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# Internship report

HydroFlex


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# 1. Introduction

**Abstract**

This report presents the work, of validating and researching on an already existing hydraulic model in Nidelva river, Trondheim (Norway) founded by HydroFlex2020 European project. Several researches on its accuracy were done: a comparison with more detailed models, a comparison with a drone orthomosaic, a velocity profile measured with ADCP and RTK-GPS points were used for the verification of the model. On base of the validated model, different scenarios and processes were tested. First a habitat analysis for different discharges was done. After the drying out process and the hydropeaking, wave propagation was studied. With the generated results, the research focused on the time of the up- and down-ramping and on possible overlay of the waves. All results show the strong influence of the frequent discharge changes caused by the hydropower plant. Upstream parts of the study site are according to the findings more affected by the dampening effects, were as downstream the tide and in some scenarios a superposition of the ramping waves dominates. The results can be used in further mitigation studies and study of different ramping scenarios. Making it easier for outsiders to understand the hydropeaking issues and its impacts, a visualization was done. 2D simulation layers of the hydraulic simulation software HEC-RAS were successfully introduced into the 3D visualization software Unity. Further work including animating a ramping scenario and adding of environmental realistic textures can use recent findings as a base.

## 1.1 The internship

HydroFlex is a research and innovation project founded by the European Union for developing new technologies for highly flexible operating hydropower plants. This flexibility includes beside of large ramping rates, frequent start-stops, as well as a large range of system services (European Union). All this should be reached considering impact on human and environment, while being economical competitive. This kind of research is urgently necessary to cover future requirements of the energy sector and avoid long-term consequences and problems in the energy supply. Further and further, the percentage of renewable energies in the total energy supply increases, so there is an immense demand for possibilities of flexible operating generating systems as well as possibilities of storing the generated energy.

The project itself consists of seven different work packages, of which barely the fifth is of interest for the internship. It deals with the "social acceptance and mitigation of environmental impacts". More in detail the internship contains mainly the modelling, simulating and studying of several different discharge scenarios (WP 5.2 Flow scenario modelling). The focus thereby is on the change of water surface elevation, water temperature and flow velocity at assumed 30 starts and stops a day.
In case of the in Trondheim (Norway) based river Nidelva, this means a rapid change of discharge between 35 m³/s and 135 m³/s. Therefore, the water surface elevation and reasonably the amount of flooded and dried out areas fluctuates extremely.

The institutions in charge for those researches are the University of Technology (LTU) in Luleå, Sweden with the river Ume älv and the University of Science and Technology (NTNU) in Trondheim, Norway with the river Nidelva. At the NTNU the executive institution is amongst others the Department of Civil and Environmental Engineering. Here the internship is absolved. (European Union)

## 1.2 Tasks and methods

**Simulations and models**

The overall task of the internship is the evaluation of the hydraulic model of Nidelva, developed for the HydroFlex project. Based on this model simulations of frequent fluctuations and set ups caused by hydropower operations need to be prepared. The gained simulation results are used afterwards for further environmental impact and mitigation studies. To generate reliable outcomes a realistic model and simulations are necessary. For this, a continuous improvement and checking of the interim results is required. All modeling and simulation works are thereby done in the simulation software HEC-RAS. For analyzing and processing the data, ArcGIS was the used software.

Parts on the studies focus on the changes of habitats, while other analyze the responses and wave propagation in different locations of the river. One key point is the retention time after changes in the turbine operation.

As an additional task, researches of a 3D visualization with the use of 2D simulation layers was done. Requirements were the physically correctness and the straightforwardness of the generated work.

**Visualization**

Another task is the visualization of the 2D river simulations in a 3D graphic. outsiders often have no knowledge about hydropeaking. Therefore, it is important to visualize certain issues in an understandable way. This visualization task includes the choosing of a fitting program / engine, which enables the user to create a realistic looking environment, including proper physics of the water. Further, there is the need for assets and add-ins to add the in HEC-RAS simulated 2D data in the software and generate a 3D view out of it. More in detail, a way must be found, to add a georeferenced, digital elevation model (DEM) and display it as a 3D file. Afterwards the likewise georeferenced water surface elevations of every single timestep need to be inserted and displayed as a 3D file. The approach is then a moving animation, where you can see the increasing / decreasing water surface elevation. Additionally, it was the goal to somehow add velocity parameters generated by HEC-RAS and combine them with a realistic texture, to receive a realistic visualization of the hydropeaking issue.

## 1.3 Relevance of the internship

Regarding the climate change issue, the EU was forced to change their way to generate energy. Therefore, the percentage of renewable produced energy is increasing since a couple of years. Anyhow, the environmentally friendly way of producing energy brings new challenges. One of those challenges is the storage capacity, which is needed due to the variable generated energy, for instance wind farms. Based on the land surface of Europe, there is a need for storage to create a flexible energy market. Some of this storage can be provided by Norway. It has a total storage capacity of 84 TWh, which corresponds to 50 % of the capacity of total Europe. Infrastructure should now enable the EU to use those capacities for storing energy and balance variations in the net. (Graabak und Korpås 2016) (Korpås et al. 2013, S. 79) The main storing and balancing of energy in Norway is based on hydropower. (Korpås et al. 2013, S. 81) Therefore, especially a need of "stored hydro" power plants is existing. (Korpås et al. 2013, S. 82) They are acting with a reservoir and can equalize fluctuations in the energy net. For generating energy, water is taken out of the reservoir and released through turbines often into open waters. The frequent up- and down- ramping is also known as hydropeaking. Although, this procedure can have impacts on water ecosystems downstream as e.g. (Korpås et al. 2013, S. 93) or (Hayes et al. 2019) are mentioning.

More into detail it can effect dewatered spawning sites (Adeva-Bustos et al. 2019b), reduction of wetted areas (Adeva-Bustos et al. 2019b), changes in water temperatures (Zolezzi et al. 2011), changes in the habitat variability (Casas-Mulet et al. 2014) or stranding of wetted areas (Hedger et al. 2018, S. 6). All of them are affecting the fauna seriously and can have even after a stop of the hydropeaking long time consequences (Hedger et al. 2018, S. 6–7). Often the mortality of fish is not just caused by the ramping itself, other factors like time of day, morphology, and temperature changes are also playing an important role (Saltveit et al. 2001, S. 618) (Hayes et al. 2019).

To size and estimate the impact and create further a base for mitigation possibilities, the WP5 of HydroFlex is doing the hydraulic modelling. Results as - time until stranding and size of dry areas are important information for mitigate the impacts of frequent turbine operating.

## 1.4 Structure of the report

After a general introduction into the topic, the report of the internship describes the relevance of the research. This report gives a rough overview of the practical semester. Therefore, it lists in the second chapter all the activities and tasks during the internship and focusses then on the analyses based on models. The focus enables the reader to get a deeper insight of the whole project and the work. Additionally, issues and problems which appeared during the semester will be mentioned and explained. In the third chapter the report concentrates on the generated results. Here, a listed overview of all results is described and following again to focus on one topic. This will be explained more in detail and extend the understanding for the relevance of the work. Afterwards, the results will be discussed in the fourth chapter. This gives an overview over the results and allows a weighing up of them compared to comparable findings. Further, an opinion about the work and results of the internship can be found. Finally, the internship will be summarized in the fifth chapter and gives the reader a final overview of the internship.

# 2. Activity and Tasks

## 2.1 Activities

- Introduction meeting with supervisor
  - Briefing to HydroFlex project, schedule and tasks
  - Basic information about hydro peaking
- Orientation and training in hydraulic modelling and simulation software “HEC-RAS“ of the US Army Corps of Engineers, focus lays here on the 2D modeling and simulating
  - Training with the help of video tutorials and already computed simulations of the HydroFlex project
  - Training with demo files and examples of the program itself
  - Training through reading in the user manual
  - Training by creating smaller test models/simulations

Creating of different sized models in Nidelva (Fig. 1) and simulations with different discharges, caused by the hydropower plant (depending on the energy demand).

In figure 1, the study site for the HydroFlex project is pictured. The blue part shows an approximately 9 km long extent of “nedre” Nidelva. This extend reaches from the power plant at Leierfossen to the area, where the Elgester bru of Trondheim crosses Nidelva. Upstream at Leierfossen, the outlet of a hydropower plant is located, which mainly controls the discharge of the river. At the downstream end the river flows into the Trondheimsfjord. Therefore, downstream parts of the research area are mainly affected by the tide of the sea.

The numbers in the graphic are showing locations, which will be mentioned during this report. An explanation of the numbers and locations is below in table 1.

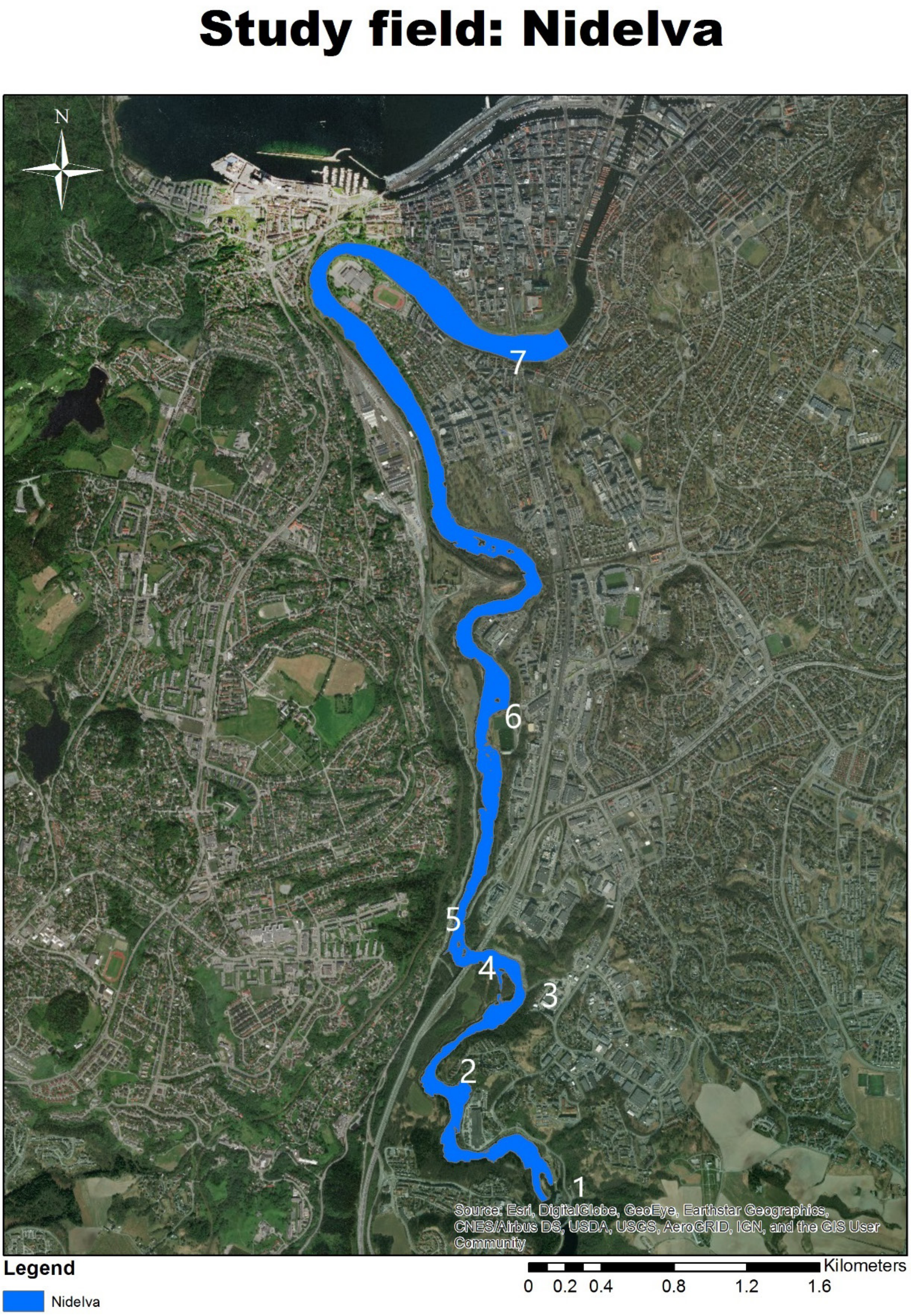


*Figure 1: Study site Nidelva*

*Table 1: Locations*

| | |
|---|---|
| 1 | Leierfossen |
| 2 | Kroppan Pool |
| 3 | Trekanten |
| 4 | Kroppan Bru |
| 5 | Sluppen Bru |
| 6 | Tempe |
| 7 | Elgeseter Bru |

- First model:
  Small river section beginning short before "Trekanten" and ends at "Sluppen bru", shown by figure 2.

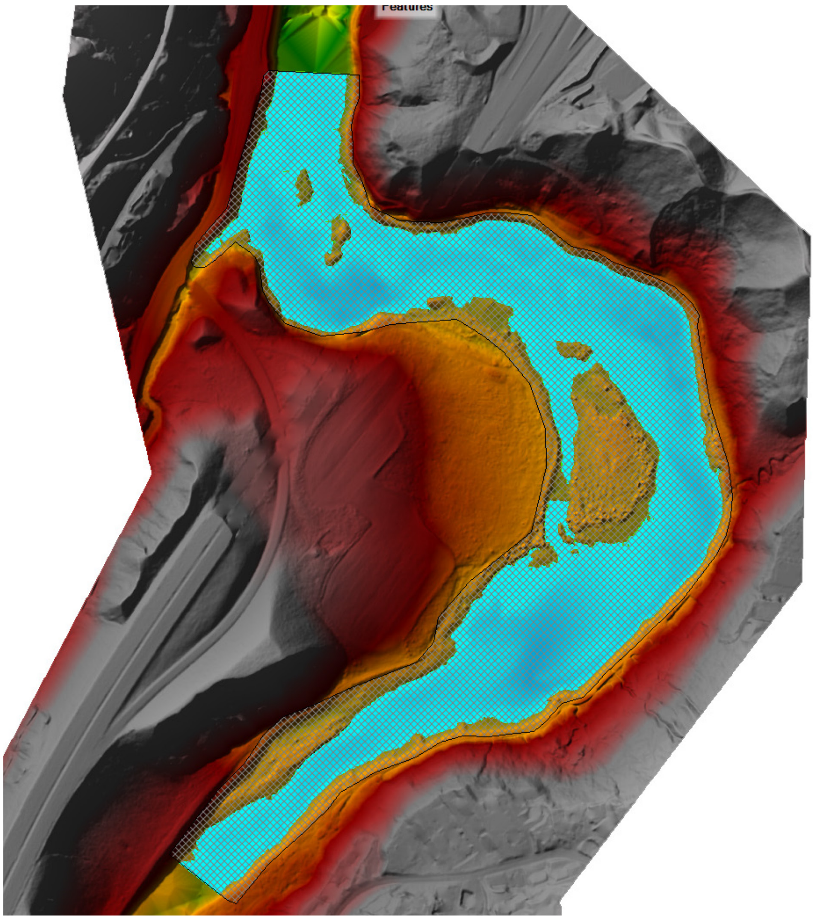

*Figure 2: Model Trekanten - Sluppen bru*

First started with a wide mesh, then refined it down to a cell size of 0,3 m x 0,3 m (for as detailed as possible results)

    - Simulation plans (Trekanten – Sluppen bridge):
        1. Simulation plan with two hours observation period, low flow of Q = 35 $m^3/s$ and mesh resolution of 1 m x 1 m
            - Several changes in geometry, flow and further options of the computations (Full momentum / diffusion wave, manning values, iterations) until results were satisfying
        2. Second simulation plan corresponds to the first. The discharge was changed up to 135 $m^3/s$ and the resolution of the mesh was changed to 0,3 m x 0,3 m.
        3. Third simulation plan overtakes the mesh size of the second plan, but the flow changes to 80 $m^3/s$.
        4. Fourth simulation plan includes a ramping of the discharge from 135 $m^3/s$ to 35 $m^3/s$ in a time of 5 min (this should simulate a turbine shut down).
- Second model (Leierfossen – Sluppen bru):
  Same river section begins just further upstream at the hydropower plant "Leierfossen" and ends at "Sluppen bru", shown by figure 3.

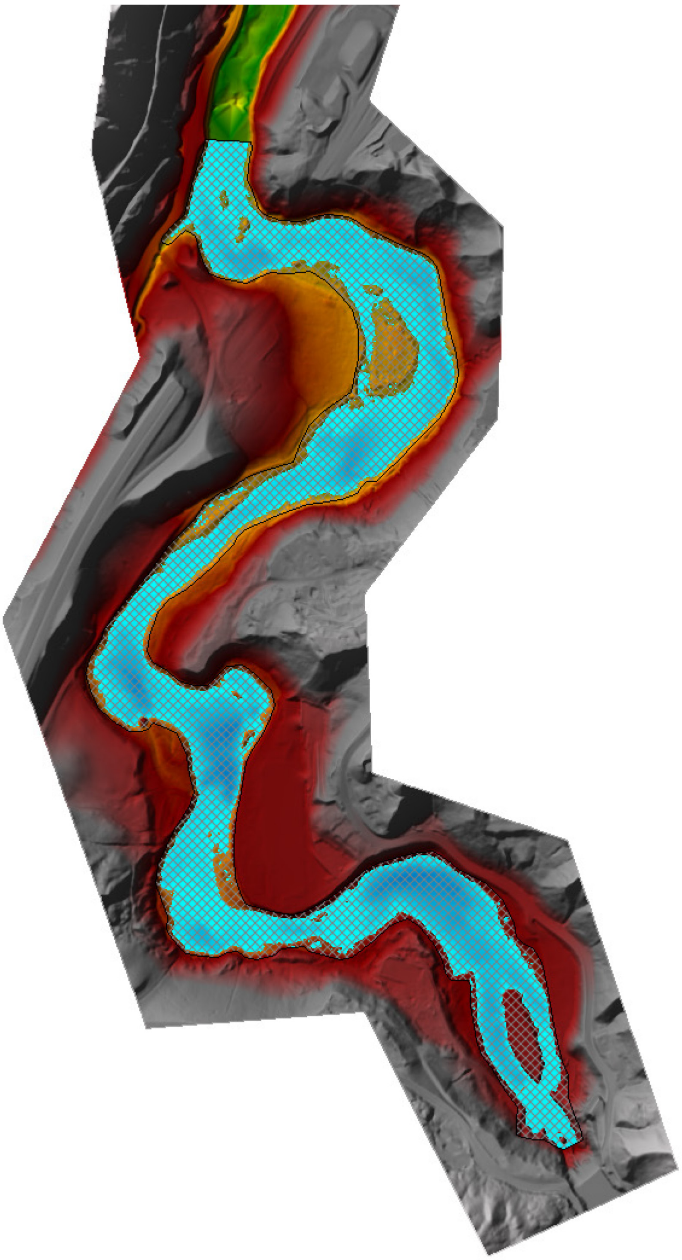

*Figure 3: Model Leierfossen - Sluppen bru*

- Simulation plans:
    1. First plan with 3 hours simulation time, mesh cell size of 0,5 m x 0,5 m and discharge of Q=135 m³/s
    2. Second plan has due to the flow of 80 m³/s a longer simulation time of 5 hours, the mesh size stays the same
    3. The third plan corresponds to the fourth simulation of the first model, just the mesh size (0,5 m x 0,5 m) and the simulation time of 8 hours is different.

