Master's thesis

NTNU
Norwegian University of Science and Technology
Faculty of Engineering

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Hydraulic modeling of the Lærdal river

Master's thesis in Civil and Environmental engineering
Supervisor: Knut Alfredsen
June 2019

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Kunnskap for en bedre verden

Abstract

Hydraulic modeling is a useful tool to analyze the impacts from changes in the flow and in the morphology of a river. To achieve accurate results it is necessary to collect detailed data of the topography of the area, especially of the river channel. In this type of landform, conventional red LiDAR data is not suitable as the near-infrared wavelength is largely absorbed by water bodies. Nevertheless, the increasing availability of high precision remote sensing techniques allows to gather this data by using green light in a so-called ALB process.

In this project, both red and green LiDAR data were processed in order to create an accurate hydraulic model for the river of Lærdal, which is listed as a Norwegian national salmon river. However, some flood protection works should be carried out in this river due to the high risk of flooding in the area. In order to analyze this, inundation maps for a 200-year recurrence interval were prepared in HEC-RAS, both for the current situation and for the case in which flood protection works are included in the river. The modifications to protect the area against floods were based on the NVE plans and include the construction of a wall in the lower part of the river and some excavations to modify the shape of the river.

The green LiDAR data used to set up the hydraulic model was validated first. Comparisons of this data against red LiDAR and manual GPS measurements proved that the differences in elevation obtained with these three systems were, except in some local areas, within 10cm.

Subsequently, the hydraulic model created was calibrated against the measured water surface elevation collected the day when the green LiDAR flight took place. The calibration was performed by changing the Manning's n coefficient of the river bed, since it was proved to be the most influential parameter. A final value of 0.035 offered the most suitable results.

The simulations run with the final model proved that a 200-year flood event in the village could be prevented with a flood protection wall about 1m high in most of its extension when the effects of climate change on the hydrological parameters of the area are not considered.

Acknowledgements

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I would also like to thank Ana Juarez for the transmission of your knowledge, your full willingness to help me and your great patience at all times.

Finally, I would also like to thank Morten Stickler for your interest in my work and for some of the tips you gave me.

In addition to this, I appreciate the opportunity to visit Lærdal to see first-hand the area of study, learn about how fieldwork is performed and become fully aware of the concern of local people about the problem addressed in this thesis.

I hereby declare that the work submitted is my own and all the guidance taken from other studies is referenced.

Trondheim, June 2019

Sonia Seguin García

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Abbreviations

ALB - Airborne Laser Bathymetry

ALS - Airborne Laser Scanning

DEM - Digital Elevation Model

DOM - Digital Overflate Modell (Norwegian)

DSM - Digital Surface Model

DTM - Digital Terrain Model

DW - Diffusion Wave

GPS - Global Positioning System

HEC-RAS - Hydrologic Engineering Center’s River Analysis System

LiDAR - Light Detection and Ranging

NVE - Norges Vassdrags og Energidirektorat

SW - Shallow Water

USACE - United States Army Corps of Engineers

WSE - Water Surface Elevation

XS - Cross Section

1. Introduction

1.1. Background

Hydraulic modelling is a useful tool to analyze the impacts from changes in the flow of a river and to obtain a full understanding of its hydraulic behavior. The increasing availability of high precision remote sensing techniques combined with the use of a Geographic Information System (GIS) enables the creation of a detailed hydraulic model. This model can serve to evaluate how flood protection works influence the water covered area and the environmental conditions in the river.

In this project, both green LiDAR data from the river of Lærdal and red laser data from Høydedata were processed in order to create a Digital Terrain Model of the area. Lærdalselva is a Norwegian national salmon river and historically an important river for recreational salmon fishing. However, the NVE considers it as a watercourse of potential damage due to its susceptibility to flood occurrence. In order to analyze this, inundation maps for a 200-year recurrence interval were prepared in HEC-RAS (Hydrologic Engineering Center's River Analysis System) using the digital model previously created in ArcMap. These maps could be used as a tool for municipal planning and for an optimum design of flood protection works. In this case, there are some already available flood protection alternatives developed by the NVE. These plans include the construction of a wall in the lower part of the river and some modifications in the river itself that will remove islands and increase its width. The digital terrain was therefore modified according to these alternatives and new simulations were run to create maps showing the effect of the different flood protection scenarios under a 200-year flood event (with and without considering the influence of climate change on the hydrological parameters of the area).

1.2. Scope of the thesis

The main objective of this thesis is to create flood inundation maps of Lærdal for a 200-year flood event using LiDAR data as a starting point. This data was first processed and integrated in ArcMap to obtain a terrain model including the main features of the landscape of the area. This terrain was imported into HEC-RAS to run the 2D unsteady flow simulations whose results showed the hydraulic behavior of the stream and the water covered areas under different scenarios. To achieve this, the following tasks must be completed:

- Validate the accuracy of the bathymetric LiDAR data. To do so, the coverage of the green LiDAR in the study reach is analyzed and the elevation values are compared with the ones coming from red LiDAR measurements from Høydedata in the common areas. A comparison between the green LiDAR data and GPS measured points taken during a fieldwork in Lærdal (May 2019) is also carried out.

- Collect the necessary hydrological data to define the discharge of the river in the different situations under analysis: the day of the flight when the ALB data was collected, a 200-year flood event under current climate conditions and a 200-year flood event considering hydrological variations due to climate change.

- Integrate the bathymetric and the topographic data to build a detailed model of the lower part of the river, from the Eri border down to the fiord. Some simulations of this model are performed under normal discharge conditions in order to calibrate it. Once the model is calibrated, new simulations are run for a 200-year flood event.

- Modify the geometry of the model according to the flood protection plans of the NVE and run new simulations to evaluate their effect. Further, the extent of the morphological changes in the river that are necessary to prevent floods in the city of Lærdal is analyzed.

- Create the relevant maps to identify the water-covered areas under the different conditions.

1.3. Structure of the thesis

Following the standard scientific format, this report is divided in 6 chapters. After this short introduction, chapter 2 presents the area of study (Lærdal) and some theoretical highlights of the main concepts that are discussed throughout the thesis. Chapter 3 describes the methodology followed in order to achieve the objectives of this study. For ease of reading, this chapter contains 3 different sections depending on the part of the procedure being explained: pre-processing, processing and post-processing. Chapter 4 displays the most important results from the green LiDAR validation, the sensitivity analysis performed in HEC-RAS, the calibration of the model and the final results of the hydraulic simulations (both with and without flood protection works in the terrain). Chapter 5 discusses the results presented in the previous section and summarizes the main findings of this study. Chapter 6 presents some remarks and conclusions as well as some suggestions for further and improved work.

2. Study site and conceptual framework

2.1. Area of study

The study area is located in the southeastern part of Sogn og Fjordane county in Norway (see Figure 1). Lærdal is a 1,342km^2 municipality with a population of 2,161 inhabitants (Statistics-Norway, 2019). The administrative center of Lærdal is the village of Lærdalsøyri, with a population of 1,120 (2013) inhabitants. An important part of this village is the area called Gamle Lærdalsøyri, which contains 161 historic buildings that represent one of the best-preserved original old wooden house communities in Norway. This means that it is important to ensure that this area remains protected in case of floods.

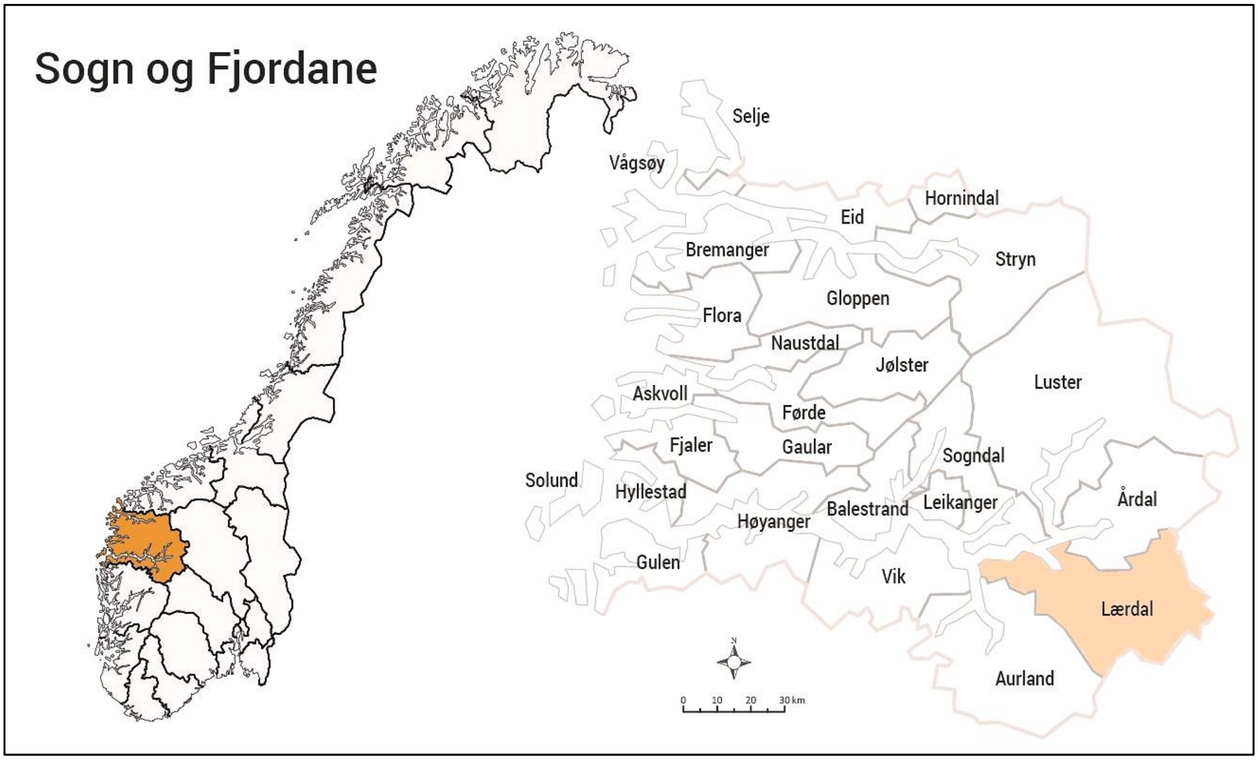


Figure 1: Location of Lærdal in Sogn og Fjordane county – Norway

The river of this region, Lærdaselva, is a national salmon river, so it also must be ensured that any of the measures implemented to prevent the floods is detrimental to the salmon.

Lærdal watercourse has its origin in the confluence of Mørkedøla and Smedøla and opens into the fiord at Lærdalsøyri. The whole river is 44km long and the watershed is around 1180 km^2, measured from the mouth of the river. An overview of the complete watercourse is shown in Figure 2. This map was created by the Norwegian Water Resources and Energy Directorate (NVE – Norges Vassdrags og Energidirektorat), and includes the gauging stations of the area and the location of the reservoirs and hydropower plants.

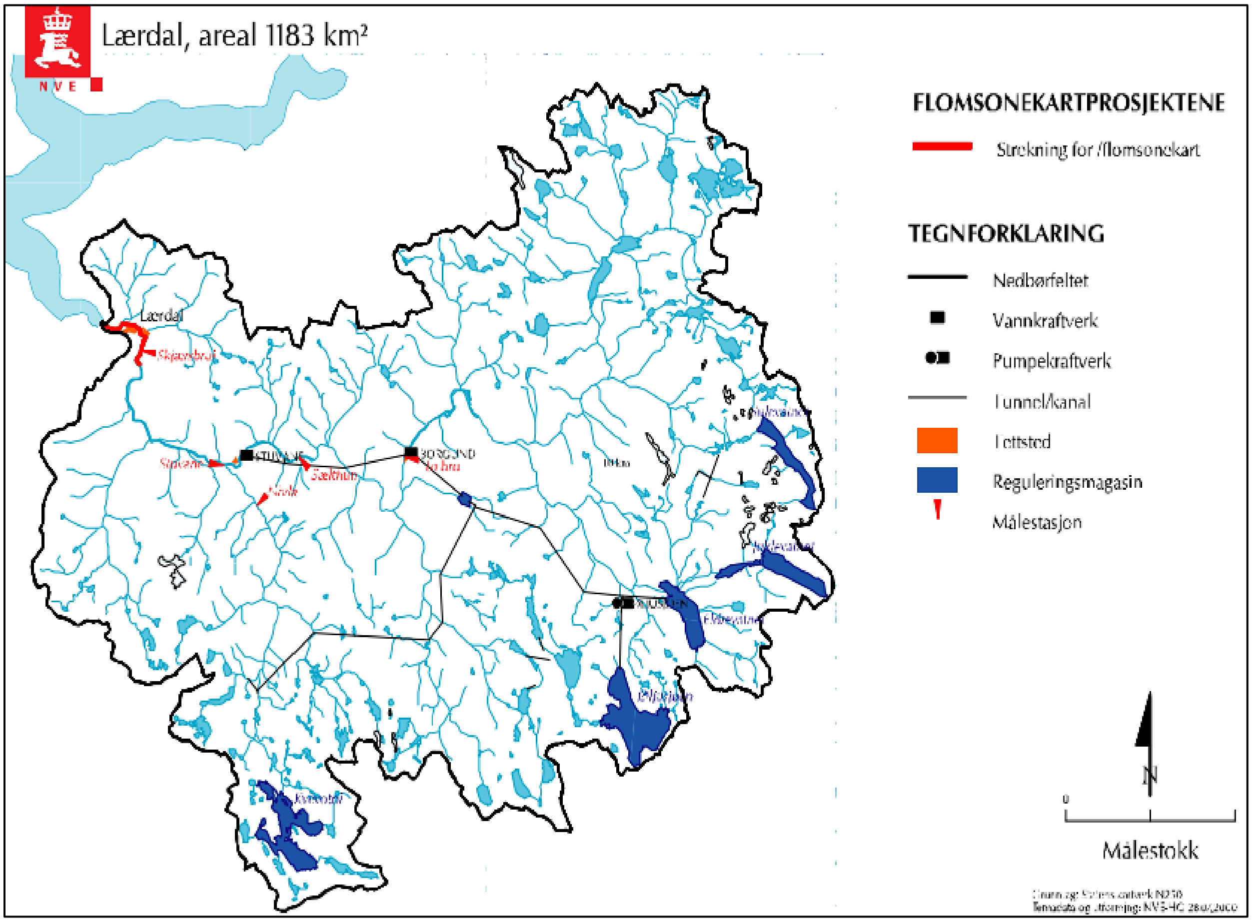


Figure 2: Complete Lærdal watershed measured from the lowest point of the river

The regulation of this watercourse started in the 1970s with the construction of some reservoirs for hydropower. In total, there are 3 hydropower plants and 7 reservoirs in the area, whose total volume amounts to 274 mill m^3.

The average annual flow was reduced by 20% after the regulation. Figure 3 shows the monthly average water flow measured in Skjærsbrui both before and after the regulation. The observations before the regulation were measured between the years 1964 and 1970 and the ones after the regulation between 1988 and 1998. The measurements in this last period were actually taken in Stuvane and scaled afterwards, because Skærsbrui station was destroyed during the floods of 1971. (Holmqvist, 2000).

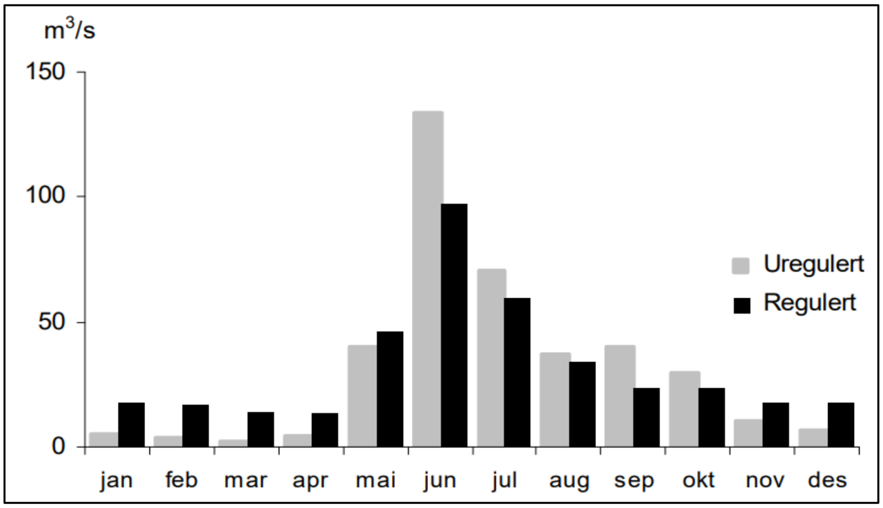


Figure 3: Monthly average discharge before and after regulation

The extent of this project is the lower part of the river, including the area between the Eri border and down to the fiord (see Figure 4). This approximately 5 km long area is very flat and has experienced several cases of floods, despite the existence of flood protection works along both sides of the river. The aim of the present work is to obtain some maps showing the water covered areas in case of a 200-year flood event when new flood protection works are implemented. The objective is to see their effectiveness and to analyze if floods in some parts of the village could be prevented without drastic morphological changes in the river. These flood protection works are based on the already existing NVE plans (see appendix A). More precisely, the 3D terrain modifications presented throughout the project (wall inclusion and excavation of some areas of the river) rely on the alternative number 1 (Figure A.1).

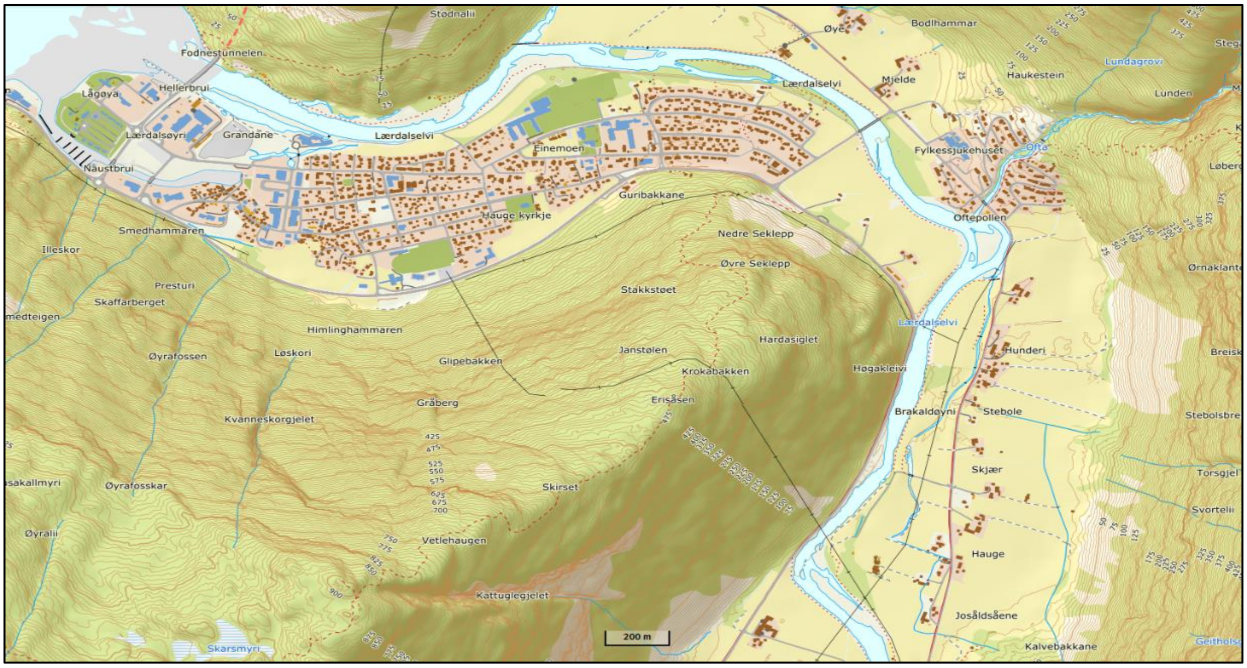
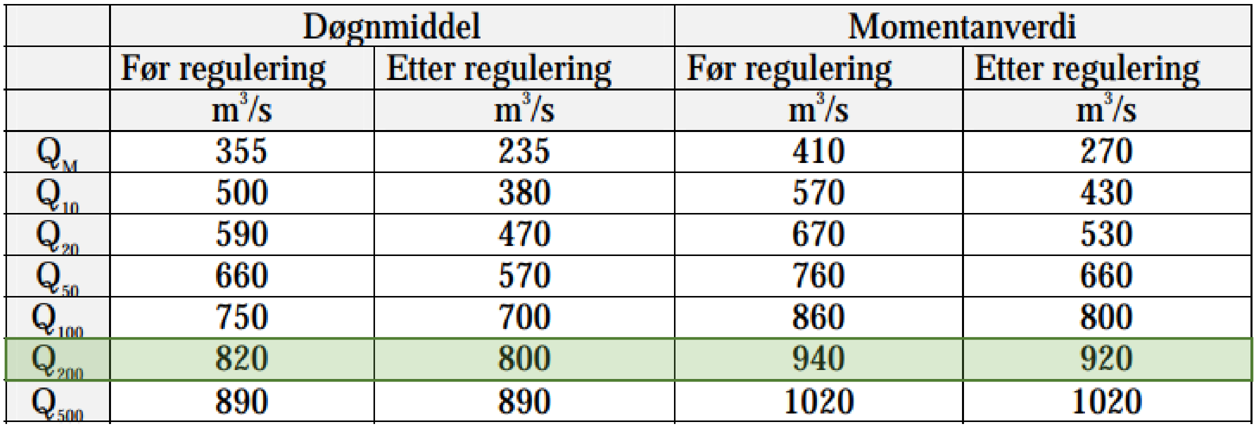


Figure 4: Part of the river studied

The discharge values in this part of the river for different recurrence intervals (measured according to the previously existing gauge station Skjærsbrui) appear in Table 1. These values were obtained by the NVE through performing different frequency analysis from flood values in Lærdal and in neighboring watercourses. Note that the effect of the regulation decrease for increasing flood values and that there is an uncertainty of at least 20% in the values (Holmqvist, 2000).



	Døgnmiddel		Momentanverdi	
	Før regulering	Etter regulering	Før regulering	Etter regulering
	m^3/s	m^3/s	m^3/s	m^3/s
Q_M	355	235	410	270
Q_{10}	500	380	570	430
Q_{20}	590	470	670	530
Q_{50}	660	570	760	660
Q_{100}	750	700	860	800
Q_{200}	820	800	940	920
Q_{500}	890	890	1020	1020

Table 1: Flood values for the area of study, before and after the regulation. For this project, only the values corresponding to a 200-year flood event were analyzed (green row).

2.2. Previous work in Lærdal

Since Lærdal has experienced numerous flood events (last significant one in October 2014), different analysis in this area have been carried out in order to obtain flood zone maps as reliable as possible. Special mention must be made to the NVE reports "Flomberegning for Lærdalvassdraget - 2000" (Holmqvist, 2000) and "Flaumsonekart Delprosjekt Lærdal – 2002" (Edvardsen & Svegården, 2002). Discharges and maps showing the areas covered by water under different recurrence intervals floods can be found in both documents. However, as a result of the floods in July 2011, it was decided that the model used for these reports should be recalibrated to create new flood maps in this area. This new analysis was carried out by Norconsult in 2014.

The three aforementioned documents were used as a basis for comparing the results obtained in this project. In addition, some values for the model setup (as the discharge in the river for a 200-year flood or the tidal level) were taken from these documents, as will be mentioned in due course. Nevertheless, none of the features of the terrain and none of the parameters of the hydraulic model created for this thesis were modified in order to obtain the same or similar results as in the other reports.

2.3. Flood risk and flood mapping

The European assessment and management of flood risks directive defines flood as "temporary covering by water of land not normally covered by water, including flood from rivers, mountain torrents and floods from the sea in coastal areas but excluding floods from sewerage systems" (European-Parliament, 2007). Floods are usually described in terms of their statistical frequency, a value chosen depending on the degree of risk that needs to be assessed (OAS, 1993). Within this project a 200-year flood is studied, which means that the area is subjected to a 0.5% probability of a flood of the size under study in any given year.

Flood risk is, as defined by the European directive, "the combination of the probability of a flood event and of the potential adverse consequences for human health, the environment, cultural heritage or any economic activity" (European-Parliament, 2007). In all the river basins with significant potential of flooding, flood risk maps must be created as a preliminary step in order to analyze different mitigation measures and its effect as well as any other regional policy.A flood risk map is a special topographic map in which the hypothetical flood characteristics are shown graphically (Marco, 1992). To obtain this kind of map it is necessary to estimate the discharge of the river within a catchment based on flood frequency analysis (note that the discharge values change depending on the return period studied), and to create the hydraulic model in the area of study. Once having this, relevant simulations can be run in order to obtain different maps showing the water covered areas and its depth. This means that the creation of a reliable hydraulic model could be the basis for certain projects in the river to be carried out or not.

2.4. Airborne Laser Scanning: red and green LiDAR

Topographic Airborne Laser Scanning (ALS) is an active remote sensing technique where **near-infrared** light pulses are emitted towards the Earth’s surface and a photodiode records the backscattered echo (Wagner, Ullrich, Ducic, Melzer, & Studnicka, 2006). The variable distance between the laser scanner and the Earth (or any other feature above the ground reflecting back the light) is calculated from the time the laser pulse emitted takes to return to the sensor. As a result, topographic information of the Earth surface is obtained. However, the near-infrared wavelength is largely absorbed by water bodies making ALS systems unsuitable when water penetration is required (Doneus et al., 2013). In these cases, longer wavelengths are required, so **green light** is generally used in a process called Airborne Laser Bathymetry (ALB) or LiDAR bathymetry. Similar to ALS, a bathymetric laser scanner is mounted in an aircraft or helicopter, from where green light pulses are emitted. The time between pulse emission and reception is measured to calculate the distance between the laser and the object that was hit. The use of airborne acquisition combined with moderate flying heights and high pulse repetition frequency high resolution is achieved (Mandlburger, Hauer, Wieser, & Pfeifer, 2015).

For this project, data coming from both red (for the floodplains) and green (for the river channel) LiDAR is used. The sources and extent of each are explained in detail in section 3.1.

2.5. DEM, DTM and DSM

The 3D points obtained using any of the available LiDAR procedures are processed to create a Digital Elevation Model (DEM). These points are firstly classified into two categories: ground (bare earth) and above ground (natural or built features on the Earth's surface. This means that there exist two different ways of modeling elevation: DTM and DSM. The elevation model derived from points classified as ground type is called Digital Terrain Model (DTM). This concept is not only limited to Earth's visible terrain surface, as also bathymetric surfaces are included. Digital Surface Models (DSM) include also the vegetation, buildings and other man-made features above the ground (ArcGIS-PRO, 2019; Hirt, 2014). Both models can be described as a 3-D representation of a terrain based on the X,Y,Z coordinates of a point cloud stored in a digital form. The selection of the model that is used depends on its application. While DSM are often useful for landscape or city modeling, DTM are usually required for flood modelling or land use studies (Mason, Horritt, Hunter, & Bates, 2007).

Within this project, the type of elevation model used is DTM. However, the buildings, roads and most important features above the ground are included afterwards, as explained throughout section 3.

2.6. ArcMap

ArcMap 10.6 and 10.7[1] was the software used in this project to create the 3D terrain during the pre-processing and the flood maps from the results obtained in HEC-RAS during the post-processing. ArcMap is the central application used in ArcGIS. ArcMap represents geographic information as a collection of layers and other elements in a map, and it allows its users to create and edit datasets and to perform a wide range of GIS tasks. (ESRI, 2019).

All the functions of ArcMap used within this project are mentioned in section 3, and the detailed procedure and specific tools used for the most complex tasks is included in Appendix D.

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[1] The version 10.7 was released in March 2019, while the project was in progress

2.7. HEC-RAS

HEC-RAS (Hydrologic Engineering Center – River Analysis System) is a software that models the hydraulics of water flow through natural rivers and other channels. It allows the user to perform one or two dimensional flow calculations, sediment transport/mobile bed computations and water temperature and quality modeling. The program was developed by the United States Army Corps of Engineers (USACE) and it is publicly available without charge (USACE, 2019). The first version of the software was released in 1995, with the ability to perform only one-dimensional unsteady flow calculations. Constant updates have been made to the software and two-dimensional modeling is available since the version HEC-RAS 5.0 was released in 2016. For this thesis, versions 5.0.6 and 5.0.7 are used[2].

In this section, the most relevant theoretical points of the software are explained, so that the reader knows the main principles and equations in which the software relies. For a deeper insight into this part, the chapter 2 of the "Reference Manual" of HEC-RAS should be consulted, as the information below is based on it (Brunner, 2016).

2.7.1. 2-D hydraulic equations

The Navier-Stokes equations describe the motion of fluids in three dimensions. In order to obtain a flood model, some simplifications of these equations are imposed. In HEC-RAS, there is the possibility to work with two different simplified set of equations: Shallow Water (SW) equations (also referred as Full Momentum) and Diffusion Wave (DW) equations. The method used is selected by the user[3]. HEC-RAS developers recommend developing the model using the Diffusion Wave approach as it is faster and more stable. Once the model is in good working order, they suggest running another simulation using Full Momentum as the computational method, as it is slower but more accurate. If significant differences appear between the two

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[2] Version 5.0.7 was released in March 2019

[3] DW Equations are set as default

runs, it should be assumed that the results obtained using the Full Momentum option are the most accurate ones.

Regardless of the equation set used, the mass conservation law is included and computed with a sub-grid bathymetry approach in order to decrease the computation time. Thereby, the computational grid can be relatively coarse because the transport of fluid relies in the information contained in the more refined underlying topography.

