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Hydrodynamic modelling of physical habitat conditions for fish in the Ekso river near Flatekval

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Hydropower Development

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Abstract

In this study, a 2D hydrodynamic model HEC-RAS is used to simulate the flood inundation, water depths and flow velocities of the river reach in the Eksingedal watercourse near Flatekval in western Norway. The objectives are to simulate the water depths and flow velocities with different scenarios and to assess the effect of flood regulation on habitat quality of the brown trout. The data is pre-processed and post-processed in ArcGIS. The model is set up and calibrated from historical flow data as well as the flood inundation area of the drone image. In addition, the sensitivity analysis of various factors such as roughness values, mesh resolution and time steps are conducted. Based on the results from the 2D HEC-RAS model, the information about the suitable area for different life stages of the brown trout and the distribution of the different habitats are obtained. This area covers the requirements of water depth and flow velocity for fish of different life stages decreases after regulation. Based on literature review, other factors (for example shore vegetation, water temperature, water chemistry, fish food etc) that may have affected the fish population are also discussed.

Keywords: Hydrodynamic model, 2D-HEC-RAS, ArcGIS, River regulation, Brown trout

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1. Introduction

1.1 Background

The river regulation schemes will have the environmental effects and it is important to assess these impacts and utilize this information to do some mitigations. The development of hydropower influences the environmental condition in the affected rivers. The methods for assessing and mitigating impacts are important for planning and operation of hydropower. The availability of more precise data and new simulation provide new possibilities for impact assessment that can be used to establish effective management strategies. The SusWater project focuses on water management in regulated rivers and has studied the important river user interests in Norway. For the Hordaland case area, the river reach in the Eksingedal watercourse near Flatekval is identified as very relevant with respect to fish-related user interests. Because of the river regulation, the water quality, quantity, current conditions, substrate distribution and other relevant factors will change accordingly, which may have impacts on the population of the fish. There is a need to increase our understanding of the effect of hydropower development in Norwegian mountain-rivers on the physical habitat conditions of brown trout (*Salmo trutta*).

1.2 The objectives of the thesis

The main objective is to investigate physical habitat conditions for the brown trout before and after the river regulation by using the 2D HEC-RAS, in particular during high flows with the inundation of floodplain features. The detailed tasks are described as follows:

1. Literature review on habitat requirements of brown trout focusing on fish behavior (different life stages) during flood events.
2. Description of the study area and a brief summary of the theoretical background that related to hydrodynamic modeling.
3. Analysis of water level and discharge statistics (i.e. flood frequencies) before and after the regulation.
4. GIS-based preparation of data sets for river bathymetry/morphology, substrate, vegetation and waterlines.
5. Set-up and calibration of a 2D hydrodynamic model (HEC-RAS 2D) including pre-and

post-processing for the river reach upstream from Flatekval waterfall.

6. Model-based scenario investigations to assess the effect of flood regulation on the habitat quality and diversity (before/after regulation) based on the flood levels determined in task 3.

7. Analysis and discussion of modeling results with respect to habitat conditions for fish in cooperation with the fish experts.

1.3 Structure of the thesis

Chapter 2----Methodology of the study and study area description.

Chapter 3-----Hydrodynamic model.

Chapter 4----- Data preparation and methods.

Chapter 5---- Model set-up, calibration and scenario simulations.

Chapter 6---- Results.

Chapter 7----discussions

Chapter 8----Outlook.

1.4 The habitat requirements of brown trout in rivers and streams

The population and distribution of the brown trout are affected by the habitat condition. There are many factors that influence the habitat condition in a complex way. The important factors are depth, flow velocity, substrate and cover (Heggenes, 1990). This section is to review these variables and briefly summarize the influence of oxygen concentrations and temperature.

Habitat is considered within the categories: spawning, nursery, summer rearing, in-stream over-wintering and up-river migration stages of the life cycle.

1.4.1 Spawning habitats

Trout spawn during the autumn and winter months. Spawning occurs mainly between October and December and maybe last for a period of only 2 or 3 weeks. Brown trout in New Zealand spawned at a mean water velocity of 39.4 cm/s within a range 15–75 cm/s (Shirvell and Dungey, 1983). Trout in southwest Ontario spawned at a mean velocity of 46.7 cm/s within a flow range 10.8–80.2 cm/s. The variation between individual was due to fish size because larger fish can stand higher velocities (Witzel and MacCrimmon, 1983). The mean depth used by trout spawning in New Zealand was 31.7 cm (in the range 6–82 cm) (Shirvell and Dungey, 1983). In southwest Ontario, the mean water depths used by trout spawning was 25.5 cm (Witzel and

MacCrimmon, 1983). The ranges of substrate sizes used by brown trout were broadly in the gravel range 8–128 mm (Ottaway and Clarke, 1981; Chapman, 1988; Shirvell and Dungey, 1983). High oxygen concentrations were required for the development and survival of brown trout alevins (Eklov et al., 1999). A survey of redd sites of brown trout recorded oxygen concentrations >83% saturation (Witzel and MacCrimmon, 1983). Temperature has an important controlling influence in the spawning of salmonids and a direct effect on the survival of eggs and the rate at which alevins develop (Crisp, 1993, 1996). The mortality of trout ova was low (<5%) between 1 and 9°C or 10°C but increases as temperature rises (50% at 12°C and 100% at temperatures above 15.5°C) (Jowett, 1992; Crisp, 1993).

1.4.2 Nursery habitat

The nursery habitat is the area used during the first summer after hatching. Newly emerged brown trout prefer to live in the habitat with the water velocity of 0–20 cm/s using increasing velocities as they grow (Bardonnet and Heland, 1994). Small brown trout parr prefer to stay in the habitat with moderate velocities (20–50 cm/s) but move to deeper areas as they grow (Heggenes, 1996; Crisp, 1993). The optimal range of depth for YOY trout is 5–35 cm. When offered a choice of the substrate in artificial channels, YOY brown trout preferred the coarsest gravel substrate (50–70 mm diameter) (Heggenes, 1988b).

1.4.3 Rearing habitat

Parr may move from nursery areas during autumn and winter or continue to grow near where they are spawned (Rimmer et al., 1983, 1984). However, they use different local habitats as they grow. Mean velocities used by adult brown trout in southeast Norway were in the range 10–70 cm s⁻¹ (Heggenes, 1988a). In southeast Norway, adult brown trout preferred stream areas >50 cm water depth (Heggenes, 1988a). In Norwegian lacustrine environments, both Atlantic salmon parr and juvenile brown trout predominantly used the littoral and sublittoral zones, usually at depths of 0–6 m and occasionally at depths of up to 10 m and avoided pelagic zones (Halvorsen et al., 1997). Generally, brown trout occur at sites with large amounts of medium-sized (8–128 mm) substrate (Eklov et al., 1999). The oxygen requirements of fish depend on activity, feeding and temperature. However, the general level of survival is between 5.0 and 5.5 mg/l and the ideal degree of saturation is 80% (Crisp, 1993). A survey of 36 rivers

in Wyoming indicated that the productivity of trout was maximal at the summer temperatures between 12.6 and 18.6 °C (Binns and Eiserman, 1979).

1.4.4 Over-wintering habitat

Brown trout during winter days used significantly substrates in the range of 6.4–51.2 cm diameter. Heggenes et al. (1993) studied the behavior of brown trout in southeast Norway during winter. During the day, the smaller fish stayed in the substrate and the larger fish gathered in deep slow areas. At night, the fish started to move actively above or on the substratum. (Heggenes et al., 1993).

1.4.5 Habitat used during up-river migration

The cover is important for the adult fish during up-river migration, both as protection from predators and strong sunlight (Crisp, 1996). Temperature is another factor which influences the migratory activity of adult fish. The rate of upstream migration is influenced by low temperature (Gowans et al., 1999a, b) and increasing in temperature (Alabaster, 1990).

2. Methodology of the study and study area description

2.1 Methodology of the study

1. Define the factors that are particularly important in affecting the production of brown trout by literature review, find out the range of acceptable conditions for fish and select the factors that can be modeled by HEC-RAS.
2. Prepare the terrain data for 2D HEC-RAS by using the software ArcGIS.
3. Prepare roughness data by distinguishing and drawing different vegetation and substrate zones in AREGIS, then setting different roughness values in different zones.
4. Prepare flow data before and after the regulation.
5. Set-up, calibrate and run 2D HEC-RAS model with different flow conditions.
6. Compare the results with the range of acceptable conditions and discussions.

2.2 Study area description

2.2.1 Location and river regulation

The Eksingedalen River is located in Vaksdal Municipality, approximately 50 km NE of Bergen, in the western part of Norway. The study reach is in the middle part of this river near Flatekal. The Figure 2-1 shows the entire area of the study area. The study area consists of the main channel in the upstream of the waterfall (the white polygon in the bottom left corner of the figure), the lake called Ospetjørni (the black circle in the middle of the lower part of the figure) and the floodplain along the river banks. The study reach is indicated by the yellow line and the modeling reach is shown in blue line.



Figure 2-1. The study area.

The unregulated catchment for the Eksingedalen river is 410 km² and the mean annual

discharge is 34.2 m³/s. Note that the numbers are based on information extracted from EVE's online source "Nevina" and "NVE-Atlas". The main river regulation system in this river is the Evanger hydropower system. The map of the catchment with the river regulation system can be found in Figure 2-2. As we can see from the figure, the Eksingedal watercourse is regulated into two parts. The upper part of the watercourse is transferred to Evanger power plant in the neighbor watercourse Vosso. The water from lower part of the watercourse Nesevatnet is transferred through a tunnel to Myster power station. The concession of the project was granted in 1966. After several construction periods, the first abstractions to Evanger power station was in 1972 and the Myster power station started to work in 1987 (Fjellheim, 1999).



Figure 2-2. Map of the catchment with the river regulation system (Fjellheim, 1999).

2.2.2 Vegetation and substrate

The terrestrial vegetation in the study area mainly consists of woods, cultivated land. The areas along the river are commonly dominated by the common type of the riverbank vegetation, such as small-reed and other grass species. In the river itself, the mosses constitute the greatest part of the flora in fast flowing area, while other dominated vegetation are floating bur-reed (*Sparganium angustifolium*), water horsetail (*Equisetum fluviatile*) and bottle sedge (*Carex*

rostrata). The typical vegetation for the study area can be found in Figure 2-3. We can see from the figure that the willows and Calamagrostis are located at onshore, the Carex is represented by light green and Equisetum fluviatile is shown near the water. The floating bur-reed is often observed near stones and boulders. The water horsetail occurs in different density, it is very sparse in deeper zones, while it is dense in shallow zones. The bottle sedge can be discovered in the shallow place close to the shore. The typical water depth of the bottle sedge is around 0.3m during the growing season.



Figure 2-3. Typical vegetation: Willows/Calamagrostis (onshore), Carex (light green) and Equisetum fluviatile (near water).

The main substrate for the study reach is the gravel with some vegetation. In the low energy sites, the river bed is covered with the fine or sand. At a few locations, the large boulder can be found. The figure about the detailed distribution of the substrate is illustrated in Appendix 2. The figure is made in ArcGIS by identifying different substrate from the aerial image (drone image). We can tell the substrate type from the corresponding ID number shown in Appendix 2 for this study reach.

3. Hydrodynamic model

3.1 Overview of hydrodynamic model

Hydrodynamic modeling is an efficient and comprehensive method to represent water dynamics. These are numerical computational models, which can be used to simulate currents, water levels, sediment transport and salinity. The objective of this thesis is to make maps of water surface level, flow velocity and flood inundation area for the study area.

The flood maps can be generated by using different methods. Until now, most applications for one dimensional (1D) flood extent modeling use the approximation or full treatment of Saint Venant Equations to represent the movement of the flow (e.g. with MIKE 11, HEC-RAS), then the equations can be solved by numerical solution techniques. In the end, flood maps are simply derived from the projection of water levels on digital elevation model (DEM). 1D methods will only give a partial and limited representation of the complex processes. It is not suitable for wide and flat floodplains because the flows go into the overbank area and the water will take multiple flow paths and have varying water surface elevations and velocities in multiple directions. Additionally, the 1D method cannot obtain detailed velocities for the hydraulics of flow around an object.

Using of 2D models is most likely to obtain the best result of flood extent mapping (e.g. with MIKE 21, TELEMAC-2D, 2D HEC-RAS). They can represent complex floodplains topography, dynamic wetting and drying of the floodplain (Horrit et al. 2007). The 2D approaches require a large amount of data and significant computational time. A 3D method is also a possible option. Zinke et al. (2010) successfully applied the SSIIM 3D unsteady hydraulic model to simulate the discharge distribution within the Øyeren delta.

3.2 2D HEC-RAS model

HEC-RAS (Hydrologic Engineering Center's River Analysis System) is a useful software for hydraulic simulation and analysis. The software is developed at the Hydrologic Engineering Center (HEC), which is a division of the Institute for Water Resources (IWR), U.S. Army Corps of Engineers. HEC-RAS is capable of performing 1D and 2D hydraulic computation, sediment transport simulation, water quality and temperature modeling.

3.2.1 Equations for the model

The mass conservation and the momentum conservation are the main laws, which control the

water flowing in the channel. The 2D-unsteady HEC-RAS use the Shallow Water equation (SW) and the sub-grid bathymetry mass conservation equation to describe the motions of water.

Mass conservation equation

The sub-grid bathymetry mass conservation equation is shown below:

$$\frac{\Omega(H^{n+1}) - \Omega(H^n)}{\Delta t} + \sum_k V_k \cdot n_k A_k(H) + Q = 0, \quad (3.1)$$

where $\Omega(H)$ represents a finite volume cell, as a function of water elevation n , $n+1$ is the time-step, Δt is the difference between two consecutive time-steps, V_k and n_k are the average velocity and unit normal vector at face k , $A_k(H)$ is the area of face k as a function of water elevation and Q represents any flow that crosses the surface of the cell.

Momentum equation

Based on Newton's Second law, the momentum equations are developed, known as shallow water equations:

$$\frac{\partial u}{\partial t} + u \frac{\partial u}{\partial x} + v \frac{\partial u}{\partial y} = -g \frac{\partial H}{\partial x} + v_t \left(\frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial y^2} \right) - c_f u + fv, \quad (3.2)$$

$$\frac{\partial v}{\partial t} + u \frac{\partial v}{\partial x} + v \frac{\partial v}{\partial y} = -g \frac{\partial H}{\partial y} + v_t \left(\frac{\partial^2 v}{\partial x^2} + \frac{\partial^2 v}{\partial y^2} \right) - c_f v + fu. \quad (3.3)$$

Note that u and v are the velocities in the Cartesian directions, g is the gravitational acceleration, v_t is the horizontal eddy viscosity coefficient, c_f is the bottom friction coefficient, R is the hydraulic radius and f is the Coriolis parameter.

In some shallow flows, the dominant forces are gravity and the bottom friction. The momentum equation can be replaced by the two-dimensional form of Diffusion Wave Approximation. Combining this equation with mass conservation will result in one equation model, which is named by the Diffusive Wave Approximation of the Shallow Water (DSW) equations shown by

$$\frac{\Omega(H^{n+1}) - \Omega(H^n)}{\Delta t} + \sum_k \alpha \nabla H \cdot n + Q = 0, \quad (3.4)$$

where

$$\alpha = \alpha(H) = \frac{(R(H))^{\frac{2}{3}} A_k(H)}{n |\nabla H|^{\frac{1}{2}}}. \quad (3.5)$$

$\Omega(H^n)$ is the cell volume at time n , $A_k(H)$ is the area of face k , as functions of water elevation.

3.2.2 The 2D HEC-RAS modeling methodology

The 2D HEC-RAS has two equation sets that can be used to describe the water flowing over the computational mesh, the Diffusion Wave equations and the Shallow Water equations. The 2D model simulates the water depth and the velocities on the 2D flow area. The 2D flow area is constructed by the computation meshes. The computational meshes can be triangle, square, or even five and six-sided element, different mesh resolutions can be applied to different areas following the requirements and the nature of the study. After the mesh has been created, 2D flow area pre-processor processes the cell and the cell face into detailed hydraulic property tables based on the underlying terrain used in the modeling process. The mesh will, therefore, represent the terrain at a defined spatial resolution. The 2D flow area needs to be connected with the boundary conditions. Then the 2D unsteady flow equations solver uses an Implicit Finite Volume algorithm to obtain the water level and the flow velocity for the cells.

3.2.3 Limitation of the 2D HEC-RAS

The main objective is to model the factors that have an effect on the habitat condition of the brown trout; the main factors are water depth, water velocity, sediments and water quality etc. However, in the current version, the 2D HEC-RAS cannot perform water quality modeling and the sediment transport modeling in 2D flow areas.

The 2D HEC-RAS can only model a few factors. There are still other factors which could not be modeled but have a close relationship with the population of the brown trout.

4. Data preparation and methods

4.1 Data preparation in ArcGIS

Before importing the data into HEC-RAS, we need to handle the data in ArcGIS. ArcGIS is a geographic information system, which has different applications and can be used for data collection and preparation. It is also a useful tool for presenting and analyzing spatially represented data. The data is pre-processed and post-processed with the help of the ArcGIS 10.5.

The data are provided by my supervisor Dr. Peggy Zinke. The data includes the DEM, ADCP and GPS data and the drone image.

4.1.1 DEM

Digital elevation model (DEM) is a 3D representation of a terrain's surface. The DEM can be represented as a raster (a grid of squares,) or as a vector-based triangular irregular network (TIN). The DEM below we used for this study is a raster data and the grid size is 1×1 m. The DEM includes the study area is shown in Figure 4-1. The difference in the darkness indicates the different elevation values and the regions with light color represent the regions with the higher elevation. Notice that the DEM for the study is from the State Map Agency.

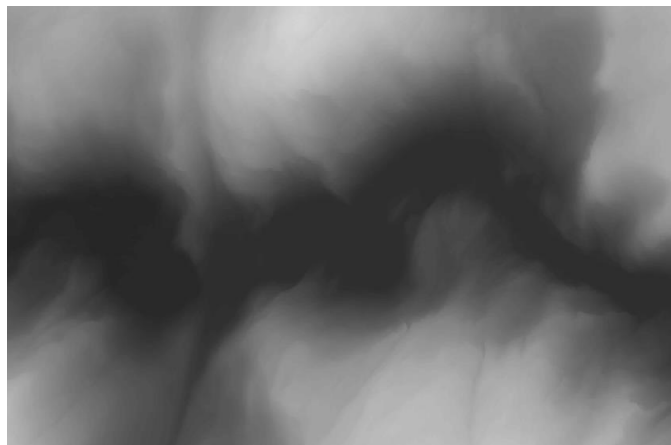


Figure 4-1. The DEM includes the study area.

4.1.2 ADCP

Acoustic Doppler Current Profiler (ADCP) is a hydroacoustic current meter, which use the Doppler effect of sound waves to measure the water depth. The ADCP data we need were measured and collected from 12.July 2017 to 14.July 2017. The distribution of ADCP data is

shown in Figure 4-2. We can see from the figure that distribution of the ADCP points are so dense that looks like black lines.



Figure 4-2. The distribution of ADCP data

4.1.3 GPS

GPS is a device which can receive information from GPS satellites and calculate the geographical position of the device. The GPS data were collected during July 2017 by my supervisor and her master student. The table below (Table 4-1) is a part of attribute table for the GPS data. The z is the elevation of the measured point.

FID	Shape	Code_Name	M-Ref	E	N	Z	Dev
0	Point	WL	GPS0001	334058.062	6742643.602	296.22	0.026
1	Point	WL	GPS0003	333872.542	6742487.339	280.97	0.103
2	Point	WL	GPS0004	333872.493	6742487.301	280.97	0.041
3	Point	WL	GPS0005	333870.599	6742487.052	281.01	0.067
4	Point	WL	GPS0006	333870.605	6742487.082	281.02	0.068
5	Point	WL	GPS0007	333870.651	6742487.069	281.02	0.054
6	Point	WL	GPS0009	333878.584	6742487.631	280.99	0.043
7	Point	WL	GPS0010	333890.099	6742489.539	281.00	0.034

Table 4-1. Attribute table of the GPS data

4.1.4 Drone Image

Drone is the device used for aerial photography with the high flying camera that used to capture a unique view of objects. The drone image clearly shows the distribution of the vegetation and the substrates. The drone image is collected by C. Haas during 8th July 2017. The figure (Figure 4-3) below is the drone image which covers the main part of the study area. The image does not include the Ospetjørni lake.