4. Fourth model is a more frequent ramping (3 shutdowns) within 8,5 hours with a mesh size of 0,5 m x 0,5 m

- Third model (whole Nidelva; Leierfossen – Elgeseter bru):
  Whole research area from the turbine outlet at Leierfossen to the sea at Elgeseter bru, shown by figure 4

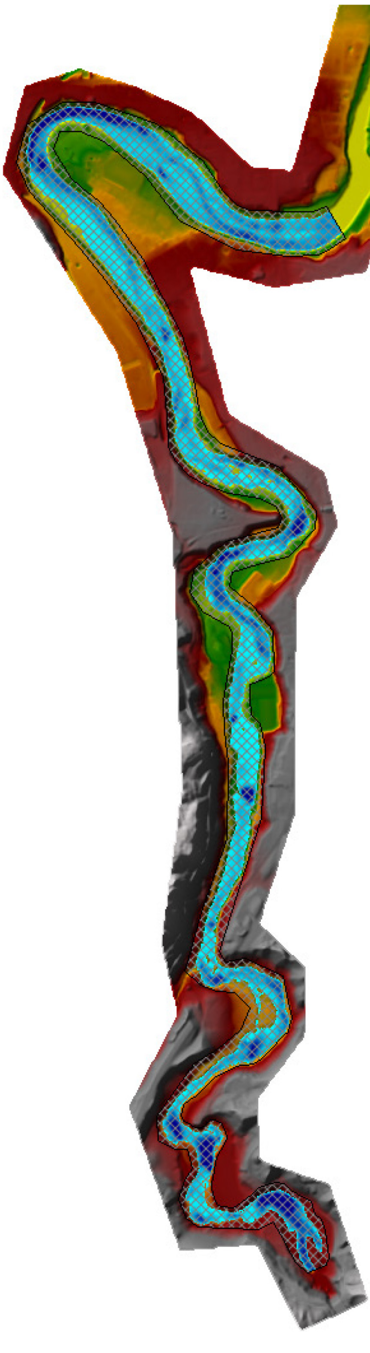

*Figure 4: Model Leierfossen - Elgester bru*

- Simulation plan:
    1. First plan with 8 hours simulation time, low flow of 35 m³/s and a mesh resolution of 1,5 m x 1,5 m.
    2. Second simulation plan with 14 hours simulation time and an output interval of 1 min, ramping from 135 m³/s to 35 m³/s and same geometry as the first plan.
    3. Third simulation plan with initial restart file of 135 m³/s discharge, therefore just six hours simulation time for the down ramping to 35 m³/s needed. Additionally, the output interval is 5 min. Geometry stays the same.
    4. Forth plan simulates in 8 hours and 35 min a frequent up (135 m³/s) and down ramping (flow 1 hour + 5 min ramping time of turbine) with an output interval of 5 min. Geometry stays unchanged.
    5. Fifth plan simulates a turbine start, what means an up ramping from 35 m³/s to 135 m³/s.
    6. Sixth simulation displays 30 starts and stops of a turbine within 24 hours. All parameters apart of the flow are unchanged.
    7. Seventh simulation overtakes the data from the fifth, but simulates just 12 hours, because the 24 hours generated to much data for the software (→ it crashed)!
    8. Eighth simulation has the discharge data of the time; the pressure transducer measured
    9. Ninth simulation is comparable to the seventh just the simulated time is changed

- Fourth model (side channel at Trekanten):

  Very small model of just the side channel flowing around the island of Trekanten, shown by figure 5

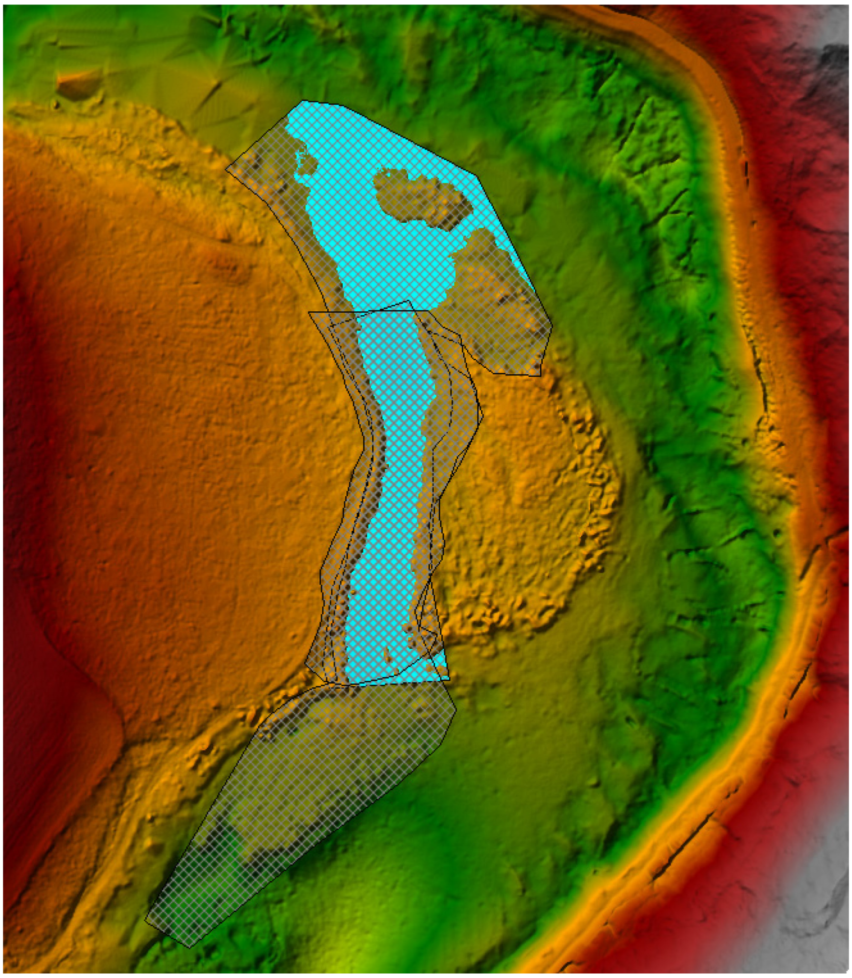

*Figure 5: Model side-channel Trekanten*

  - Simulation plan:
    1. First plan with 2 hours simulation time, a flow of 8 m³/s (discharge supposed before measurement), geometry of the side channel extent with a mesh resolution of 0,1 m x 0,1 m and an output interval of 1 min.
    2. The second plan is completely the same just with the difference of 10 m³/s discharge instead of 8 m³/s.

3. The third plan has an extended geometry upstream, so that the flow can settle better compared to the second model.
4. The fourth plan is additionally extended downstream, because backwater effects were supposed after the third model was not satisfying.

- Accuracy check of created models and simulations with comparisons of different data in ArcGIS:
    - Mesh comparison 1,5 m to 6 m on the big model.
    - Stranding area size compared to older existing stranding data.
    - Velocity comparison inside the side-channel.
    - Comparison of different sized models (one, two and three (see above):
        - Adding of the depth layers of all three models,
        - Clipping of all models to the size of the smallest,
        - Calculating differences in depths of each model with the raster calculator,
        - Colored displaying of the results with a tolerance.
    - Comparison of models and simulation results with satellite orthophotos at a certain day/ discharge:
        - Creating of shapefiles which show the river based on georeferenced orthophotos of certain days with defined discharge;
        - Shapefiles should be compared to a simulation with the same flow and be used to improve (e.g. improve manning's´) or verify the model.
        - Discharge values at days of the photo capture not available or clearly defined → Need for drone orthophotos at a certain flow.
    - Comparison of models and simulation results with drone orthophotos, which were captured while a certain flow:
        - Adding of the merged and georeferenced orthophoto and boundary conditions of model 3 at 135 $m^3/s$ to GIS,
        - Visual comparison through overlaying of the different layers,
        - Creating shapefile with river extent from the orthophoto,

    - Receiving amount of overlapping and missing areas in the simulated results through clipping and erasing the shapes from each other.
  - Comparison of models and measured pressure transducer data.

- Analysis for different approaches of certain simulation results
  - Habitat analysis at 135/80/35 m³/s discharge
    Analysis of two stranding areas, with the purpose to see if and how much habitat for fish is lost due to the ramping of the river. Some parameters are therefore elementary:
    - Velocity (HEC-RAS data)
    - Depth (HEC-RAS data)
    - Shear stress (HEC-RAS data)
    - Sediment (Analysis of orthophotos with “base grain”) → failed due to too low resolution of orthophotos
  - Wave analysis
    Deals with the process and especially time of discharge change flowing like a wave through the river. Studied parameters are:
    - Stranding area process in the whole river,
    - Water surface elevation change process in the complete river,
    - Retention time after turbine shut down (time until end of model adepts discharge to upstream),
    - Retention time after turbine turn on,
    - Retention time on selected cross sections,
    - Water surface elevation on selected cross sections,
    - Wave overlapping in case of 30 starts and stops a day.
- Fieldwork and measurements:
  RTK-GPS point measurements, drone flights, ADCP and acoustic doppler velocity meter
  - Getting used to the measurement devices and the software,
  - Install or prepare devices if necessary (divers),
  - Doing measurements with the devices,
  - Import, store and process the data for further analysis.

- 3D visualization of the in HEC-RAS generated simulation results (2D):
    - Research for fitting program which fulfills all/ most requirements,
        - Physically correct (at least able to handle this data)
        - Free or cheap
        - Easy to operate and user-friendly
        - Accept data formats
    - Focus on and choosing between ArcScene, Unreal Engine, Paraview and Unity (Unity fits best),
    - Training in Unity (Video tutorials, tutorial exercises, test models),
    - Adding of DEM and water surface elevation (requires transforming of data formats and further processing).

### 2.1.1 Explanation of a single task – Analyses based on models

After preparing a model, it needs to be decided, about which discharge situation should be studied. Based on this a simulation plan is created. For instance, in case the river should be studied while the turbines running on full production the discharge is 135 m³/s. To study still standing turbines (means Nidelva with low flow), a discharge of 35 m³/s needs to be simulated. According to the turbine operation, different simulations were done for certain analyses. One of those simulations is the wave analysis, which has the approach to generate information about changes in water surface elevations, inundation boundaries and drying out areas. Quintessential is here especially the time shift after changes in the turbine operation and the reaction of the river to those changes.

The first of those wave analyses is the cross-section study. In this case nine cross sections of different locations are in the simulated HEC-RAS model. Locations for the cross sections are areas of interest and areas with influencing attributes (e.g. a bigger pools). Along the cross sections the simulation data are extracted. This cross-section study focusses on the water surface elevations and on the flow in each section, compared to the time after the turbine stops. The downstream, affection after a turbine shutdown, can be displayed by adding the simulation data in a water surface elevation–time-graph. Alternatively, a flow–time-graph can be created. Further, it is possible to extracted how long the river needs at this section to stabilize and at which elevation the new balance is adjusted.

A further study is the retention from upstream to downstream after a turbine shutdown. It deals with the time the whole river takes after a turbine stop to adapt its discharge from 135 m³/s down to 35 m³/s. Therefore, a simulation is prepared, which fills the model up with 135 m³/s. After the whole river has the discharge of 135 m³/s the turbines are shut down within 5 min. Flow hydrographs can be extracted at the up- and downstream boundaries. Displaying those afterwards in Excel delivers the retention time of the river, meaning the time the river takes to adapt to the low flow.

Additionally, to the case described above a further study with the difference, that the turbines are turned on was studied (Nidelva with low flow at the beginning). Logically, the need for a second simulation going from 35 m³/s up to a flow of 135 m³/s is necessary. After having the result, the up- and downstream hydrographs can be extracted. Displaying them in Excel delivers again the retention time of the river.

Moreover, there is a wave analysis focused on the drying out process of the river and its stranding areas. The approach of this is to visualize the progress of drying out and size of stranding areas. To display this, a simulation showing a down-ramping from 135 m³/s to 35 m³/s is needed, comparable to the retention time analysis after the turbine shutdown. This time it is necessary to export the inundation boundaries of the whole river in certain time intervals (here 5 min) after the shutdown. Then, those shapefiles are added in ArcGIS, where every single file is clipped with the shape of the full discharge boundary. The results will show the location and the amount/size of the drying out areas. Those are displayed afterwards in a map to visualize the results.

Finally, one study was made on the water surface elevation in a longitudinal profile of Nidelva, after shutting down the turbines. The results show the process of decreasing water levels along the river run. Further, the time course is visible in the generated profile. To accomplish this aim, there is the need to draw a longitudinal profile through the complete river model in HEC-RAS. The water surface elevations along this line can be exported. In this study an interval of 5 min between the single elevation layers is chosen. A smaller interval would be more detailed but would also lead to a much bigger calculation time. All the extracted water surface elevations can be displayed in a water surface elevation-time-graph in Excel. For better visualization, the terrain lengthwise Nidelva can be additionally exported out of HEC-RAS. Afterwards it´s possible to guess approximately the depths at each point.

## 2.2 Methodical approach

To set up a realistic model, it is necessary to base it on measured data. Since most parts of the model set up were already done before the internship, it was necessary to prove its correctness. Therefore, simulations need to be run, compared and analyzed to validate the model or find potential for improvements. To generate validation data additional models with smaller extents are created. The smaller extent allows a more precise simulation mesh, which can then be used for comparison/validation of the big model. Another way to prove the big model is to capture and measure data. After processing, the data can be compared to the simulated results. Differences or similarities can either prove or disprove the model's correctness.

As soon as the model is validated, the simulation of discharges and the operation of the turbines follows. These simulations can after analyzing them, predict how the river is reacting to certain turbine operations. With knowing about the reaction of the river to different turbine operations, it is possible to estimate the environmental impact of the ramping. According to this, mitigation and operations with less impact can be tested and performed.

## 2.3 Used material and methods

Through the whole internship the most important tool was the simulation software HEC-RAS. It is an open source program designed by the US Army Corps of Engineers and made to simulate one-dimensional steady flows and two-dimensional unsteady flows (HEC-RAS). Based on this software, all the simulations are made for Nidelva. For analyzing the HEC-RAS data, Arc-GIS was the selected tool. Exported data layers of HEC-RAS could be easily imported to Arc-GIS and processed. Further, the software of Arc-GIS has a connection to Python, what allows the adding of scripts. Moreover, Arc-GIS was used to analyze measured data, when they were georeferenced (drone data, GPS-Points and ADCP measurements).

As just mentioned, Python is also sometimes used to make certain working progresses more efficient. Frequently repeated work steps are done by the software automatically. For the visualization “Unity” is the software of choice. For research the software is free, there are a lot of useful add ins and it is not too difficult to work with the program. Further, ways to import HEC-RAS data (after processing) with a physically right background were found.

Excel was the software which was used mostly to display and analyze results. The straightforward handling of the software allows creating graphs in a short time and visualization of the results is possible.

To create the merged and georeferenced drone orthophoto “Agisoft Metashape Professional” is used. It is a photo processing software, able to handle the drone photos and create a 3D model out of a couple of 2D orthophotos. Finally, for the measurements there was a need of proper equipment and devices. Beside of 2 drones pressure transducers (including a barometer), an ADCP boat, a highly precise RTK-GPS device.

## 2.4 Implementation

**Realization**

Clear time management is necessary, to avoid losing too much time during the simulation processes. This results in an effective way of working. Since the hydraulic simulations in HEC-RAS take the most time to compute their set up and simulation always have priority. Some of them can take depending on the performance of the computer up to two weeks. After setting up, the simulations can be simulated by the workstation in the background without requiring more work. Even if other tasks need to be interrupted due to the simulation it is the most efficient way of work.

**Issues**

1. One issue constitutes in the long computation times for the hydraulic simulations. Even on a computer with high performance a computation can last for a couple of days. For instance, a mistake in the simulation set up can then cause an immense loss of effective working time.
   This issue is faced from the beginning by having two or more (remote) computers for running simulations at the same time. Nevertheless, the computation time stays an issue.
2. Also, a delay of fieldwork needs to be faced. First, the drone flights are only possible with certain weather and light conditions (wind, rain, sun standing), but Trondheim is a city with barely fewer sunny days. Additionally, the dependency of the energy supplier, who is in charge of the river regulation plays with the turbine operating an important role. Finding the needed flows for the capturing

and measuring, requires spontaneous adaption to the operating of the supplier. Because of low flow just during the night, the capturing of orthophotos was according to the light conditions not possible. Both factors together generate difficulties in finding fitting days for the field work.

3. Furthermore, there were issues with the 3D visualization of the 2D simulations. Especially finding a fitting and cost-free program for the required tasks, took a couple of days. Some programs turned out, to be too complicated and time consuming to work into them. Others didn`t support certain data formats. Visualization of 2D files is a known issue in the whole study field, due to the missing of adjusted programs. The only possible way was, to work with some available add-ins for the finally chosen program. This allowed transforming the files step by step and finally visualize them. However, it is a very long and complicated procedure to follow this approach.
4. Moreover, the storage consumption of some simulations and the concluding data organization caused issues. After running a couple simulations, the computer with around 200 GB of free storage capacity, was running out of capacity. Some of the simulations needed over 17 GB of storage capacity. It was necessary to save data on an external drive, what was not just time consuming. The organization of data was also getting more complicated due to the different storage locations.

# 3. Results

## 3.1 Accuracy check of created models and simulations with comparisons of different data in ArcGIS

The following experiments and researches were done to get a verification of the created models. Therefore, different methods and data were used to compare the work and prove the accuracy of the simulations.

- Comparison of different sized models with different mesh sizes:

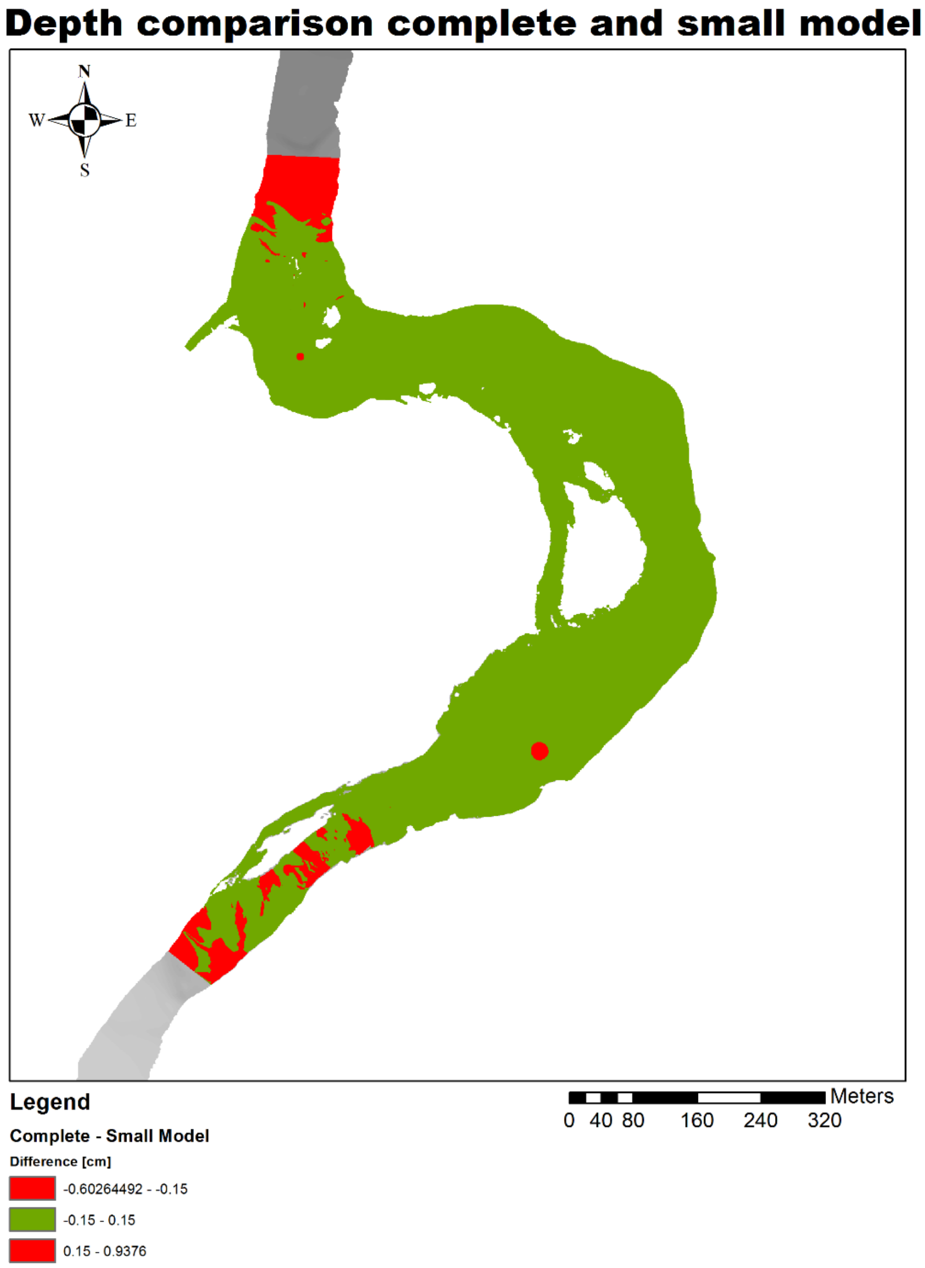


*Figure 6: Depth difference between different sized models*

Figure 6 shows one of three result layers of the comparison between different sized models, with different fine mesh sizes. This comparison was done to prove the model of the complete Nidelva and that it doesn´t vary too much due to the size of the mesh. For the comparison a tolerance limit of +/- 15 cm deviation in water depth was set. That means every variation in depth up to 15 cm, are in the allowed tolerance to verify the models. A variation between the models of a depth “0” in a cell would mean, that the models are identical in this area. All deviations in the tolerance field are colored green above. In all regions where the depth deviates more than the set depth limit, the color is red.