2.7.1.1. Mass conservation

Assuming incompressible flow, the unsteady differential form of the mass conservation equation is:

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

Where:

H = water surface elevation [m.a.s.l]

h = water depth [m]

t = time [s]

u,v = velocity components x,y [m/s]

q = source/sink flux term [m/s]

As a sub-grid bathymetry is used, the general mass calculation equation above is transformed after some substitutions into the sub-grid bathymetry mass conservation equation:

$$\frac{\Omega(H^{n+1})-\Omega(H^{n})}{\Delta t}+\sum_{k} V_k \bullet n_k A_k(H)+Q=0$$

Where:

$\Omega(H)$ = finite cell volume as a function of the water elevation [m^3]

$A_k(H)$ = face area of the face k as function of the water elevation H [m]

V_k = average velocity of the face k [m/s]

n_k = normal vector of the face k

Δt = time step [s]

2.7.1.2. Momentum conservation

2.7.1.2.1. Shallow water equation

The SW set of equations are obtained from the Navier-Stokes equations when the following is assumed: the pressure is nearly hydrostatic, the density is uniform, the flow is incompressible and the vertical velocity terms are neglected. The equations thus obtained are:

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

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

Where:

u,v = velocities in the Cartesian directions [m/s]
g = gravitational acceleration [m/s^2]
H = water surface elevation [m.a.s.l]
v_t = horizontal Eddy viscosity coefficient [m^2/s]
c_f =bottom friction coefficient [l/s]
f = Coriolis parameter [l/s]

2.7.1.2.2. Diffusion wave equation

The Shallow water approach can be simplified when the following is assumed: shallow and gravity controlled flow; disregarded unsteady, advection, turbulence and Coriolis terms and velocity determined by a balance between barotropic pressure gradient and bottom friction. This simplification leads us to obtain the equation known as the Diffusion Wave Approximation of the Shallow Water equation, whose classical differential form is:

$$\frac{\partial H}{\partial t}-\nabla\bullet\beta\nabla H+q=0$$

3. Methods

The methodology followed in order to obtain the floodplain maps of Lærdal is divided in three major stages that are described in the subsequent sections: pre-processing, processing and post-processing. Although this study was done for a specific river, this methodology is applicable for the analysis of any other river system.

To facilitate the follow-up of the reading, a diagram containing the main steps of each stage is included in Figure 5.

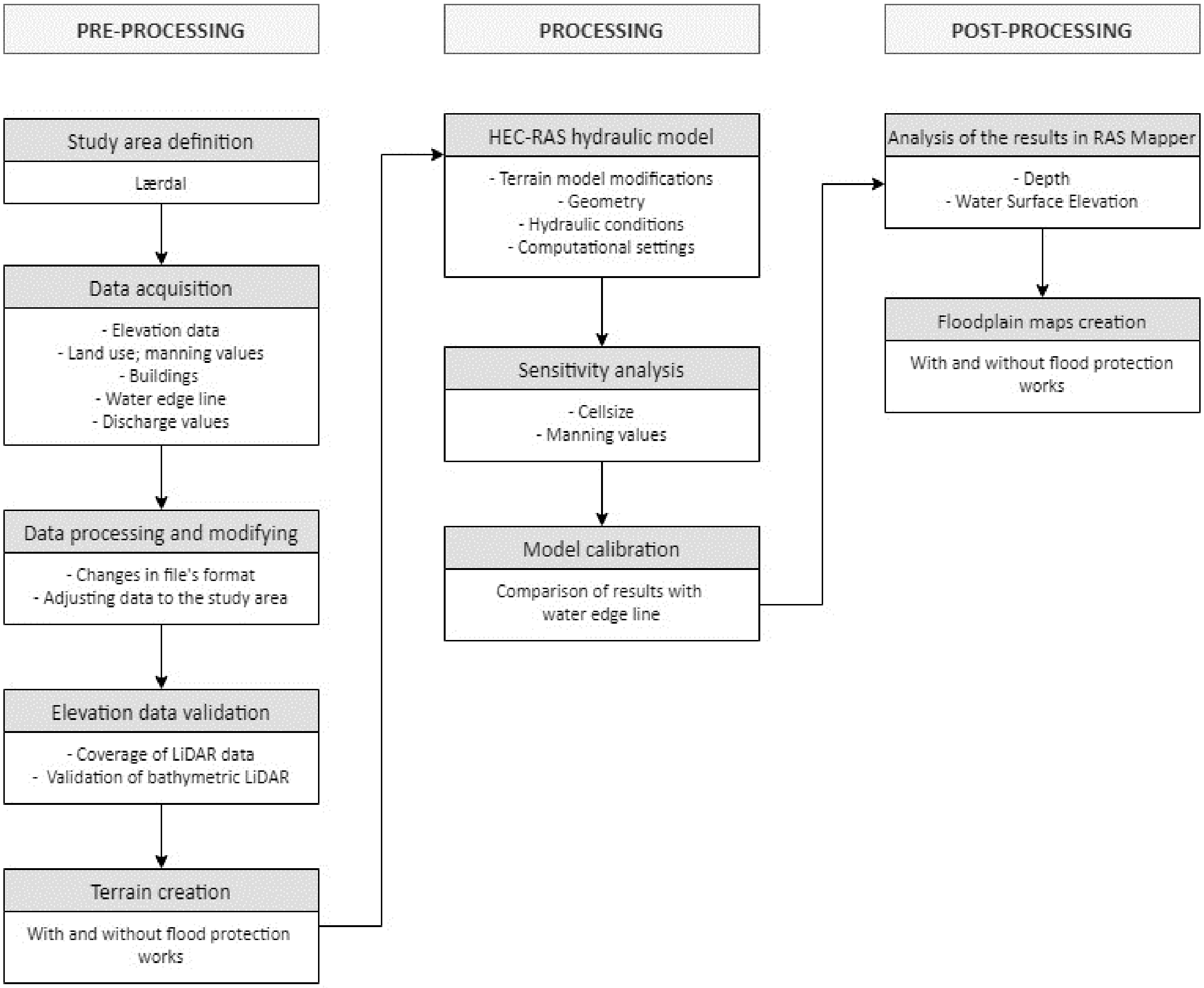

Figure 5: Sketch of the methodology followed to obtain the floodplain maps of Lærdal using ArcMap and HEC-RAS

The preprocessing (section 3.1) part includes the entire process of acquiring, analyzing, modifying and processing the input data in order to obtain an accurate 3D terrain. The rest of the parameters (discharge, manning values according to the land use…) that are necessary to run the simulations in HEC-RAS are also obtained. ArcMap is the software used for most of the preprocessing. The processing stage (section 3.2) refers to all the procedure performed in HEC-RAS using the data and terrain model obtained during the pre-processing. The post processing (section 3.3) consist in analyzing the results of the simulations and in creating the most relevant maps and graphics.

3.1. Pre-processing

The objective of this part is to obtain the 3D terrain of the study site in .tif format and the rest of the parameters and shape files required for the simulation in HEC-RAS, as it is explained in detail below.

3.1.1. Data acquisition and modifying

The very first step of the preprocessing part is correctly defining the area of study: Lærdal. This includes a geographical and hydrological definition and a proper understanding of the reasons why a floodplain analysis is required in Lærdal. In this area, numerous cases of flooding have been recorded both before and after the regulation, the last one in October 2014. This is why different studies containing flood maps under different recurrence intervals are available. In addition, there is a growing interest in carrying out flood protection works in the area, being some alternatives created by the NVE under consideration. The most relevant information about this is summarized in sections 2.1 and 2.2, and the NVE alternatives are included in Appendix A.

Once having some knowledge about the study area, the data required as input for the hydraulic model was collected. This data were:

a) Elevation data
b) Land use and manning values
c) Flow data (discharges of the river for different situations)

d) Other data (shapefile containing the buildings and roads of the area, water edge line for calibration)

a) Elevation data

- *Elevation data for the floodplains (Source: Høydedata)*

The DEM for the floodplain area was downloaded from Høydedata (Høydedata, 2019). The elevation data in this webpage is open and free for everyone who request it. In addition, it is possible to download the elevation model in raster format or the original point cloud. If the elevation model is chosen, both the DSM (DOM – Digital Overflate Modell in Norwegian) and the DTM data are received.

There are 3 available projects of Lærdal in Høydedata, from the years 2009, 2014 and 2017. The coverage of each of the projects is shown in Figure 6.

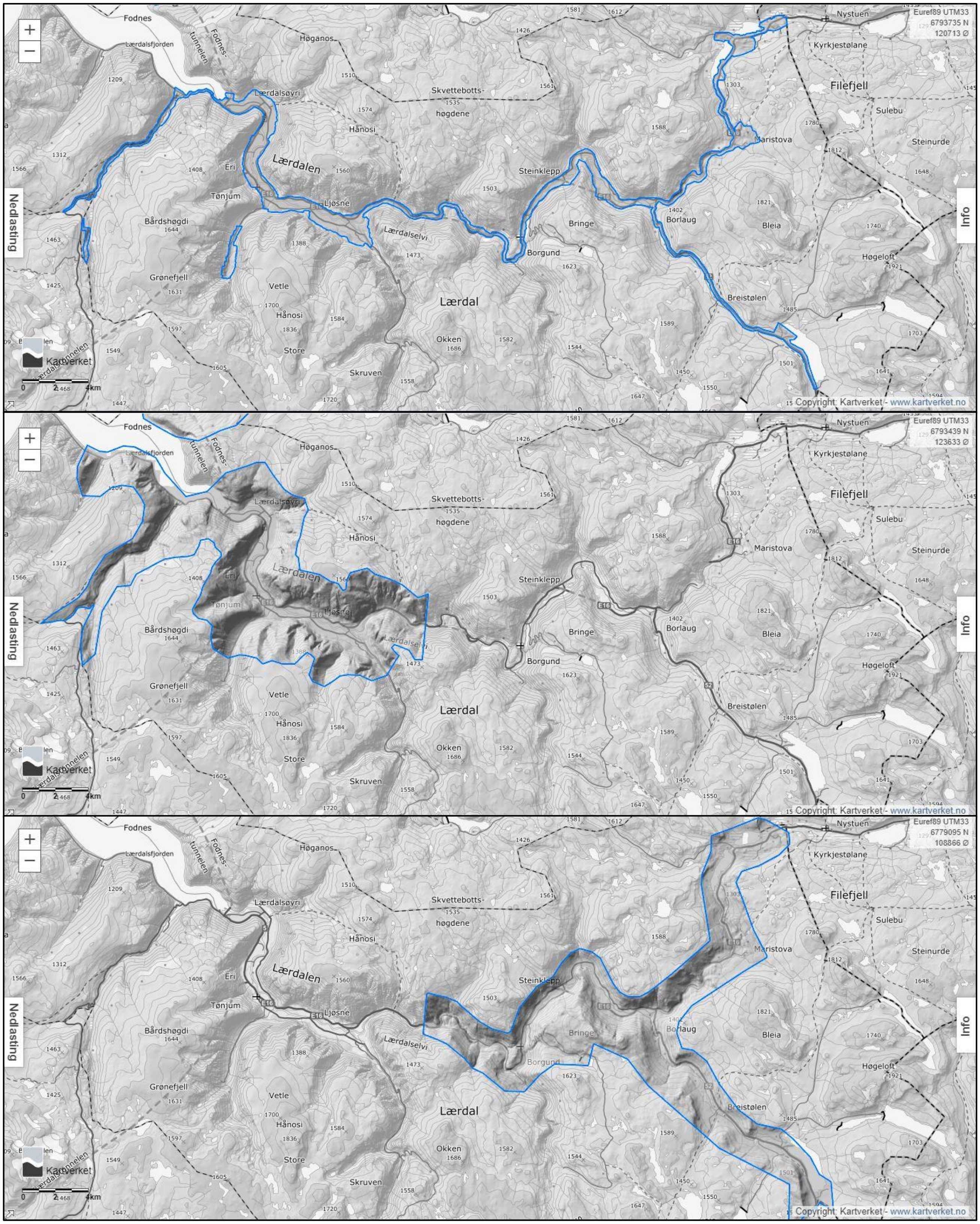

Figure 6: Coverage of the different projects available in Høydedata of the region of Lærdal. First picture shows the project "Sogn og Fjordane (2009)". Second picture shows "Sogndal, Aurland, Lærdal (2014)". Third picture is the area covered in "NDH Lærdal (2017)". The project downloaded for this thesis was the second one, as it covers the extent under analysis in the hydraulic model.

For this thesis, the DTM from the project “Sogndal, Aurland, Lærdal (2014)” was used, as it is the only one that fully covers the area of interest. Some relevant information of this project is shown below:

Flight date	Supplier	Type of LiDAR	XY Coordinate system	Z Coordinate system
22.09.2014	Blom Geomatics	Topographic (red)	Euref89 UTM32	NN2000

Table 1: Most relevant information of the project "Sogndal, Aurland, Lærdal (2014)" downloaded from Høydedata.

Note that the flight to obtain this data took place on September 22, 2014 and this area experienced a large flood event in October of the same year. The deposition of sediments and erosion during this flood is one of the reasons why some areas could show differences in elevation when compared to more recent data. Section 5 explains this issue in detail.

The DTM was preferred over the DSM (difference between this two concepts is explained in section 2.5) in view of the inaccuracies that the DSM presented in areas covered by trees or other elements above the bare ground. Graphical explanation of the error is shown in the picture below (ACP-EU, 2019).

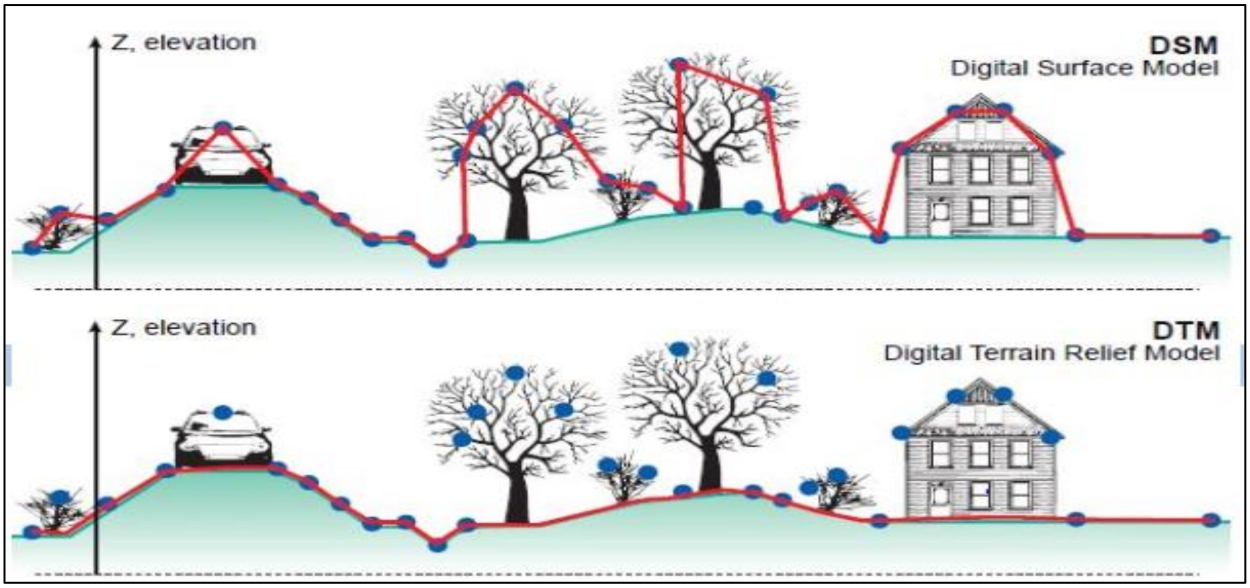

Figure 7: Graphical explanation of why the DTM was preferred over the DSM. The main obstacles to the flow of water over the bare ground will be included afterwards.

The DTM downloaded from Høydedata contains many rasters in .tif format with a spatial resolution of 0.5m. In order to work with this data in ArcMap, it was first necessary to mosaic them all into a new single raster of the whole area. This was done in ArcMap with the use of the "Mosaic to new raster" tool.

As the elevation data from Høydedata was collected using red LiDAR, it does not contain the underwater depth information of the river channel. This means that the bathymetric data from the river had to be collected from a different source and merged with the Høydedata elevation model for the floodplains afterwards.

- *Elevation data for the river channel (source: green LiDAR)*

The missing bathymetric data were made available by my supervisor. This data were given in two different LAZ files, according to the classification of the points as "dry terrain" or "ground water". The technique used to collect them was green LiDAR, as this wavelength is short enough to penetrate the water column of the river. The total area covered with this surveying method is shown in Figure 13. The flight collecting the data took place on May 29, 2018 from 16:00 to 17:00. This information is required in order to obtain the value of the discharge that day and compare and calibrate the hydraulic model in HEC-RAS when a simulation with the same discharge value is run. In this study, this calibration was done graphically, by visual comparison of the results in HEC-RAS with the water edge line given by the supplier of the green LiDAR.

Some details of the green LiDAR data used are included in the table below.

Flight date	**Type of LiDAR**	**XY Coordinate system**	**Z Coordinate system**
29.05.2018	Bathymetric (green)	Euref89 UTM32	NN2000

Table 2: Most relevant information of the green LiDAR data

b) Land use and manning values

A layer containing the land use of the different zones of Lærdal was made available by my supervisor. This layer contained other specifications about the area besides the land use, so it was necessary to classify it according to the code ARTYPE (Areal Type). Under this code, the land use is classified into 8 categories: living area, roads and railways, full-grown soil, cultivated soil, cultivated pastures, forest area, open land and water bodies. Appendix B shows the description (in Norwegian) of each category taken from Kartverket (Kartverk, 2014).

When the different type of land uses were identified, the most appropriate manning value for each area was chosen. This information was taken from different tables found in Chow's book (1959), which are compiled in the HEC-RAS manual and collected in Appendix B. This appendix shows the final manning value selected for each area too.

c) Shapefiles

Other information collected prior to the creation of the hydraulic model is a file containing the shape and position of the buildings and roads in Lærdal and the water edge line of Lærdaselva the day of the green LiDAR flight.

- *Building shapefiles*

  As explained in subsection a, the digital elevation data used is coming from a DTM, so it only includes the elevation of the bare ground. In order to create the maps and see the buildings of which areas are at risk, it is necessary to include them in the digital terrain. A feature format file (.shp) containing this information was made available by my supervisor.

- *Water edge line*

  The water edge line at the time of flight was used as a reference to calibrate the model. This information was given by the green LiDAR supplier as a .shp format file. No modifications were necessary in this file, which is shown in Figure 8.

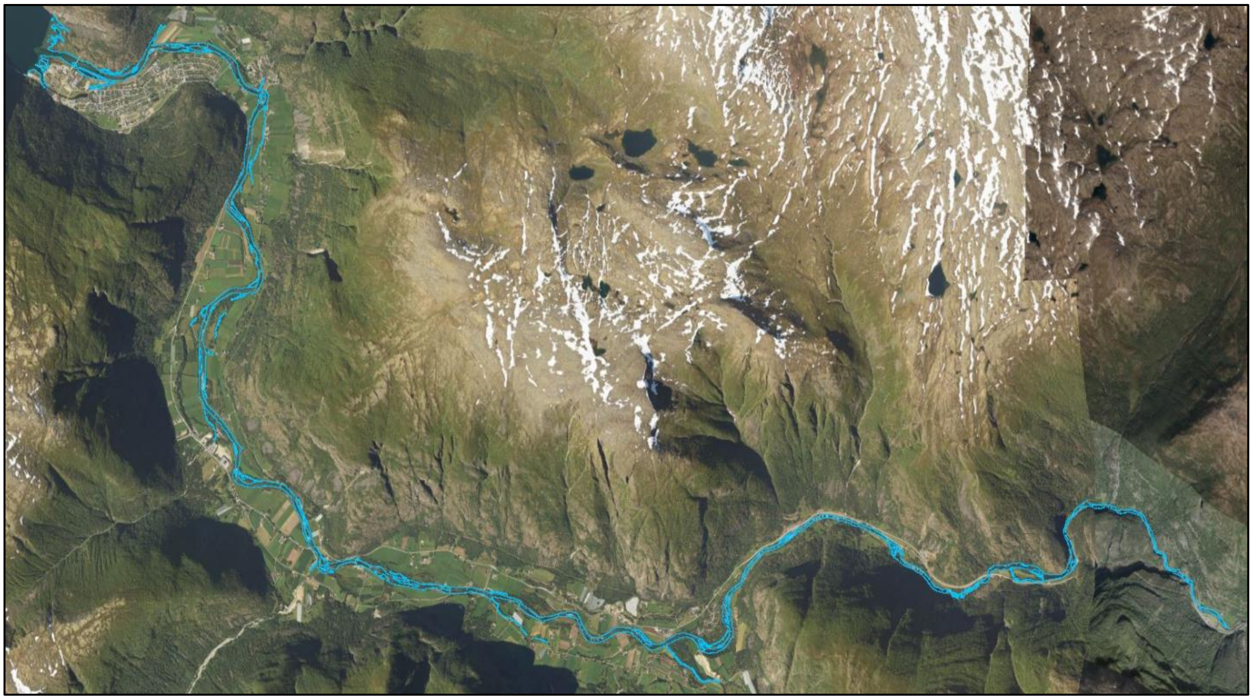

Figure 8: Water edge line (blue line) obtained from an aerial photograph taken the day of the flight when the underwater bathymetry data was collected (29.05.2018).

d) Hydrological data: discharge values

Another indispensable input data for the simulations in HEC-RAS were the discharge values of the river. Simulations with at least 3 different discharge values were necessary. First of all, the discharge value of the day of the flight was obtained in order to compare the results with the water edge line and calibrate the model according to it. Once the model replicated accurately the reality thanks to the calibrations, new simulations were run using the discharge for a 200 years flood and the discharge for a 200 year flood plus climate change. The sources and calculations to obtain these 3 values are explained in this section.

- *Discharge value for calibration*

The value of the river discharge on the day of the flight was known in the Stuvane gauging station: 94m^3/s. However, there is a great distance between this gauging station and the starting point of the hydraulic model, with some tributaries in between.

Figure 9: Distance between the starting point of the hydraulic model and closest gauging station (Stuvane).

In order to account for the tributary inflow, scaling was used taking Flåm Bru's watershed as reference. The value of the river flow of Flåm Bru on May 29, 2018 was extrapolated to the area of the watershed between Stuvane and the start of the hydraulic model, considering the size and the runoff of each catchment. The result was an estimate of how much the flow value from Stuvane should be increased. Note that this was just an approximation whose level of uncertainty is difficult to measure.

The equation used to calculate the tributary inflow between the points marked with a cross in Figure 9 is:

$$Q_{tribut} = Q_{Flåm} \cdot \frac{A_{tribut} \cdot F_{tribut}}{A_{\text{Flåm}} \cdot Q_{Flåm}}$$

Where:

Q = Measured discharge in the river [m^3/s]
A = Catchment area [km^2]
F = Runoff [$l/(s \cdot km^2)$]

As a result, an increase of $12m^3/s$ in the discharge recorded in the Stuvane gauging station was obtained, being the final value of the discharge used for the calibration of the model equal to **$106m^3/s$**. The details of the calculations, as well as more information about the watersheds (taken from NEVINA) are included in appendix C.

- *Discharge value for a 200-year flood event*

The value selected was taken from the NVE report "Flomberegning for Lærdalvassdraget - 2000". The values that appear in this report for different recurrence intervals are shown in Table 1. Between them, the culmination discharge value for a 200-year flood event was taken: **920m^3/s**. Note that there is a big uncertainty in the value.

- *Discharge value for a 200-year flood event plus climate*

Climate change may cause significant changes in hydrological patterns leading to more frequent and intense flood events. According to NEVINA, the climate factor of the Lærdal watershed is 1.4. In order to run a simulation including the climate change effect, a discharge value of **1288 m^3/s** ($920 \cdot 1.4$) was used.

3.1.2. Data modifying and processing

Some of the data presented in the previous section required some previous work before being used for the creation of the terrain. For some of the input files, this just consisted of some computational processing (decompressing, format changing…). In other cases, modifications of the data were made. A detailed explanation for each case is given in this section.

a) Elevation data

The elevation data of the floodplains (from Høydedata) was downloaded as a raster, so it did not require any format modifications before being imported into ArcMap. However, the underwater bathymetry data (from the green LiDAR) needed some processing as it was provided in .LAZ format.

In order to work with LiDAR data in ArcMap .LAS is the starting format. Still, the point cloud data representing the 3D surfaces is usually provided in .LAZ format, the compressed form of .LAS, in order to save space and transfer time.

As the underwater bathymetry data had to be decompressed, the software LASTOOLS was used[4]. As the procedure followed was short, a step by step is presented below:

1. Inside the LAStool’s folder, open las2las.exe
2. Click browse and search for the LAZ files that are going to be converted into LAS.
3. Choose the directory where the LAS files are going to be included.
4. Click merge files into one so that all the LAZ files are decompressed in just one LAS file.
5. Select the format in which the data will be converted.
6. Press run32 or run64 depending on the bits of the computer Window’s system (64 bits in this case).
7. A new window is opened automatically. Wait until it disappear, which means that the process was complete successfully and the data is now in LAS format.

Note that in this procedure the coordinate system was not selected as it would be included once the data is opened in ArcMap.

After this processing stage, the underwater bathymetry data was ready to be imported and used in ArcMap.

b) Land use

The collected file containing the land use covers an area much bigger than the extent of the hydraulic model, as shown in figure 10.

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[4] LASTOOLs software was used because of being a user-friendly software, but it could have been done directly in ArcMap using the “spatial ETL” tool.

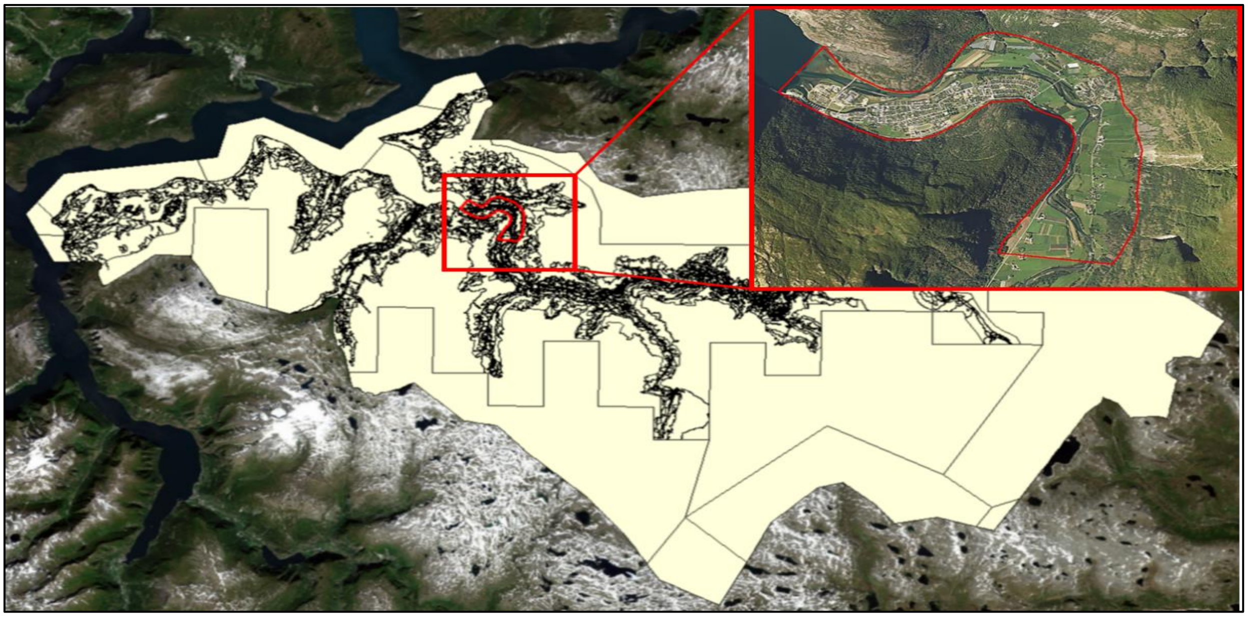

Figure 10: Complete area included in the land use file (in cream color). The red line encloses the area included in the hydraulic model. The land use file was clipped according to it

Therefore, the first modification was to clip the file according to the boundaries of the model. Some discrepancies appeared in the classification of some areas when compared with the ortophoto of Lærdal of 2017 from Geonorge, which was considered more accurate because of being more recent. To fix this, the land use shapefile was manually modified in ArcMap. Figure 11 shows the land use classification before and after the modifications.

Figure 11: Land use of the different areas enclosed in the hydraulic model. The left picture shows the original classification. The right picture shows the modified file.

c) Building shapefile

Some of the buildings of Lærdalsøyri were missing in this shapefile, probably due to its antiquity. Therefore, it was manually modified in order to include them (see Figure 12), using the ortophoto of Lærdal from Geonorge (2017) as a reference.

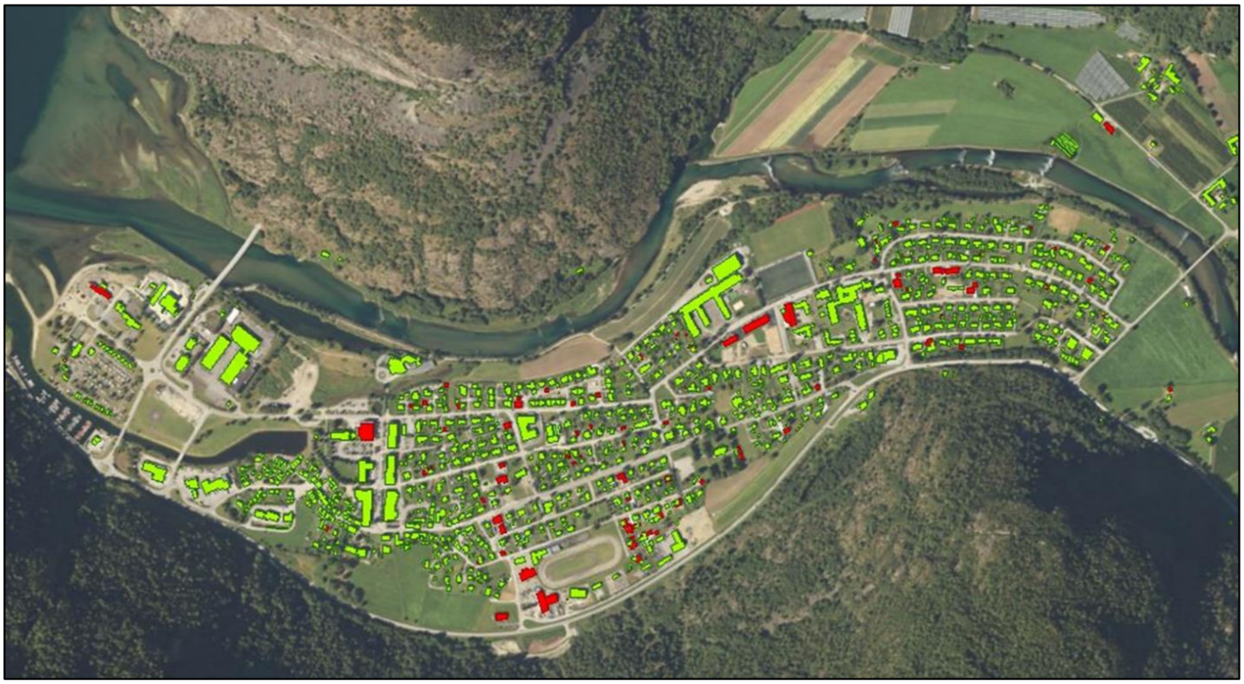

Figure 12: Buildings in the area of Lærdalsøyri. The red polygons represent the originally missing buildings that were manually drawn according to an Orto photo of Lærdal of 2017.