Figure 4-3. Drone image for the main part of the study area.

4.2 Flow data preparation

4.2.1 Regulation periods for Ekso

The river is unregulated before 1972. In 1972, the water from upper Ekso catchment was first abstracted to Evanger power station. In 1987, the water from lower part of the catchment was transported to the Myster power station, it caused no changes in discharge in the study reach but the gauge station Nese was closed. The Nygård pump storage plant started to work in 2005. The table below (Table 4-2) is the main information for the regulation periods.

Time	Regulation condition	Data resource
Before 1972	unregulated	Nese 1909 – 1972
1973 – 1986	Regulation period 1	Nese 1973 – 1986
1987 – 2005	Regulation period 2	No data available
After 2005	Regulation period 3	Vegaskiftet 2011-2018

Table 4-2.Regulation periods for the Ekso catchment

4.2.2 Gauge information

The data we used for the flood analysis is from the Nese gauge station. we get some more data for another measurement site from BKK (Vegaskiftet 2011-2018), but there is no time to analyze it. There is also more data from other measurement stations further away, which potentially could be used for estimating discharges at our site. Here we only analyze the design flood for the period before river regulation and for the regulation period 1. The figure below (Figure 4-4) is the location of the gauge station.

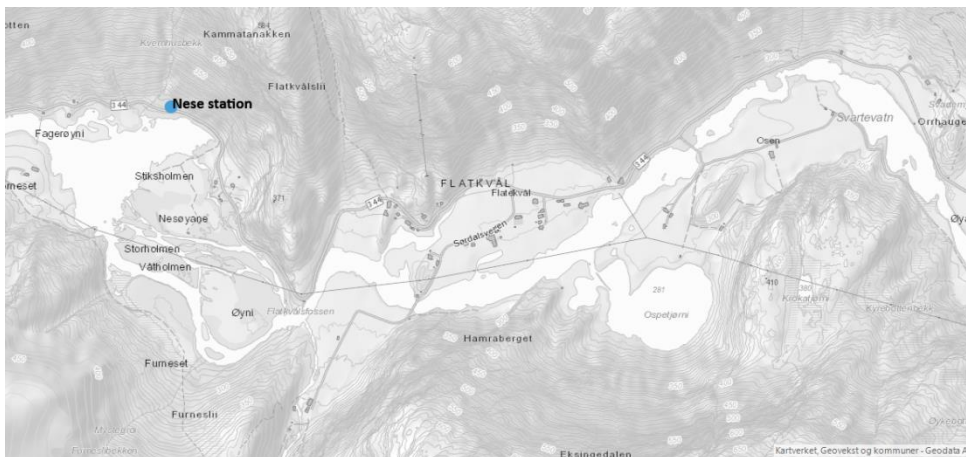


Figure 4-4. The location of the Nese gauge station.

4.2.3 Flood analysis methods

We use the graphical method and frequency factor method to analyze the flood frequency (Dingman, 2015).

4.2.3.1 Graphical methods

The detailed process of Graphical methods is explained below:

Step 1: Pick the annual maximum flow value.

Step 2: Sort the data in descending order.

Step 3: Rank the values with the highest as rank 1 and the lowest as rank n , note that n is the number of the values.

Step 4: Using the formula equation below to calculate the probability of each flood,

$$p(q) = \frac{1}{T} = \frac{m}{n+1}, \quad (5.1)$$

where p stands for probability, T is the return period, m is the rank, n is the number of values.

Step 5: Plot the data on the probability paper.

Step 6: Extrapolate the needed return period.

4.2.3.2 Frequency factor method

Use the following equations to calculate the T-year flood,

$$X_T = M + K_T \cdot \sigma, \quad (5.2)$$

$$K_T = -\frac{\sqrt{6}}{\pi} \left[0.5772 + \text{Ln} \left(\text{Ln} \left(\frac{T}{T-1} \right) \right) \right], \quad (5.3)$$

where X_T is the T-Year flood, M is the mean annual flood, K_T is the frequency factor and σ is the standard deviation of the flood series.

5. Model set-up, calibration and scenario simulations

5.1 Terrain model

The DEM (digital elevation model) includes the information about the elevation of the ground that is the main resource to generate the terrain of the study area but it cannot reflect the real bathymetry of the river. In another word, the terrain data does not include the actual terrain underneath the water surface in the channel region. So the main idea behind the method is to replace the DEM data in the channel region with the new elevation data, which are generated from ADCP, GPS and the drone image.

The ADCP contain the depth of the water and the riverbed elevation data that can be obtained by using the water surface elevation minus the water depth. The GPS data have already contained the information about the elevation of the ground. The drone image shows the distribution of the vegetation. We can infer the depth of the water according to the characteristic of the vegetation habitat requirement.

The following is the explanations about how to include a channel in a terrain model using ArcGIS.

5.1.1 Get the elevation data from ADCP

Here are the steps about how to get the elevation data from ADCP:

Step 1: Open ArcMap and use the import button to add ADCP files to the view. After that the main window will show the figure below (Figure 5-1).

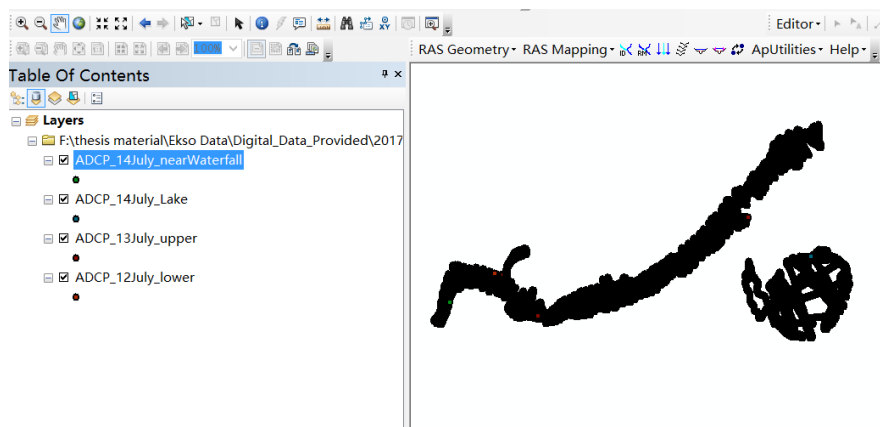


Figure 5-1. ADCP data shown in the main window.

Step 2: Set the projection system.

Check if the shapefiles of ADCP have the project coordinate system where the projection is already set. The projection system is “**ETRS89_UTM_zone_32N_N_E**”.

Step 3: Calculate the bed levels based on the water depth data for each point.

The study is used a mean water level of 280.9 m so the elevation of the river bed is equal to 280.90 minus the water depth. The reason why this thesis uses a constant water level is that the slope along the river reach during the measurement period is very low and can be neglected. The water levels do not change very much (+- 5-7 cm) compared to the water depth during the survey period. The detail process for calculating the elevation of the river bed is described in Appendix 5-1.

5.1.2 Elevation get from GPS

The GPS data includes some points, where the elevations referred to the water level and not to the ground level. Therefore, these points should be selected and deleted accordingly. The detailed procedure is described in Appendix 5-2.

5.1.3 Get elevation from vegetation type

There exist some regions without ADCP or GPS data. In order to develop a good terrain model, a solution is needed. First, based on the observed vegetation type in the study area and their habitat characteristic, the typical water depth of vegetation can be defined. Next step is to use the mean water surface elevation minus the water depth and the bed level can be calculated accordingly.

The main vegetation types in the study area are described in Appendix 1. Appendix 1 includes two tables that are provided by my supervisor and the information was gained during the fieldwork in July 2017. Appendix 1-1 describes the main vegetation type, typical impression in drone image and the typical water depth for the vegetation. Appendix 1-2 is the information about the locations of vegetation and substrate.

Based on this information, the vegetation type can be defined. The figure below (Figure 4-6) is the result. Different colors of the polygons indicate different vegetation type. The Water horsetail is shown in light green color. The orange polygons represent sedge. The pink color indicates the bur-reed.

Estimate the water depth for different zones according to different vegetation habitat

requirements for water depth in order to calculate the bed level for different vegetation zones.



Figure 5-2. The distribution of the vegetation.

5.1.4 Generate water lines

In order to improve the output of the terrain result, we need to draw the water line, the detailed The detailed procedure is described in Appendix 5-3.

The contour lines of the bed level for the channel region are shown in Figure 5-3.

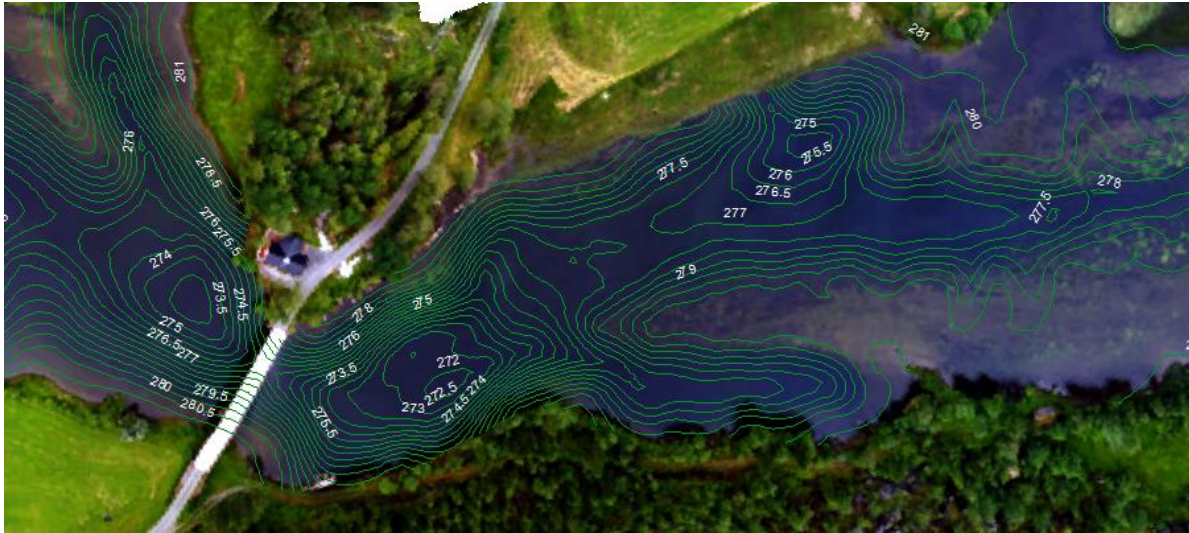


Figure 5-3. Contour lines for the channel region.

5.1.5 The elevation point from DEM

The original DEM includes a large area, which is outside the study area and does not reflect the real terrain underneath the water surface in the river channel. So it needs to be clipped. After clipping the original DEM, we need to convert the raster to shapefile (point). The detailed process is described below.

Step 1: Define the area of the DEM that we use. There are two shapefiles provided by the supervisor, one is the shapefile of the study area and the other one is the shapefile of the area covered by water (the shapefile of the area covered by water is from the State Map Agency). Figure 5-4 below shows the two shapefiles. The pink area is the water surface area, the blue area is the study area. The main idea is to copy the shape of the water area and paste it into the shapefile of the study area, then use clip tools in editor toolbar to discard the intersect. After all the steps are applied, we can get the shapefile of the DEM that we needed shown in Figure 5-5.

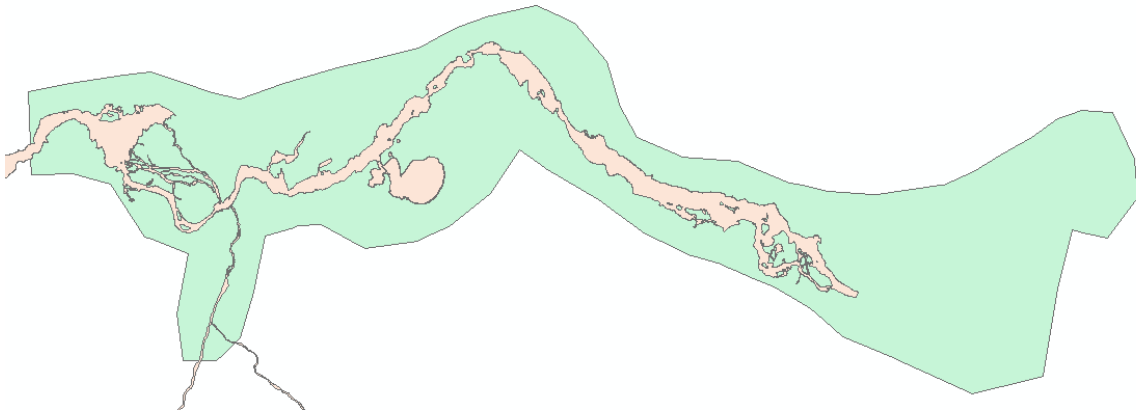


Figure 5-4. The study area and water-covered area.

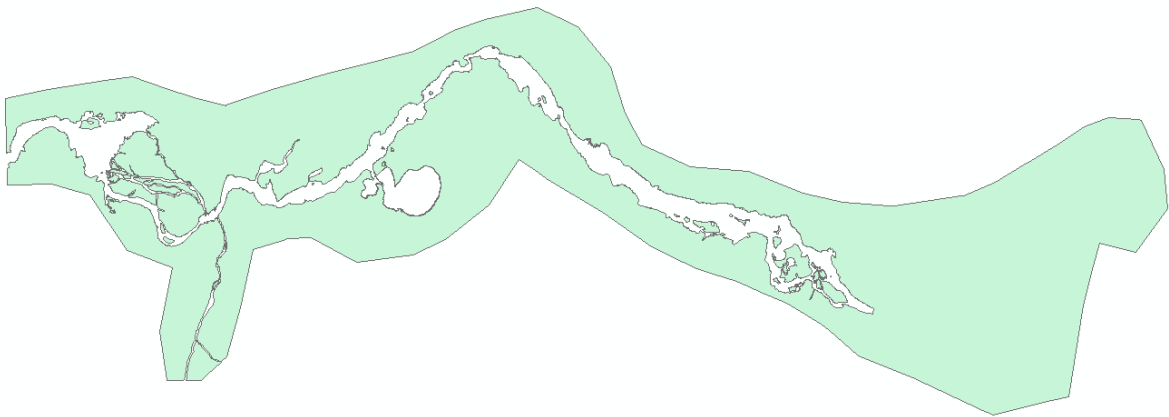


Figure 5-5. The shapefile of the DEM needed.

Step 2: Clip the DEM raster and convert the DEM Raster to point.

5.1.6 Create the terrain model

Merge all the point data (ADCP, GPS, VEGETATION, WATER LINE POINT, CLIPPED DEM) that we have made before and use Geostatistical Analyst to create the terrain model.

The detailed steps about how to create the terrain model is described in Appendix 5-4

5.2 Set up the 2D HEC-RAS model

It is straightforward to use the HEC-RAE to perform 2D simulation. A summary of the main steps developing 2D HEC-RAS model is shown in Table 5-1. After setting up the model, the calibration and verification of the model are conducted. The sensitivity analysis of the mesh resolution and roughness are performed. The Optimized model parameters are obtained from the calibration. In the end, different scenarios are simulated based on the calibrated parameter.

Step	description
1	Import the terrain model into HEC-RAS.
2	Import land classification data into HEC-RAS Mapper and set Manning's n values.
3	Draw the boundary of 2D Flow Area.
4	Generate the 2D computational mesh for 2D Flow Area.
5	Add boundary condition data.
6	Set 2D Flow Area computational options and perform the unsteady flow simulation.
7	View the result in RAS Mapper

Table 5-1.The main steps developing 2D HEC-RAS model.

5.2.1 Input parameters

5.2.1.1 Terrain layer

The terrain model is created in ArcGIS. The terrain model is shown in the figure below (Figure 5-6) after importing into the HEC-RAS.

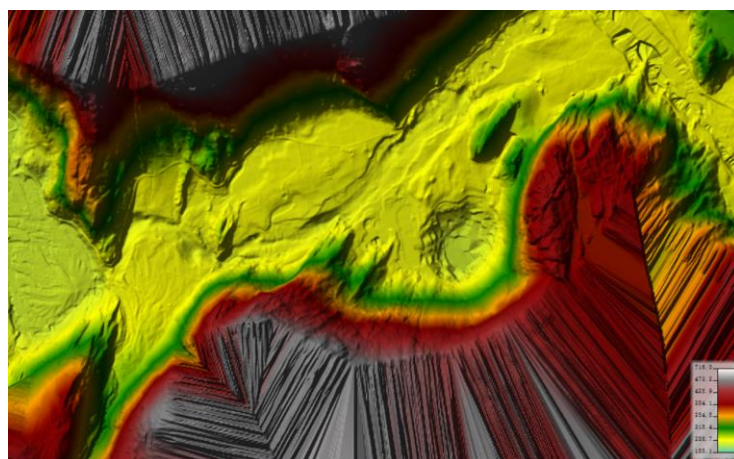


Figure 5-6.The terrain model for the study area.

5.2.1.2 Manning's Roughness Layer

In the current version of HEC-RAS, the land use layer can be imported in both polygon

(shapefile) and gridded formats. For this study, the land use information is in polygon formats. Land use data from State Map Agency (AR5) is used as the base land use coverage data for the entire study area. More accurate land cover map for the river channel has been created in ArcGIS. The detail process about how to create it in ArcGIS is described in Appendix 2. By setting the more accurate shapefile as the higher priority, the land use from the accurate shapefile will be used for the river channel and the base land cover data will be applied to the other areas.

After importing the land cover data, the Manning's n value for each Land Cover type can be set. In order to set the spatially varying roughness within HEC-RAS, we need first go to RAS Mapper, then select New Land Cover from the Tools menu. The Land Cover Layer window will break into three sections: Input Files, Selected File Land Cover Identifiers and Output File. Manning's n value for each Land Cover type can be entered from the Output File section. The values used in this study are determined by using Manning's n table (Chow, 1959). The tables below (Table 5-2 and 5-3) are the detailed information about the roughness values that we have estimated for the main channel and the entire study area.

No	Type	Manning's n
1	cultivate land	0.04
2	forest	0.11
3	grassland	0.04
4	living	0.09
5	open land	0.045
6	road	0.025
7	surface soil	0.025
8	swap	0.04
9	river channel	0.035

Table 5-2. Manning's n values for the entire study area.

No	Type	Manning's n
1	bedrock	0.02
2	large boulders	0.045
3	vegetation	0.04
4	gravel	0.03
5	gravel,stone	0.04
6	mud with vegetation	0.025
7	stone with moss	0.045
8	sand,fine	0.026
9	gravel with little vegetation	0.032
10	stone, gravel covered by fine and vegetation	0.042
11	gravel,sand,fine	0.042
12	gravel with some vegetation	0.035
13	sand,fine with vegetation	0.028
14	boulder with vegetation	0.05
15	mud	0.022

Table 5-3. Manning's n values for the river channel.

5.2.1.3 2D Computational Mesh

Resolution of the mesh plays an important role. The best mesh resolution should with the higher

resolution and needs less computational time. The method about how to create the 2D computational mesh is described below.

2D flow area must be added by using the 2D flow area drawing tool in the Geometric Data editor. The 2D flow area defines the boundary where the computation will be conducted. The computational meshes (or computational grid) are created within the 2D flow area. To create a 2D flow area computational mesh, we select the 2D Flow Area editor button on the left panel of the Geometric Data editor. The figure for 2D flow area with the computational mesh after applying the procedure described above is shown in Figure 5-7.