It is obvious, that especially on the ends of the compared area red color outweighs. Therefore, a very simple explanation can be found. Due to boundary and backwater effects, which can occur in HEC-RAS, the flow didn´t settled properly. Consequently, the bigger deviation of the depths can be explained with a too small extent of the prepared model. After the flow settled in the model, the differences are mostly less than the 15cm limit, what verifies the big model. Just smaller deviating points can be found. In the end, the comparison was a successful way to prove the accuracy of the big model and that there is no need for smaller, more detailed models.

- Comparison of models and simulation results with satellite orthophotos at a certain day / discharge:

The satellite orthophotos were not usable due to missing data. The source of the satellite photos did not provide a time, when the photos were captured. Hence, no discharge value could be matched to the orthophoto. Further, the platform for the discharges did not provided discharge values for every day. On some dates only a “error” was reported.

- Comparison of steady and ramping simulation results with drone orthophotos, captured with a flow of 133 m³/s (→ tolerance when comparing model and reality):

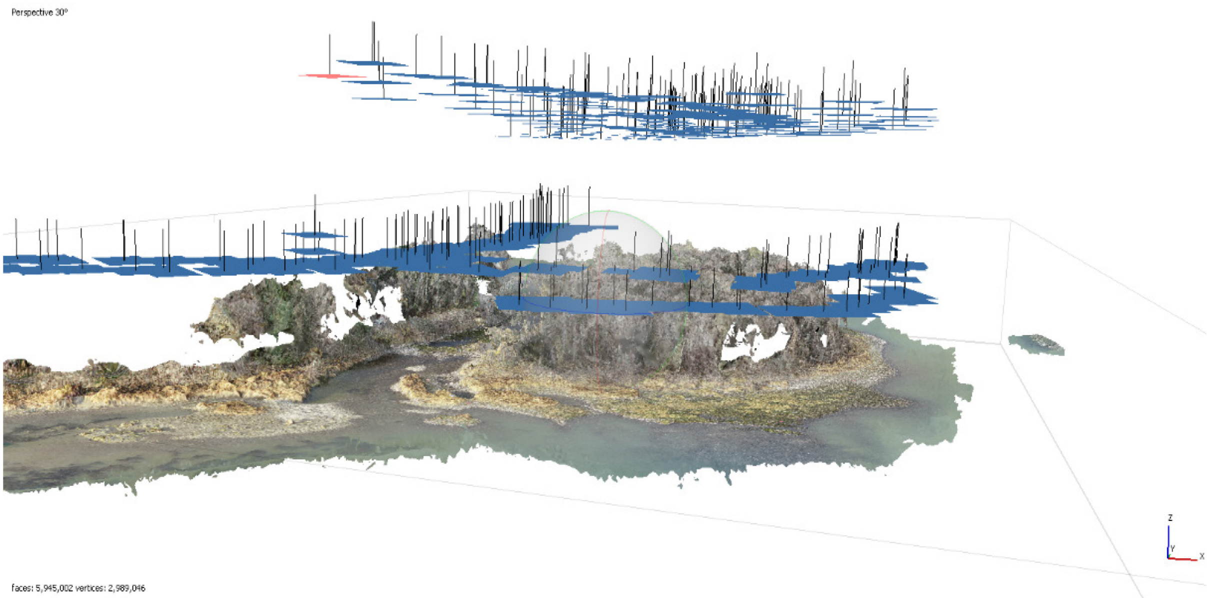


*Figure 7: Georeferenced 3D model*

Creating a georeferenced orthomosaic of the whole Trekanten area, required a merging of the single 2D orthophotos the drone took. Figure 7 displays the 3D model of Trekanten, which was merged and generated by the software “Agisoft Metashape”. It is an intermediate step to generate the point cloud, before the geotiff orthophoto is extractable. The blue rectangles above the terrain are the single positions, out of which the drone took the photos of the area. Figure 8 shows the exported georeferenced orthomosaic of Trekanten. It was subsequently used for further verification of the complete Nidelva model. One advantage of creating the orthomosaic with the drone is the much higher resolution (5472 x 3648 pixels) of the image, than of a satellite photo (1630 x 1437 pixels). Based on the lower flight altitude of the drone, the pictures are not just only sharper, but also more detailed. Further, with the date of the 26.10.2019 and the time 14:40:08, the exact capturing data are noted. This made it easy to find afterwards the fitting discharge of 133 m³/s.

*Figure 8:Merged orthomosaic of Nidelva at the 26.10.2019, ca. 14:45 o´clock*

**WSE comparison of drone orthophoto and ramping simulation (Q35)**

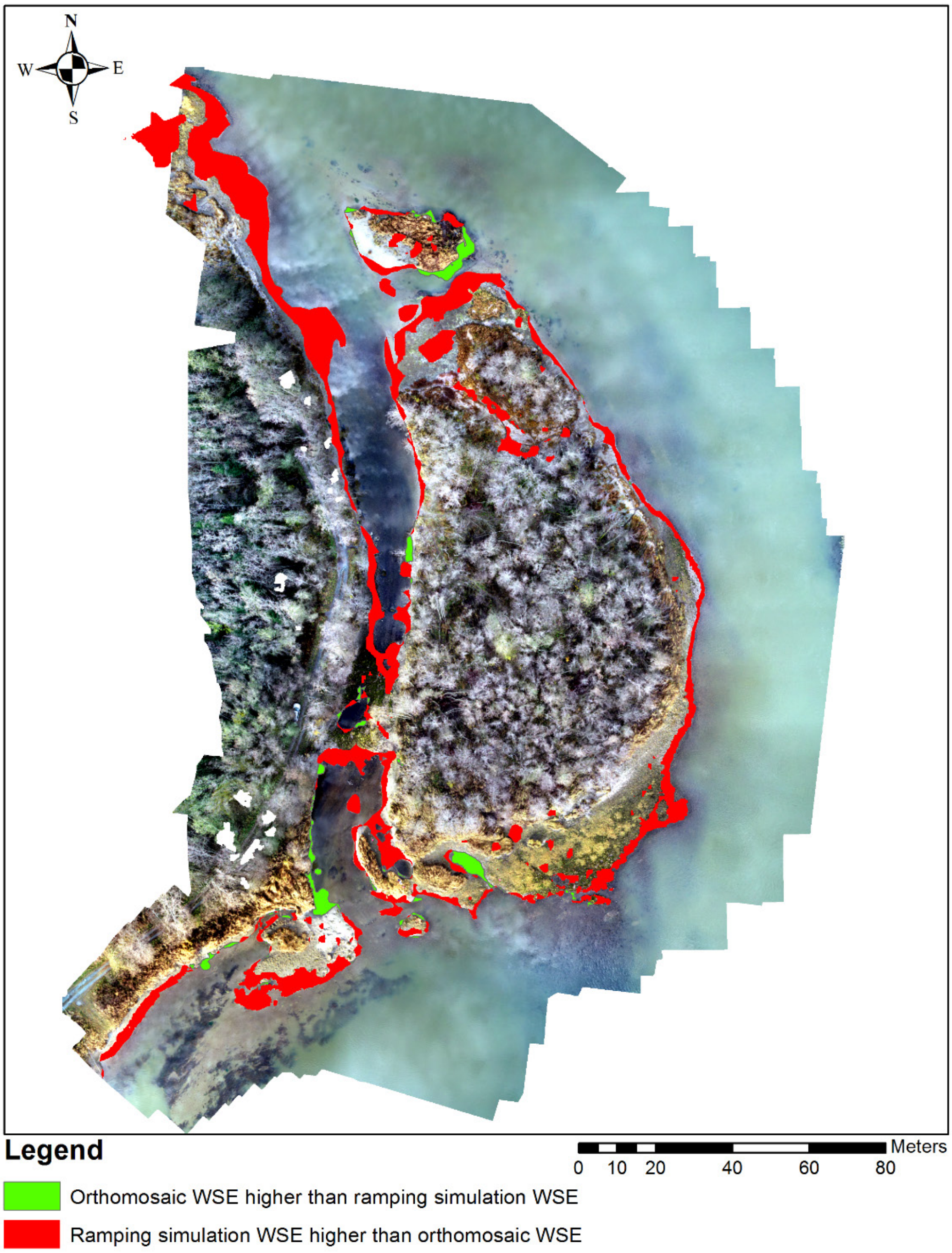


*Figure 9: Comparison of ramping simulation and drone orthomosaic*

Figure 9 displays the water surface elevation (WSE) comparison of the previous created orthomosaic and the simulation results of HEC-RAS after a down-ramping from 135 m³/s to 35 m³/s. Green areas show, where the orthomosaic water surface elevation (WSE) is higher than the simulations elevation. Red shows where the simulation layer exceeds the orthomosaic elevation. Even if it seems, there is big error between the two boundaries, the results are very satisfying and verify the HEC-RAS model. Reason for this conclusion, is the discharge of 133 $m^3/s$ when the orthomosaic was taken. The HEC-RAS simulation was run with 135 $m^3/s$. According to this, the water level in the orthomosaic would be at the same discharge (135 $m^3/s$) higher. Thus, the red areas would shrink. Furthermore, HEC-RAS does not consider infiltration in wet areas after the water level goes down. Therefore, small ponds are also displayed red, even if they probably don´t exist. Regarding those two factors the results are very convincing and prove the model one more time (see table 2).

Figure 10 below, is showing almost the same than Figure 9. Only difference is the consideration of the HEC-RAS ramping error. In this result violet shows, where the orthomosaic is overlapping and yellow where the simulation is. Issue here is that likewise existing ponds are not considered. The discharge in the simulation has steady 35 $m^3/s$, therefore existing ponds couldn´t fill with water. As a consequence, the reality is somewhere between Figure 9 and 10. Nevertheless, considering the unequal discharge, the results here are also very good (see table 2).

**WSE comparison of drone orthophoto and steady simulation (Q35)**

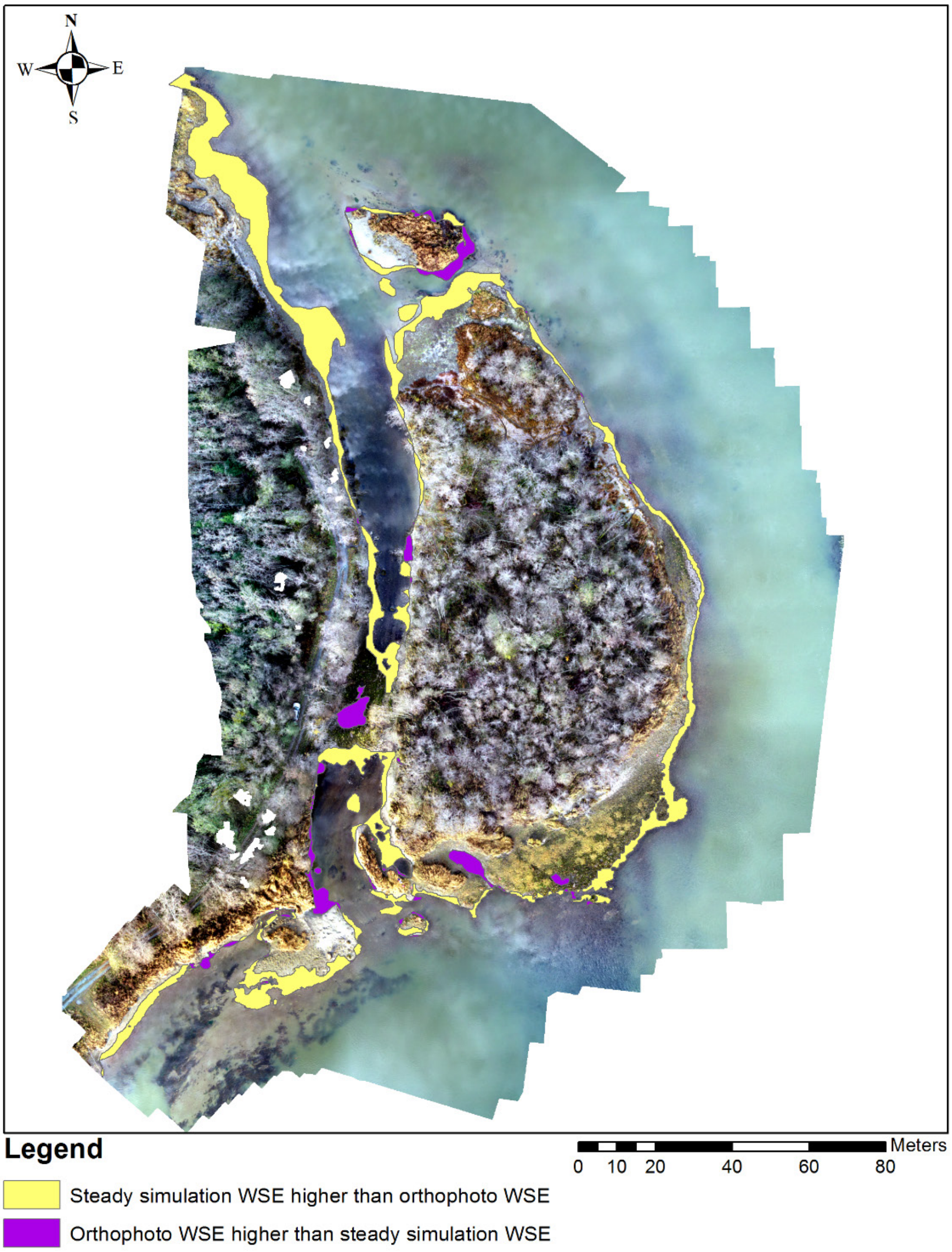


*Figure 10: Comparison of steady simulation and drone orthophoto*

The analysis of the area sizes gives further information of the accuracy of the two comparisons between simulation and orthomosaic. While the area of figure 9 deviants about 16,09 % from the orthomosaic, the areal difference in figure 10 is just

13,60 %. To receive the total inaccuracy, one needs to add the sizes of both overlapping areas and divide the sum through the total size of the orthomosaic boundaries, which corresponds with the real size of the wetted areas.

*Table 2: Inaccuracy of simulations compared to drone orthomosaic*

| **Ramping** | Model ramping | Orthomosaic | Difference | Total inaccuracy compared to reality |
|---|---|---|---|---|
| Area Size total [m²] | 16660,1 | 14696,6 | 1963,50 | |
| Area bigger than other area [m²] | 2164,1 | 200,6 | 1963,50 | |
| | | | | **2364,7** |
| | | | | **16,09%** |
| | | | | |
| **Steady** | Model steady | Orthomosaic | Difference | Total inaccuracy compared to reality |
| Area Size total [m2] | 16164,2 | 14696,6 | 1467,6 | |
| Area bigger than other area [m2] | 1732,9 | 265,3 | 1467,6 | |
| | | | | **1998,2** |
| | | | | **13,60%** |

- Comparison of models with wider mesh (6 m x 6 m) and finer mesh (1,5 m x 1,5 m):

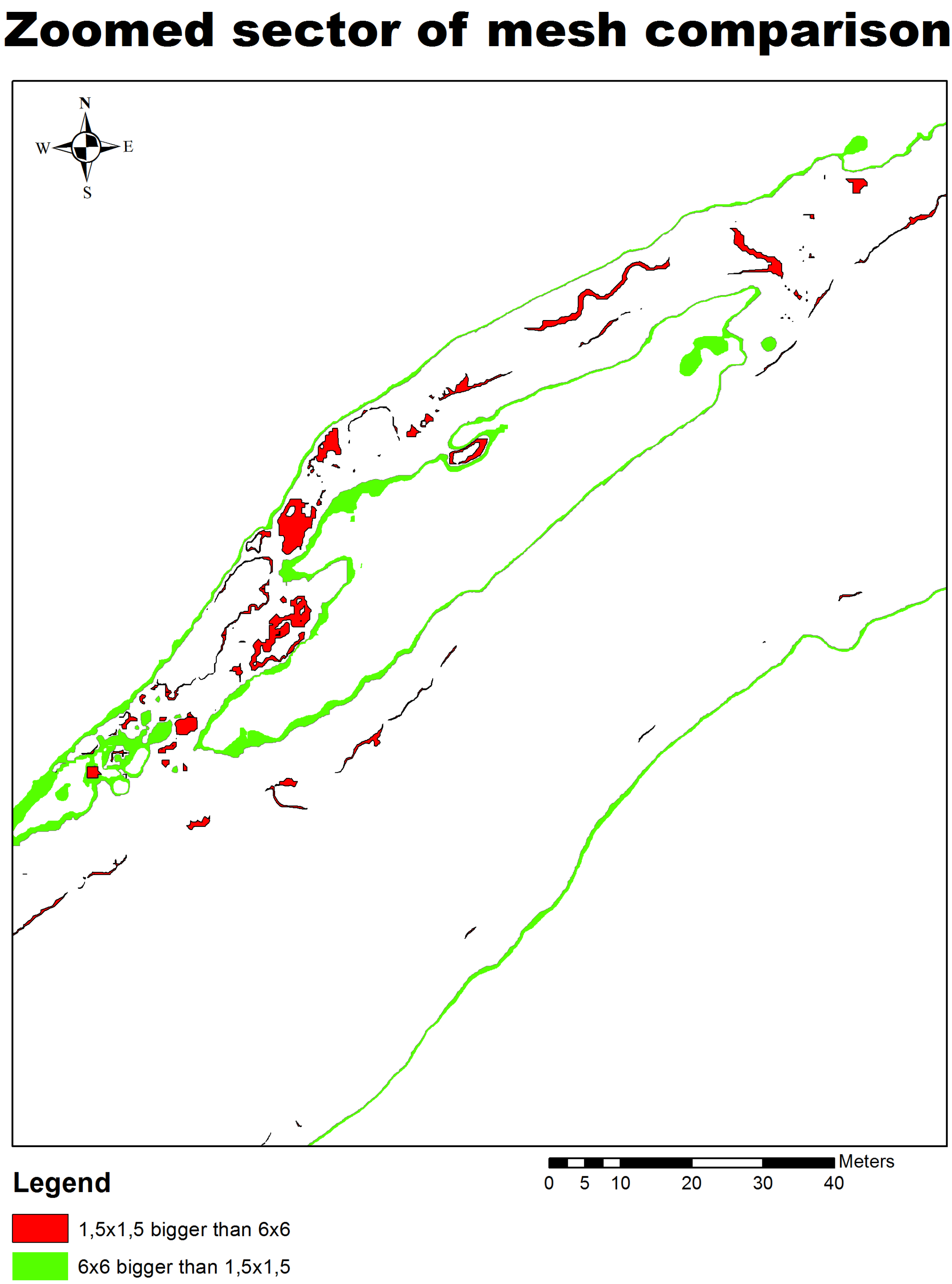


*Figure 11: Comparison of wide and narrow mesh*

Figure 11 pictures a clipped extent of the comparison between two simulations with different sized meshes. One mesh has a size of 1,5 m x 1,5 m the other one 6 m x 6 m. This comparison was done to evaluate the impact of the mesh size to the necessary computing time. Due to the smaller number of cells, the simulation with a mesh of 6 m x 6 m takes significantly less time to complete the calculation. On the other side, it can be assumed that the smaller sized cells will result in a much higher accuracy. In the figure above, areas in which the boundary shape of the finer mesh is bigger, the areas are colored red. In case of the boundary of the 6 m x 6 m mesh is bigger, the areas are colored green. First - the results of the use of a wider mesh looks to be a real opportunity. Looking into the error sizes in table 3, also confirms that. The point for choosing the finer mesh anyway was, that smaller elevations points of the DEM can be within one cell. Computing the simulation HEC-RAS does not recognize those elevations and flows dry areas. With a finer mesh, higher elevation points can be detected and areas which are dry, because of the terrain also stay dry in the model. Alternatively, working with breaking lines is possible. Along the whole 9 km of Nidelva, this would generate a big workload. With keeping the mesh size small the need for breaking lines can be reduced. Especially, in case of changing flows also the breaking lines probably would have to be changed. 1,5 m x 1,5 m is at the same time the finest mesh possible to choose. A finer mesh would lead to a higher number of cells, which HEC-RAS can´t handle without crashing in the computation.

