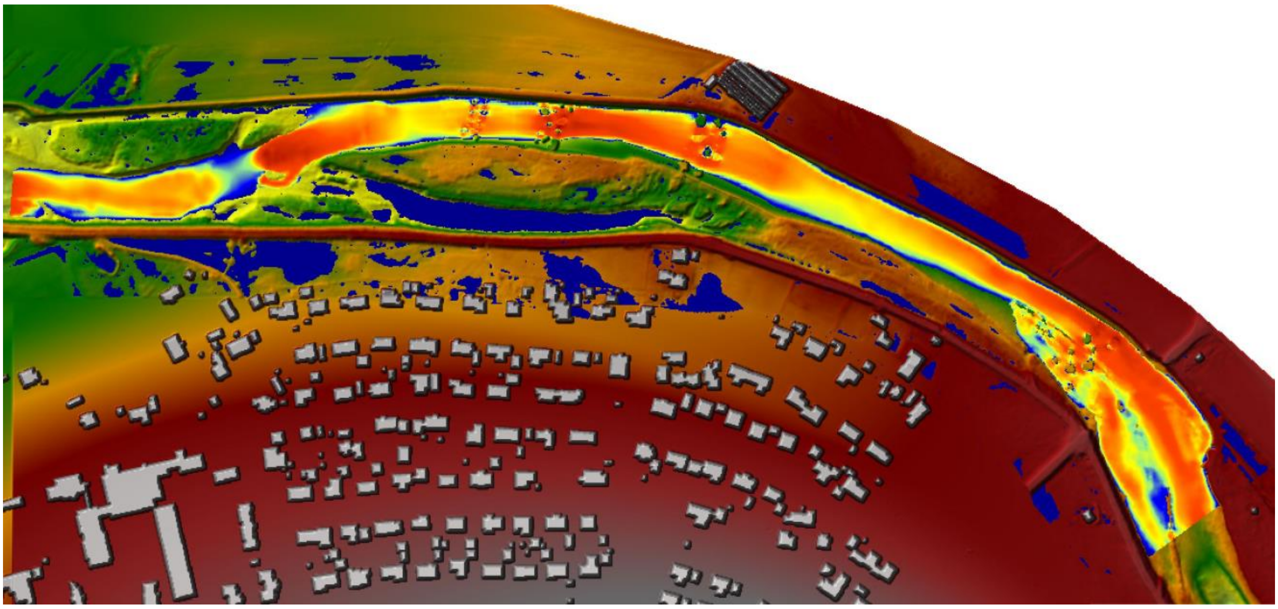


Figure: Velocity Pattern, Q=30 m^3/s

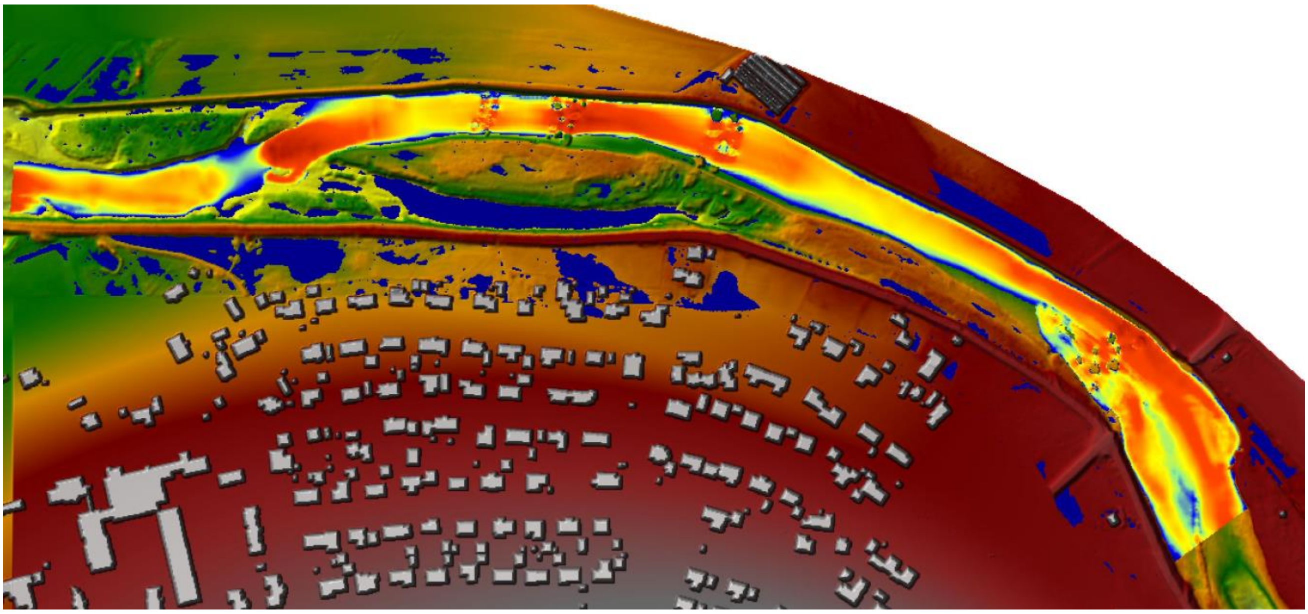