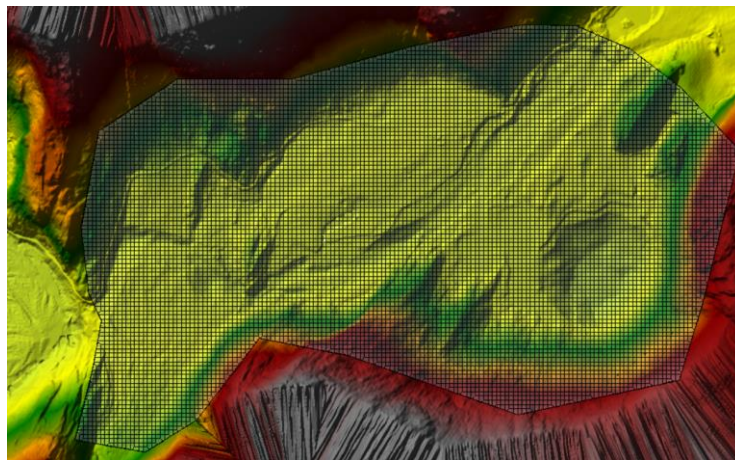


Figure 5-7. 2D flow area with computational Mesh.

5.2.1.4 Boundary Conditions

To add external boundary conditions to a 2D flow area, click the button called **SA/2D Area BC Lines** and draw the lines along the outer boundary of the 2D area boundary condition. Then go to **Unsteady Flow Data editor** and select boundary condition type for the boundaries. Flow hydrograph is usually selected as an upstream boundary condition and stage hydrograph is used to define the downstream boundary condition. In our case, we only conduct steady flow calculation. For the case without observed stages, the normal depth boundary condition is an option. When using the normal depth boundary condition, the Friction Slope is required to compute a normal depth.

5.2.2 Performing the Computations

After adding all necessary data and associating the geometry files with the terrain layer and any Land Cover Layer, the model is ready for computation.

To run the model, open the Unsteady Flow Analysis window, select the geometry and an

unsteady-flow file and other computational settings. Then press the Compute button to begin the run.

Once a good computational mesh is created, an appropriate computational time step needs to be selected. The computational time step is a function of the cell size and the flow velocity. The guidelines for deciding a computation time step is described below.

Shallow Water Equations:

$$c = \frac{V\Delta T}{\Delta X} \leq 1.0, \quad (5.1)$$

where C is the courant number, V is the flood wave velocity(m/s), ΔT is the computational time step(s) and ΔX is the average cell size(m).

Diffusion Wave Equations:

$$c = \frac{V\Delta T}{\Delta X} \leq 2.0. \quad (5.2)$$

5.3 Calibrate the 2D HEC-RAS model

Before using the 2D HEC-RAS model for the application, we need to calibrate it. In another word, we need to adjust parameters of the 2D HEC-RAS model until the model can reproduce observed data to an acceptable accuracy. In our case, we need to calibrate the model in two specific flow conditions.

5.3.1 The methods for calibration

The following is the process for calibration.

1. Add all input parameters.
2. Run the computation.
3. Compare the result of inundation area with the water area in drone image.
4. Compare the computed water surface elevation or water depth with observed data.
5. Modify the terrain or other parameters until a good reproduction is obtained.

5.3.2 Calibration in low flow condition

For this case, the discharge for calibration (12 to 15 July 2017) is 5.8 m³/s. This is the average

value of two ADCP-transect measurements that were undertaken on 12 July approximately 360 m upstream from the waterfall. For the downstream boundary condition at the waterfall, we use the measured water level of 280.84 m.a.s.l. as “stage hydrograph”. The modeling result of water depth is shown in Figure 5-8.

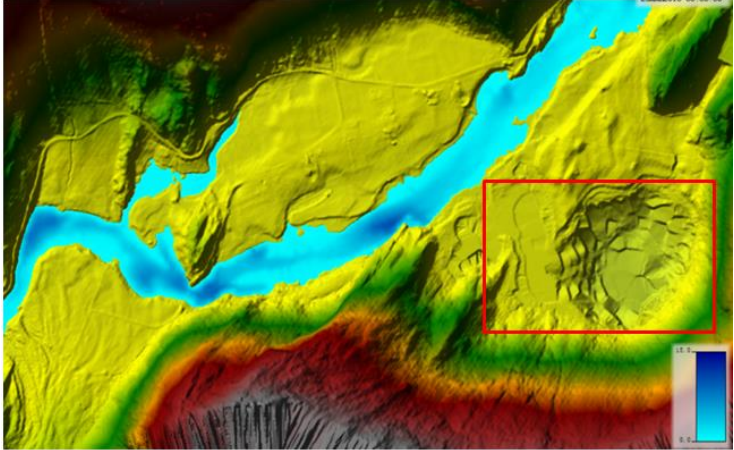


Figure 5-8. The modeling result of water depth.

It shows the result of the water depth of the inundation area within 2D flow area. The difference in the darkness of the blue indicates a difference in the water depth. The highlight region is a lake called Ospetjørni, it should be covered with water in this flow condition. Because of lacking in depth data of the lake inlet, the terrain here is interpolated by the elevation in the surrounding. The terrain is a bit higher than reality so the terrain needs some modification. The detailed process to modify the terrain is described in Appendix 5-5.

After modifying the terrain, load the new terrain and run the computation again, then the result is obtained and shown in Figure 5-9 below.

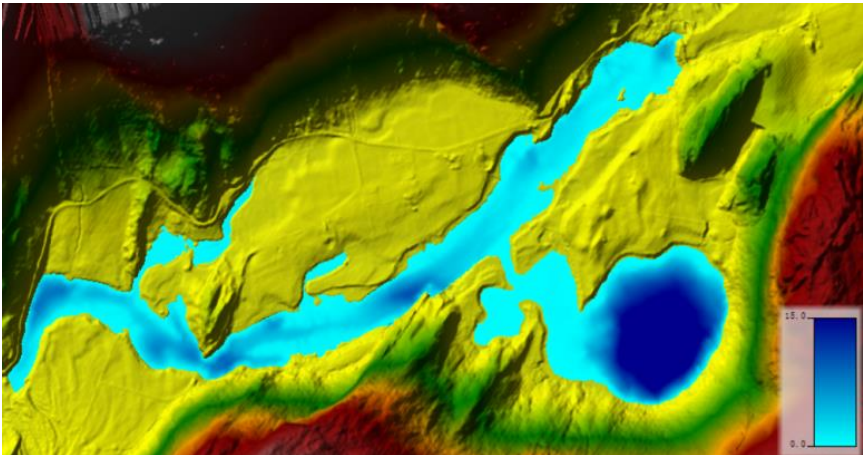


Figure 5-9. The modeling result of water depth with modified terrain.

Models with different roughness sets and different mesh resolutions are also conducted to get

a better model result. The detailed process and the influence to the result are described in next section (5.4 Sensitivity analysis).

Here is the result of the model with the detailed roughness set for the main channel. The mesh resolution is 10×10 m. In order to assess the modeling accuracy, the calculated water-covered area and the digitized water-covered area from the drone image for the field conditions in July 2017 need to be overlapped with each other.

The inundation boundary computed by the 2D HEC-RAS is shown in Figure 5-10 below.

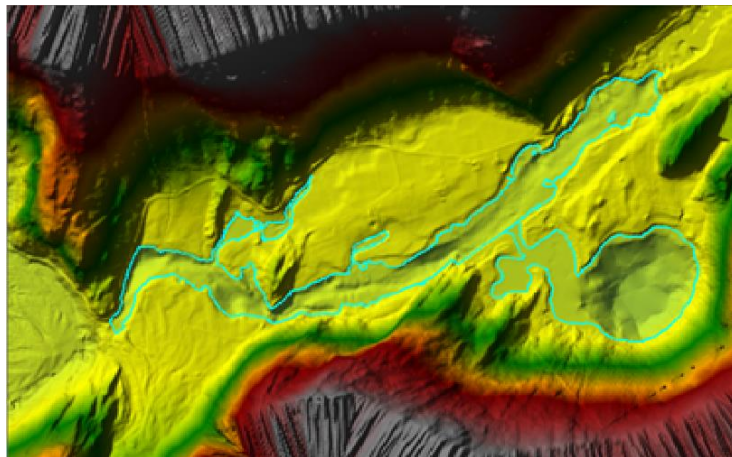


Figure 5-10. The inundation boundary.

After adding the inundation boundary layer and the digitized water-covered area into ArcGIS, the figure (Figure 5-11) below will display. The red color is the water covered area and the yellow one is the computed inundation area.



Figure 5-11. The comparison of the observed and computed water-covered area

Figure 5-11 shows that the two layers overlap well with each other. The red area is 214936 m² and the yellow area is 198892m². The difference between them is about 7.46 %.

Next, the observed and modeled water surface elevations are compared. As we mentioned

before, we assume a mean water surface elevation of 280.90m.a.s.l for the entire study reach. The computed mean value is 280.848m.a.s.l, the minimum is 280.840m.a.s.l, the maximum is 281.302 and the standard deviation is 0.025.

5.3.3 The flood condition

Another flow condition we simulated is the flood in 1971. We use the observed maximum discharge as the upstream boundary condition with the discharge is 310m³/s. For the downstream boundary condition, the friction slope of 0.002 is used to calculate the normal depth. The friction slope is roughly estimated by using water surface difference in the study reach, which is divided by the length of the study reach. The terrain used is the modified terrain and the mesh resolution is 10×10 m. The resulting map of the water depth is obtained after putting all in necessary data and running the model.

To evaluate the accuracy, some comparison is required. First, we check whether the computed inundation area is coincident with the area description of the local people or not. Secondly, the computed water depth and the observed water depth are being compared for a few points.

The figure below (Figure 5-12) contains the main information that can be utilized for validation of the model result. The location 1 and location 2 are in the middle of the road and the average water depth is around 15cm and 10cm, respectively. But the ground elevation for the two locations may be changing because of the road construction. Location 3 is near a small bridge. According to the description of the local people, the water depth during this flood is above bridge up to the knees and 0.6 m of the water depth is assumed. Location 4 is the boundary of the flooded area, water depth is around 0 m since all the information are used for evaluating the model accuracy, therefore, it may cause the evaluation is not good enough.

Location	Description of the local people for the flood
1	10-20cm above the road, average 15cm
2	10cm above the road
3	above bridge up to the knees
4	the boundary of the flooded area

Table 5-4. Description of the local people about the flood in 1971



Figure 5-12. Information about water levels that have been observed during large floods (position approximately).

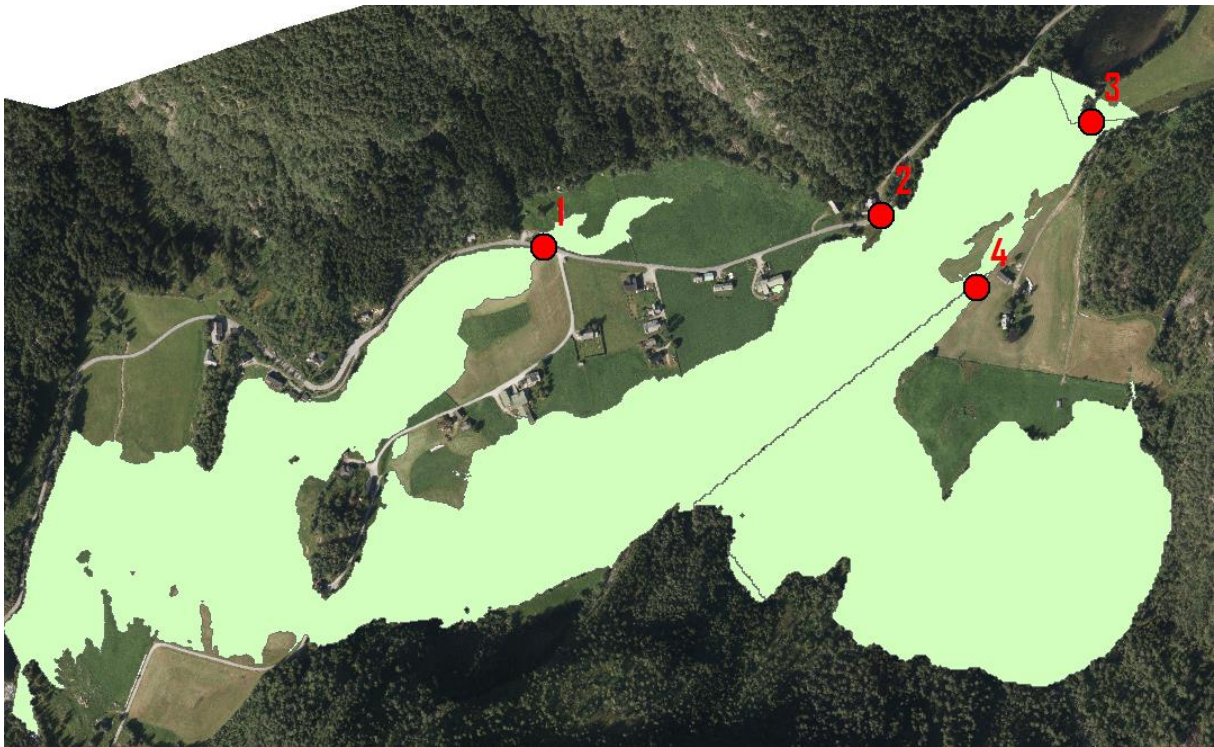


Figure 5-13. The simulated inundation area for the flood in 1971.

The computed inundation area for the flood in 1971 is shown in Figure 5-13. The area covered location 3 and the edge of the computed inundation area is passed by the location 4 while does not covers the point 1 and point 2. The reason for this may be because that the terrain

around location 1 and 2 we modeled are not represented by the terrain in the 1970s. During these years, the terrain has changed a lot while the detailed elevation in the 1970s for the two locations is unknown so the terrain is not modified. Instead, the computed water depths of the points located beside these two locations are used to compare with observed water depths. The Table 5-5 is the water depths for these four locations. The observed and simulated water depth for 4 different locations is shown in Figure 5-14. The tendency of the calculated average water depth for 4 different locations can be matched with the observed water depth, which indicates our simulation is accurate in general.

Location	Calculated water depth (m)	Calculated Average water depth(M)	Observed water depth(m)
1	0.12,0.34,0.43,0.61,0.53,0.58	0.43	0.15
2	0.48,0.31,0.21,0.38,0.1	0.29	0.1
3	0.34,0.88,0.53,0.39	0.54	0.6
4	0.05,0.22,0.26,0.07,0.12,0.003	0.12	0

Table 5-5. The water depth for 4 different locations.

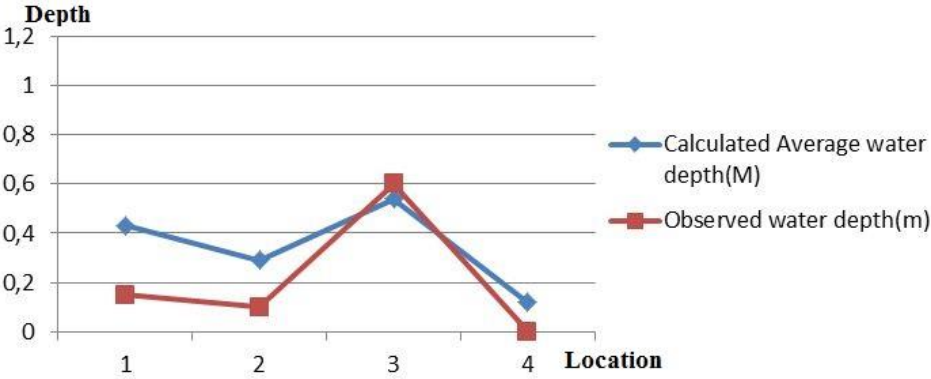


Figure 5-14. Observed and simulated water depth for 4 different locations

5.4 Sensitivity analysis

Sensitivity analysis is performed simultaneously as the calibration. The purpose is to obtain optimum parameters for simulation. When one parameter is being analyzed, the other parameters should be fixed. The influence on the model response from three parameters: roughness, mesh resolution and time steps are being investigated.

5.4.1 Parameters

5.4.1.1 Roughness

The modeling result is affected by roughness. In order to evaluate the effects, different roughness value for one specific region is applied. For the study reach, the bed is covered with gravel in the most part of the river, so we set a single roughness value of 0.035 for the main channel. The second roughness set for the main channel is described in Table 5-6: The main channel is divided into different substrate zones with different roughness values. For the floodplain, the values for two roughness sets are the same.

roughness set	description
roughness set 1	a single roughness value for the main channel.
roughness set 2	different roughness values for the main channel

Table 5-6. Description of two roughnesses set.

5.4.1.2 Mesh resolution

The effect of mesh resolution on the predictions of the 2D unsteady hydraulic model is assessed in this study. Four different mesh grids of different spatial resolutions are created to evaluate the impact of mesh resolution. The four different type of mesh grids are described in the table below (Table 5-7).

Mesh type	1	2	3	4
Cell size(m×m)	2×2	5×5	10×10	20×20
Number of cells	280778	44781	11157	2757
Max. Area [m ²]	9.19	45.22	194.51	678.25
Min. Area [m ²]	3.04	19.18	9.41	328.19
Avg. Area [m ²]	4.01	25.13	100.87	408.21

Table 5-7. Description of various mesh resolution.

5.4.1.3 Time steps

The selection of the computational time steps is decided by the mesh resolution and the flood velocity. The inappropriate time step will influence the model stability. Here is the example to explain the responses of the model with different time steps shown in Table 5-8.

example	flow condition	roughness	Mesh cell size (m×m)	Time step (s)
1-1	Flood in 1971	roughness set 2	10×10	30
1-2	Flood in 1971	roughness set 2	10×10	10

Table 5-8. Description of models with a different time step

One can see from the table above, the main difference between the model sets here is the time step. To ensure the stability of the mode, the Courant number should be less than 1.0, which means that the time step should not be larger than the ratio between the mesh cell and the flow velocity. The average cell size is 10 m and the velocity is around 1.0 m/s, so the time step cannot larger than 10s.

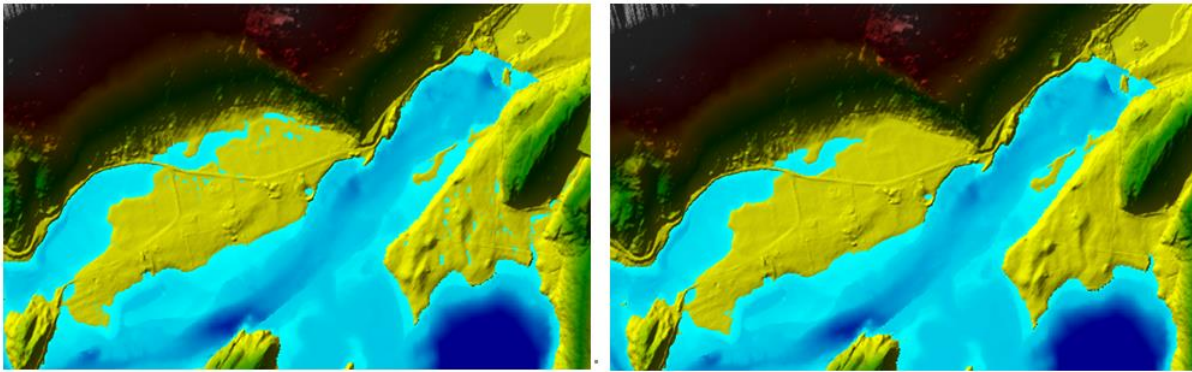


Figure 5-15. The comparison of the model stability with different time steps

The comparison of the model stability with different time steps is shown in Figure 5-15 left and right, respectively. We can see from the figure that the figure in the left is the map of water depth with a time step of 30 seconds. This model run fast and the total computational time is only 58 second while the stability of this model is not good enough and there exists many fragments. On the contrary, the stability of the model is good without any fragments in the right figure (Figure 5-15, right). The time step for this model is 10 seconds and the total computational time is 4 minutes.

5.4.2 Low flow condition

The root mean square error (RMSE) is the tool to evaluate the responses of the model to the change in parameters in low flow condition. The RMSE describes the differences between values computed by a model and the values observed are defined by

$$RMSE = \sqrt{\frac{1}{N} \sum_{i=1}^N (C_i - O_i)^2}, \quad (5.3)$$

where N is the number of data points, C is the computed values and O is the observed values. We applied a water level of 280.90m for the entire study reach as observed water surface level. Results from the model responses computed from different roughness set and mesh resolution are presented in the tables below (Table 5-9 and 5-10).