Table 3 displays just one more time the sizes of the error areas along Nidelva.

*Table 3: Total inundation boundary sizes for both mesh sizes*

| **35$m^3$/s** | 6x6m | 1,5x1,5m | Common | 6x6 m > 1,5x1,5m | 1,5x1,5m>6x6m |
|---|---|---|---|---|---|
| Areas [$m^2$] | 810117,44 | 806838,94 | 800301,3 | 9815,78 | 6537,61 |

- Comparison of models and velocity in side-channel:

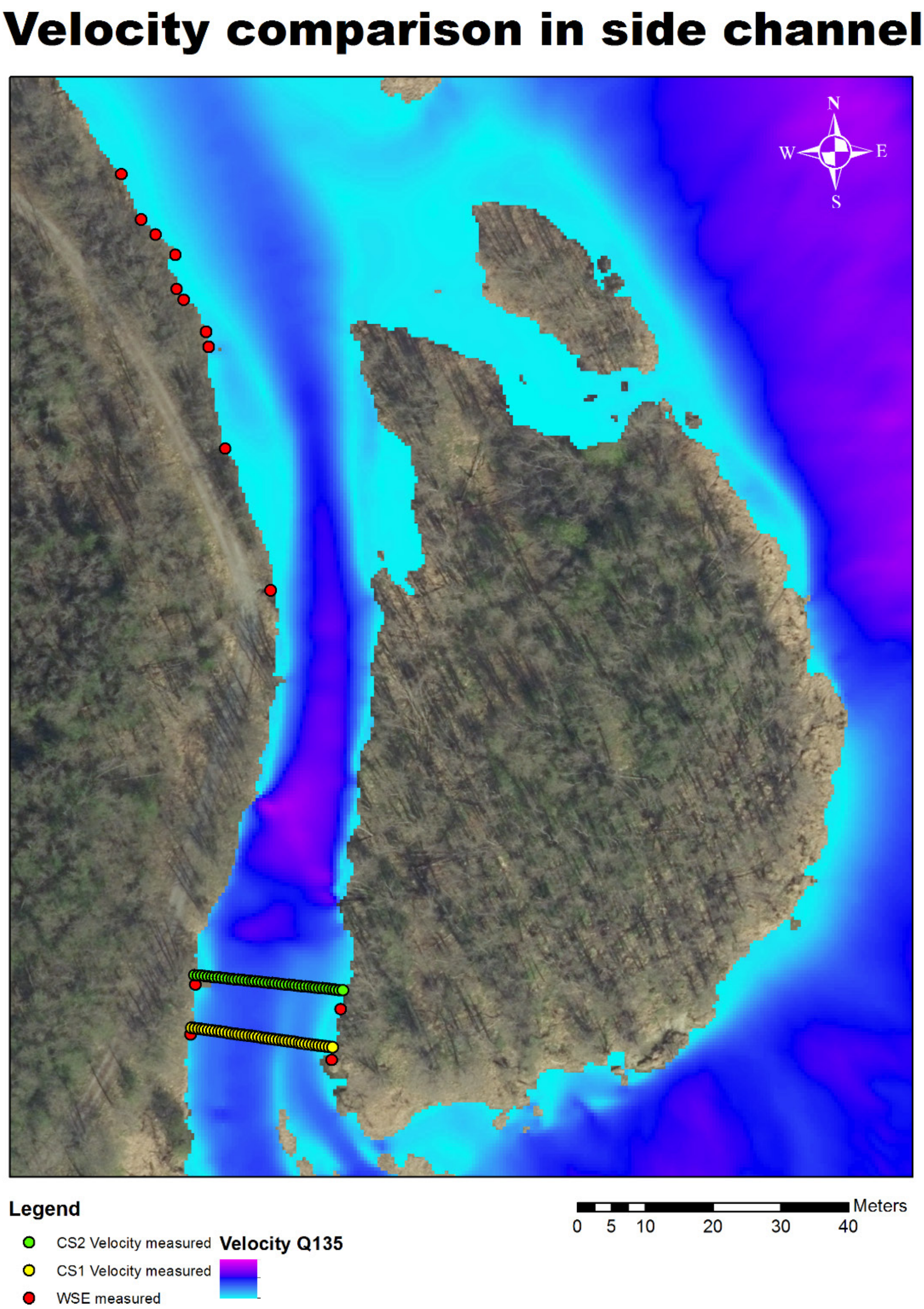


*Figure 12: Velocity + GPS comparison in side-channel*

One further way to verify the big model, was to compare flow velocities of the simulation with measured data. Since Nidelva is a wide river, a lot of work would be necessary to measure the velocity in a complete cross section. Therefore, it was decided, to measure velocities along two cross sections in a side channel at Trekanten. Figure 12 displays these two cross sections (yellow and green points), as well as the red GPS points, which were also measured to compare them with the boundaries of the simulation. As a first conclusion, the GPS points of the boundary are almost fitting perfectly with the simulated layer. The accuracy of the model fits very well.

Following Figure 13 and 14 demonstrate the distribution of velocity along the cross section. Additional to the big model a small model just for the side channel with a mesh resolution of 0,1 m x 0,1 m was created. Aim was a further verification of the big model with the help of a smaller detailed on. After bigger deviations in the velocity distribution, the model was extended to exclude backwater and boundary effects. In the graphs below the x-axis is the length of the cross section, while the y-axis is an extent for the flow velocity.

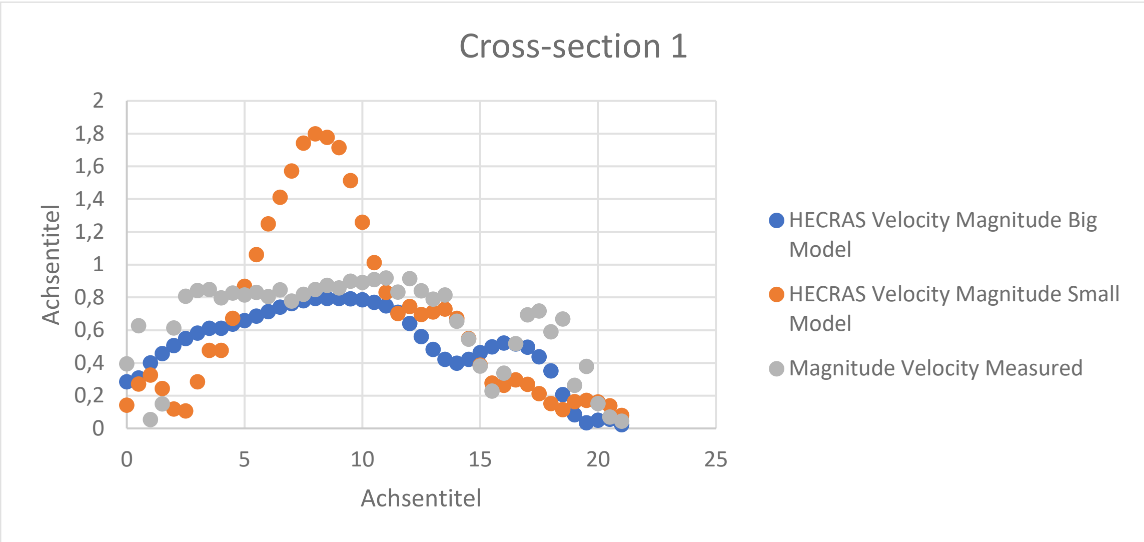


*Figure 13: Velocity comparison cross-section 1*

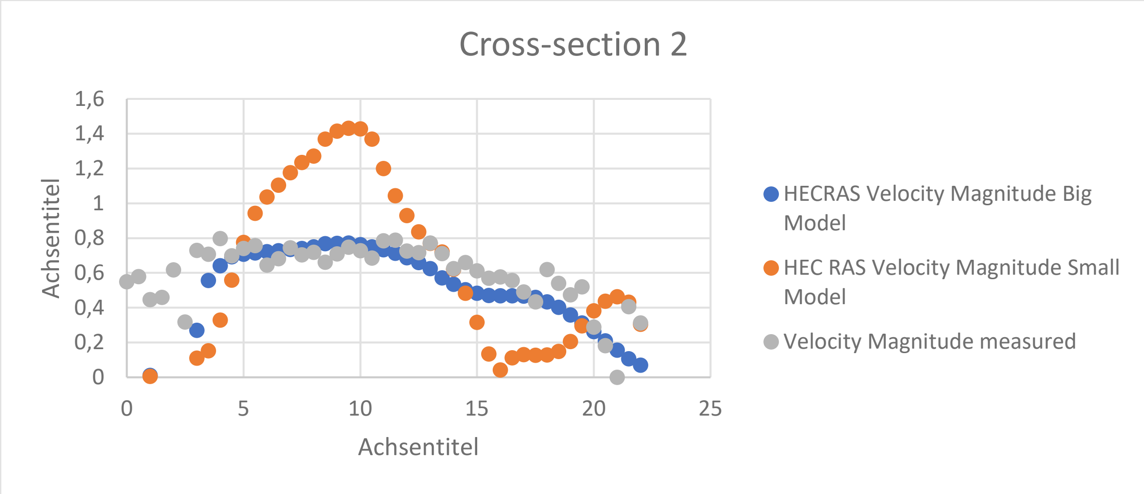


*Figure 14: Velocity comparison cross-section 2*

Both figures show, that the blue velocity values of the big simulated model and the grey ADCP velocity values are almost covering. This is another proof for the accuracy and the fit of the models. Less accurate is the velocity data of the small, extended side channel model. It seems like the boundary effects are influencing the distribution of velocity still too much. Consequently, there are big visible differences in the side channel velocity and a comparison between the big and the detailed model wouldn´t make sense.

## 3.2 Analyses based on models/simulations

The section “analyses with models/simulations” is about researches, which were made with the verified model. Typical discharge scenarios and turbine operations were simulated and evaluated. Conclusions were tried to find out afterwards. Those might be the foundation for further mitigation projects and researches.

- Habitat analysis at 135/80/35 $m^3/s$ discharge:

  The habitat analysis deals with three different parameters and their limits which fish can survive. Those parameters are velocity, depth and shear stress. According to this research result, layers of all parameters at flows of 135 $m^3/s$, 80 $m^3/s$ and 35 $m^3/s$ were exported and studied. Enclosing the research area, Trekanten area was chosen for the study.

  Figure 15, 16 and 17 show the simulation results for the velocity, representative for all parameters. The gradation of the velocity layers goes from yellow – slower water movement, to dark blue – higher water velocities. Figure 16 and 17 (flow 80 $m^3/s$ and 35 $m^3/s$) also have red, which illustrates dried-out areas compared to the flow of 135 $m^3/s$.

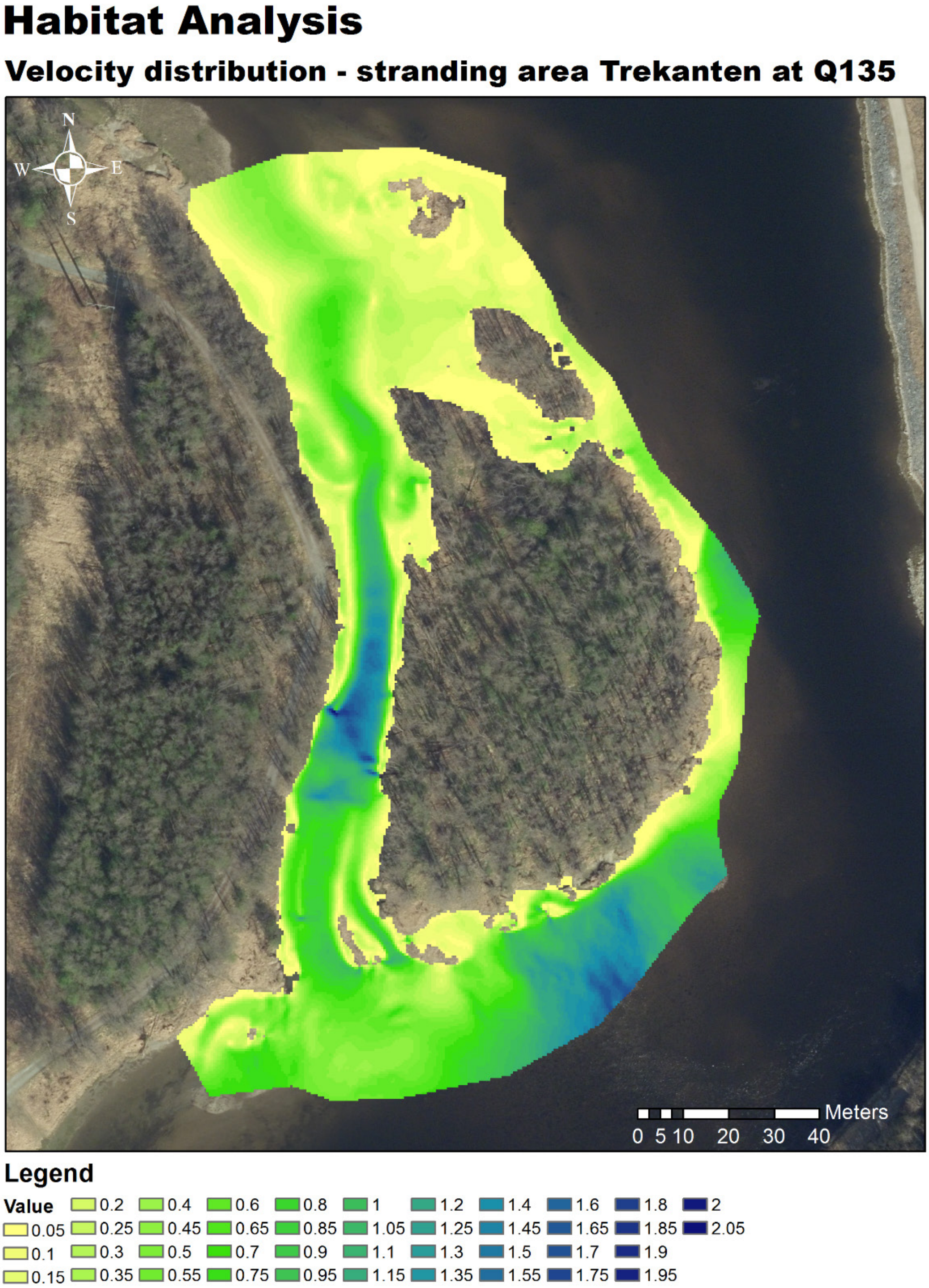


*Figure 15: Velocity at Q 135*

135 m³/s is for this research the assumed maximum flow. Therefore, no dried-out areas are visible. Good visual in the figure above is the filled side channel with a high velocity, especially in the region of the rapid. This layer also shows some potential spawning areas. Two of them are for example the side channel and the

place with higher velocity in the main channel. Here fish could lay down eggs and stay for longer time.

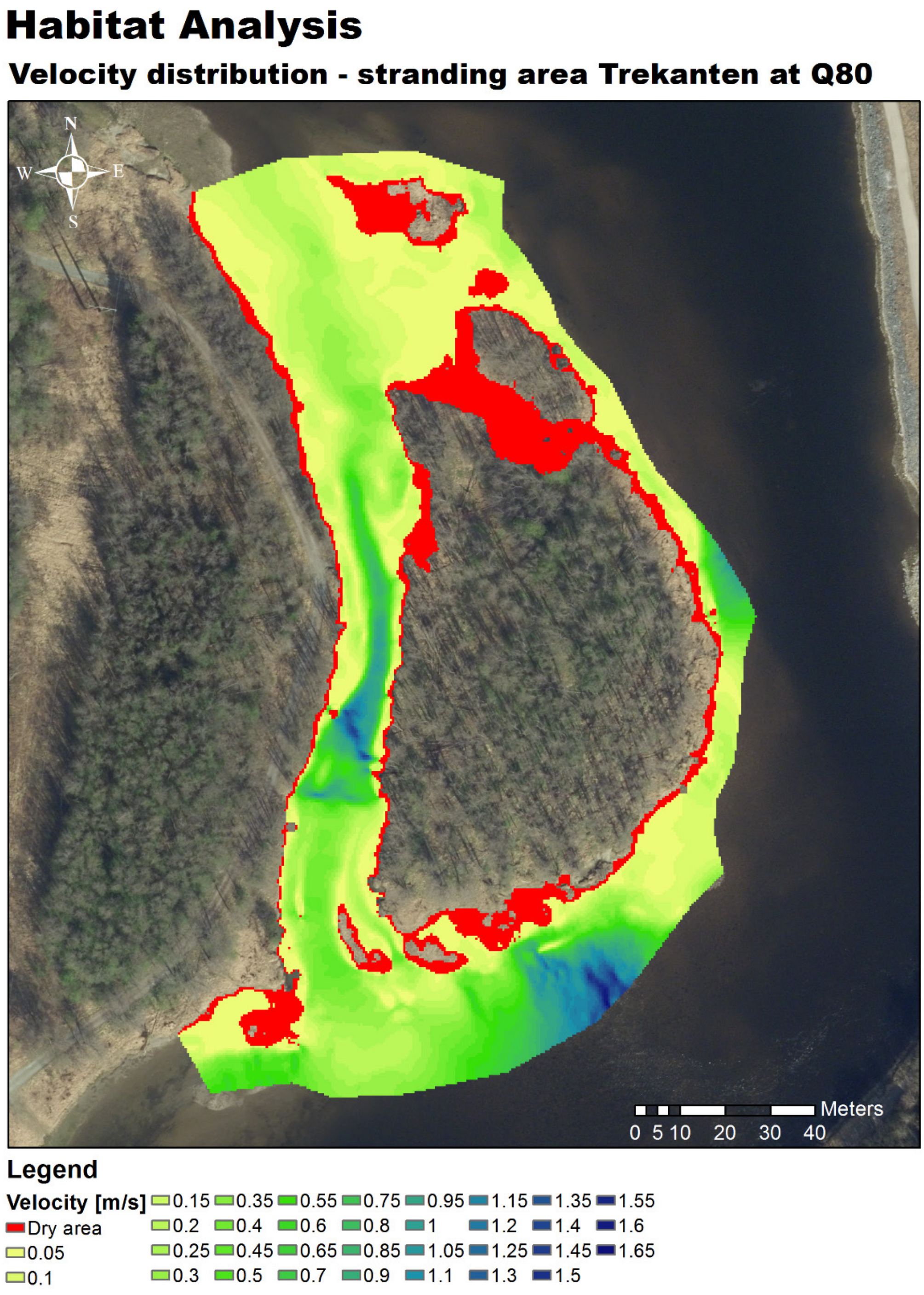


*Figure 16: Velocity at Q 80*

In the 80 m³/s layer obviously big areal parts fall dry. Particularly, parts along the banks like the small channel north of the island are drying out. Moreover, the velocity in the side channel left of the island goes rapidly down. First parts in this side channel already start to dry out, regarding the red point beside of the rapid. The spawning area just shrinks a bit in its size.


