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Hydrodynamic optimization of wetland restoration measures at the Storelva river floodplain with its meanders and oxbow lakes in Southern Norway

Master's thesis in Civil Engineering
Supervisor: Dr. Peggy Zinke
March 2019

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Abstract

The "Fellesprosjektet Ringeriksbanen og E16" is an infrastructure project in the south of Norway connecting Oslo and shortening the travel time with the new housing and development area of Ringerike. For the connection of Sundvollen and Hønefoss the FRE16 project is planned to cross the river Storelva and its neighboring wetlands. The area under investigation is partly defined as a Ramsar conservation area and important to many wildlife and vegetation species.

The planning institution has provided two alternatives for the crossing of the river Storelva and the wetland Mælingen north of the main channel. Alternative A, a bridge over Mælingen and Alternative B, a bridge with a partly dam over Mælingen were investigated for the flood event of 1967 with a numerical 2D unsteady flow model with HEC-RAS 5.0.6 and compared with the actual condition of the Storelva area. Furthermore the statistical flood events HQ10 and HQ200 were implemented into the 2D model for Alternative B and the actual condition and analyzed. As a comparison of the influence of the regulation of the Storelva, the statistical 0.9 percentile of an annual flood over two periods, before and after the regulation, were calculated and the results are presented. For the future restoration of the oxbow lakes one calculation was made with a deepened bed to 58.3 m above-normal in the oxbow lakes Juveren and Synneren and the flow hydrograph for HQ200. The numerical model was calibrated and validated and inaccuracies in the existent bathymetry files were modified and technical objects implemented.

The results of the numerical model for Alternative B show a decrease of the water levels in the oxbow lakes Juveren and Synneren for a statistical flood event HQ10 of maximum 11 cm. For the flood events of 1967 and HQ200 however, the water surface elevation increases in the investigated oxbow lakes by 5 cm for the 1967 flood event and 1 cm for the HQ200 statistical flood. Nevertheless, the values of the water surface elevation results are smaller than the overall vertical resolution of the underlying terrain data with 25 cm and this accuracy has to be taken into account. The investigating of the velocities at the wetland Mælingen showed a decrease of the flow velocities at the Mælingen cross section for the statistical flood HQ10 and an increase of the velocities for the 1967 flood event and the HQ200 flood by twice the values of the actual condition.

For the ecological restoration it is recommended to implement a best management practice to reduce the inflow of non-point sources into the oxbow lakes. These methods have to be planned for each oxbow lake and managed to match the ecological needs of the conservation area. Furthermore the removal of Canadian pondweed should be considered and strategies for the measures should be undertaken.

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Abbreviations

AC	Actual condition of the terrain
Alt-A	Alternative A of the FRE16 project
Alt-B	Alternative B of the FRE16 project
DEM	Digital Elevation Model
DTM	Digital Terrain Model
FRE16	Fellesprosjektet Ringeriksbanen og E16 Infrastructure joint project railway “Ringeriksbanen” and highway “E16”
ha	hectar
HEC - RAS	Hydraulic Engineering Center - River Analysis System
HQ10	statistical 10 - year flood
HQ50	statistical 50 - year flood
HQ200	statistical 200 - year flood
LIDAR	Light Detection and Ranging
MW	megawatts
NVE	Norwegian Water Resources and Energy Directorate
WSE	Water Surface Elevation

1 Introduction

The history of travelling from Oslo, Norway to the northern parts of Norway has a long tradition. One of the most important structural paths from the past is the Old King's Road (Gamle Kongenvegen) which leads from Oslo to Bergen through the province of Buskerud. Like the Old King's road, several pilgrim paths connect different areas of Scandinavia with the final destination, the Nidaros Dome, in Trondheim. Another important pilgrims path is the Gudbrandsdalen path that starts in Oslo and leads over Hønefoss, the main city in the region Ringerike, a part of the province Buskerud, to Trondheim crossing the Tyrifjorden and Steinsfjorden at Sundvollen (National Pilgrim Center/NDR, 2018). With its former importance it is no surprise that even in the 21st century the infrastructure connection from Oslo to Hønefoss and to the northern parts of Norway, is still important.

In April 2017 the Norwegian Ministry of Transport and Communications submitted the National Transport Plan (Meld. St. 33 (2016-2017)) to the Storting, the Parliament of Norway, and presented it to the public. In this National Transport Plan the Norwegian transport sector describes the tasks to reach the overall objective of "[…] A transport system that is safe, enhances value creation and contributes to a low-carbon society […]" (Samferdselsdepartementet, 2017). One of these infrastructure projects is the "Fellesprosjektet Ringeriksbanen og E16 (FRE16)", a joint project of Statens vegvesen (Norwegian Public Roads Administration) and Bane NOR SF, the state-owned railway administration in Norway. The main significance of the NOK 26 billion project is to develop the region of Ringerike in terms of new housing and establishment areas near the capital Oslo by shortening the travel time by car on the E16 highway and on railway transport with the Ringerike Line to the main capital Oslo (Bane Nor, 2016).

To reach the goals of the National Transport Plan, the line haul of the FRE16 project will pass, among others, about 23 km of railway tunnel from Sandvika to Sundvollen and 3 km of tunnel in the northwest of Sundvollen. Following the path from Sundvollen to Hønefoss the FRE16 will cross several waterbodies, for example Tyrifjorden and the Storelva river with its wetland systems and conservation areas in the Buskerud area especially in the Ringerike Area (Botnen, 2016).

Associated with these plans and on behalf of the county Governor of Buskerud, the Norwegian Institute for Nature Research (NINA) was conducted to investigate the interdisciplinary project “Assessment and suggestions of wetland restoration measures in oxbow lakes and floodplain structures along Storelva river in Ringerike and Hole Municipality”. The project is a cooperation between the NINA, Dokkadeltaet Nasjonale Våtmarkssenter AS (DNV), the Norwegian University of Science and Technology (NTNU) and the wetland group of the Norwegian Ornithological Association (NOF), Department Hedmark.

This thesis will investigate the influence of the FRE16 infrastructure project on the hydrodynamics of the oxbow lakes and discuss scenarios for the restoration and improvement of the hydrological conditions.

2 Ecology and restoration of oxbow lakes

Natural abandoned channels are formed due to the tendency of rivers to meander within their floodplain to balance transport of water and sediment. With this dynamical behavior of the river, two kinds of natural cutoffs can occur (Gepp, 1985; Julien, Shah-Fairbank, & Kim, 2008). First the neck cutoff, where sediment is continuously deposited on the convex bank and sediment is eroded form the concave bend. Due to this process the two bends gradually converge to each other until eventually the river forms a straight line and leaves an abandoned channel, by sealing the cutoff through sediment, leaving an oxbow lake (Julien et al., 2008). In Figure 2.1 an example of the meandering stream evolution of a neck cutoff is shown.

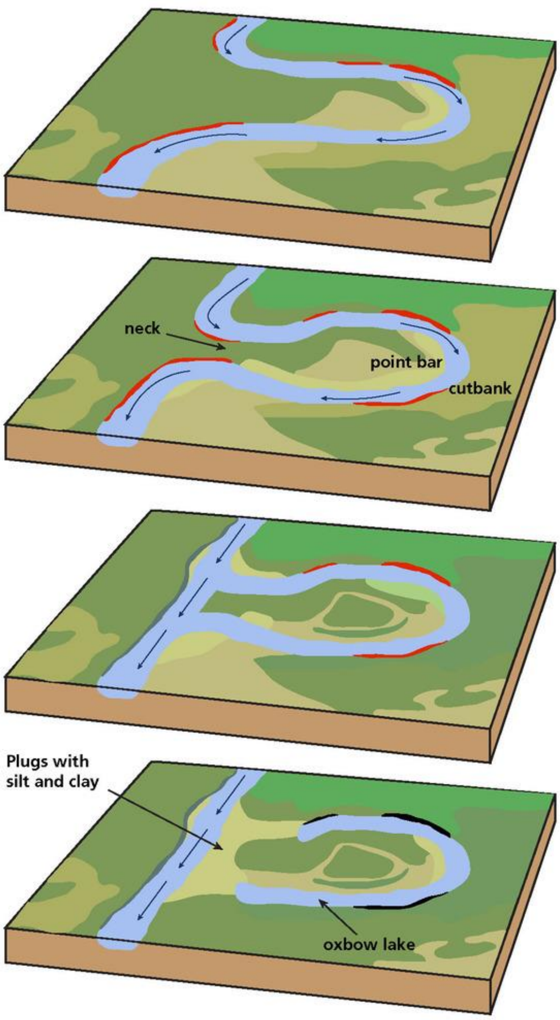


Figure 2.1: Stream evolution neck cutoff (1) stream channel within meander belt; (2) development of a nearly closed meander loop; (3) high water flowing across the neck of loop, making a cutoff; (4) deposition of sediment sealing the loop and creating an oxbow lake (Reiker, 2019)

A second possibility of an oxbow lake formation is the chute cutoff (Figure 2.2). This cutoff usually occurs, when high water flows develop a chute across the inside of a point bar by overflowing the terrain, decreasing the sinuosity of the river forming a middle bar. With this process, rivers increase the slope of the riverbed and with higher velocities occurring, the capacity of sediment transport increases (Julien et al., 2008).

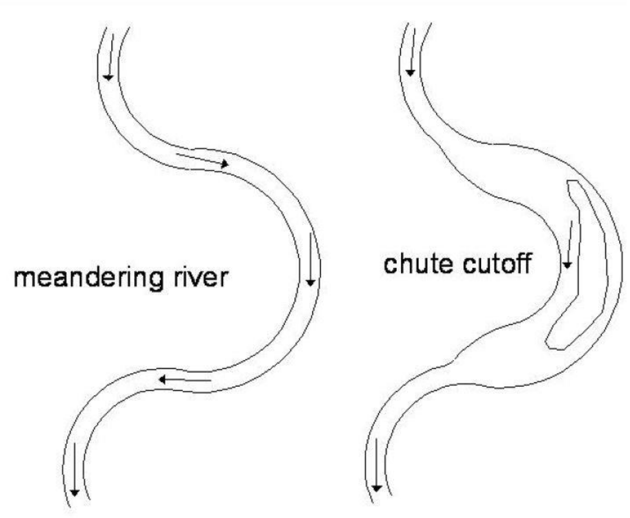


Figure 2.2: Stream evolution chute cutoff (Julien et al., 2008)

Furthermore, oxbow lakes can be formed by engineering. Similar to the natural evolution of an abandoned channel, a straight pilot channel is constructed to aid with navigation and flood control and cutting off the bow of a river. In this case it is important to construct revetments upstream and downstream of the concave side of the river to pretend an uncontrolled meandering.

Since rivers are highly dynamic and many parameters influence the ecology of oxbow lakes, each oxbow lake and wetland system has to be investigated for its feasibility to improve the actual condition into a more natural state, if possible. This includes an exact survey of the single oxbow lake.

The ecology of oxbow lakes is an intermediate status between flowing water and standing water. Characteristic for the ecosystem of flowing waters is the factor of streaming. The higher the stream velocity, the more characteristic is the biocenosis. But in oxbow lakes, similar to ponds, the low stream velocity has no impact on the ecological factor (Gepp, 1985). Different species of vegetation can be found in oxbow lakes and their biological opulence can be compared with rainforests in tropical areas (Lüderitz, Langheinrich, & Kunz, 2009). The variety of littoral zones with deeper and shallower areas and possibilities for silting up, offers a good habitat for flora and fauna (Gepp, 1985). Oxbow lakes are also important in matter of fish migration for reproduction and as a hiding area for young fish of different species (Gepp, 1985; Penczak, Zieba, Koszalinski, & Kruk, 2003).

Oxbow lakes are a product of the natural aging process of river systems. Ever since rivers were used and modified for human needs it had an influence on oxbow lakes (Lüderitz et al., 2009). The impact of humans is not only significant in the investigated areas itself but the whole watershed. This includes the land use of the whole catchment area, the usage of hydro energy and the constructions along the river for the protection of flood water and use as infrastructure (Gepp, 1985; Julien et al., 2008).

Therefore the main impact to the ecology of oxbow lakes has to be identified. One of the most influential impacts is the input of sediment and its contaminants changing the water quality (Julien et al., 2008). The cause of regulating the river for hydro power plants and change in land use can affect the oxbow lakes to fall dry by being disconnected to the main river due to plugged sediment. As later seen in chapter 5.4 the discharge of the floods that used to overflow these wetland systems in a periodical matter decreased thus lacking a dynamical exchange of water and sediment.

Julien et al. (2008) have come up with a table for the classification and the resulting benefit of restoration in abandoned channels on different rivers in the United States (Table 2.1). After identifying the main issue for the oxbow lake, three categories of restoration efforts can be applied.

The construction of oxbow lakes as a replacement for wetland is a method to mitigate the destruction of wetlands. Overall it is tried to imitate the ecological behavior of natural oxbow lakes by surveying naturally formed oxbow lakes and thus constructing an oxbow lake environment. This restoration method was adapted at the Kachituli Oxbow at the Sacramento River in North Carolina and accompanied by an management plan including the artificial migration of fish and weeds (Hey & Philippi, 1999; Julien et al., 2008).

Best management practices (BMPs) can increase water quality of oxbow lakes significantly (Julien et al., 2008). The goal of BMPs is to reduce the input of sediment and non-point source pollutants from agricultural runoff, especially in areas with high agricultural land use (Cullum, Knight, Cooper, & Smith, 2006). These practices include agronomics, edge-of-field practices, stream buffer strips and bank stabilization.

Furthermore the restoration of oxbow lakes can be engineered. Nevertheless, engineered solutions can never replace the complex dynamic processes and ecological coherences of a natural oxbow lake evolution (Lüderitz et al., 2009). In some cases engineered solutions like weir constructions and dams or gates will improve the water quality of oxbow lakes but cause other problems regarding fish migration or maintenance of technical objects (Julien et al., 2008; Lüderitz et al., 2009).

Additional to this knowledge it can be said that the reconnection of abandoned channels, particular oxbow lakes can improve the ecological state and are essential in retaining the high biological fish diversity as investigated at oxbow lakes in Poland (Obolewski et al., 2016) or used in different areas in Germany (Akkermann, 1994; Lüderitz et al., 2009). Furthermore oxbow lakes are important for nutrient transport towards the river relying on regulation and are conducive to nutrient supply in the ecosystem of the main river (Glińska-Lewczuk, 2009; Ndikumana, 1999).

Table 2.1: Classification and benefits of restoration (Julien et al., 2008)

	Type of Restoration	**Benefits**
Wetlands	Riparian Wetlands	Improved water quality
		Enhance of wildlife habitat
BMPs	Agronomics	Reduce sediment, nitrogen and phosphorus
	Edge of Field practices	
	Stream buffer strips	
	Bank stabilization	
Engineered Solutions	Weir construction	Increase flow interaction Improve water quality Improved navigation in main channel
	Dam and gate	Increase flow interaction Improve water quality
	Pump to divert flow	improve water quality remove organics
	Dredging	deepen lake
	Adding water from power plant	Increase flow depth
	Riparian Buffer	Prevent channel migration
	Lock and dams	Improve navigation in channel

3 Area of investigation

3.1 Ringerike and Hole

The investigated area is located in the municipalities of Ringerike and Hole. They are a part of the province Buskerud in the south-east of Norway with the nearest city Oslo in the south-east. Ringerike was inhabited well before 200 AD and was the childhood home of the greatest early kings of Norway during the 10th century (Encyclopædia Britannica, 2018). Ringerike has an area of 1553 km^2 and a population of 36.200 (Utne, 2018). Figure 3.1 shows the position in Norway (top) and the borders of the Ringerike Municipality (bottom). Hole is the neighboring municipality south of Ringerike. The boarder between the two municipalities is defined by Storelva until Helgelandsmoen and then crossing the conservation area Lamyra. The border can also be seen in Figure 3.1, bottom right, as a dashed line. In the following the investigated area of Ringerike and Hole will be noted as Ringerike.

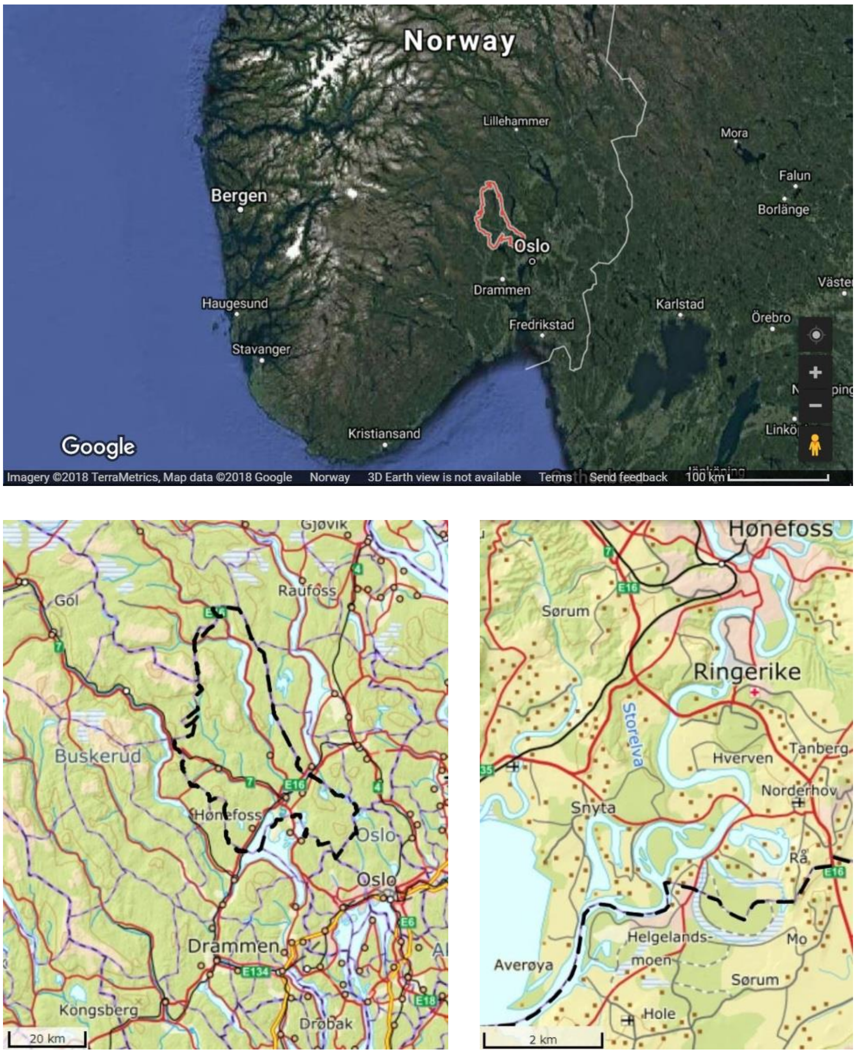


Figure 3.1: Commune Ringerike (top, red outline and bottom left, black outline) and river Storelva from Hønefoss to Tyrifjord with the border between Ringerike and Hole (bottom right, dashed line), modified. (Google Maps, 2018; Norconsult Informasjonssystemer, 2018)

3.2 Storelva river system

The main body of water in the investigated area of Ringerike is the Tyrifjorden. Tyrifjorden is the fifth largest lake in Norway and has a surface area of 137 km^2 storing 13 km^3 of water (Seppälä, 2005; Thorsnæs, 2018a). The main feeding source to Tyrifjorden is the river Storelva located in the northern branch of the landlocked fjord. Storelva can be translated in the Norwegian language to "large river" and can be found as a name giver for rivers all over Norway. At Vikersund in the south-western branch of Tyrifjorden, the outlet stream continues the so called "Drammensvassdraget", the river system of Drammen, with the river Drammenselva as the lowest part, into "Drammensfjorden" (Thorsnæs, 2017).

Storelva is the joining product of the two rivers Ådalselva and Randselva (Figure 3.2).

Ådalselva is the lower part of the river Begna, coming from the lake Sperillen in the north of Tyrifjorden. Ådalselva is a water rich stream and heavily used for hydropower production. Alongside the river are four hydropower plants, Begna (Svinefoss), Hennsfoss, Hofsfoss including Follumfoss and Hønefoss with a total electrical performance of 71.3 megawatts (MW) and an average annual production of 383 gigawatt hours (2016) (Thorsnæs, 2018b).

The second water source for Storelva is the river Randselva. Randselva connects the Randsfjord in the north with the joint in Hønefoss. Like Ådalselva, Randselva is also used as a power distributor for the hydropower plants Bergerfoss, Kistefoss I and II, Akerudfoss and Viulfoss combining an electrical performance of 31.9 MW (Vinjar, 2019)

The accompanying values for the discharge of Ådalselva and Randselva are further described in chapter 4.2.7.

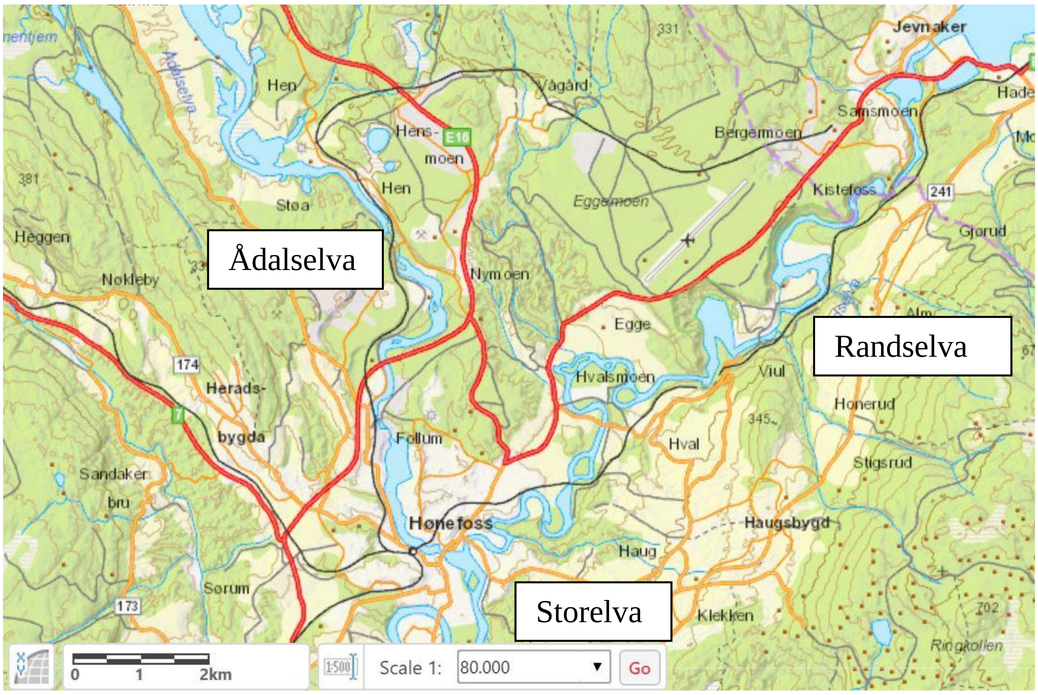


Figure 3.2: Map with the rivers Ådalselva and Randselva joining to Storelva, modified (Norges vassdrags- og energidirektorat, 2019).

The river Storelva begins at the foot of the Hønefoss waterfall in Hønefoss, Norway. The waterfall is bypassed by a hydro power plant with an annual energy outtake of 124 GWh which provides 7700 household with electrical power. The dam for the Hønefoss power plant was erected in 1978 and has an average discharge of 90m³/s of which 10% actually is used to run the turbines (Ringerikskraft, 2018). During its path to the inlet into Tyrifjorden the river meanders through a diverse and unique wetland system passing Helgelandsmoen.

3.3 Ramsar conservation areas

The Nordre Tyrifjord Wetland system became a designated Ramsar conservation area on the 18th March of 1996. This cluster of five different conservation areas (Figure 3.3) forms a total area of 322 ha and is an important inland site for migrating and wintering wetland birds (Norwegian Environmental Agency, 2018). It consists of the mouth of Sokna, where it flows into the Tyrifjorden (Karlsrudtangen), the Storelva mouth (Averøya) and the oxbow lakes Juveren, Lamyra and Synneren.

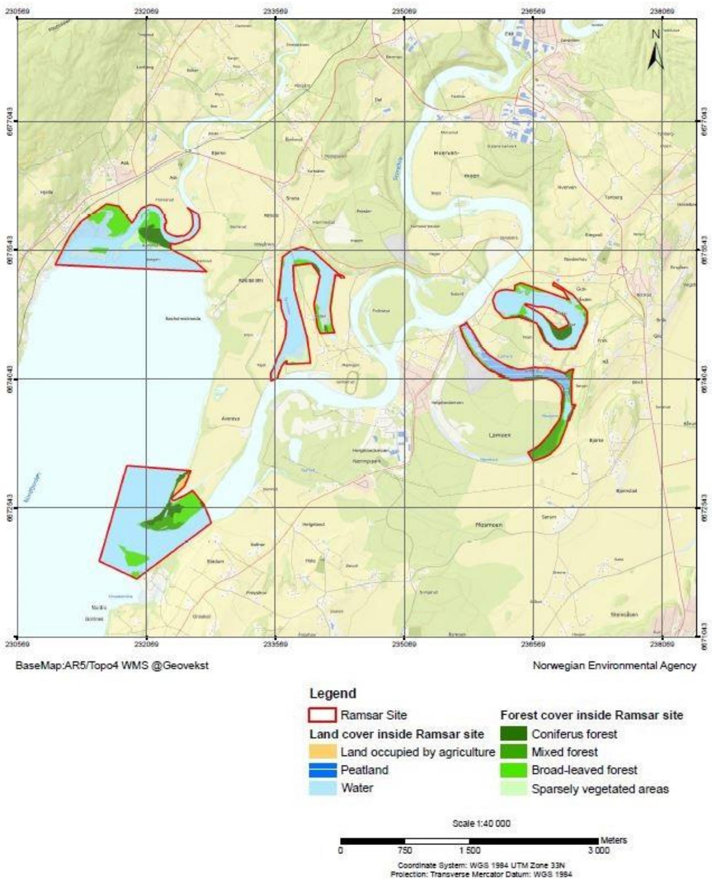


Figure 3.3: Nordre Tyrifjord Wetlands Systems (Norwegian Environmental Agency, 2018)

The importance of the site and its status as a Ramsar site comes from the following criteria. The delta of Tyrifjord is formed by transportation of sediments from the rivers Storelva and Sogna where the delta itself functions as a barrier and trap for sediments and therefore as an important retention of nutrients. Furthermore, according to the Ramsar report, the Nordre Tyrifjord Wetland system is one of the largest inland deltas in south Norway. With its slow flowing meandering rivers and the several oxbow lakes with varying stages in its development, they carry a large and interesting biological diversity (Karr, 2018). Due to this unique role a vast amount of animals and bird species as well as a high diversity of vegetation can be found and looked up in the Ramsa Site Report 802.

3.4 Abandoned channels of Storelva

Between Tyrifjord and Hønefoss several abandoned channels can be found. As described in 3.3 they have become Ramsar conservation areas in 1996, except the area of Busundevja (Figure 3.4) north of Lamyra across the river. Because of the high ecological importance of the area it is planned to establish a new conservation area "Nordre Tyrifjorden og Storelva" including the different nature reserves (Figure 3.5).

The oxbow lakes Juveren, Lamyra and Synneren mentioned in this thesis can be compared with the suggested forms of the evolution of oxbow lakes. It can be said, that the evolution of a neck cutoff most likely happened at Juveren, Lamyra and Synneren. These oxbow lakes show the approach of their branches which is characteristic for a neck cutoff as described in chapter 2. The bypass of Storelva is not yet an oxbow lake and still connected to the main river and traversed with water flow. Nevertheless, first indications of the evolution of a chute cutoff, probably formed by a large flood event in 1860 (Zinke & Dervo, 2018), can be mentioned.