Roughness set	Minimum(m)	Maximum(m)	Mean(m)	Std	RMSE(m)
1	280.84	281.25	280.85	0.021	0.061
2	280.84	281.30	280.85	0.025	0.063

Table 5-9. RMSE for different roughness set.

Mesh resolution type	Time step	computational time	Min (m)	Max (m)	Mean(m)	Std	RMSE(m)
1(2×2m)	15S	3h18min	280.84	281.30	280.85	0.029	0.069
2(5×5m)	30S	0h53min	280.84	281.23	280.85	0.022	0.062
3(10×10m)	60S	0h12min	280.84	281.30	280.85	0.025	0.063
4(20×20m)	180S	0h2min	280.84	281.14	280.86	0.011	0.045

Table 5-10. RMSE for different mesh resolution.

From the tables above we can get the information that the roughness has little influence on the model responses for the low flow condition. Changing in roughness setting results in a small difference (0.2 cm) in RMSE.

We can see from Table 5-10 that a large difference (2cm) of RMSE between the mesh 4 and the other mesh and the mesh 4 lost the maximal value of the water level. Moreover, the three other meshes are obtained similar RMSE value.

5.4.3 The flood condition

Due to the lack of enough observed data, the RMSE methods will not be applied to assess the model results for the flood condition in 1971. Instead, water surface elevations for some casual points with different mesh resolutions and roughness sets are compared.

Roughness set	Mesh cells	Minimum(m)	Maximum(m)	Mean(m)	Std
1	10×10m	283.225	284.013	283.487	0.052
2	10×10m	283.439	284.015	283.698	0.051

Table 5-11. The statistics for different Roughness set.

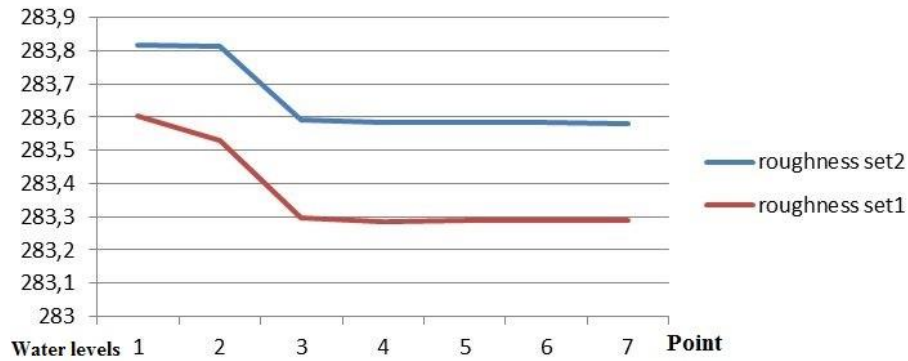


Figure 5-16. The simulated water surface elevation for different roughness set.

We randomly select seven points in the simulation area to calculate the corresponding water surface elevation using two sets of roughness shown in Figure 5-16. We can see from the figure that the difference in roughness set induces a large difference in water levels for the flood situation so the calibration of the roughness value is vital. But because lacking of enough observed data, it is hard to get a conclusion about which roughness set gives a better modeling result. Here we only compare the different roughness set for the main river channel while different roughness set for the floodplain is not discussed. We assume roughness set 2 is a better set.

Mesh resolution type	Time step	computational time	Min (m)	Max (m)	Mean(m)	Std
1(2×2m)	2S	8h5min	283.565	285.452	283.782	0.046
2(5×5m)	5S	0h25min	283.546	284.471	283.75	0.048
3(10×10m)	10S	0h4min	283.439	284.015	283.698	0.051
4(20×20m)	15S	1min	284.07	284.349	284.235	0.035

Table 5-12. The statistics for different mesh resolution.

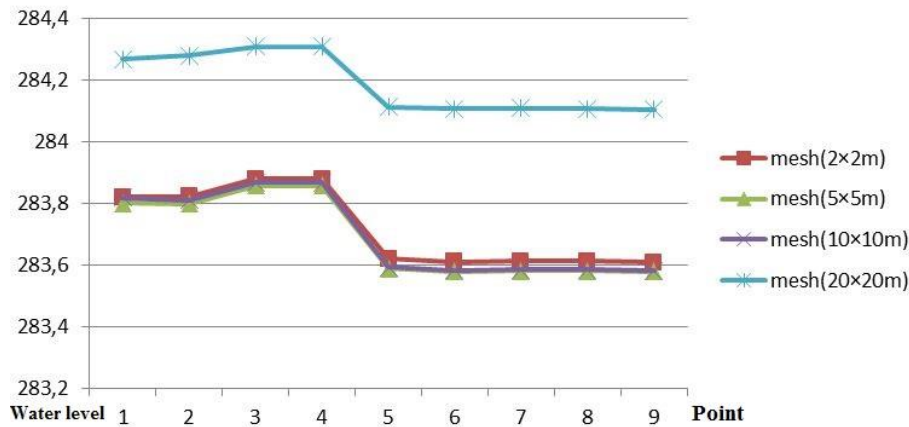


Figure 5-17. The simulated water surface elevation for different mesh resolution.

It is necessary to understand the impact of mesh resolution in the flood condition. The simulated water surface elevation for different mesh resolution is shown in Figure 5-13. We can see from the figure above that it is possible to directly observe the considerable difference (50 cm) between the resulting from the use of a coarse mesh (Mesh 4) and the three other meshes. The three other meshes behavior similarly. The statistics by using different mesh resolution is shown in Table 5-12. From the table, we can notice that the model the maximum water surface elevation value decreases with the increase of the mesh cell size, which indicates the model needs smaller cells in localized areas where the water surface elevation and slope change more rapidly.

5.5 Simulated cases

After setting-up and calibrating the model, we can use the model to simulate different scenarios using the result of water depth and flow velocity as a base to evaluate the habitat conditions for the brown trout before and after the regulation.

As it is described in Chapter 4, the frequency factor method is used to calculate the discharge for designed floods before and after regulation. The discharges are used as the upstream boundary. The discharge of the different design floods is shown in Table 5-13. The table clearly shows the discharge for upstream boundary conditions for the scenarios we modeled. As for the downstream boundary condition, the friction slope of 0.002 is used to calculate the normal depth.

T	mean	5	10	20
Q before(m3/s)	258.47	326.13	381.16	433.95
Q after(m3/s)	221.43	268.46	306.71	343.4

Table 5-13. The discharge of the different design floods.

For the simulated scenarios, an average cell size of 10m and 2m cell sizes for some areas needed is applied. The roughness set 2 is applied. The resulting map for the mean flood is shown as below and the other maps are shown in Appendix 3.

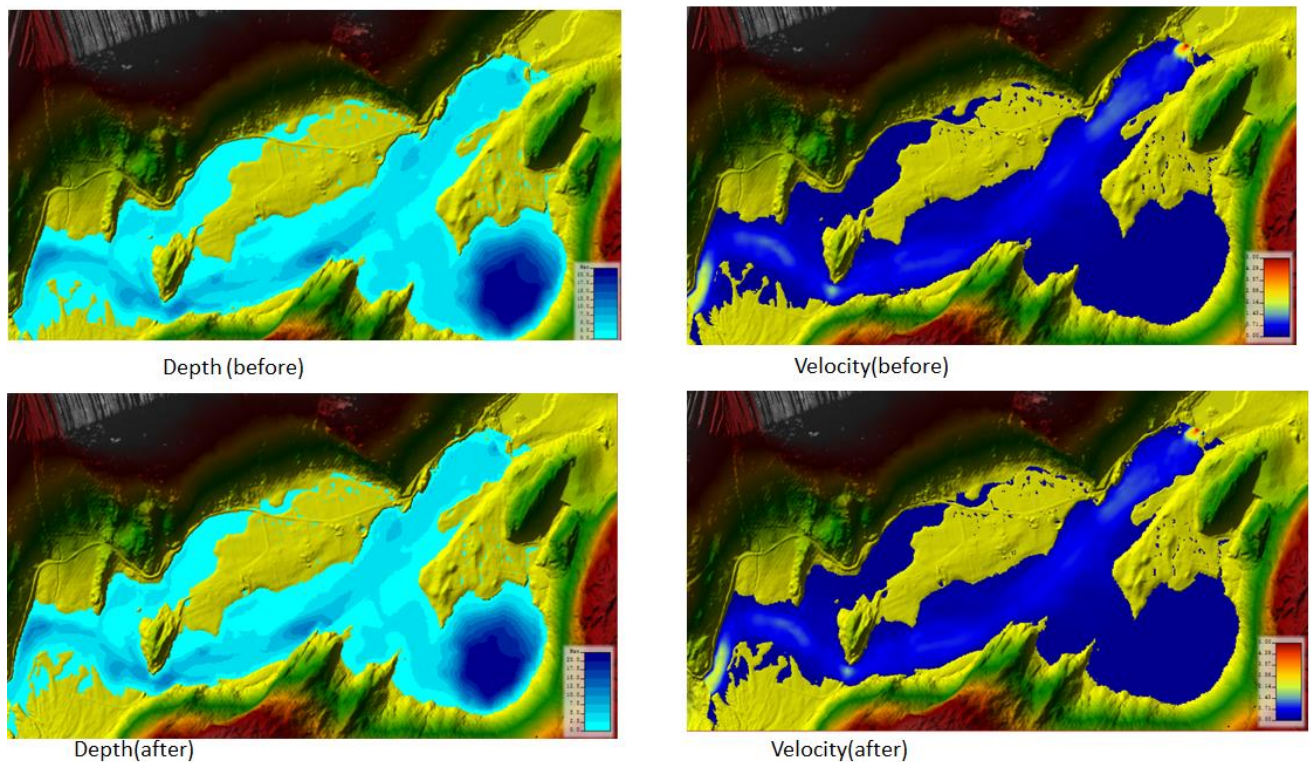


Figure 5-18. The resulting map for the mean flood.

The resulting map for the mean flood is shown in Figure 5-18. From the figure above, we can get the conclusion that the inundation area and velocity are larger than these after the regulation.

5.6 Statistics in ArcGIS

In order to get more conclusions, we need do more data analysis. The main idea is according to the habitat requirement for the brown trout in different life stages. We reclassify the water depth and flow velocity in ArcGIS, select and calculate the area that meets the water depth and velocity requirements for the fish in different life stages before and after regulation.

By literature review, we summarize the suitable water depth and water velocity for fish in

different life stage.

For the spawning habitat, the water depth is between 6 cm and 82 cm while the preferable range for the velocity is from 0.1 m/s to 0.8m/s.

For the nursery habitat, newly emerged brown trout prefer to live in the water depth between 5cm and 35cm while the preferable range for the velocity is from 0 m/s to 0.2m/s. Small parr prefers to live in the water depth is between 5 cm and 35 cm while the preferable range for the velocity is from 0.2 m/s to 0.5m/s.

For the rearing habitat, the water depth is between 0.5 m and 6 m, while the preferable range for the velocity is from 0.1 m/s to 0.7m/s.

Based on the information described above, we divide the water depth and velocity into different classes and describe them in the Tables 5-14 and 5-15, respectively, as below.

CLASS	DEPTH(M)	Spawning	Nursery: new emerged	Nursery: small parr	Rearing
1	0-0.05				
2	0.05-0.35				
3	0.35-0.5				
4	0.5-0.8				
5	0.8-1.5				
6	1.5-3				
7	3.0-6.0				
8	>6.0				

Table 5-14. The classes for water depth.

CLASS	V (m/s)	Spawning	Nursery: new emerged	Nursery: small parr	Rearing
1	0-0.1				
2	0.1-0.2				
3	0.2-0.5				
4	0.5-0.7				
5	0.7-0.8				
6	0.8-1.0				
7	1.0-1.5				
8	1.5-2.0				
9	2.0-3.0				
10	3.0-4.0				
11	>4.0				

Table 5-15. The classes for water velocity.

The process about how to get the map and the statistical result is described in Appendix 5-6.

5.7 Discussions about the uncertainty of the modeling result

The uncertainties of the modeling results caused by terrain model, mesh resolution, roughness selection are discussed here.

5.7.1 Terrain

A detailed and accurate terrain model is very important for hydraulics model. It is a challenge to represent the bathymetry in a good and correct way. The quality of the terrain model depends on the quantity and the quality of the data and the selection of the interpolation methods. Here we evaluate the uncertainties caused by different interpolation approaches.

Figure 5-19 shows that large variation can be found in the appearance of the terrains when using different interpolation approach in an area with low data density.

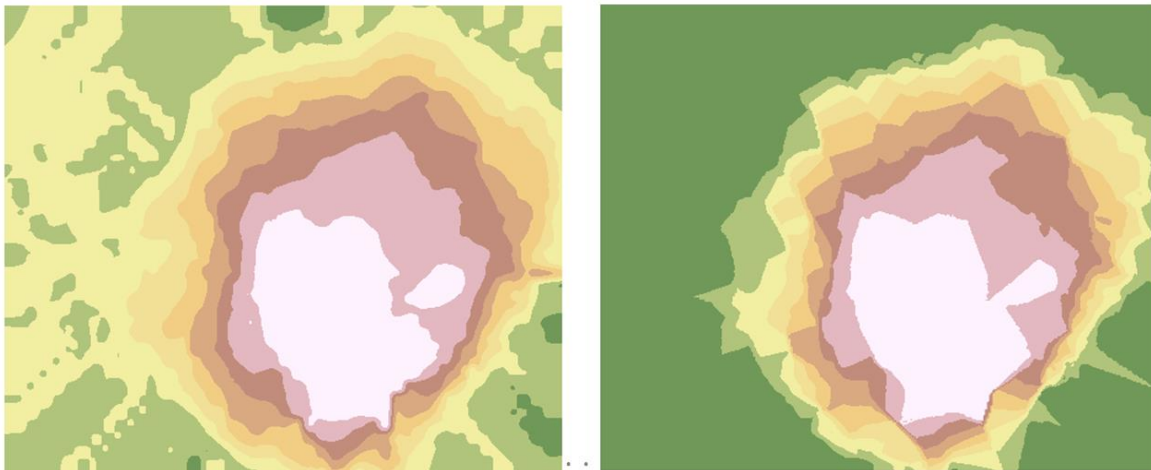


Figure 5-19. Interpolation of the bathymetry with Spline (left) and Kriging (right) interpolation methods in an area with a low sampling density.

5.7.2 Resolution mesh

As discussed earlier in the sensitivity analysis (Section 5.4), the resolution mesh also induces the difference of the output. The Figure 5-20 shows the flood extent with different mesh resolution. The figure on the left is the result of the model with the larger cell size so the mesh lost the accuracy of the terrain and the water can flow further. However, the flow is held back by the road with high elevations shown in the figure right.



Figure 5-20. The flood extent with different mesh resolution.

5.7.3 Roughness selection

As discussed earlier in the sensitivity analysis, the roughness also influences the output. In this study, the optimum roughness is not found. The roughness set 2 is assumed to be a good roughness set so it will increase the uncertainty of the model result and decrease the reliability of the model result.

Uncertainties in the model can be also caused by other factors such as:

- ADCP's precision.
- The bathymetry in shallow water areas.
- Insufficient data for calibration (velocity).
- Insufficient data for calculation of design flood after regulation.

6. Results

6.1 Results of flow frequency analysis

6.1.1 Flow analysis before regulation

The result of the probability method is shown in the figure below,

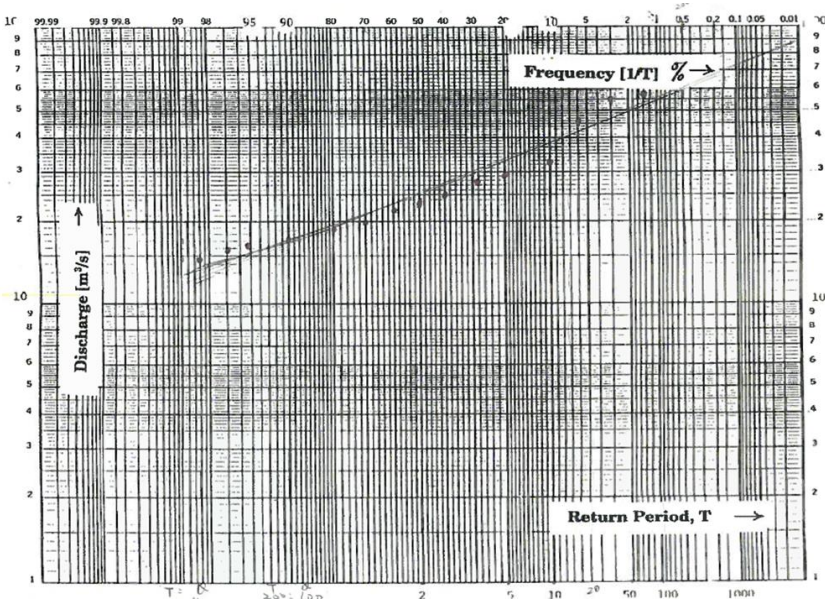


Figure 6-1. Graphical method, before regulation.

The result of the frequency factor method is shown in the table below.

T	M	std.dev	KT	Q(m ³ /s)
5	258.47	94.05	0.72	326.14
10	258.47	94.05	1.30	381.17
15	258.47	94.05	1.63	412.22
20	258.47	94.05	1.87	433.96
30	258.47	94.05	2.19	464.32
40	258.47	94.05	2.42	485.73
50	258.47	94.05	2.59	502.28
100	258.47	94.05	3.14	553.49
200	258.47	94.05	3.68	604.50
500	258.47	94.05	4.39	671.81
1000	258.47	94.05	4.94	722.67

Table 6-1. Frequency factor method before the regulation.

6.1.2 Flow analysis after regulation

The result of the probability method is shown in the figure below,

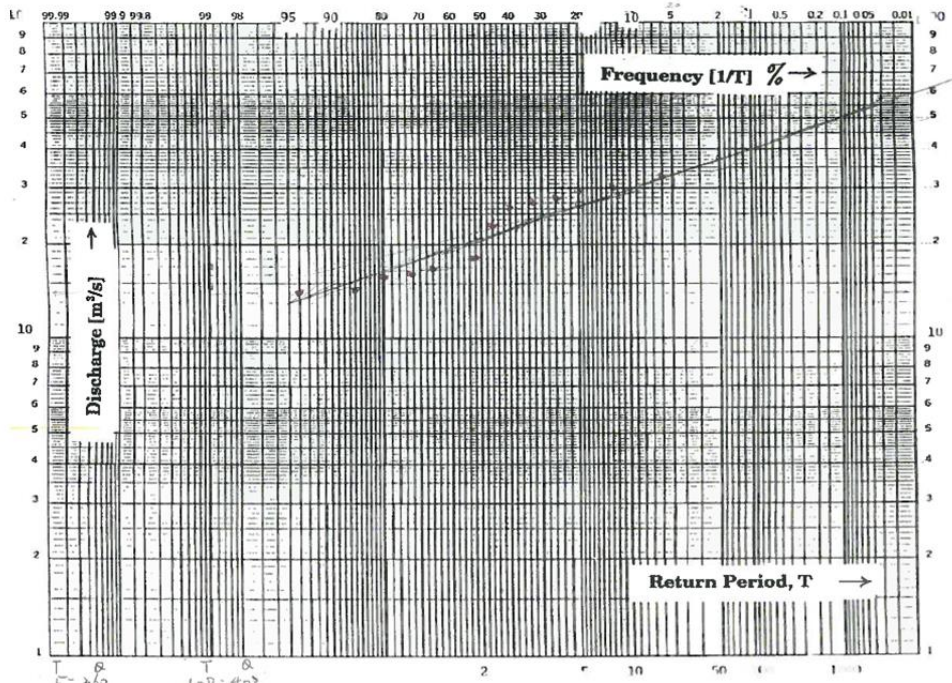


Figure 6-2. Graphical method, regulation period 1.

The result of the frequency factor method is shown in the table below,

T	M	std.dev	KT	Q(m ³ /s)
5	221.43	65.37	0.72	268.46
10	221.43	65.37	1.30	306.71
15	221.43	65.37	1.63	328.29
20	221.43	65.37	1.87	343.40
50	221.43	65.37	2.59	390.89
100	221.43	65.37	3.14	426.48
200	221.43	65.37	3.68	461.94
500	221.43	65.37	4.39	508.72
1000	221.43	65.37	4.94	544.07

Table 6-2. Frequency factor method, regulation period 1.