*Figure 17: Velocity at Q 35*

The drying-out trend, which was illustrated in figure 16, persisted so that the velocity layer in figure 17 has even more red parts. Striking is the side channel east of the island. It lost compared to the previous figure the upstream connection, so that there is a completely dry area in between. Areas which had a slow velocity along the banks in figure 15 are now dry. The complete or just partly drying out could have serious consequences for the fish spawning in this area. It is not just the drying out itself, which is for example an issue for fish eggs. Due to the missing water predators have also easier access to the spawning areas. As well as, low water levels and low velocities can lead to ice formation which would also kill the young fish. Further, it is visible that the spawning area in the main channel changed again.

Following the habitat analysis, the distribution for each parameter was displayed in a histogram. Figure 18 to 20 are the matching distribution histograms to the previous velocity layers. It stands out, that the maximum velocity of the layers is lower when the discharge is lower. Further, the width of the histograms decreases connected to the discharge of the river. Concluding to this one can assume, that the variability of the habitats is decreasing according to decrease discharge of the river.

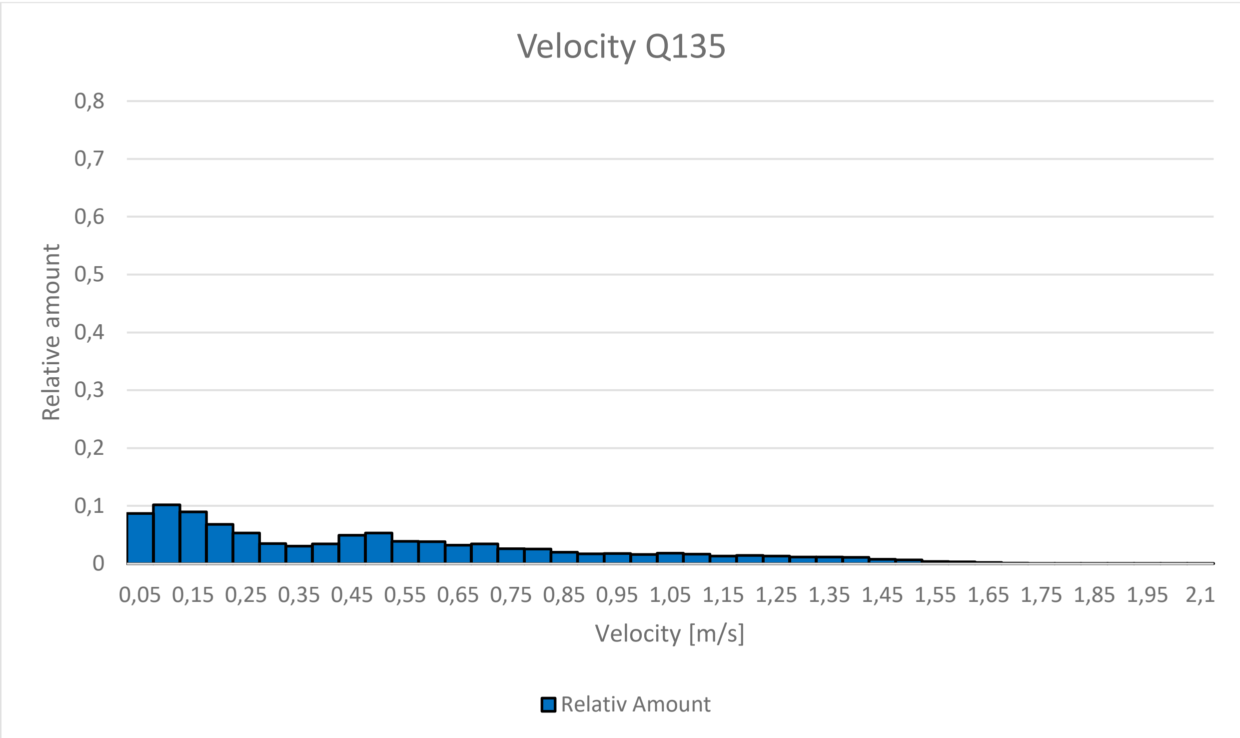


*Figure 18: Velocity distribution Q 135*

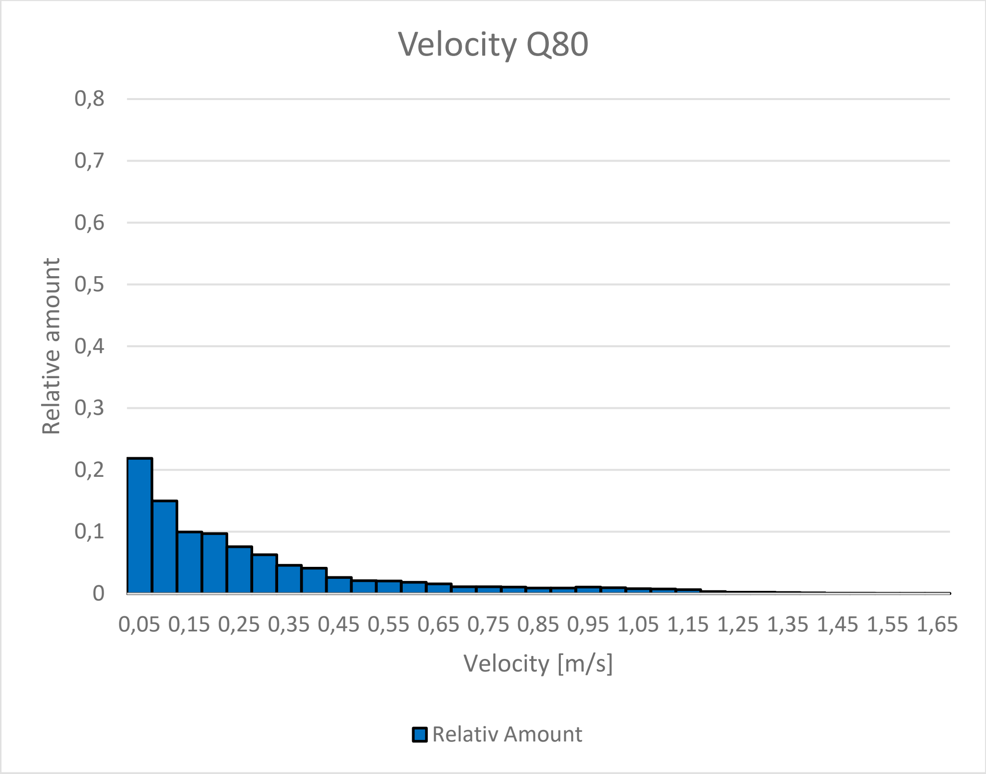


*Figure 19: Velocity distribution Q 80*

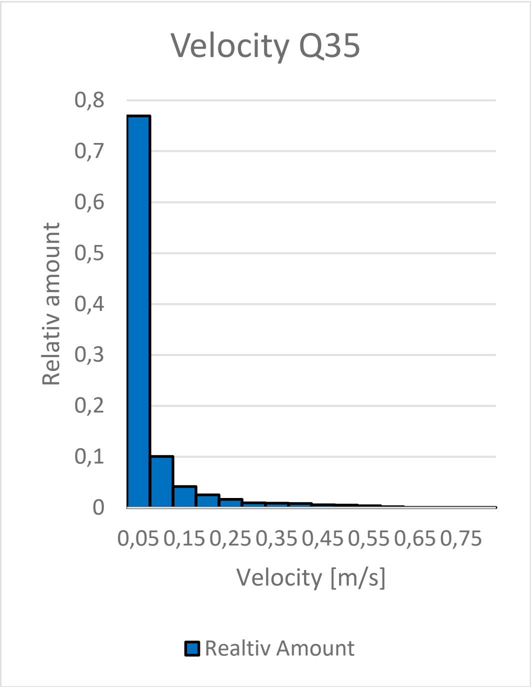


*Figure 20: Velocity distribution Q 35*

- Wave analysis for total Nidelva:

This research focusses on the analysis of the time, the different discharge “waves” take to go through Nidelva. The waves are created by the operation of the turbines of the hydropower plant.

The first experiment shows the drying out process through the whole river under consideration of the needed time. For this, a simulation with a down-ramping (turbine shutdown) was computed. Figure 21 demonstrates the full extent of the study area. It includes the from HEC-RAS exported boundary condition layers in steps of 30 mins from the turbine stop. The time layers are colored differently to visualize the drying out process in connection to the time.


*Figure 21: Drying out process total Nidelva*

Since the scale of figure 21 is too undetailed to realize stranding areas, it was necessary to zoom in. Figure 22, 23 and 24 are showing different locations from up- to downstream, including the colored stranding areas. A small map on the right top of each figure are locating the exemplary spots.


*Figure 22: Drying out process before Kroppan Pool*

The figure above shows biggest parts in green. Consequently, that almost all the dry areas are stranding during the first 30 min after the turbine shutdown. According to the location close to Leierfossen, where the river is regulated, the short retention time is totally reasonable.

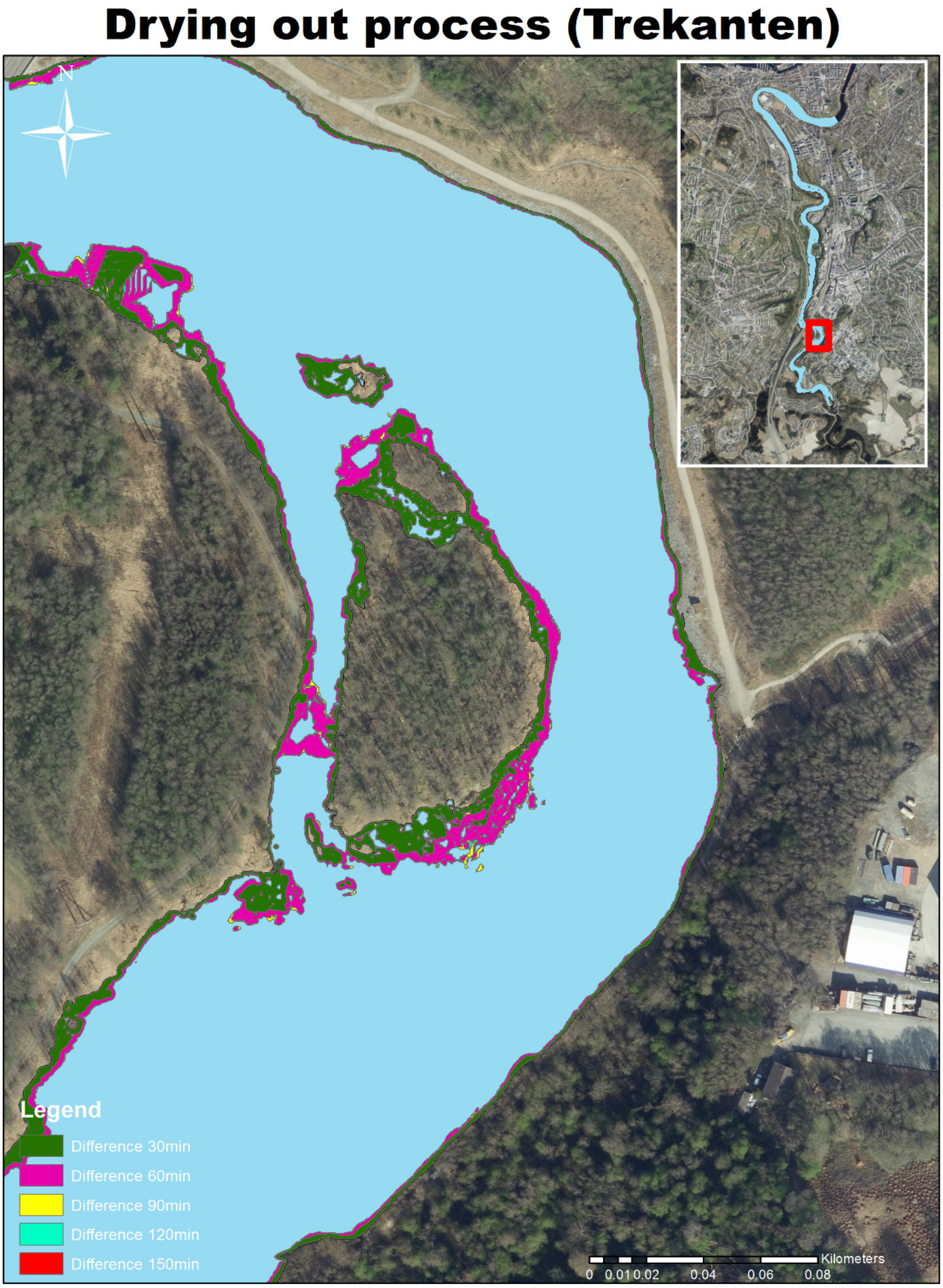


*Figure 23: Drying out process at Trekanten*

While most parts of the location upstream of Kroppan Pool were dominated by green, the results at Trekanten changed a bit. As figure 19 illustrates, half of the stranding happens in the first 30 minutes. The other half takes 60 minutes after the down-ramping. Exclusively, small parts take even longer than the first 60 minutes.

## Drying out process (Tempe)

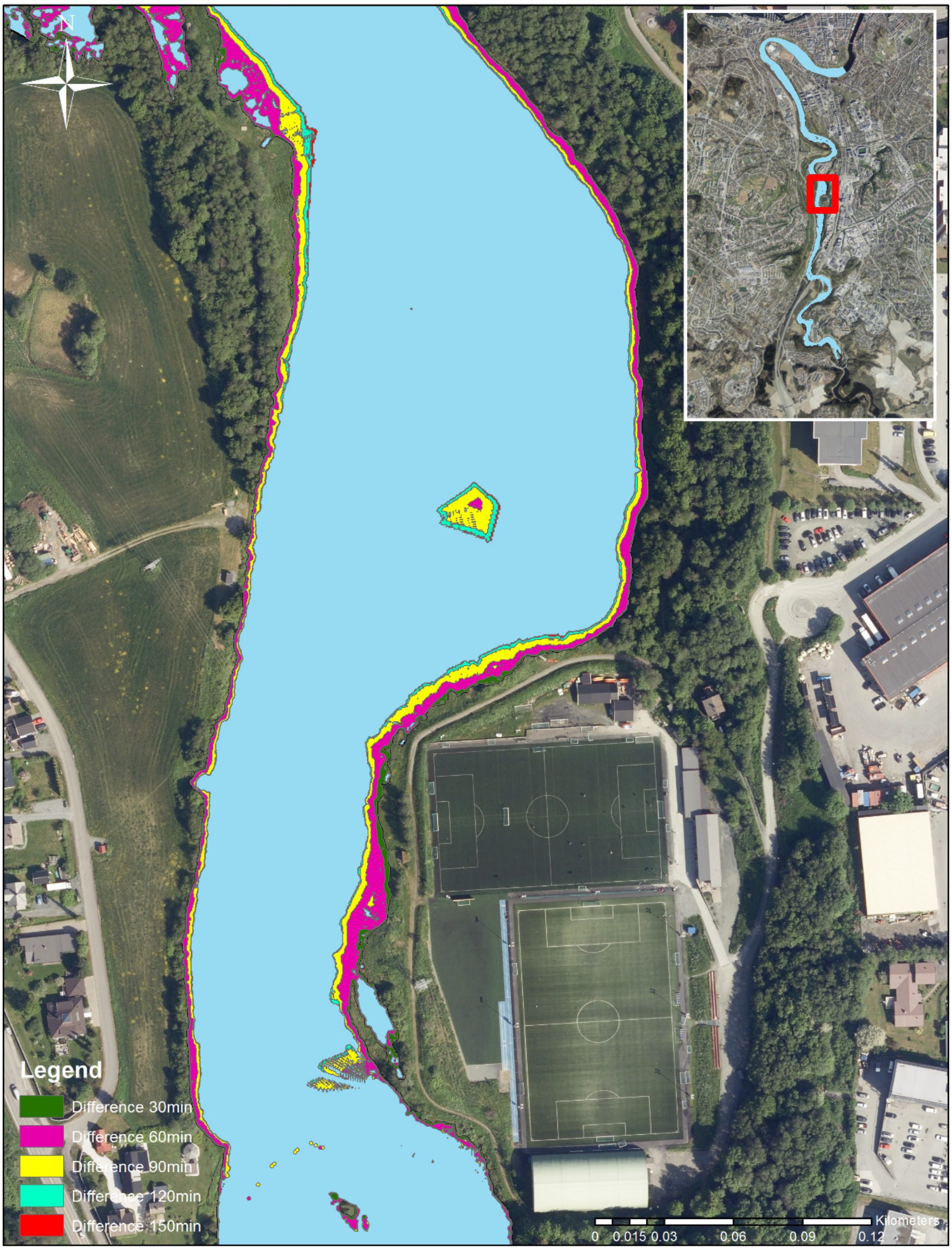


*Figure 24: Drying out process at Tempe*

Further downstream, there are just some green areas. The first 30 minutes show only a small influence in this area. Pink and yellow colored areas are the biggest part of the stranding areas. That means most areas at this location are dried out between 60 and 90 minutes after the turbine stop. Additionally, small parts are covered with turquoise color. These areas are dried out two hours after the down-ramping.

Small zoomed areas are for the conclusion not enough and an overview of the complete river was generated in figure 25. While the x-axis describes the time after the turbine shutdown, the y-axis is an indicator for the dry areas along Nidelva. After 2,5 hours the graph begins to approach an asymptote at approximately 75.000 m². This result shows that the river adjusted its complete discharge after more or less 2,5 hours. Furthermore, a drying-out area caused by the ramping of a bit more than 75.000 m² is assumable.