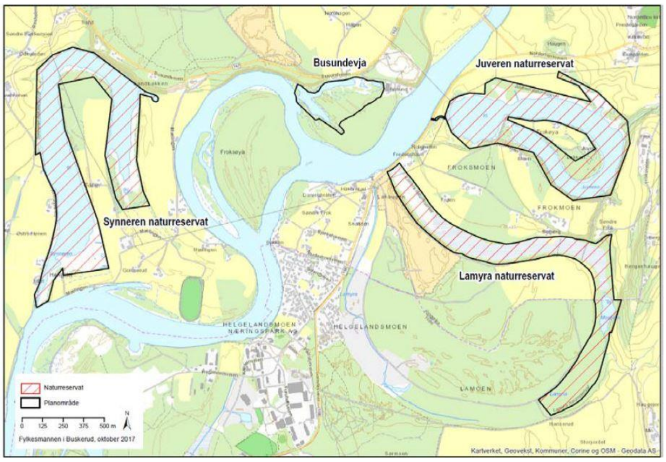


Figure 3.4: Oxbow lakes and branch of Storelva near Helgelandsmoen (Engen, 2018)

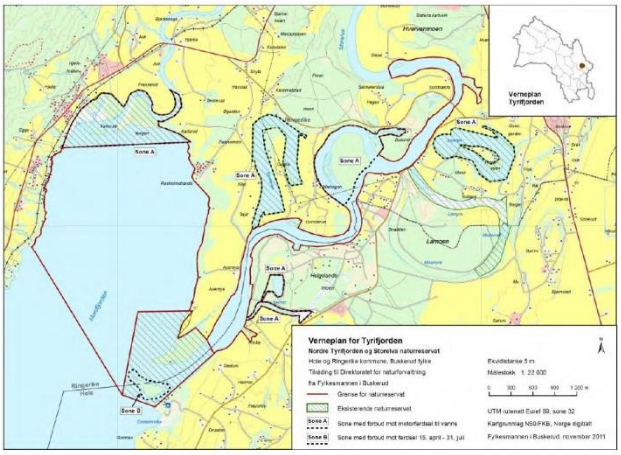


Figure 3.5: Plan for conservation area "Nordre Tyrifjord og Storelva" (Fylkesmannen i Buskerud, 2016)

3.4.1 Juveren

Juveren (Figure 3.6) is situated in the northeast of the investigated area. It is an oxbow that formed approximately 1.100 to 1.700 years ago and is connected through a box culvert under the neighboring street with the main river, Storelva (Zinke & Dervo, 2018). In 1985 the 440 ha of Juveren were declared as a conservation area to preserve the wetland vegetation, birds and other wildlife that is associated with this area of nature (Ringerike kommune, 1985; Zinke & Dervo, 2018). From a limnological point of view, Juveren is quite important. According to the management report from the County Governor of Buskerud (Fylkesmannen) it maintains a dichotomous pH environment despite the high calcium content caused by the adjacent lime stone formations in the eastern part. Furthermore interesting phenomenas are mentioned due to ferric and phosphorous exchange. During floods Juveren receives a large amount of humus which is rare in calcareous lakes in Norway and leads to a various vegetation (Runningen, 2017). But it can also be mentioned that some limnological parameters have changed in the past years due to the additional input from agriculture run off (Fylkesmannen i Buskerud, 2016; Runningen, 2017). Juveren is located approximately 63 m above-normal, which also corresponds with the highest regulated water level of Tyrifjorden. Therefore the oxbow lake is influenced by the water level of Tyrifjorden (Runningen, 2017).

Figure 3.6: Aerial view of Juveren (Google Maps)

3.4.2 Lamyra

Lamyra (Figure 3.7) lies south of Juveren and is approximately 5000 years old (Zinke & Dervo, 2018). The Lamyra oxbow lake has a significant value for the neighboring habitants since the mire in the eastern part of the bend has been described in many poetries and myths (Zinke & Dervo, 2018). It is vegetated with swamp forest and accommodates a small pond called Mostjern at the furthest point from Storelva (Runningen, 2017; Zinke & Dervo, 2018). Lamyra is still connected to Storelva with a culvert but a ground sill was built to hold the water level in Lamyra to a specific height. The water level in Lamyra is usually higher than in Storelva during low flow or mean flow conditions and getting flooded during larger flood events (Zinke & Dervo, 2018). During a visit in December 2018 it was mentioned, that the ground sill is still present. Lamyra is fed by groundwater and established a swamp environment (Runningen, 2017).

Figure 3.7: Aerial view of Lamyra (Google Maps)

3.4.3 Synneren

Synneren, just as Juveren, is an oxbow lake still connected to Storelva and lies in the north-west of the investigated area at a height of ca. 63 above normal (Runningen, 2017). Similar to Juveren, the oxbow lake was formed about 1.100 to 1.700 years ago (Zinke & Dervo, 2018). Synneren is connected over a small channel with rock walls on both sides to Storelva in the south. According to Brandrud (1998) the chemical and ecological parameters are quite similar to those in Juveren. Also it is assumed that the inflow of nutrients benefitted the development of the same vegetation.

At the northeast reaching into Mælingen, is a branch of Synneren impacted by the FRE16. The line haul will cover the area in total and cut it from its natural connection to Synneren. To this date it is not a part of the conservation area but still an important part of the diverse wet-land system in the Storelva river system.

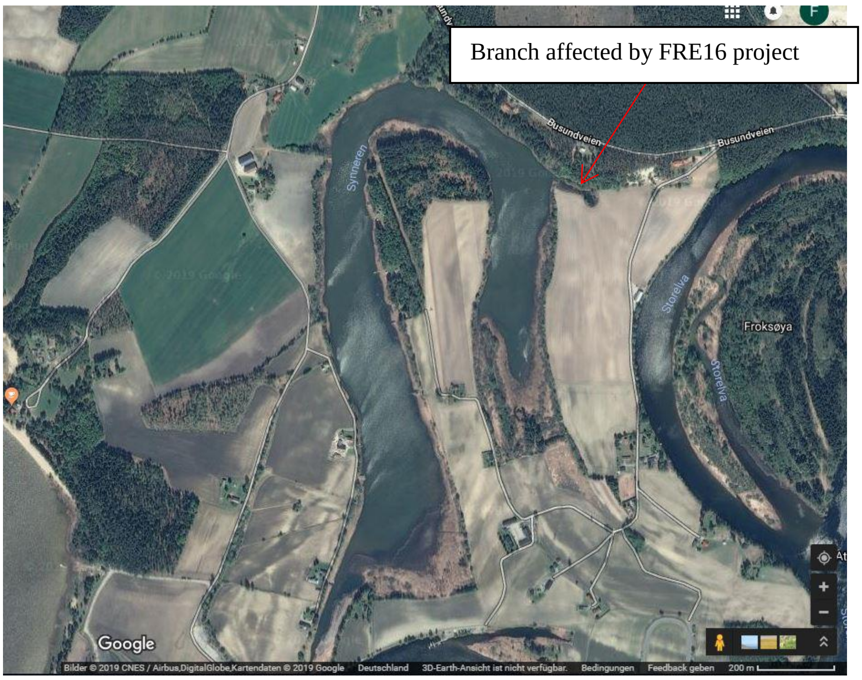


Figure 3.8: Aerial view of Synneren and affected branch (Google Maps)

3.5 Infrastructure project FRE16

With the submission of the National Transport Plan (Meld. St. 33 (2016-2017) the start of the "Fellesprosjektet Ringeriksbanen og E16" could be realized. The object of this thesis was to investigate the hydrodynamic influence of the FRE16 project on the adjacent oxbow lakes and wetlands.

In Figure 3.9 the proposed path of the FRE16 with the crossing at the investigated area at Helgelandsmoen is shown.

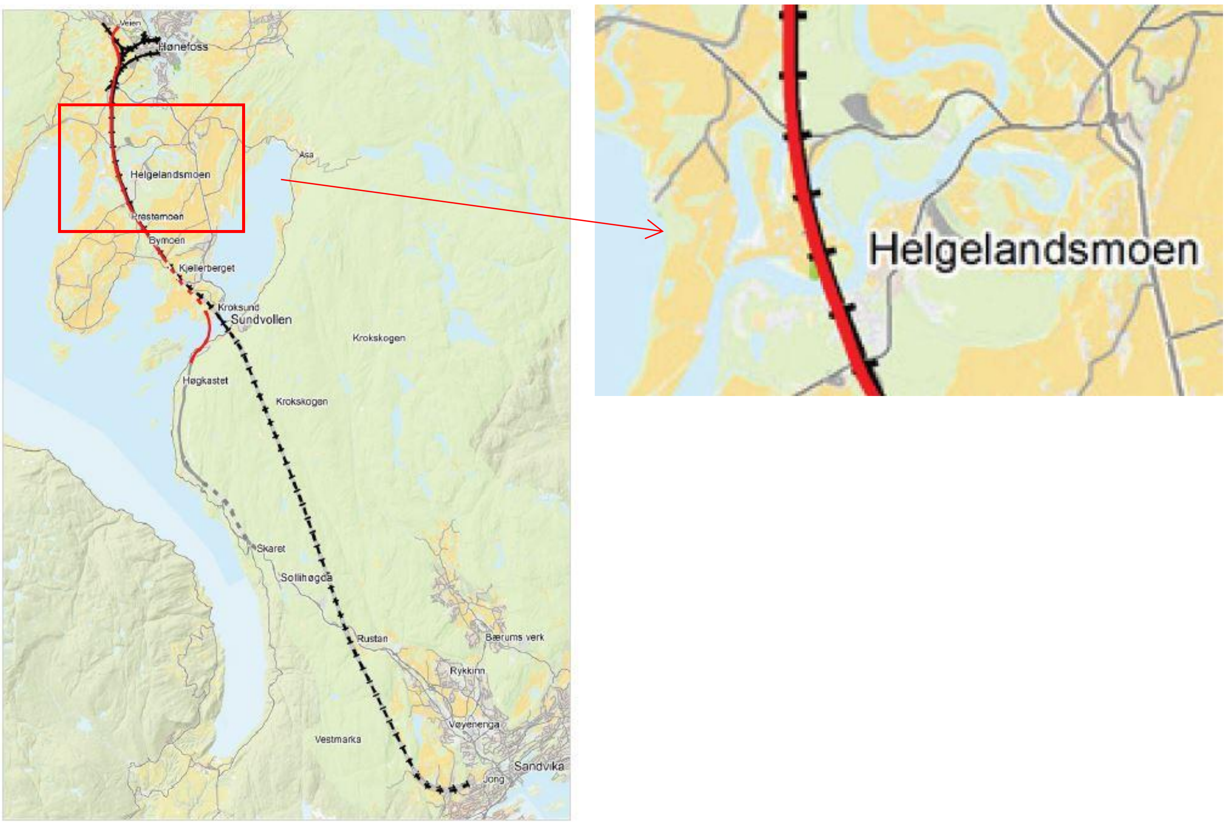


Figure 3.9: Path of the FRE16 project (Bane Nor, 2018)

The planned crossing of the Storelva involves a high impact on the nature and wildlife. Two different alternatives were proposed by BaneNor and are further described: Alternative A with a bridge over Mælingen (Figure 3.10) and Alternative B with a 600 m long embankment at Mælingen (Figure 3.12).

Norconsult provided LandXML files (.xml) of the future terrain modifications. LandXML files are 3D files of objects and usually used for planning in AutoCAD. The LandXML included the bridge poles for alternative A and the dam and bridge poles for alternative B. Since HEC-RAS 5.0.6 cannot process LandXML files the provided files had to be converted into a format that can be handled by HEC-RAS. To convert the LandXML files, AutoCAD Civil 3D was used. The files were imported as LandXML files and saved as Digital Terrain Model (DTM) files. DTM files are a format, commonly used in the AutoCAD environment and describe two or three dimensional objects in a binary form.

These DTM files had to be projected from the coordinate system “Euref 89, Zone 10”, used by Norconsult to the coordinate system “WGS84” which was used for the bathymetry file from Høydedata, to match the geographic location of the investigated area and to fit with the modified bathymetry used for the actual condition. After assigning the projection, a new DTM file was constructed from the DTM files by using 3D polylines. After this step the elevation data of the produced 3D polylines could be retrieved and assigned to the DTM file.

Following, the retrieved DTM file can be exported to a DEM file which can be modified and imported to the terrain editor RAS-Mapper of HEC-RAS 5.0.6. DEM is the Digital Elevation Model and it adds the surface parameters to the data for the use in HEC-RAS 5.0.6. By combining the modified bathymetry and the DEM files in HEC-RAS, a shift of the elevation of the infrastructure body could be mentioned. Therefore the DEM was modified to match the bottom of the surface to the surrounding terrain described by the bathymetry. The resulting terrain files used for the calculation of the different infrastructure options can be seen in Figure 3.11 and Figure 3.13.

Alternative A of the crossing of the Storelva consists of a bridge over Storelva proceeding to bridge the wetland of Mælingen via a path on poles. In Figure 3.10 the draft of the Alternative A is shown.

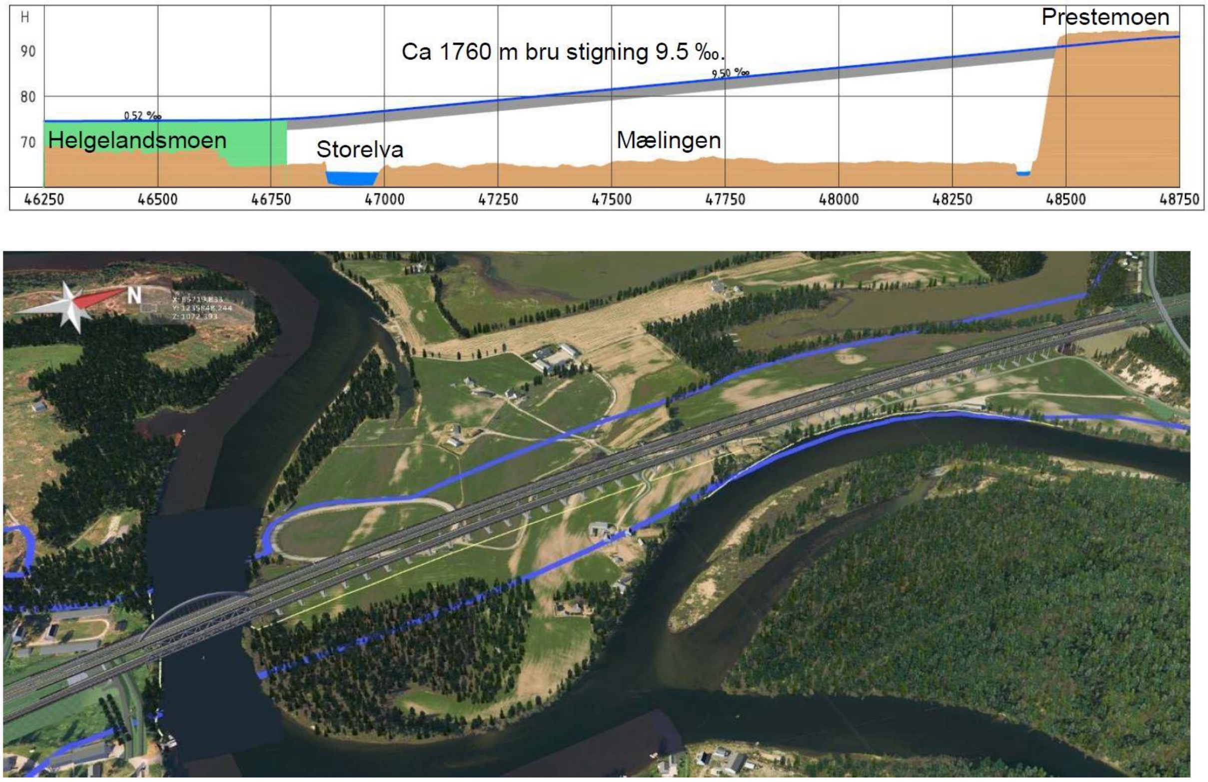


Figure 3.10: Alternative A: Bridge over Mælingen (Bane Nor, 2018)

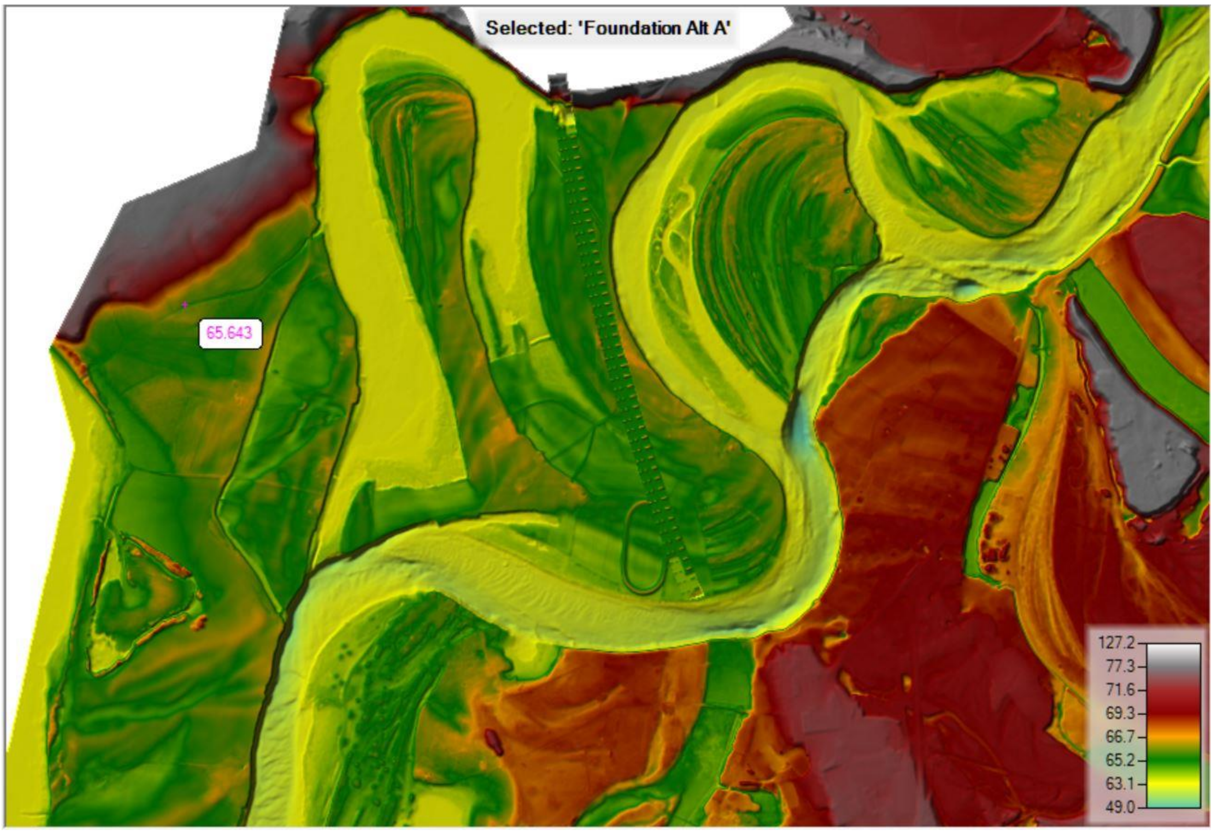


Figure 3.11: Terrain file Alternative A

Alternative B is a hybrid of a bridge and a dam. The crossing of Storelva consists of a bridge merging into an overpass on a 600 m long dam and continuing with a bridge connecting Mælingen and Prestemoen. This planed construction can be seen in Figure 3.12.

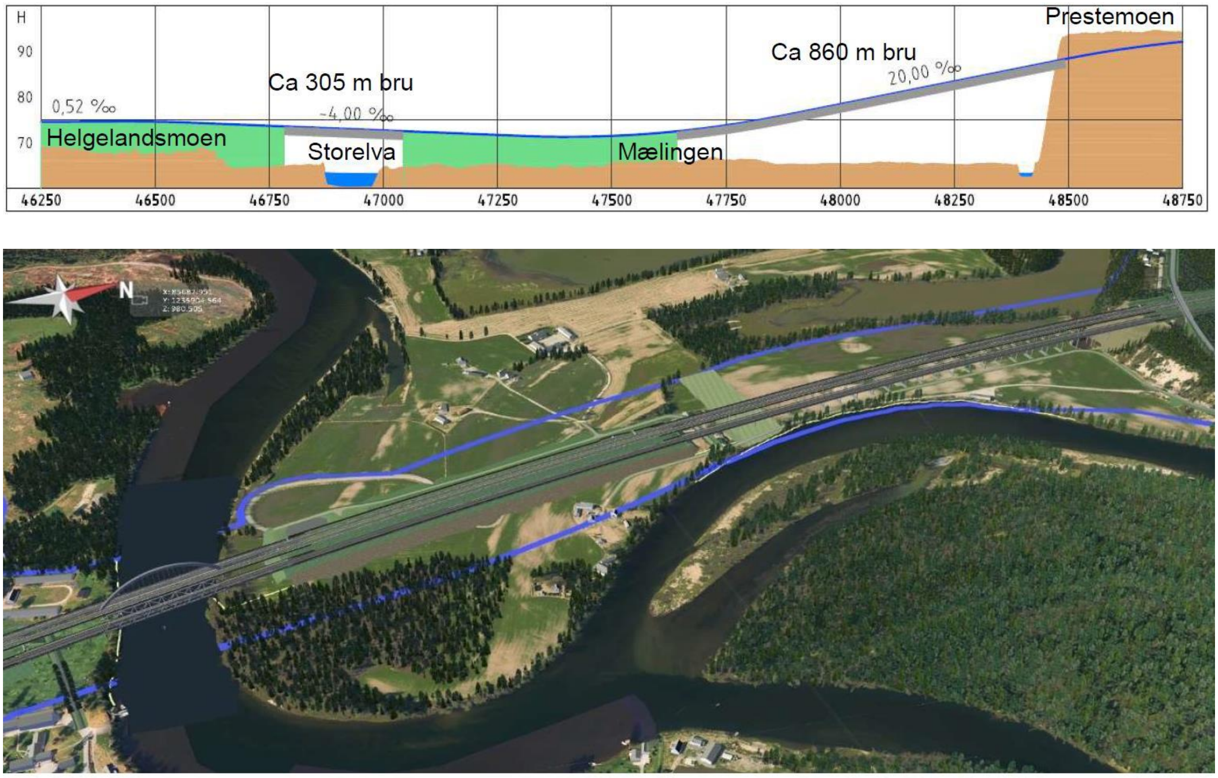


Figure 3.12: Alternative B: Partly dam in Mælingen (Bane Nor, 2018)

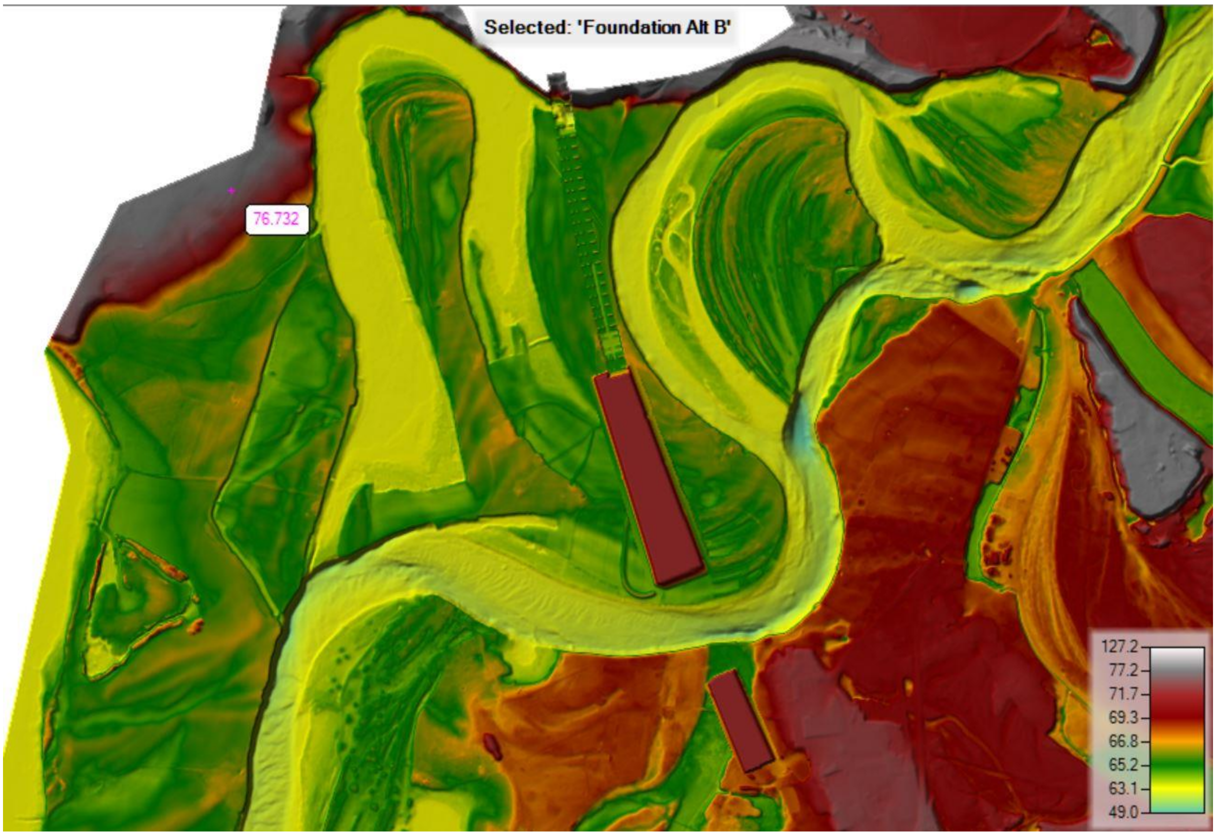


Figure 3.13: Terrain file Alternative B

4 Setup, calibration and validation of the hydrodynamic model

To investigate the Storelva river system in a hydraulical and ecological matter, HEC-RAS 5.0.6 (November) was used. HEC-RAS 5.0.6 is the latest version of the HEC-RAS modelling software. (November, 2018).

HEC-RAS is a software application offered by the US Army Corps of Engineering and free of charge. Since the establishing in 1967 HEC-RAS went through a large variance of opportunities of modelling river systems and water related topics (Hydrologic Engineering Center, 2019). The prediction of future circumstances in projects becomes more and more important. With a look at the ecology, environment and usage in river related themes, numerical models play a big role in investigating the impact of e.g. human impact as well as the climate change.

At the beginning of every numerical modelling it begs the question which application should be used and which borders, boundary conditions and initial conditions should be defined.

In HEC-RAS two approaches of modelling a river or wetland system can be made. For a first brief investigation it is good use to start with a 1D model. These models show the change of water levels and discharge along an estimated and predicted channel line within a river channel. Another tool to examine a river system is the 2D application, whereas a whole area, depending of the underlying terrain layer can be investigated. In 2D modelling changes of flow direction, overflow mechanisms of floodplains and water level changes can be predicted.

Nevertheless one can argue on which model, 1D or 2D, describes the real conditions in the investigated area the best. Brunner (2016a) gives some suggestions in the HEC-RAS 2D Modeling User's Manual on how to choose between the two model variations.

Adapted to the investigation of the river system Storelva at Ringerike, it is suggested to use a 2D model approach in bays and estuaries, alluvial fans, very wide and flat floodplains and applications where it is important to obtain detailed velocities (Brunner, 2016a).

Anyhow there are some negative points in using a 2D model and applications that cannot yet be solved with the 2D capabilities of HEC-RAS like sediment transport erosion and deposition or water quality analysis. However, in the end it is always the decision of the user and the audience it has to be presented. Furthermore it is known that the differences between 1D and 2D are in such a small matter, that it is more likely that inconsistencies appear due to the accuracy and resolution of the input data (Brunner, 2016a).

4.1 Theoretical background

In 1871 Adhémar Jean Claude Barré de Saint-Venant developed the first mathematical description of unsteady flow in open channels (Saint-Venant, 1871). These so called Saint-Venant equations are derived from the Navier-Stokes equations which describe the motion of fluids in three dimensions. By assuming incompressible flow, uniform density and hydrostatic pressure these equations reduce to a simpler form, the Shallow Water equations. Turbulent motion is Reynolds averaged which means that the turbulence is approximated using eddy viscosity. Furthermore is assumed that the vertical length scale is much smaller than the horizontal length scale, which leads, as a consequence, to a small vertical velocity and hydrostatic pressure and therefore to the differential form of the Shallow Water equations (Brunner, 2016b).

The HEC-RAS 5.0.6 software uses an implicit finite difference solution algorithm to discretize time derivatives and hybrid approximations combining finite differences and finite volumes, to discretize spatial derivatives (Brunner, 2016b; Ederle, 2017). This implicit method allows for larger computational time steps other than the explicit method. With allowing the user to choose between either the 2D Saint-Venant equations or the 2D Diffusion Wave equations a large range of problems can be investigated. Since 2D Diffusion Wave equations allow for a faster and more stable calculation the 2D Diffusion wave equations are used in this study.

The terrain surface elevation in the subsequent segments is defined by z(x,y) and the water depth by h(x,y,t) at a specific time t, which results in the water surface elevation H(x,y,t) = z(x,y) + h(x,y,t) also shown in Figure 4.1 schematically.