Figure: Velocity Pattern, Q=40 m^3/s

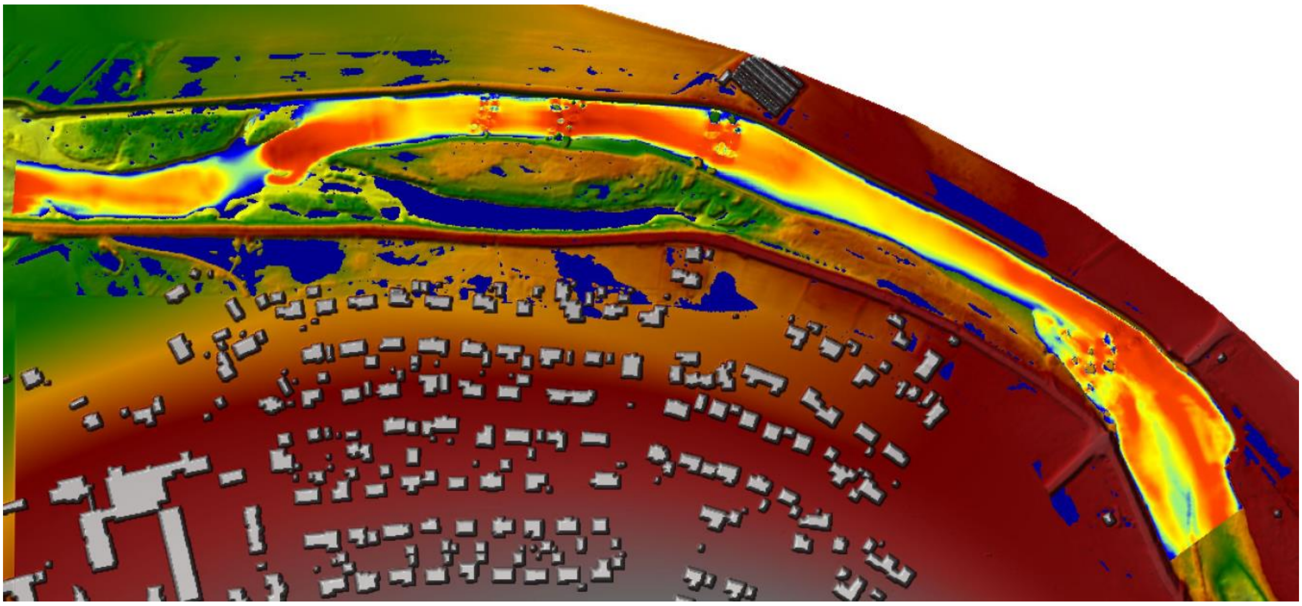


Figure: Velocity Pattern, Q=50 m^3/s

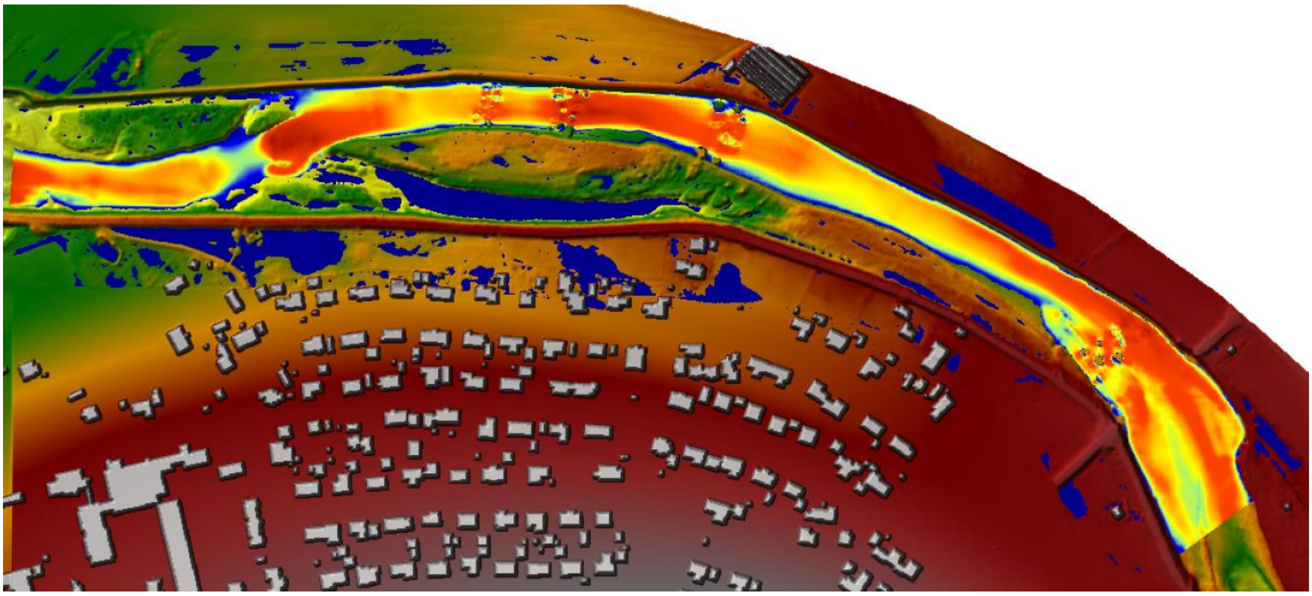