The comparisons in two methods with different return period (T) for the year 1909-1972 and 1973-1986 are shown in Table 6-4 and 6-5, respectively. As we can see from the tables below, the design floods decrease by around 100m³/s after the river regulation. The two methods give the similar result of the design flood calculation for the unregulated periods (1909-1972). For the regulated period 1 (1973-1986), the divergence increases with the design floods with a higher return period and the data series are too short for secure application of the statistical methods and the result of the flood analysis is not reliable for the return period that large than 20 years.

The result from the frequency factor method is chosen as the computed design flood for the 2D HEC-RAS model because the problems with fitting the line and extrapolation of the T-year floods can be encountered when applying the graphical methods because of the insufficient flow data after river regulation.

METHOD	T	5	10	20	50	100	200	500
Graphical methods	Q	330	380	430	500	550	600	680
Frequency factor method	Q	326.13	381.16	433.95	502.28	553.48	604.5	671.8

Table 6-3. Flood analysis for 1909-1972.

METHOD	T	5	10	20	50	100	200	500
Graphical methods	Q	260	290	330	375	400	430	470
Frequency factor method	Q	268.46	306.71	343.4	390.89	426.48	461.94	508.72

Table 6-4. Flood analysis for 1973-1986

6.2 Results of different scenarios

6.2.1 The result for mean flood

The inundation area for the mean flood before river regulation is 356670 m². After river regulation, the inundation area decreases up to 339828 m² by 4.72 %. The area in water depth between 1.5 m and 6 m accounts for around 50 percent of the total inundation area. The area with the water velocity smaller than 0.1 m/s occupies almost half of the total water covered area. The area can be used by brown trout before regulation is 158509 m² while the area after the regulation is 152389 m² and decreases by 3.86 %. The summary of the suitable area for different life stage of the brown trout is list in the table below (Table 6-5) and the distribution of the different habitats is shown in the figures below (Figure 6-3 and 6-4).

HABITAT TYPE	BEFORE(m2)	BEFORE(%)	AFTER(m2)	AFTER(%)	PERCENTAGE OF CHANGES (%)
SPAWNING	15716	9.91	14015	9.20	-10.82
NURSETY:NEW	18705	11.80	19574	12.84	4.65
NURSETY:SMALL PARR	3637	2.29	3510	2.30	-3.49
REARING	120451	75.99	115290	75.66	-4.28
TOTAL	158509	100.00	152389	100.00	-3.86

Table 6-5.The area of habitats for the mean flood.

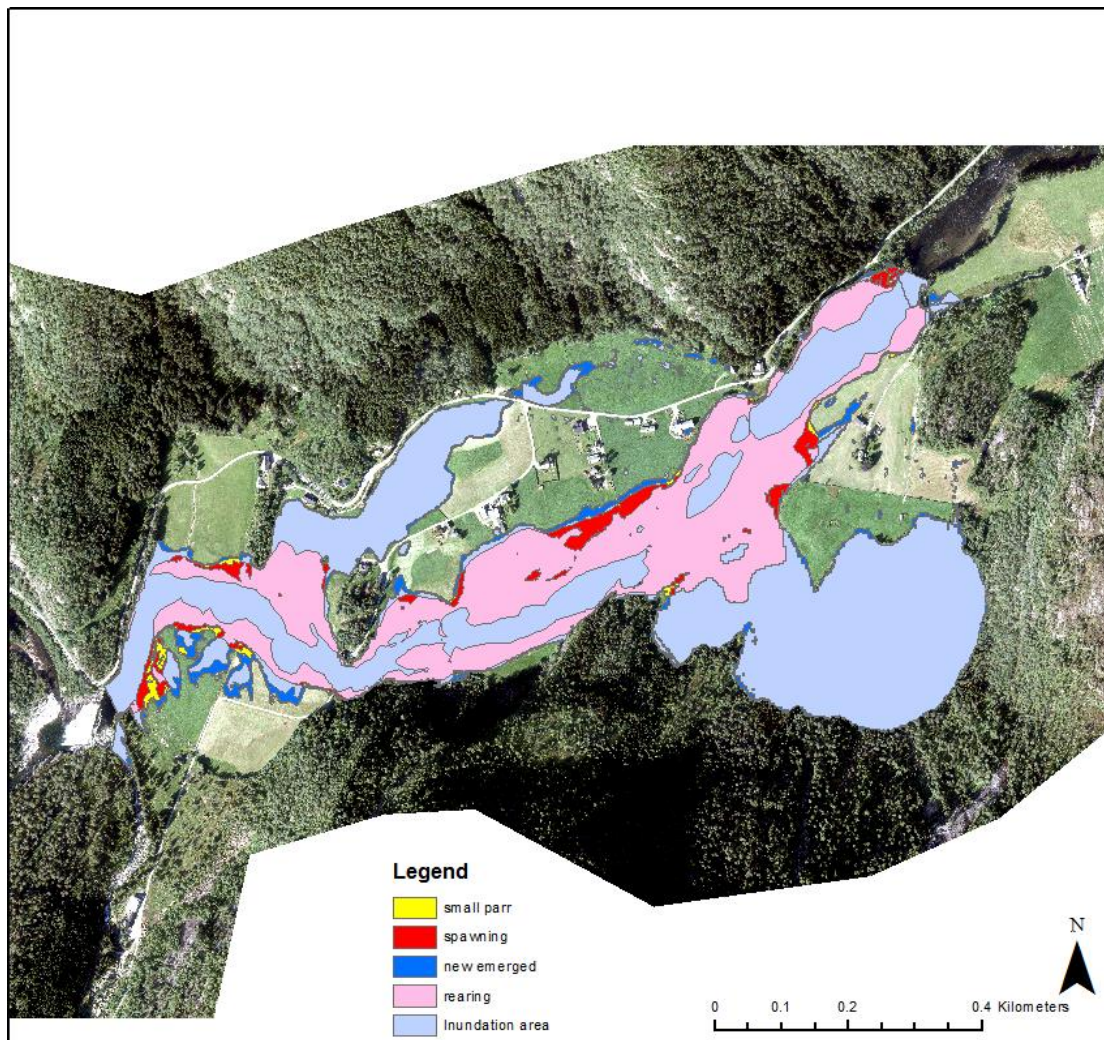


Figure 6-3.The distribution of the different habitats for the mean flood before regulation.

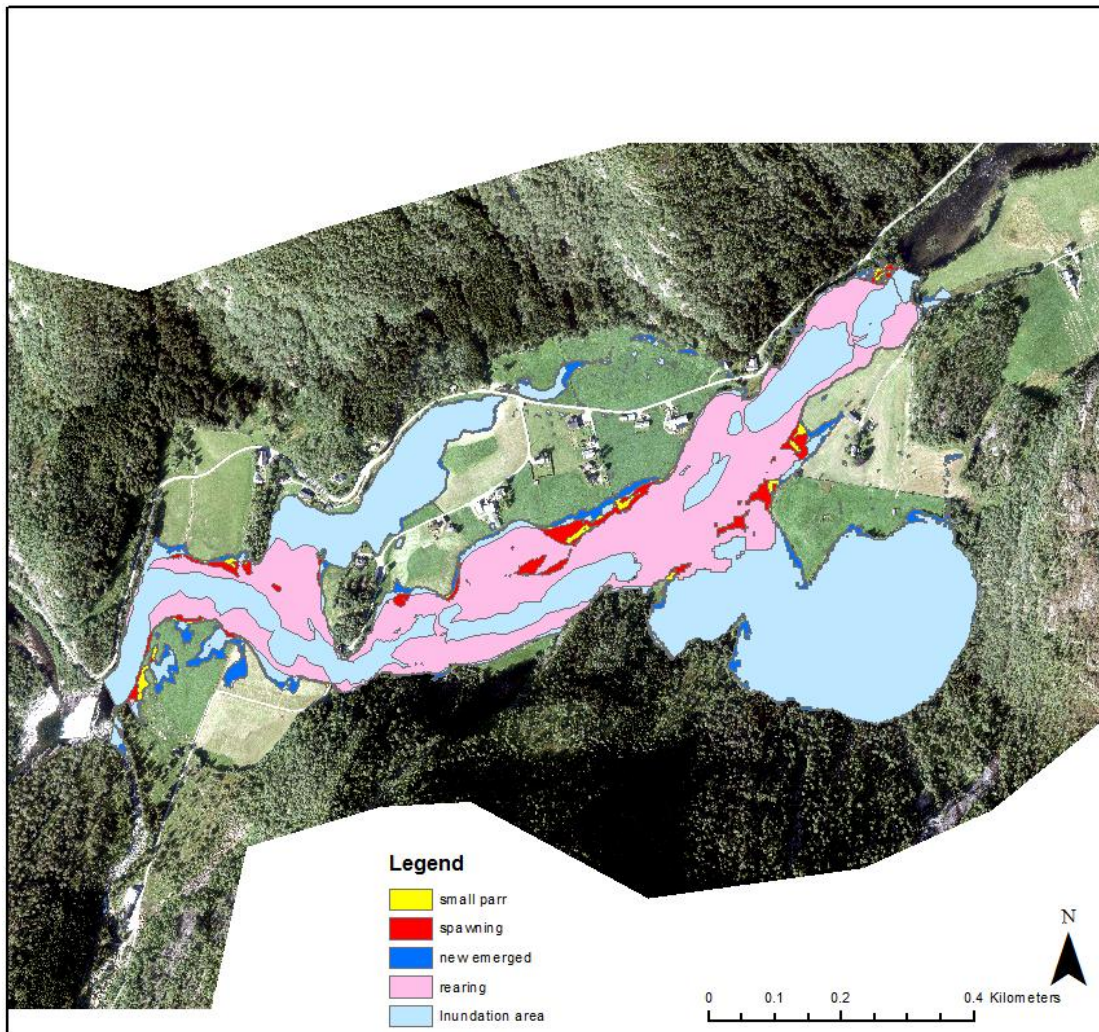


Figure 6-4. The distribution of the different habitats for the mean flood after regulation.

6.2.2 The result for 5-year flood

The inundation area for the 5-year flood before river regulation is 383880m². After river regulation, the inundation area decreases up to 360367 m² by 6.12 %. The area of the water depth between 1.5 m and 6 m accounts for around 54 percent of the total inundation area. The area with the water velocity smaller than 0.1 m/s occupied around 45 percent of the total water covered area. The area can be used by the brown trout before regulation is 173315 m² while the area after the regulation is 160503 m² and decreases by 7.39 %. The summary of the suitable area for different life stage of the brown trout is listed in the table below (Table 6-6) and the distribution of the different habitat is shown in the figures below (Figures 6-5 and 6-6).

HABITAT TYPE	BEFORE(m2)	BEFORE(%)	AFTER(m2)	AFTER(%)	PERCENTAGE OF CHANGES(%)
SPAWNING	20785	11.99	16290	10.15	-21.63
NURSETY:NEW	18079	10.43	18629	11.61	3.04
NURSETY:SMALL PARR	5938	3.43	4079	2.54	-31.31
REARING	128513	74.15	121505	75.70	-5.45
TOTAL	173315	100.00	160503	100.00	-7.39

Table 6-6. The area of habitats for the 5-year flood.

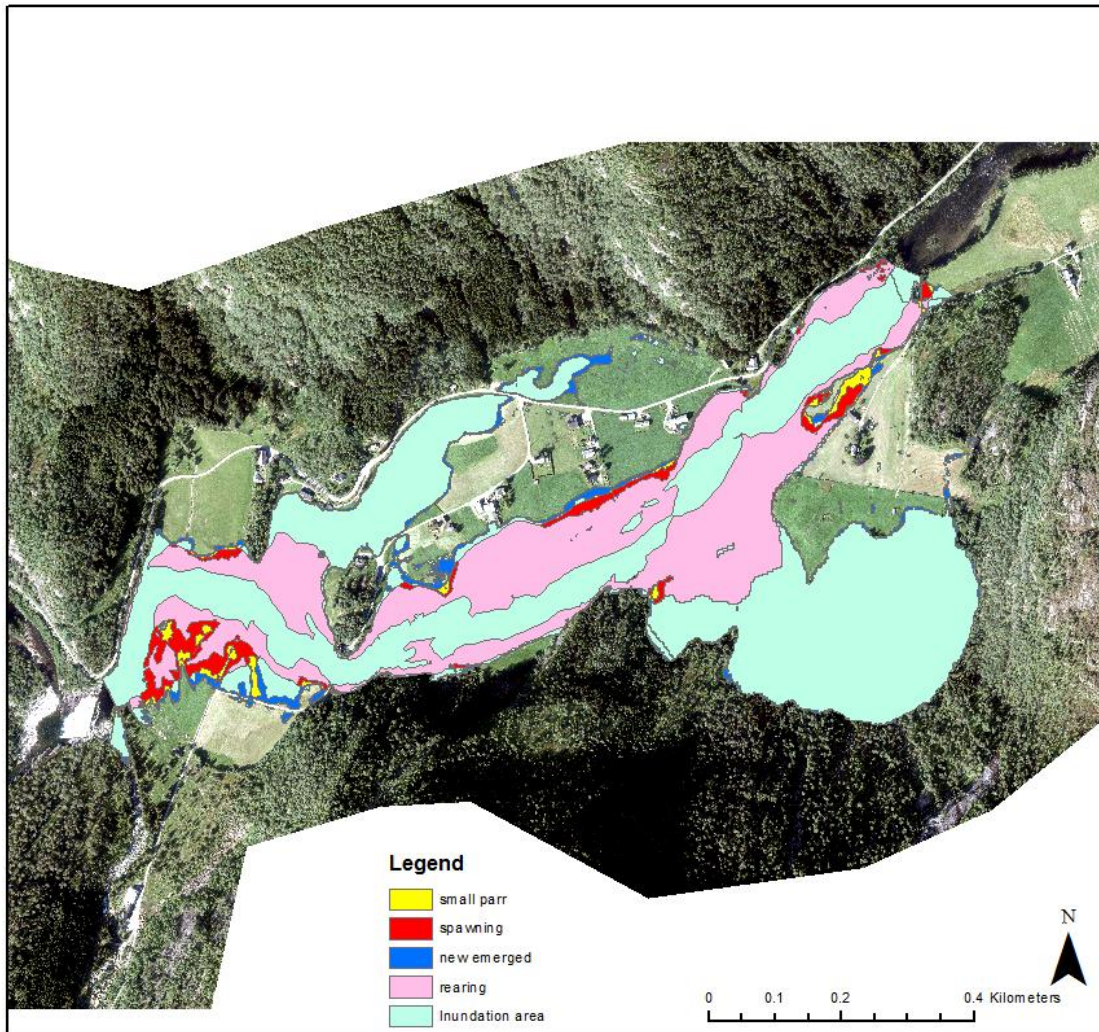


Figure 6-5. The distribution of the different habitats for the 5-year flood before regulation.

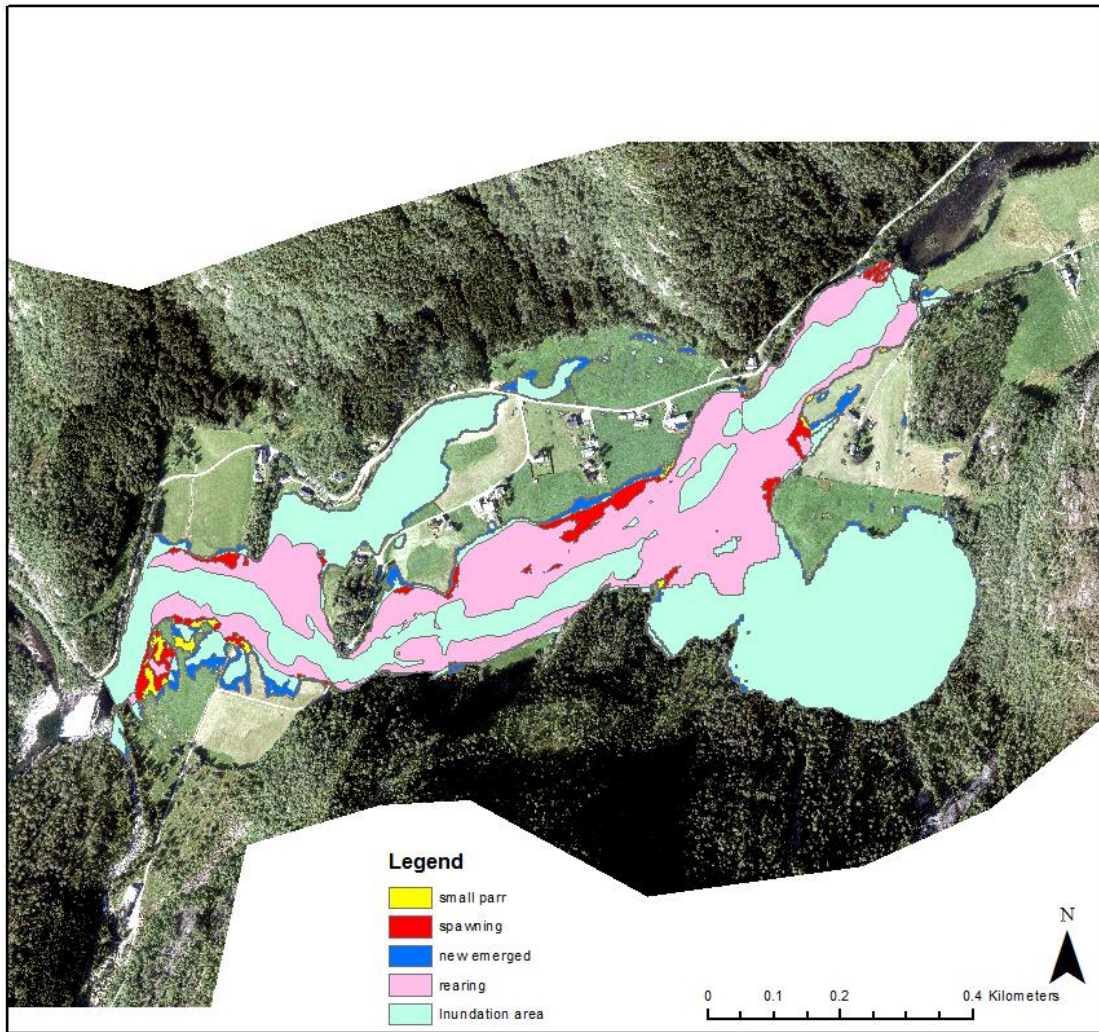


Figure 6-6.The distribution of the different habitats for the 5-year flood after regulation.

6.2.3 The result for the 10-year flood

The inundation area for the 10-year flood before river regulation is 406671 m². After river regulation, the inundation area decreases up to 375507 m² by 7.66 %. The area of the water depth larger than 0.8m accounts for around 85 percent of the total inundation area. The area with the water velocity smaller than 0.7 m/s occupies around 80 percent of the total water covered area. The area can be used by the brown trout before regulation is 191676m² while the area after the regulation is 167349 m² and decreases by 12.69 %. The summary of the suitable area for different life stage of the brown trout is listed in the table below (Table 6-7) and the distribution of the different habitat is shown in the figures below (Figures 6-7 and 6-8).

HABITAT TYPE	BEFORE(m2)	BEFORE(%)	AFTER(m2)	AFTER(%)	PERCENTAGE OF CHANGES(%)
SPAWNING	25571	13.34	18372	10.98	-28.15
NURSEY:NEW	21145	11.03	18244	10.90	-13.72
NURSEY:SMALL PARR	7244	3.78	5456	3.26	-24.68
REARING	137716	71.85	125277	74.86	-9.03
TOTAL	191676	100.00	167349	100.00	-12.69

Table 6-7. The area of habitats for the 10-year flood.