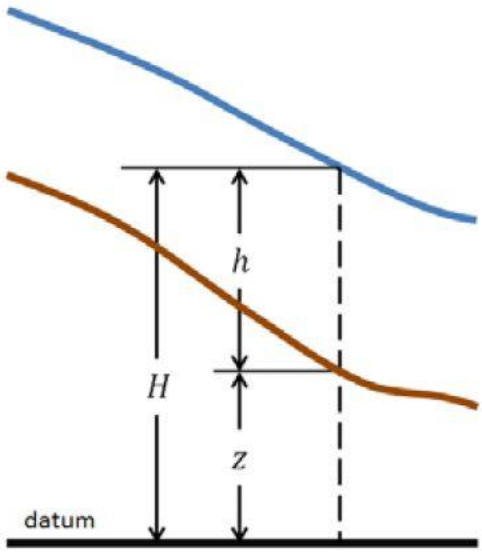


Figure 4.1: Definition water surface elevation (Brunner, 2016b)

4.1.1 Mass conservation

In the mass conservation equation [1] where t is time, u and v are the velocity parameters in the x- and y- direction and q is the flux term it is assumed that the flow is incompressible. Also mass is always conserved in fluid systems, meaning that the inflow of a control volume equals the outflow of the control volume with no external and additional in- or outflow disturbing the system. This assumption is also called continuity and takes the vector form shown in equation [2] (Brunner, 2016b; Ederle, 2017):

$$\frac{\partial H}{\partial t} + \frac{\partial (hu)}{\partial x} + \frac{\partial (hv)}{\partial y} + q = 0 \quad [1]$$

$$\frac{\partial H}{\partial t} + \nabla \cdot hV + q = 0 \quad [2]$$

where V=(u,v) is the velocity vector and the differential operator ∇ is the vector of the partial derivative operators given by ∇=(∂/∂x, ∂/∂y).

4.1.2 Momentum conservation

In some shallow water flows the bottom friction and the gravity, or barometric gradient, are dominant in the momentum equations. Therefore unsteady, advection and viscous terms can be disregarded. This leads to the momentum equations becoming a two dimensional form of the Diffusion Wave Approximation. By combining the Diffusion Wave Approximation with the mass conservation equation the Diffusion Wave Approximation of the Shallow Water equations are resulting (Brunner, 2016b). The Shallow Water equations [3] and [4] of the momentum conservation equations declare that the net rate momentum entering a control volume plus the sum of the external forces resulting from pressure, gravity and friction, are equal to the accumulation of momentum in the control volume. The parameters 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 the bottom friction coefficient and f the Coriolis parameter (Brunner, 2016b; Ederle, 2017).

$$\frac{\partial u}{\partial t} + u\frac{\partial u}{\partial x} + v\frac{\partial u}{\partial y} = -g\frac{\partial H}{\partial y} + v_t\left(\frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial y^2}\right) - c_f u + fv \qquad [3]$$

$$\frac{\partial v}{\partial t} + u\frac{\partial v}{\partial x} + v\frac{\partial v}{\partial y} = -g\frac{\partial H}{\partial y} + v_t\left(\frac{\partial^2 v}{\partial x^2} + \frac{\partial^2 v}{\partial y^2}\right) - c_f v + fu \qquad [4]$$

The left side of the equations contain the acceleration term whereas the right side is described by the internal or external forces impacting the fluid. The momentum conservation equations can also be written in the single differential vector form [5], where k is the unit vector in the vertical direction (Brunner, 2016b).

$$\frac{\partial V}{\partial t} + V \cdot \nabla V = -g\nabla H + v_t \nabla^2 V - c_f V + fk \times V \qquad [5]$$

In a shallow frictional and gravity controlled flow, a simplified version of the momentum equation can be used. Unsteady, advection, turbulence and Coriolis terms can be disregarded (Brunner, 2016b). Then flow movement is driven by the barometric gradient and balanced by the bottom friction. This leads to the more classical diffusion wave form of the momentum equation [6]:

$$V = \frac{-(R(H))^{2/3}}{n} \frac{\nabla H}{|\nabla H|^{1/2}} \qquad [6]$$

where V is the velocity, R is the hydraulic radius, ∇H is the surface elevation gradient and n is the empirically derived Manning's n.

4.1.3 Bottom friction

In HEC-RAS the bottom friction of the terrain surface is described by the Chézy equation [7]:

$$c_f = \frac{g|V|}{C^2 R} \qquad [7]$$

where g is the gravitational acceleration, |V| is the magnitude of the velocity vector, C is the Chézy coeeficent and R the hydraulic radius.

The Chézy coefficient is not dimensionless and measured in $m^{1/3}/s$. With the empirical approach of estimating the velocity of the channel flow by the Gauckler-Manning-Strickler formula it shows that $C=R^{1/6}/n$, where n is the empirical derived roughness coefficient Manning's n (Brunner, 2016b). Therefore equation [7] can also be written as:

$$c_f = \frac{n^2 g|V|}{R^{4/3}} \qquad [8]$$

using Manning's formula.

4.1.4 Numerical discretization

As mentioned before HEC-RAS 5.0.6 is a numerical river analysis software. Numerical analysis uses approximations of mathematical equations, like differential equations, to solve complex problems. For the analytical calculation a discretization of the study area is needed. This allows converting the continuous area into discrete parts which can be solved numerically. Among several numerical discretization methods available the most known techniques are the Finite Difference Method, the Finite Element Method and the Finite Volume Method usually used in computational fluid mechanics (Martin, 2011). The HEC-RAS 2D simulation uses the explicit method of discretization. In this case the current state of the system is used to calculate the next step. This allows for simpler equations but with a smaller time step according to the implicit method which uses the current state and the next step in a system of more complex equations which allows larger time steps (Brunner, 2016b; Martin, 2011).

HEC-RAS 5.0.6 uses a hybrid discretization combining the Finite Difference Method and the Finite Volume Method. If a grid is orthogonal the faces can be approximated by the Finite Difference Method. If the grid face is not orthogonal, the normal derivative has to be split as the sum of a finite difference and a finite volume approximation (Brunner, 2016b).

Orthogonal grids produce two-point discretization stencils. To solve the grids more efficiently, a pre-process routine is used to identify regions with orthogonal grids and advise the discretization techniques to solve purely with finite difference approximations. Non-orthogonal grids are solved using Finite Volume Methods producing larger stencils (Brunner, 2016b).

The approximation of finite differences in space is defined in equation [9], where two adjacent cells with water surface H_1 and H_2 and the directional derivative n', determined by the cell center, is used. Δn' is the distance between the cell centers. In Figure 4.2 the cell directional derivatives are shown. If the direction n' happens to be orthogonal to the face between the cells (Figure 4.2, left), the grid is said to be locally orthogonal and the Finite Difference Method can be used.

$$\nabla H \cdot n' = \frac{\partial H}{\partial n'} \approx \frac{H_2 - H_1}{\Delta n'} \qquad [9]$$

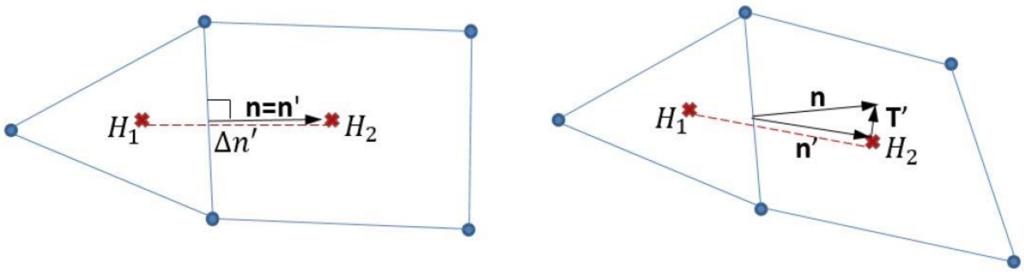


Figure 4.2: Cell directional derivatives (Brunner, 2016b)

With the direction n' non-orthogonal to the cell face (Figure 4.2, right), the finite volume approach is used to discretize. The Finite Volume Method demands the definition of control volumes which are defined around the mesh with center of gravity being the node itself. The solution then is obtained by calculating the flow at each border of the control volume In Figure 4.3 the blue nodes represent the computational mesh whereas the grey control volume is represented by the red dashed lines and crosses. The numerical flow is pictured by n_k (Brunner, 2016b). With the finite volume method being more complex than the finite difference method in general it benefits from the usability with arbitrary meshes. (Ederle, 2017)

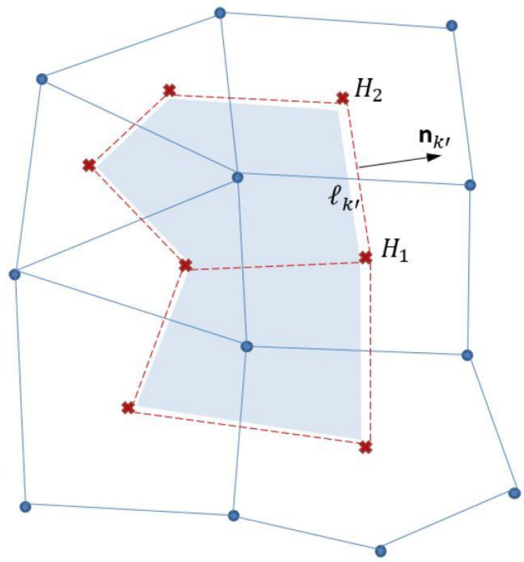


Figure 4.3: Exemplary Cell Finite Volume Formulation (Brunner, 2016b)

To get results in HEC-RAS 5.0.6 for the diffusion-wave approximation of the shallow water equation it is assumed, that the velocity is determined by a balance between barometric pressure gradient and bottom friction. Then the diffusion wave form the momentum equation ([6]) can be used in place of the full momentum equation and simplified to a one equation model with the corresponding system of equations. Substituting the diffusion wave equation in the mass conservation equation it yields to equation [10], the diffusion-wave approximation of the shallow water equation (Brunner, 2016b; Ederle, 2017).

$$\frac{\partial H}{\partial t} - \nabla \cdot \beta \nabla H + q = 0 \qquad [10]$$

where :

$$\beta = \frac{(R(H))^{5/3}}{n|\nabla H|^{1/2}} \qquad [11]$$

4.2 Input data

For developing a model for the Ringerike area, in particular the oxbow lakes of Juveren, Lamyra and Synneren south of Hønefoss in Norway, it is essential to have good input data that describe the terrain, the land use, the connecting structures, flow data and stage data. Any model output can only be as accurate as the least detailed input data. In the following chapters these different input data will be described and each individually assessed by its quality and accuracy.

4.2.1 Terrain and bathymetry data

To develop a 2D model in HEC-RAS 5.0.6 the elevation data of the investigated area has to be implemented in the program. Since most of the available terrain data only covers the surface and does not penetrate the water surface, additional measured bathymetry should be assembled to describe the real shape and elevation of the surface and the river bed in the area.

The bathymetry used in this thesis was downloaded from www.hoydedata.no. Terratec AS, a mapping company based in Norway, was instructed by the Norwegian Water Resources and Energy Directorate (NVE) to implement the collection of the bathymetry data for the Storelva, Randselva and Begna area in 2016 (Høydal, 2017). The data was retrieved from a light detection and ranging scan (LIDAR) by overflying and an accompanying sonar scanning under bridges and inaccessible areas by boat. In Figure 4.4 the outline of the investigated area pictured with the flight plan of the LIDAR scan is shown.

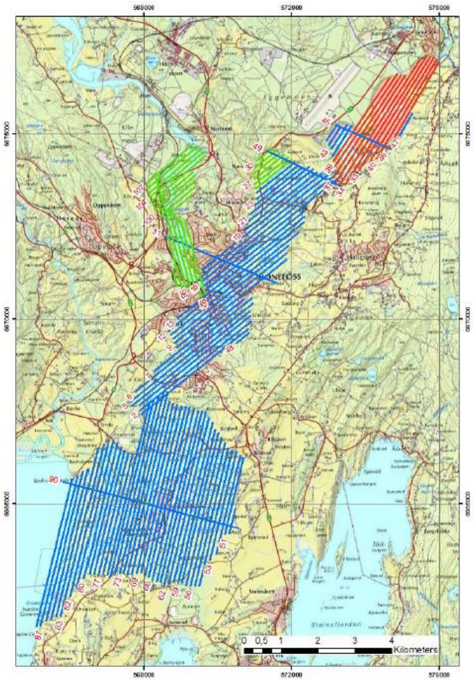


Figure 4.4: Flight plan of LIDAR scanning at Ringerike (left) (Høydal, 2017).

Since the LIDAR is not able to measure the depth below the water surface accurately due to differences in density between water and air the reflected beam of the LIDAR experiences a delay by penetrating the water surface and the measured length appears longer than in reality. This occurring error was adjusted and corrected by Terratec AS (Høydal, 2017). In addition a sonar scan of the main channel of Storelva, Ådalselva and Begna was executed. In Figure 4.5 (left) the drive path of the boat with the sonar equipment can be seen. Despite the detailed data collection of the main rivers, the oxbow lakes Juveren, Lamyra and Synneren were not inspected by sonar (Figure 4.5, top right). According to that circumstance, a statement for the depth in the oxbow lakes cannot be made without any doubt. In shallow and vegetated areas, that could not be reached by the sonar scanning boat, smaller miniature boats with Norbit-multibeam scanning were used to collect the bathymetry (Figure 4.5, bottom right).

Figure 4.5: Sonar inspection of Storelva, Randselva and Begna (left, red), detail sonar inspection at the oxbow lakes in Ringerike (top right, dark blue) and Norbit - multibeam miniature boat (bottom right) (Høydal, 2017).

The combination of LIDAR and sonar inspection then results in a terrain file that can be used for the development of the 2D model (Figure 4.6). The terrain data has a resolution of 0.25 m in each three dimensions but as described above, the accuracy of the data in the oxbow lakes is questionable.

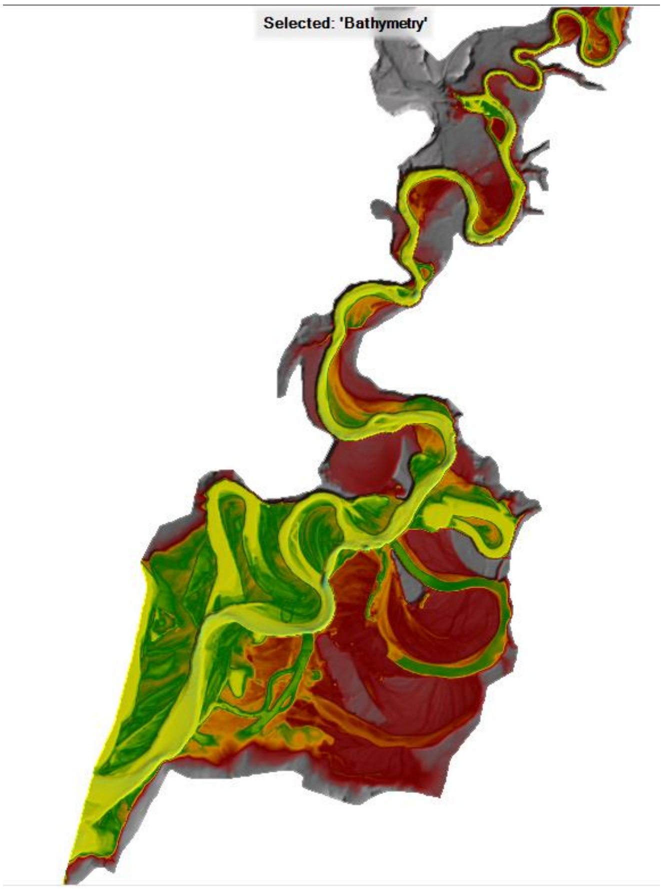


Figure 4.6: Terrain file of the investigated area in RAS Mapper. Not to scale.

Bathymetry data from LIDAR scans and sonar inspections is not always consistent under structures and culverts as well as in in- and outlets. The beams cannot penetrate structures and consequently no or wrong data is available for the terrain elevation beneath those. This results in point clouds at some underpasses and non-accessible culverts where no additional scanning was executed. In Figure 4.7 and Figure 4.8 the data inaccuracy for the two culverts located at Juveren and Lamyra is pictured. These inaccuracies cause an unreal representation of the real conditions. Therefore the existing point clouds have to be modified to describe the real conditions in these special areas by removing the hill-formed terrain data points.

By applying profile lines in RAS Mapper following a structure, in this case the "Norderhovsveien" and the connection of the oxbow lake with its main river, a plot of the existing terrain without modification can be shown.

Similar to the modification of the bathymetry data the 2D-model in the future state described in chapter 3.5 was also modified similar to the above.

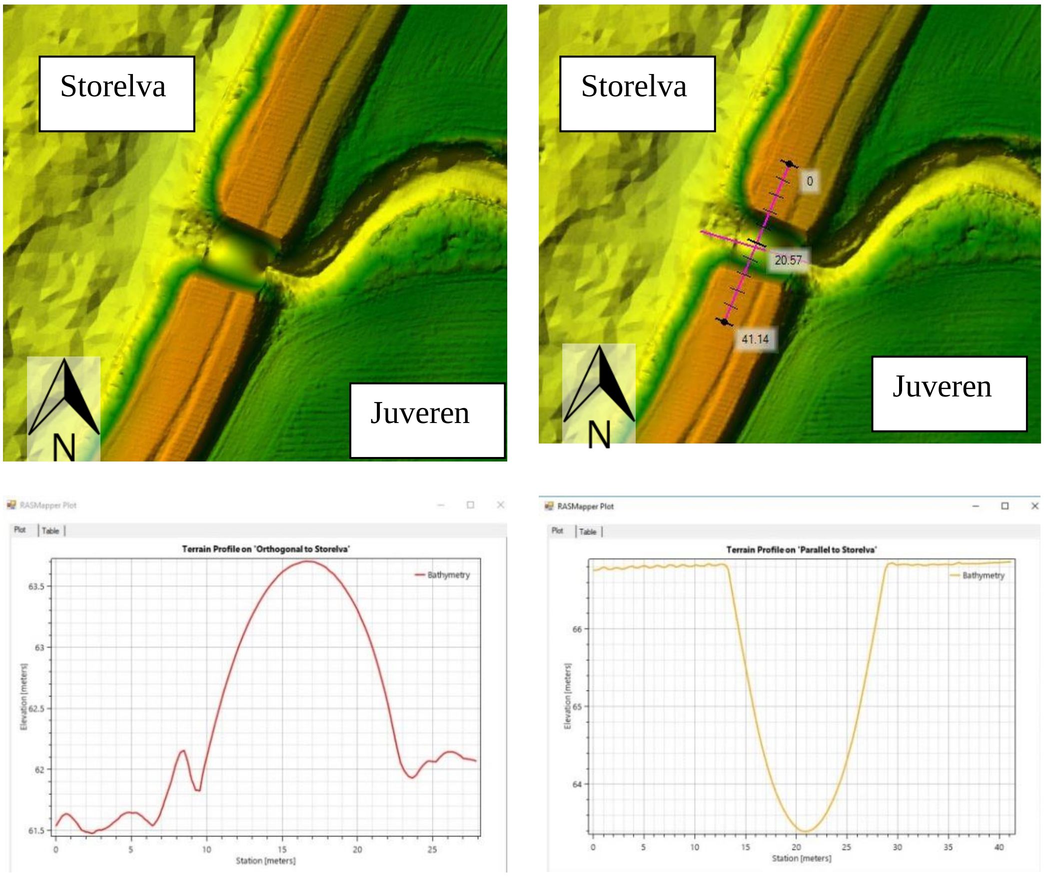


Figure 4.7: Inaccuracies of LIDAR data at the box culvert between Storelva and Juveren

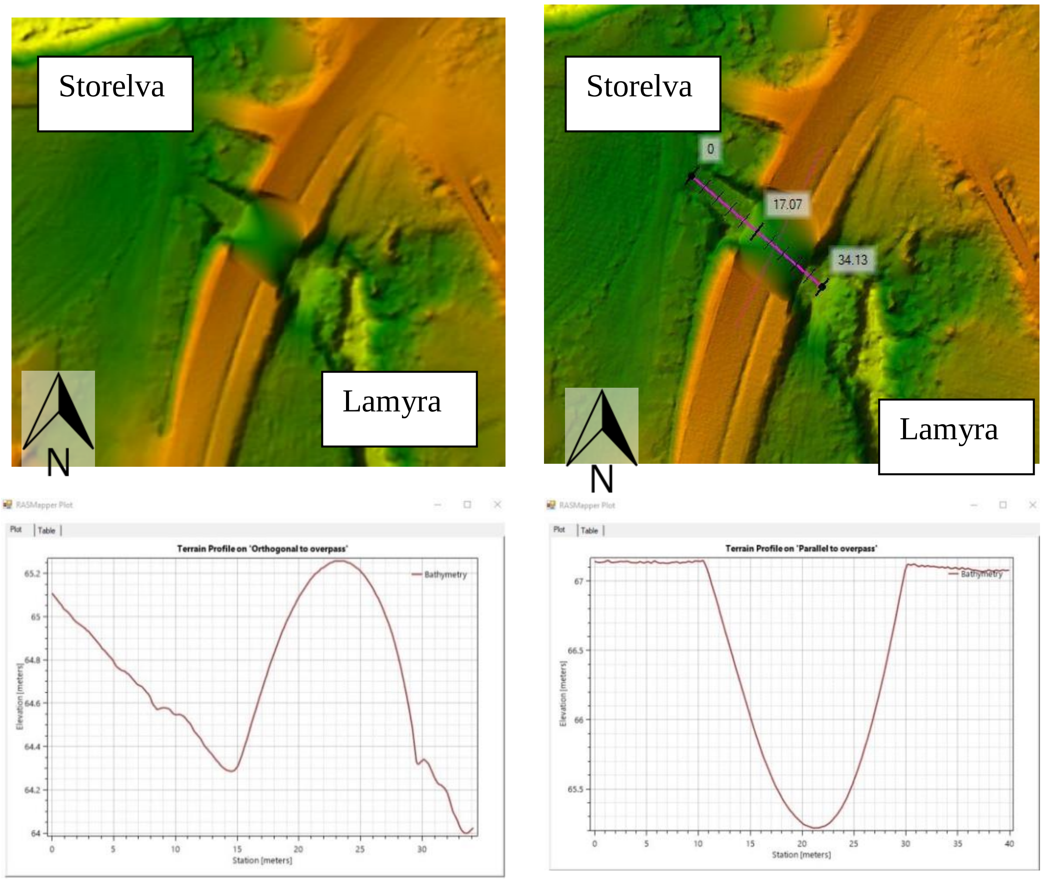


Figure 4.8: Inaccuracies of LIDAR data at the overpass of the southern arm of Lamyra

Because of the small size of the connecting culvert at the northern branch of Lamyra no data points for the culvert were adapted from the original bathymetry data (Figure 4.9). Nevertheless the indication of the culvert as a connection to the oxbow lake Lamyra is vaguely perceptible.

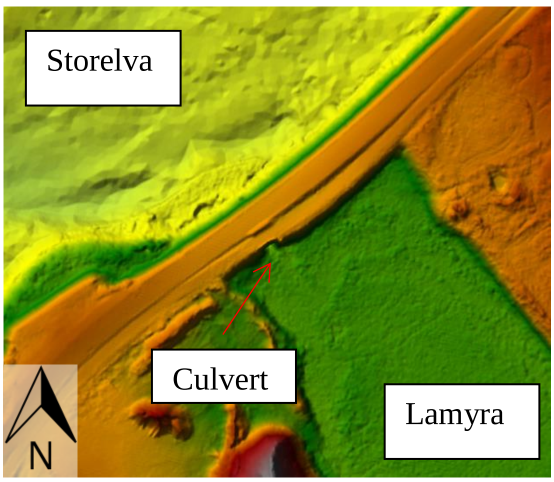


Figure 4.9: Original bathymetry data of culvert connection at northern arm of Lamyra

4.2.2 Actual conditions in the investigated area

To get a better insight of the investigated area and for the correct implementation in the 2D HEC-RAS model, the oxbow lakes Synneren, Juveren and Lamyra were visited on the 06.12.2018. During this visit pictures of the culverts and the conditions of the designated areas were taken. These pictures were also consulted to modify the terrain data for the HEC-RAS modeling. The culverts at Synneren and Lamyra were known previously and pictures of the construction in 2013 were provided (Wiman, 2013). Figure 4.10 shows the southern arm of the oxbow lake Lamyra. By comparing Figure 4.10 with Figure 4.8 the difference of the collected bathymetry data and the real condition, an underpass used as compound area of the neighboring scrap yard, is clear.

Figure 4.10: Underpass at southern branch of Lamyra. Picture taken 05.12.2018.

In the following pictures Figure 4.11, Figure 4.12 and Figure 4.13 the particular connection of the oxbow lakes Synneren, Juveren and Lamyra are shown. The connecting channel of Synneren with Storelva (Figure 4.11) shows no significant difference with the adapted bathymetry data. Furthermore the channel is secured by rock walls on both banks which ensure the accessibility of the oxbow lake by boat.

Figure 4.11: Connecting channel at Synneren. Viewing direction to oxbow lake. Picture taken 05.12.2018

In Figure 4.12 and Figure 4.13 the constructed culverts with securing rock walls on both banks and the inlets are shown. Since these connections to Storelva are engineered objects, the construction plans (Statens vegvesen, 2012) for the culverts were consulted to implement the dimensions into the HEC-RAS model. The implementation of the objects is further discussed below.

Figure 4.12: Box culvert at Juveren. Viewing diretion to Storelva. Picture taken 05.12.2018

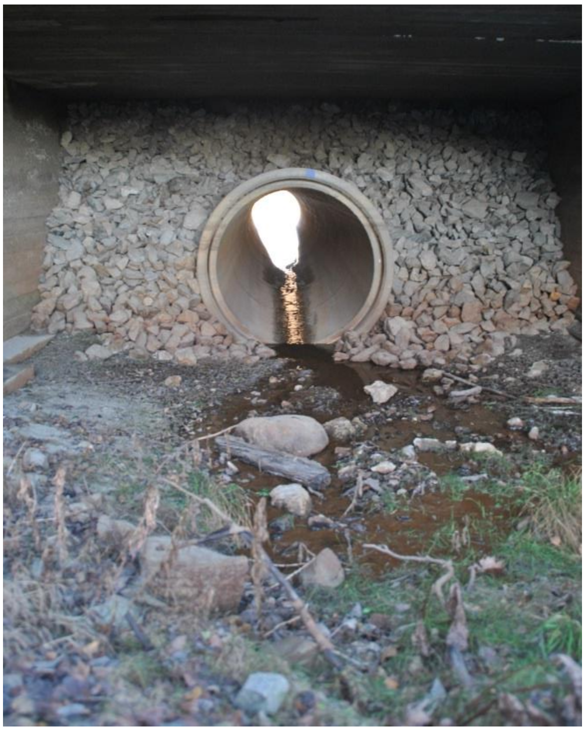


Figure 4.13: Culvert at conservation area Lamyra. Looking to Storelva. Picture taken on 05.12.2018

With the known circumstances in situ and the provided bathymetry data of the investigated area it can be assumed that for an accurate 2D HEC-RAS model changes in the bathymetry and implementing of technical object were necessary.

For the terrain data used in the 2D HEC-RAS model two different attempts of modifying the bathymetry data have been made.

4.2.3 Modification of bathymetry data and terrain

To modify the bathymetry and terrain data, one possibility is to change the elevation data of the terrain file itself. For this situation HEC-RAS 5.0.6 offers the possibility to edit the geometry of lines that describe the river, the bank lines and the corresponding cross-sections. Usually these lines are used in the 1D HEC-RAS modelling application to calculate water levels and manipulate the geometry of the investigated river system. For the terrain modification, this possibility of variation is taken into account to change any terrain to the conception of the user and is used in several practical applications (Goodell, 2018).

For a start, the area that has to be modified has to be identified and the existing data has to be examined. As part of this thesis several modifications of the terrain data have been made but to show the use of this editing tool, only the underpass of Lamyra in the southern branch of the oxbow lake is shown.

First the actual bathymetry data retrieved from Høydal (2017) was loaded into RAS Mapper as a terrain layer. Then a "river" (blue) with the corresponding bank lines (red) was implemented and two cross-sections were drawn (green) (Figure 4.14, left). As a next step the cross-section editor was opened and the elevation data between the both bank lines was changed to approach the real conditions in situ (Figure 4.15). In the bottom cross-section in Figure 4.15 it is also visible, how the new data has changed to the previous bathymetry data. With the cross-sections modified, the difference of the two previous cross-sections can be interpolated whereas a distance of five meters as a maximum between every cross-section was chosen (Figure 4.14, right).