3.1.3. Elevation data analysis and validation

As the elevation data affects directly the output of the simulations and the degree to which the model replicates the real situation, the quality of these data was checked.

Further, before merging the two sources of elevation data, an analysis of the areas covered by each of them, as well as of its most relevant statistics was carried out. Once this was done, the two sources were compared to check if both contain similar elevation values in the common areas and prevent inaccuracies in the model. A deeper insight is presented in this section.

a) Coverage and statistics

The elevation data from both sources in .las format were imported into ArcMap, where the “Create LAS Dataset” tool was used. This tool provides an option to compute statistics. The most relevant results are included in Table 3.

	Point count	Point spacing	Zmax	Zmin	Classification
Red LiDAR	1,499,928,792	0.245	2400.32	-4.38	Unnasigned, ground, noise, rail, bridge deck
Green LiDAR	744,993,985	0.123	429.35	-7.73	Ground, reserved

Table 3: Most relevant statistics of the Las datasets from the red and the green LiDAR

Note that in order to analyze the red LiDAR, the point cloud data from Høydedata was used. As explained in section 3.1.1, Høydedata gives the possibility to download the elevation data both in raster format (.tif) or in its original point cloud form (.laz). Even if the terrain model was created using the raster, the point cloud data was also downloaded in order to analyze it. To do so, the .laz data was converted into .las in LAStools, following the procedure explained in section 3.1.2.a.

With the lasdataset created, the areas covered by both sources were displayed (see Figure 13 and Figure 14).

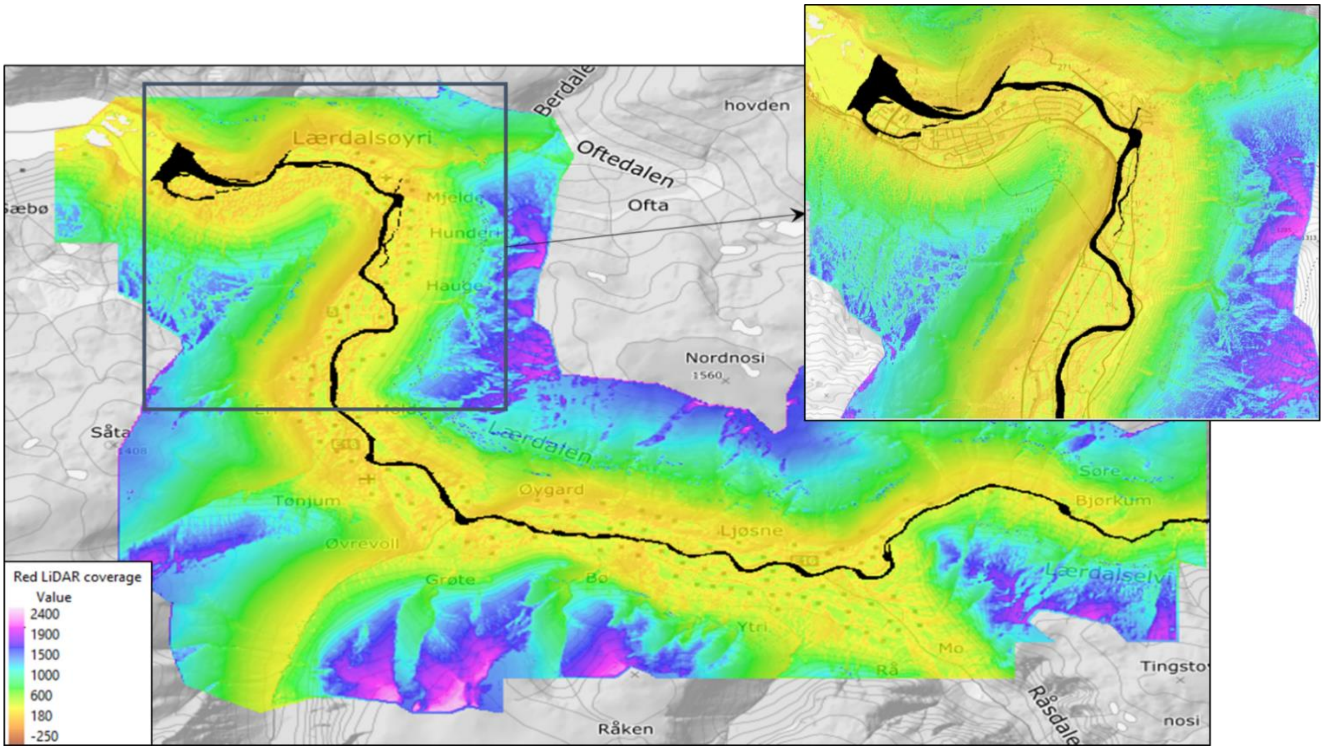

Figure 13: Area covered by the topographic LiDAR. The river channel (in black) was clipped from the rest of data because the red light does not penetrate the water column so the elevation values did not contain the depth of the soil in the river bed.. The figure on the right is an enlargement where only the area of interest is shown.

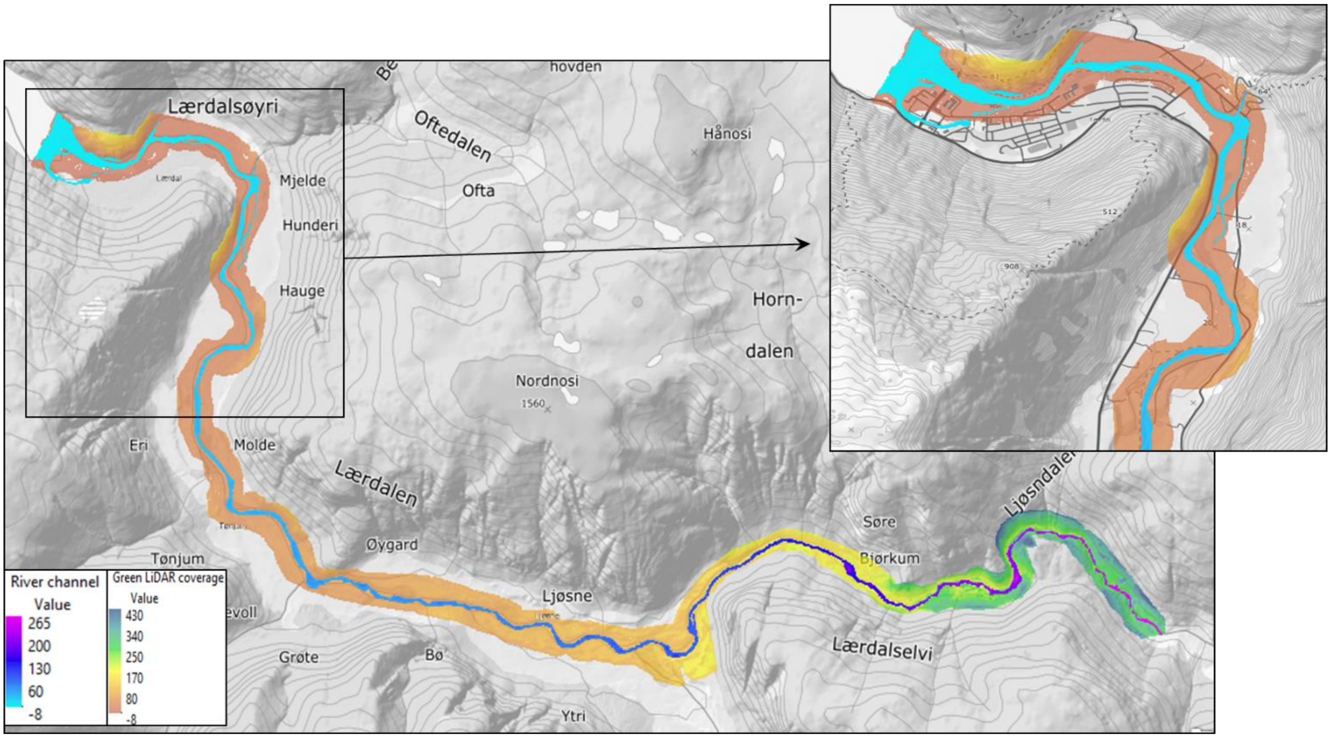

Figure 14: Area covered by the bathymetric LiDAR. The river channel was clipped from the rest of data because it is the only area of interest of the green LiDAR (the elevation data of the floodplains is taken from the red LiDAR). The figure on the right is an enlargement where only the area of interest is shown.

b) Validation of the green LiDAR data

Before creating the digital terrain that integrates the red (for the floodplains) and green (for the river channel) LiDAR in ArcMap, the underwater bathymetry data was validated. The reasons to do this were:

- To check the accuracy of the bathymetric LiDAR data. It is always important to double check the data given to test its reliability, especially in cases like this one, where the data was new and had not been analyzed before.

- To ensure that there was not a systematic error in the elevation values between the two sources of data. In this case, the errors could be due to having used two different measurement systems or even a different Z coordinate system. If not detected, this error could lead to some discrepancies in the final terrain, as the values from Høydedata and LiDAR had to be merged into one single model. The solution of a case like this would be simple. For example, if a +20cm elevation difference were found in almost all the points of LiDAR when compared to Høydedata, it would be enough to increase 20cm the elevation raster of Høydedata.

Two different comparisons were made to analyze the data coming from the ALB. The procedure followed in each of them is explained in the following sub-sections.

b.1) Comparison red - green LiDAR

As the survey of the whole terrain was made with two different methods, it is necessary to check that both have a common reference. In order to do this, 4 different types of areas were selected to be compared. These areas were classified depending on its land coverage as: open land, gravel, grass and roads. 3 areas of each type were analyzed, resulting in a total of 12 comparisons. The corresponding shapefiles enclosing the selected areas are shown below.

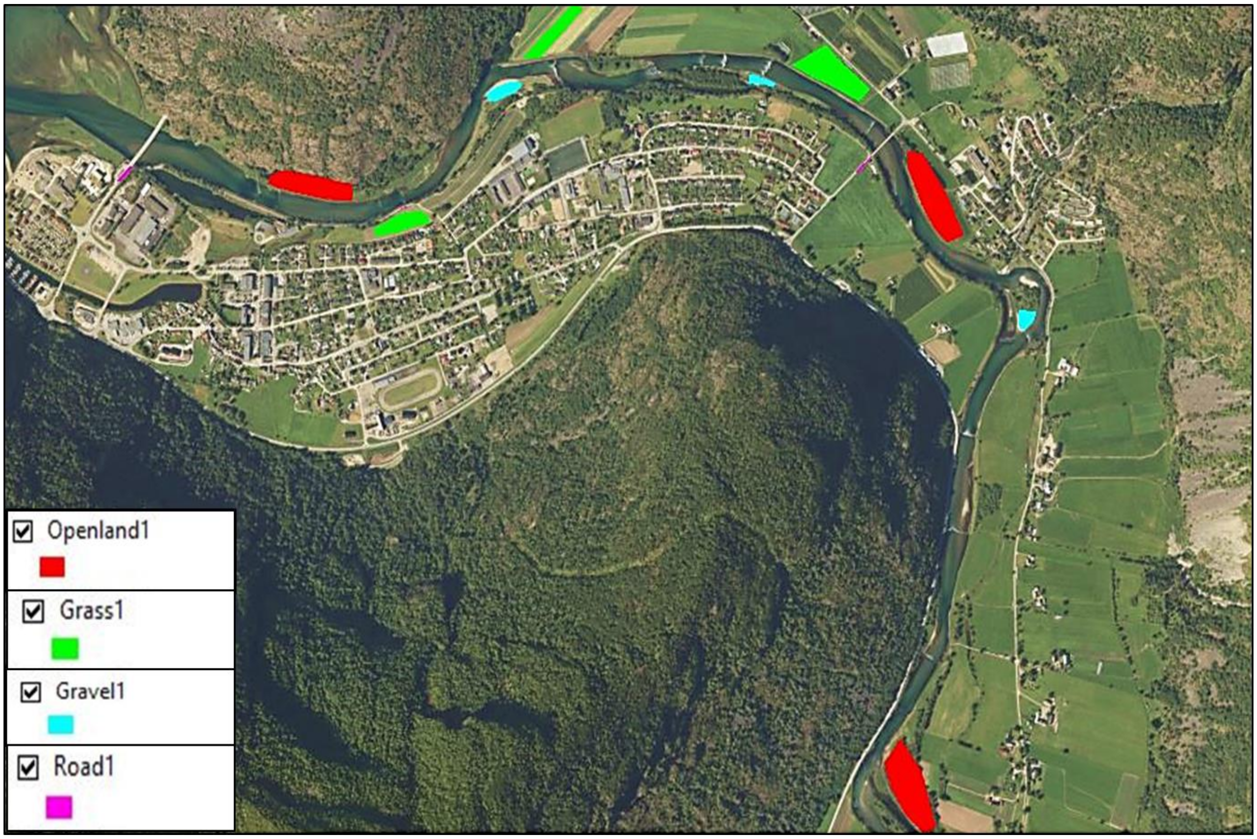

Figure 15: Areas selected to compare the elevation data from the green and red LiDAR. 4 different types of areas were chosen depending on the land coverage, classified as: open land, grass, gravel and roads. Within each category, 3 areas in different locations were studied.

The elevation points contained in each of the areas were extracted, both from the green and the red LiDAR. The point cloud from Høydedata contained not only the elevation of the bare ground but also of all the other features above it (ground, brushes, low vegetation…). These points were first classified so that only the ones labeled as "Ground" were kept for the comparison. Regarding the green LiDAR data, as the point density from this source was proved to be very high, a 0.04m resolution raster was created from it. Therefore, a comparison between the points from Høydedata and the raster from the green LiDAR was carried out using the "Extract values to points" tool of ArcMap. The output of this tool is a point feature dataset whose attribute table contains the original elevation value of the point (which correspond to the elevation from Høydedata) and the elevation of this same point extracted from the raster. The only thing left was comparing the differences in elevation of every point in the attribute table, both numerically and graphically.

As the procedure followed is long and complex, a detailed step by step is attached in appendix D.

Note that, again, the point cloud downloaded from Høydedata was used instead of the DTM because an accurate comparison was necessary. If the DTM had been used instead, the elevation of some of the points (particularly in the cells of the raster that did not contain any LiDAR point) would have been obtained by interpolation and not because its elevation had been really measured. These inaccuracies were avoided with the procedure that was followed. However, once the LiDAR was validated, the DTM was the data used for the construction of the digital terrain.

b.2) Comparison GPS points (fieldwork in Lærdal) - Green LiDAR

A different method for assessing the accuracy of the green LiDAR data is to compare it with manually measured points. The manual measurements taken with GPS were conducted during the fieldwork in Lærdal on May 6 and 7, 2019. The idea was to double check the green LiDAR data with more recent elevation information, as the data from Høydedata was taken in 2014 and some flood events took place afterwards. This could lead us to think that the green LiDAR data is unreliable or not accurate enough in cases where the differences are due to sediment transportation or changes in land coverage. The way to proceed in this case was almost the same as the one explained in section b1. Again, the elevation of each of the GPS points was compared to the elevation of these same points when extracted from the 0.04 resolution rasters created from the underwater bathymetry data (green LiDAR). In this case, the areas compared were classified as gravel, roads and gravel roads.

Note that in order to compare the points, the GPS elevation values were first adjusted to the NN2000 coordinate system (original coordinate system of the points was NN1954). A Z coordinate system adjustment can be achieved by increasing or decreasing the elevation value of the points according to a constant given depending on their location on the map, as represented in Figure 16, taken from Kartverket. In this case, it was necessary to increase the altitude values of the GPS points +6cm, which were added directly in ArcMap by modifying the attribute table of the points (Field Calculator tool).

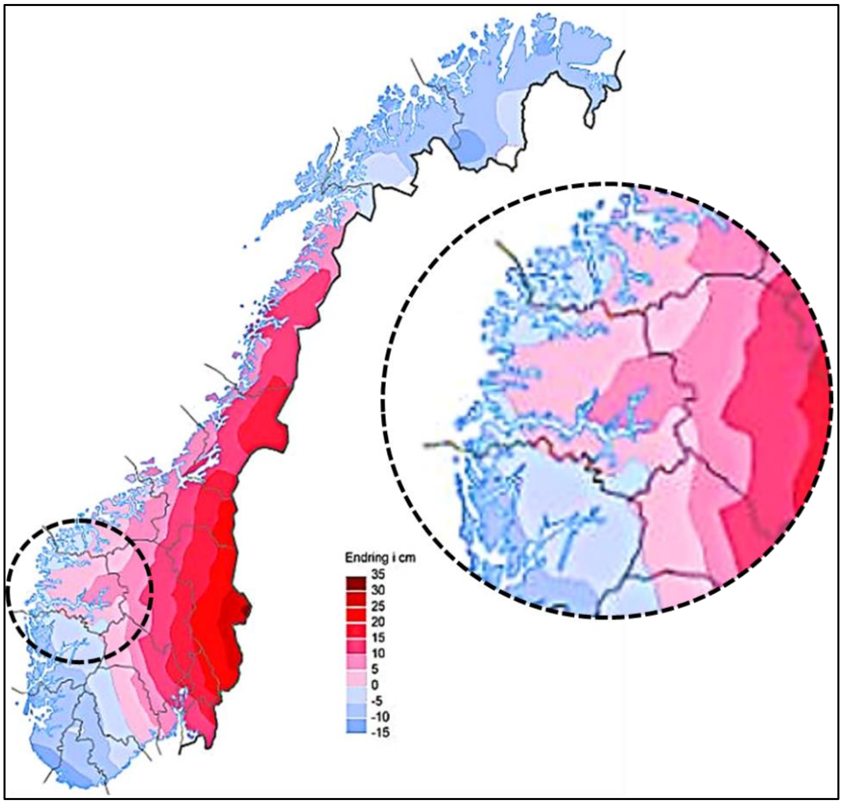

Figure 16: Conversion of the elevation values from NN1954 to NN2000

3.1.4. Terrain construction

The core of the preprocessing part is the digital terrain creation in ArcMap. The most important highlights of the process are explained in this section. A deeper insight is given in Appendix D.

As previously mentioned, the data used in this thesis came from 2 different sources: red LiDAR for the floodplains (Høydedata) and green LiDAR for the river channel (underwater bathymetry). In addition, the elevation model selected from Høydedata was the DTM, containing only the bare ground, so the buildings had to be be modelled and included in the terrain afterwards. As the sources of data were different, their treatment was different too. However, prior to create the terrain merging the data from both sources, it must be ensured that all the files used within the project contained the same coordinate system. Because of the location of the area of study, the coordinate system selected was ETRS1989 UTM Zone 32N (XY coordinate system) and NN2000 (Z coordinate system).

a) Bathymetric terrain for the river channel

Using the LAS data file obtained in LAStools (section 3.1.2.a) a raster was created in ArcMap with the “LAS dataset to raster” tool. Here, two important parameters were chosen:

- <u>Interpolation type</u>

  As the LiDAR data was given as a point cloud, the void spaces needed to be filled in order to create a complete underwater terrain of the river. This was done using an interpolation technique between the measured points. The interpolation method chosen in ArcMap was the binning approach. Within this technique, the interpolation options chosen were: Average for the output cells containing LAS points (each cell value is calculated from the average value of all the points in the cell) and Natural Neighbor for the output cells that fell in areas without LAS points.

- <u>Cellsize</u>

  As the resolution of the LAS data is very good and the average point spacing is small (see Table 3), the selected cellsize of the raster was 0.35. In general, the selection of this parameter is not simple, as a balance between better resolution and other practical requirements as processing time and storage space occupied needs to be found. After a first trial with a bigger cellsize, it was reduced to the final value of 0.35. Big differences in the processing time were not detected with this reduction, probably because the extent of the river channel is not very large (the cellsize chosen for the floodplains was bigger, as it will be explained during the Høydedata procedure).

The obtained 0.35m resolution raster was clipped so that it only encloses the river channel (see Figure 14). The river bed terrain was created in this way.

b) Terrain for the floodplains

In this case, the input data were multiple rasters (.tif), each of them containing the DTM of a small area. A single raster out of all of them was created. The resulting DTM is shown below:

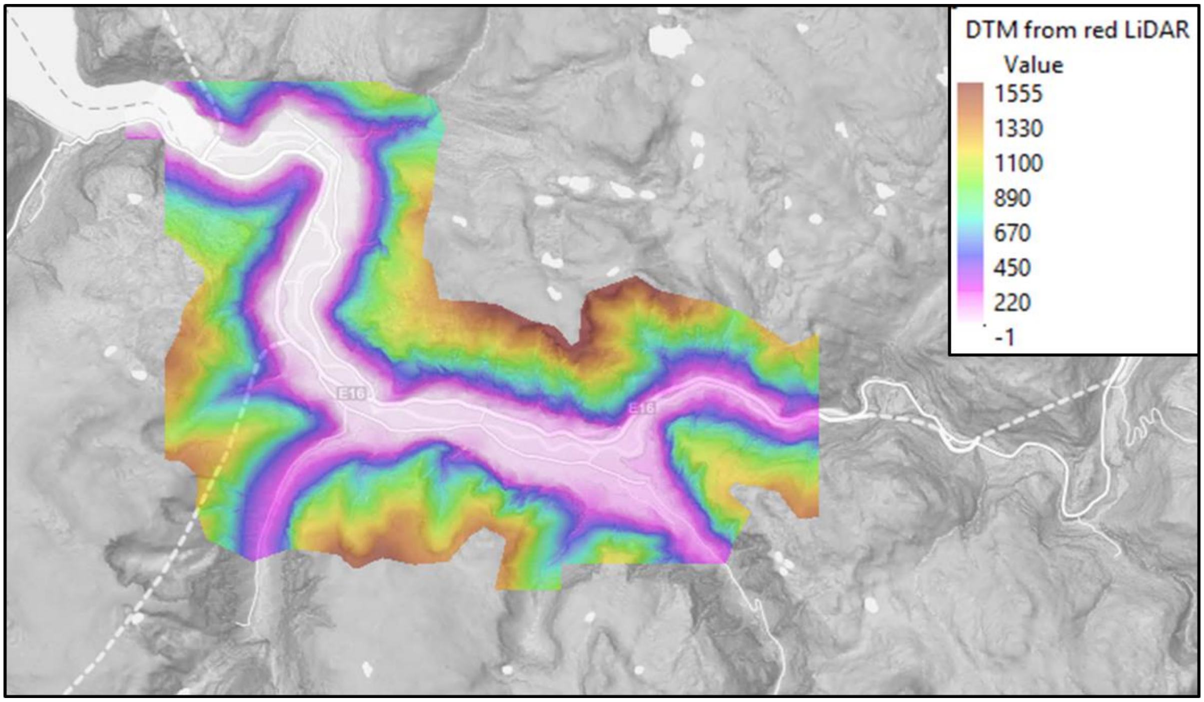

Figure 17: Final DTM in raster format obtained by joining the files downloaded from Høydedata. Note that the lowest Z value is -1m, which proves that the red LiDAR does not penetrate the water column of the river.

This terrain was created with two different cellsizes (1m and 0.5m) in order to the test if some differences appeared in the results of simulations because of the sub-grid bathymetry function of HEC-RAS. This is discussed in Section 4.2.

c) Inclusion of buildings and roads in the digital terrain

As explained in section 3.1.2.c the shapefile containing the buildings was modified to include all the dwellings in the area. The next step was to create a raster containing these buildings and to give it an extra height so that they act as an obstacle for the water flow in the flood simulations in HEC-RAS. This was done by extracting the land occupied by the buildings from the DTM and increasing 3m its height using the “Raster calculator” tool. This tool allows the user to operate with raster layers using the syntax of an algebraic expression. Deeper insight of the procedure is explained in appendix D. A 3D view of the shape of the buildings obtained is shown below:

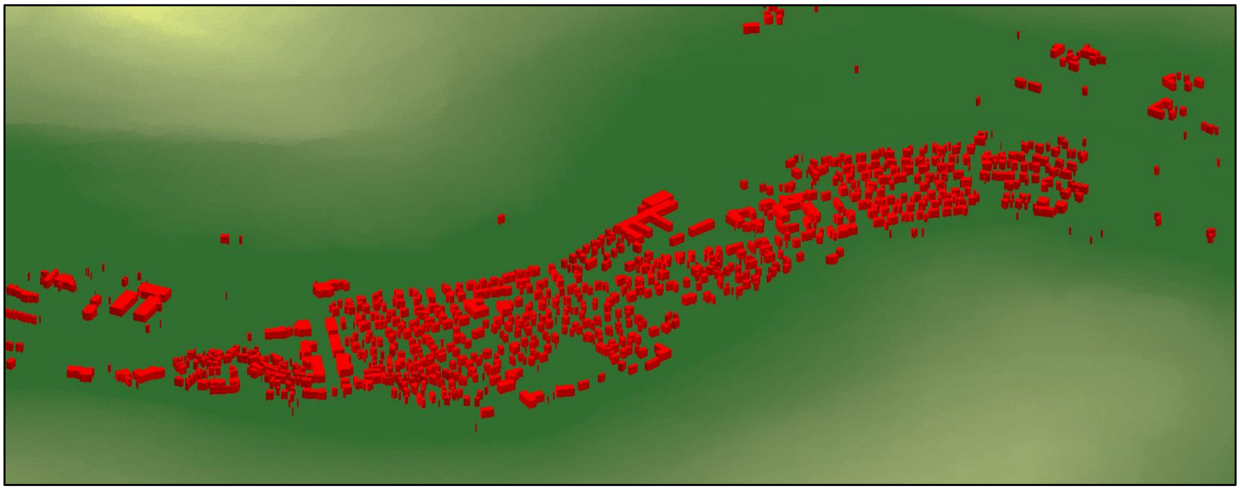

Figure 18: 3D visualization in ArcScene of the buildings created in ArcMap from the feature layer containing their shape. The polygons enclosing the dwellings were extracted from the DTM and given an additional height of 3m.

d) Final terrain including all the parts

With the three raster layers created (sections a,b,c), the last stage in the process was to join them together. This was done using the “Mosaic to New Raster” tool. Note that in the overlapping areas it is necessary to determine an order of preference so that ArcMap maintains the elevation value of the raster that was given priority. Preference was given in the following order: underwater bathymetry (river channel), buildings, høydedata (floodplains). The cellsize selected for this final terrain was also 0.35 so that the high resolution of the underwater bathymetry raster was not lost. In addition, as explained in section 2.7. HEC-RAS perform the calculations using a sub-grid method. This means that if a terrain with a good resolution is used as input in this software, the cellsize of the mesh in HEC-RAS can be increased without losing too much precision in the results as the calculations take the terrain below the geometry into account. Considering the high number of simulations that were performed in HEC-RAS, this could save a lot of time.

A picture of the final terrain (once in HEC-RAS) is shown in Figure 19.

3.1.5. Terrain modification to include the flood protection wall

In the previous section, the methodology followed to obtain the initial 3D terrain that was imported into HEC-RAS is explained. This terrain was used to calibrate the hydraulic model and to analyze the areas at risk under a 200-year flood event when no flood protection work is carried out. However, there are some existing plans to modify the area in order to minimize the consequences of the floods. These plans were developed by the NVE (Appendix A) and are still under consideration.

Prior to any morphological change in the river, a simulation showing the potential impacts caused by the modifications is required. This is the reason why the initial terrain, representing the actual features of the area, was reshaped according to the alternative number 1 of the NVE (Figure A.1). This alternative indicates the areas where the ground must be raised (same effect as building a protection wall) and the river zones that must be widened.

The wall was created in ArcMap from a polygon feature (.shp) of 4m wide and positioned according to the NVE plan. The terrain occupied by this polygon (simulating the wall) was extracted from the DTM and its height was increased using the "Raster calculator" tool. The new raster with a higher elevation in the areas enclosed by the wall was then merged into the initial terrain. A more detailed explanation of the procedure is included in Appendix D.

After some trials with different heights, the design of final wall and its elevation are detailed in Appendix E.

3.2. Processing

All the tasks included in the processing part were carried out using HEC-RAS. Therefore, this section starts with importing the terrain created in ArcMap into HEC-RAS.

The processing part is divided in 3 sections: hydraulic model creation, sensitivity analysis and calibration of the model.

3.2.1. 2D hydraulic model in HEC-RAS

The methodology for the creation of the 2D floodplain model in HEC-RAS is described in this section. Although the hydraulic model was created and modified for the river of Lærdal, the main steps presented are common for any 2D unsteady state simulation.

a) Terrain model

The terrain created in the preprocessing was imported into HEC-RAS using RAS Mapper, which supports three different formats (.tif, .flt and .adf). The terrain layer used in this case was a single raster in .tif format. Figure 19 shows how the terrain looks like in HEC-RAS.