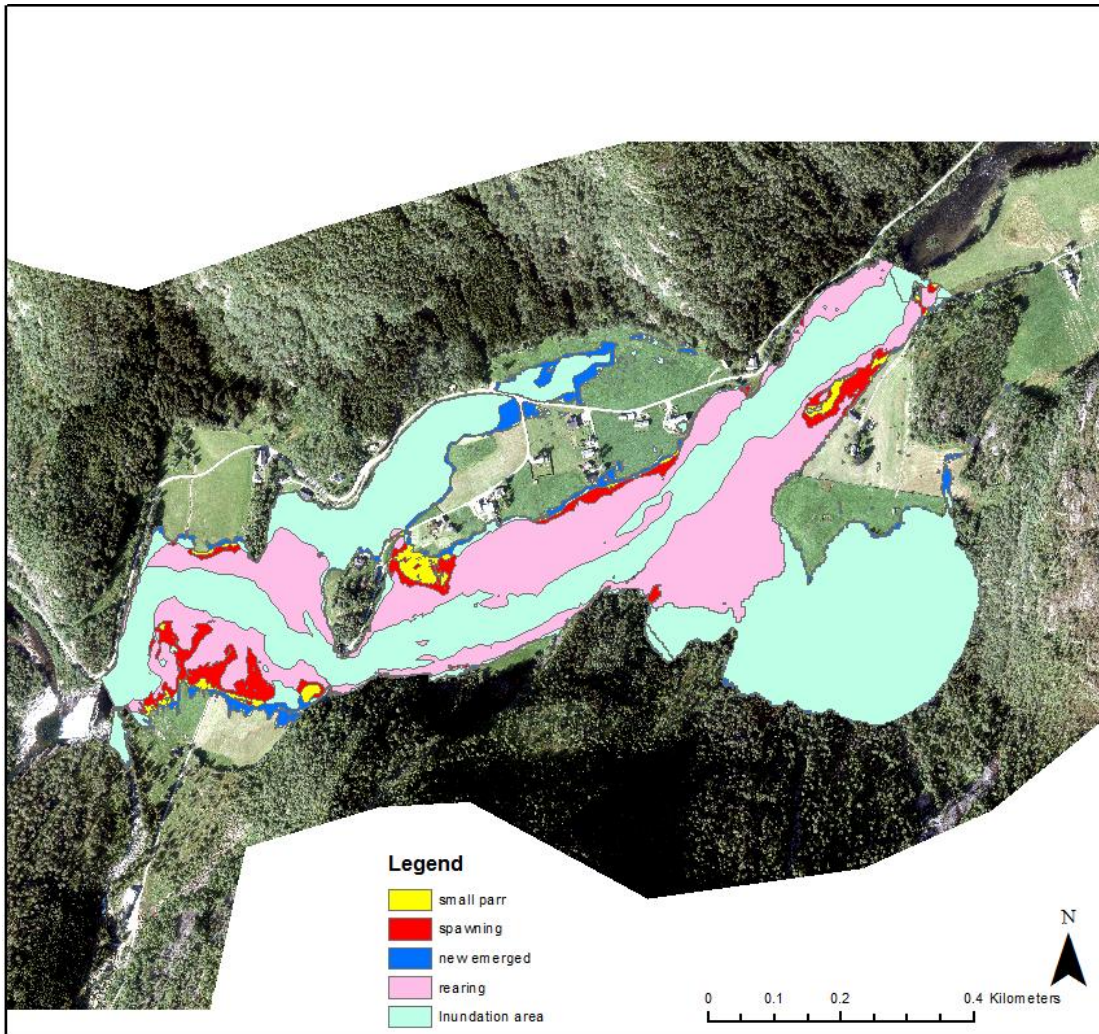


Figure 6-7. The distribution of the different habitats for the 10-year flood before regulation.

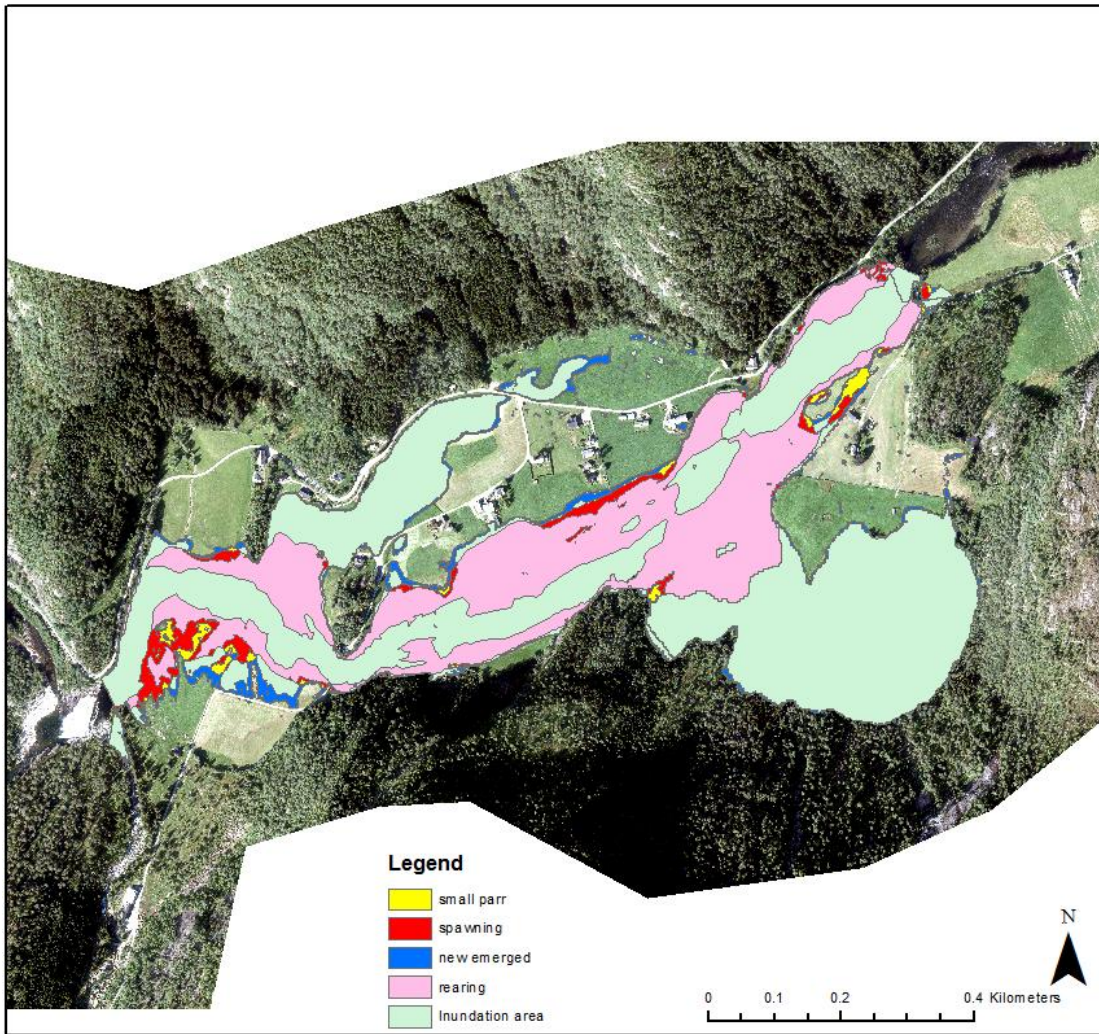


Figure 6-8.The distribution of the different habitats for the 10-year flood after regulation.

6.2.4 The result for the 20-year flood

The inundation area for the 20-year flood before river regulation is 428247 m². After river regulation, the inundation area decreases up to 392049 m² by 8.45 %. The area of the water depth larger than 0.8 m accounts for around 80 percent of the total inundation area. The area with the water velocity smaller than 0.5 m/s occupies around 70 percent of the total water covered area. The area can be used by the brown trout before regulation is 195335 m² while the area after the regulation is 179738 m² and decreases by 8%. The summary of the suitable area for different life stage of the brown trout is listed in the table below (Table 6-8) and the distribution of the different habitat is shown in the figures below (Figures 6-9 and 6-10).

HABITAT TYPE	BEFORE(m2)	BEFORE(%)	AFTER(m2)	AFTER(%)	PERCENTAGE OF CHANGES(%)
SPAWNING	22009	11.27	22363	12.44	1.61
NURSETY:NEW	22866	11.71	19839	11.04	-13.24
NURSETY:SMALL PARR	4116	2.11	6458	3.59	56.90
REARING	146344	74.92	131078	72.93	-10.432
TOTAL	195335	100.00	179738	100.00	-7.985

Table 6-8. The area of habitats for the 20-year flood.

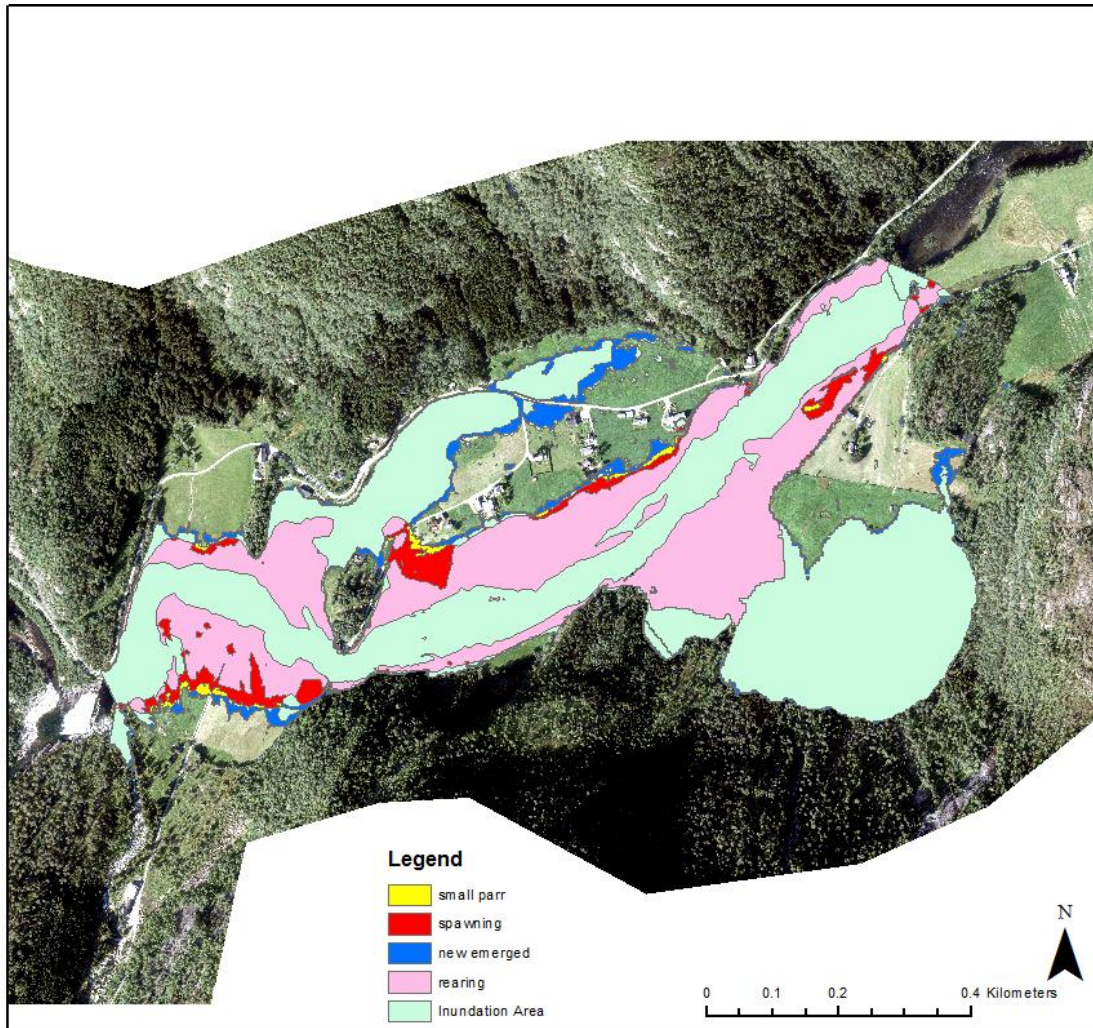


Figure 6-9. The distribution of the different habitats for the 20-year flood before regulation.

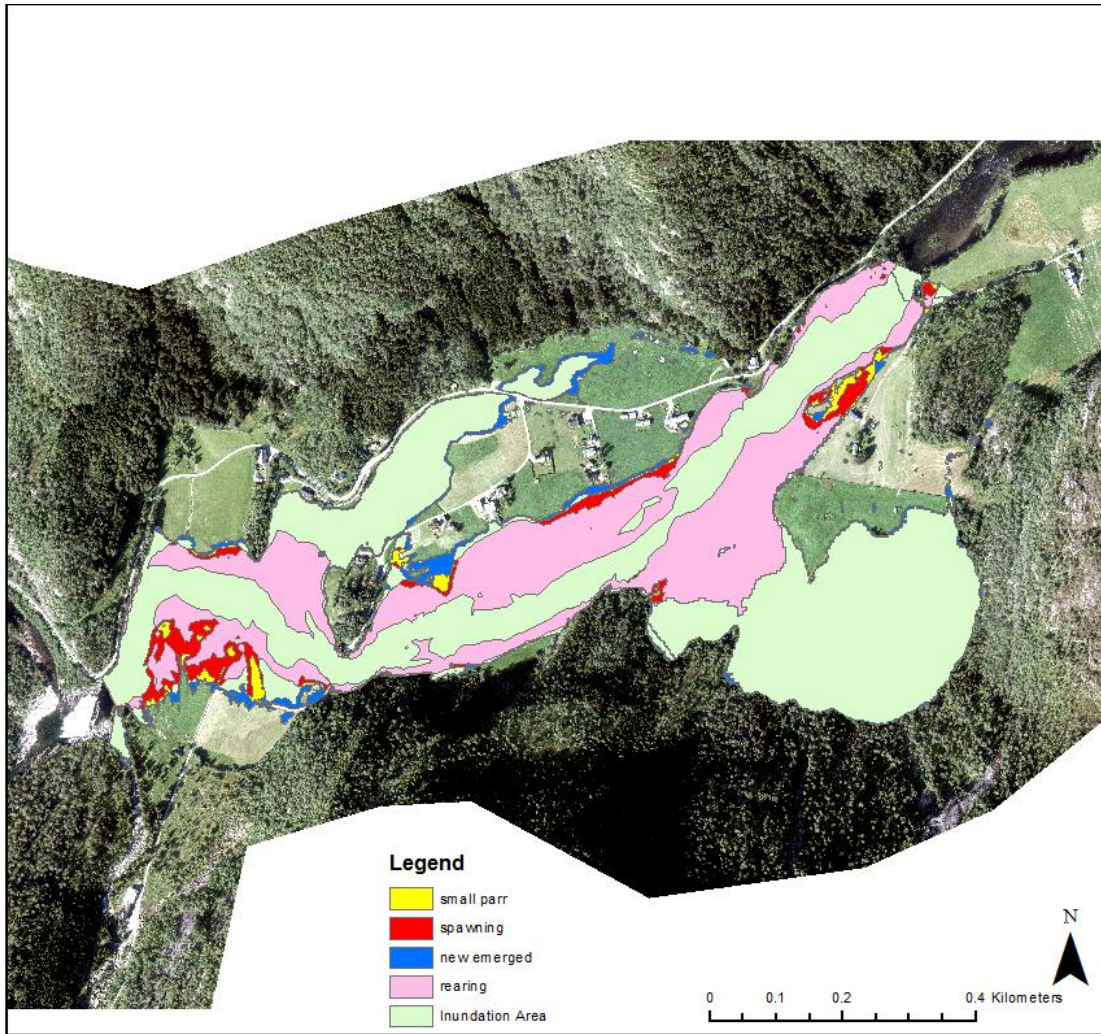


Figure 6-10. The distribution of the different habitats for the 20-year flood after regulation.

7. Discussion

7.1 Discussion about the impact of river regulation based on the modeling result

7.1.1 Discussion about the impact of river regulation based on the modeling result

By comparing the map of the inundation area, water depth and flow velocity before and after the river regulation, it is easy to find that the inundation area decreases after regulation and the water velocity and water depth decreases for the same location after regulation.

The areas cover the needs of all life stages of the brown trout decreases after regulation by the summary of the area, which meets the requirements for the water depth and flow velocity for different life stages of the brown trout. For rearing habitat, it decreases after the regulation. The spawning habitat and habitat for small parr decrease but for the 20-year flood after regulation the area they increase because the distribution for the water depth and water velocity has changed a lot.

We can see from the Table 7-2 that the area, that suitable for the new emerged fish, increase after the river regulation during the inundation area of the 5-year flood. The reason for this is that the area for the water depth in the range of 5 cm to 35 cm increase.

For all scenarios, the spawning habitat is closed to the nursery habitat so the fish doesn't need to migrate a long distance for survival.

The deep pools should be a favorable place for the brown trout but the modeled water velocity is less than 0.1 m/s and the water depth for this region is larger than 2 m, so it is the reason why the modeled results show no favor on this region.

Above we discussed the suitable areas for brown trout during flood. It seems that the floodplain is important for the fish during flood. Here we discuss the suitable area for the fish in low flow condition. The Figure 7-1 below is the map for low flow condition. Compared with the result for the flood condition, there exists more space in main channel for the new emerged fish in low flow condition. Therefore, the flow condition has large effect on the fish habitat and the distribution of the habitat has changed extraordinary.

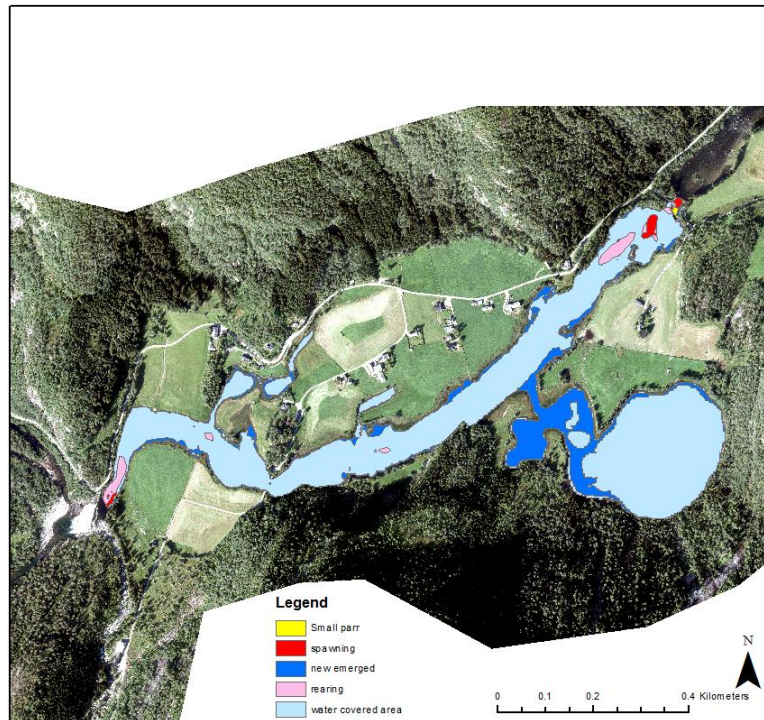


Figure 7-1. The distribution of the different habitats for low flow condition.

The habitats that meet the requirements for water velocity and water depth is necessary for fish but it is not sufficient condition for the production and survival of the brown trout. Other factors such as adequate food, temperature, water chemistry, substrate and cover have been shown to affect the population and the distribution of the brown trout.

7.1.1 Discussion about the uncertainty of the modeling result on the fish habitat investigation

As we mentioned in Section 5.5, the terrain model, the mesh resolution, the roughness sets and the design flood and other factors influence the distribution of the water depth and water velocity. Here we will discuss the potential influence of these factors on the area and distribution of the different habitats.

Different interpolation methods will result in different terrain models, different terrain will induce different water depth, flow direction and flow velocity, which means the distribution of the different habitats will have small different in total and large different locally, especially in low density data area. As we discussed in in Section 5.5, the total inundation area will increase when larger mesh size is applied, and the increase inundation area caused by different mesh resolution have the characteristic of shallow water depth and low flow velocity.

Therefore, when we applied larger mesh size, the suitable area for the new emerged fish will increase. Due to the lack of sufficient year in the flow data after the river regulation, the analysis for the flood frequency is not reliable. The result of the discharge for the design flood may be larger or smaller. Accordingly, the condition for the distribution and area of the habitat with different discharge will totally different. The different roughness sets influence the area and distribution of the different habitats, especially for the flood with larger return period.