Figure: Velocity Pattern, Q=60 m^3/s

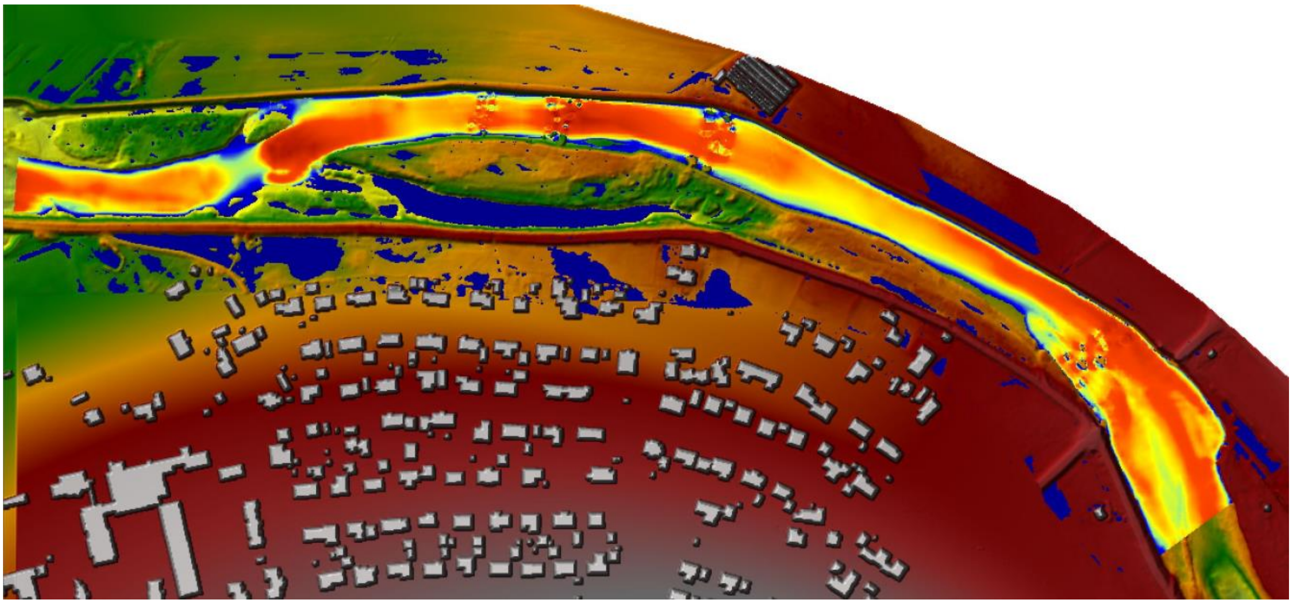


Figure: Velocity Pattern, Q=70 m^3/s