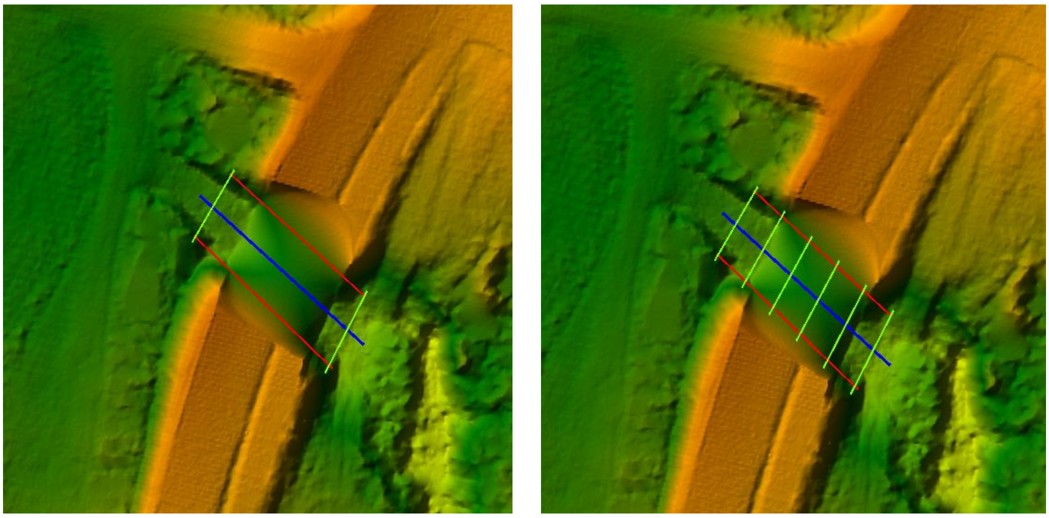


Figure 4.14: Modification underpass Lamyra. River line (blue), bank lines (red) and cross-sections (green)

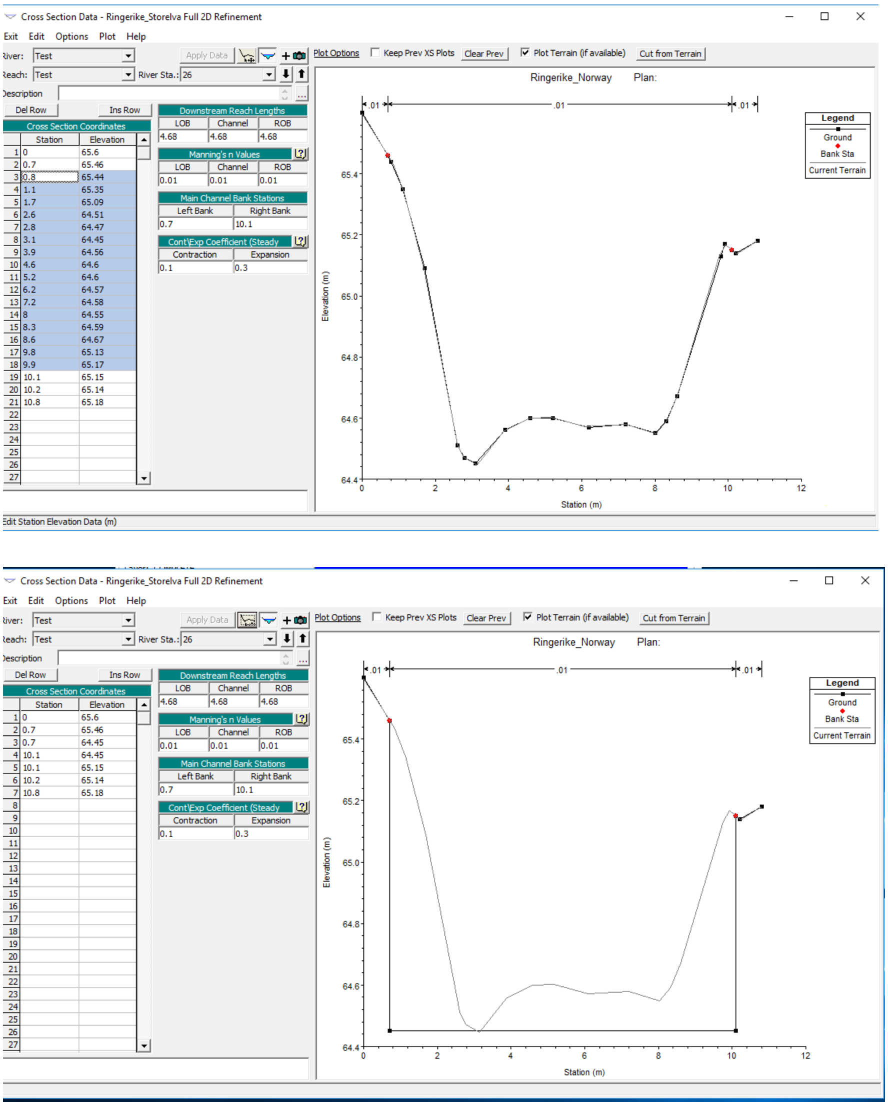


Figure 4.15: Modification cross-sections underpass Lamyra

These editing steps do not change the bathymetry data immediately since only a new shape file with elevation information was implemented. This shape file can then be exported from RAS Mapper into a GeoTIFF file. During this conversion the software asks for the cell size of the newly implemented data. To match with the original bathymetry data from Høydal (2017) the cell size was set to 0.25 m. In a next step the previous bathymetry file and the new GeoTIFF file can be merged to form a new bathymetry file which can be used in the 2D HEC-RAS model. In Figure 4.16 the difference from the original data (left) to the modified data (right) with the above adapted and described process can be seen.

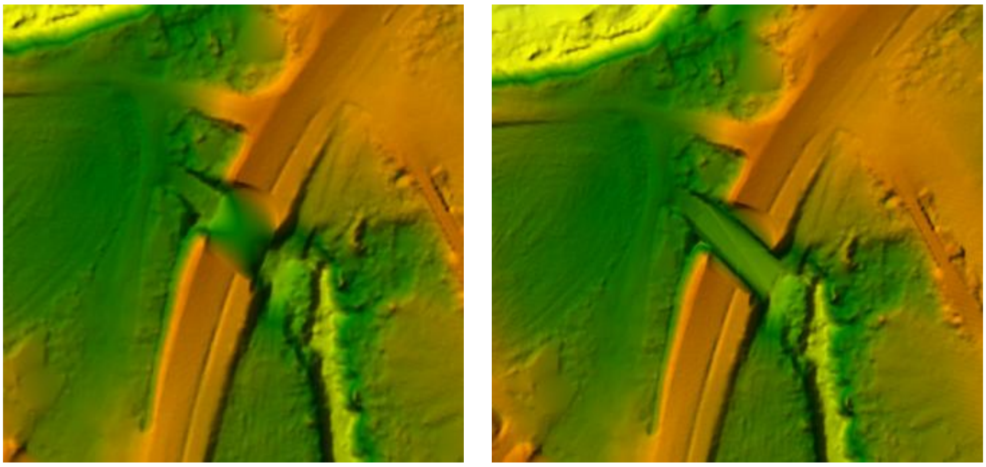


Figure 4.16: Terrain data at underpass Lamyra before (left) and after (right) modification

The in this thesis executed example only shows the modification of the southern branch of Lamyra. Every change in bathymetry and terrain occurring in the following chapters was realized as previously described.

4.2.4 Implementation of technical objects

Where terrain modification is not necessary, because of engineered structures or technical objects, another editing tool of HEC-RAS 5.0.6 can be utilized to approach the natural conditions for the calculation of the 2D model.

Culverts, bridges, weirs and gates are usually structures with set or planned dimensions. For the investigated area in Ringerike two structures were identified (Figure 4.12 and Figure 4.13). With the dimensions retrieved from an earlier construction plan for the adjacent street, the two culverts can be implemented into the geometry editor of HEC-RAS 5.0.6.

The undertaking of inserting culverts starts with defining a centerline of the barrel in RAS Mapper by putting a shape file layer (.shp) on the existing terrain file. This shape file then can be used to import the centerline coordinates into the structure editor within the geometry editor. In Figure 4.17 the implemented culverts with its centerline (right, red color) can be seen for the Juveren oxbow lake.

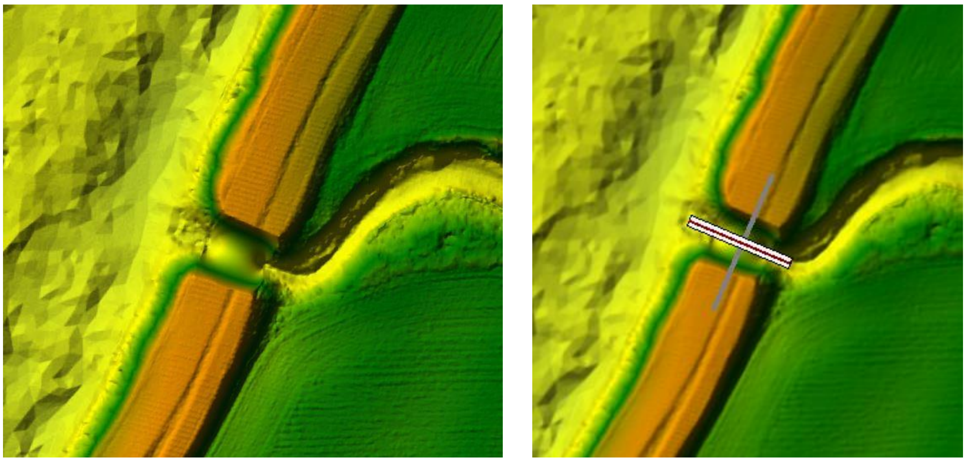


Figure 4.17: Modification culvert at Juveren

With the known location of the culvert, the dimensions of the pipe or the box culvert can be inserted. The original data for each connection of the oxbow lakes to the main river is different due to the different accessibility as described in chapter 4.2.1. At Juveren (Figure 4.17) a point cloud similar to the data at the southern arm of Lamyra (Figure 4.16) can be seen. In the geometry editor the actual dimensions of 4 m in height and 3 m in width of the box culvert is inserted. Furthermore a downward slope of 0.1 m from upstream, the inlet from the river to Juveren, to the outlet is minded and represented with a dashed line in the cross-section (Figure 4.18). With the dimensions set in the structure editor, the weir in which the culvert is located has to be designed. For the implementation of the weir pictured in Figure 4.18 (grey area) a new line is drawn in a layer in the RAS Mapper terrain file, imported as a .shp-file and included into the structure editor of the geometry editor. The basepoint of the weir is set to the lowest point of the original data. The top of the weir follows the original data from the bathymetry file and is modified in the section where the error of the original data occurred (red line).

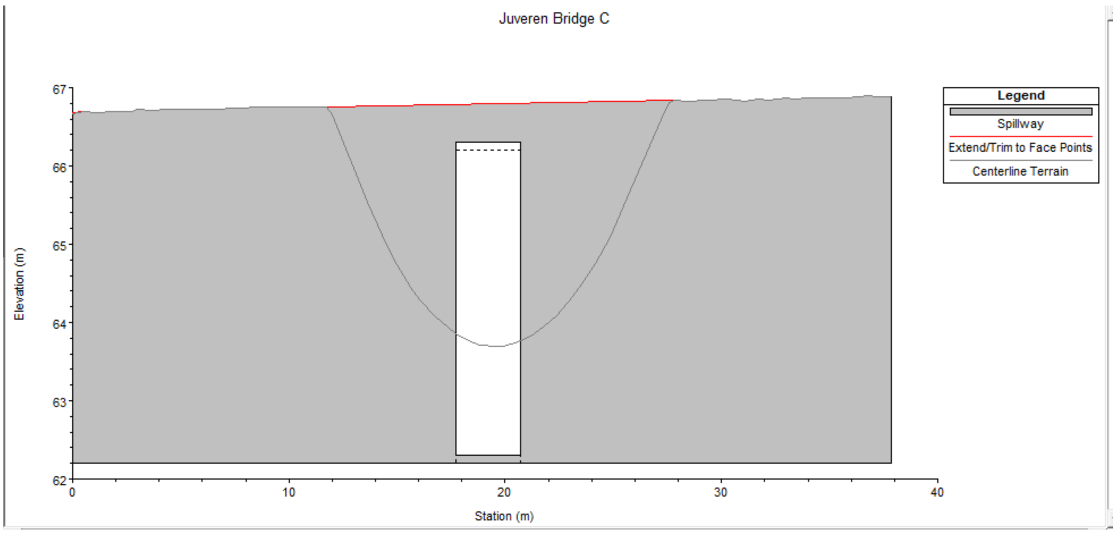


Figure 4.18: Cross-section box culvert at Juveren

The Lamyra (Figure 4.19) culvert is edited in the same matter as the box culvert at Juveren. In this case the shape of the culvert is round and has a diameter of 1.4 m. Moreover a modification of the weir was not necessary since the terrain data had no interruption in its elevation following the street. The cross-section for the completed structure at the northern branch of Lamyra for the insertion into the 2D model can be seen in Figure 4.20.

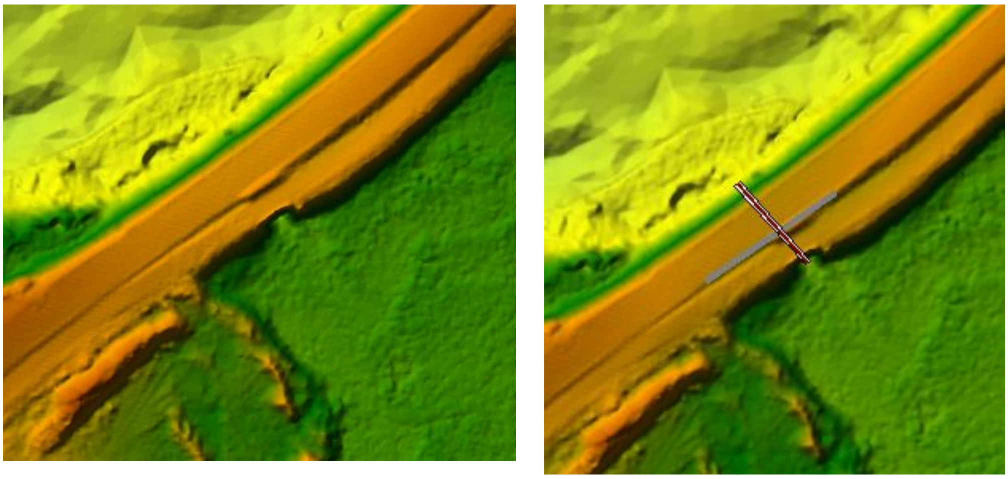


Figure 4.19: Modification culvert at Lamyra.

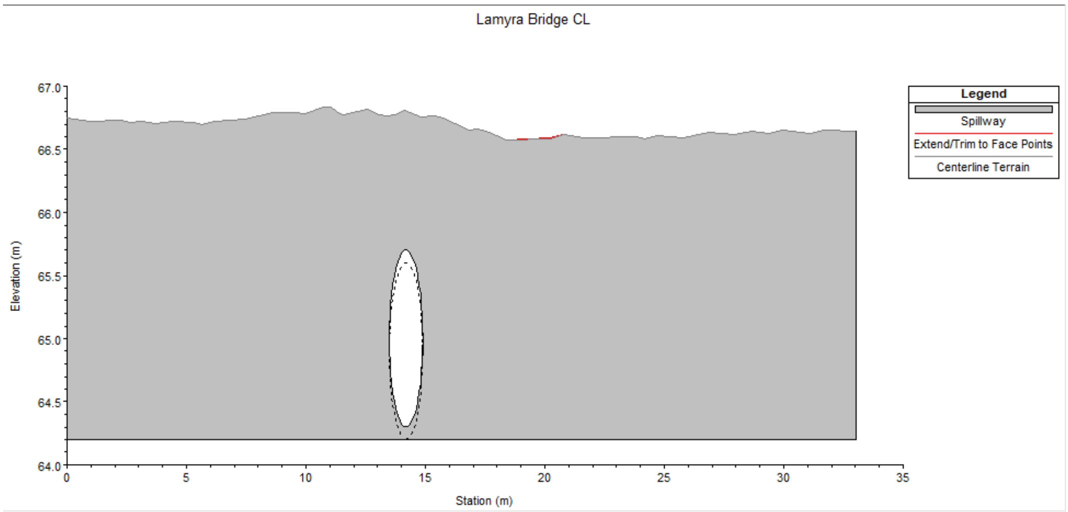


Figure 4.20: Cross-section culvert at Lamyra.

After changing and modifying the bathymetry data and implementing existing culverts and weirs the fundamental data for the 2D HEC-RAS model in HEC-RAS 5.0.6 is finished. In combination with the geometry data including the calculated mesh and boundary conditions no more changes for the further investigation of the actual state are necessary.

4.2.5 Roughness coefficient Manning's n

The roughness coefficient described by the Manning's n value is a common parameter in describing the different values of surface roughness of different land uses and properties of banks and channels with different grading curves. Manning's n is an empirical developed value to describe the roughness of a surface

In HEC-RAS 5.0.6 the value for Manning's n is set to 0.06 in default if no additional Manning's n layer is implemented. To get a realistic model of the Ringerike area, a new Manning's n layer was included. The land use areas were retrieved and the land use properties were set to values matching the area they appear, based on the description provided by the Norwegian Mapping and Cadaster Authority (Bjørkelo, 2011). The values for Manning's n were retrieved from Chow (1959) and associated with the geometry file. This tells the HEC-RAS software to use the different Manning's n values for the roughness parameter in the to be calculated cells. Therefore the different land uses appearing in the investigated area can be taken into account and allow the results to be more reasonable for the investigation. The different Manning's n values and the covering areas in the investigated area are shown in Figure 4.21.

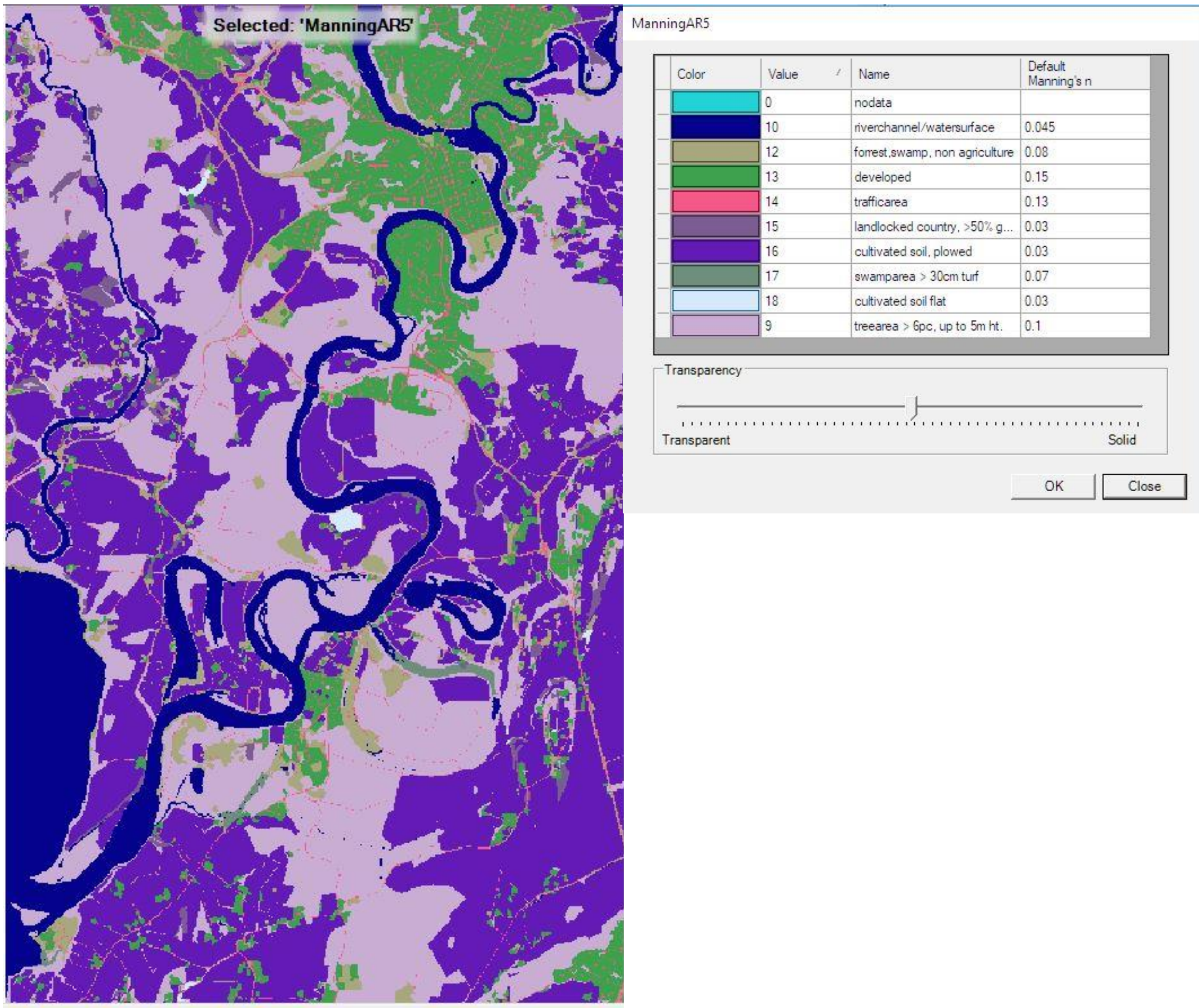


Figure 4.21: Manning's n layer map

4.2.6 Implementation of model boundaries

When starting a model it is always good practices to think about the mesh size used for the 2D calculations. Depending on the size of the investigated area and the resolution of the underlying bathymetry data it is not always necessary to use the smallest mesh size possible. Furthermore HEC-RAS 5.0.6 has a limited number of total cells that can be calculated in one simulation and with more cells in the geometry data the calculation time of the investigated area extends to an unnecessary length (Brunner, 2016a). Therefore each HEC-RAS 2D model is dependent on the engineering work of the user and different assumptions in resolution and accuracy.

For the numerical investigation of the Storelva river system in this master's thesis the upstream boundary condition was set to an area close to the first oxbow lake to reduce the mesh size. Furthermore the mesh was adjusted to the higher areas of the riverbanks where a chance of overflowing could be negotiated. Since the outlook of this thesis was to investigate the wetlands and oxbow lakes, it was decided to set the mesh size for the whole area to a 20m to 20m mesh. At the oxbow lakes and wetlands a refinement was adapted with a mesh size of 5m to 5m. This allows shortening the calculation time, the file size and still gives accurate results for the investigated research areas. Nevertheless the calculations are always dependent on the accuracy of the input data. Therefore no significant change in the results would appear by using a finer mesh.

Along the river banks break lines were implemented to cling the cells to the shape of the main river. This also forces the numerical model to calculate the cells at the break line when the elevation of the beneath terrain is overtopped and reduces iteration errors at this specific area. With the development of the geometry, the mesh consisted of 197152 cells, 398049 faces and 202074 face points.

Only using the input data described in the chapters before the HEC-RAS 5.0.6 software does not know where to begin with its calculations. To start a numerical simulation, it is necessary to set boundary conditions at an upstream and a downstream border. As the downstream condition the stage data of Tyrifjorden, described in the following chapter 4.2.7, and for the upstream condition the discharge data of Storelva described in chapter 4.2.8 was used. With these boundary conditions the 2D simulation has the starting point to calculate each cell and going step by step to the next cell in each calculation step.

In Figure 4.22 the mesh used for the calculation with the upstream and downstream conditions, the refinement areas and the break lines is shown.

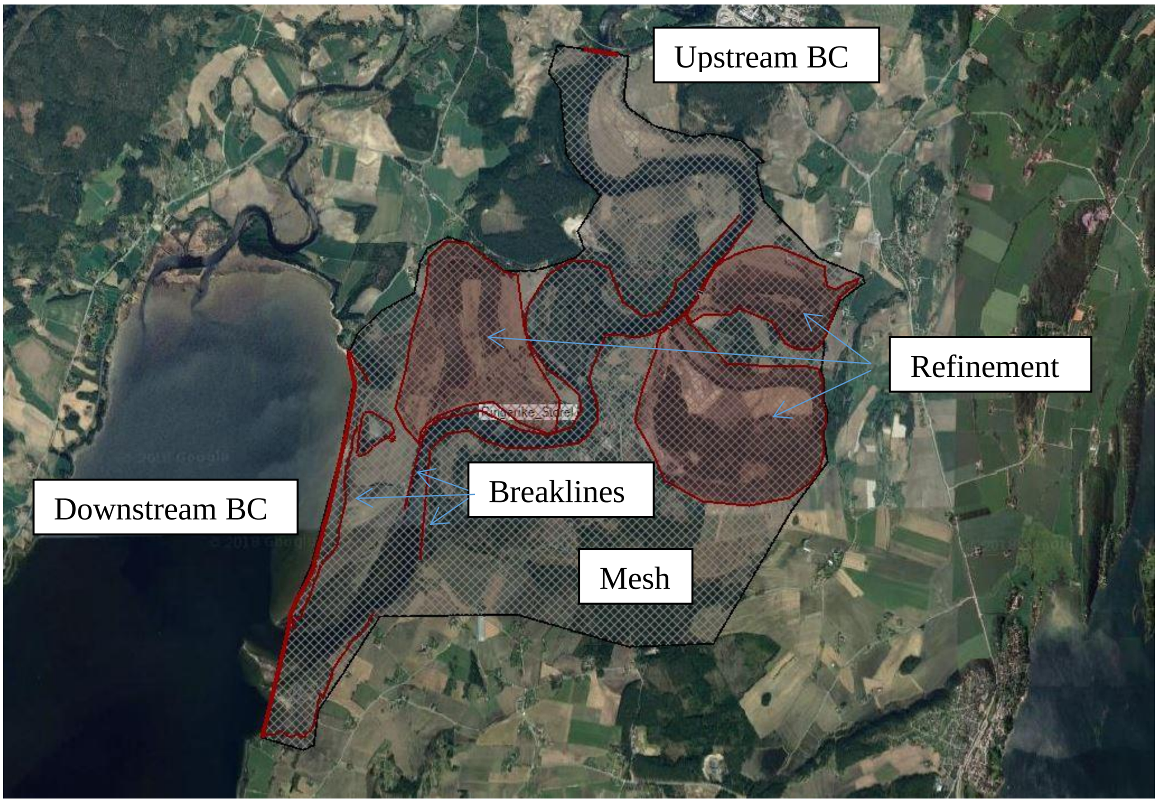


Figure 4.22: Calculation mesh with upstream and downstream boundary condition (BC), Break lines and Refinement area

To get a stable model a so called warm up was implemented. A ramp up time of 48 hours was set for the model. This ramp up time forces the model to calculate an initial condition of 48 hours reaching the first value of the boundary conditions and starting at 50% of the first value described by the stage and flow hydrograph set for the boundary conditions. With the "ramp up" the model calculation for the set values and times will not start dry and will be more stable (Brunner, 2016a).

Furthermore a new feature of HEC-RAS 5.0.6 was implemented. To run a 2D unsteady flow model, it is important to set the calculation time step right. A too large of a time step will cause instability and a too small of a time step will cause a unnecessary long model run time (Brunner, 2016b). Therefore the courant condition comes into place. In HEC-RAS 5.0.6 it is possible to set an adjustable time step for the calculation of the model. By implementing the Courant number, in this case C = 1 and a minimum and maximum time step, the software will chose the right time step according to the Courant number (Figure 4.23). With this application the time step of the model can be adjusted and in cases, where a larger time step is possible, the model will execute this. That allows for smaller calculation times and file sizes.

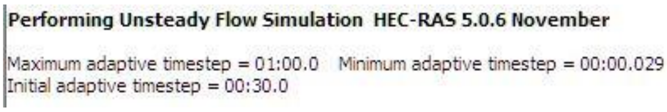


Figure 4.23: Example of maximum, minimum and initial time step

In Figure 4.24 a summary of the applied model boundaries for the calculation can be seen at the example of the HQ10 flood event described in chapter 5.2.

Figure 4.24: Example results information HEC-RAS 5.0.6

4.2.7 Stage data Tyrifjorden

The stage data at Tyrifjorden located downstream of Storelva describes the water surface elevation of the lake. The measurement point for Tyrifjorden is at Skjerdal which is in the north-west next to the inlet of the river Sogna.

The data for the discharge and stage for Storelva and Tyrifjorden was given with the elevation datum NN1954. In contrast, the elevation datum of the digital elevation model for the bathymetry was NN2000. The mean difference of the two different elevation systems was 16 cm (Figure 4.25) and was taken into consideration for the stage data used in the downstream boundary condition for the HEC-RAS model. For a better presentiveness the stage data is plotted in the diagrams of the flow hydrographs for each flood event.

The use of the different elevation system was discovered during a project seminar with Bane-Nor in January 2019. The need for corrections required the recalculation of some model scenarios with the adjusted boundary condition.