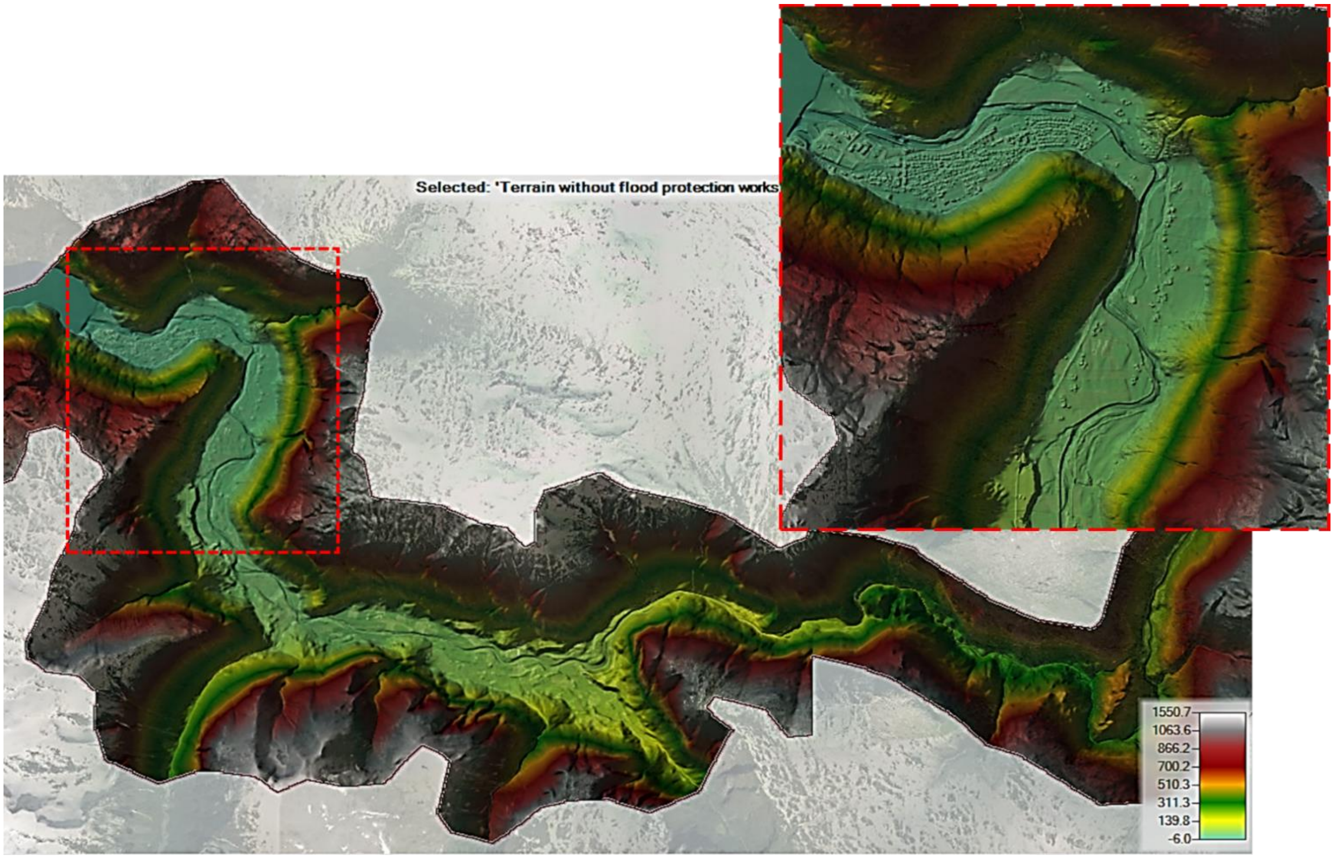

Figure 19: Terrain created during the preprocessing displayed in HEC-RAS. This terrain does not contain any of the flood protection measures.

In some cases, the terrain layer imported requires some modifications in order to include or remove some features, as happens with detention basins, bridges, roadways channels or bathymetric data, among others. Since the version 5.0 of HEC-RAS was released, it is possible to reshape the terrain by modifying the geometry from RAS Mapper. To achieve this, the river layer creator and the cross section editor are used. The new terrain features are automatically interpolated between the modified cross sections when the layer including the adjustments is exported.

In this project, this feature of HEC-RAS was used to remove some of the river islands and to excavate the river channel to widen it according to the NVE plan. Further details are given below:

- **Terrain modification in HEC-RAS:**

In order to lower the elevation of the digital model in the areas indicated by the NVE plans, a new 1D geometry of the features to be modified was created. The centerline of each feature was delineated and both longitudinal edges were marked. Some cross sections were also included (at least two are required, but the more cross sections included, the more accurate are the results of the modifications). Figure 20 shows which areas have to be modified and the 1D geometry lines created to achieve it in HEC-RAS.

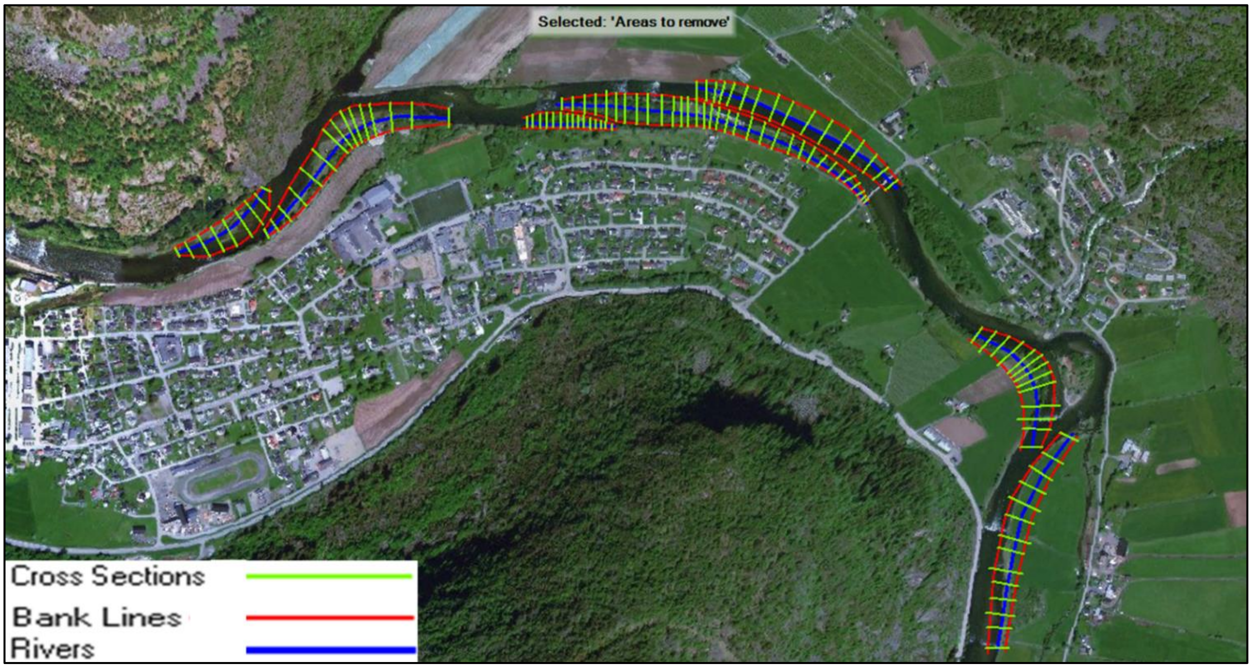

Figure 20: Islands and areas of the river terrain that should be removed according to the NVE alternative 1. The figure shows the 1D geometries drawn in HEC-RAS to modify the terrain.

Once these 1D geometries were created and saved, the elevation of the terrain in the marked cross sections was reshaped in the usual Geometry editor. An example showing the excavation of the land in two arbitrary cross sections is shown below.

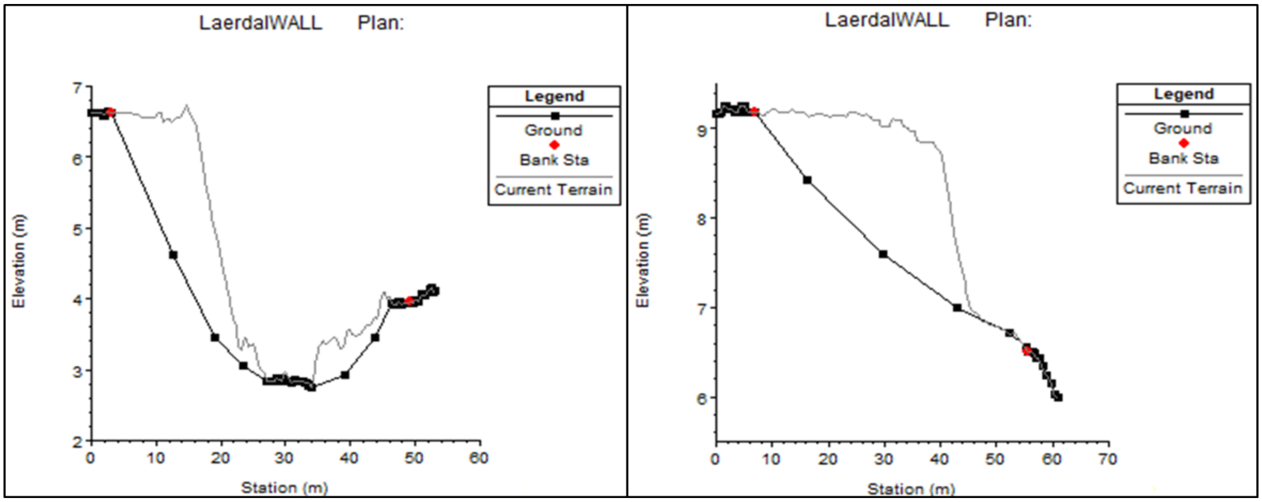

Figure 21: Modification of the cross sections. The thin line shows the terrain in the cross sections prior to any change. The thick black line represents the new shape of the river channel in this XS.

When all the cross sections were modified as desired, the new geometry layer was exported in a raster format. The elevation data of the areas in between the cross sections were automatically interpolated and the new terrain generated this way was opened in HEC-RAS to run the simulations corresponding to the island removal.

b) Geometry

Drawing the 2D flow area was the first step in the creation of the geometry, along with the selection of the cellsize of the mesh. This parameter is very important, as the cell size should be small enough to produce stable computations and accurate results but also big enough to do this in a reasonable period of time. Because of the complexity of the decision, this parameter was subjected to a sensitivity analysis, as described in section 3.2.2. With the 2D area delimited, the boundary condition lines for upstreams and downstreams were drawn.

Another important feature that may be included in the geometry are the break lines. These lines can be manually drawn in specific areas of the terrain, as along the crest of high ground features in the topography that act, completely or temporarily, as a barrier to water flow. When this lines are drawns, the cell faces of the mesh are aligned along them. This new distribution of the mesh helps HEC-RAS to keep the water out of the “dry” side of the breakline until the water surface elevation is higher than the terrain where the breakline was delineated.

In this project, break lines along the flood protection wall were included for the simulations of the 200-year flood including protection work, as incoherent results were obtained when the simulation was run without them[5].

c) Unsteady flow data -boundary conditions definition

The boundary conditions used for the upstream and the downstream lines drawn in the geometry editor were:

- Upstreams: Flow hydrograph. With flow hydrograph as boundary condition, it is possible to vary the discharge with respect to time, so the volume of water entering to the model per unit of time is controlled. The hydrographs chosen for the calibration of the model and for the 200-year flood simulations (with and without climate change) werer plotted and included in Figure 22.

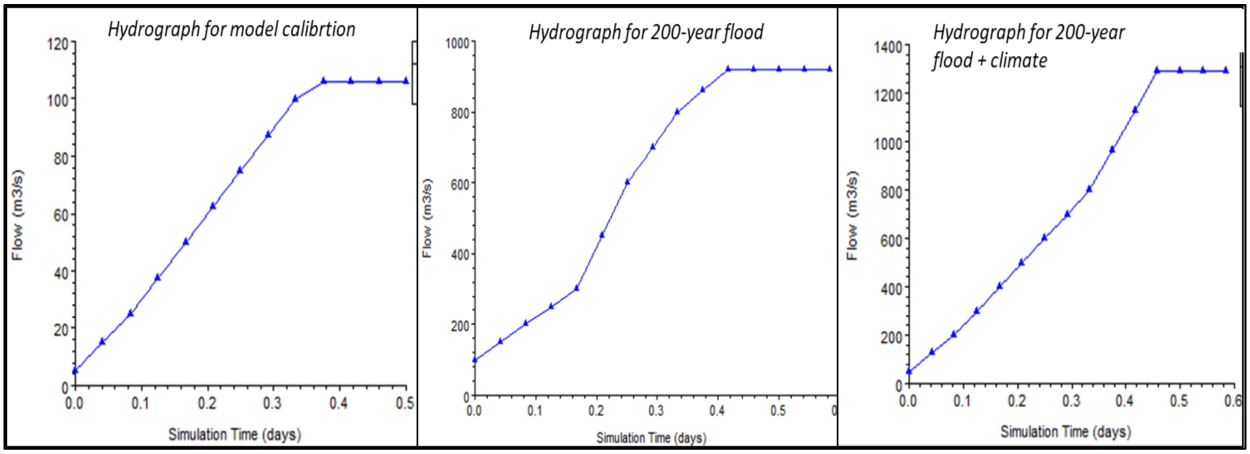

Figure 22:Hydrographs showing the water flow chosen for the simulations in HEC-RAS. The hydrogrph on the left shows the values chosen for the calibration of the model (maximum value: 106m3/s). The one in the middle shows the 200-year flood values (maximum: 920m3/s). The right hydrograph shows the values of a 200-year flood event considering new hydrological conditions due to climate change (maximum: 1288m3/s).

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[5] The break line features were included in the mesh after discovering that in the simulations in which the flood protection wall was included in the terrain, the water was entering the village center through an area where the terrain elevation was higher than the WSE. This problem was solved after including breaklines along the wall.

Note that for the 200-year flood events the peak discharge remains 4 hours. This amount of time was chosen according to the model of Norconsult, and because it proved to be time enough to reach the steady state in the simulations.

- Downstreams: Stage hydrograph. This option requires a value for the tide level. In this case, a constant value of 1.24m was chosen, based on the model carried out by Norconsult.

d) Computational settings

Last step was performing an Unsteady Flow Simulation. In this stage of the procedure, it is very important to make sure that the correct geometry (associated with its corresponding terrain) and unsteady flow data files are selected. Once this is done, the settings of the simulation are introduced. For the case under study, the most relevant settings were the ones below:

- Simulation time: 14 hours, according to the flow hydrograph condition for the upstream boundary selected in the previous step. In the case of the 200-year flow simulation, only 4 of these 14 hours contains the culmination values for the discharge. A period of 14 hours of simulation was chosen because it was proved that good and stable results were obtained within around 15 clock hours (which was considered an acceptable waiting time).

- Computation settings: The courant condition option was used, as it allows variable time steps of the simulation based on the computed velocities. The initial computation time step was set in 4 minutes, as it was proved to be enough.

After the selection of the settings, the simulations were run. The results were shown in the RAS Mapper extension of HEC-RAS. This part is included in the post-processing.

3.2.2. Sensitivity analysis

The sensitivity of the hydraulic model to variations in Manning's number (n) and in cellsize was evaluated. This procedure involves running simulations holding all the parameters constant except the one under analysis in each situation. The objective is to check which parameters have a major influence in the model so that they are carefully selected in the final model.

a) Cellsize

Two different types of cellsize sensitivity analysis were carried out. First, the cellsize of the mesh of the geometry in HEC-RAS was analyzed. In addition, as HEC-RAS works with a sub-grid bathymetry approach[6], also the effect of modifying the cellsize of the raster terrain created in Arcmap was studied.

- **Cellsize of the mesh in HEC-RAS**

  Maintaining the rest of the parameters constant, two cellsizes were used: 2x2 and 3x3 (meters).

- **Cellsize of the raster containing the terrain in ArcMap**

  The cellsize of the raster containing the river was in all of the cases of 0.35m (explanation in section 3.1). However, cellsize of the raster for the floodplains (from Høydedata) was analyzed for 2 different resolutions: 0.5m and 1m.

b) Manning

Prior to include the land use layer in HEC-RAS with more accurate manning values depending on the type of land coverage, the influence of the manning value was study. To analyze it, two different simulations were run using a single manning number for the whole area: 0.03 and 0.05.

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[6] As explained in section 2.7, HEC-RAS computations for the transport of fluid take into account not only the mesh created in the geometry editor of the software but also the information contained in the underlying terrain (the one created in ArcMap during the preprocessing)

3.2.3. Calibration of the model (with water edge line)

In the absence of accurate observed data under a flood event, the model was calibrated using the discharge value of the day of the flight when the underwater bathymetry data was collected. This took place on May 29, 2018 from 16:00 to 17:00. The discharge at this time in the starting point of the model 1 was approximately 106 m^3/s (Section 3.1.1.d). As a shapefile containing the water edge of this day was available, the model was calibrated by running simulations with 106m^3/s and comparing the simulated water covered area with the water edge line. This way, the most appropriate manning number for the river channel was determined.

3.3. Post-processing

All the tasks carried out once the computations in HEC-RAS were finished are included in the post-processing section. HEC-RAS 5.0.7 allows users to create 2D flow area models and to observe the results in RAS Mapper. The three available result layers in RAS Mapper are Depth, Water Surface Elevation and Velocity. In this project, the two first ones were used. Thus, floodplain inundation boundaries and their depths were calculated. In addition to the 2D flood map analysis, some profile lines were created to analyze the water surface elevation of some sections with higher detail.

One of the objectives of the post-processing is to check that the results obtained are computationally correct (if there are some instabilities in the model or some of the selected parameters as cellsize or time step are not appropriate, it is easily detected when visualizing the result layers in RAS Mapper). Furthermore, the areas at risk and the effect of the flood protection works is studied in this stage.

4. Results

The main results obtained following the methodology presented in section 3 are presented in this chapter.

4.1. Validation of green LiDAR data

The objective of this validation is to test the accuracy of the bathymetric data provided.

For each of the areas selected when comparing the green LiDAR, both with the red LiDAR and with the GPS points took during the visit to Lærdal, 2 statistic measures were calculated: the mean and the standard deviation. The formula used for the standard deviation is:

$$Standard\ deviation = \sqrt{\frac{\sum |x - \overline{x}|^2}{n}}$$

Where:

x = difference in the Z elevation of the point being compared

$\overline{x}$ = mean value of the differences in each area

n = number of points compared in this area

Some graphs were also created for each area, all of them with the same format. The elevation value of each point corresponding to the red LiDAR or the GPS measurements is represented in the x-axis. The y-axis displays the height of the same point according to the green LiDAR. Also, an x=y line is plotted to analyze how much the results differ from the ideal case where the elevation of each point is the same in both sources of data.

Note that the differences were calculated by subtracting the red LiDAR or GPS elevations minus the green LiDAR ones.

4.1.1. Comparison red - green LiDAR

The numerical results obtained by susbtracting the elevation values red – green LiDAR are presented in this section. The graphical classification carried out in ArcMAP is included in Appendix F.

a) Gravel

	Gravel 1	Gravel 2	Gravel 3
Number of points	16959	7871	15631
Mean	0.25	0.09	0.03
Standard deviation	0.17	0.23	0.08

Table 4: Main statistics of the differences in elevation (red-green LiDAR) obtained for the areas classified as "Gravel"

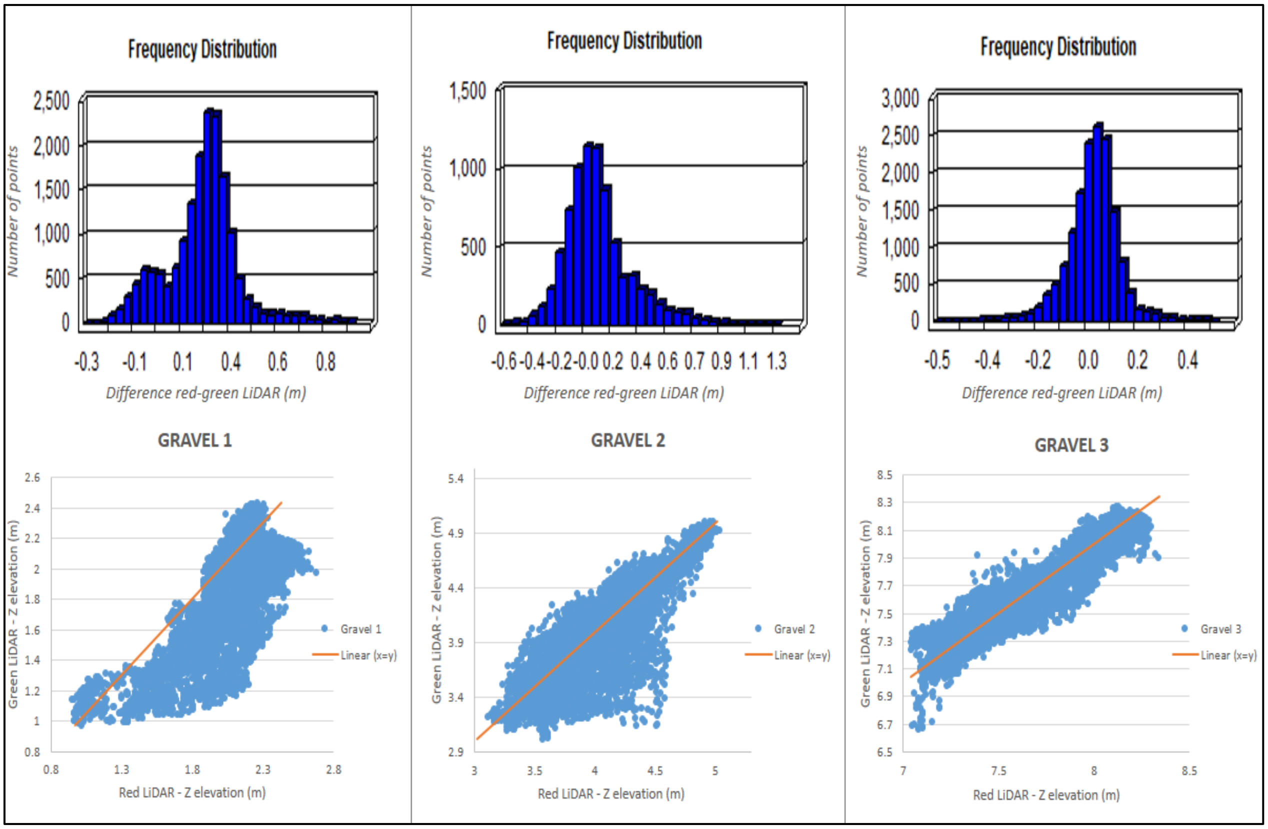

Figure 23: Red - green LiDAR comparison graphs for the points included in the areas classified as "Gravel"

b) Roads

	Road 1	Road 2	Road 3
Number of points compared	4465	4225	803
Mean of the differences	0.007	0.133	0.010
Standard deviation	0.100	0.103	0.026

Table 5: Main statistics of the differences in elevation (red-green LiDAR) obtained for the areas classified as "Road"

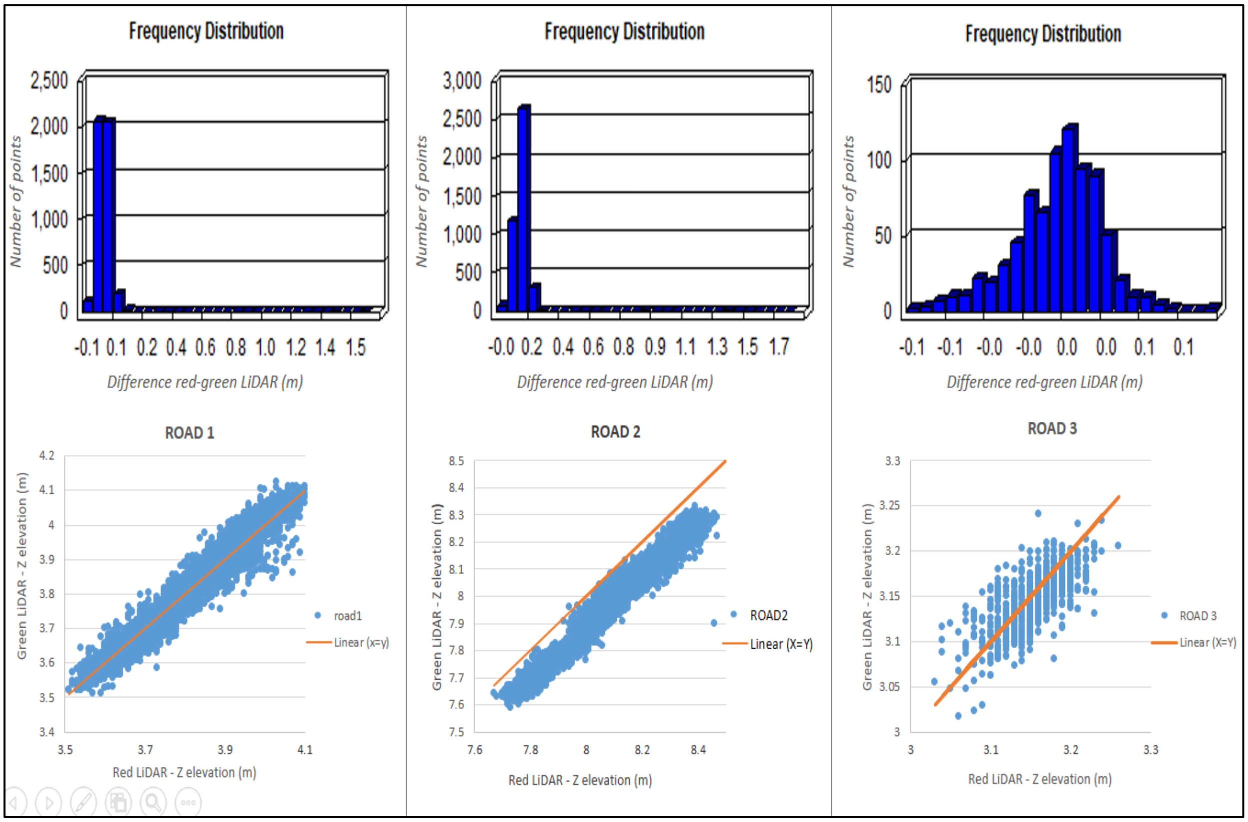

Figure 24: Red - green LiDAR comparison graphs for the points included in the areas classified as "Road"

c) Open land

	Open Land 1	Open Land 2	Open Land 3
Number of points	61174	91808	77868
Mean	-0.04	0.04	0.02
Standard deviation	0.21	0.16	0.10

Table 6: Main statistics of the differences in elevation (red - green LiDAR) obtained for the areas classified as "Open land"

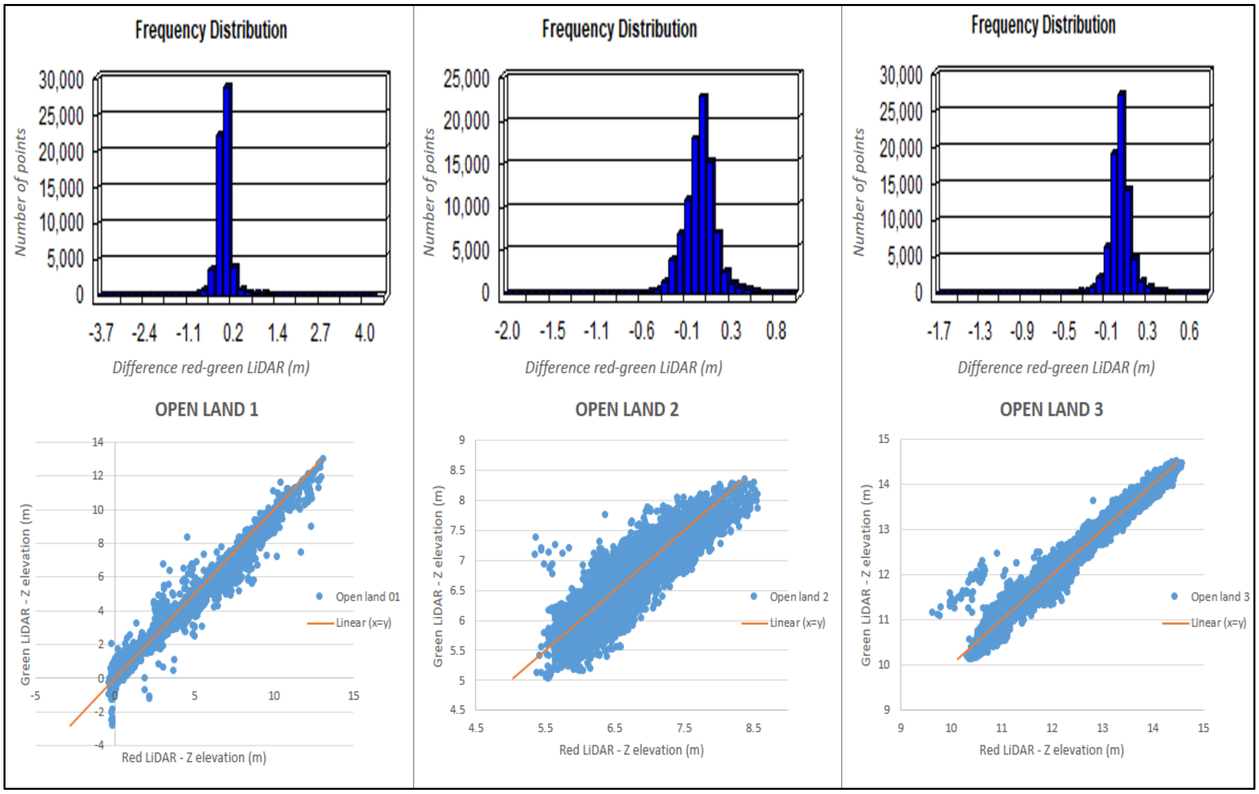

Figure 25: Red - green LiDAR comparison graphs for the points included in the areas classified as "Open land"

d) Grass

	Grass 1	Grass 2	Grass 3
Number of points compared	52634	130173	164050
Mean of the differences	0.043	0.010	-0.234
Standard deviation	0.06	0.12	0.11

Table 7: Main statistics of the differences in elevation (red-green LiDAR) for the areas classified as "Grass"