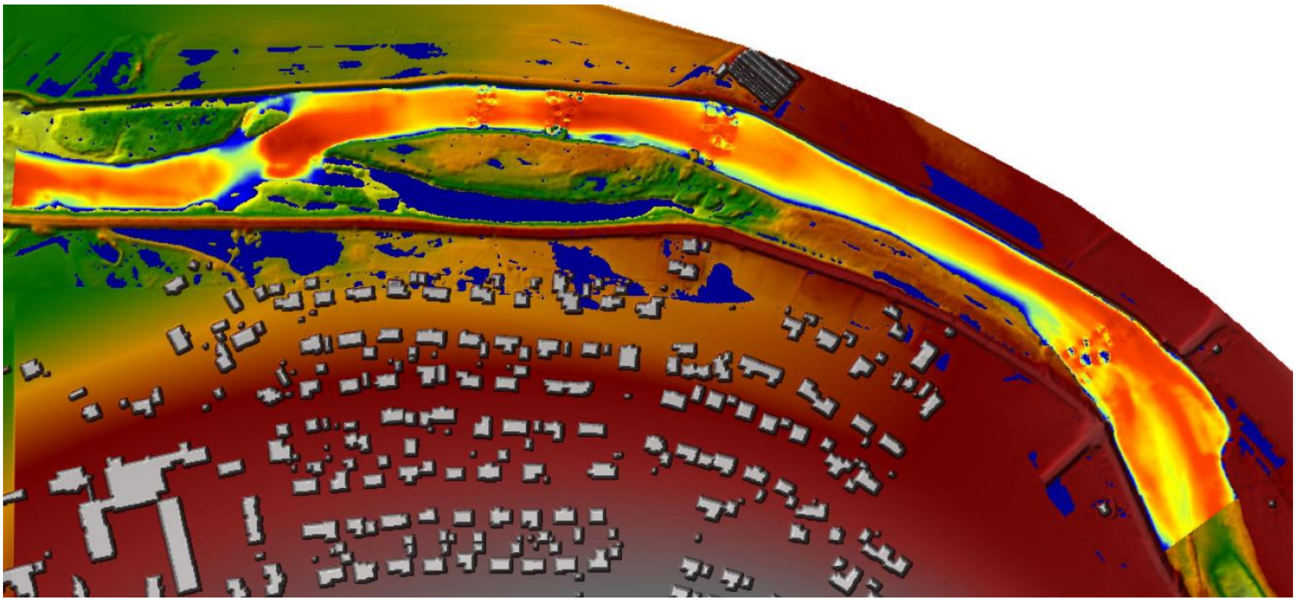


Figure: Velocity Pattern, Q=90 m^3/s

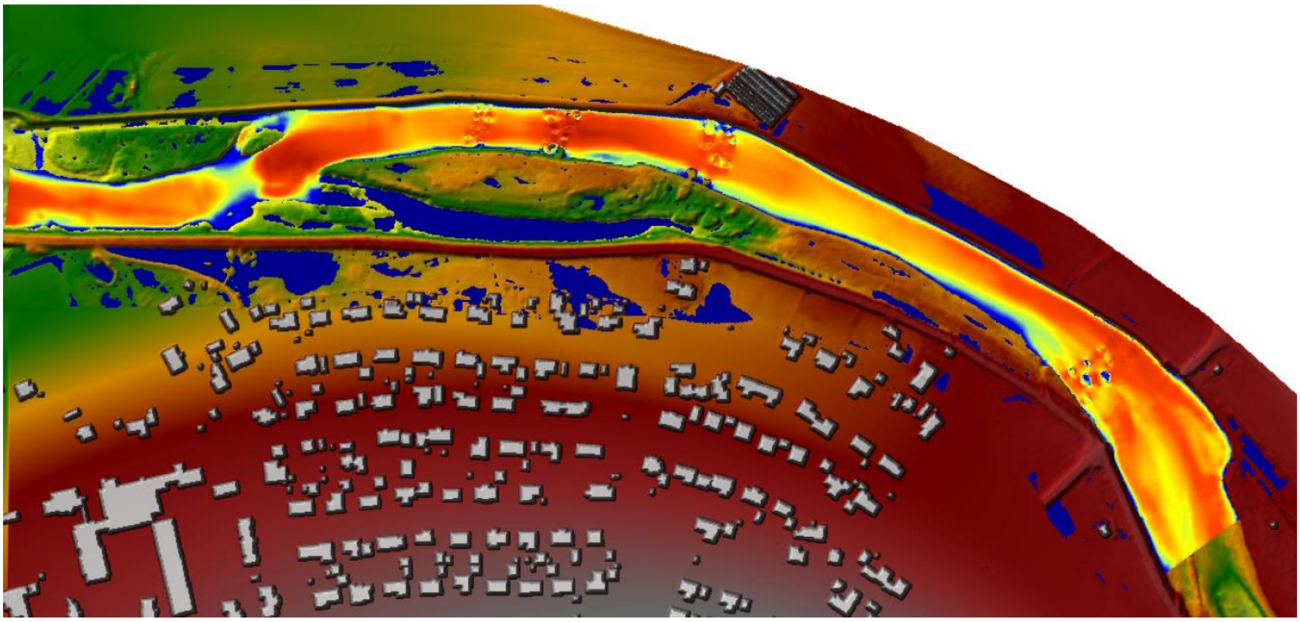