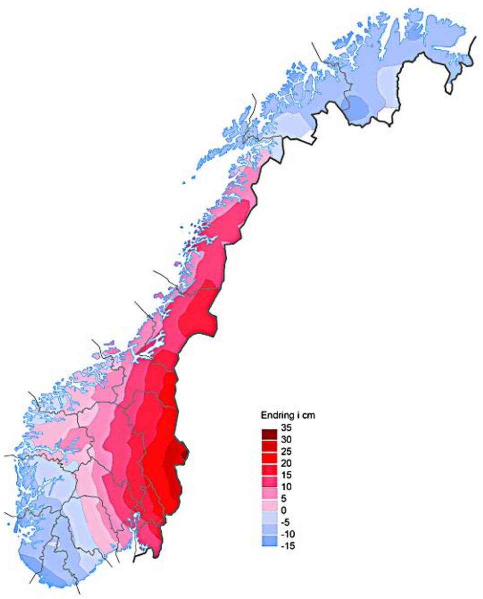


Figure 4.25: Differences of terrain elevation from NN1954 to NN2000. (Norwegian Mapping Authority, 2018)

4.2.8 Flow Hydrographs for Storelva

For the calculation of the unsteady flow model, it is also necessary to have the input flow data for the flood events that have to be investigated. With no active measure station at the Storelva river no discharge data and stage data is available for the Storelva river itself. The data was retrieved by adding the values of the two rivers Ådalselva and Randsleva, which merge together at the bottom of the Hønefoss waterfall behind the hydro power plant. Both, Ådalselva and Randselva have gauging stations upstream. For Randselva the measure station is Kistefos and for Ådalselva it is Strømsø. For the calculation of the total discharge for Storelva it is usual practice in different reports to add the single discharge data of the rivers (Bane Nor, 2018; Holmqvist, 2002).

The river hydro power plants have no temporal delay on the flood waves for this model. The power plants receive the same water about 20 to 30 min. later than at the measuring points at Kistefos and Strømsø. The discharge and stage data taken as input hydrographs were daily mean measures and provided as a daily value.

The relevant flood events of 2013 and 2015 for the calibration and validation are shown in the following chapter.

For the investigation of the impact of the infrastructure project FRE16, four flood events were implemented: The flood event of 1967, HQ10, HQ200 and an annual flow hydrograph with the 0.9 percentile values.

After the calibration and validation, the flood hydrograph of the 1967 flood event was used for the numerical calculations. This flood event happened in 1967 and is still a significant flood event and mentioned in narratives by the neighboring habitants (Zinke & Dervo, 2018). The flood reached a peak discharge of 1060m^3/s in Storelva and a peak stage at Tyrifjorden of 65.28 m (Bane Nor, 2018). These values represent a statistical flood of about HQ50 when compared with the statistical values as seen in Table 4.1 and Table 4.2. The flow hydrograph is shown in Diagram 4.1.

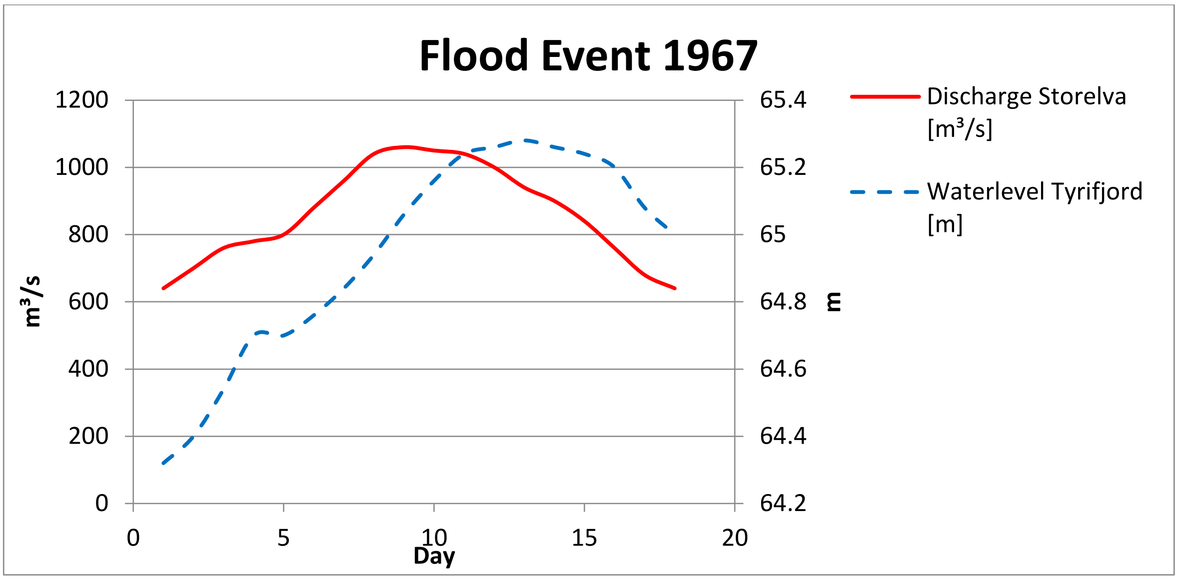


Diagram 4.1: Water level and discharge of the 1967 flood event. Retrieved from Bane Nor (2018).

During floods, the water level at Tyrifjorden raises and affects the river delta of Storelva. Therefore two approaches of the statistical values can be used. First the statistical flood with the corresponding stage (Table 4.1) and second the statistical flood water level with the corresponding discharge (Table 4.2). It appears that the river system and adjacent oxbow lakes are more affected by the stage level of the Tyrifjorden than the discharge from the upstream rivers (Stokseth & Svegården, 2003). Juveren has the same elevation of ca. 63 m above-normal, as the maximum regulated water elevation in Tyrifjorden. Therefore, using the Tyrifjorden-affected values seems reasonable. For this reason, the results of the statistical flood events HQ10 and HQ200 in chapter 5 are calculated with the values of Table 4.2.

Table 4.1: Summary flood-discharge of Storelva and corresponding water level at Tyrifjorden

	Middel flood	5-year flood	10-year flood	20-year flood	50-year flood	100-year flood	200-year flood	500-year flood
Discharge Storelva (m^3/s)	620	800	890	960	1050	1390	1490	1680
Water level Tyrifjorden (m)	64.0	64.5	64.7	64.9	65.0	65.4	65.4	65.7

(Stokseth & Svegården, 2003)

Table 4.2: Summary flood water level at Tyrifjorden and corresponding discharge of Storelva

	Middel water level	5-year water level	10-year water level	20-year water level	50-year water level	100-year water level	200-year water level	500-year water level
Water level Tyrifjorden (m)	64.2	64.7	64.9	65.1	65.2	65.6	65.6	65.9
Discharge Storelva (m^3/s)	560	720	800	870	950	1250	1340	1520

(Stokseth & Svegården, 2003)

To investigate the influence of the regulation of the river system Storelva the 0.9 percentile values of a whole year were implemented in the 2D HEC-RAS model. This hydrograph is a statistical approach to describe a typical annual flow hydrograph where the values fall below 90% of the values observed. The stage data and discharge data for the regulation periods were retrieved from Zinke & Dervo (2018) (Figure 4.26) and modified for the input of the numerical model. The results were analyzed and are shown in chapter 5.4.

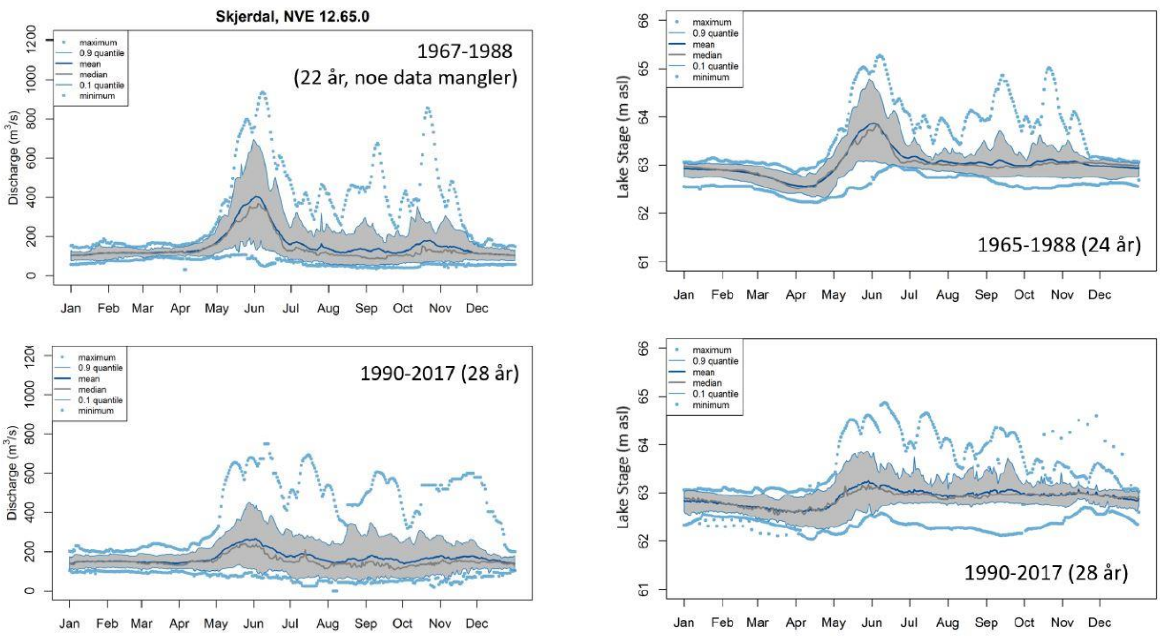


Figure 4.26: Values of stage data (left) and discharge data (right) for the regulation periods at Skjerdal (Zinke & Dervo, 2018)

4.3 Calibration and Validation of the HEC-RAS model

The calibration of the HEC-RAS model involves adjustments of some uncertain model parameters in order to obtain sufficiently accurate modelling results. By calibrating the model it is assured, that the results of the predicted floods and changes due to the infrastructure project are reasonable.

With the available data provided from different sources and analyzed due to its quality and accuracy, following uncertainties can be mentioned:

- Retrieving and modification of the bathymetry data (Chapter 4.2.1, Chapter 4.2.3, Chapter 4.2.4)
- Implementation of Manning's n (Chapter 4.2.5)
- Choice of geometrical parameters of the 2D HEC-RAS model (Chapter 4.2.6)
- Stage data of Tyrifjorden (Chapter 4.2.7)
- Flow hydrographs of the Storelva river system (Chapter 4.2.8)

All these uncertainties have to be taken into account to make a statement regarding the accuracy of the calculated results.

For the calibration and subsequently validation of the 2D HEC-RAS model two different existing floods were implemented into the model with the set geometry parameters described in chapter 4.2.6. The results were compared with aerial views of the flood event and analyzed.

For a first approach the spring flood of May 2013, with the discharge of Storelva and the accompanying water elevation of Tyrifjorden for this flood event (Diagram 4.2) was implemented into the model and calculated by HEC-RAS 5.0.6. By running the model a depth layer for the investigated area was created for each calculated time step. These results then can be pictured in RAS Mapper and used for comparison with, for example, an aerial view or any other implemented layer.

The results of the HEC-RAS model are shown in Figure 4.27. The aerial image was taken on the 26.05.2013 at an unknown time. By overlapping the layers the best match of the flood affected areas can be found and the time step of the model can be gathered. The time step calculated by the model is the 26.05.2013 at 16:05. Since the bathymetry data was measured in 2016 some inaccuracy can appear due to the natural change of the surface. Nevertheless, the comparison shows a good match of the model results and the real conditions and significant areas are pointed out with red arrows.

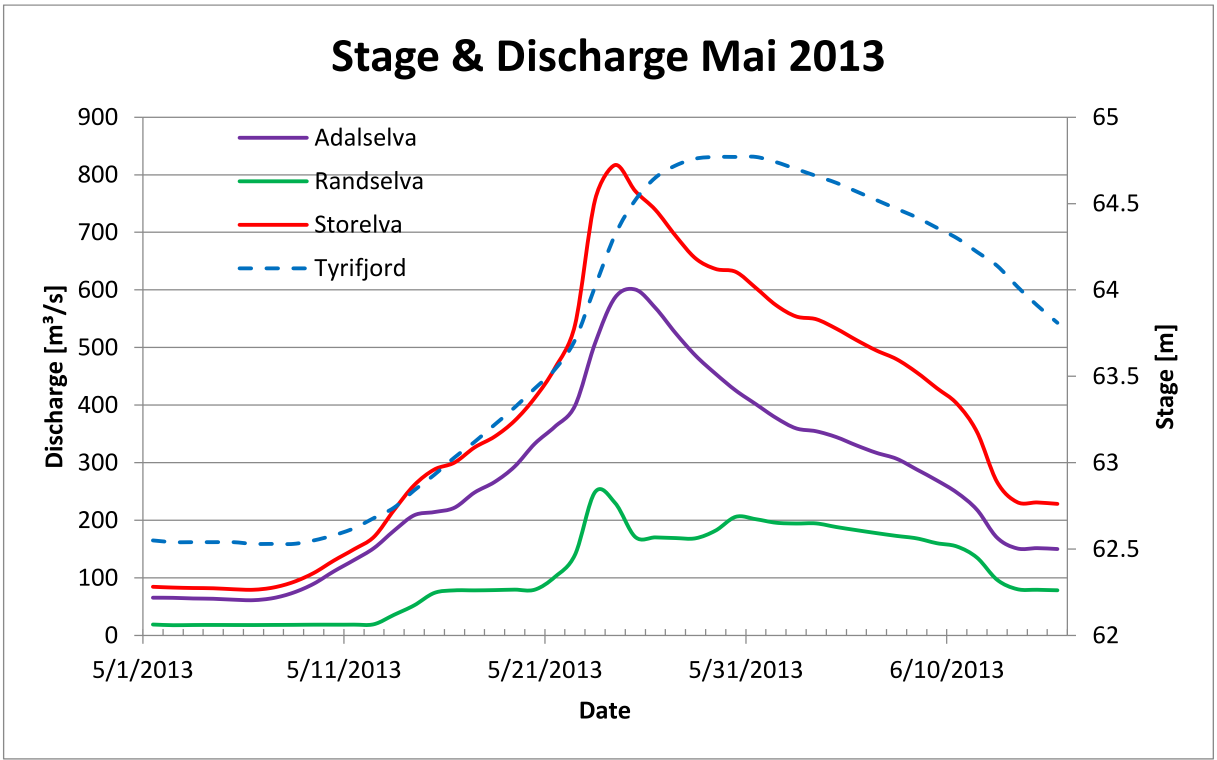


Diagram 4.2: Stage and flow hydrograph flood May 2013

Figure 4.27: Calibration Flood May 2013

With the results for the May 2013 flood it can be said that the model can represent the real conditions of the Storelva river system and the surrounding oxbow lakes and wetlands. Nevertheless it is necessary to validate the results of the previous calculation. For the validation of the 2D model a second real flow hydrograph, the flood of September 2015 (Diagram 4.3) was used and implemented with the previous set geometry parameters of the HEC-RAS model. The flood of September 2015 features a different pattern of the flow hydrograph since two flow peaks occurred during the flood event. Also the stage at Tyrifjorden adjusts with these two discharge peaks. As pictured in Figure 4.28 the calculated result layer for the depth at 19.09.2015 at 17:05 and the aerial image taken on 19.09.2015 (time unknown) show a similar outline of the water surface in the significant areas (red arrows).

With the result of the two real natural flood events and the comparison with the aerial views of the given day, it can be said that the previous made assumptions and the input data is reasonable and can be used for the further calculations of the impact of the FRE16 project and the consequent impacts to the wetland system and oxbow lakes.

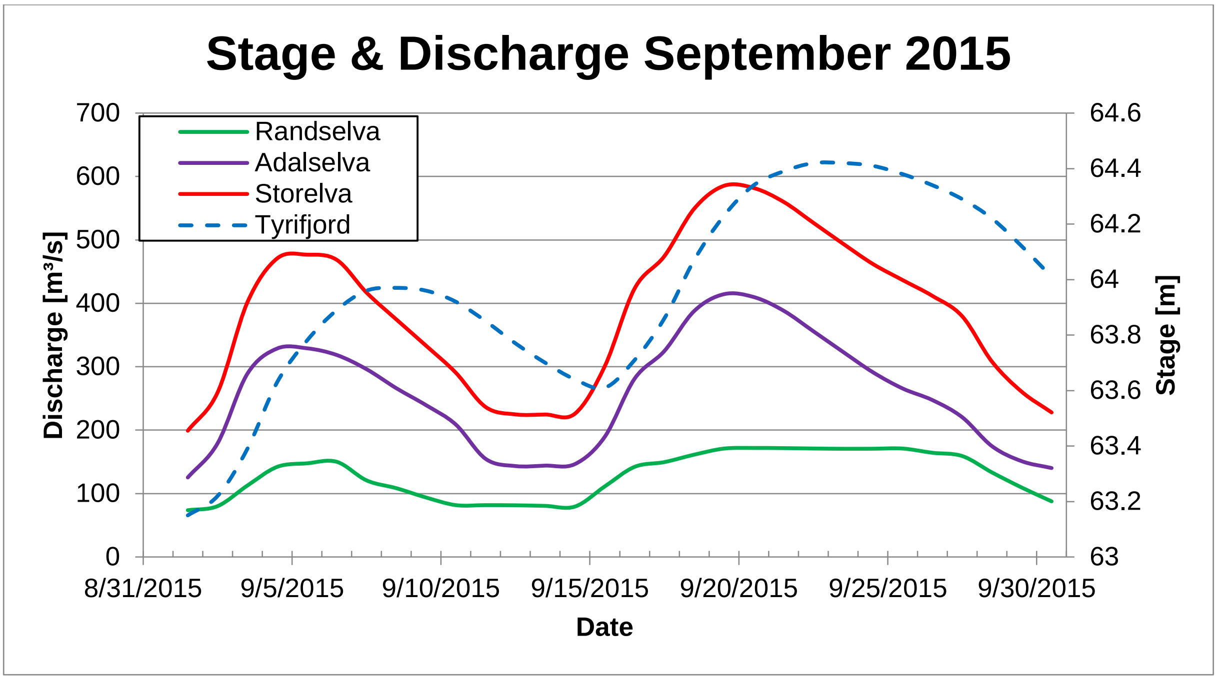


Diagram 4.3: Stage and flood hydrograph flood September 2015

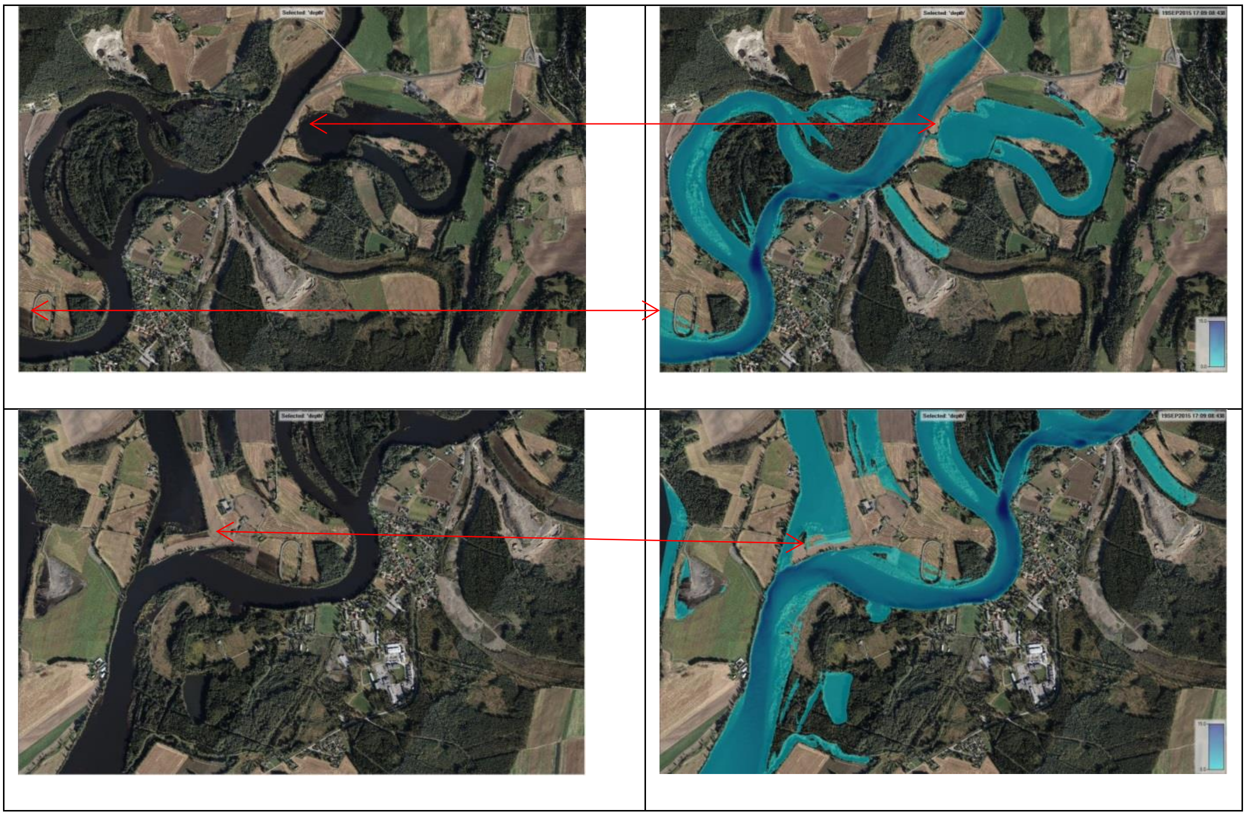


Figure 4.28: Validation Flood September 2015

5 Results of the 2D HEC-RAS Model

The goal of the 2D HEC-RAS model is to predict the impact of the two infrastructure alternatives described in chapter 4.2.5 and restoration measures, and its influence to the adjoining oxbow lakes and wetlands. All following calculated numerical models have been executed after the calibration and validation process described in chapter 4.3. All parameters previously set during the calibration and validation described in chapter 4.2 were used, and no further changes were applied.

To investigate the impact of the two infrastructure alternatives on the wetland system and the oxbow lakes at the Nordre Tyrifjord conservation area, several hydrographs were used and calculated with the modified terrain data for each infrastructural impact. As described in chapter 4.2.5, two alternatives were merged with the available terrain data and the actual condition from 2016 without the impact of the FRE16 project was examined.

To sort the flood events and statistical flood, abbreviations for the used terrain and the calculated corresponding floods were made. The used terrain files and its geometry, linked with their 2D unsteady flow condition hydrographs are named with the date of the year they appeared. For example the flood hydrograph of 2013 with the terrain file of the Actual Condition (AC) is named in the abbreviation as "AC-2013". Alternative A and Alternative B are named with their abbreviations "Alt-A" and "Alt-B" and their linked flow hydrograph year or statistical flood event (e.g. Alt-A-1967, Alt-B-HQ200).

Additional to the validating and calibrating floods of 2013 (AC-2013) and 2015 (AC-2015) the flood event from 1967 was applied to the actual condition (AC-1967), Alternative A (Alt-A-1967) and Alternative B (Alt-B-1967). Profile lines were implemented in the RAS Mapper tool of HEC-RAS 5.0.6 in order to picture the differences of each infrastructure alternative with the result layer for the different flood hydrographs. To show the changes at the oxbow lake Juveren, a profile line was set as a cross section through the oxbow lake (Figure 5.1). To show the changes at Synneren and the wetland area at the chute off another profile line was implemented through the Mælingen area (Figure 5.2). Each result layer therefore can be compared with any other result layer and terrain layer by activating the significant layer in RAS Mapper.

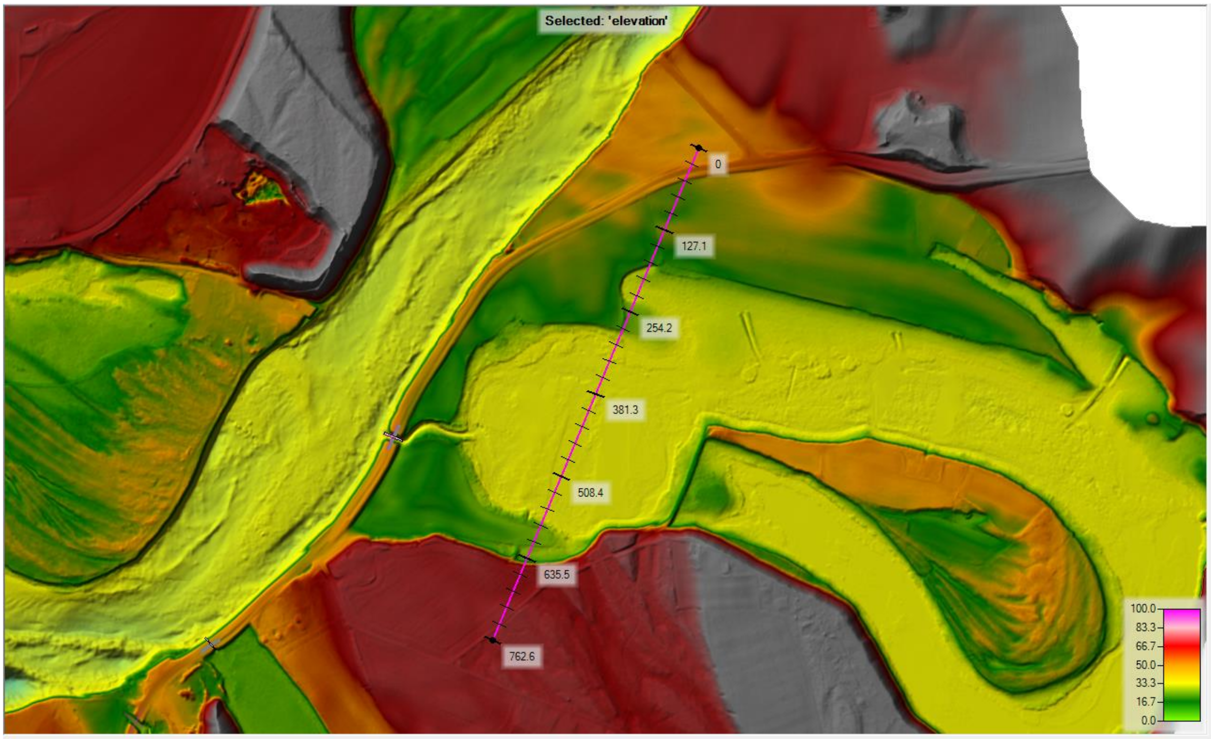


Figure 5.1: Profile cross section at Juveren

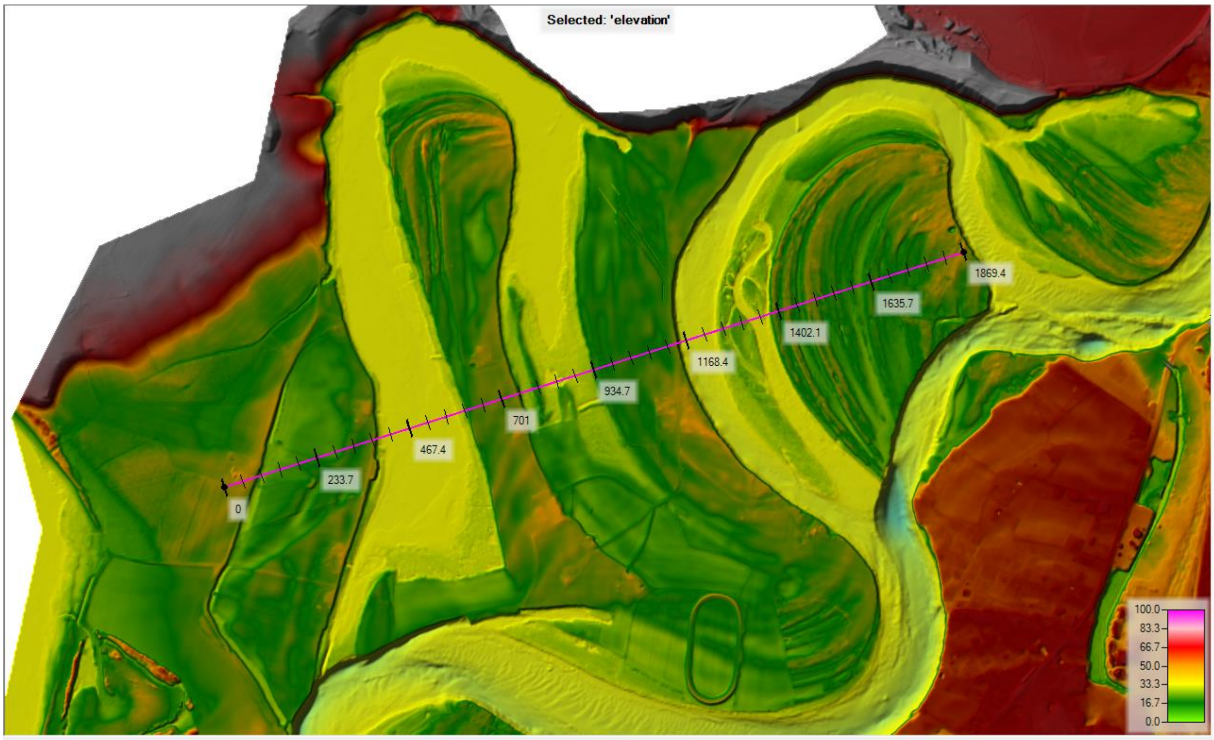


Figure 5.2: Profile cross section at Mælingen

On January 25th, 2019 a meeting with the planning engineers of the FRE16 infrastructure project was held at Sandvika, Norway to collect information and update all involved parties on behave of the hydrological and environmental impact of the infrastructure project FRE16. During the meeting it was mentioned that the involved parties will propose Alternative B, partly dam and bridge over Mælingen, to the deciding administration. Respective of this decision, more focus of the results in this thesis was put towards Alternative B and two more statistical flood events, HQ10 and HQ200, were calculated with HEC-RAS 5.0.6 with the underlying terrain files of Alternative B.