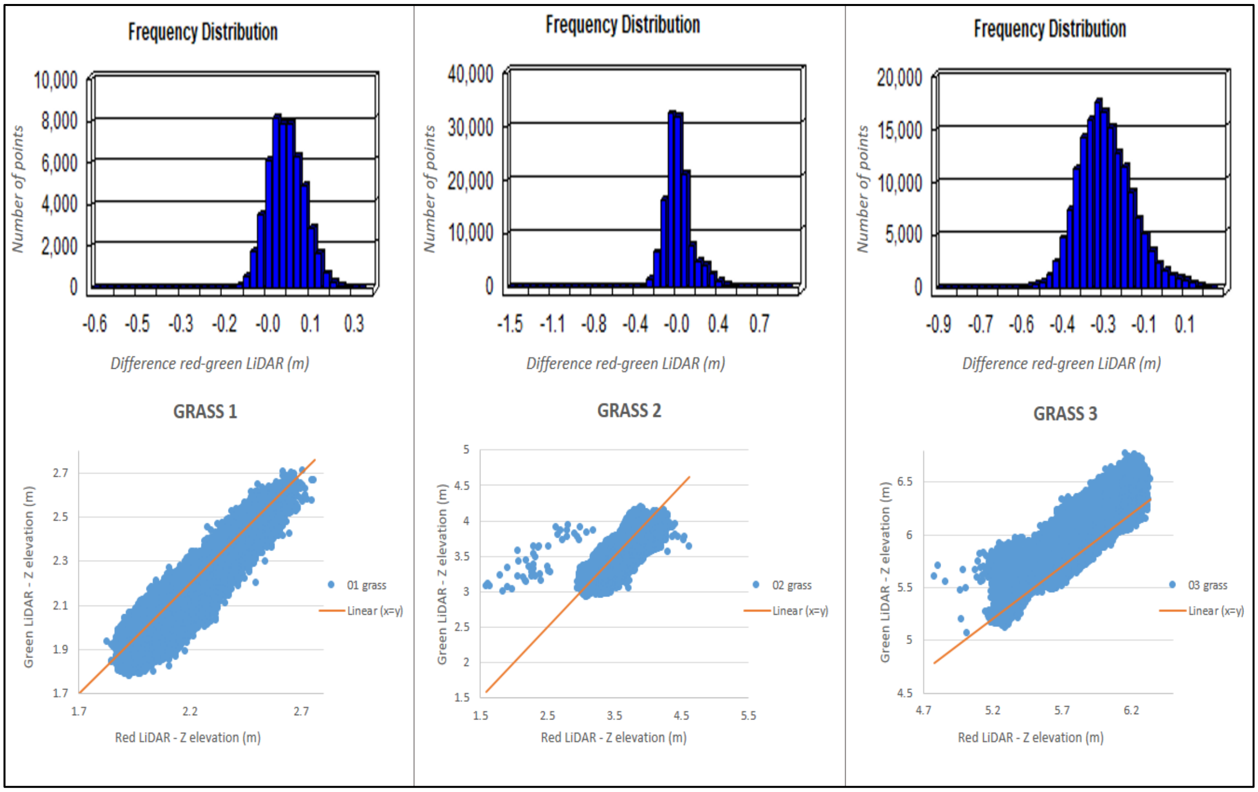

Figure 26: Red - green LiDAR comparison graphs for the points included in the areas classified as "Grass"

4.1.2. Comparison GPS points - green LiDAR

The GPS points were measured in the areas where the comparison red – green LiDAR required a double check. These areas were classified as gravel, gravel roads and roads. Again, only the numerical results are presented in this section, being a graphical classification included in Appendix F.

a) Gravel

	Gravel A	Gravel B	Gravel C
Number of points compared	52	100	95
Mean of the differences	-0.034	0.39	0.201
Standard deviation	0.043	0.33	0.173

Table 8: Main statistics of the differences in elevation (GPS - green LiDAR) for the areas classified as"Gravel"

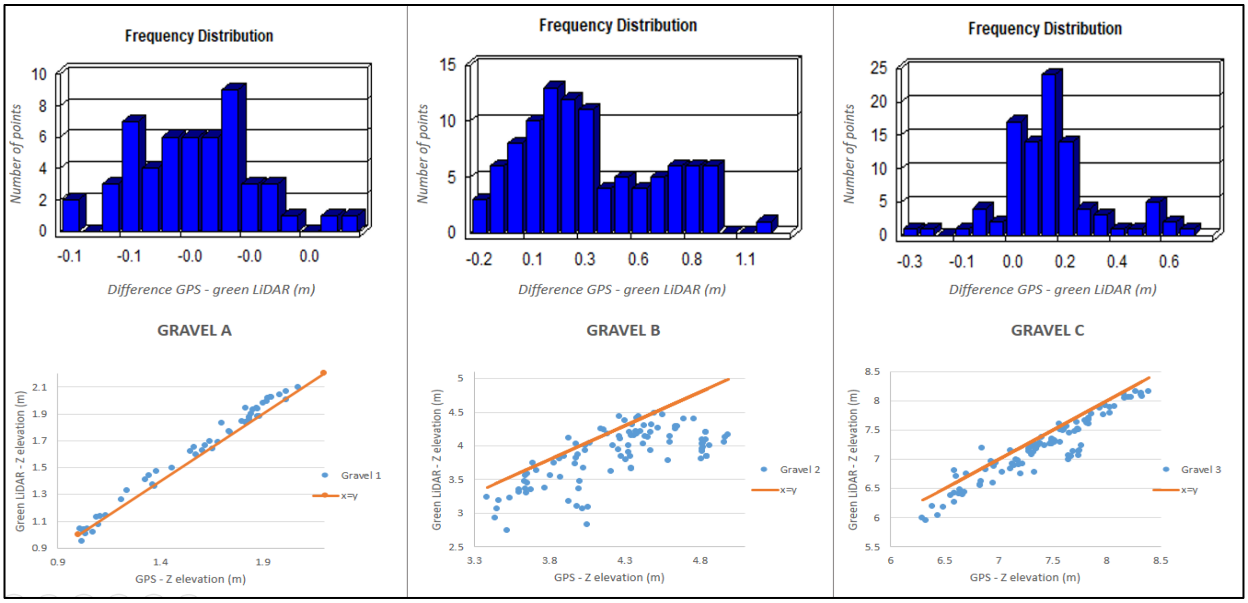

Figure 27: GPS - green LiDAR comparison graphs for the points included in the areas classified as “Gravel”

b) Roads

	Road A	Road B	Road C
Number of points	12	49	43
Mean	0.088	0.106	-0.057
Standard deviation	0.04	0.08	0.13

Table 9: Main statistics of the differences in elevation (GPS - green LiDAR) for the area classified as “Road”

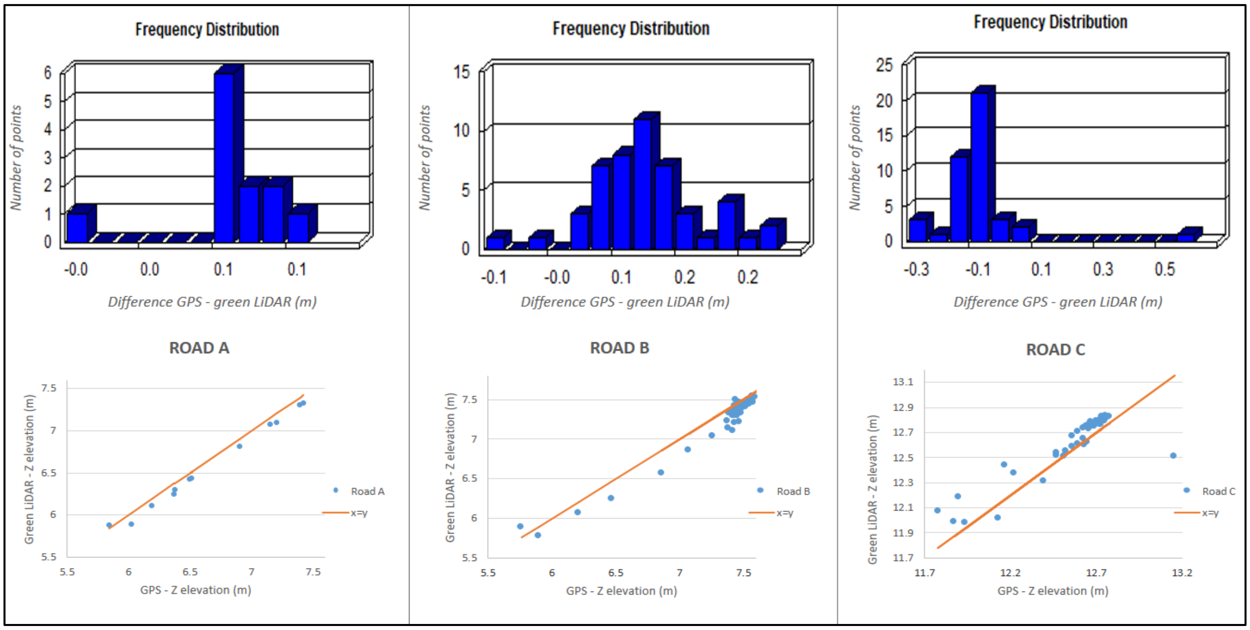

Figure 28: GPS - green LiDAR comparison graphs for the points included in the areas classified as “Roads"

c) Gravel roads

	Gravel road A	Gravel road B	Gravel road C
Number of points	27	54	23
Mean	0.66	0.086	0.847
Standard deviation	0.11	0.108	0.157

Table 10: Main statistics of the differences in elevation (GPS - green LiDAR) for the areas classified as "Gravel roads"

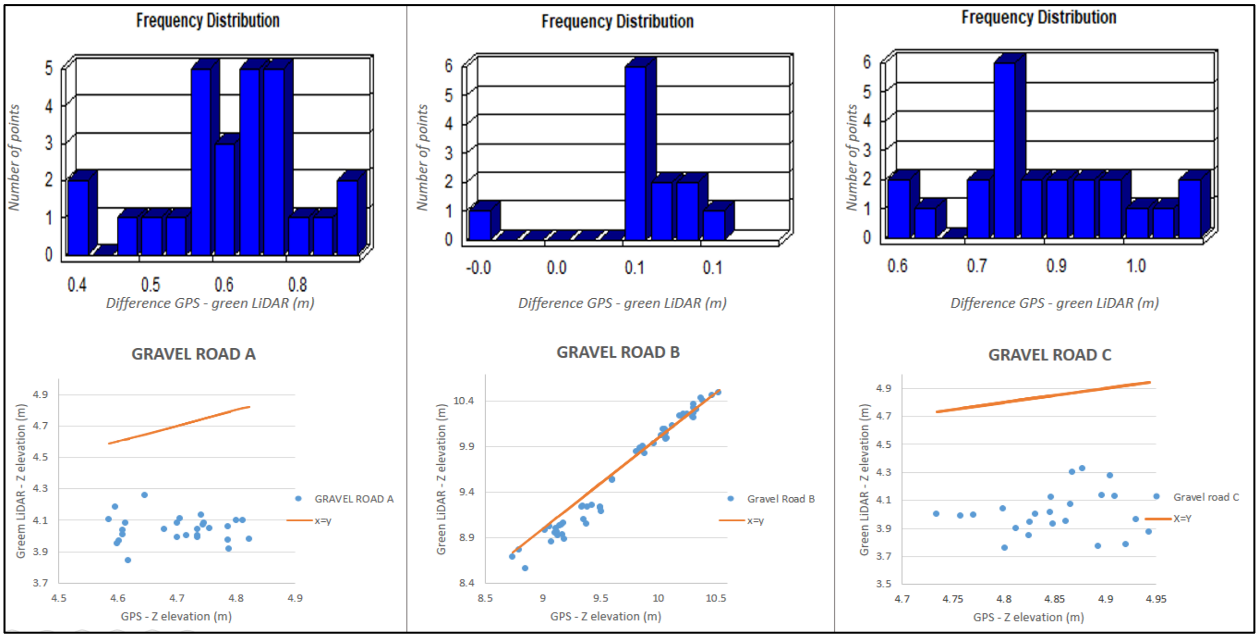

Figure 29: GPS - green LiDAR comparison graphs for the points included in the areas classified as "Gravel Roads"

4.2. Sensitivity analysis

To try to allocate the most significant uncertainty sources in HEC-RAS, two input parameters were analyzed: cellsize and manning number. The degree to which modifications in these parameters affect the results of the simulations is shown below

a) Cellsize

Both the effect of changing the cellsize of the mesh in HEC-RAS and the cellsize of the raster containing the digital terrain in ArcMap were analyzed.

- **Changing the cellsize of the mesh in HEC-RAS**

The mesh of Hec-Ras was created with two different spacing values: 2m x 2m and 3m x 3m. The results and comparison are shown below.

	Number of cells of the mesh	Computational time
2x2	1594271	44h 21'04"
3x3	729672	14h43'04"

Table 11: Number of cells and computational time for two different meshes in HEC-RAS

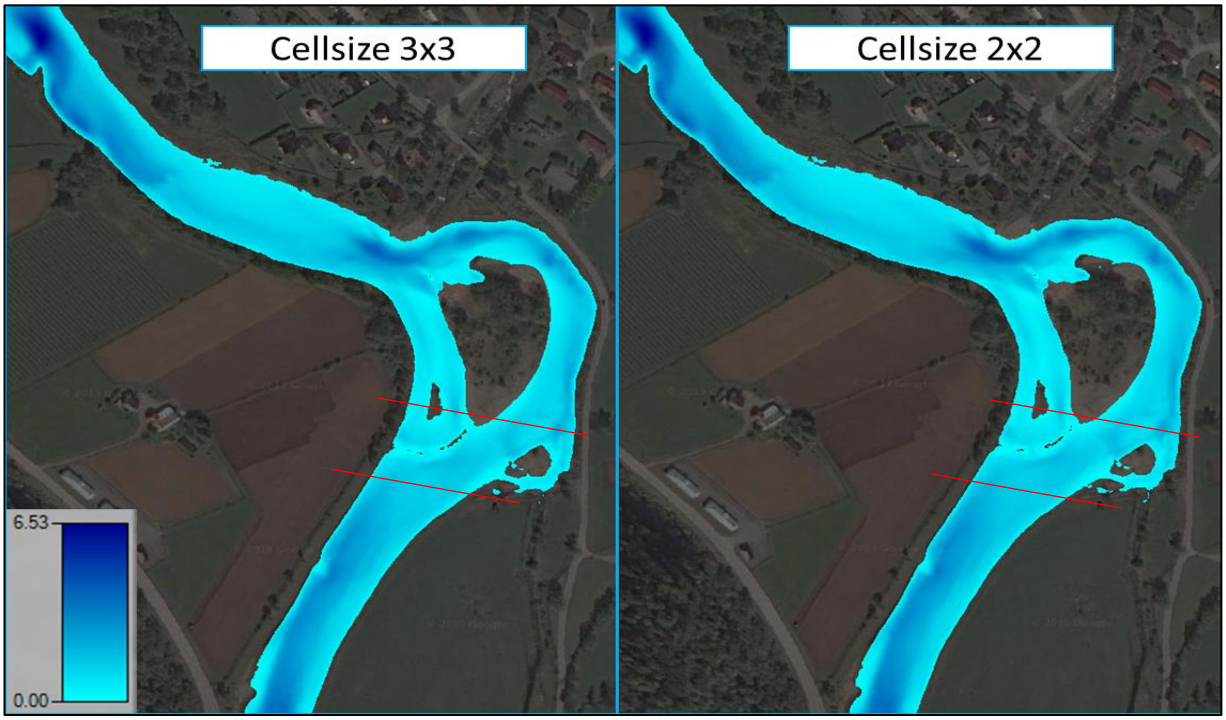

Figure 30: Results of the simulations (water depth) in Ofta for two different cellsizes of the mesh

For both cases, the discharge value chosen was 106 m^3/s. The figure above shows that there was practically no difference in the results. In order to double check this, two profile lines (marked with red lines in Figure 30) were created to check the water surface elevation in both cases. The terrain and WSE profiles in these cross sections is displayed in Figure 31.

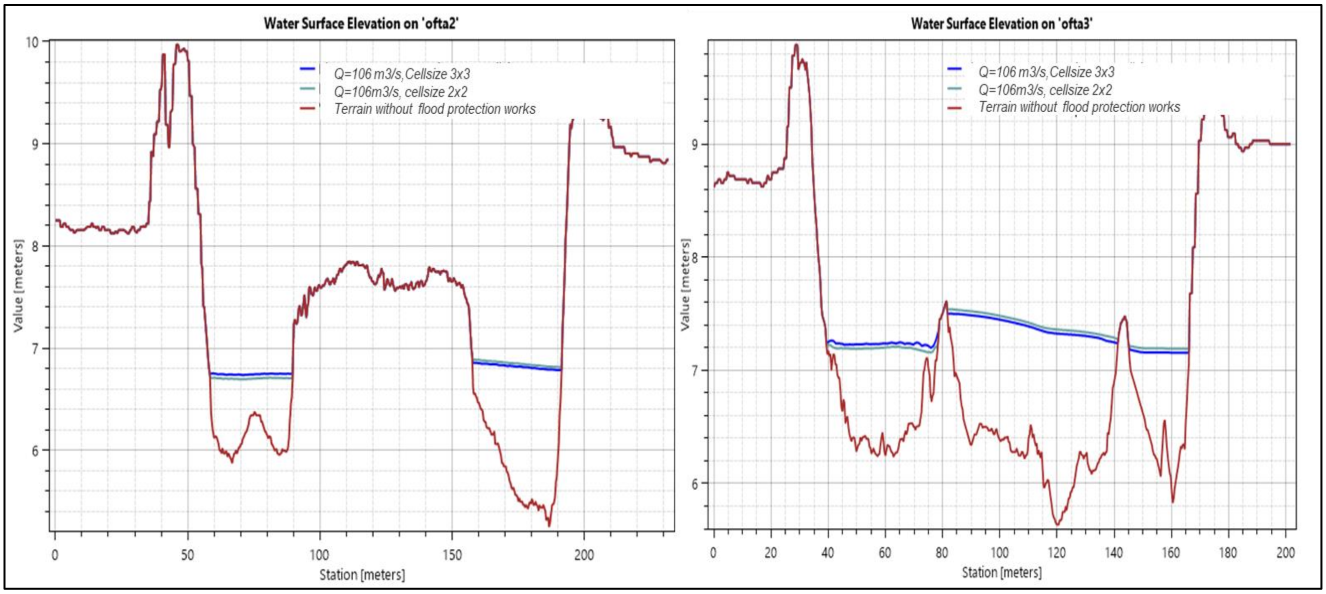

Figure 31: Water surface elevation in the two cross sections drawn in Ofta for two different cellsizes of the mesh

Figure 31 proves that the differences in elevation are only a few centimeters (3-4 cm). However, the computational time was almost four times bigger when a cellsize of 2x2 was used. This proves that the size of the cell has a great influence on the computational time, creating a trade off between time and precision in the results. It was proved that for this case cells of 9m^3 were small enough since more accuracy was not achieved by reducing their size further.

- **Changing the cellsize of the raster containing the terrain in ArcMap**

Two different terrains were created in ArcMap. In the first one, the raster cellsize of the floodplains was 1m; in the second one, it was reduced to 0.5m. The raster cellsize of the river channel was maintained in both cases at 0.35m.

Two different simulations were carried out with a discharge value of 920m^3/s in order to check if significant differences appear in the results considering the sub-grid bathymetry approach of HEC-RAS. The rest of the parameters selected are shown below.

	Cellsize of the mesh	Manning value	Computational time
Raster 1m	3m x 3m	River channel: 0.035 Floodplains: 0.07	32h16'12"
Raster 0.5m	3m x 3m	River channel: 0.035 Floodplains: 0.07	34h29'53"

Table 12: Most important parameters for the raster's cellsize sensitivity analysis

Note that even if the rest of the inputs were maintained with the same values in both cases, a higher resolution of the initial terrain increased the computational time. However, the differences in the results were insignificant, as shown in the figure below.

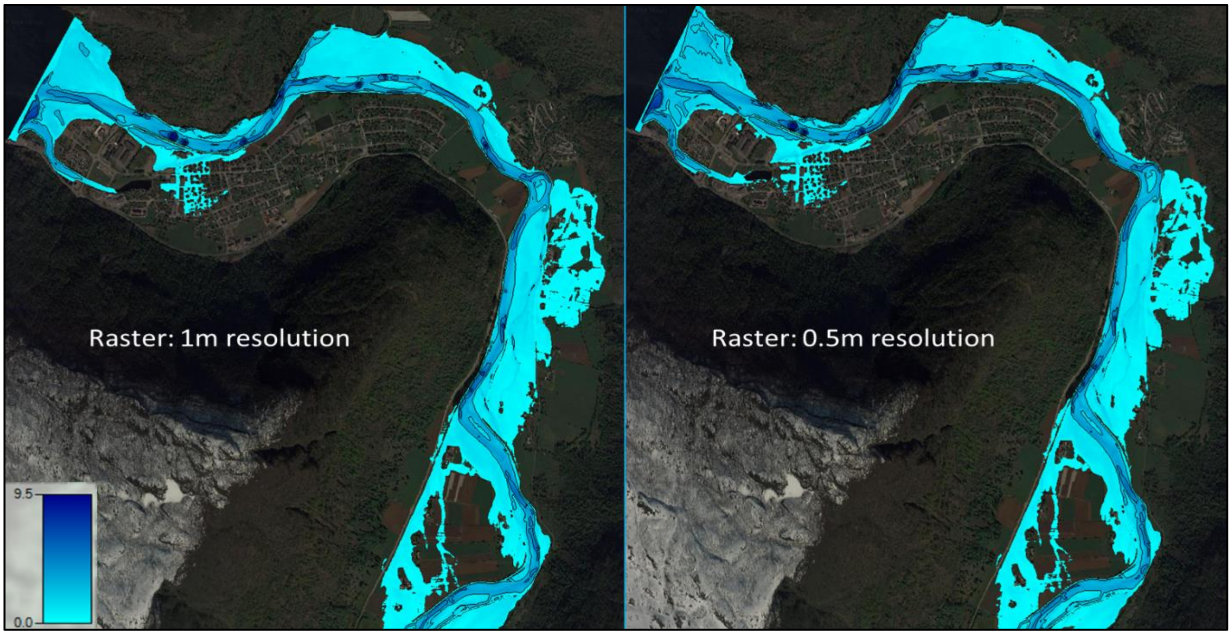

Figure 32: Results of the simulations in HEC-RAS when a terrain with different resolution is imported

The conclusion of this was not that the sub-grid bathymetry does not have any effect in the results (more simulations with bigger raster resolutions should be compared to affirm that), but that for this case a resolution of 1m for the floodplains was enough, since the only appreciable change was the computational time, which increased.

b) Manning number

Before importing the land use file into HEC-RAS and selecting a different manning value for each area according to its coverage, it was necessary to check how important it is to choose a suitable manning number and to what extent it affects the results.

To do so, two simulations with a discharge of 920 m^3/s were run maintaining all the parameters constant except from the manning value, which was changed from 0.03 to 0.05 (for the whole area).

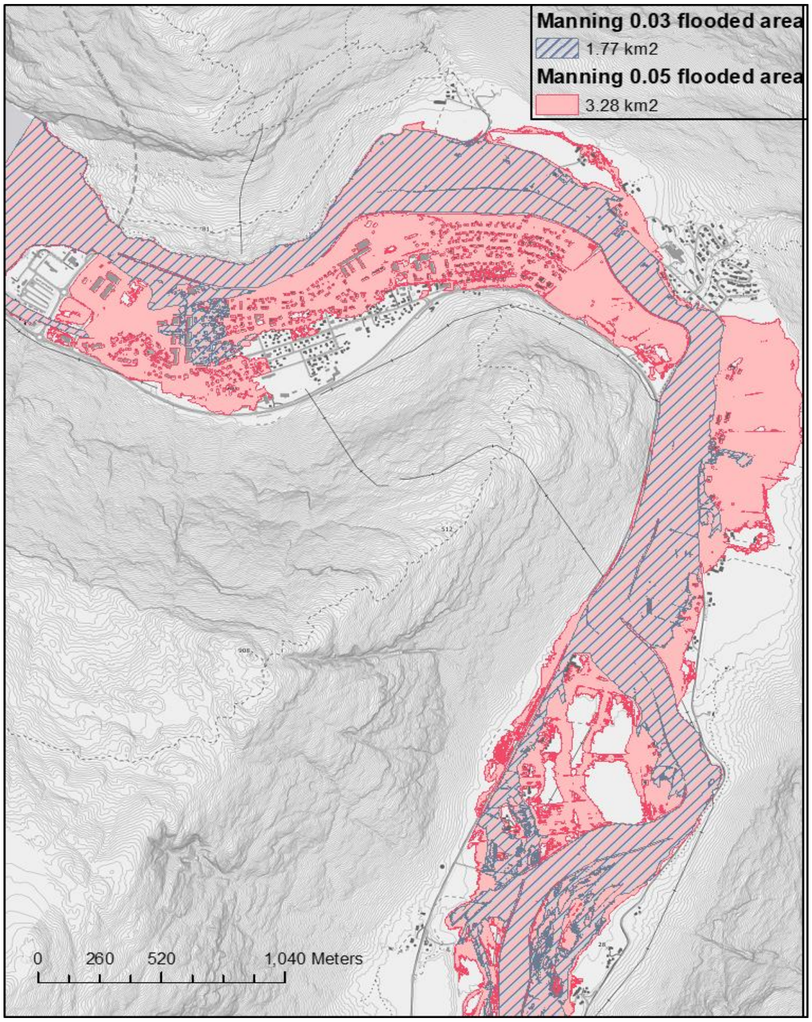

Figure 33: Comparison of the results when different manning numbers are used for the whole area

The results obtained show clearly the great importance of choosing properly the manning value. Because of this, the manning values for the different areas (classified according to their land used were carefully chosen in order to obtain accurate results.

4.3. Calibration of the model

As the results of the sensitivity analysis showed that the parameter with the greatest influence was the manning value, different simulations changing the manning number of the river channel were run. The aim was to find the value that made the results of the simulation as close as possible to the water edge line. According to the literature reviewed, for natural channels like the one under study, the minimum and maximum manning values are 0.03 and 0.04 respectively (see Appendix B). The results obtained for different values within this range are shown in figure 34.

Note that only the manning value of the river channel was calibrated due to the lack of any reference to compare the manning number of the floodplains (there was no information about the water covered area or inundation boundary under a flood event).

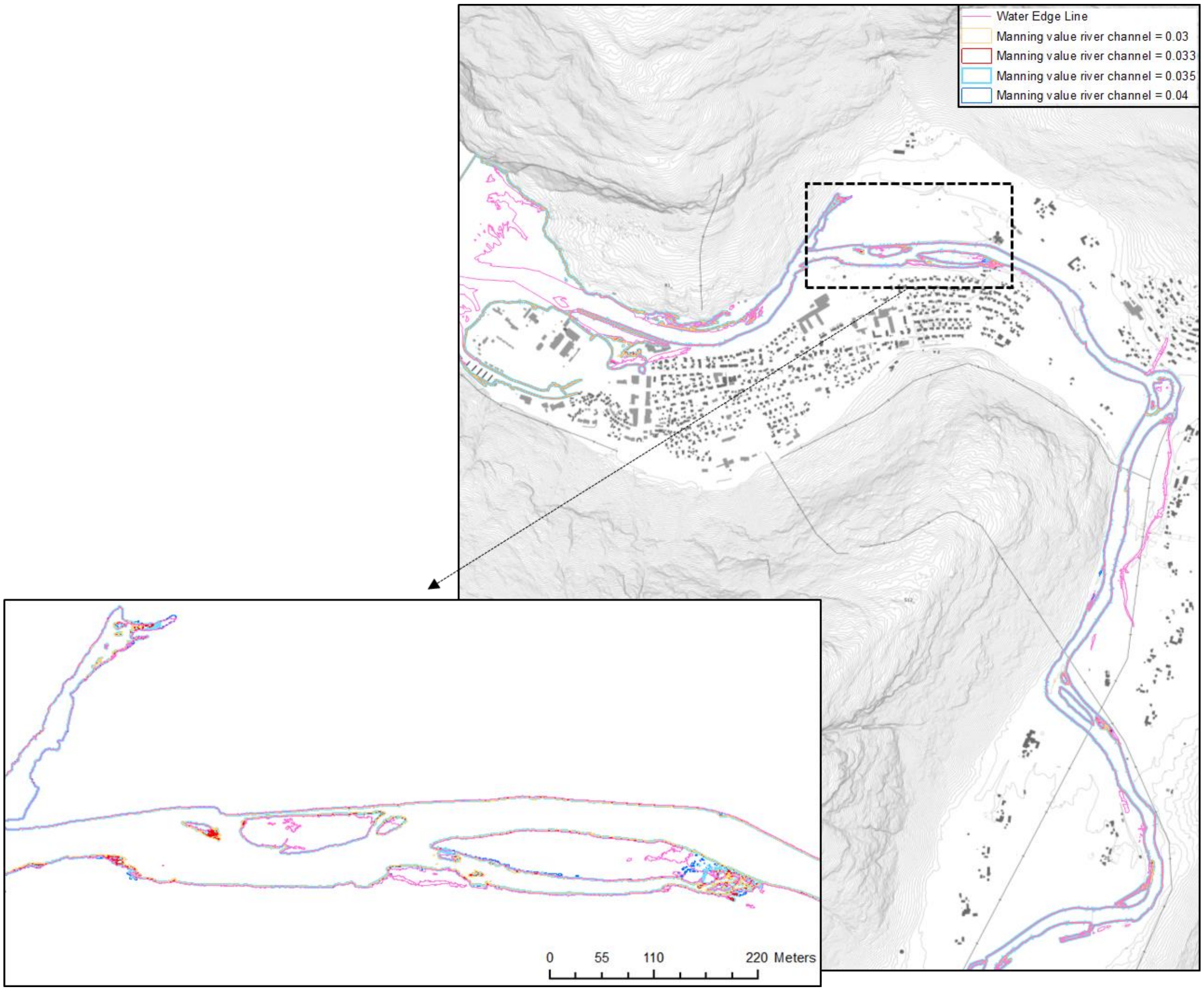

Figure 34: Comparison of the different inundation boundary obtained changing the manning values in the river bed. The water edge line of the day of the green LiDAR flight was used for the comparisons.

The figure above shows that the results were very close to the reality when the manning value for the river channel is within the range 0.03 to 0.04. Even if the differences were almost insignificant, the results obtained using a value of 0.035 were the most accurate ones. Since no other parameter is negatively affected by choosing one or the other value, 0.035 was the manning value selected for the river bed in order to perform the final simulations and obtain the flood maps.

4.4. Final results

This section includes the flood maps obtained with the final terrains (with and without flood protection workd) once all the parameters analyzed were chosen. As a summary, the most significant ones are included in the following table.