7.2 Other factors related to the river regulation on the habitat condition of brown trout

7.2.1 Water temperature

Water temperature is an important factor that controls the growth and the survival of the brown trout. However, we do not consider the factor of water temperature in the modeling. The water temperature is especially important for the fish at the emergence and the higher mortality was observed in years with lower water temperatures at the emergence (Jensen, A. J., and B. O. Johnsen, 1999). The water temperature has the effect on the swimming performance of the brown trout. The fish can withstand the higher flow velocity with an increasing water temperature (Heggenes & Traaen 1988).

7.2.2 Substrate

The substrate provides the shelters for the brown trout. The large floods change the distribution of the substrate. A study shows that the discharge larger than $11 \text{ m}^3/\text{s}$ has the ability to move the sediment with a diameter of 20 mm (Junker, 2015). The erosion and the redistribution of the sediments will influence the population of the brown trout considerably, especially in the spawning and incubation phase. Large flow happens in incubation phase that leading to the damage of the egg and fry due to the erosion while high flow event occurred during spawning phase will rearrange the spawning habitats and wash out the fine sediment, which is a benefit for the survival of the brown trout. (Unfer et al., 2011, Zeh & Dönni, 1994). After the regulation, the annual discharge pattern in the study reach has changed. The peak of the spring flood has reduced by approximately 35 % and the duration of the spring flood has reduced by about a month. The winter discharge is reduced a little bit (Fjellheim, 1999). So

the flush ability has decreased and the pattern of the bed transport has also changed and it will influence the fish population for our study reach.

7.2.3 Vegetation

The cover is possibly the most important single site attribute determining salmonid abundance. (Milner, 1982). The vegetation provides cover for the fish. During the summer and autumn in Finland, juvenile brown trout favored areas of the stream with a high percentage (80–100%) of aquatic vegetation (Maki-Petays et al., 1997). The habitat used most extensively by adult brown trout in a Norwegian river tended to have >50% overhead cover (Heggenes, 1988a). The vegetation is important for the fish adult salmonids during up-river migration, both as protection from predators strong sunlight (Crisp, 1996).

By comparing the old aerial image with the aerial image recently, we can easily find that the condition of the vegetation after river regulation is changed in some regions. The vegetation has increased in recently years, which can be found in the figure below (Figure 7-2) that indicated in yellow rectangular region. Note that the image was ordered as scan based on paper photos from the Central Aerial Image Archive of the State Map Agency (flight No. NF-0256 from 1964). For the tributary river indicated in blue, the helophyte vegetation has changed a lot after river regulaton. Changes in vegetation will alter the distribution of water velocity but we did not consider the vegetation change in the model.



Figure 7-2. Old aerial image for parts of the study area.



Figure 7-3. Aerial image recently for parts of the study area.

7.2.4 Water chemistry

The quality of the water plays an important role in the living of the fish. We only assess the water quality after the river regulation and the one before the river regulation will not be analyzed. Based on the information from the website *Vann-net*, the ecological status of the study reach is classified as “bad” for the water quality. We find that the factors like pH value,

labile aluminum (LAl), ammonia ($NH_3 - N$ and $NO_3 - N$) and water hardness (Ca) affect the growth and the survival of the brown trout through the literature review.

The test results in adult or juvenile trout show that the survival possibility in trout at pH values below 5.0. However, for early trout stages, the tolerance to low pH is not well developed (Molony, 2001). The mortality is increasing for parr when the pH values <5.6 or cationic Al concentrations > 45 μgL^{-1} , and when pH was <5.1 and cationic Al exceeded 90 μgL^{-1} , the mortality is mainly recorded (Kroglund et al, 2008). Water hardness is the total of calcium and magnesium. A suitable level of water hardness benefits a lot in trout culture such as decreasing the toxicity risks of most ions (e.g. zinc, copper), buffering highly acidic waters and the reduction in disease risks (Molony, 2001). Ammonia is usually measured as $NH_3 - N$ and nitrate ($NO_3 - N$) is the most toxic nitrogenous compound to fishes in freshwater. For successful salmonid culture, the level of ammonia as $NH_3 - N$ be kept below 0.01 $mg.L^{-1}$ (DFO 1973 in Barton 1996) and 0.0125 $mg.L^{-1}$ (Piper et al. 1982).

Station Nesevatn recorded the development in pH, calcium and labile aluminum (LAl) in Ekso 1995-2000 shown in the Figure below in Figure. We can see from the figure that most of the pH values in station Nesevatn are >5.6 while some values are closed to 5.5 and occasionally, the value approaches to 5.0, where is the mortality is increasing. For LAl values, most data recorded are <30 μgL^{-1} . However, for some parts are closed to 45 μgL^{-1} and one record in January 1999 is larger than 60 μgL^{-1} , which is unsuitable for the survival of the parr. For the water hardness (measure of Calcium), the requirements for successful growth and survival is on the range (4-160 $mg.L^{-1}$) (Stickney, 1991), apparently, the values in station Nesevatn are not fall into this range since this reach belongs to soft water.

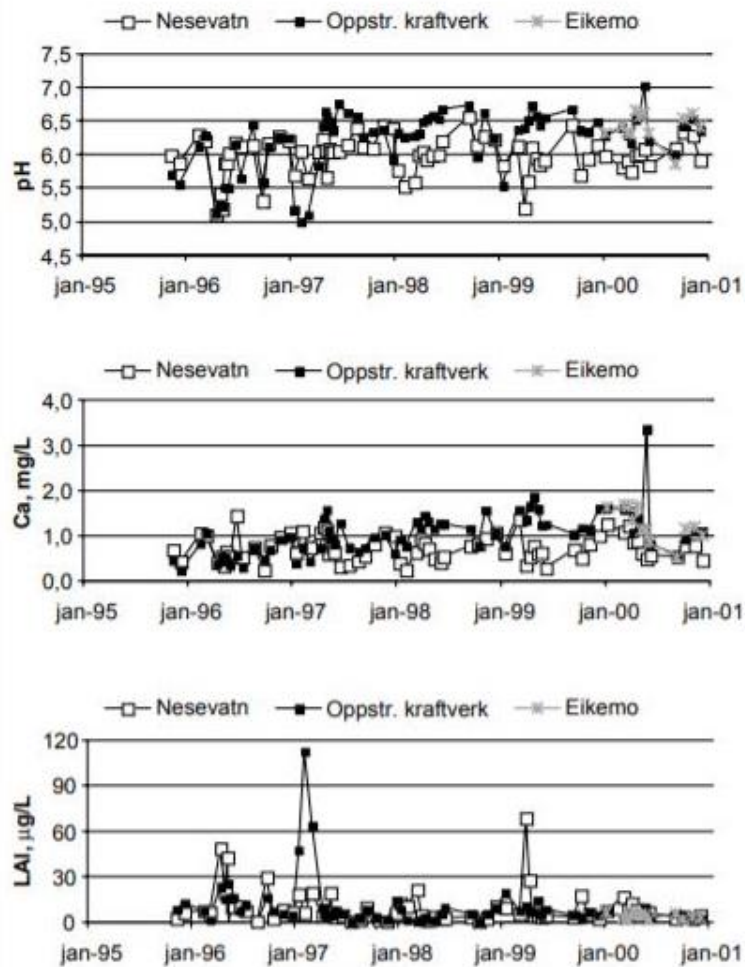


Figure 7-4. The development in pH, calcium and labile aluminum (LAI) in Ekso 1995-2000.

(<http://www.miljodirektoratet.no/old/dirnat/multimedia/47997/Eksovassdraget.pdf>)

Since the pH values recorded at station Nesevatn are all <7.0 , the ammonia ($NH_3 - N$) is $<0.01 \text{ mg.L}^{-1}$, which fits the standard growth and survival requirement ($NH_3 - N < 0.0125 \text{ mg.L}^{-1}$, Soderberg et al, 1983). The value of nitrate ($NO_3 - N$) recorded at station Nesevatn is from minimal 0.034 mg.L^{-1} to maximal 0.148 mg.L^{-1} , which are all locates on the survival zone with the standard value for survival in nitrate ($NO_3 - N$) is $<0.25 \text{ mg.L}^{-1}$. However, the recorded values are all not suitable for the growth where the standard growth nitrate ($NO_3 - N$) is $<0.025 \text{ mg.L}^{-1}$. In general, the situation of the water chemistry at the study area reaches the survival standard while some of them are not fulfill the growth requirement.

7.2.5 Food

The invertebrate is the main food for the fish. A study said that the biomass of the considered macroinvertebrate would increase with the discharge (Fornaroli,2016) but the invertebrate abundance was decreased by at least one-half after flood events (McMullen,2012). A study shows that the rainbow trout population increased following the flood because the increased invertebrate prey in production and drift concentrations that supported a large proportion of trout production (Cross,2011). Cross (2011) also explained that the spring flood happened in March before the spawning time of the rainbow trout. The conditions after spring flood help the biological processes to recover rapidly. It is good for the 0+ fish, so the time of the flood is an important factor for the response for the fish.

It is not easy to draw a conclusion whether the brown trout can benefit from the controlled floods or not. It depends on the frequency of the floods, the time of the flood and the type of invertebrate drifted by the flood etc.

8. Outlook

Our data has its own limitation to proof a good performance of our model for large floods due to the missing of the respective calibration data. My supervisor Dr Peggy Zinke has installed a webcamera that is recording the flood water levels in Spring 2018 while this data is not yet available for my study. It is recommended that this newly collected data could be used to check and improve the model calibration for the flood case. A better or longer time series for the flood frequency investigation for the time after regulation should be used, for example by including the new data from BKK while it comes too late for my study.

My investigation is applied only on steady flow conditions for peak discharges, while it may be important to investigate unsteady flow behavior during floods. The temporal distribution of flows and duration of appropriate habitat conditions has not yet been studied but could be important for the overall assessment of suitability. The other factors and for fish investigations are worth to be investigated in the future.

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APPENDIX 1 USEFUL INFORMATION ABOUT THE VEGETATION AND SUBSTRATE FOR THE STUDY AREA

GIS code	Description	Typical impression in drone image	Note
5300	Floodplain vegetation (not specified)		
5301	Water horsetail (Equisetum fluviatile)		Occurs in different densities (very sparse in deeper zones, dense near shore); Typical water depth during growing season: 0.3 m
5302	Sedges (Carex spec.)		Typical water depth during growing season: 0.2 m
5303	Purple marshlocks (Potentilla palustris)		Here only at few locations
5304	Small-reed (Calamagrostis spec.)		On shore; often mixed with other grasses and herbs Typical water depth during growing season: <0.05 m

5310	Willow shubs (<i>Salix spec.</i>)		Different species (different colours and shapes); on shore – but tolerates some inundation during floods
5400	Aquatic vegetation (not specified)		Several species/plant communities; here not specified; may look differently; occurs often in depths between >0.3 to 1 (1.5) m
5401	Bur-reed (<i>Sparganium spec.</i>)		In Ekso often observed at stones and boulders; Assumed typical water depth during growing season 0.7 m (but probably with a wide range – compare with ADCP depth data!)

Appendix 1-1. Vegetation information for the study area.

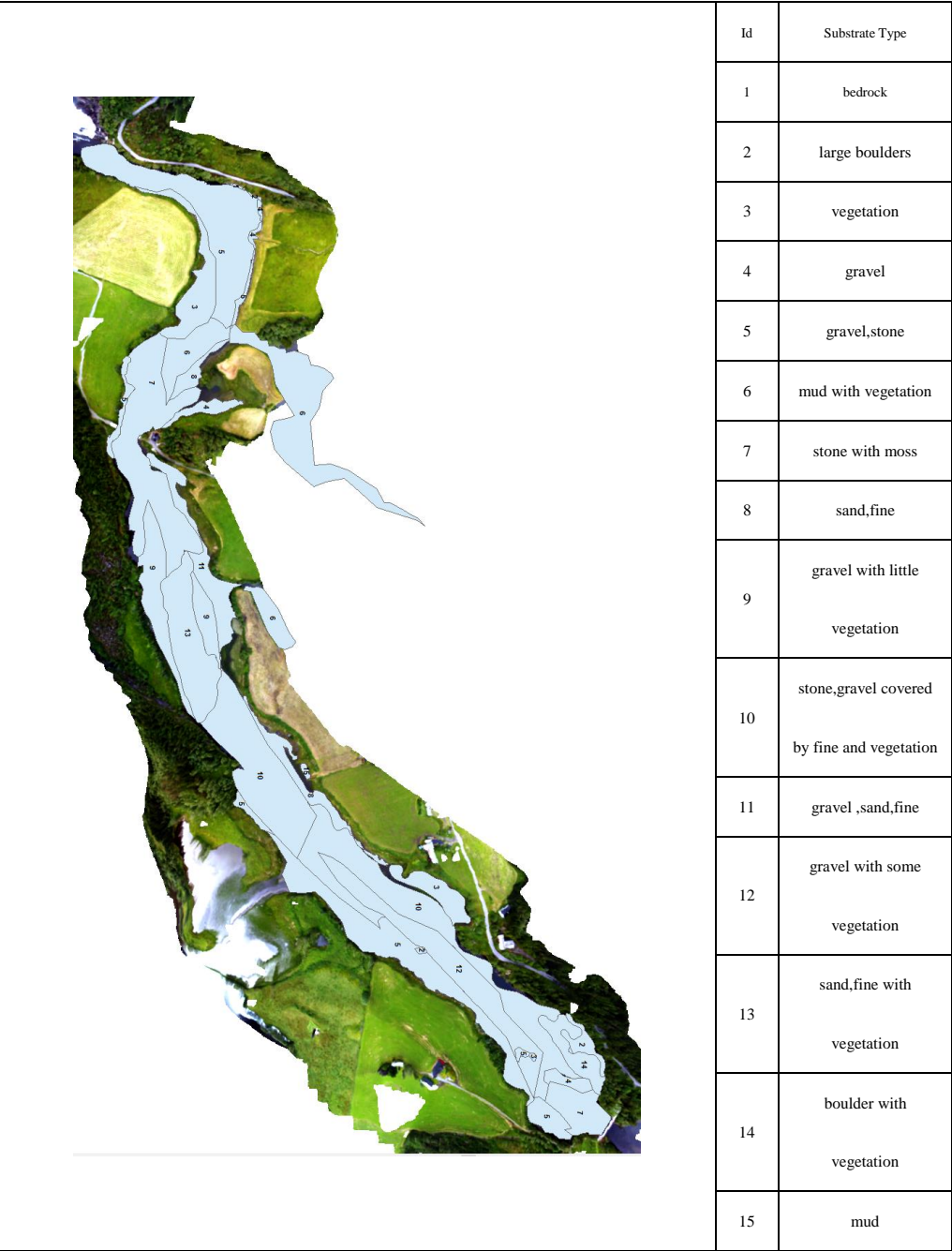
FID	Shape *	id	Fieldmap
0	Point	0	Substrate near shore: stones
1	Point	0	Substrate: stones from the incoming stream
2	Point	0	2m along shore: stones, gravel
3	Point	5301	Vegetation: Equisetum fluviatile
4	Point	5303	Vegetation: Potentilla palustre
5	Point	5301	Substrate: Mud; Vegetation: sparse Equisetum fluviatile and others
6	Point	0	a little bit deeper
7	Point	0	Substrate: fines/mud, with aquatic vegetation
8	Point	0	Substrate on shore: Boulders from the hill
9	Point	5401	Substrate: boulders, with aquatic vegetation (Sparganium)
10	Point	0	Substrate: stones, in the middle of the river covered by moss
11	Point	0	Substrate on shore: bedrock
12	Point	0	Substrate: boulders (1-3 m diameter)
13	Point	5401	Vegetation: Sparganium
14	Point	0	Substrate: gravel
15	Point	0	Substrate: stones/gravel covered by fines, locally with aquatic vegetation (Sparganium, Juncus bulbosus)
16	Point	0	Substrate on shore: boulders from the hill
17	Point	0	Substrate: sand/fines, with aquatic vegetation
18	Point	0	Grass island (formerly open)
19	Point	0	Substrate: stones/boulders on hilltop
20	Point	0	Substrate: bedrock or boulders, with stones and gravel in between
21	Point	0	Substrate: gravel with aquatic vegetation
22	Point	0	large boulders
23	Point	0	Substrate: gravel, locally with aquatic vegetation; few single boulders
24	Point	0	Substrate: stones with moss; close to shore locally with gravel in between
25	Point	5301	Vegetation: Equisetum fluviatile
26	Point	0	Substrate: stones and gravel covered by fines and aquatic vegetation
27	Point	0	Substrate: mud
28	Point	5301	Vegetation: Equisetum fluviatile
29	Point	0	Substrate: sand
30	Point	5302	Vegetation: Carex
31	Point	5301	Vegetation: Equisetum fluviatile
32	Point	5302	Vegetation: Carex
33	Point	5302	Vegetation: Carex
34	Point	0	Substrate: gravel
35	Point	0	Substrate near shore: stones
36	Point	5401	Substrate: boulders and stones with aquatic vegetation (Sparganium)

Appendix 1-2. Information about vegetation and substrate distribution.

APPENDIX 2 THE DISTRIBUTION OF THE SUBSTRATE FOR THE RIVER CHANNEL

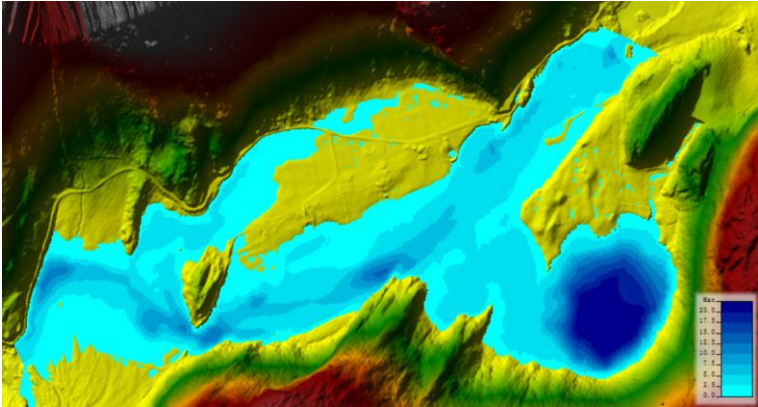
The drone image provides the information about the vegetation and substrate distribution. The thing that we need to do in ArcGIS is drawing the different zones and setting a suitable value in HEC-RAS. The process is presented as follows: Step1: Create a new shapefile.

Step2: Draw polygons and add some descriptions to each zone.

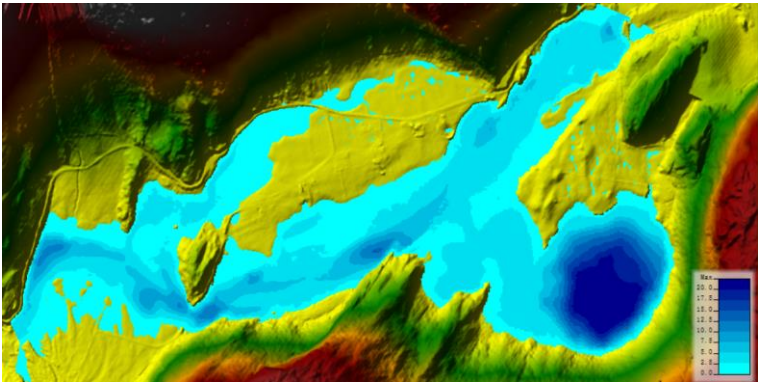


Appendix 2-1. The distribution of the substrate for the river channel.