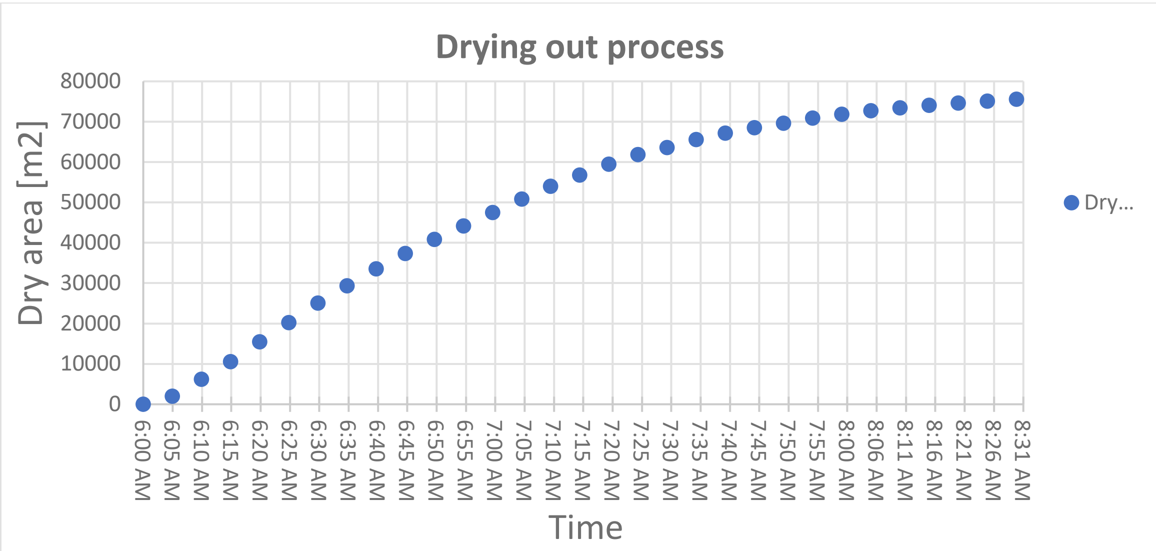


*Figure 25: Drying out process - area size*

- Water surface elevation analysis in longitudinal profile:

Another way of visualizing the whole river extent in one graphic shows figure 26. It displays the longitudinal profile of Nidelva. The ground terrain is black, the water surface elevations at different timesteps after the turbine shutdown. Following the graph, it is displayed how the first 2000 meters of the river are affected by the first 30 minutes after the down-ramping. Here the blue color is visible for water levels. Below are all covered by the red line. That means the water surface elevations adjusted after 30 minutes and isn´t changing afterwards. At approximately 2000 m the green graph is more and more visible in between. Starting form this point the water surface elevation is adapting sometimes after 30 minutes. But it is adapted before 60 minutes passed, since the purple line is still covered. First time the water level is changing still after 60 minutes. Then the purple line is becoming visible at 3500 m. The blue line is in the meanwhile covered by the green. Consequently, the area after 3500 m is not influenced by the first 30 minutes. Because all graphs are running together after 6000 m, it can be assumed, that the influence of the sea level dominates the water surface elevation. Therefore, no changes in the model at any time are expectable. The level increases according to the periodic high and low tide. It should be also mentioned that the water surface elevation in the graph falls beneath the terrain line, this doesn´t mean that the river is losing its upstream connection and runs dry along the whole width. It does mean just the small part, where the cross-section line was drawn is running dry. Parts beside can have a lower terrain, what leads to a still flowing river.

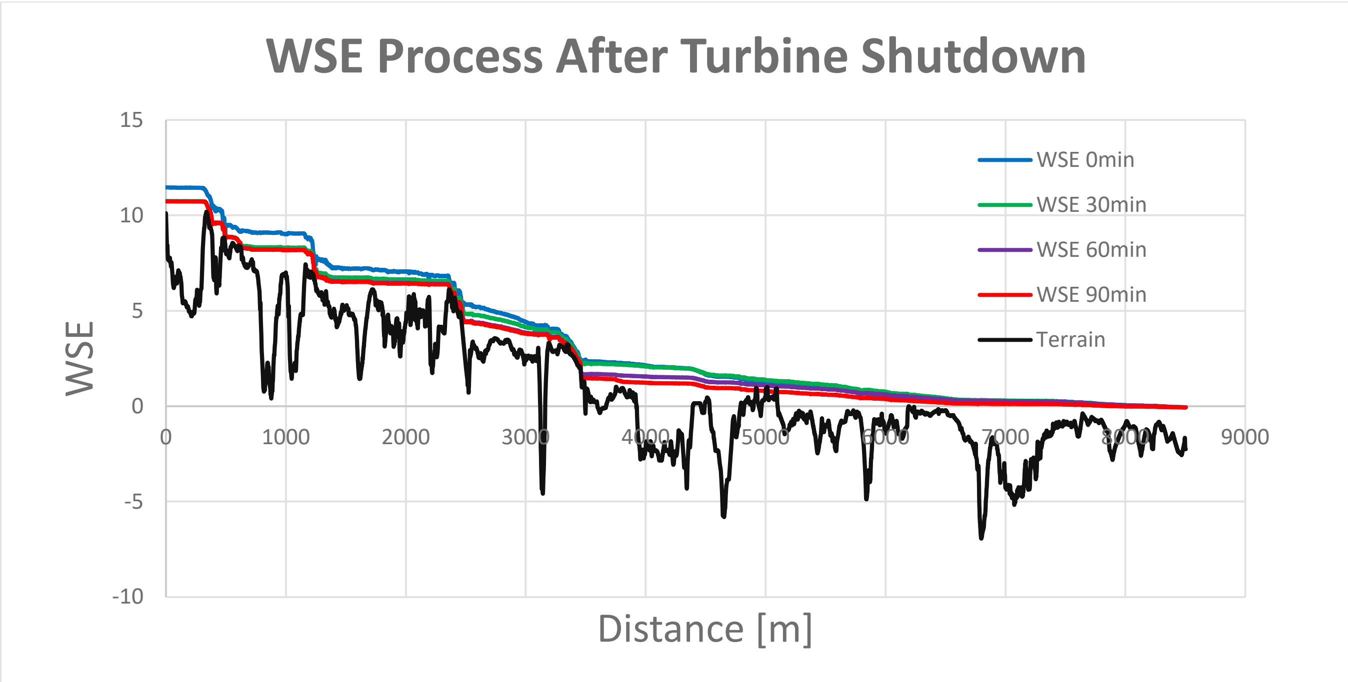


*Figure 26: Water surface elevation process along whole Nidelva*

- Cross-section analysis of retention time:

For seeing the retention time in some defined places, a cross-section analysis was done for the down-ramping. Figure 27 exemplary illustrates the process of the water surface elevation in the cross-section Tempe. Again it´s striking that the water surface elevation does not change the first 20 minutes. The first decrease of elevation is after 40 minutes. After the displayed 90 minutes the elevation stabilized. These findings are in accordance with the results of figure 24

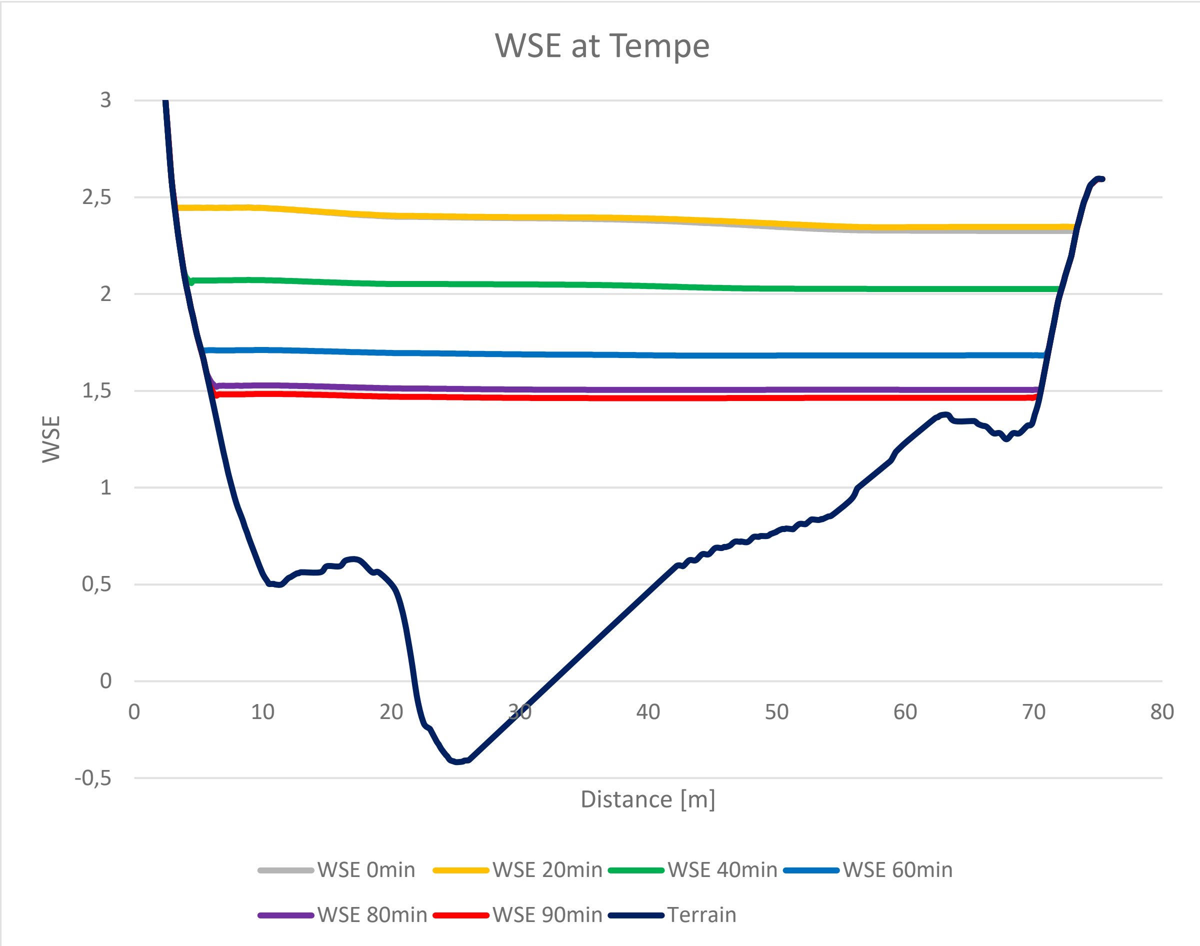


*Figure 27: Water surface elevation at cross-section "Tempe"*

- Retention time comparison for up- and down-ramping:

In order of the wave analysis, also a study on the retention time until total adaption of the river was done. For this study an up-ramping and down-ramping scenario was studied. The green and blues graphs in figure 28 show the turbine operating upstream at Leierfossen (start of model). The downstream flows are meanwhile presented by the purple and red graph. Most interesting findings out of this study is probably, that the adaption time for the up-ramping is 16 minutes shorter than of the down-ramping. Meaning it takes 16 minutes less for the river to adapt for filling, than the drying out process. For those results the 5% and 95% of the certain discharges were taken. Reason for that was the uncertainty of the flows, when they adjust to the asymptotes/stabile flows.

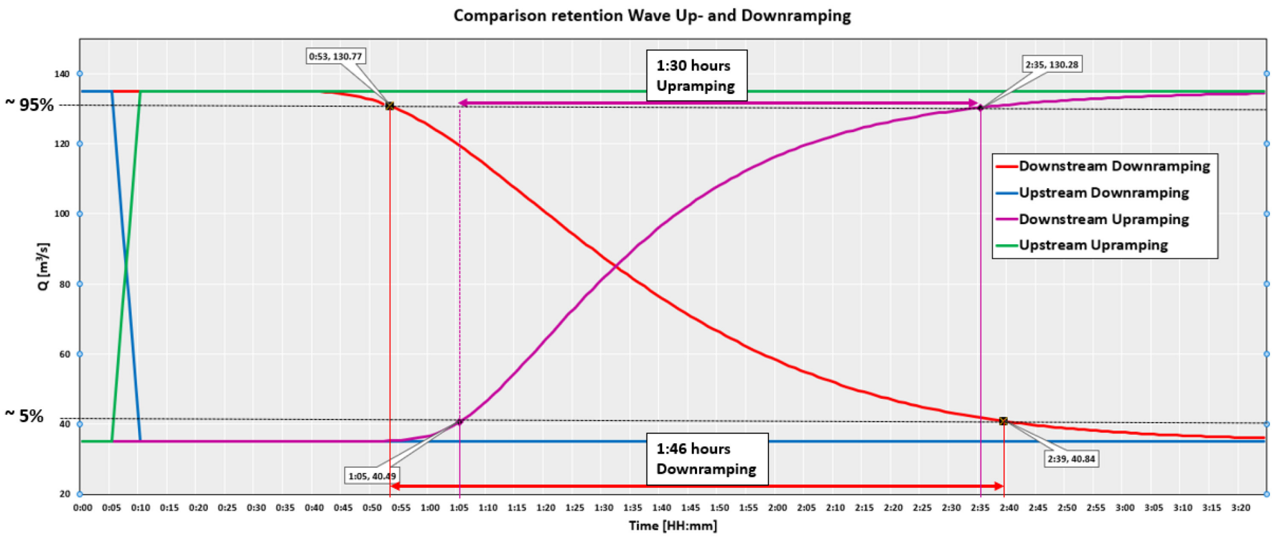


*Figure 28: Comparison retention wave up- and down ramping*

- Discharge adaption while up- and down ramping:

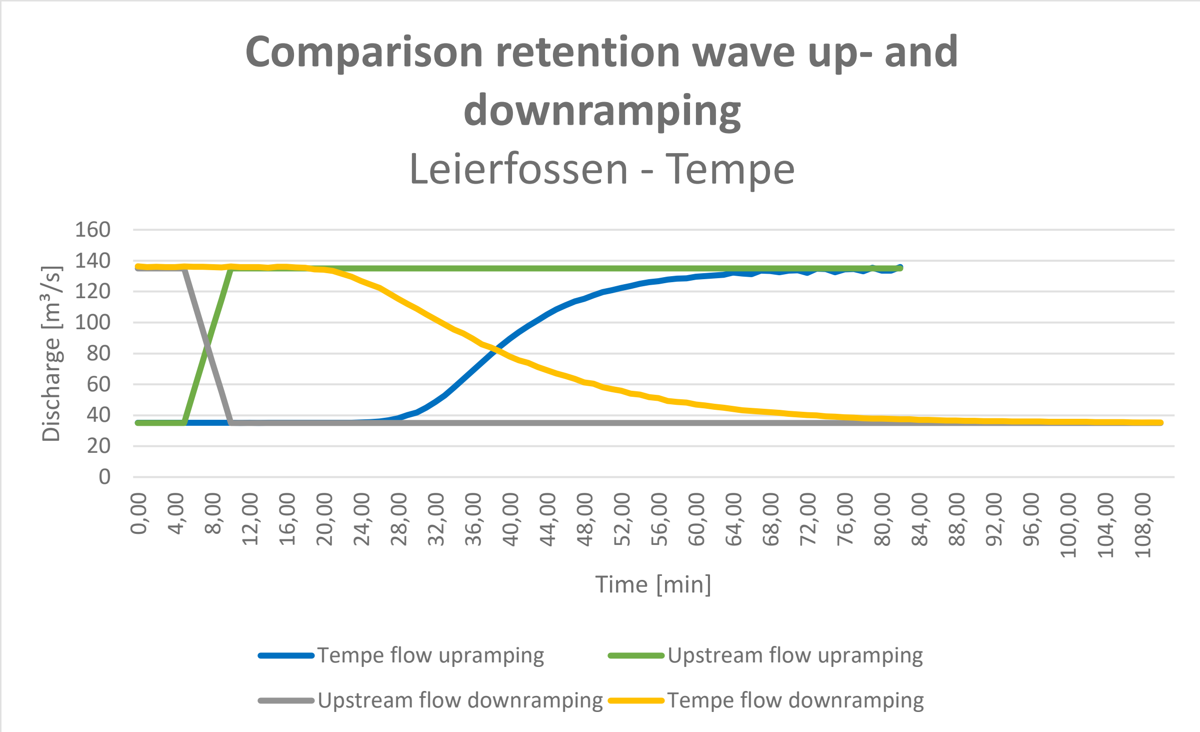


*Figure 29: Flow at cross-section "Tempe"*

Figure 29 includes the graph of the turbine operating for an up- and down-ramping scenario in green and grey. The blue and yellow graphs show the discharges at Tempe for both scenarios. It is obvious to see again, that Nidelva takes longer to adjust for a down-ramping, than for an up-ramping. Moreover, the figure shows the retention time of the discharge for the cross-section. While the turbines are changing their flow for five minutes, the cross section keeps its stabile, before it´s slowly starting to adjust.

- Analysis of 30 turbine-starts and -stops a day:

Finally, a simulation was done for 30 starts and stops of the turbine, which was the horizon for this project. Since the amount of data for 30 starts and stops in 24 hours was too big for HEC-RAS, a simulation for 15 starts and stops in 12 hours was done. Figure 30 includes the results in form of the water levels from up- to downstream. To know which “fid” stands for which location, please refer to table 4. Striking in the graphic is the overlapping, which is increasing and most clearly visible in the last graph. The peaks are not as accentuated as further upstream and the low flow can never really establish due to a new wave. Additionally, the time shift of the single waves is good recognizable, when one study the vertical black line in the graph. Upstream it starts on a peak, but until the same peak arrives downstream almost 30 minutes are gone.

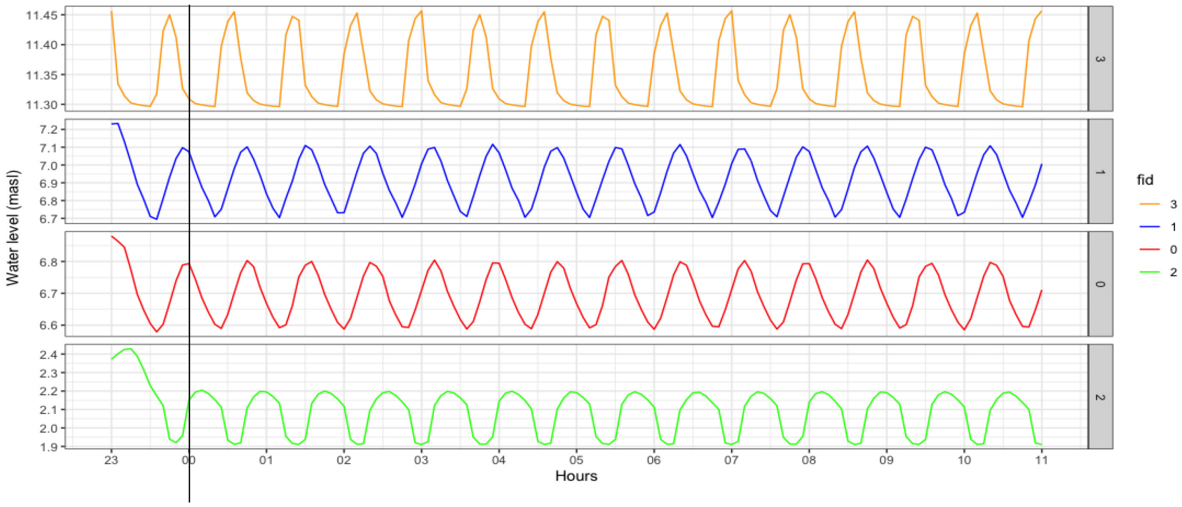


*Figure 30: Water surface elevation while 15 starts and stops in 12 hours*

*Table 4: FID to Locations*

| | |
|---|---|
| 3 | Leierfossen |
| 1 | Kroppan Pool |
| 0 | Trekanten |
| 2 | Tempe |

## 3.3 Visualization

Aim of the visualization was to create an animation, which illustrates to outsiders the ramping issue.

After finding “Unity” as a fitting visualization software, a lot of trying out, tests and experiments were necessary to finally create a first visualization. Unity was chosen due to fulfilling most of the in 2.1 mentioned requirements. Figure 31 shows this first try. Here one can see the result of adding a geotiff data as a terrain. Unfortunately, this try out was not usable, since it was not possible to add a water surface elevation.