5.1 Results of the 1967 flood hydrograph

In 1967 a flood event happened at the river system Storelva, which is still mentioned by farmers and residents of the Ringerike area (Zinke & Dervo, 2018). This event had a maximal discharge in Storelva of 1060 m³/s and a corresponding water stage at Tyrifjord of maximal 65.28 m above-normal. Both maxima didn't appear at the same time since Tyrifjord reacts slower to water level changes and the previously discussed retardation of the whole area. Nevertheless it can be said that the flood occurring in 1967 can be approximated by a statistical HQ50 flood for the Storelva river system (HQ50 = 1050 m³/s, compare Table 4.1). In Diagram 5.1 the change of the water level of the Tyrifjord and the discharge of Storelva can be seen. The time axis is not accurate with the real 1967 flood event since no data with corresponding dates was given in the original document (Bane Nor, 2018).

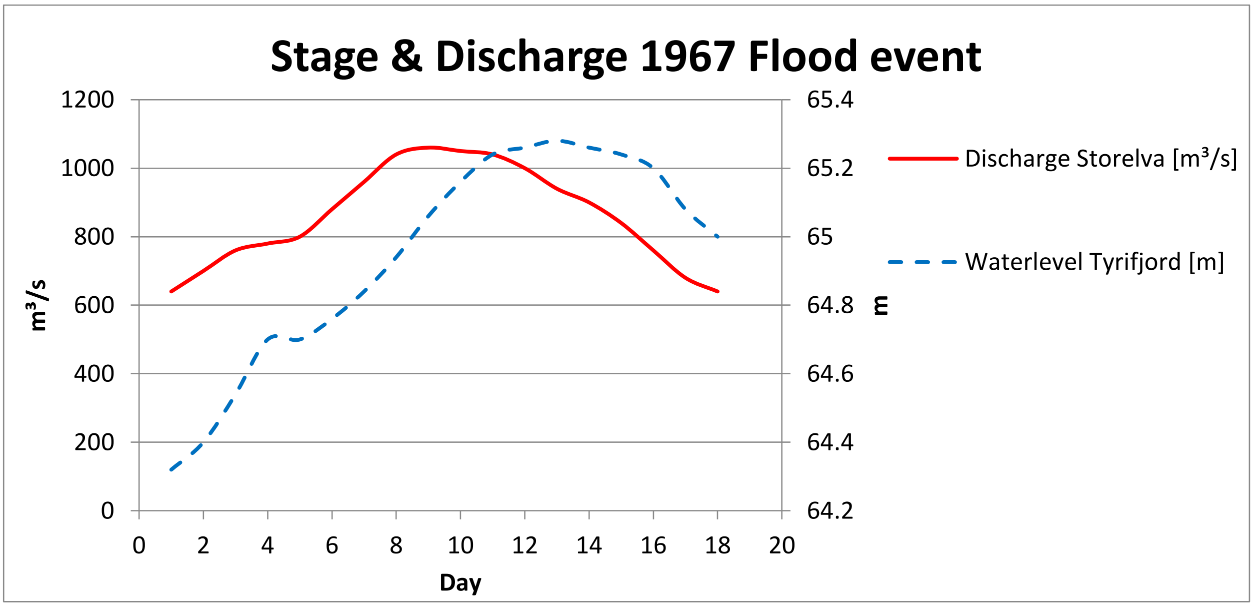
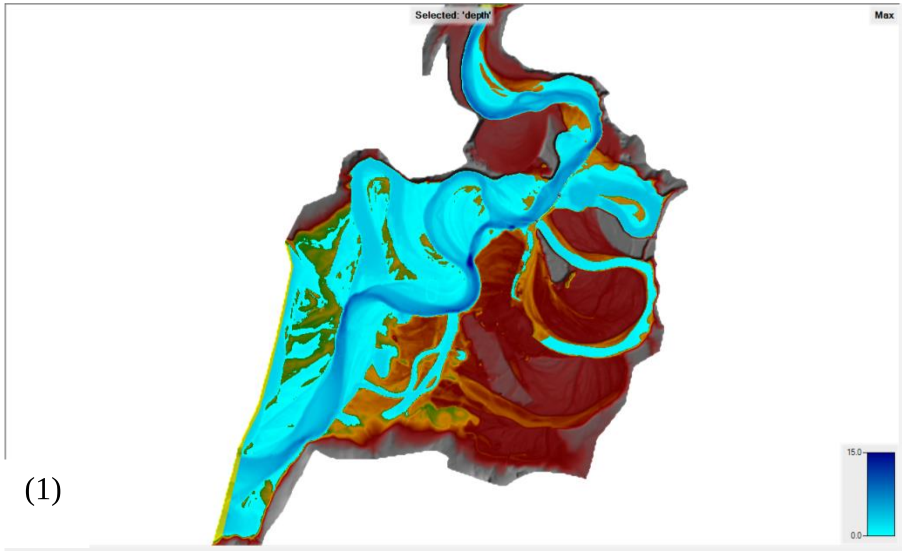
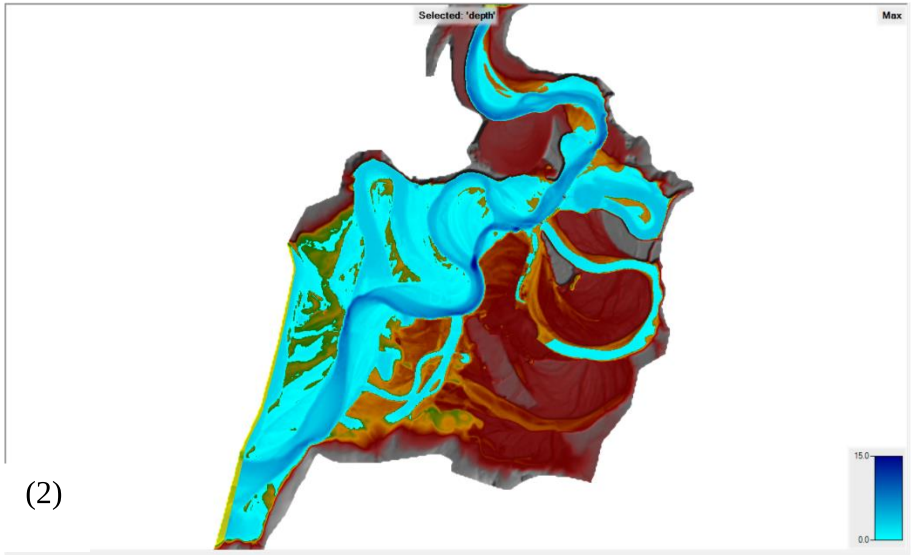


Diagram 5.1: Water level and discharge for the 1967 flood. (retrieved from Bane Nor (2018))

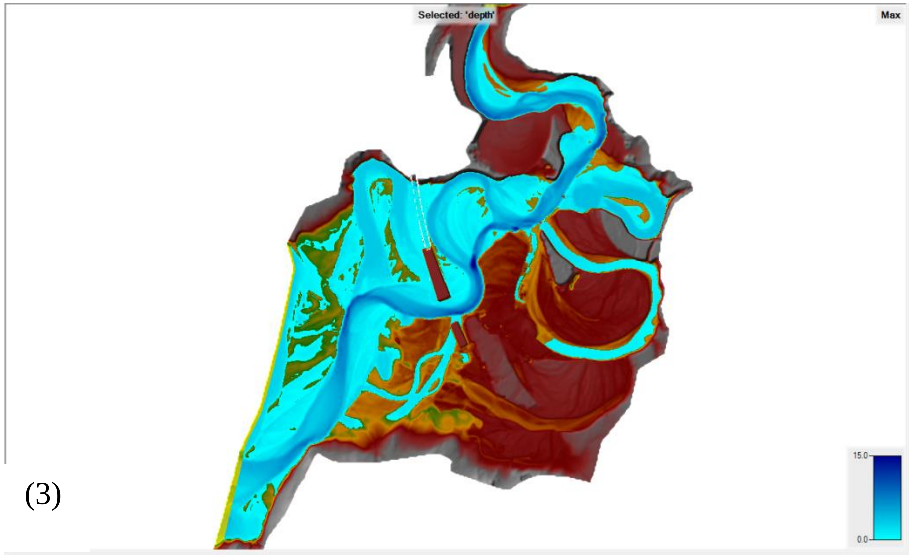
For the unsteady flow calculation in HEC-RAS 5.0.6 the above hydrograph was implemented for each terrain file (AC, Alt-A, Alt-B) in the validated 2D model. The overview in Figure 5.3 shows the maximal depth of the calculated results for each infrastructure alternative and the actual condition combined with the flow hydrograph of the 1967 flood event.



(1)



(2)



(3)

- (1) AC-1967
- (2) Alt-A-1967
- (3) Alt-B-1967

Figure 5.3: Max. depth 1967 flood for AC (1), Alt-A (2) and Alt-B (3)

By extracting the profile line from Figure 5.1 the water surface elevation for the 1967 flood can be pictured for each infrastructure alternative and the actual condition (Figure 5.4). For the representation of the real flood conditions of the 1967 flood event, the result map was set to the eleventh day of the hydrograph where the biggest coverage of water at Juveren and Synneren was seen. Since at Juveren no changes of the terrain files were made, the ground lines in Figure 5.4, representing the terrain, are coextensive to each other (yellow, green and red).

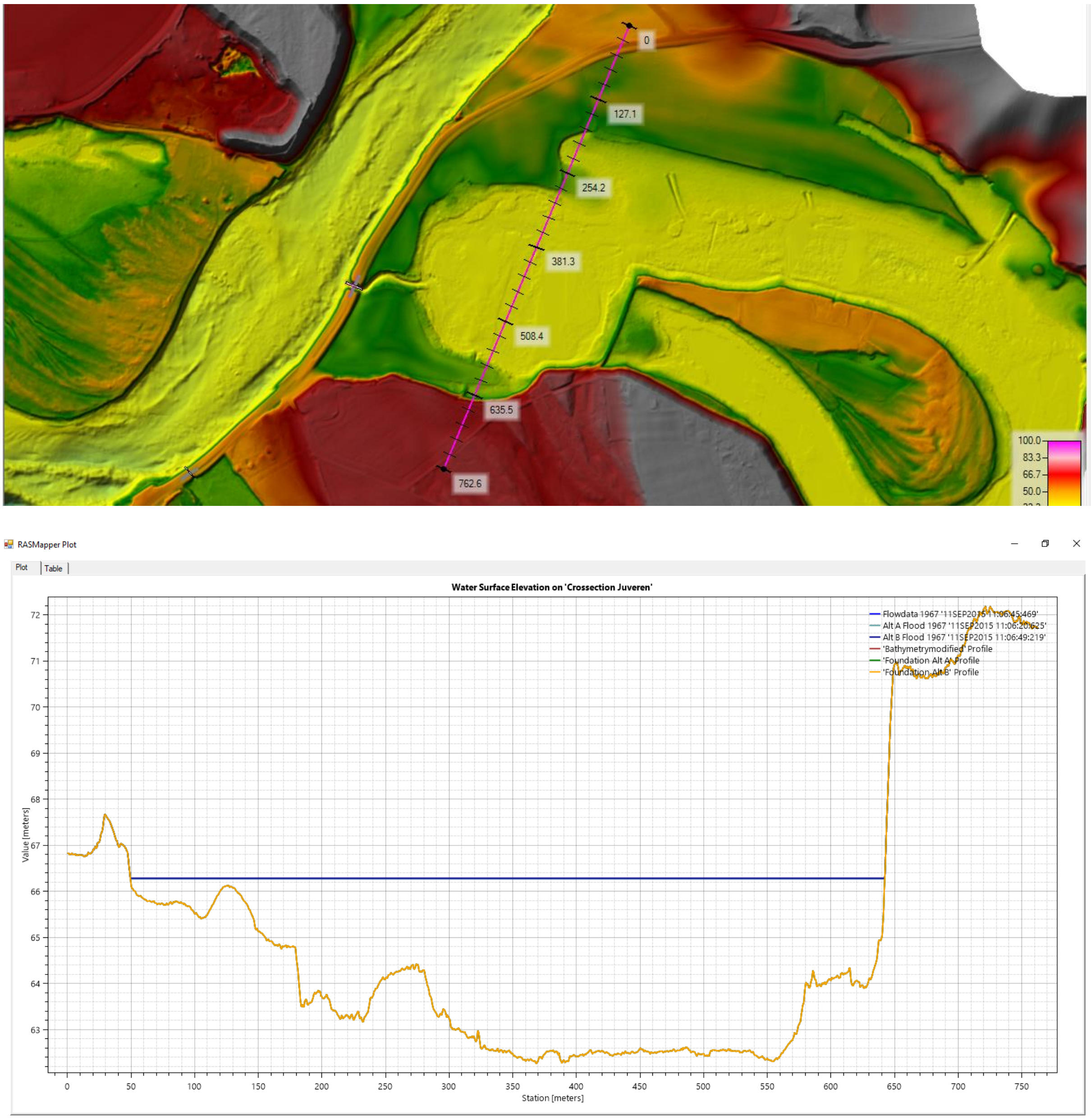


Figure 5.4: Profile line Juveren with AC-1967, Alt-A-1967 and Alt-B-1967.

As no significant changes can be seen in the full area plot (Figure 5.3) a closer look has to be made at the profile line cross section (Figure 5.5).

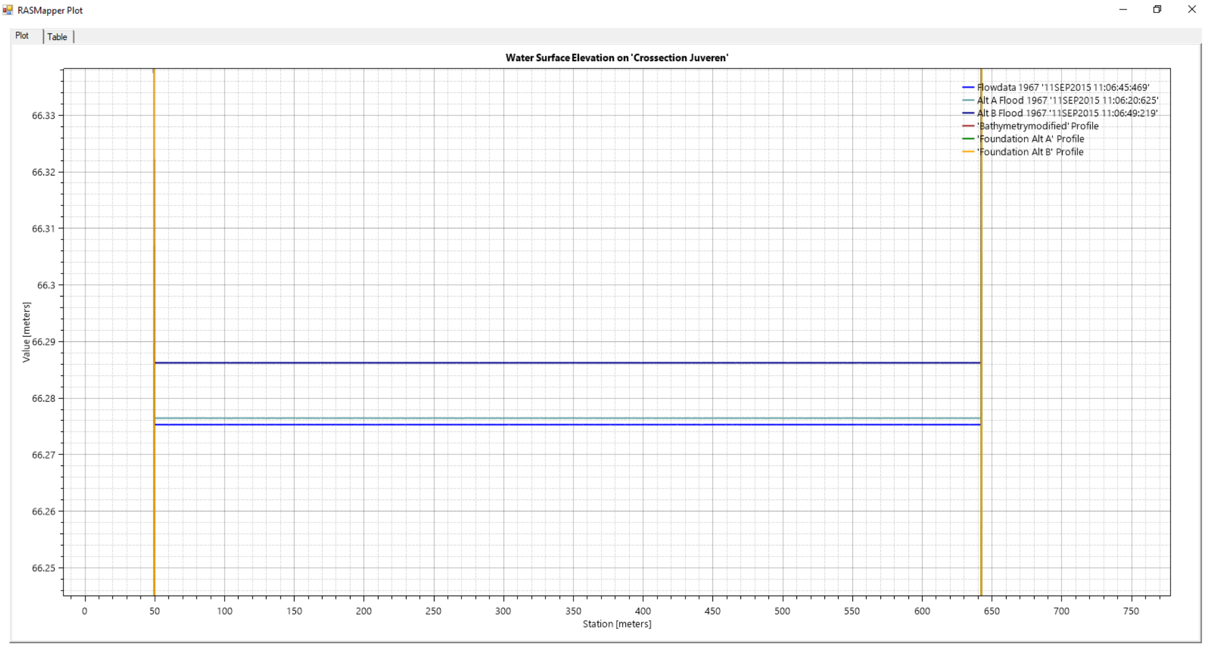


Figure 5.5: Zoomed section of profile line at Juveren.

By zooming into the cross section to get a detailed view, it shows, that the AC-1967 result delivers a water elevation above-normal of 66.275 m. The Alt-A-1967 result shows a raise of 0.001 m of the water level to 66.276 m. The Alt-B-1967 shows the biggest change of water level raise of 0.011 m to 66.286 m above-normal. Despite the calculated differences between the result layers it can be said that no significant change will impact the Juveren oxbow lake by implementing any of the two infrastructure alternatives. The total change of the water level for the worst case will be 1.1 cm which cannot be taken into account since the overall vertical resolution and accuracy of the HEC-RAS 2D model is 0.25 m as described in chapter 4.2.1.

The profile line cross section at Mælingen, as shown in Figure 5.2, shows the different water level elevation in the main channel of Storelva and the changes of the result layers AC-1967, Alt-A-1967 and Alt-B-1967. To differentiate the different locations of the branches of the oxbow lake Synneren the infrastructure alternatives and Storelva, the rough stations as seen in Figure 5.2 are shown. The western arm of Synneren is located between station 380 and station 640, the eastern arm is between station 744 and station 930. The infrastructure alternatives are located between station 1070 and station 1120 but not pictured in Figure 5.2 and Figure 5.6 since multiple terrain display is not supported. The northern branch of the Storelva chute off begins at station 1140.

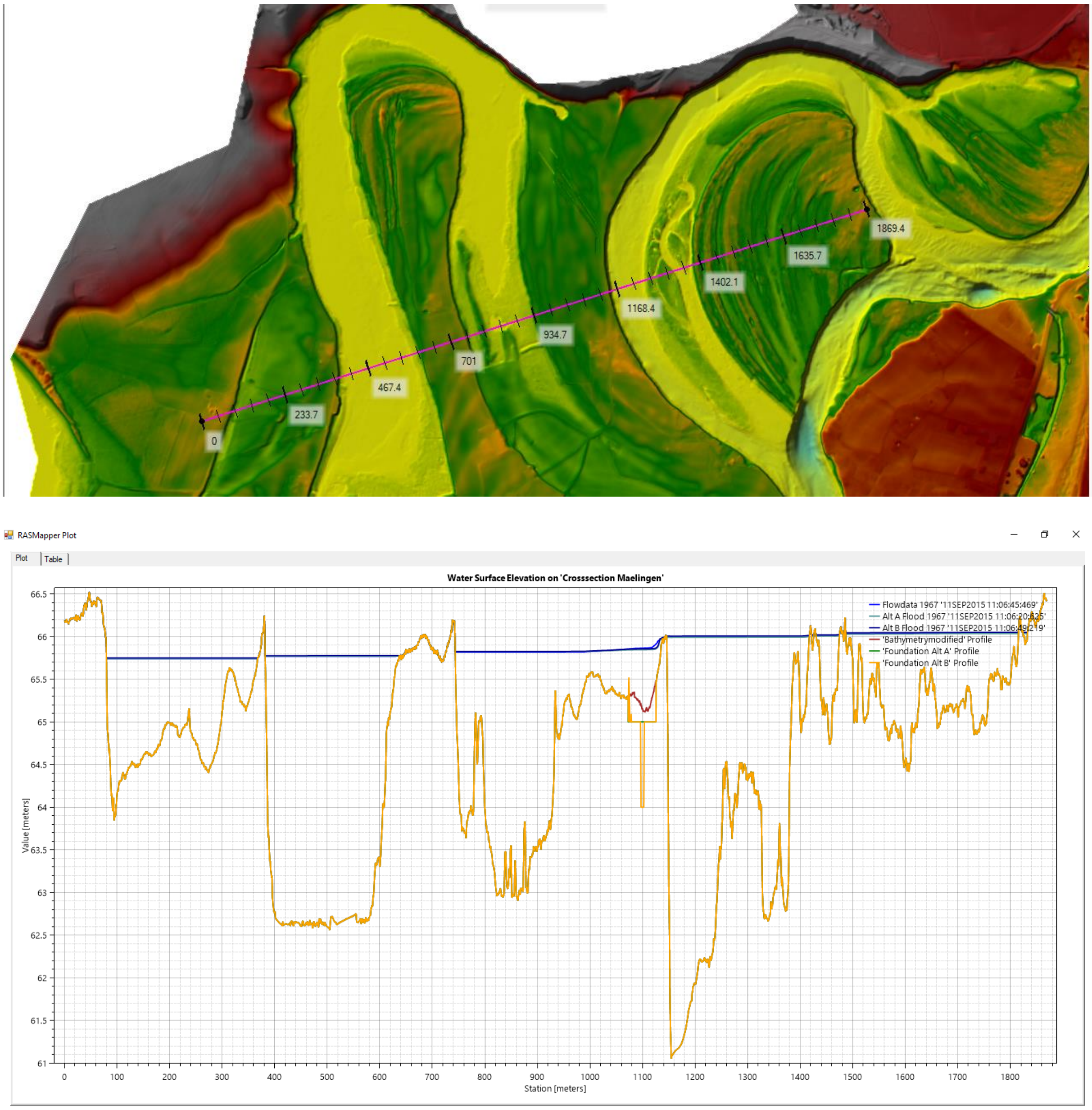


Figure 5.6: Profile line Mælingen with AC-1967, Alt-A-1967 and Alt-B-1967.

In Figure 5.6 the different infrastructure alternatives can be seen by the change of the ground line between station 1070 and station 1120 (red). Inaccuracies of the terrain are a result of the infrastructure implementation as previously described.

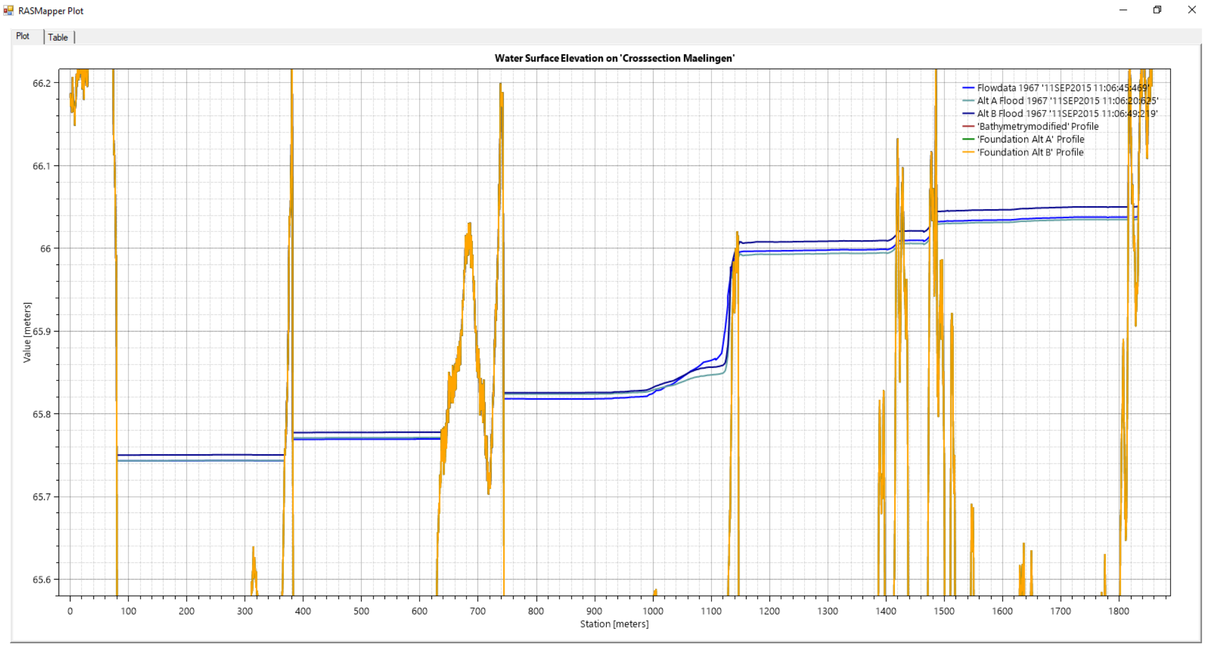


Figure 5.7: Zoomed section of profile line at Mælingen.

In contrast to the water level conditions in Juveren in Figure 5.5 the water level elevation is lowest with Alternative A at each channel branch according to the 2D HEC-RAS model. The influence of Alternative B is less than 1 cm to the water level elevation of the actual condition from 2016. Therefore the water level elevation difference, lying between Alternative A and Alternative B, is similarly less than 1 cm to the other calculated conditions.

The most significant difference can be seen at the transition point from the main channel to the Mælingen wetland between station 1120 and station 1150. As pictured in Figure 5.8, the gradient from the not impacted condition AC-1967 to Alt-A-1967 and Alt-B-1967 changes. It appears that the water level decreases in a shorter distance after it reaches a stable water level plateau. Nevertheless the largest difference between the three curves is 5 cm at station 1124. Similar to the water elevation in Juveren and in the branches of Synneren and at Mælingen this HEC-RAS calculated difference is smaller than the resolution of the underlying terrain file (0.25 m).

This change of the gradient of the water surface also influences the velocity in this area. In Figure 5.9 the velocity difference to each terrain condition for the 1967 flood can be seen. For AC-1967 the highest occurring (max.) velocity at the overbank flow reaches 0.9 m/s whereas the velocity for the two infrastructure alternatives is higher than 1.8 m/s according to the calculations of the 2D unsteady flow model.

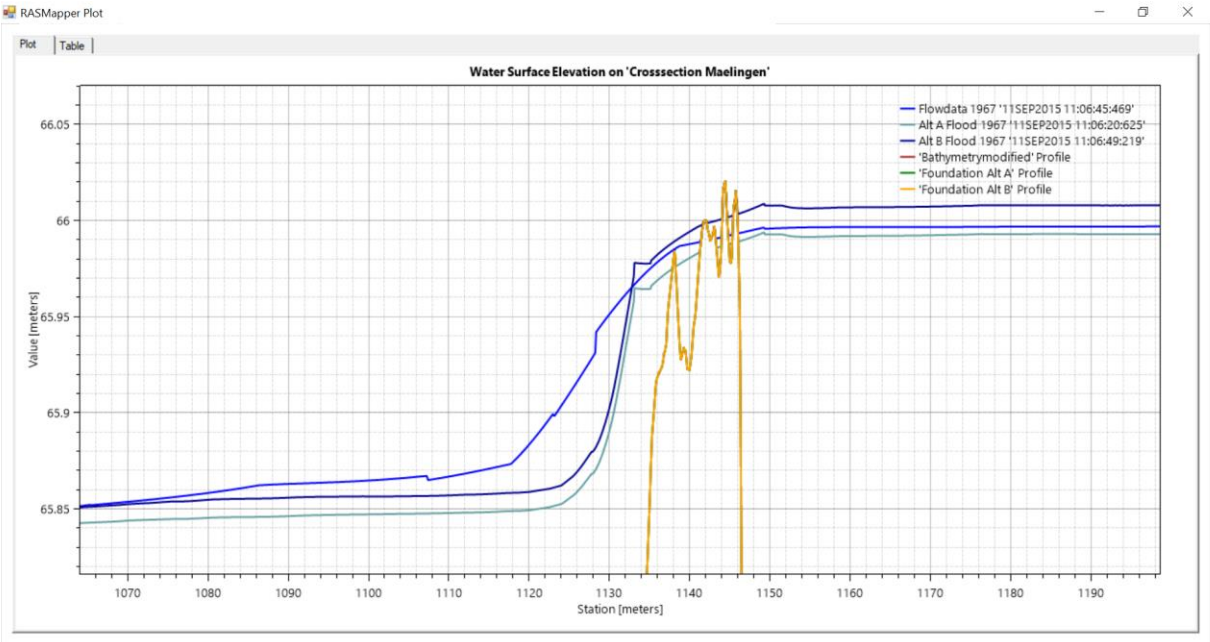


Figure 5.8: Detail water level elevation infrastructure location at Mælingen on the 11th day.