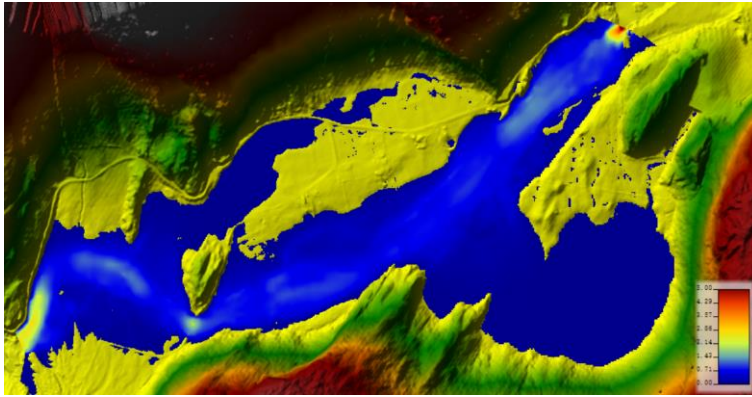
APPENDIX 3 THE MAP OF WATER DEPTH AND WATER VELOCITY SIMULATED IN HEC-RAS FOR DIFFERENT SCENARIOS



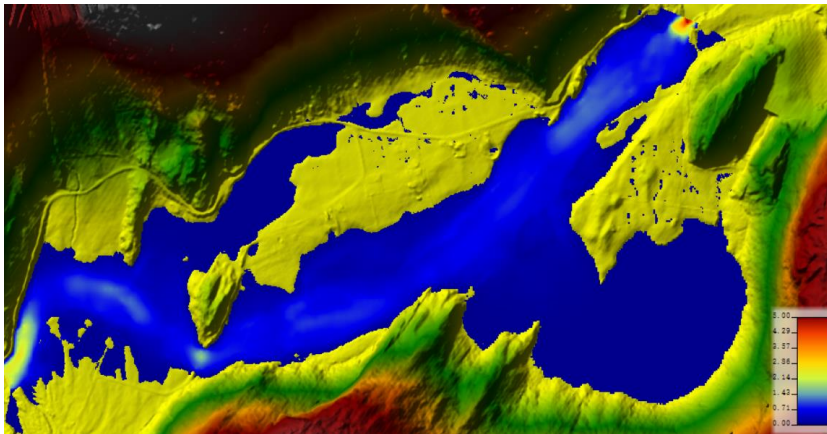
Appendix 3-1. The map of water depth simulated in HEC-RAS for 5-year flood before regulation.



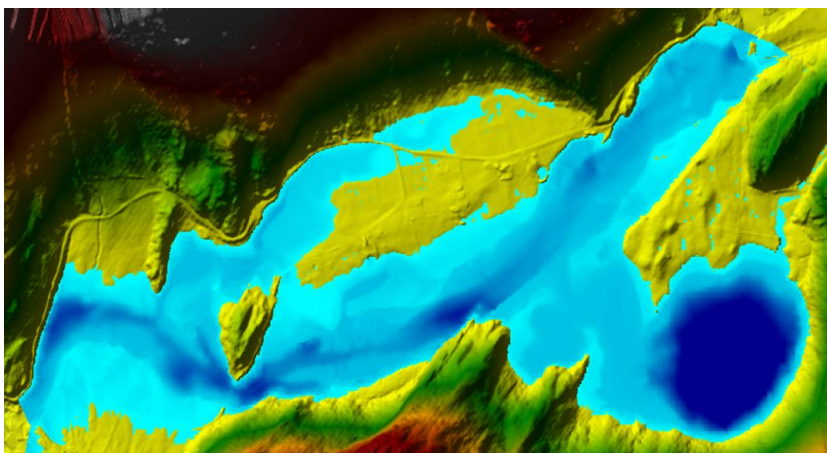
Appendix 3-2. The map of water depth simulated in HEC-RAS for 5-year flood after regulation.



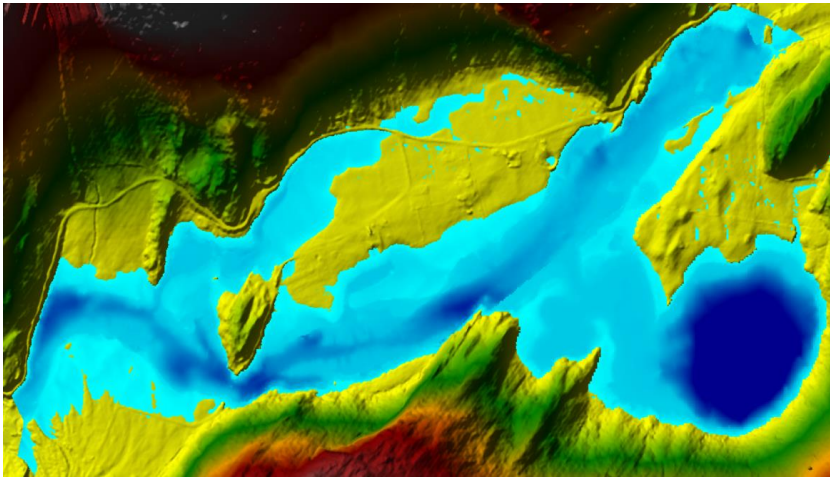
Appendix 3-3. The map of water velocity simulated in HEC-RAS for 5-year flood before regulation.



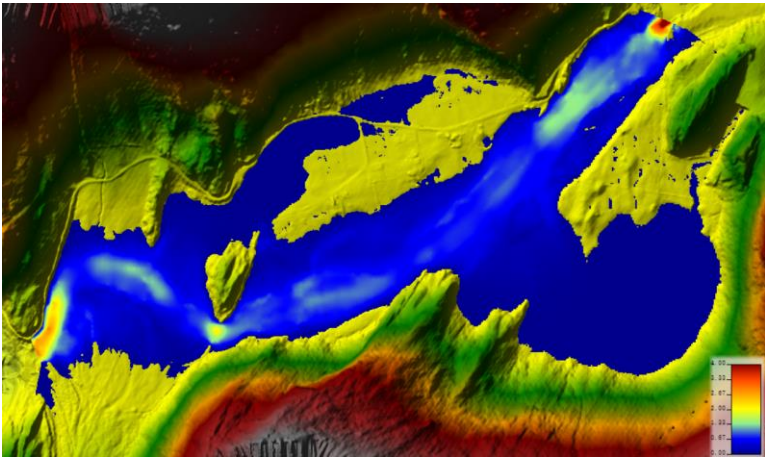
Appendix 3- 4. The map of water velocity simulated in HEC-RAS for 5-year flood after regulation.



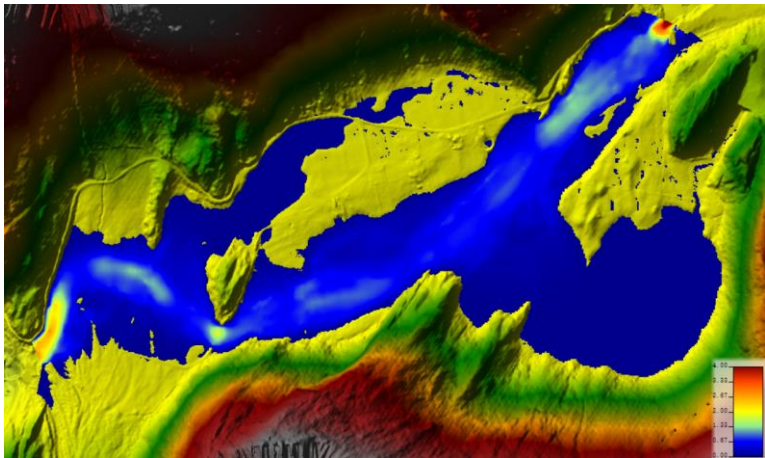
Appendix 3-5. The map of water depth simulated in HEC-RAS for 10-year flood before regulation.



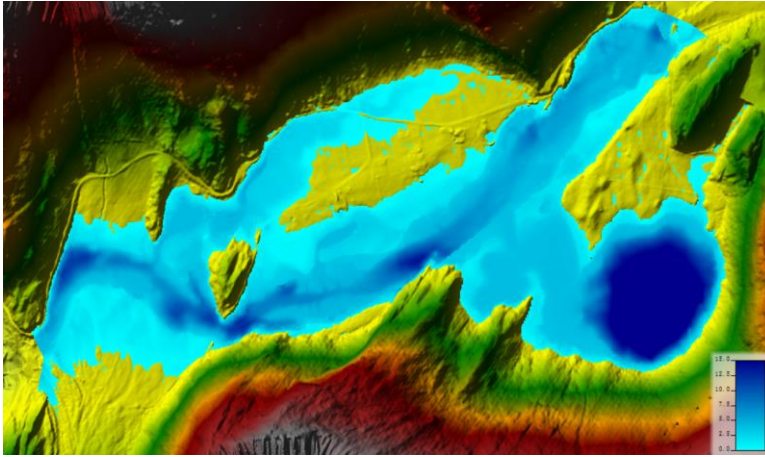
Appendix 3-6. The map of water depth simulated in HEC-RAS for 10-year flood after regulation.



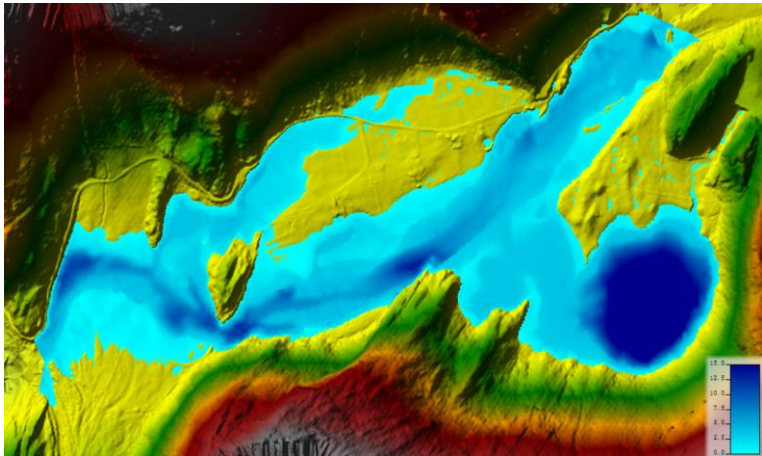
Appendix 3-7. The map of water velocity simulated in HEC-RAS for 10-year flood before regulation.



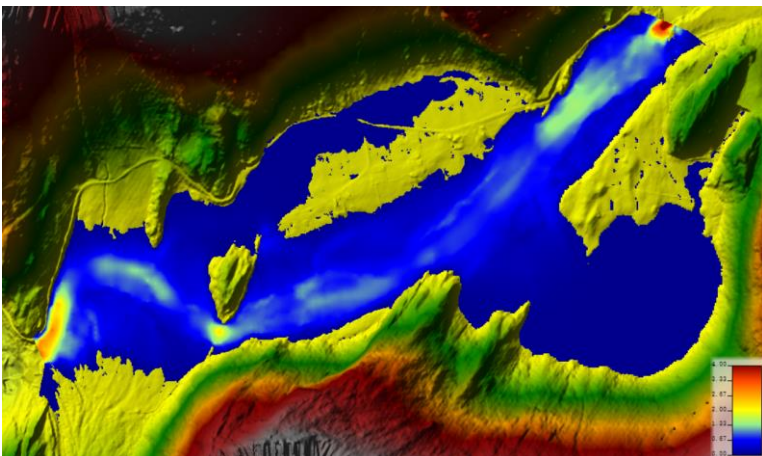
Appendix 3- 8. The map of water velocity simulated in HEC-RAS for 10-year flood after regulation.



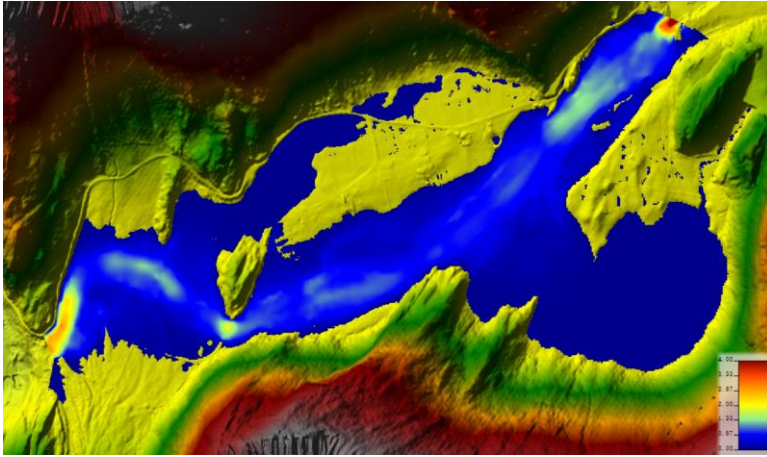
Appendix 3-9. The map of water depth simulated in HEC-RAS for 20-year flood before regulation.



Appendix 3-10. The map of water depth simulated in HEC-RAS for 20-year flood after regulation.



Appendix 3- 11. The map of water velocity simulated in HEC-RAS for 20-year flood before regulation.



Appendix 3-12. The map of water velocity simulated in HEC-RAS for 20-year flood after regulation.

**APPENDIX 4 STATISTICS FOR AREA OF WATER
DEPTH AND WATER VELOCITY IN DIFFERENT
CLASSES**

CLASS	DEPTH(M)	AREA(M ²)before	AREA(M ²)after
1	0-0.05	6224	5853
2	0.05-0.35	20767	21071
3	0.35-0.5	9632	10861
4	0.5-0.8	21024	16451
5	0.8-1.5	34539	36255
6	1.5-3	103921	110677
7	3.0-6.0	91500	72865
8	>6.0	69063	65795
TOTAL		356670	339828

Appendix 4-1. The area summary of the water depth in different classes for the mean flood.

CLASS	V(m/s)	Area(m ²)before	Area(m ²)after
1	0-0.1	164941	162258
2	0.1-0.2	30450	29654
3	0.2-0.5	64376	61960
4	0.5-0.7	49679	48559
5	0.7-0.8	16794	14243
6	0.8-1.0	17355	14031
7	1.0-1.5	8823	5381
8	1.5-2.0	1855	1849
9	2.0-3.0	2103	1648
10	3.0-4.0	200	174
11	>4.0	94	71
TOTAL		356670	339828

Appendix 4-2. The area summary of the water velocity in different classes for the mean flood.

CLASS	DEPTH(M)	AREA(M ²)before	AREA(M ²)after
1	0-0.05	6328	5909
2	0.05-0.35	21109	20900
3	0.35-0.5	10350	9573
4	0.5-0.8	19246	20784
5	0.8-1.5	42644	35184
6	1.5-3	78959	97385
7	3.0-6.0	130596	100605
8	>6.0	74648	70027
TOTAL		383880	360367

Appendix 4-3. The area summary of the water depth in different classes for the 5-year flood.

CLASS	V(m ³ /s)	Area(m ²)before	Area(m ²)after
1	0-0.1	163340	164589
2	0.1-0.2	34072	31138
3	0.2-0.5	74077	65221
4	0.5-0.7	46093	49497
5	0.7-0.8	21594	17311
6	0.8-1.0	24673	18432
7	1.0-1.5	14982	9807
8	1.5-2.0	1974	1833
9	2.0-3.0	2673	2229
10	3.0-4.0	272	212
11	>4.0	130	98
TOTAL		383880	360367

Appendix 4-4. The area summary of the water velocity in different classes for the 5-year flood.

CLASS	DEPTH(M)	AREA(M ²)before	AREA(M ²)after
1	0-0.05	6087	5916
2	0.05-0.35	24287	20917
3	0.35-0.5	10175	10118
4	0.5-0.8	20145	18798
5	0.8-1.5	46251	40298
6	1.5-3	74087	82844
7	3.0-6.0	146393	123494
8	>6.0	79246	73122
TOTAL		406671	375507

Appendix 4-5. The area summary of the water depth in different classes for the 10-year flood.

CLASS	V(m3/s)	Area(m2)before	Area(m2)after
1	0-0.1	163671	163501
2	0.1-0.2	35706	33147
3	0.2-0.5	83597	70650
4	0.5-0.7	43313	47200
5	0.7-0.8	24666	20056
6	0.8-1.0	30342	22678
7	1.0-1.5	19808	13431
8	1.5-2.0	2187	1895
9	2.0-3.0	2905	2587
10	3.0-4.0	319	241
11	>4.0	157	121
TOTAL		406671	375507

Appendix 4-6. The area summary of the water velocity in different classes for the 10-year flood.

CLASS	DEPTH(M)	AREA(M ²)before	AREA(M ²)after
1	0-0.05	7102	6586
2	0.05-0.35	24891	22752
3	0.35-0.5	11359	9874
4	0.5-0.8	21408	19842
5	0.8-1.5	45328	44640
6	1.5-3	80829	76409
7	3.0-6.0	153734	135875
8	>6.0	83596	76071
TOTAL		428247	392049

Appendix 4-7. The area summary of the water depth in different classes for the 20-year flood.

CLASS	V(m ³ /s)	Area(m ²)before	Area(m ²)after
1	0-0.1	169856	164571
2	0.1-0.2	32596	33669
3	0.2-0.5	92304	77295
4	0.5-0.7	39774	45700
5	0.7-0.8	27085	22444
6	0.8-1.0	35022	26805
7	1.0-1.5	25589	16331
8	1.5-2.0	2386	2047
9	2.0-3.0	3077	2761
10	3.0-4.0	379	284
11	>4.0	179	142
TOTAL		428247	392049

Appendix 4-8. The area summary of the water velocity in different classes for the 20-year flood.

APPENDIX 5 DETAILED INFORMATION ABOUT USING THE ARCGIS TO FINISH SOME TASKS

1. Add a field in the attribute table, right-click the field heading of z and click Field Calculator.

2. Use the Fields and Functions to develop the expression for calculation.
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Appendix 5-1. Process for calculating the elevation of the river bed in ArcGIS.

1. Open Attribute Table.

2. Click Selection, click Select by Attributes, write the selection expression and click Apply.

3. Right-click the row button and chose Delete Selected.
--

Appendix 5-2. Select and delete useless points in ArcGIS.

Step 1: Merge ADCP data. It is accomplished by clicking the ArcToolBox button, selecting data management tool/ general/merge and adding the dataset that needs to be merged.

Step 2: Open the ArcToolbox, select 3D Analyst tools/raster interpolation/Topo to raster. After that we add the layer created in step 1 and choose the location of output surface raster, after that click ok.

Step 3: Open Arctoolbox /spatial analyst/surface/contour. Add Input feature data: add the raster layer created in step2, then define contour interval: define the interval of the contours (0.5m).

Step 4: Use the shapefile of water area to clip the feature that we create in step 3.

Step 5: Open the layer attribute table and use the field calculator to generate bed level.

Step 6: Create point features along polylines at fixed intervals or by percentage.

The contour lines will become the green dots after Step 6 .

Appendix 5-3. Process for making water lines in ArcGIS.

Step 1. Merge all the point data we made before. It is accomplished by clicking the ArcToolBox button, then selecting data management tool/ general/merge, adding the dataset need to be merged (ADCP, GPS, VEGETATION, WATER LINE POINT, CLIPPED DEM) and clicking ok.

Step 2. Interpolation. Go to customize- toolbar and make sure Geostatistical analysis is selected. Click Geostatistical Analyst and select Geostatistical Wizard. This selection will bring up a new window shown in Figure 4-14 below, then choose the interpolation method (Empirical Bayesian Kriging method) and select the source dataset which is the merged shapefile we made in step 1. Click next. The computer starts to progress. After a while, the layer of the result will be displayed in the main window.

Step 3. Export the data. Right-click the layer to generate in the last step, then select Data-Export to raster. A new window will be brought up. Select a folder to store the output surface raster and name it. Select the output cell size. Then click ok. The terrain for the study area is ready for importing into the HEC-RAS.

Appendix 5-4. The steps about how to create the terrain model in ArcGIS.

1. Create a new point shapefile and draw some points contained elevation information around the inlet of the lake.

2. Merge this file with other elevation data files.

3. Run Geostatistical analysis.

Appendix 5-5. Process to modify the terrain in ArcGIS.

Step 1: Save the result maps of the water depth and velocity for different scenarios as raster data in HEC-RAS.

Step 2: Import the resulting map into ArcMap.

Step3: Go to the toolbox, open Spatial Analyst – Reclass and Reclassify (reclassify the water depth and flow velocity according to the table 6-13 and table 6-14).

Step 4: Convert the reclassified raster layers to the polygon by using conversion tools.

Step5: Select the area meet the requirement for specific fish by using the selection by attribute table.

Step 6: Intersect water depth area and velocity area meet the requirements for the specific stage.

Appendix 5-6. The process to get the maps and the statistical results of the suitable area for brown trout in ArcGIS.