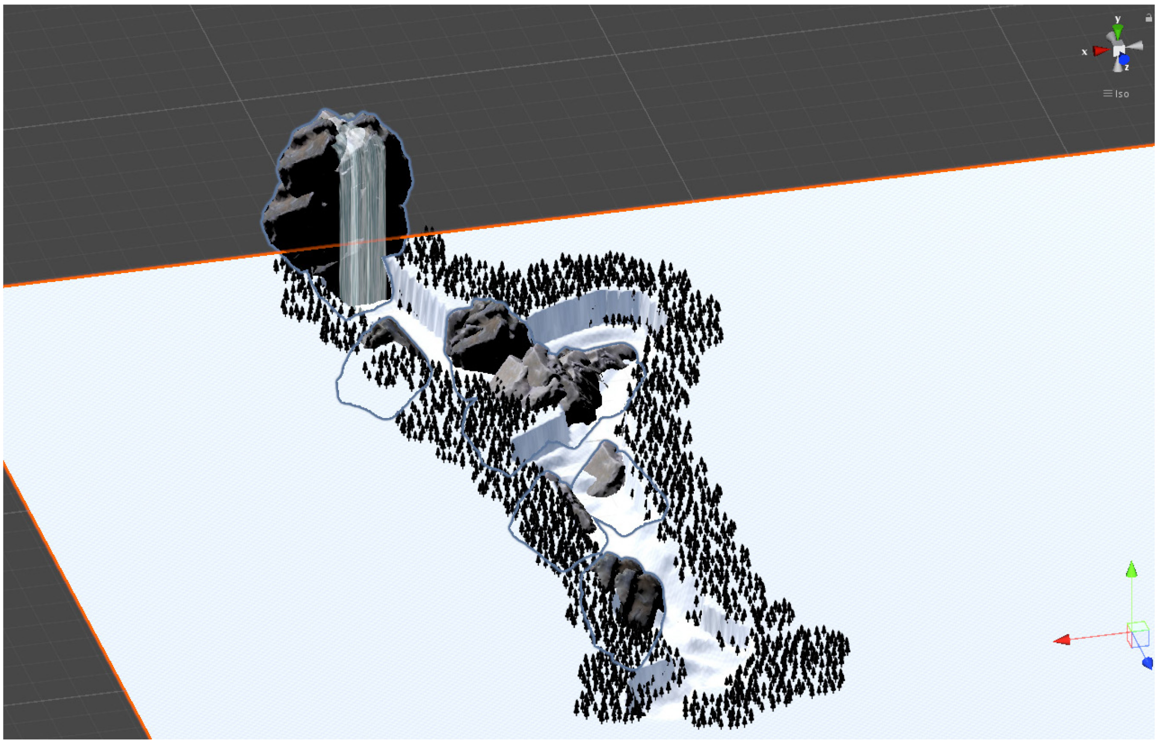

*Figure 31: First visualization in Unity*

For a second try an asset called “River Auto Material – RAM” was bought. With it was possible to create different shaped river runs with different texture. A screen-shot of this visualization is displayed in figure 32. Issue with this visualization was, that the river was adjusted in many manual steps. Hence, there was no physical correctness in the visualization of the river. Additionally, creating the total river run would cause an addition big workload.

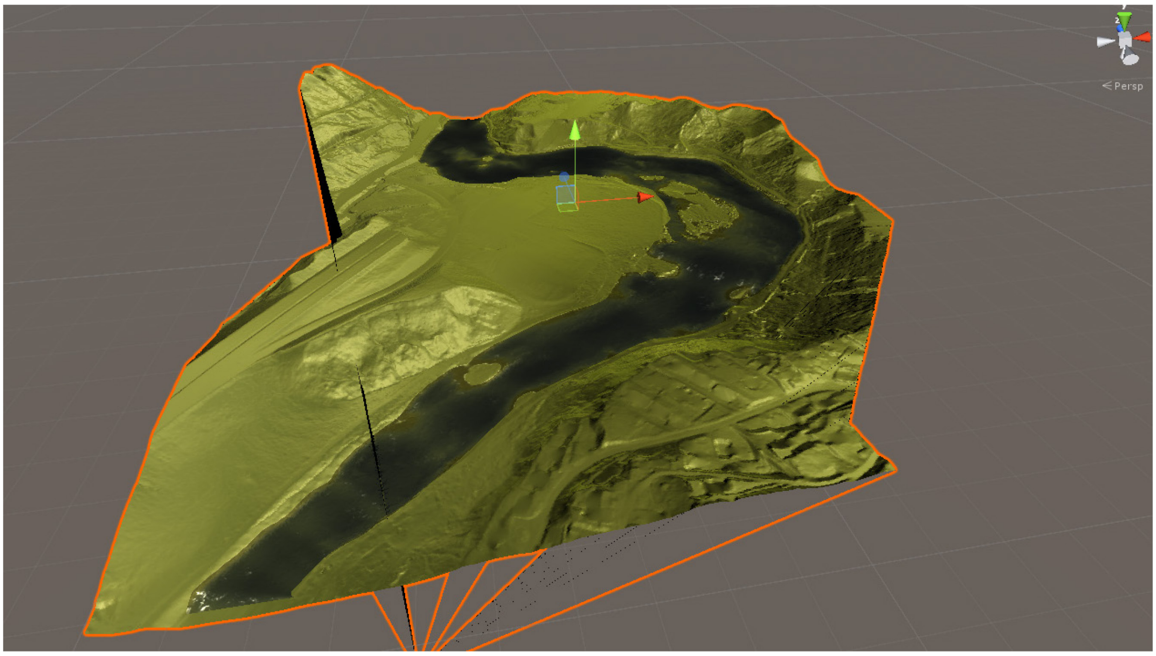


*Figure 32: Second visualization*

Finally, the “TerrainImporter” asset was found. It enabled to add HEC-RAS output files in the .tif format directly in Unity. Figure 33 is an outtake on the way to the visualization. The image shows the terrain mesh, before the water surface elevation layer was added. Following, figure 34 and 35 are showing a small visualization of only Trekanten, which was first done. Figure 36 and 37 show the visualization of the total river run. Concluding figure 38 and 39 compare the discharges of 35 $m^3/s$ and 135 $m^3/s$ at Trekanten. All water surface elevation data was used from HEC-RAS. Therefore, it is ensured that the water boundaries are physically correct. With the help of moving textures, the model looks realistic. Just a up and down moving of the water surface elevation layer according to the ramping was so far not possible. However, the workload was reduced and a physically background was ensured.