Raster resolution	Mesh cellsize	Manning values	Discharge values	Time step simulation
Floodplains: 1m River channel: 0.35m	3x3	River channel: 0.035 Living area: 0.085 Roads: 0.013 Full grown soil: 0.04 Surface cultivated soil: 0.03 Cultivated pastures: 0.04 Forest: 0.11 Open land: 0.1	200-year:920m3/s 200-year+climate: 1288m3/s	4 min + Courant condition

Table 13: Most important input parameters used for the creation of the final floodplain maps

The first map (Figure 35) shows the water covered areas in case of a 200-year flood event (with and without considering the effect of climate change) when no measure against floods is implemented in the area. The second map (Figure 36) shows the same flood event but including a flood protection wall in the terrain. The third map (figure 37) adds the excavation of the river bed and the removal of some of the river islands as marked by NVE. The fourth map (Figure 38) illustrates the situation of a normal spring discharge if the river channel was reshaped (same terrain as for the third map was used).

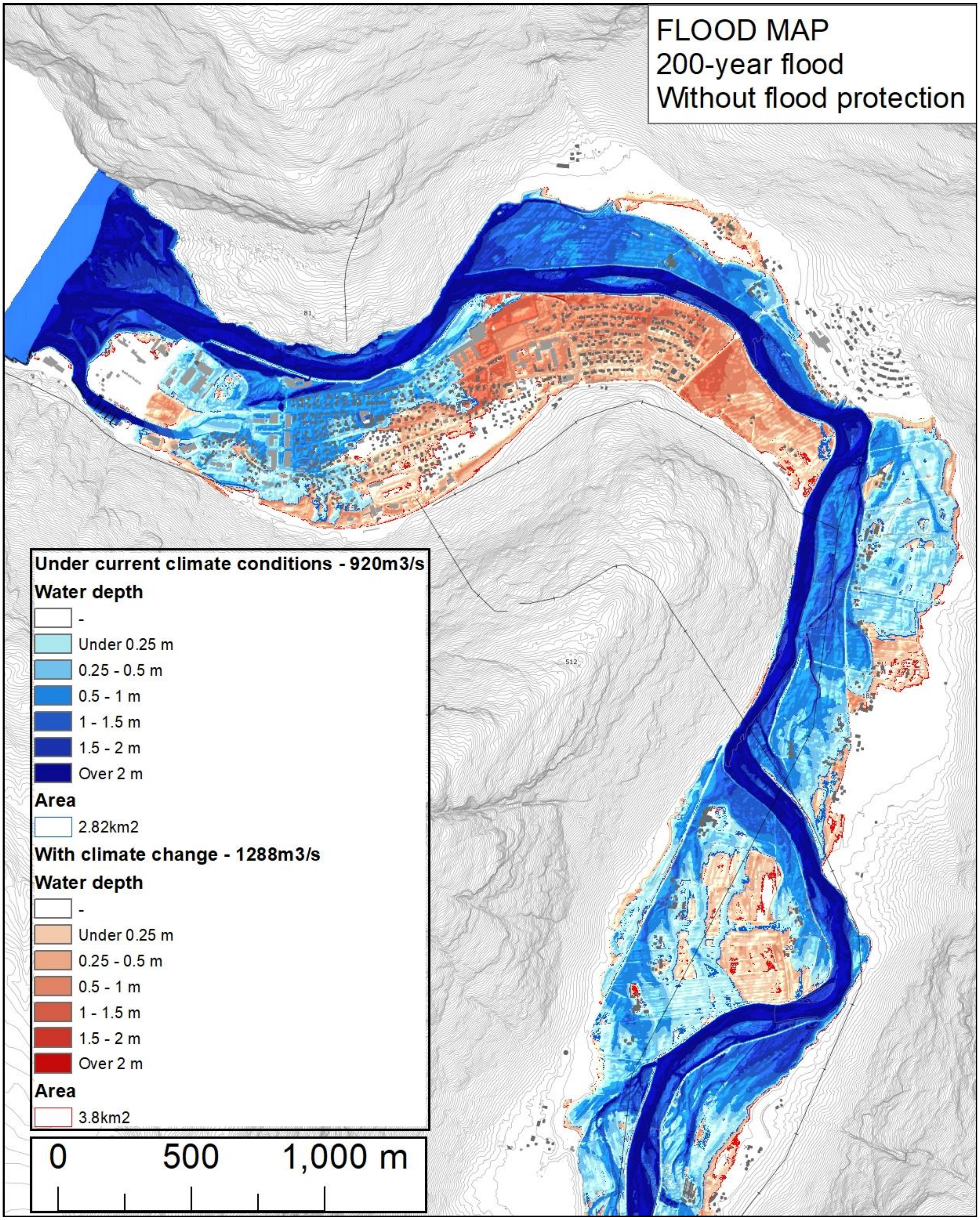

Figure 35: Water covered areas and inundation depth for a 200-year flood event without flood protection

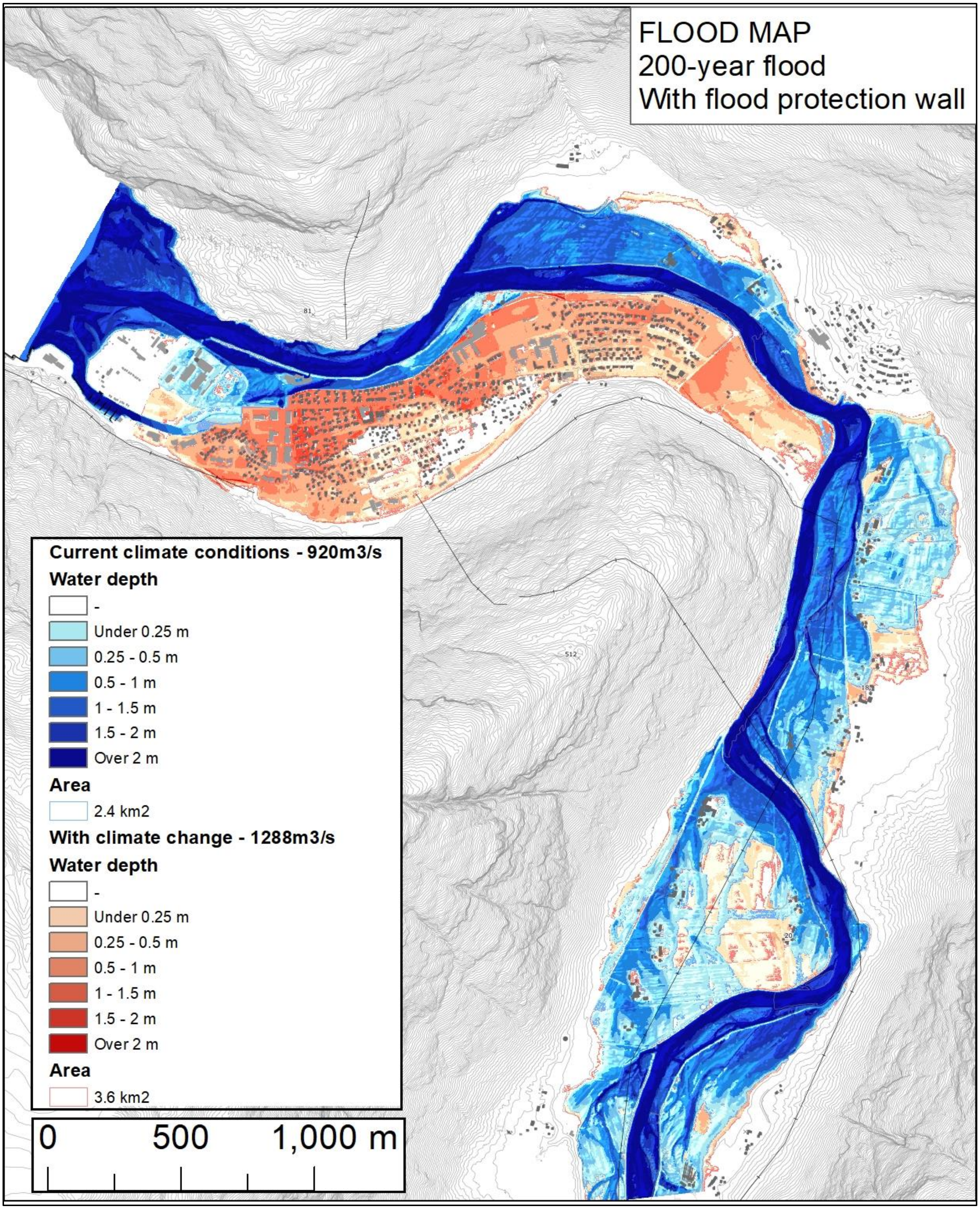

Figure 36: Water covered areas and inundation depth for a 200-year flood event with a flood protection wall included in the terrain

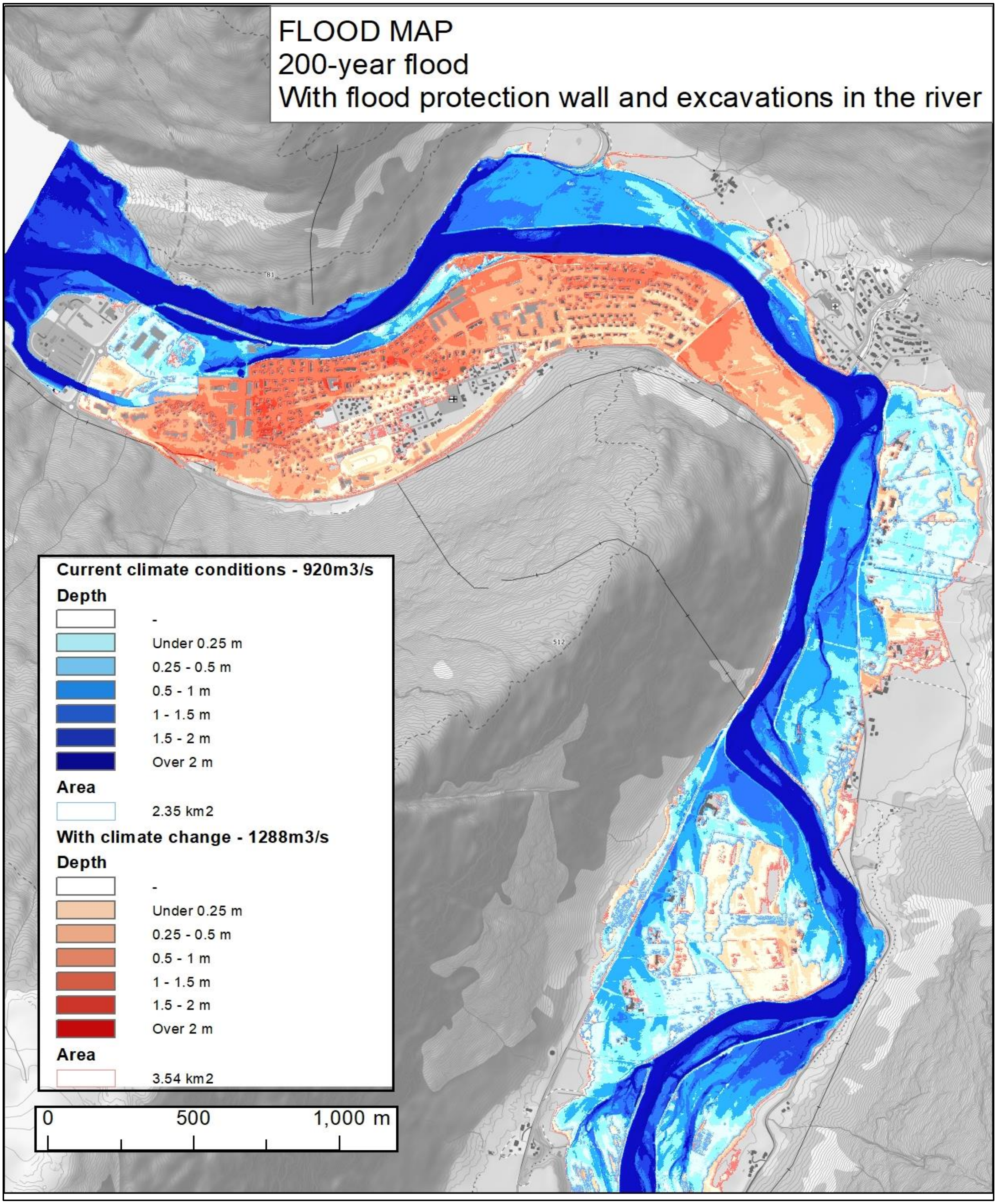

Figure 37: Water covered areas and inundation depth for a 200-year flood event with a flooding protection wall and excavations in the river

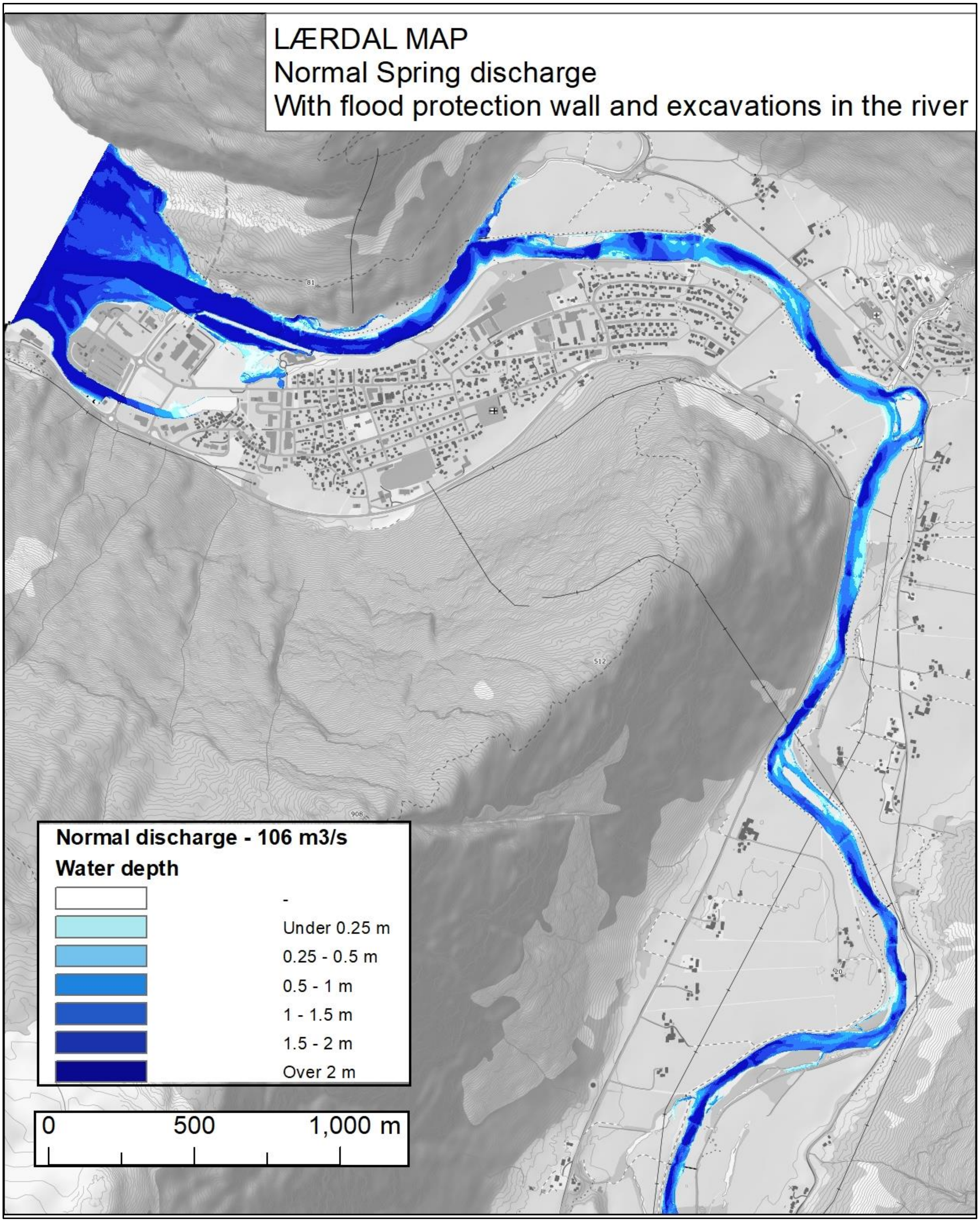

Figure 38: Water covered area and depth for an ordinary spring discharge when some of the islands of the river are removed. The same discharge as for the calibration of the model was used (106m3/s)

5. Discussion

This thesis has evaluated the accuracy of the bathymetric LiDAR data measured in May 2018 in Lærdal. The aim was to validate the green LiDAR data and use it for the creation of a digital terrain of the area (once it was merged with the available topographic LiDAR data for the floodplains). ALB is known to be a powerful method for collecting the elevation data of areas covered by shallow waters. Nevertheless, the coverage and precision of the data must be checked prior to the construction of the hydraulic model. To do so, this study checked the coverage of the green LiDAR and compared it with the red LiDAR data downloaded from Høydedata and with some GPS points taken during a fieldwork in Lærdal in May 2019. The analysis showed that the green LiDAR data covers the whole river bed and its banks with no missing areas. Its point density is very high and its point spacing very small, which allowed the creation of a high resolution raster of the area. In addition, it was proved that the green LiDAR data is accurate enough to be merged with the topographic data even if some type of areas presented a small deviation from the expected values, which is discussed in detail in this section.

After the validation of the input data, the hydraulic model of Lærdal was created in HEC-RAS. Some simulations were run for different discharge conditions in order to calibrate the model and to predict the areas affected by floods for a 200-year event with and without considering the effects of climate change (which account for an additional river discharge of 40%). The initial terrain was modified to include the flood protection works designed by the NVE. The results proved that the floods of the city center could be avoided with an adequate design of a flood wall. Further details are given in this section.

5.1. Validation of the Green LiDAR data

The green LiDAR data was validated by comparing the elevation of some of its points with the elevation of the same points when they are measured using other techniques: red LiDAR (measured in 2014) and GPS (measured in 2019). In view of the results obtained, it was assumed that the green LiDAR provides reliable data. A more detailed discussion is offered in the following subsections.

5.1.1. Comparison red-green LiDAR

In the case of the red – green LiDAR comparison, the mean of the differences in elevation ranged from a minimum of 1cm to a maximum of 25cm.

The areas classified as gravel were the ones considered susceptible to greater differences, so it was decided to take GPS points in the same locations to double check the green LiDAR data with more recent information. To help the follow-up of the discussion, the location of the gravel areas is presented again in Figure 39.

Figure 39: Location of the areas classified as "gravel"

Surprisingly, “gravel area 1” was the area with the highest differences in the red - green LiDAR comparison (25cm) and the one with the lowest difference values when compared with the GPS points (3.4cm). The areas “gravel 2” and “gravel 3” showed just the opposite: small differences in the red – green LiDAR comparison (9 and 3 cm respectively) but greater variations when contrasted against the GPS points (39 and 20 cm). Probably, the reason of these imprecisions in the results is that these areas are covered by stones and other substrate with great potential to be moved and deposited in a different location when the discharge of the river is high.

With regards to the rest of the areas, the results showed differences within a range that was considered acceptable, especially in the “open land” areas (with mean differences from 2 to 4 cm). In the case of the areas classified as “grass”, the small variations from both sources of data reflect the stand of the grass depending on the month when the measures are taken.

In general, the differences in elevation obtained with this comparison were quite small, which was considered satisfactory.

5.1.2. Comparison GPS points-green LiDAR

In the case of GPS – green LiDAR comparison, the results were a bit more difficult to read because the values obtained for the mean of the differences in each area ranged from a minimum value of 3.4cm to a maximum of 84.7cm. Even in areas classified within the same group, the differences varied considerably depending on where this area is on the map. However, after a deeper analysis of the results, it was found out that the highest differences appear in all the cases in the same location, which is marked in red in Figure 40.

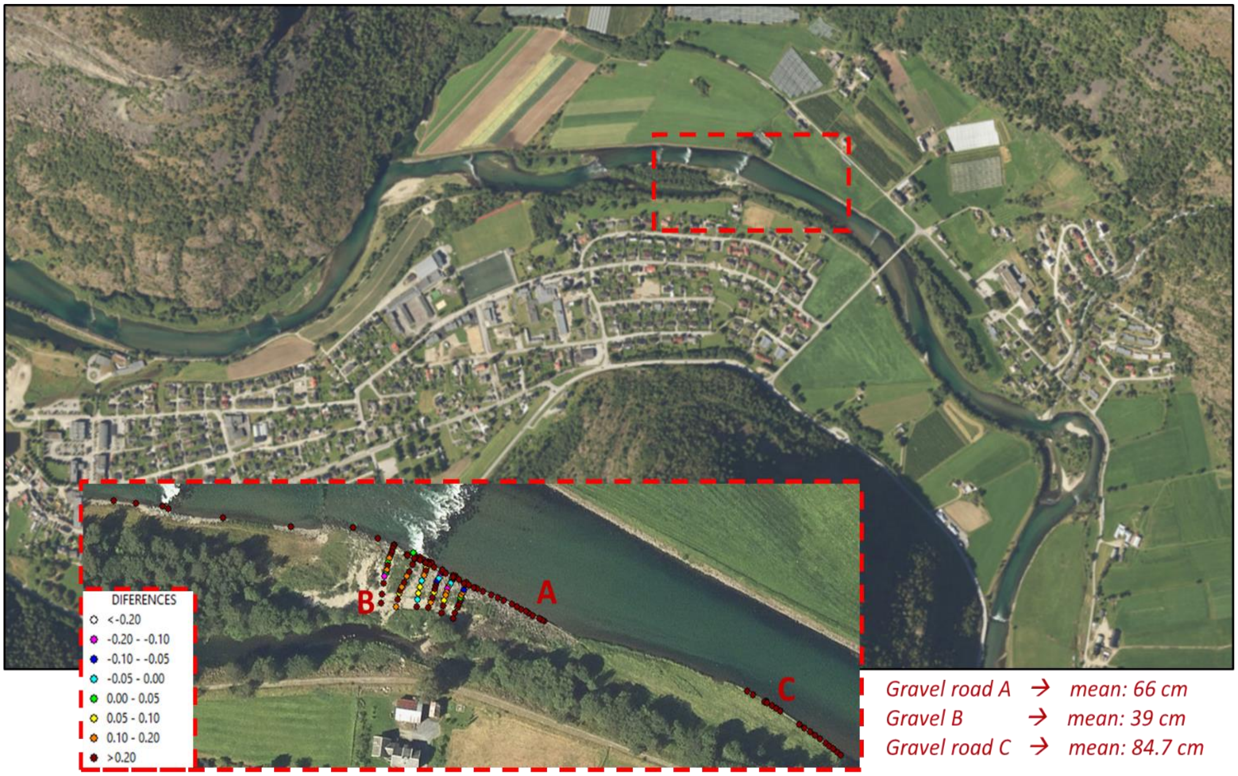

Figure 40: Location of the areas where the highest differences in elevation (GPS – green LiDAR) appeared. A and C are classified as "Gravel Roads" and B as "Gravel area"

The fact that all the big differences appeared in the same zone gave rise to the idea that maybe there is a local error in this area. More points should be compared in this location to confirm it. In any event, these errors would not affect considerably the overall results of the simulations as they were located in a small area.

In the rest of the areas compared, the mean values of the differences ranged between 3 and 10 cm. Considering that the precision of the measure systems used is up to 10 cm (Meneses, Baier, Geist, & Schneider, 2017) and that there is a small uncertainty in the conversion of the GPS points from NN1954 to NN2000, it is possible to conclude that this is an acceptable range.

In the light of the results, it was assumed that the bathymetric LiDAR data supplied is of high accuracy and that it gives similar elevation values to those obtained with other type of topographic techniques. This allowed to merge both sources of elevation data (red and green LiDAR) as convenient in order to create the final terrain that was used to perform the hydraulic simulations.

5.2. Final results - flood maps

The results of this study support that the application of LiDAR data to create a digital terrain model and its later use in HEC-RAS is a reliable approach to obtain flood maps under different conditions and to predict the effect of including flood protection works in the area.

It was proved that the results of the 2D model could change drastically by modifying different parameters, so it is very important to analyze which ones have the most significant influence. In this case, the manning value proved to be a determining factor in the magnitude of the floods, so it was chosen carefully. Another important parameter is the culmination value of the river discharge selected for the floods and included in HEC-RAS. In this case, this parameter was obtained from previous studies carried out by the NVE. However, as stated in the "Flomberegning for Lærdalvassdraget - 2000" report, the uncertainty of the value is high.

According to the maps obtained, the center of Lærdal would experience extreme floods for a 200-year flow condition. This would lead to disastrous consequences, both in the river (morphological changes, redistribution of the sediments…) and for the village itself (infrastructural damage, loss of livestock, destruction of crops…). However, this study proved that this situation could be avoided with proper flood protection works.

In the first alternative, the river shape was not modified in any of its parts, and the flood protection works consist in rising the terrain level in certain areas (marked by the NVE). The second alternative added morphological changes in the river bed itself. These changes included the removal of some of the river islands and some excavations in the terrain to make the river wider. The results showed that, without considering the climate change factor, it is possible to prevent the city from being covered by water thanks to properly design a wall around the administrative center of the village (position of the wall is shown in Appendix 1). In addition, it was proved that the necessary wall height is only one meter in most of its extension (accurate geometry shown in Appendix E). Nevertheless, the results showed that the center of the village would be covered by water when the effects of climate change on hydrology are considered.

The results obtained when the terrain was excavated and the river bed was widened in some of its parts were almost the same as when just the wall was included: the floods would be avoided when the climate change factor is not included but the village would be fully covered by water when climate change is considered. However, the morphological changes in the river showed to have an appreciable effect in cases of low discharge. This should be studied in depth, as it would affect negatively not only to the visual impact of the river but also to the species that inhabit it. Considering that the river of Lærdal is a national salmon river, it is essential to ensure that any of the measures taken is harmful to its life cycle.

6. Conclusions

In this study, flood maps of Lærdal have been created to analyze if the execution of flood protection works in the area would prevent the center of the village from being covered with water under a 200-year flood event. The results proved that the proper design of a wall[7] would be enough to achieve this (when the effect of climate change is neglected). According to these results, the necessary height of the wall would be only one meter in most of its length. Nevertheless, a wall of that height would not prevent floods (according to the the simulations) when an extra discharge due to climate change is included.

In addition to this, this project proved the power of hydraulic modeling when an accurate model is created, which is only possible when proper input data are available. To ensure the reliability of the data, it must be carefully analyzed prior to the development of the model. In this case, this was carried out by comparing elevation measurements surveyed using different techniques (red LiDAR, green LiDAR, GPS). As a result it was proved that the level of detail of the data provided by the ALB was high. Results like these are very encouraging for the continuous development of LiDAR systems, which is very benefitial due to their wide application in hydraulics and river morphology development, among others.

6.1. Recommendations for further work

Given that the extension and time for this project were limited, a list of suggested future work is presented below:

- Check that the calculations carried out by the NVE for the discharge values under different recurrence intervals are up to date, as they were calculated in 2000. Probably there is a more accurate approach to do the same nowadays.

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[7] In the 3D model, a wall was created to simulate the rise of the ground level.

- Try to collect more data of any of the flood events that took place in Lærdal, or try to record more information if this situation happens again before any of the measures against floods start to be executed. This could help to improve the hydraulic model as it could be calibrated using the data from a real flood event as reference.

- Further investigate some other computational options of HEC-RAS that were out of the scope of this thesis. Specifically, create inundation maps using the Full Momentum equations instead of the Shallow Water ones.

- Design the wall more accurately to identify exactly its minimum height in each of its sections.

Last but not least, it is important to keep the flood maps constantly updated so that they forecast the different events under study as accurate as possible.

References

ACP-EU, N. D. R. R. P. (2019). Digital Elevation Models. Retrieved from http://www.charim.net/datamanagement/32

ArcGIS-PRO. (2019). Generate elevation data using the DEMs wizard. Retrieved from https://pro.arcgis.com/en/pro-app/help/data/imagery/generate-elevation-data-using-the-dems-wizard.htm

Brunner, G. W. (2016). *HEC-RAS, River Analysis System Hydraulic Reference Manual*: US Army Corps of Engineers USACE.

Doneus, M., Doneus, N., Briese, C., Pregesbauer, M., Mandlburger, G., & Verhoeven, G. (2013). Airborne laser bathymetry - detecting and recording submerged archaeological sites from the air. *Journal of Archaeological Science*, *40*, 2136-2151.

Edvardsen, S.-M., & Svegården, J. (2002). *Flaumsonekart Delprosjekt Lærdal. Oslo*

ESRI. (2019). ArcMap Desktop. Retrieved from http://desktop.arcgis.com/en/arcmap/10.3/main/map/what-is-arcmap-.htm

Directive 2007/60/EC of the European parliament and of the council on the assessment and management of flood risks, (2007).

Hirt, C. (2014). Digital Terrain Models. In E. Grafarend (Ed.), *Encyclopedia of Geodesy* (pp. 1-6). Cham: Springer International Publishing.

Holmqvist, E. (2000). *Flomberegning for Lærdalselva (73.Z)*. Oslo

Høydedata. (2019). Nasjonal Digital Høydemodell - Lærdal. Retrieved from https://hoydedata.no/LaserInnsyn/

Kartverk. (2014). *SOSI Del 3 Produktspesifikasjon for FKB - AR5*.

Mandlburger, G., Hauer, C., Wieser, M., & Pfeifer, N. (2015). Topo-bathymetric LiDAR for Monitoring River Morphodynamics and Instream Habitats - A Case Study at the Pielach River. *Remote sensing*, 6160-6195.

Marco, J. B. (1992). *Flood risk mapping. In: Rossi G., Harmancioğlu N., Yevjevich V. (eds) Coping with Floods* (Vol. 257): Springer, Dordrecht.

Mason, D. C., Horritt, M. S., Hunter, N. M., & Bates, P. D. (2007). Use of fused airborne scanning laser altimetry and digital map data for urban flood modelling. *Hydrological processes, 21*(11), 12. doi:10.1002/hyp.6343

Meneses, N. C., Baier, S., Geist, J., & Schneider, T. (2017). Evaluation of Green-LiDAR Data for Mapping Extent, Density and Height of Aquatic Reed Beds at Lake Chiemsee, Bavaria—Germany. *Remote sensing, 9*(12), 17.

OAS, O. o. A. S. (1993). Floodplain definition and flood hazard assessment. Retrieved from https://www.oas.org/dsd/publications/Unit/oea66e/ch08.htm

Statistics-Norway. (2019, 01/01/2019). Lærdal Befolkning. Retrieved from https://www.ssb.no/kommunefakta/laerdal

USACE, U. A. C. o. E. (2019). HEC-RAS v5.0.7. Retrieved from https://www.hec.usace.army.mil/software/hec-ras/

Wagner, W., Ullrich, A., Ducic, V., Melzer, T., & Studnicka, N. (2006). Gaussian decomposition and calibration of a novel small-footprintfull-waveform digitising airborne laser scanner. *ISPRS Journal of Photogrammetry and Remote Sensing, 60*(2), 100-112.