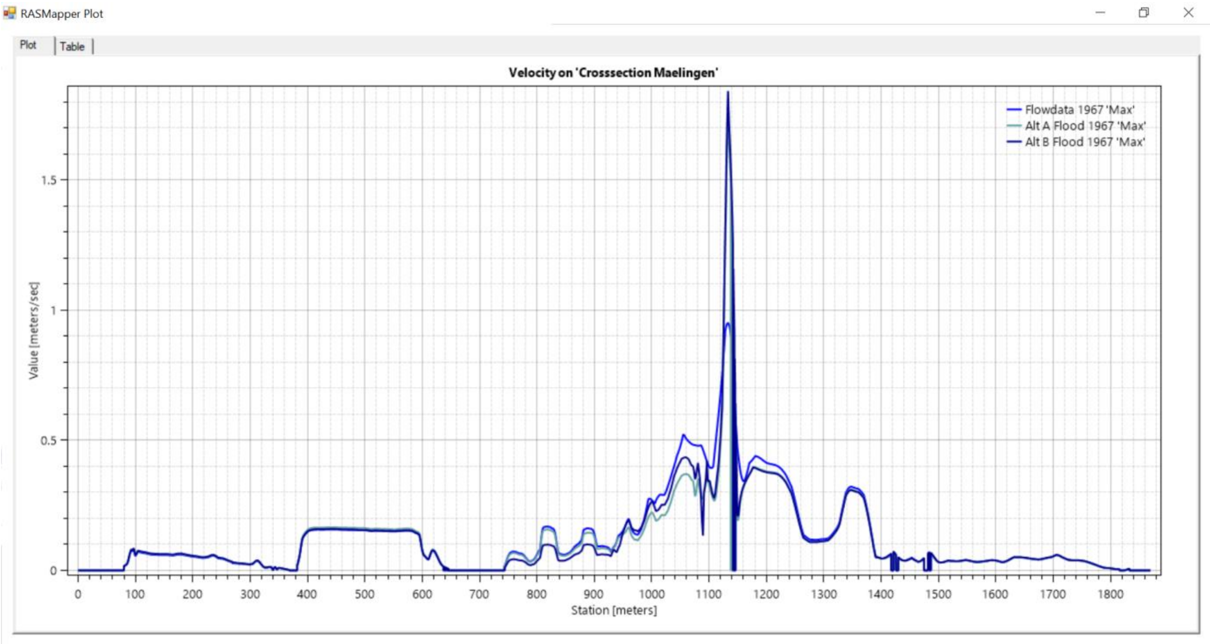


Figure 5.9: Max. velocity on cross section Mælingen

In the hydraulic report presented by Bane Nor a difference of maximum 4 cm compared to each infrastructure alternative is predicted (Bane Nor, 2018). In the last meeting on the 25.01.2019 with Bane Nor, it was said that the difference of the water surface elevation will make less than 2 cm (personal note). Despite the differences in the modelling approach the results presented in this study for the 1967 flood seem reasonable.

5.2 Results of the HQ10 flood hydrograph

At the meeting of the participating parties in Sandvika, Norway on the 25.01.2019 it was annotated, that Alternative B, partly bridge and dam over Mælingen (Figure 3.12), will be proposed to the deciding committee. Nevertheless both alternatives were planned and investigated by those involved.

By analyzing the results of the 1967 flood event, representing a HQ50 flood event, it was seen, that the changes in water elevation at the oxbow lakes is less than the resolution of the underlying terrain (0.25 m) with a maximum of 5 cm.

Due to these results and the probable proposal by BaneNOR, it was decided that further results calculated by HEC-RAS should be connected with the infrastructure Alternative B.

In Figure 5.10 the results of the calculation AC-HQ10 (left) and ALT-B-HQ10 can be seen. The most significant change is the raise of water elevation at the northern part of the bridge east of Synneren. This “filling” is because of the implementation of the infrastructure itself as described in chapter 3.5. By comparing both result layers with each other (Figure 5.11) it can be seen that for the maximum water surface elevation parts of the banks are more overflown for Alt-B-HQ10 (blue). Due to the display in RAS-Mapper the overflown areas seem larger than they are. By zooming into the result layer (Figure 5.12) the display of the WSE gets smaller and shows changes in the area of the bridge in the north east of Synneren.

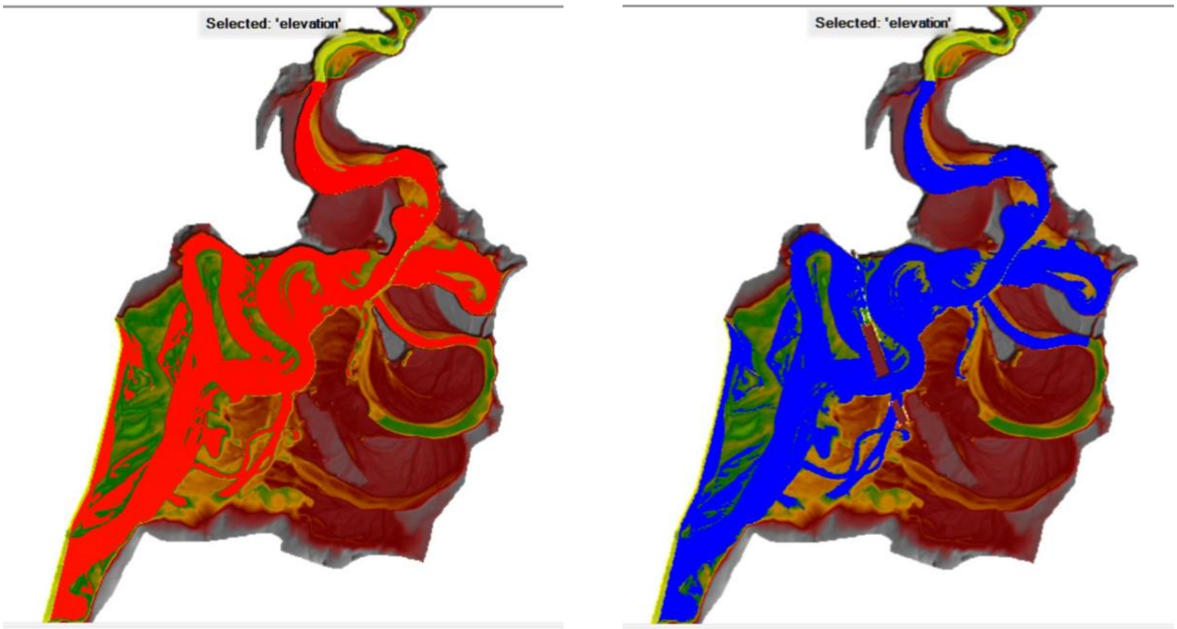


Figure 5.10: Results HQ10 actual condition (left) and Alternative B (right)

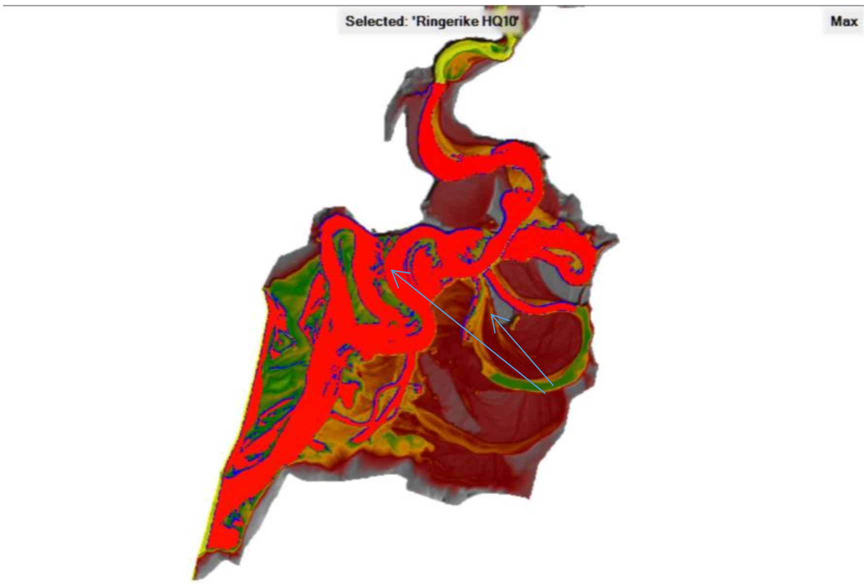


Figure 5.11: Comparison HQ10 of AC-HQ10 and Alt-B-HQ10

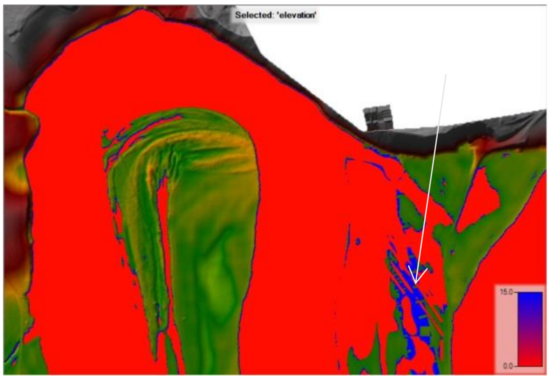


Figure 5.12: Detail water surface elevation Synneren, AC-HQ10 and Alt-B-HQ10

The total change of the WSE for the maximum values in the investigated area at Synneren increased by 5 cm in the western branch and 4 cm in the eastern branch (Figure 5.13 and Figure 5.14). At the wetland area Mælingen the water elevation decreases by 11 cm. This fall may be caused by the physical blocking of the dam and thus changing the water distribution, regulated by the downstream condition at Tyrifjorden, in the oxbow lake Synneren and the wetland at Mælingen. Nevertheless the results are smaller than the resolution of the underlying bathymetry and indifferences can be caused by the implementation of the infrastructure.

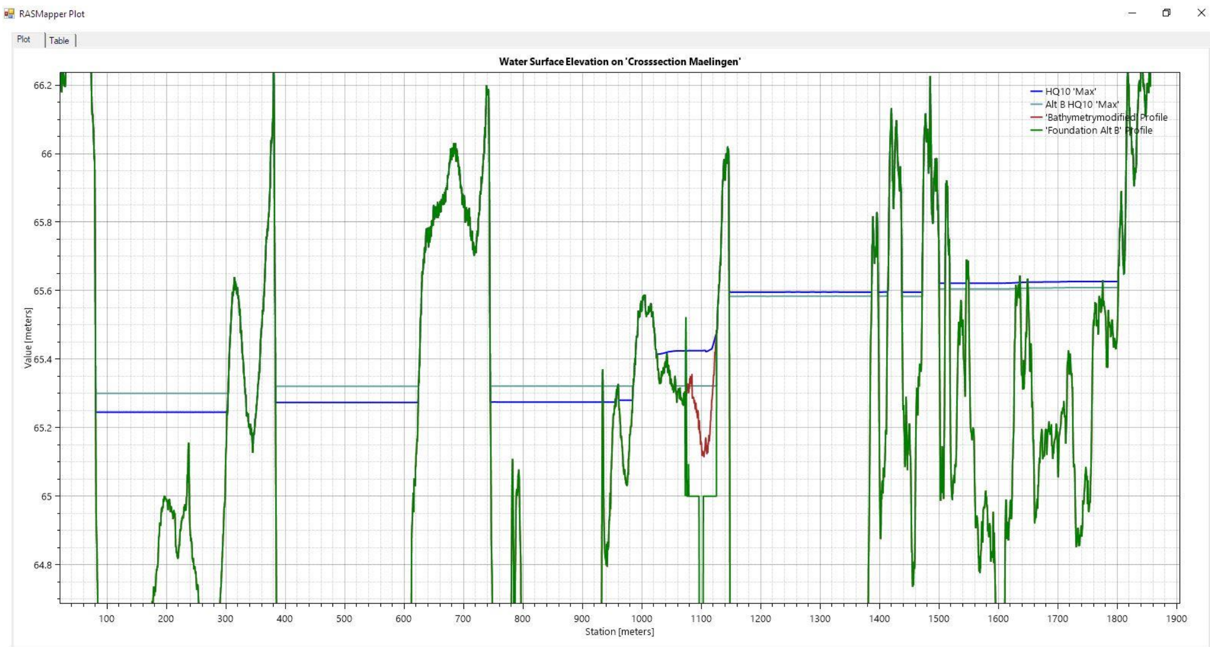


Figure 5.13: Crossection Mælingen HQ10

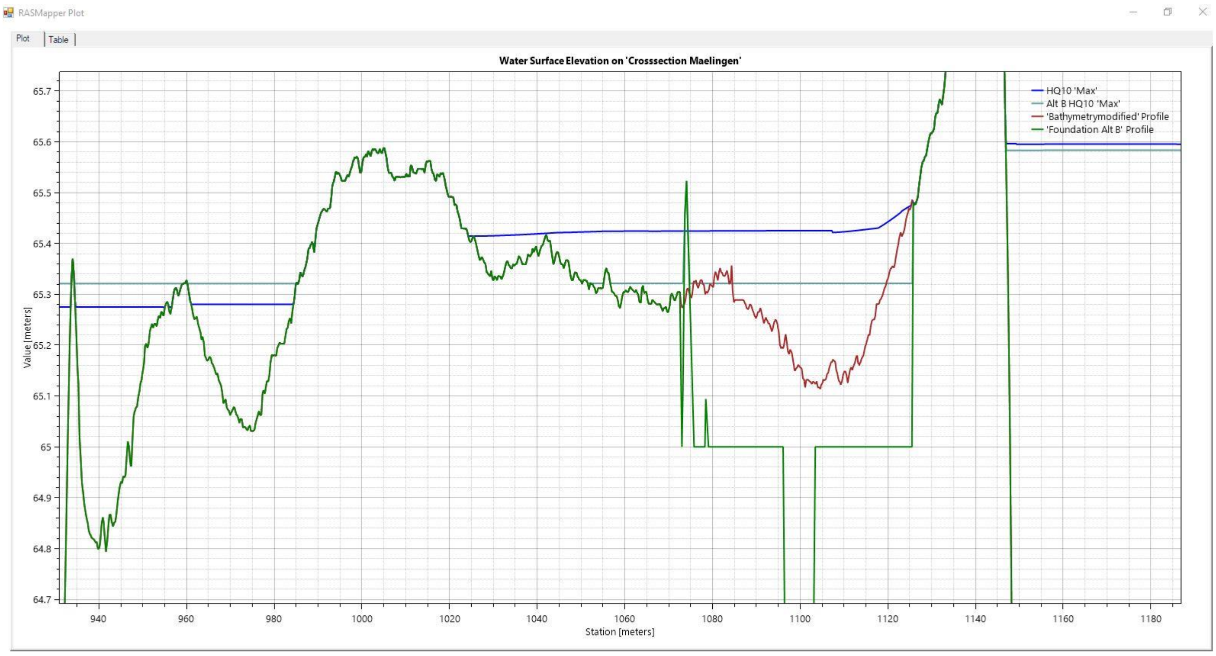


Figure 5.14: Detail cross section Mælingen HQ10

The results for the HQ10 flood event not only show the decrease of the water level elevation but also a decrease of the velocities at the eastern river bank. The flow velocity decreased from 0.41 m/s to 0.35 m/s. This reduction of velocity can be caused by the larger water depth, which with respect to continuity, is reasonable. Therefore, it can be said, that during a statistical 10-year flood event the water distribution at Mælingen will change in a mentionable matter and influence the ecology of the wetland itself.

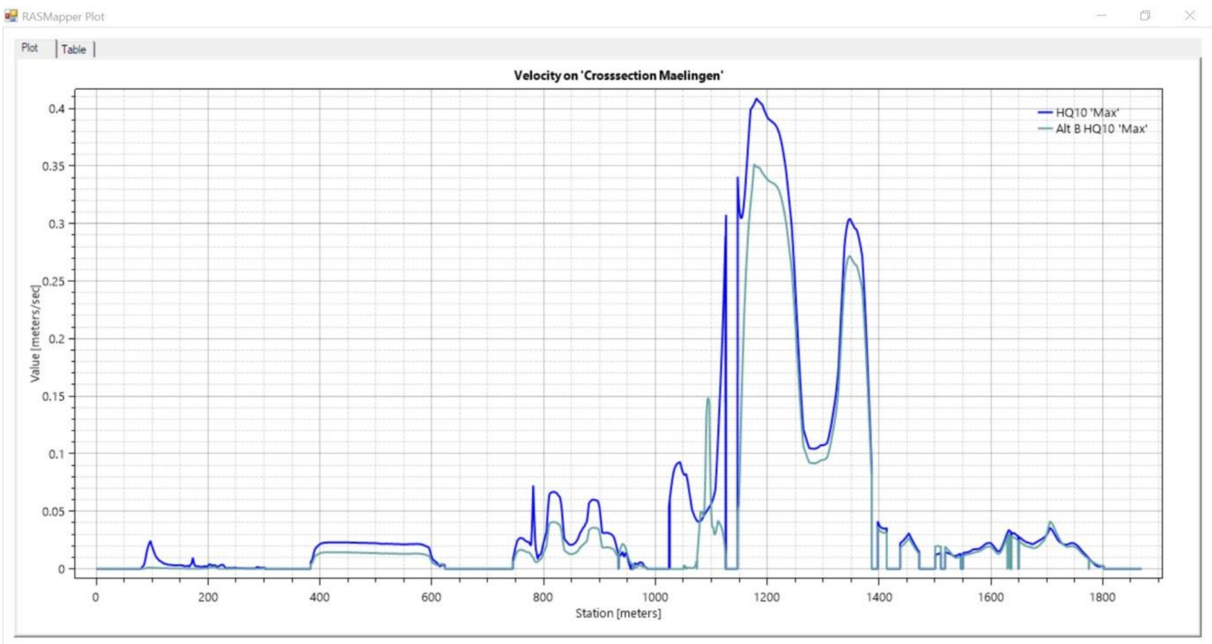


Figure 5.15: Velocities at cross section Mælingen for HQ10

At Juveren, according to the 2D unsteady flow model of HEC-RAS 5.0.6, the water level will fall by 6 cm. Tyrifjorden affects the water level at Juveren. The dam of Alternative B retards the propagation of water, keeping it in Synneren, and therefore forcing a decline of the water level in Juveren (Figure 5.16). But as previously mentioned, the change of the WSE is less than the resolution of the terrain file and thus has to be put into perspective.

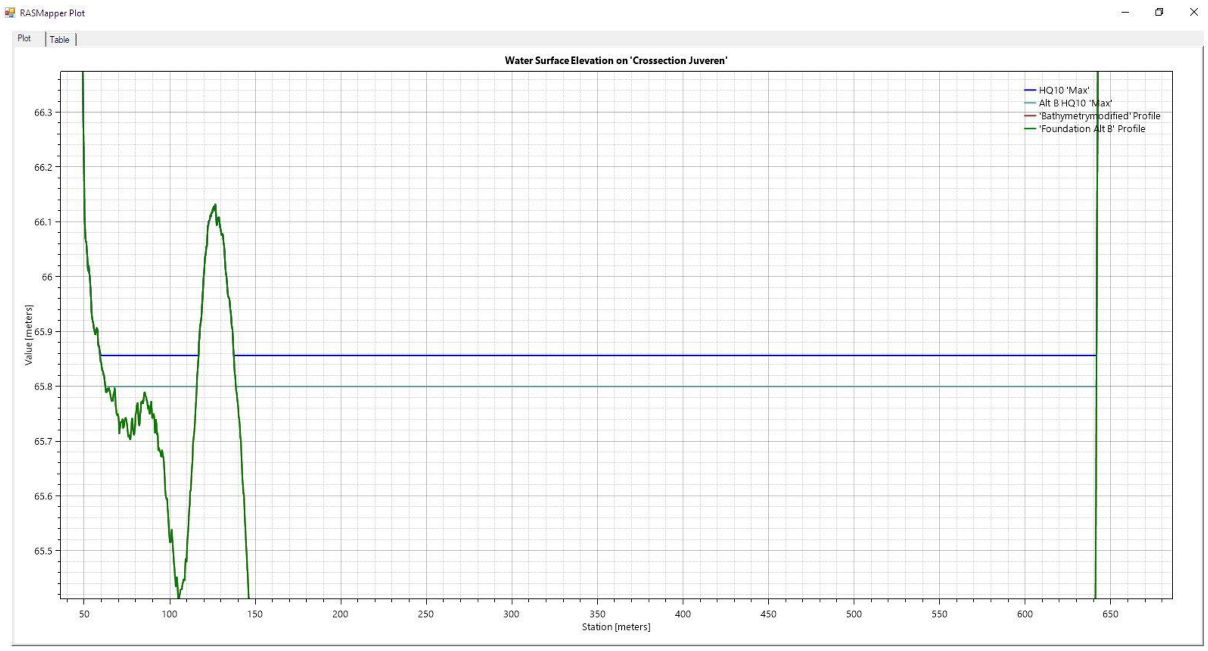


Figure 5.16: Cross section Juveren HQ 10

5.3 Results of the HQ200 flood hydrograph

The statistical 200 year flood event (HQ200) was also calculated with the HEC-RAS 2D model. As previously described the results for the alternative B (Alt-B-HQ200) are shown and compared with the actual condition (AC-HQ200) in Figure 5.17. In the branch of Synneren the difference of the water surface elevation between the actual condition and alternative B is 1 cm, where Alt-B-HQ200 delivers the higher water surface elevation. At the main channel of Storelva, east of Mælingen, the WSE change is less than 1 cm. Other than in Synneren the water elevation of AC-HQ200 is lower than for the results of Alt-B-HQ200. The most recent change can be seen in Figure 5.18 at the river bank from the Storelva bypass to Mælingen. Similar to the results of the 1967 flood and HQ10, the water surface experiences a faster drop. This change of the gradient leads to higher velocities in this particular area. The maximum velocities for AC-HQ200 reach 0.70 m/s by flowing into the wetland of Mælingen. The calculated results of HEC-RAS show an increase of the velocity to a value of 1.36 m/s (Figure 5.19).

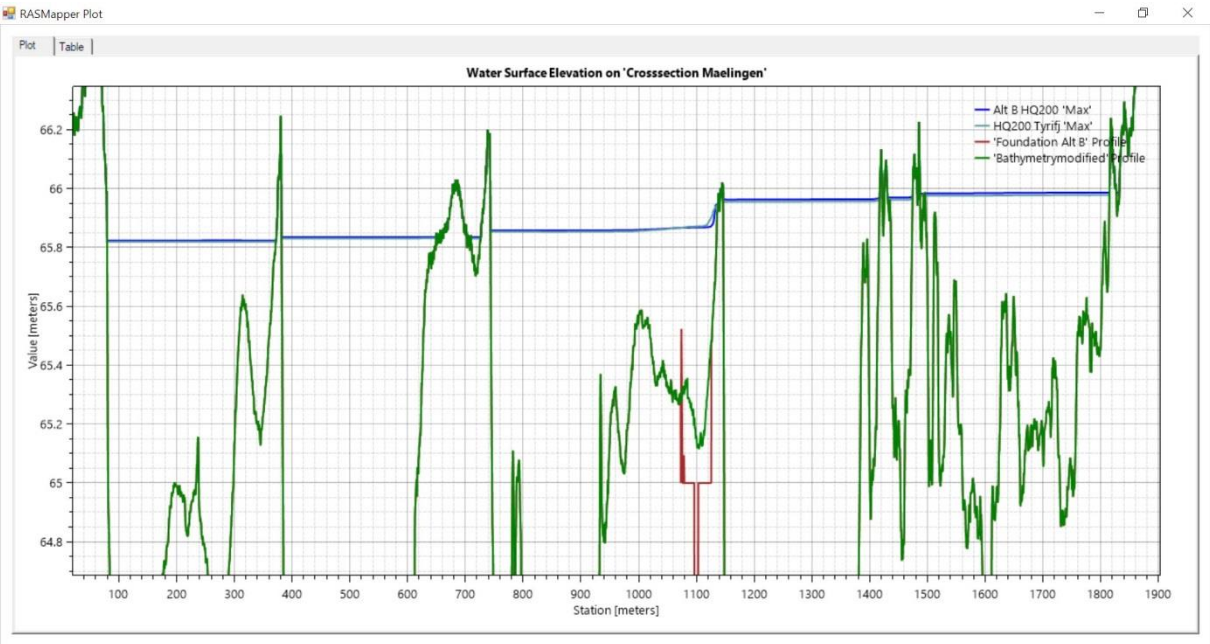


Figure 5.17: WSE at cross section Mælingen for HQ200

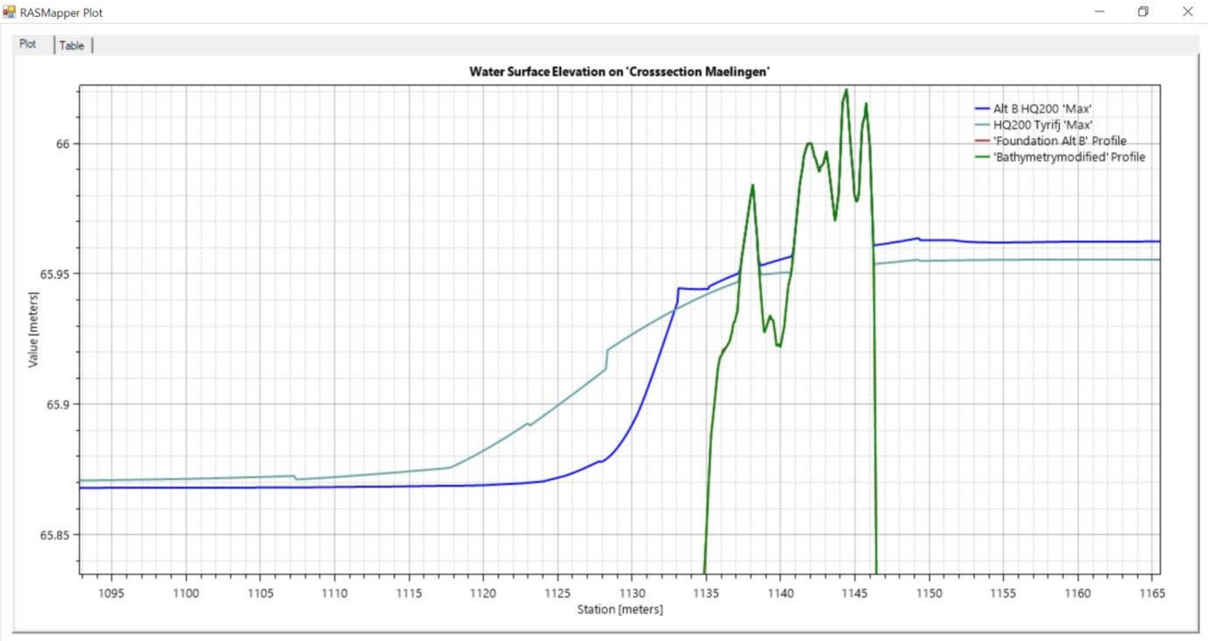


Figure 5.18: Detail of WSE at cross section Mælingen for HQ200

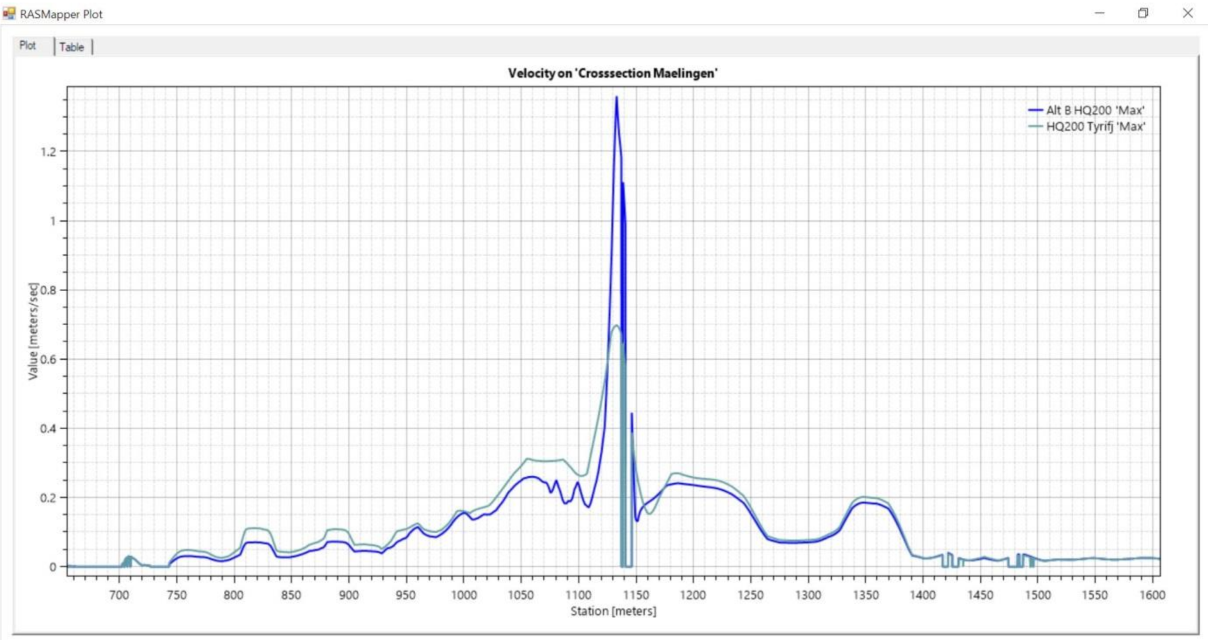


Figure 5.19: Velocities at cross section Mælingen for HQ200

At the oxbow lake Juveren, the impact of the infrastructure alternative B can be seen as a rise in the water level elevation (Figure 5.20). By implementing the terrain of the alternative B the 2D unsteady flow model calculates an increase of the WSE of 1 cm.