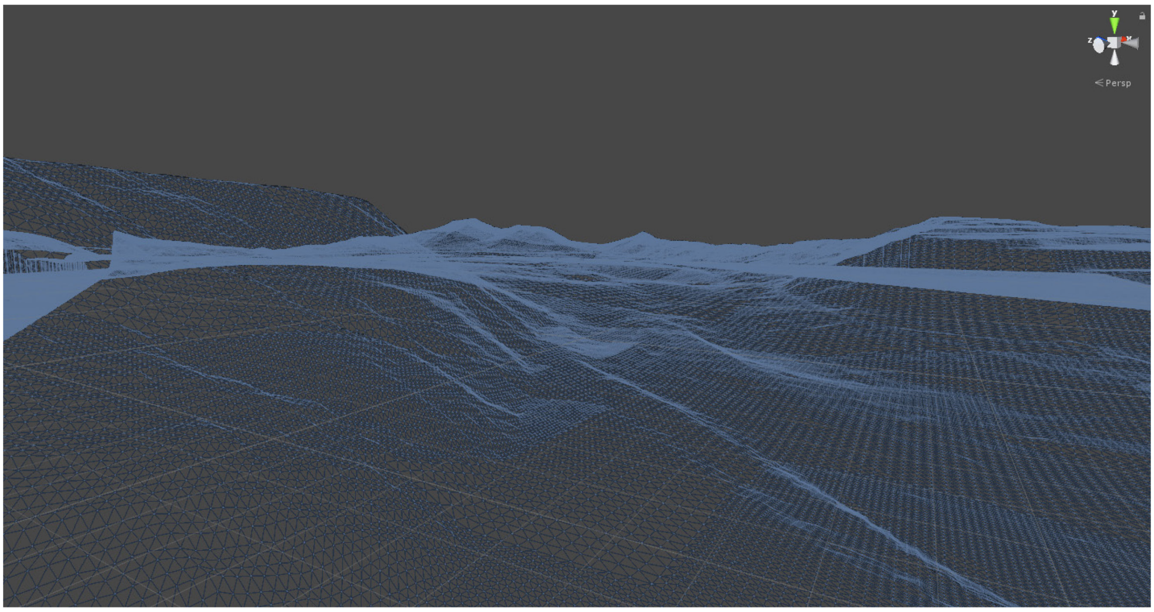


*Figure 33: Terrain Mesh*

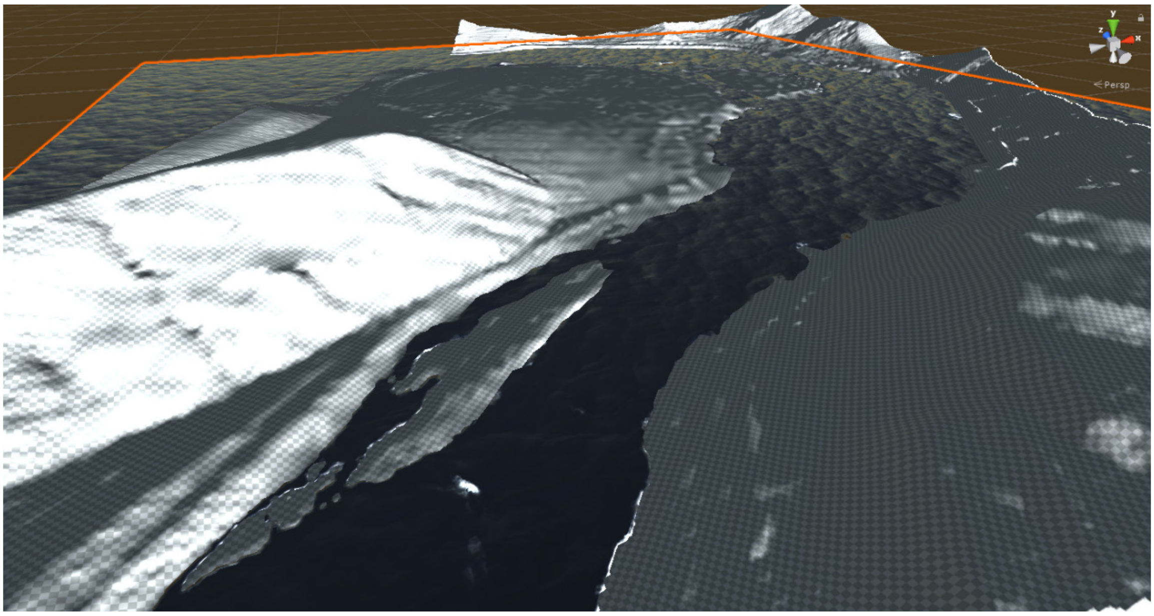


*Figure 34: Visualization Trekanten 1*

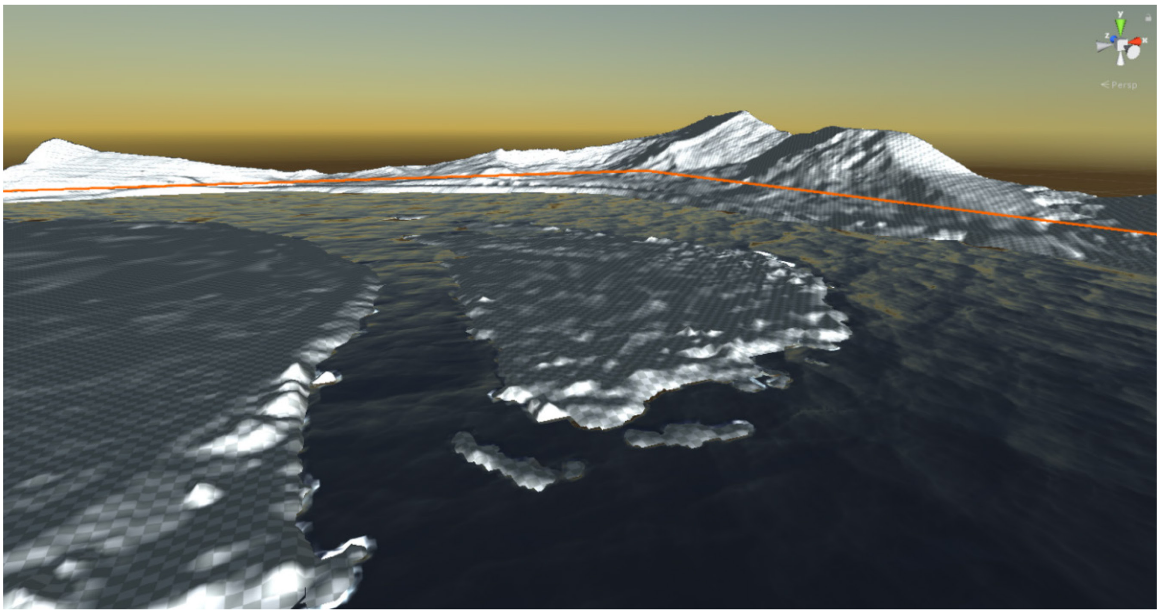

*Figure 35: Visualization Trekanten 2*

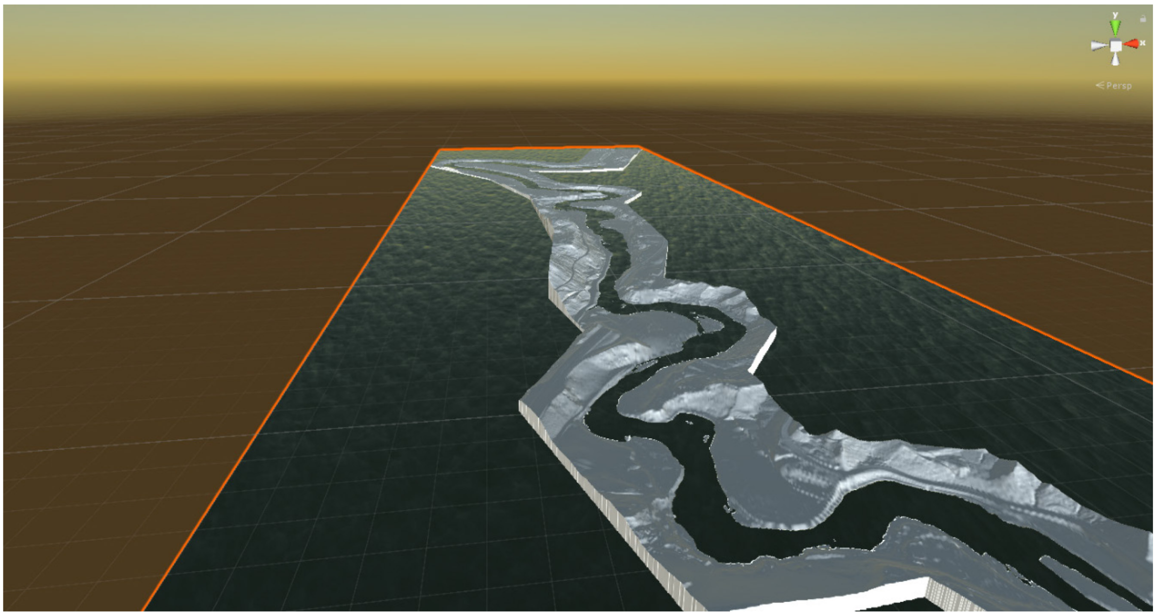

*Figure 36: Visualization total Nidelva*

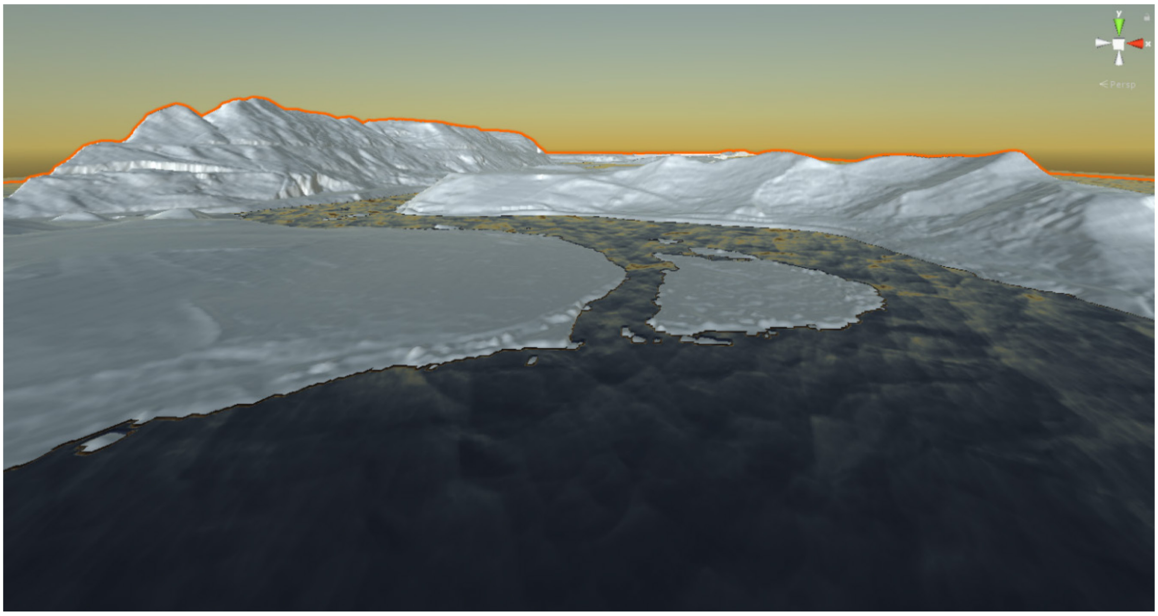

*Figure 37: Visualization total Nidelva – Trekanten*

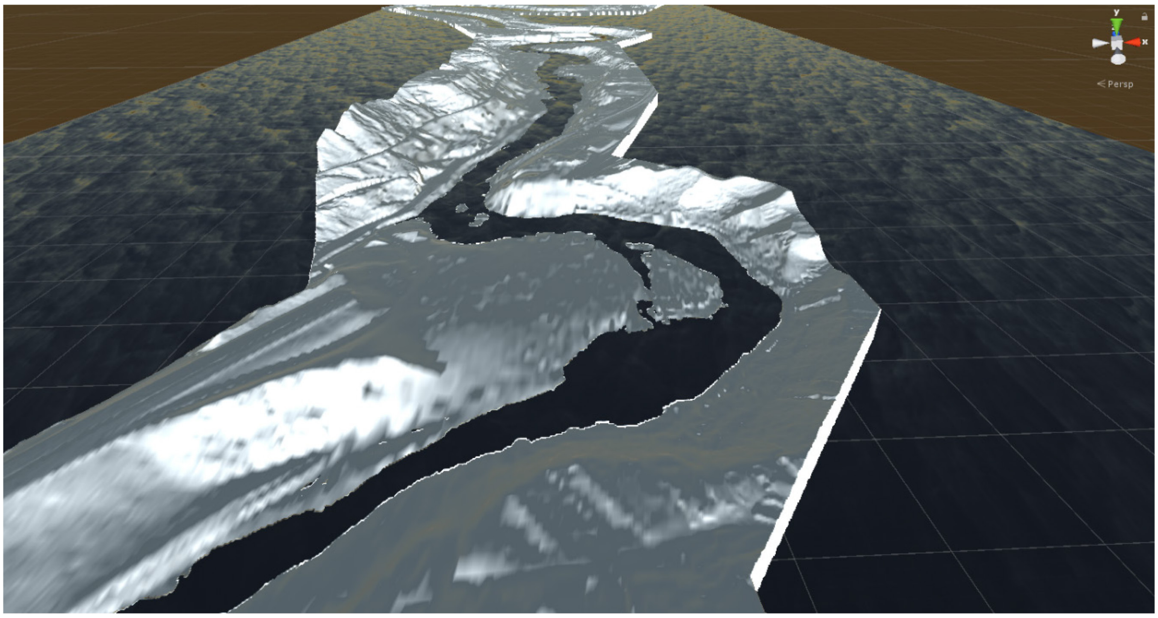

*Figure 38: Visualization comparison Trekanten Q 35*

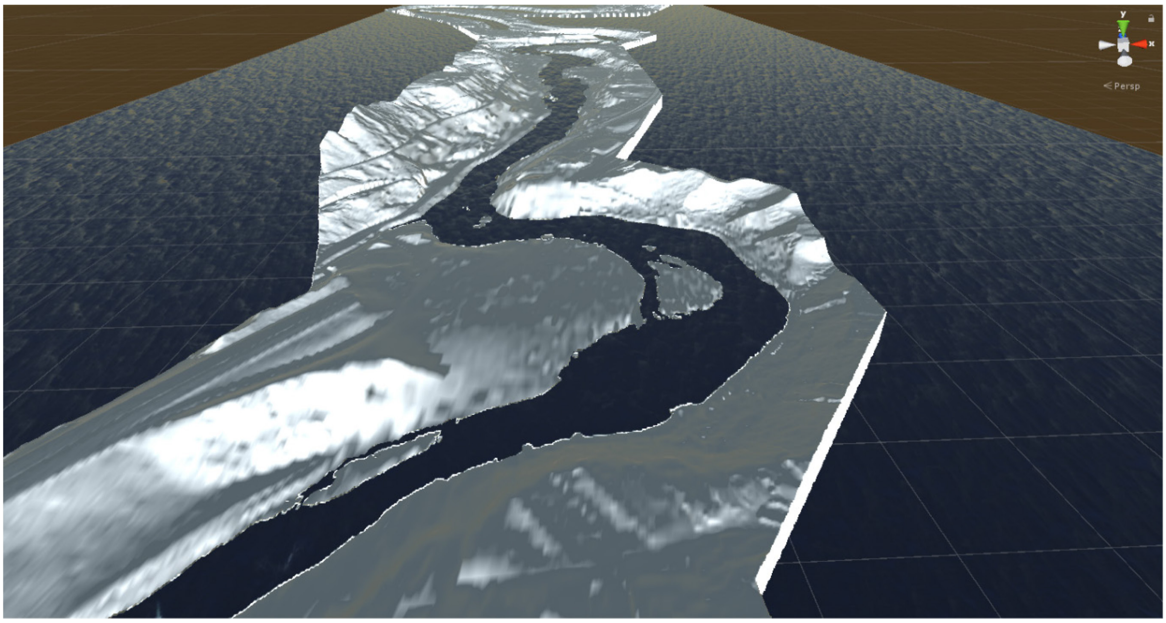

*Figure 39: Visualization comparison Trekanten Q 135*

# 4. Discussion

## 4.1 Summary and critical valuation of results and methods

The results are split into two parts. The first conclusion deals with the verification of the used model. The second is about hydropeaking researches based on the approved model. Finally, it is possible to conclude that the model is more precise than expected.

The results show that the model is very precise and perfectly suitable for further impact studies. Especially, in the first comparison with the smaller and more detailed meshed models, where the big model proved its accuracy and that there is no need for finer mesh resolution. Those smaller models had more likely the tendency to be inaccurate in the up- and downstream regions, because of certain boundary issues. In the big model even more detailed regions were simulated well. The comparison with the drone orthomosaic illustrated this very good, despite the differences in flow and the error of the DEM.

Further, the model has the maximum of possible preciseness due to the limitation of cell numbers. Within this study the model also made clear that a bigger cell size is possible and would shorten the simulation time. However, here the issue would be the not detecting of smaller height variability in the DEM. This would lead to flooding of areas which would be dry in the finer mesh. Therefore, it was necessary to keep the mesh size of 1,5 m x 1,5 m in the big model. Another indicator for the accuracy is the velocity comparison in one of the side channels. The big model was even more precise than the small very detailed model. The reason for this accuracy is the mesh extent itself, the model is not so accurate in the areas surrounding the boundary conditions, which introduce a large error in the small model as the study area is highly influenced by this boundary conditions. Therefore, it can be concluded that it was no more accurate to simulate the hydropeaking in Nidelva with the smaller model, since using finer mesh introduce errors in the areas where new boundary conditions are placed.

After verifying and proving the accuracy of the HEC-RAS model, simulations studies based on these were made. Firstly, the habitat analyses show the dry areas very clearly. Additionally, they show that potential habitat for fish and macroinvertebrates, like the side channel at Trekanten is lost due to the down-ramping. The building of ponds, lower velocities, lower depths and many more are endangering especially spawning areas like the one shown. Ice, easier access for predators and drying out of areas are for illustration consequences, which can be caused by the mentioned factors and lead to a significant increase in mortality. Due to the down-ramping effects also a significant loss of habitat variability was perceptible.

A further finding of the done research, is the wave propagation through Nidelva. It is easily possible to extract the time it takes to certain areas, until effects of the ramping are visible. Moreover, all created results were verifying between each other, by showing approximately all the same time sequence for in this case - the study area at Tempe. Striking are the time differences of the wave arrival. In parts upstream (region of Leierfossen) the river reacts fast to changes in the discharge and totally adjusts within 30 minutes, while further downstream, for example at Trekanten it takes around 60 minutes or at Tempe even longer for fully adaption of flow and water levels. This circumstance is also displayed in the very last wave analysis research. But further the graph shows that the farther you go downstream, more overlapping in the ramping waves. At Tempe neither a high nor low flow situation can establish, due to catching up of the waves. Further downstream to the end of the model, figure 26 displays the increasing influence of the sea level. Meaning the ramping influence has starting here no more effects to water levels.

Finally, a 3D visualization of the river at high flow (135 m³/s) and low flow (35 m³/s) was achieved by utilizing Unity, which can be useful for showing the visual effects of hydropeaking to the stakeholders. This visualization was physically correct as their layers were imported from HEC-RAS results. There might be some further work necessary for running ramping animations properly. As well, there is the need for realistic textures and objects. However, a good base to start from was done within this work.

## 4.2 Comparison with similar studies

The accuracy check of the big model of Nidelva is based on several different data sources, some of them recently taken. Consequently, it can be assumed that the current data base is the most detailed, ever existed for Nidelva. Although, the data used for the study of "Thermal implications of hydropeaking activity in regulated Arctic rivers" was also already based on ADCP data, the data were just introduced to a 1D model with 58 cross-sections (King 2012) (Zitation nicht komplett, Jahr fehlt (Auch unten in Quellangaben) !). The data for this research is in comparison in a 2D model with more input data.

This accuracy is further perceptible in the accuracy checks of the Nidelva model. These checks are different ways to verify the model and simulations, which are processed at the beginning. First simulations of the model with the full extent where compared to simulations of models with a smaller extent. Then an orthomosaic of Trekanten was created and compared to the simulation of the big model. Subsequently, there was a try to enlarge the simulation mesh size with an additional study of the accuracy. And finally, the velocity of two cross-sections and several RTK-GPS-points along the boundary were measured to compare them with the simulated data.

The first accuracy check was the comparison of different sizes models. The model to prove was the model with the full extent of the study area (Leierfossen to Elgester bru). This was compared to a medium sized model (Leierfossen to Sluppen bru) and a smaller model (shortly upstream of Trekanten to Leierfossen). For the comparison, the simulations of all three models were clipped to the extent of the smallest model. The results showed that most parts are in a tolerance range of 15 cm depth-difference. Red parts in figure 6 occur mainly at the boundary of the compared models. The reason for these phenomena is found in boundary conditions and backwater effects which are represented in the small model. Those issues are getting less as soon as the computational mesh of the model is extended. The finding proved the accuracy of the biggest model and excluded the need of several small, detailed models.

An accuracy test with help of orthophotos was already done in the study: "Performance of a Two-Dimensional Hydraulic Model for the Evaluation of Stranding Areas and Characterization of Rapid Fluctuations in Hydropeaking Rivers", difference to the HydroFlex study is just the source of the orthophoto. For the river Storåne satellite orthophotos were used to check the accuracy of the model (Juárez et al. 2019). In the HydroFlex research a new drone (DJI phantom 4) with a highly precise RTK-GPS made it possible, to take a high-resolution orthomosaic of Trekanten. Therefore, the orthomosaic is even more precise than the satellite orthomosaic. In conclusion, the accuracy which was studied afterwards with the help of HEC-RAS simulations proves one more time how detailed the full extended model is.

Shorten the simulation time through enlarging the simulation mesh in HEC-RAS from 1,5 m x 1,5 m to 6 m x 6 m wouldn´t lead to a big loss of accuracy. Hence, it would make sense to just simulate with a wider mesh. But, due to a wider mesh HEC-RAS couldn´t fit the mesh as good on the terrain as necessary. Either a smaller mesh or breaking lines would be necessary to create a proper fitting simulation mesh (Goodell 2015). That again would lead to a bigger computing time and a repeated simulating in case of wrong or missing breaking lines. Following from this, a use of small and as precise as possible mesh was chosen.

The last accuracy check was based on measured values. Two velocity cross-sections in a side-channel of Trekanten were measured, as well as several GPS points along the boundary. In addition, a small model for the side channel was created to compare the simulation results of it with the full extended model. The comparison of the velocities showed that the big model is very precise. The side-channel model however, did not fit with the velocities. It is assumable that the flow did not had an extended enough model to settle and distribute the flow properly in the side-channel.

After verifying the model, it was possible to do studies based on it. At first an analysis of the habitats around Trekanten was done. The physical parameters velocity, depth and shear stress were simulated, extracted and analyzed. Further, the drying out process and wave propagation lengthwise Nidelva was studied. The following cross section analysis should add further knowledge about the wave propagation and the with it connected retention time. To see if the times are the same for both ramping (up and down) a comparison between an up- and down-ramping scenario was studied. This comparison was extended through studying the up- and down-ramping at different cross sections. After knowing approximately, the retention times a scenario of 30 starts and stops of a turbine within a single day was simulated and analyzed.

The gained habitat analysis results are covering partly the findings of other studies. Researches show the same changes of habitats, which were studied at Trekanten in Nidelva. Depths, velocities and shear stresses are decreasing with decreasing discharge. Further, the point of decreasing sizes of available areas, due to down-ramping is covering with the recent findings. (Casas-Mulet et al. 2014) Differences to the studies of Casas-Mulet et al. were when it comes to the change of habitat variability. While Casas-Mulet observed a not linear relationship between decreasing flow and decreasing habitat variability, the habitats were getting constantly less variable with decreasing flow in Nidelva. Reason for the deviant results at Lundesokna river, could be caused by the morphology of the river, which is also mentioned in the other scientific work. It is not excludable, that observing other locations in Nidelva wouldn´t lead also to non-linear relationships between flow and available areas. (Casas-Mulet et al. 2014).

Another study showing similar results in decreasing velocity and further in drying out of areas was observed at the Storåne river. Phenomena like drying out side-channels and down slowing velocities were also a finding of this work. Therefore, the habitat analysis and the drying out process study are strengthened by the findings of the previous work. (Juárez et al. 2019)

However, one should be aware of the fact, that hydropeaking and the reduction of discharge does not automatically lead to stranding. One main point is the river morphology like results of studies of interactions between hydropeaking and river morphology have shown. (Vanzo et al. 2016, S. 435) In Nidelva it is observable too, that some parts are affected by the hydropeaking even if they are approximately at the same location. But hydropeaking definitely dries out a noticeable part of the river. In case of the Ljungan river the dampening led to a "sharp decrease of wetted areas". (Adeva-Bustos et al. 2019b). Even if the dewatering “is not equivalent to mortality” (Saltveit et al. 2001, S. 618), it need to be clear that mortality is caused by reduction of wetted areas. (Adeva-Bustos et al. 2019b) (Hedger et al. 2018, S. 6). This damages to the fauna can in turn have long time consequences on the whole ecosystem (Hedger et al. 2018, S. 6–7).

Regarding the wave analysis and the drying out process in Nidelva, we can see one more time the good quality of the results. Adaption times of the river to changes in the turbine operations last from upstream with approximately 30 minutes towards downstream to over 90 minutes. In between we can find Trekanten, where already stranding researches were done. One of the findings of this study was the adaption time of Nidelva at the location of Trekanten. Figure 1 of "FIELD EXPERIMENTS ON STRANDING IN JUVENILE ATLANTIC SALMON (SALMO SALAR) AND BROWN TROUT (SALMO TRUTTA) DURING RAPID FLOW DECREASES CAUSED BY HYDROPEAKING". A look into the shown graph provides a time of 60-75min after which the river is totally adapted. (Saltveit et al. 2001, S. 611) A similar time is also extractable regarding figure 23.

The longitudinal profile of Nidelva in figure 26 is again proving the results of the results of the drying out process. The stranding is mostly completed after 90 minutes. Further, the time retention and the influence of the tide were displayed. On the same time the prove of stranding time in both results verifies the wave propagation time. The cross sections as well as the analysis from upstream to downstream concluded totally reasonable time values.

Taking the time of the up- and down-ramping (fig. 28) one can extract the times between the waves before they overlap. For a total down-ramping the river takes at the downstream end approximately 1 hour and 46 minutes. The up-ramping wave takes 1 hour and 30 minutes. Findings of faster up- than down-ramping are covering with the researches of Ven Te Chow. He describes in his book “Open-channel hydraulics” amongst other things the faster up-ramping rates in open channels (Chow 2009). Considering the times for a total down-ramping and how long it takes for an up-ramping wave to show effect at the downstream end, it is predictable that if the time between up- and down-ramping is less than ca. 55min the waves are starting to overlay at the downstream end. It is assumable, that with further shorting of the time between up- and down-ramping the wave overlay happens more upstream. Figure 25 shows the retention time at Tempe and supports therefore also the previous assumption.

The frequent 15 starts and stops of the turbine within 12 hours proves further the overlap assumption. In figure 30 the water surface elevations are displayed, and one can clearly see the overlap of the waves. The certain flows never can really adapt to the turbine flows. Consequently, the lower parts of Nidelva are less affected by the hydropeaking. Although the upper parts are strongly influenced by the ramping.

The visualization of the HEC-RAS output with help of the software Unity and the asset “TerrainImporter” provided a satisfying solution for a first visualization. This is also a start of further work with animated 3D visualizations based on physically correct hydraulic simulations. The terrain itself is displayed detailed, but an improvement could be done by working with airborne light detection and ranging (LiDAR) data like it is already available for other rivers (Adeva-Bustos et al. 2019a). The resolution of the terrain especially under the water surface could be increased like that. Moreover, the hydraulic models could be simulated with an even more accurate data base.

Further work:

Looking back on this report, there is big potential for following work. First, as mentioned the visualization can be proceeded. An animated and moving visualization would make the consent of the hydropeaking issue even more clear. Velocity layers created by HEC-RAS including the flow direction could be inserted in the visualization. Connecting them to realistic seeming textures would make the visualization look even more plausible. Following this, the environment around the river could be designed with suiting assets. These visualizations or probably the direct HEC-RAS output files could be visualized with the Trimble SiteVision device to show outsiders certain aspects of the hydropeaking.

Regarding the data base of Nidelva, an airborne light detection and ranging (LiDAR) dataset would increase the accuracy of the models and simulations as well as of the visualization. Still there are locations in the river run which have an upgradeable data background. Additionally, a further use of drones could provide the project with a new data source. For illustration the flow velocity could be measured with the LSPIV method to gain data out of locations which were not accessible before (Lewis und Rhoads 2018).

For additional proving of the model's accuracy, pressure transducer tests can be performed. The transducers can measure water elevations, which can be compared afterwards with the water surface elevations of a HEC-RAS simulation. Barely a simulation fitting the discharges of Nidelva, while the transducers are measuring is needed.

Considering the future energy market and turbine operations more realistic scenarios can be simulated with the proven model. As soon as there is more information input about future peaking plans of other HydroFlex work packages, realistic future procedures can be studied. Based on the results of them mitigation studies can be carried out. ACUR is for example one of those mitigation projects. The idea behind this project is an underground pool which releases the turbine water with some retention time to mitigate the dampening effects. Moreover, there are ideas stricter regulations like minimum flows (Hayes et al. 2019). Also, the ideas of habitat restorations and morphology improvements are suggested (Moreira et al. 2019) (Vanzo et al. 2016, S. 421) (Adeva-Bustos et al. 2019b).

# 5. Conclusion

Concluding this work, it is important to say that all researches based on HEC-RAS simulations, were done on a well proved and verified model. Comparisons of the model with smaller and more detailed models, drone orthomosaic, velocity measurements and RTK-GPS point measurements confirmed the accuracy several times. There is no reason for hesitating using this model for further simulations and scenario studies. Created results based on this model showed amongst other things that there is a certain retention time until the river reacts to changes in the turbine operations. In a frequent ramping this fact can lead to a catch up of the up- and down-ramping wave in parts of the river further downstream. In these areas the hydropeaking impacts are mitigated. Closer to the turbine outlet, stranding processes take less time. Consequently, high and low discharges can settle here for a longer time and bring all the negative impacts of hydropeaking with it. In case of a less frequent ramping, the waves are not overlapping, which causes hydropeaking effects also in the downstream parts of Nidelva. Moreover, a finding was the affected drying out areas. Especially, Trekanten was here studied quiet well and validated older stranding researches in this area. An analysis of the habitats has shown that velocity, depth and shear stress values are decreasing with decreasing flow. Following out of this, the variability of the habitats at least around the area of Trekanten was decreasing. By virtue of other researches this finding is due to the morphology of the river. It is not applicable for the whole length of Nidelva, since it´s morphology varies along the reach. However, results have shown that especially upstream the lack of mitigation need to be resolved to prevent further damages to the fauna. Finally, a way was found to display 2D hydraulic modelling results in a 3D visualization. In future this can be a good opportunity to explain outsiders the hydropeaking issues.

# 6. Summary and personal conclusion of the practical semester

After working 21 weeks in the HydroFlex project, I can confirm that I got some very useful insights. Software and devices, I never have had heard of before are now no longer an issue to control and use. Further, I was forced to organize myself and find a good structure, since otherwise all the data and work I created while the internship would be lost. Sometimes I was facing real challenges with first no solution, but the experience during the internship showed me, that there is always a way to do it. Often a big frustration tolerance was needed to keep on certain task, but also these tasks are somewhen done. Beside of all the specialist knowledge I gained, the improvement of my English skills is also striking. The need to talk, read and write daily in a foreign language leads automatically to an improvement.

Moreover, I found for myself out that I am interested in the hydropower sector and even if my future may not be in the research sector, this finding was totally worth it. It´s an option for me to come back to the NTNU Trondheim for writing my Bachelor thesis or doing a master. Additionally, I found a direction in which my further studies can go. Finally, it was very good to experience the things I was working on while doing some fieldwork. Doing just the simulations wouldn´t be enough in my opinion, even more I am grateful that I had the chance to work outside the office.

Apart of all the new things I experienced at work, the time abroad enriched also my private life. New friends and international connection as well as a better knowledge about Norway and it´s culture are just parts of this half year. I was able to learn some Norwegian, which was a personal goal for me. All in all, the practical semester was a great success for me as a person and my personality. I wouldn`t hesitate to do it again like this.

At this point I wanted to thank my receiving organization, the NTNU Trondheim and the HydroFlex project for accepting me as an internship. Special thanks go to my supervisors in Norway Prof. Dr. Knut Alfredsen and Ana Juarez who supported me over the whole internship. Moreover, I wanted to thank Prof. Dr. Heidi Megerle for approving the internship and supporting me during the internship.

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