Appendices

APPENDIX A. FLOOD PROTECTION PLANS FOR LÆRDAL DEVELOPED BY THE NVE

APPENDIX B. SPECIFICATIONS OF EACH TYPE OF LAND USE AND MANNING VALUES

APPENDIX C. CATCHMENT DATA AND SCALING OF THE CALIBRATION DISCHARGE

APPENDIX D. DETAILED PROCEDURE OF SOME OF THE TASKS CARRIED OUT IN ARCMAP

APPENDIX E. DETAILS OF THE FLOOD PROTECTION WALL

APPENDIX F. CLASSIFICATION OF THE DIFFERENCES IN ELEVATION IN ARCMAP

APPENDIX G. PROFILE LINES OF THE RESULTS OF THE SIMULATIONS

APPENDIX H. FIELDWORK IN LÆRDAL (06-07 MAY 2019)

APPENDIX A. FLOOD PROTECTION PLANS FOR LÆRDAL DEVELOPED BY NVE

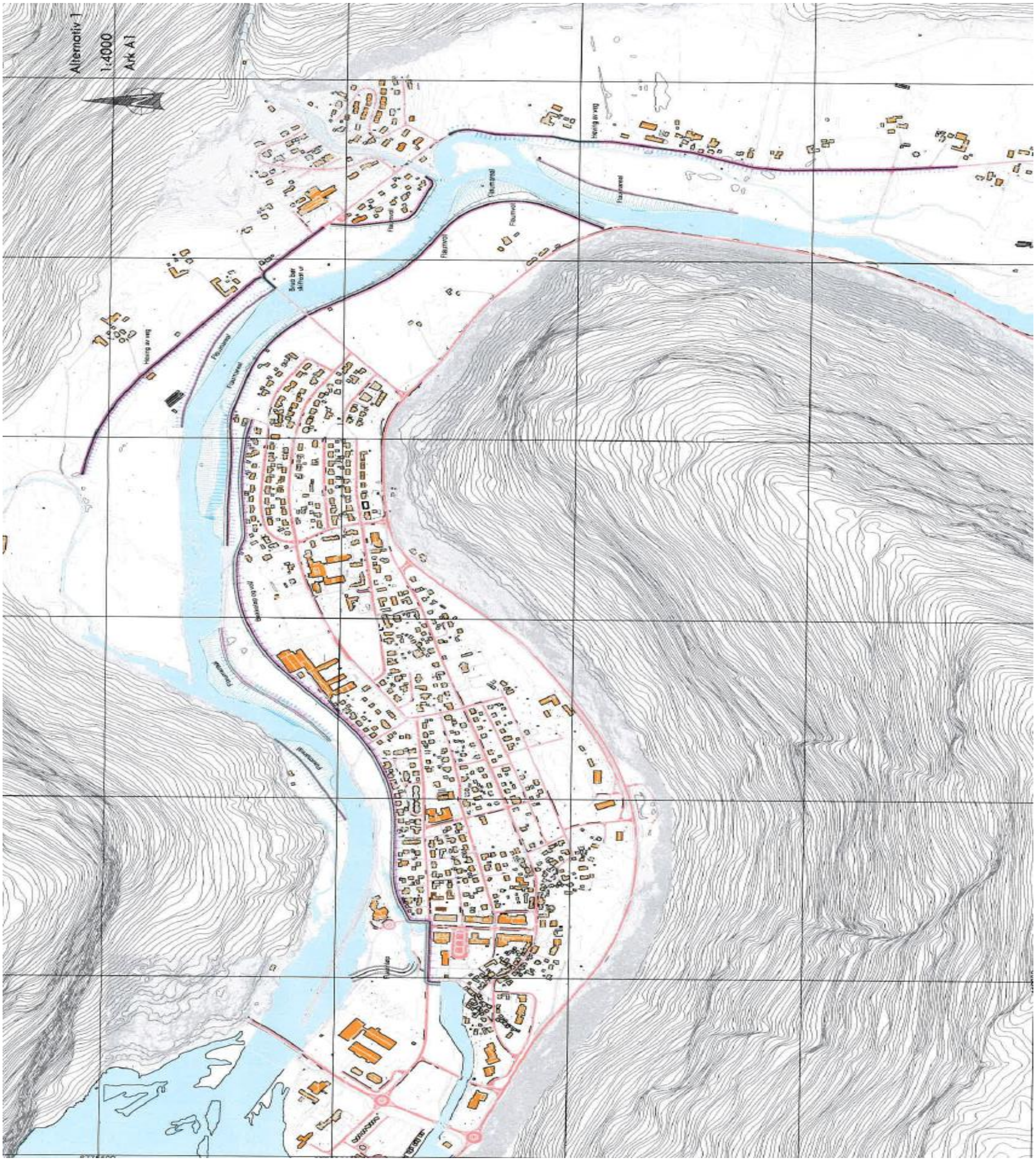
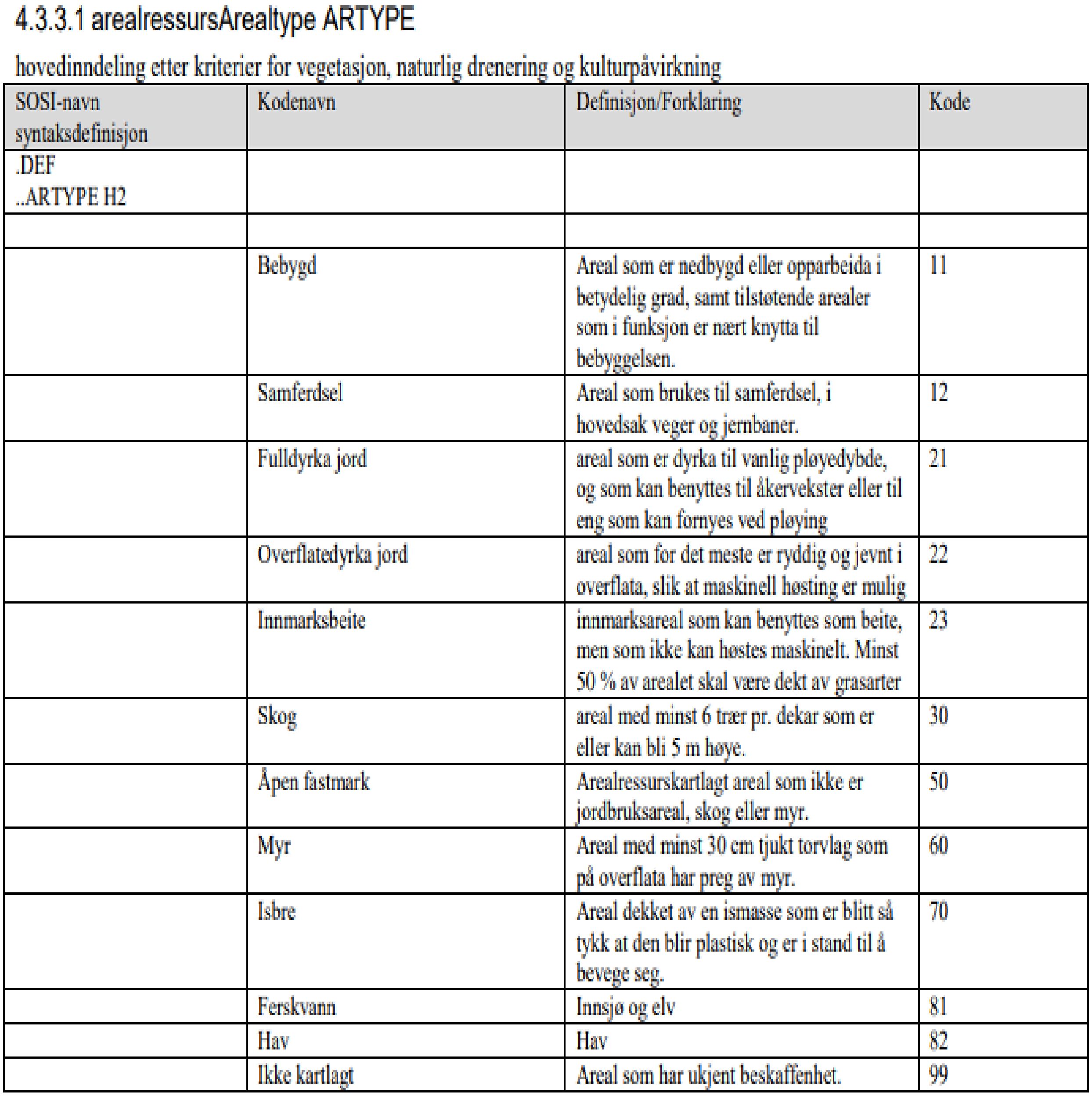


Figure A.41: Alternative 1 of the flood protection plans for Lærdal developed by NVE

Figure A.2: Alternative 2 of the flood protection plans for Lærdal developed by NVE

APPENDIX B. SPECIFICATIONS OF EACH TYPE OF LAND USE AND MANNING VALUES

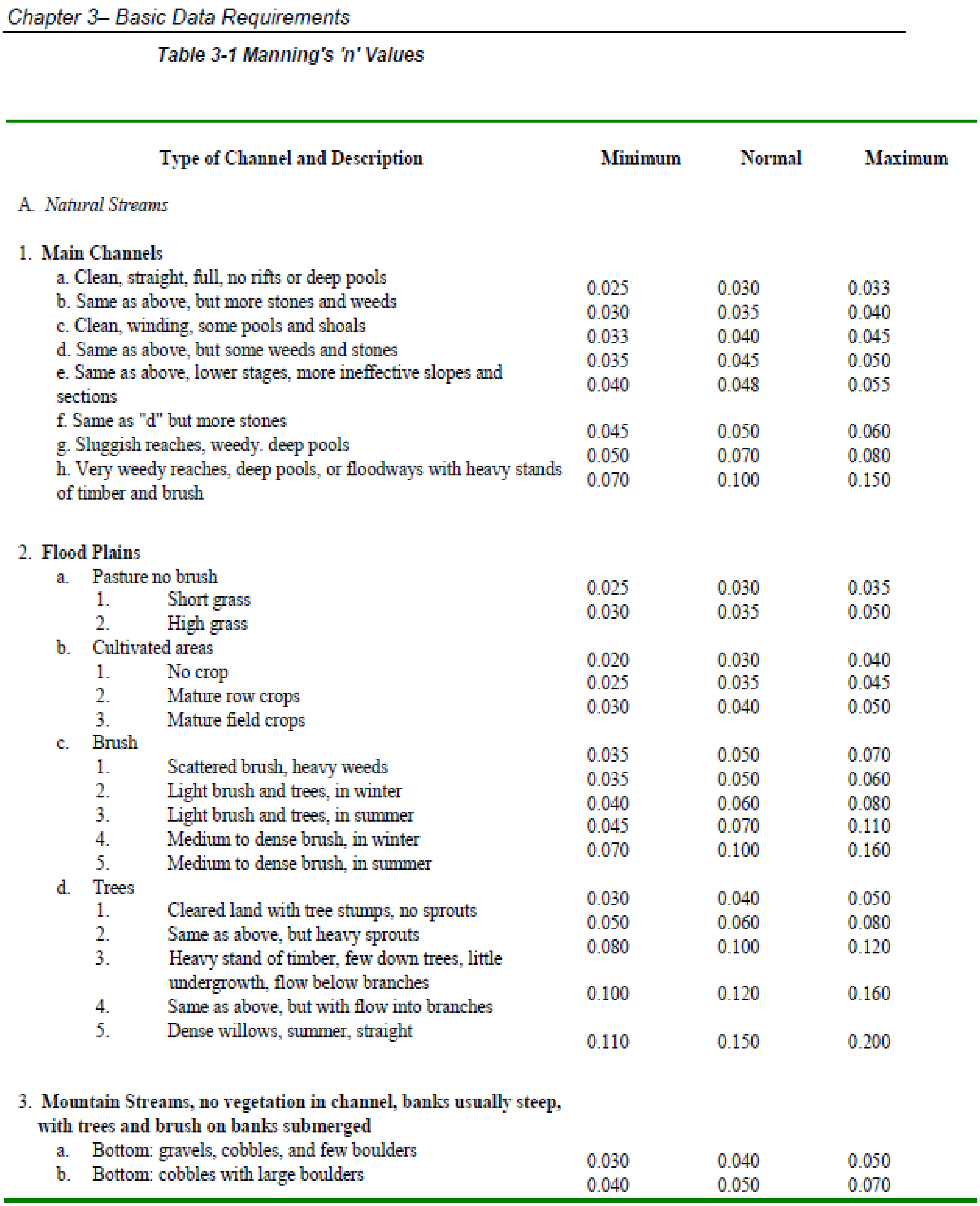


4.3.3.1 arealressursArealtype ARTYPE

hovedinndeling etter kriterier for vegetasjon, naturlig drenering og kulturpåvirkning

SOSI-navn syntaksdefinisjon	Kodenavn	Definisjon/Forklaring	Kode
.DEF ..ARTYPE H2			
	Bebygd	Areal som er nedbygd eller opparbeida i betydelig grad, samt tilstøtende arealer som i funksjon er nært knytta til bebyggelsen.	11
	Samferdsel	Areal som brukes til samferdsel, i hovedsak veger og jernbaner.	12
	Fulldyrka jord	areal som er dyrka til vanlig pløyedybde, og som kan benyttes til åkervekster eller til eng som kan fornyes ved pløying	21
	Overflatedyrka jord	areal som for det meste er ryddig og jevnt i overflata, slik at maskinell høsting er mulig	22
	Innmarksbeite	innmarksareal som kan benyttes som beite, men som ikke kan høstes maskinelt. Minst 50 % av arealet skal være dekt av grasarter	23
	Skog	areal med minst 6 trær pr. dekar som er eller kan bli 5 m høye.	30
	Åpen fastmark	Arealressurskartlagt areal som ikke er jordbruksareal, skog eller myr.	50
	Myr	Areal med minst 30 cm tjukt torvlag som på overflata har preg av myr.	60
	Isbre	Areal dekket av en ismasse som er blitt så tykk at den blir plastisk og er i stand til å bevege seg.	70
	Ferskvann	Innsjø og elv	81
	Hav	Hav	82
	Ikke kartlagt	Areal som har ukjent beskaffenhet.	99

Table B.1: Definition of each land use and classification code

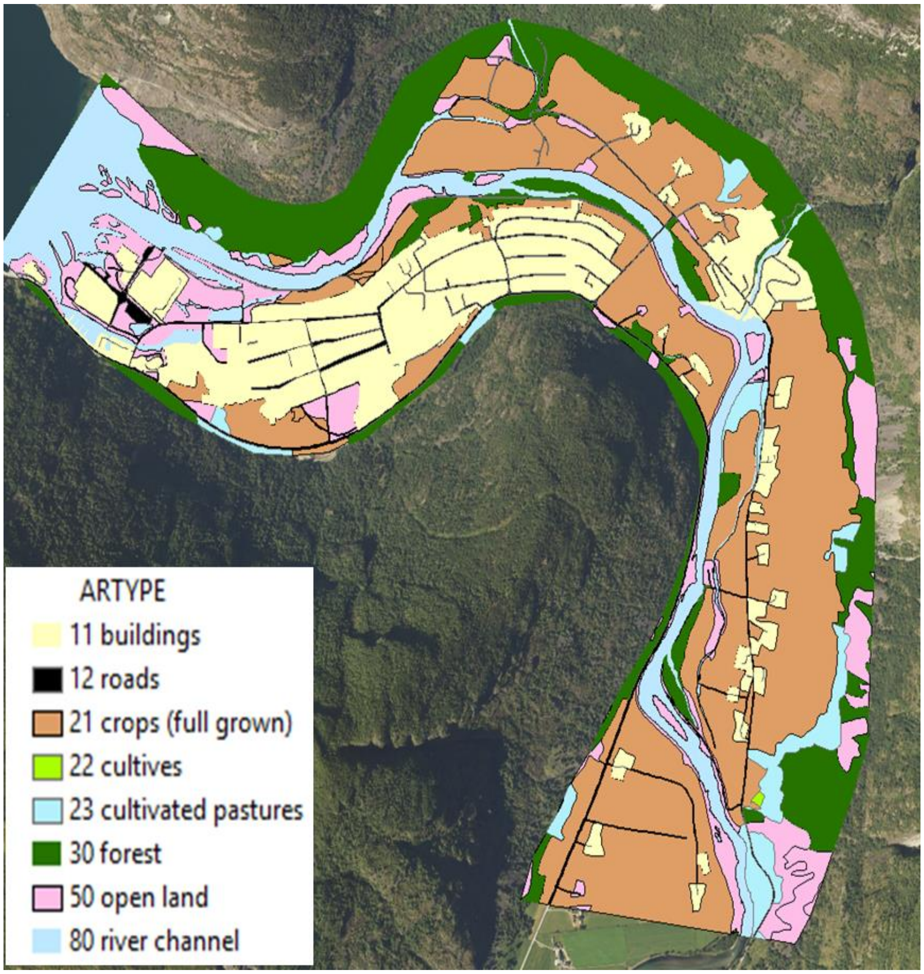


Chapter 3– Basic Data Requirements

Table 3-1 Manning's 'n' Values

Type of Channel and Description	Minimum	Normal	Maximum
A. *Natural Streams*			
1. **Main Channels**			
a. Clean, straight, full, no rifts or deep pools	0.025	0.030	0.033
b. Same as above, but more stones and weeds	0.030	0.035	0.040
c. Clean, winding, some pools and shoals	0.033	0.040	0.045
d. Same as above, but some weeds and stones	0.035	0.045	0.050
e. Same as above, lower stages, more ineffective slopes and sections	0.040	0.048	0.055
f. Same as "d" but more stones	0.045	0.050	0.060
g. Sluggish reaches, weedy. deep pools	0.050	0.070	0.080
h. Very weedy reaches, deep pools, or floodways with heavy stands of timber and brush	0.070	0.100	0.150
2. **Flood Plains**			
a. Pasture no brush			
1. Short grass	0.025	0.030	0.035
2. High grass	0.030	0.035	0.050
b. Cultivated areas			
1. No crop	0.020	0.030	0.040
2. Mature row crops	0.025	0.035	0.045
3. Mature field crops	0.030	0.040	0.050
c. Brush			
1. Scattered brush, heavy weeds	0.035	0.050	0.070
2. Light brush and trees, in winter	0.035	0.050	0.060
3. Light brush and trees, in summer	0.040	0.060	0.080
4. Medium to dense brush, in winter	0.045	0.070	0.110
5. Medium to dense brush, in summer	0.070	0.100	0.160
d. Trees			
1. Cleared land with tree stumps, no sprouts	0.030	0.040	0.050
2. Same as above, but heavy sprouts	0.050	0.060	0.080
3. Heavy stand of timber, few down trees, little undergrowth, flow below branches	0.080	0.100	0.120
4. Same as above, but with flow into branches	0.100	0.120	0.160
5. Dense willows, summer, straight	0.110	0.150	0.200
3. **Mountain Streams, no vegetation in channel, banks usually steep, with trees and brush on banks submerged**			
a. Bottom: gravels, cobbles, and few boulders	0.030	0.040	0.050
b. Bottom: cobbles with large boulders	0.040	0.050	0.070

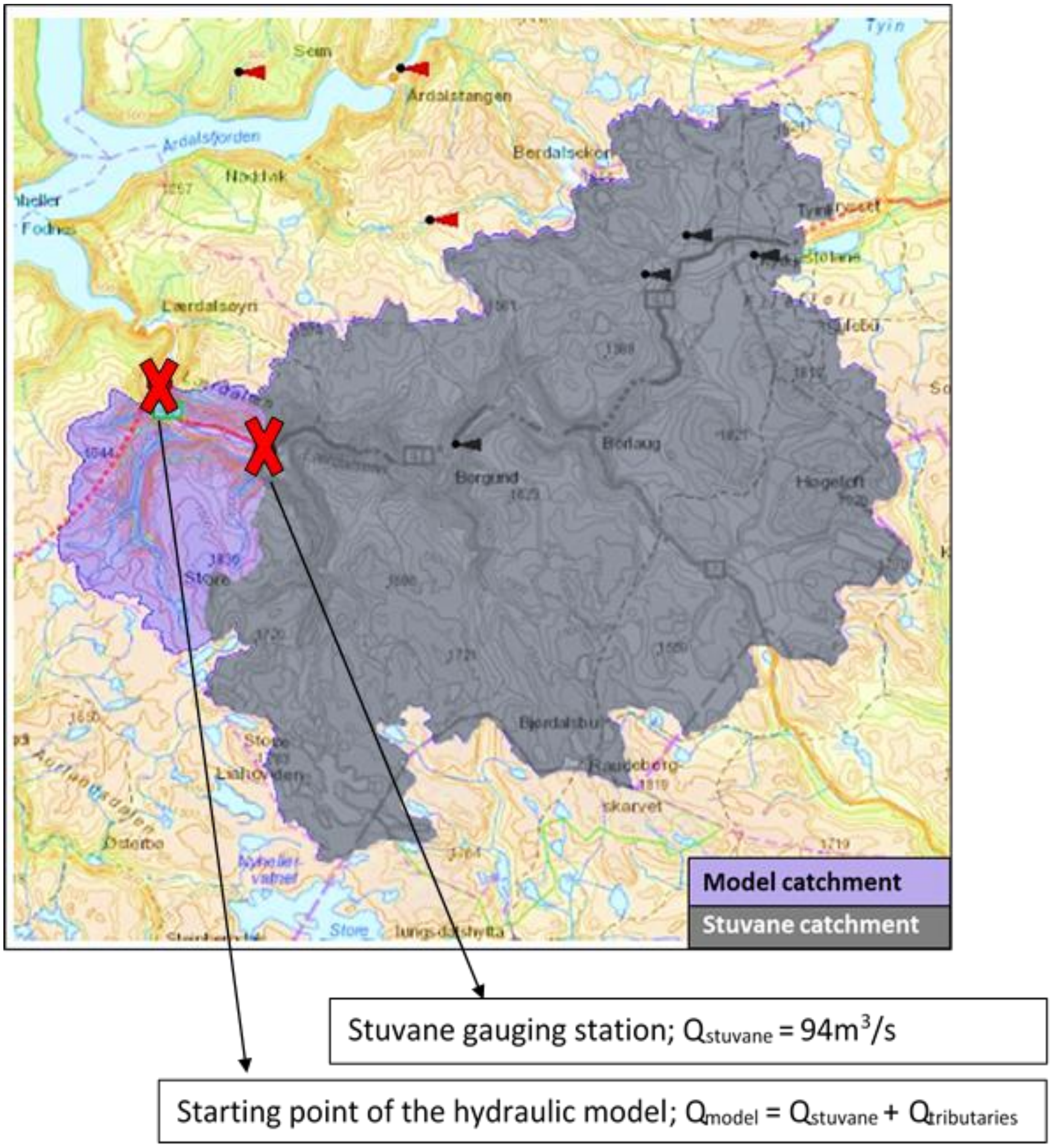
Table B.2: Recommended Manning values for natural streams. This table appears in page 3-14 of the HEC-RAS reference manual, and it is extracted from Chow's book (1959): "Open-Channel Hydraulics".



11	Living area: 0.085
12	Roads: 0.013
21	Full grown soil: 0.04
22	Surface cultivated soil: 0.03
23	Cultivated pastures: 0.04
30	Forest: 0.11
50	Open land: 0.1
80	River channel: 0.035

Figure B.2: Land use classification in the modeled area and final manning values chosen according to tables B.1 and B.2.

APPENDIX C. CATCHMENT DATA AND SCALING OF THE CALIBRATION DISCHARGE



Stuvane gauging station; $Q_{stuvane} = 94 m^3/s$

Starting point of the hydraulic model; $Q_{model} = Q_{stuvane} + Q_{tributaries}$

Figure C.1: Catchment area measured from Stuvane (grey color) vs catchment area measured from the starting point of the hydraulic model (grey area plus purple area). The area used for the tributary inflow calculation is the difference between them.

$$\left.\begin{aligned} A_{stuvane} &= 994.5\ km^2 \\ F_{Stuvane} &= 31.4\ l/(s\cdot km^2) \\ \\ A_{model} &= 1118.1\ km^2 \\ F_{model} &= 31.4\ l/(s\cdot km^2) \end{aligned}\right\} \quad \begin{aligned} A_{tributaries} &= 1118.1 - 994.5 = 123.6\ km^2 \\ F_{tributaries} &= F_{model} = 31.4\ l/(s\cdot km^2) \end{aligned}$$

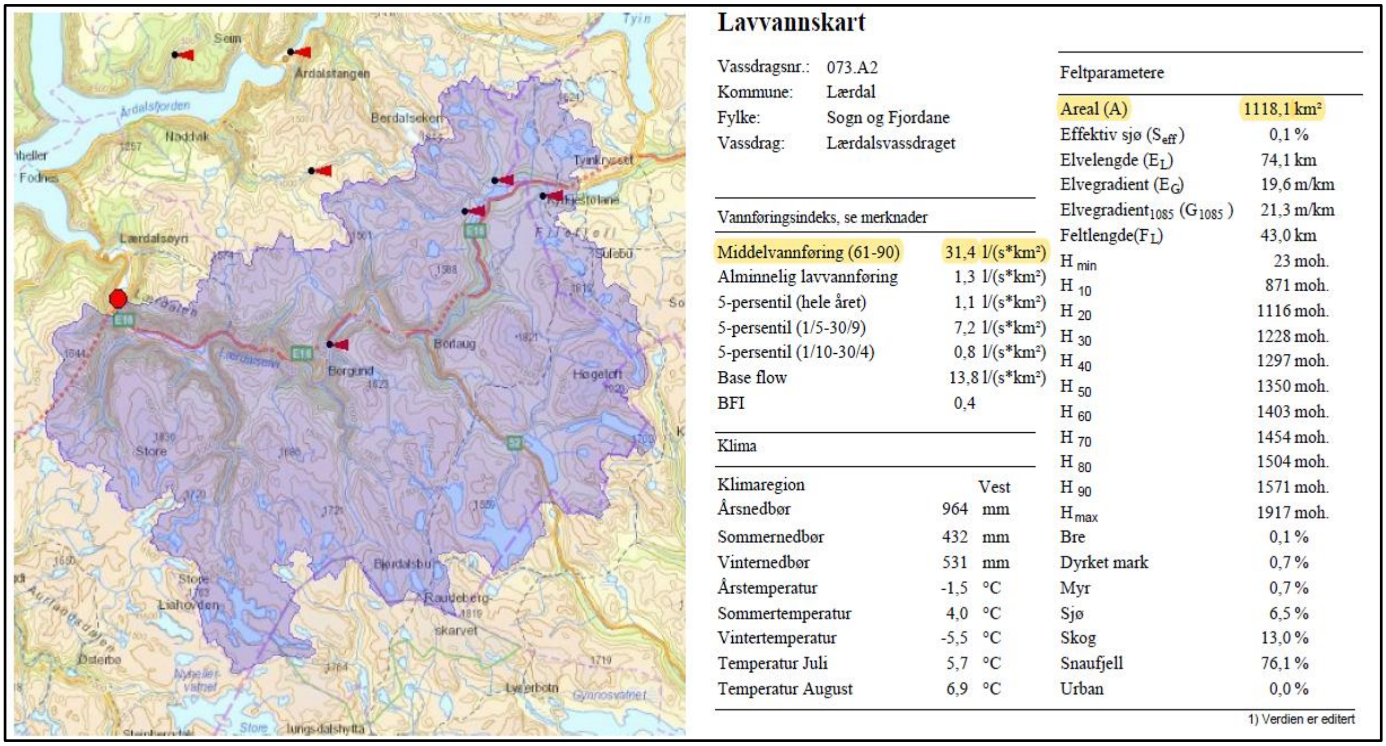
$A_{FlåmBru} = 268.7\ km^2$
$F_{FlåmBru} = 63.3\ l/(s{\cdot}km^2)$
$Q_{FlåmBru} = 52.78\ m^3/s$ *(29/05/2018 - day of the LiDAR flight)*

$$Q_{tribut} = Q_{Flåm} \cdot \frac{A_{tribut} \cdot F_{tribut}}{A_{\text{Flåm}} \cdot Q_{Flåm}} = 52.78 \cdot \frac{123.6 \cdot 31.4}{268.7 \cdot 63.3} = 12.04\ m^3/s$$

$$\boxed{Q_{model} = 94 + 12.04 \approx 106 m^3/s}$$

According to the calculations, the calibration of the model must be done with a discharge value of 106m^3/s in order to include the tributary inflow from Stuvane to the starting point of the hydraulic model.

The watershed taken as a reference for the calculations is Flåm Bru. The data of the catchments (area and runoff) were downloaded from NEVINA (Nedbørfelt-Vannføring-INdeks-Analyse), and it is included below.