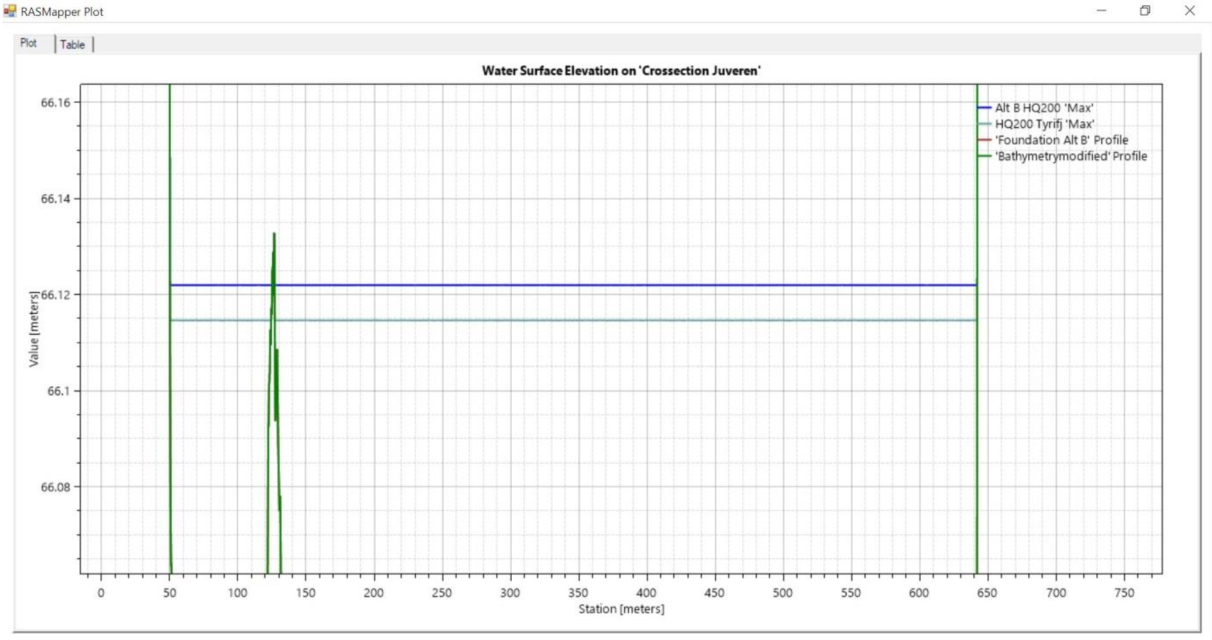


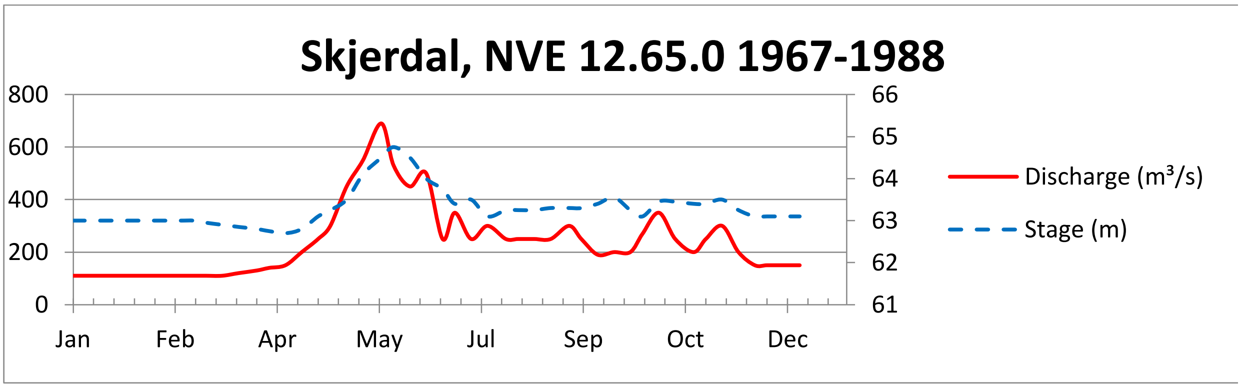
Figure 5.20: WSE at cross section Juveren for HQ200

5.4 Results of the 0.9 percentile annual flood

Another possibility to describe the wetland systems and oxbow lakes during a usual year is to take the 0.9 percentile of annual data over a longer period. In this case the data from 1967 to 1988 and 1990 to 2017 was implemented into the model. The data from 1967 to 1988 is the flow data before the regulation of the river and the 1990 to 2017 is the flow data after the regulation in consequence of the use of hydro power. It is important for wetland systems and oxbow lakes to have a certain duration of water overflow and water circulation as part of the ecology (Meyer, 2017).

The 0.9 percentile describes all discharge and stage values that are lower than 90% of the highest occurring value in the whole time series. This erases very high peaks from unusual events and describes a regular flow distribution of a full year over a long period. In Diagram 5.2 the two hydrographs can be seen. It is shown, that the spring flood at Storelva before the regulation (top) in May has a discharge of 690 m³ and a water elevation at Tyrifjord of 64.75 m above normal in the statistical average whereas after the regulation (bottom) the spring flood peaks to 450 m³/s and 63.70 m above normal in May in the statistical average.

Furthermore the regulation of the river system is viewable at the water level elevation line at Tyrifjorden. The highest difference is from 62.80 m to 63.70 which lead to 0.9 m of change in the period of 1990 to 2017. Before the regulation the difference in the water level was from 62.70 m 64.75 m, in total a change of 2.05 m.



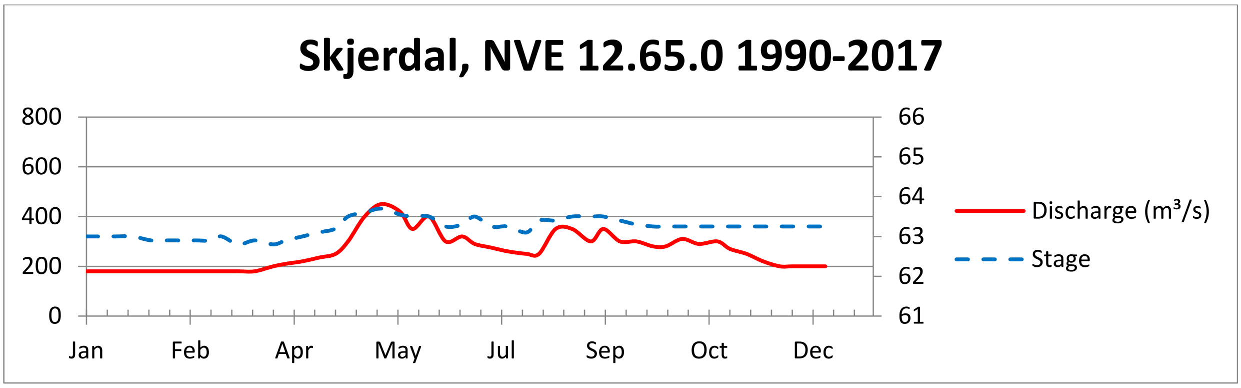
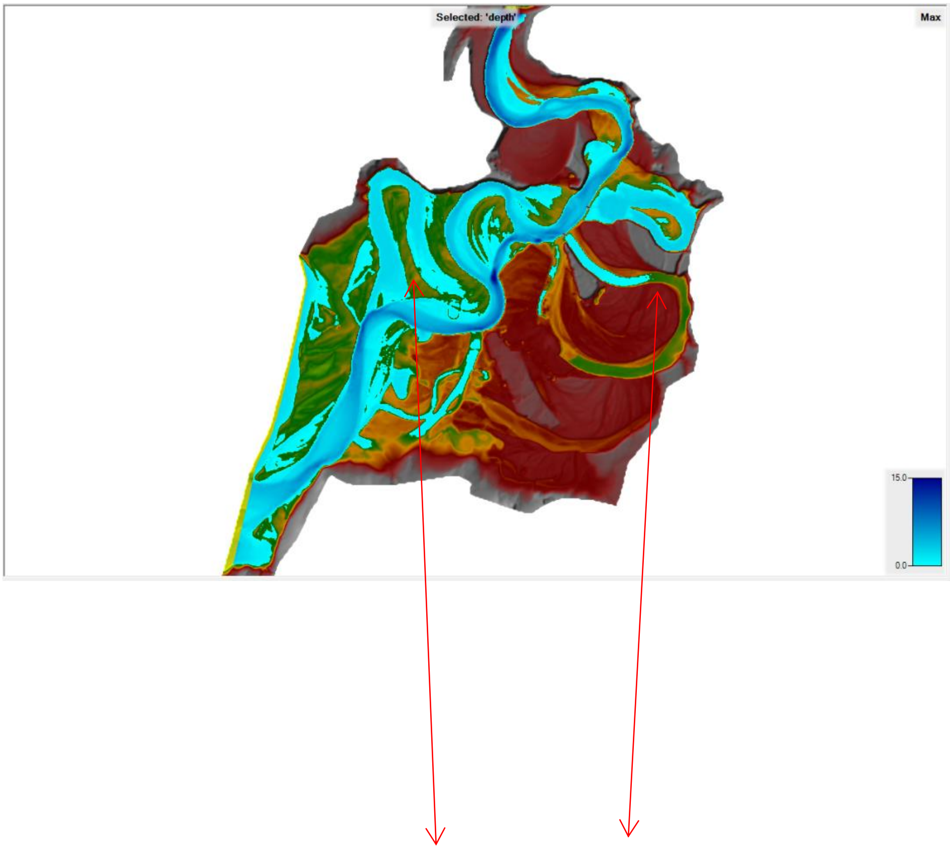


Diagram 5.2: Discharge and Stage hydrograph at Skjerdal for the time series 1967-1988 and 1990-2017

The resulting layer maps of this statistical 0.9 percentile annual flood in Figure 5.21 show the impact of the regulation. The maximum indicates that parts of Juveren, Synneren and Lamyra are not overflown as they used to be before the regulation. Therefore the exchange of water and the water level in the oxbow lakes decreased and may have changed the ecology of the wetland system.



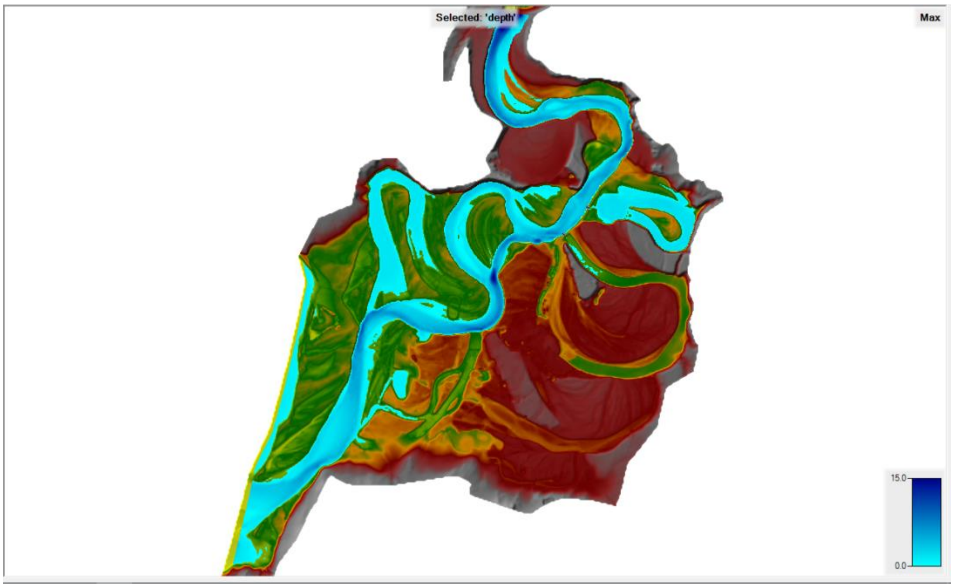


Figure 5.21: Max. depth for the 0.9 percentile annual flood from 1967-1988 (top) and 1990-2017 (bottom).

5.5 Results of the deepened oxbow lakes with HQ200

For the investigation of a deepening of the oxbow lakes Juveren and Synneren as suggested in previous reports (Fylkesmannen i Buskerud, 2016; Zinke & Dervo, 2018) a new terrain file was constructed and implemented into the HEC-RAS 2D model (Figure 5.22). The depth in the oxbow lakes was lowered to 58.3 m above normal and a model was run with the HQ200 flow hydrograph affected by Tyrifjorden.

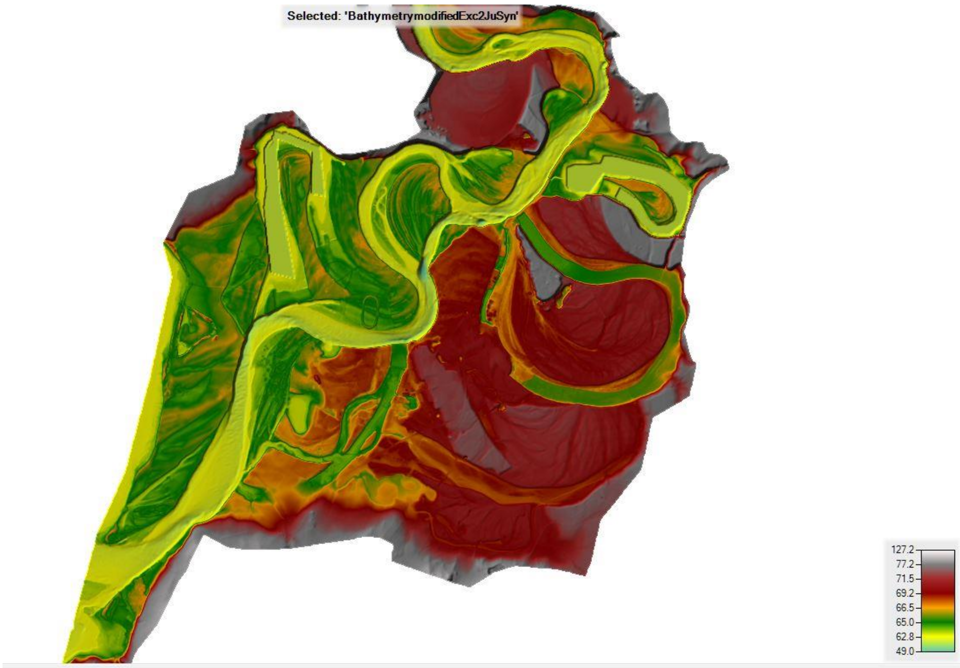


Figure 5.22: Bathymetry with deepened oxbow lakes Synneren and Juveren

In Figure 5.23 the cross section at Mælingen and in Figure 5.24 the cross section for Juveren is shown. At Synneren the water level elevation decreases by 4 cm according to the model. Upstream at the bypass of Storelva the water surface decreases by 6 cm. At the wetland Mælingen, the water level decreases by 6 cm likewise. The results at Juveren show that the water surface elevation decreases by 8 cm, if the oxbow lake bed will be excavated to a depth of 58.3 m above normal.

A change in the water distribution and direction of flow could not be mentioned. Therefore these changes would, most notably, increase the volume of the oxbow lakes and help with the retention of flood events. As observed in the results before, the change in the calculated water depth values is lower than the vertical resolution of the underlying terrain file.

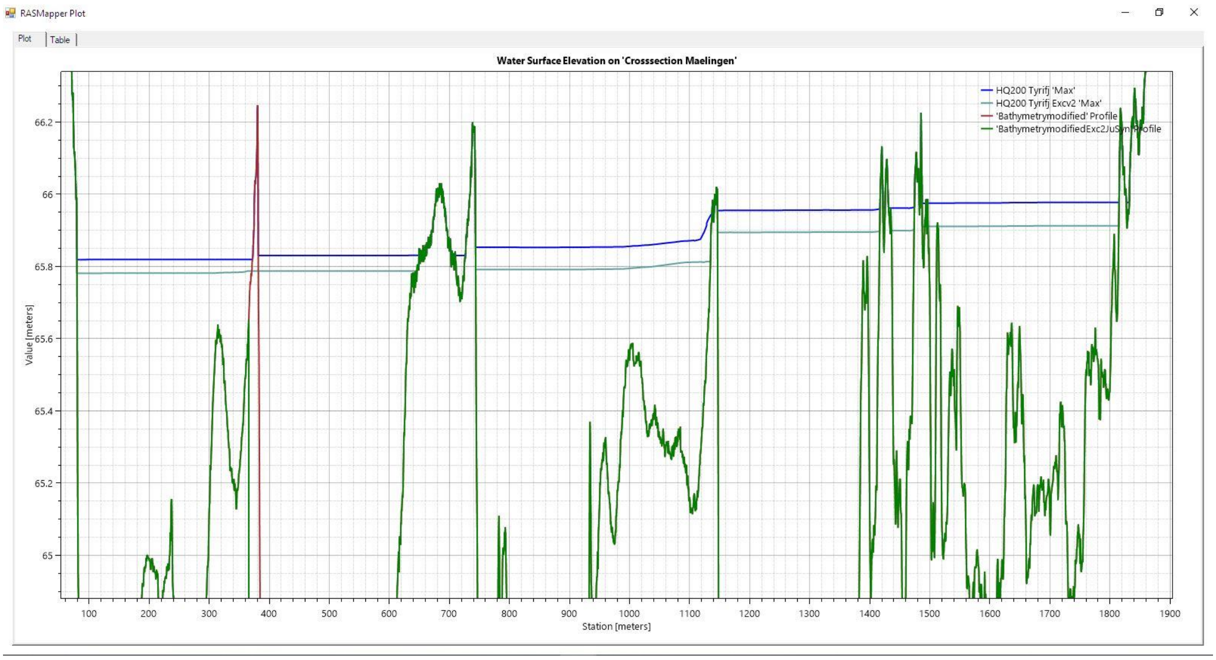


Figure 5.23: WSE at cross section Mælingen for HQ200 and excavation

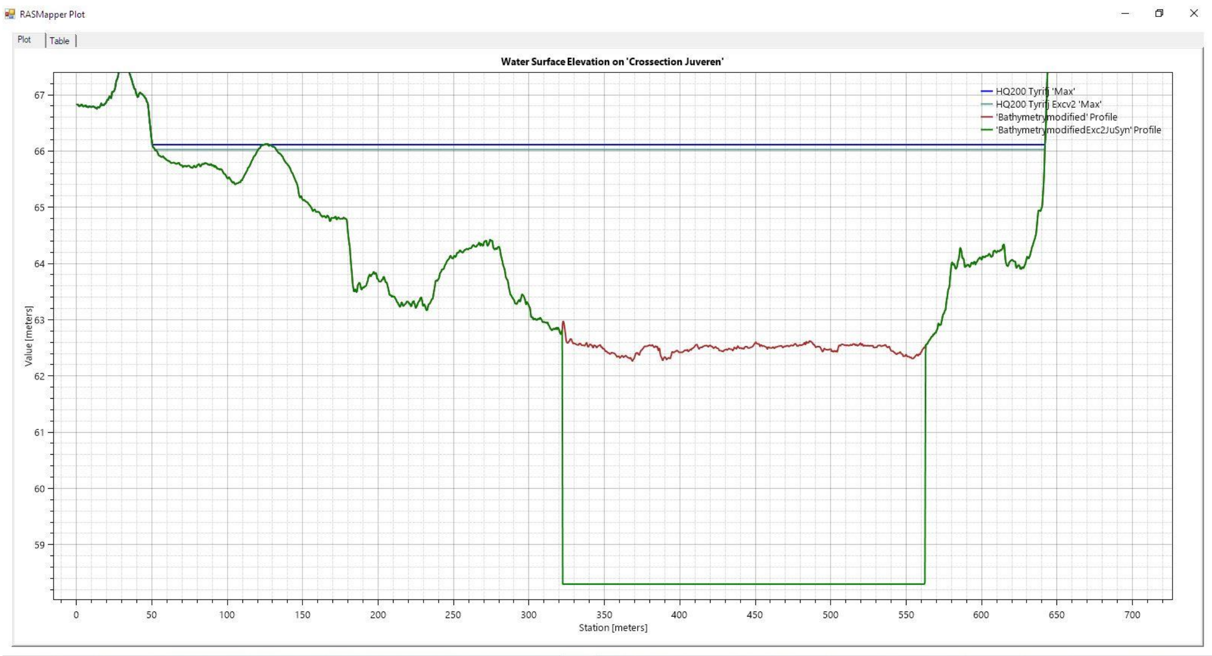


Figure 5.24: WSE at cross section Juveren for HQ200 and excavation

6 Recommondation of restoration

With the obtained results it can be said, that the FRE16 project has a small impact on the hydrodynamic matters of the adjacent oxbow lakes Juveren, Lamyra and Synneren with respect to the accuracy of the terrain files. Nevertheless the disturbance of the infrastructure project is still enormous in a matter of biological and ecological influence of the wetland system Mælingen by crossing the area.

One of the biggest threads to the ecology to the oxbow lakes is the Canadian pondweed (Elodea Canadensis). This alien invasive species can be found in Juveren and Synneren and can have a serious impact on the ecosystems and endangered Norwegian species (Norwegian Environmental Agency, 2017, Norwegian Environmental Agency, 2018). The Canadian pondweed spreads through ponds, oxbow lakes and slow flowing rivers choking the waterbody with its rapid rank growth. Physical remove can be realized but is very time consuming and expensive. Also it increases the risk of spreading since new ranks are formed from stem fragments. Lowering the water level during the summer period and exposing the weed to dry out is also an opportunity. Canadian pondweed is a plant that relies on water and grows submerged (Tasmanian Government, 2014). Nevertheless this approach would also affect the oxbow lakes itself and harm the native vegetation. Another possibility would be the control with chemical substances. Therefore it should be investigated if a chemical approach is possible and comparatively looking at the threatened native species of Norway and the whole ecosystem itself.

Previous reports recommend dredging the oxbow lakes (Fylkesmannen i Buskerud, 2016; Zinke & Dervo, 2018). An attempt of dredging at Synneren and Juveren has been made for this study and the actual condition (AC). The terrain was lowered to 58.3 m above normal in the oxbow lakes. The results showed a decrease in the water surface elevation of 8 cm in Juveren and 4 cm in Synneren. A change in the flow behavior or change in velocities entering the oxbow lakes though the culverts or channels could not be mentioned. Therefore these changes would, most notably, increase the volume of the oxbow lakes and help with the retention of flood events. However, in some cases the dredging of oxbow lakes can harm the ecosystem of the existing flora and fauna. The biodiversity decreases significantly and such radical interference in natural values is unsuitable for the preservation of oxbow lakes (Bąkowska, Obolewski, & Ryszard, 2017; Julien et al., 2008).

Another approach for the improvement of the ecology of the oxbow lakes can be the increase of the retention time of water in the abandoned river branches. Since the regulation of the Storelva river system caused a significant change in the natural overflow, an artificial extension of holding water in the oxbow lakes could improve the ecological and environmental situation.

Similar to the implementation of a dam at Lamyra (Chapter 3.4.2) a technical solution, for example a gate, at the inlet to Juveren could help regulate the water level and extension of the retention time (Zinke & Dervo, 2018). But it has to be taken into account, that a technical solution has to be planned and analyzed on behave of the needs of the oxbow lake. Since Juveren is used as a recreational area for fishing and boating, the accessibility has to be obtained. Furthermore, oxbow lakes are important retreat areas for several fish species (Obolewski et al., 2016) and retention reservoirs for flood events and sediment (Glińska-Lewczuk, 2009). By integrating a technical solution for the impounding of water, a detailed planning of the needs as such as a fish pass or an easy accessible flood gate has to be minded. In addition the maintenance and running expenses by operating a floodgate or fish pass have to be mentioned.

With several options of restoring oxbow lakes described in chapter 2, the decrease of inflow of nutrients, or edge-of-field practice, appears to be the most reasonable for the wetland systems and oxbow lakes in the Storelva river system. By implementing slotted pipes, slotted boards, grassed buffers and stiff grass hedges, non-point source pollution of the oxbow lakes and sediment inflow from erosion can be reduced. Furthermore agronomic methods like conservation tillage and winter cover crops will help establishing a natural environment for the oxbow lakes. These purposes can be implemented with the Best Management Practices tailored to the specific needs of the oxbow lakes. BMPs have been used in the USA and reduced the infiltration of nutrients and sediment from the adjacent fields significantly improving the overall water quality (Julien et al., 2008).

7 Conclusion

The “Fellesprosjektet Ringeriksbanen og E16” is a large infrastructure project in Norway. At the submission of this thesis the decision between Alternative A (bridge) and Alternative B (bridge and dam) has not been made. However it was mentioned at a project seminar in January 2019 that Alternative B: Bridge and dam over Mælingen will most likely be proposed to the decision-making body.

For the hydrodynamic investigation of the area, three different bathymetry conditions have been modeled and modified for the needs of the numerical calculation. Selected terrain conditions have been implemented into the 2D unsteady flow calculation application in HEC-RAS 5.0.6 and the results have been analyzed. The results show that Alternative B will have the highest impact on the hydrodynamic circumstances at the investigated oxbow lakes Juveren, Lamyra and Synneren and the wetland at Mælingen. Especially the reduction of the velocities during a flood event HQ10 overflowing Mælingen will change the behavior of the flow and influence the area in consequence of decreased shear stresses and the risk of soil deposition. More frequent flood events will have lower water elevation levels in the Mælingen wetlands as seen in the results of the HQ10 flood. Nevertheless, the results of the water elevation change in the oxbow lakes are in the scope of the accuracy of the elevation data used for the model input.

The results of the flood event of 1967 (HQ50) show an increase of the water surface elevation in the oxbow lakes and the Mælingen wetland area for both infrastructure alternatives. The water level change in the whole area reaches a maximum of 1.1 cm Juveren, whereas at Synneren the water level increases by less than 1 cm. The most significant result is the change in the flow velocity from the bypass of Storelva to Mælingen. It increases from 0.9 m/s to over 1.8 m/s for both, Alternative A and Alternative B. This can cause a higher erosion impact of the wetland due to increased shear stresses caused by a higher velocity.

Similar to the results of the 1967 flood event the results of the HQ200 statistical flood show an increase of the water level in the oxbow lakes Juveren and Synneren and at Mælingen. The raise of the water surface elevation however is not exceeding 1 cm. Nevertheless it should be noted that the velocities at the cross section Mælingen are increasing from 0.7 m/s to 1.36 m/s according to the 2D HEC-RAS model. Like the flood event of 1967, this increase of flow velocities can cause higher shear stresses and thus a higher possibility of erosion.

The investigation of the 0.9 percentile of a typical annual flow regime shows the high influence on the river system caused by the regulation for hydro energy and flood control. The decrease of discharge and stage elevation for the typical spring flood causes a lower water level in the oxbow lakes during this period. Oxbow lakes develop its full ecological potential when they are connected to, and fed and drained by the main river in a sufficient cycle (Lüderitz et al., 2009).

Restoration measures for oxbow lakes have to be tuned to needs of each oxbow lake and the whole river system. Engineered solutions will never reach the natural and complex processes of an untouched and dynamically formed oxbow lake. To maintain a natural ecological state, it is proposed to establish a best management practice (BMP) assigned to Juveren, Synneren and Lamyra with respect to the whole conservation area. This BMP could include the edge-of-field practice to reduce the non-point source pollution and several biological methods, e.g grass buffers to obstruct nutrient inflow into the oxbow lakes from the ambient areas.

The FRE16 infrastructure project is important for the development of the greater Oslo area. Nevertheless its negative impact on the nature and the adjacent conservation areas cannot be denied. New large infrastructure projects become more and more seldom and therefor the FRE16 offers a huge chance to follow the ecological and biological impact during the construction period. A complete and scientific project support accompanying the construction phase could help to better understand the influence on flora and fauna that occur in the course of the completion and investigate the ecological connection of the whole area.

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Declaration of Authorship

I hereby declare that the thesis submitted is my own unaided work. All direct or indirect sources used are acknowledged as references.

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