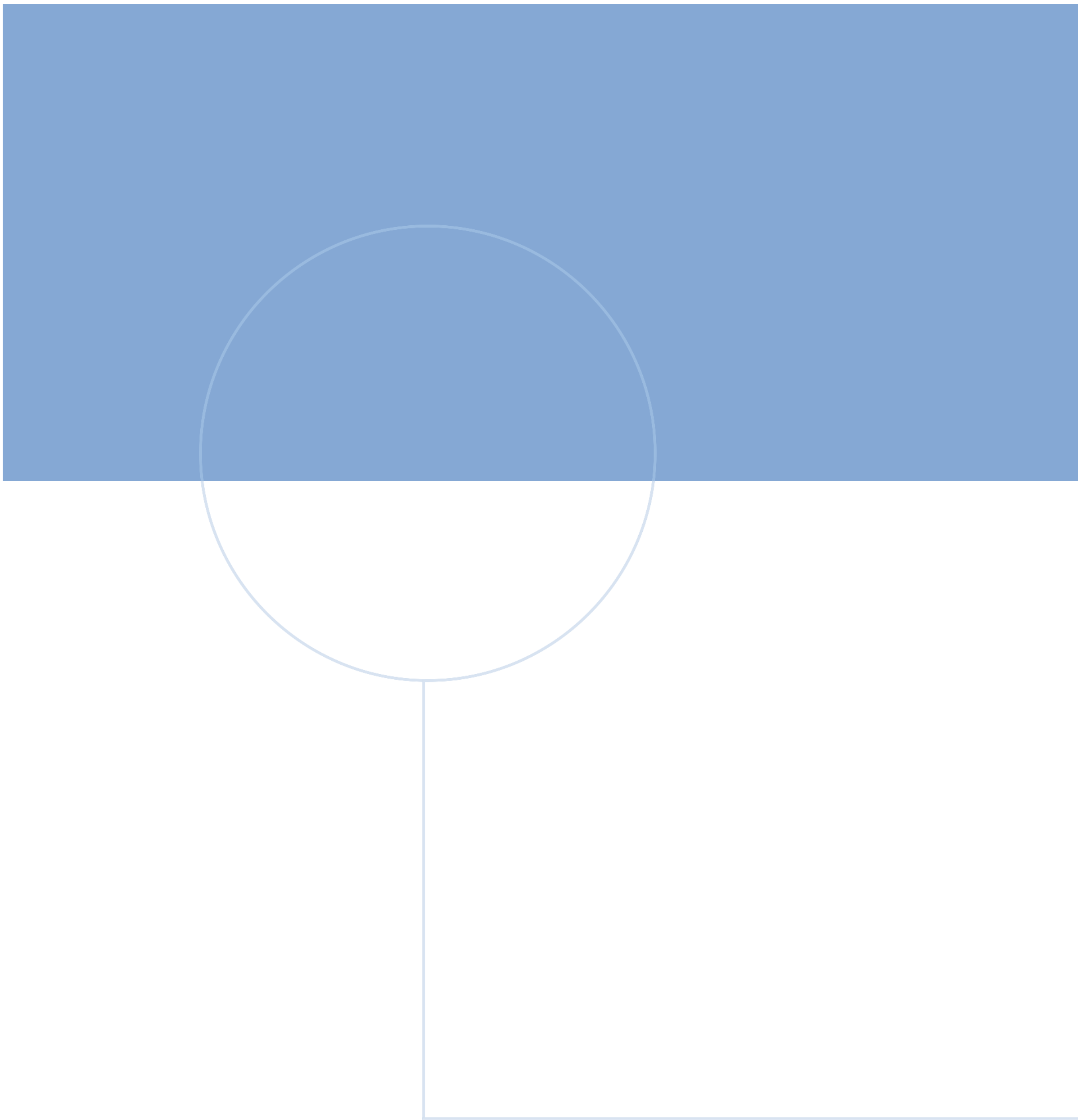


Figure: Velocity Pattern, Q=100 m^3/s



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