Lavvannskart

Vassdragsnr.: 073.A2
Kommune: Lærdal
Fylke: Sogn og Fjordane
Vassdrag: Lærdalsvassdraget

Vannføringsindeks, se merknader	
Middelvannføring (61-90)	31,4 l/(s*km²)
Alminnelig lavvannføring	1,3 l/(s*km²)
5-persentil (hele året)	1,1 l/(s*km²)
5-persentil (1/5-30/9)	7,2 l/(s*km²)
5-persentil (1/10-30/4)	0,8 l/(s*km²)
Base flow	13,8 l/(s*km²)
BFI	0,4

Klima		
Klimaregion		Vest
Årsnedbør	964	mm
Sommernedbør	432	mm
Vinternedbør	531	mm
Årstemperatur	-1,5	°C
Sommertemperatur	4,0	°C
Vintertemperatur	-5,5	°C
Temperatur Juli	5,7	°C
Temperatur August	6,9	°C

Feltparametere	
Areal (A)	1118,1 km²
Effektiv sjø (S_{eff})	0,1 %
Elvelengde (E_L)	74,1 km
Elvegradient (E_G)	19,6 m/km
Elvegradient$_{1085}$ (G_{1085})	21,3 m/km
Feltlengde(F_L)	43,0 km
H_{min}	23 moh.
H_{10}	871 moh.
H_{20}	1116 moh.
H_{30}	1228 moh.
H_{40}	1297 moh.
H_{50}	1350 moh.
H_{60}	1403 moh.
H_{70}	1454 moh.
H_{80}	1504 moh.
H_{90}	1571 moh.
H_{max}	1917 moh.
Bre	0,1 %
Dyrket mark	0,7 %
Myr	0,7 %
Sjø	6,5 %
Skog	13,0 %
Snaufjell	76,1 %
Urban	0,0 %

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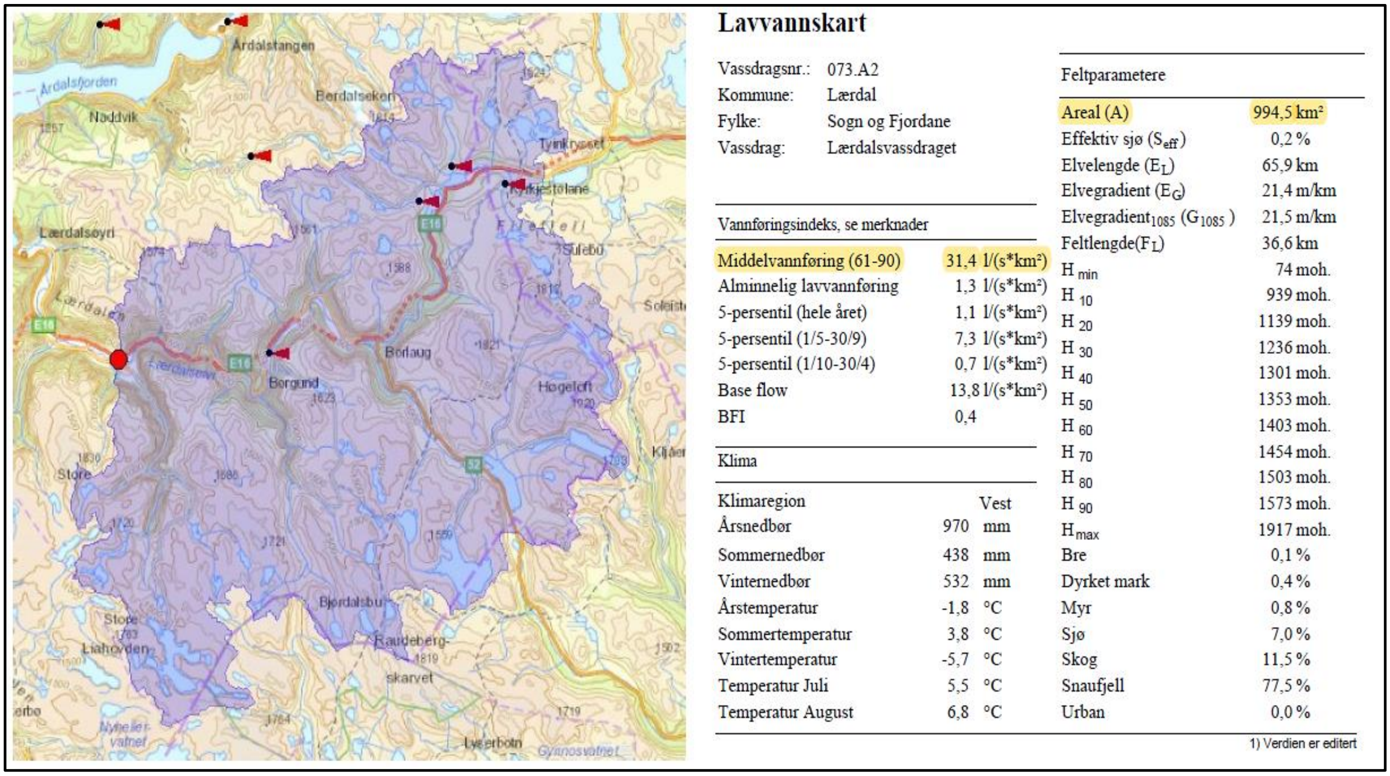
Figure C.2: Watershed parameters measured from the starting point of the hydraulic model



Lavvannskart

Vassdragsnr.: 073.A2
Kommune: Lærdal
Fylke: Sogn og Fjordane
Vassdrag: Lærdalsvassdraget

Vannføringsindeks, se merknader		
Middelvannføring (61-90)	31,4	l/(s*km²)
Alminnelig lavvannføring	1,3	l/(s*km²)
5-persentil (hele året)	1,1	l/(s*km²)
5-persentil (1/5-30/9)	7,3	l/(s*km²)
5-persentil (1/10-30/4)	0,7	l/(s*km²)
Base flow	13,8	l/(s*km²)
BFI	0,4	

Klima		
Klimaregion		Vest
Årsnedbør	970	mm
Sommernedbør	438	mm
Vinternedbør	532	mm
Årstemperatur	-1,8	°C
Sommertemperatur	3,8	°C
Vintertemperatur	-5,7	°C
Temperatur Juli	5,5	°C
Temperatur August	6,8	°C

Feltparametere	
Areal (A)	994,5 km²
Effektiv sjø (S_{eff})	0,2 %
Elvelengde (E_L)	65,9 km
Elvegradient (E_G)	21,4 m/km
Elvegradient$_{1085}$ (G_{1085})	21,5 m/km
Feltlengde(F_L)	36,6 km
H_{min}	74 moh.
H_{10}	939 moh.
H_{20}	1139 moh.
H_{30}	1236 moh.
H_{40}	1301 moh.
H_{50}	1353 moh.
H_{60}	1403 moh.
H_{70}	1454 moh.
H_{80}	1503 moh.
H_{90}	1573 moh.
H_{max}	1917 moh.
Bre	0,1 %
Dyrket mark	0,4 %
Myr	0,8 %
Sjø	7,0 %
Skog	11,5 %
Snaufjell	77,5 %
Urban	0,0 %

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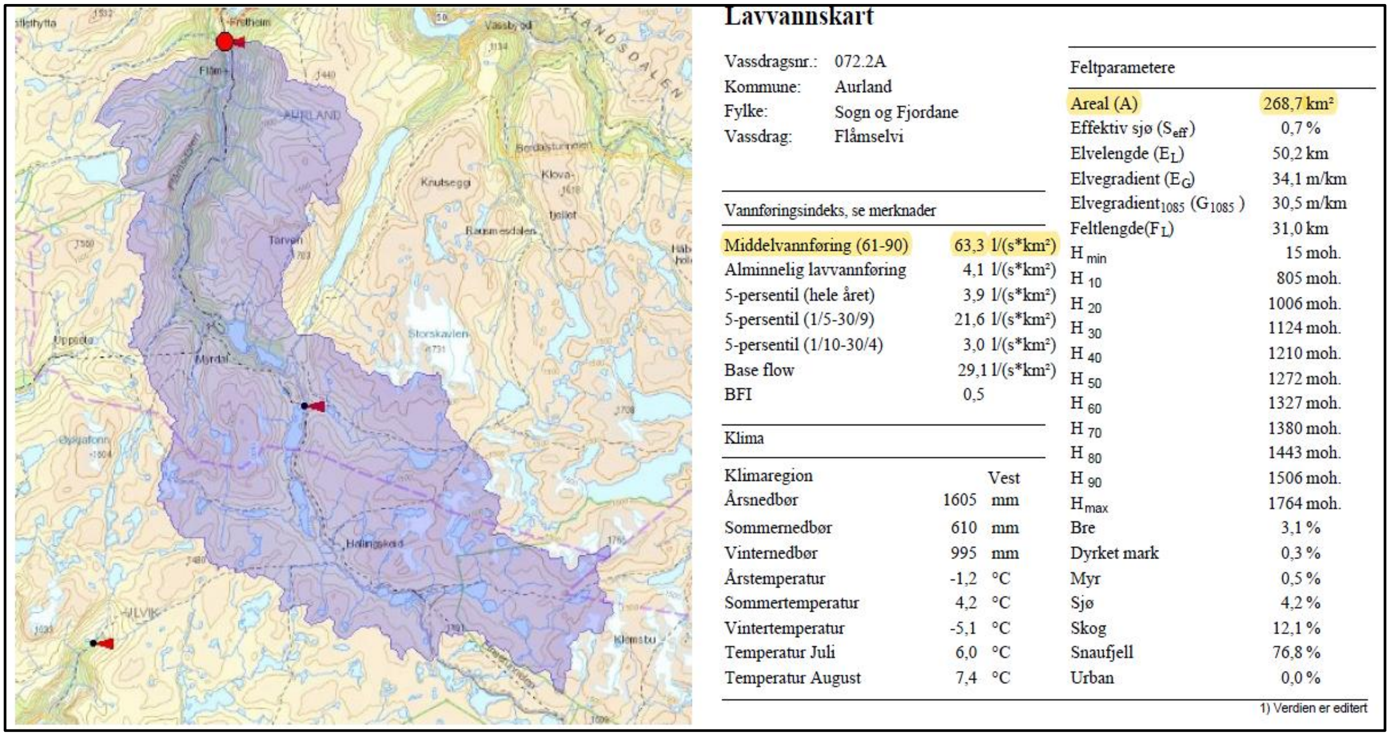
Figure C.3: Watershed parameters measured from Stuvane



Lavvannskart

Vassdragsnr.: 072.2A
Kommune: Aurland
Fylke: Sogn og Fjordane
Vassdrag: Flåmselvi

Vannføringsindeks, se merknader		
Middelvannføring (61-90)	63,3	l/(s*km²)
Alminnelig lavvannføring	4,1	l/(s*km²)
5-persentil (hele året)	3,9	l/(s*km²)
5-persentil (1/5-30/9)	21,6	l/(s*km²)
5-persentil (1/10-30/4)	3,0	l/(s*km²)
Base flow	29,1	l/(s*km²)
BFI	0,5	

Klima		
Klimaregion		Vest
Årsnedbør	1605	mm
Sommernedbør	610	mm
Vinternedbør	995	mm
Årstemperatur	-1,2	°C
Sommertemperatur	4,2	°C
Vintertemperatur	-5,1	°C
Temperatur Juli	6,0	°C
Temperatur August	7,4	°C

Feltparametere	
Areal (A)	268,7 km²
Effektiv sjø (S_{eff})	0,7 %
Elvelengde (E_L)	50,2 km
Elvegradient (E_G)	34,1 m/km
Elvegradient$_{1085}$ (G_{1085})	30,5 m/km
Feltlengde(F_L)	31,0 km
H_{min}	15 moh.
H_{10}	805 moh.
H_{20}	1006 moh.
H_{30}	1124 moh.
H_{40}	1210 moh.
H_{50}	1272 moh.
H_{60}	1327 moh.
H_{70}	1380 moh.
H_{80}	1443 moh.
H_{90}	1506 moh.
H_{max}	1764 moh.
Bre	3,1 %
Dyrket mark	0,3 %
Myr	0,5 %
Sjø	4,2 %
Skog	12,1 %
Snaufjell	76,8 %
Urban	0,0 %

1) Verdien er editert

Figure C. 4: Watershed parameters measured from Flåm Bru

APPENDIX D. DETAILED PROCEDURE OF SOME OF THE TASKS CARRIED OUT IN ARCMAP

Validation of the Green LiDAR data

a) Comparison Red - Green LiDAR

1. Download the point cloud data from Høydedata (.laz format) and decompress the LAZ files into LAS using LAStools (same procedure as the one explained in the thesis document, section 3.1.2).

2. In ArcMap, create a new Lasdataset (.lasd) for the .las file obtained in step number 1. The coordinate systems must be added in this step (XY: ETRS 1989 Zone 32N; Z: NN2000). Now, 2 different Lasdatasets must be available in ArcMap (the one just created from Høydedata and the one containing the bathymetric data that was created in a previous stage of the thesis).

3. Choose the areas for comparison and create the corresponding shapefiles.

4. Clip both Lasdatasets according to the extent of the polygons created in the 3rd step. To do so, the “Extract LAS” tool of ArcMap is used. The inputs of the tool are the Lasdataset to be clipped and the shapefile used as a boundary.

   Once both lasdatasets are clipped for the areas selected, the procedure followed is different for the data from Høydedata and for the bathymetric data.
   For the lasdataset from Høydedata, it is necessary to change its format to a feature format. The result is a shapefile (.shp) layer containing all the points of the clipped lasdatasets and its elevation values. Concerning the bathymetric lasdatasets, it is enough to turn them into a raster. The steps followed in each case are described below.

5. In order to convert each of the Lasdataset into a point feature layer, open the extension las2shp of LAStoolds. Click “browse” and open the clipped LAS files coming from the Høydedata lasdataset. Within the options of LAStools, select z and classification. In addition to the elevation values, it is important to know the classification of each point so that only the ones labeled as “Ground (2)” are kept for the comparison. As a result, all the points contained in the LAS files are now in a multipoint shapefile format.

6. Open the shapefiles created in 5 in ArcMap. Open the attribute table of each file and using the “Select by attribute” option, select all the points whose classification is different from “Ground (2)”. Enable the editor of the shapefile and press “Delete selected”. The result is a shapefile containing the points from Høydedata classified as ground.

7. Regarding to the bathymetric information, create one raster for each of the clipped lasdatasets. To do so, the “LAS dataset to Raster” tool is used. The interpolation method chosen was binning interpolation and the cellsize selected for the raster was 0.04m. The reason to create such a small raster is that for this comparison, it is important to keep the resolution as high as possible and the point spacing of the Las is very small. In addition, the rasters created in this stage are used only to compare the elevations from both sources but not to be included in the final model, which could make the rest of the processes done with the terrain slower

8. Use the “Extract Values to Points” tool in Arcmap. The inputs are each of the rasters obtained and the shapefiles containing the elevation points from Høydedata. The output is a new point feature layer whose attribute table contains the original elevation value of each point (which correspond to the elevation from Høydedata) and the elevation of the same point extracted from the raster.

9. In the attribute table open the “Field Calculator” and calculate the differences (Høydedata – bathymetry) in the elevation of the points. Some statistics can also be obtained.

b) Comparison GPS points (visit to Lærdal) - Green LiDAR

1. Connect the folder containing the GPS points in a .txt format. Right click in the file and select “Create Feature Class from XY Table”. Include the coordinate system in this step. The result is the GPS points in a point shapefile layer (.shp).

2. As the points were taken according to the NN1954, click “Open Attribute Table” and add 6cm to the elevation values of the points using the field calculator tool of Arcmap in order to convert them into NN2000.

3. From now on, the steps 6 to 8 explained in red-green LiDAR comparison procedure have to be followed for the areas containing the GPS points.

Terrain construction

a) Bathymetric terrain for the river channel

Starting from the LAS data file obtained using LAStools (section 3.1.2.a), the procedure followed is explained below.

1. From ArcMap catalog, connect the folder containing the LAS file containing the green LiDAR points.

2. “Create a new Lasdataset”. In LAS Dataset properties add the LAS file mentioned in the 1st step and include the coordinate system (XY: ETRS1989 UTM Zone 32N; Z: NN2000).

3. Convert the LAS dataset into raster, using the tool “LAS dataset to Raster”. Some parameters regarding the interpolation type and the cellsize must be chosen, which is documented in the main report.

b) Terrain for the floodplains

As the data was downloaded in a raster format, it was only necessary to include all the .tif files in a single raster. To do so the "Mosaic to New Raster" tool was used. The coordinate system and cellsize of the final raster must be included in this step.

c) Inclusion of buildings and roads in the digital terrain

1. Use the "Clip" tool in HEC-RAS, and include the DTM and the shapefile with the buildings as input. As output, a new raster containing the elevation data from the DTM but just in the areas enclosed by the polygons with the shape of the buildings is obtained.

2. Use "Raster Calculator" to increase the height of the output raster of step number 1. This tool allows the user to operate with raster layers using the syntax of an algebraic expression. The height given in this case was 3m, so the syntax was: *name_of_raster_with_buildings*+3.

Terrain modification to include the flood protection wall

1. Create a feature layer with the shape of the wall designed by the NVE. The steps followed to do this are:

- Draw a line using the polyline feature in the editor toolbar according to the NVE plan and place it in the correct position. Select the function copy parallel in the editor bar and create two new lines, each of them at a distance of 2m from the original one, which remain in the center. At both endings of the wall, draw a new line perpendicular to the previously created ones, in order to "close" the feature so that it can be converted into a polygon.

- Use the function “Feature to Polygon”, which allow us to generate a polygon from areas enclosed by input lines. Using the already created polylines as input, a polygon representing a 4m wide wall is created in a .shp format.

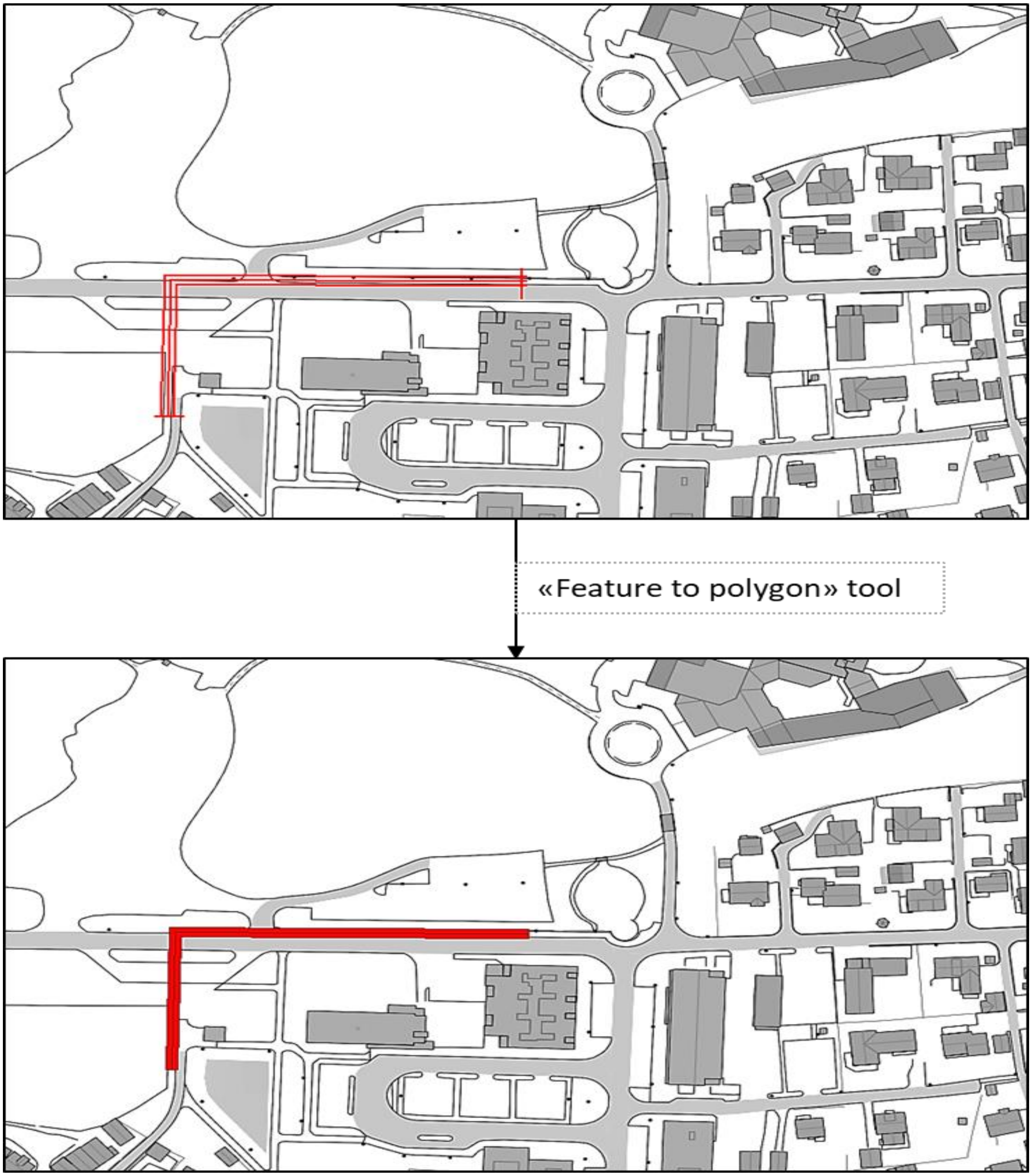


Figure D.1: First steps of the procedure followed to create the wall. The figure on the top shows the lines that surround the polygon that represents the wall. The result given by the “Feature to Polygon” tool appears in the second figure

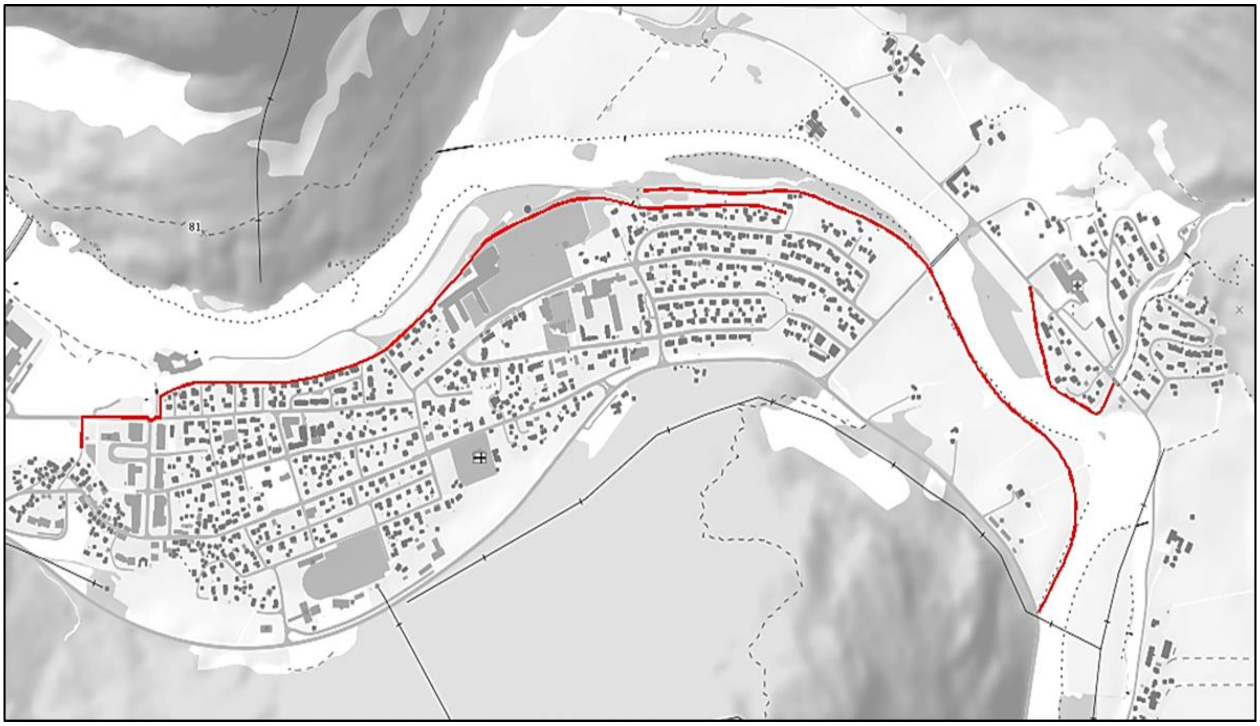


Figure D2: Final shape of the wall in ArcMap (in red). This polygon must be converted into a raster whose height will be increased.

2. Follow the method explained in subsection c of this appendix and create a raster whose height is increased using the raster calculator.

3. Use “Mosaic to new raster” to merge the wall in the original terrain of the river (the one including the bathymetric LiDAR data, the elevation model for the floodplains for Høydedata and the created 3D buildings).

APPENDIX E. DETAILS OF THE FLOOD PROTECTION WALL

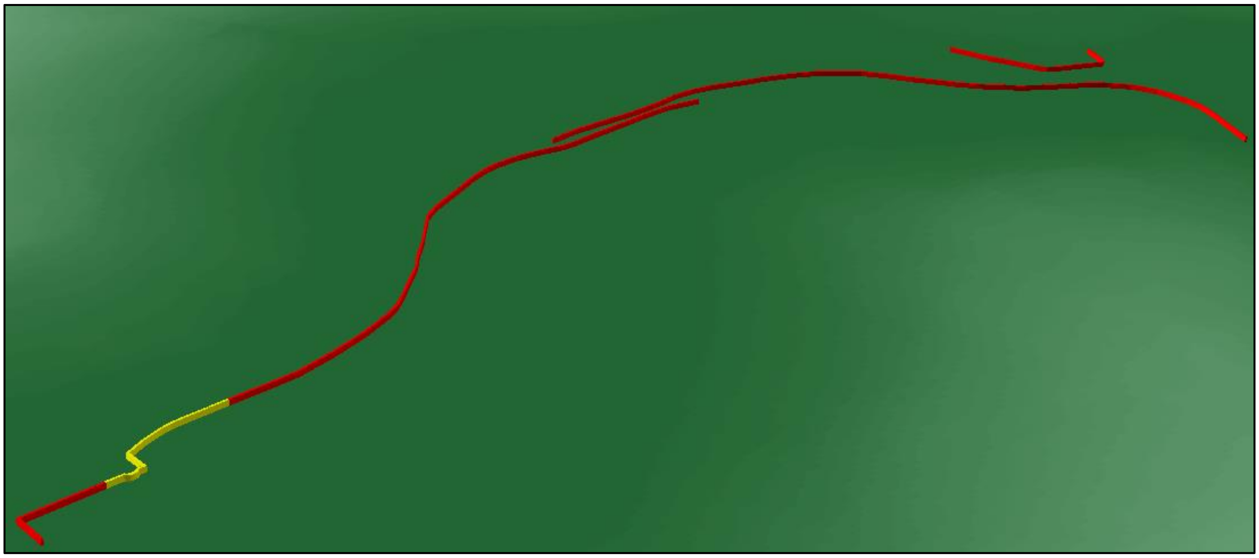


Figure E.1: 3D view of the final wall created in ArcMap

The height given to the wall shown in Figure E.1 was 1m in the areas marked in red and 2m in the yellow area. The reason of this is that the elevation of the terrain is very low in the part of the village close to the fiord, so increasing the terrain in these areas just 1m was proved to not be enough.

The wall shown in Figure E.1 is the one created in ArcMap. Once this wall was imported to HEC-RAS, some small modifications were made on it according to the results of the simulations. This minor changes were made directly in the 1D Geometry editor feature

APPENDIX F. CLASSIFICATION OF THE DIFFERENCES IN ELEVATION IN ARCMAP

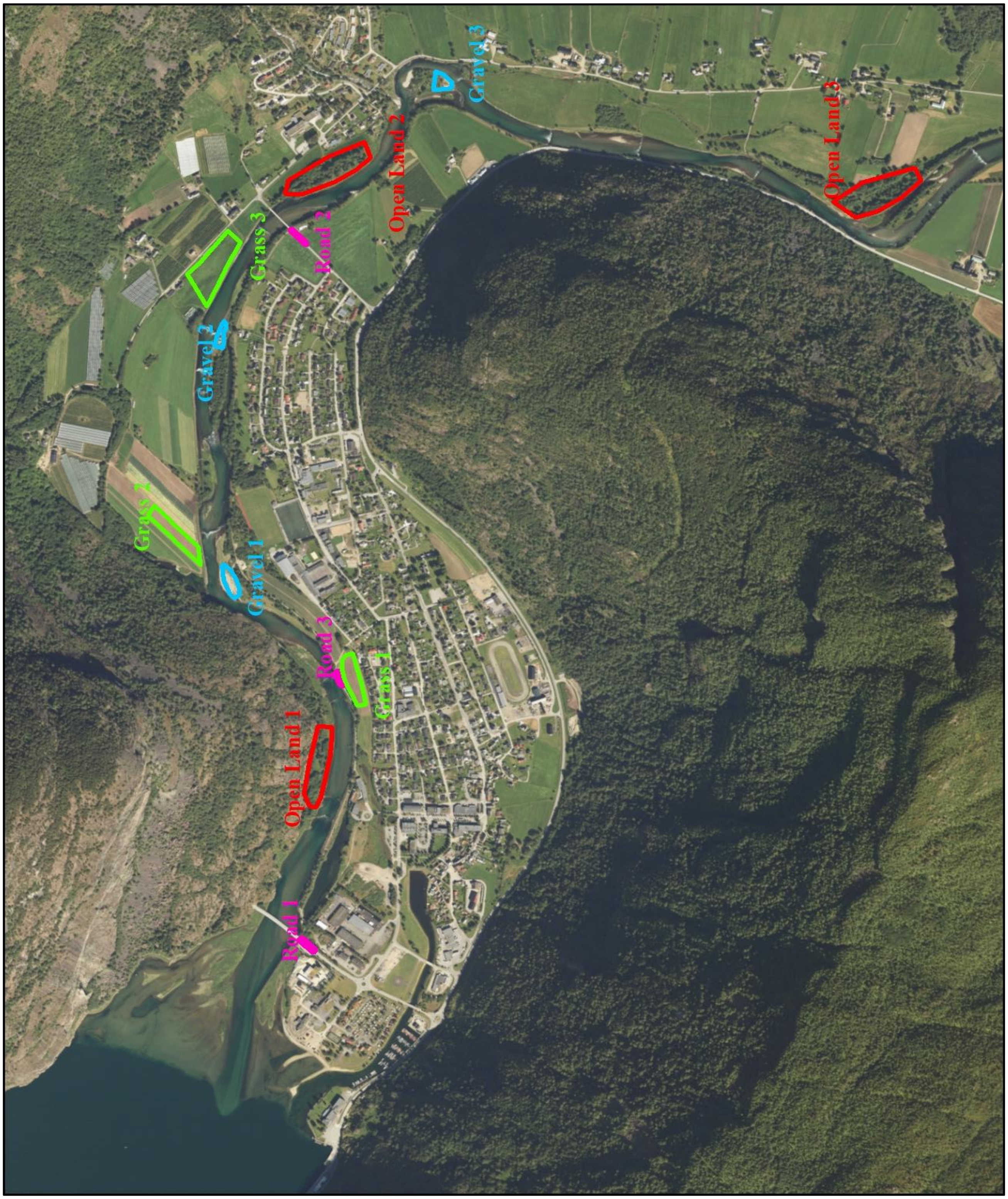


Figure F.2: Location of the areas selected for the red-green LiDAR comparison

a) Gravel

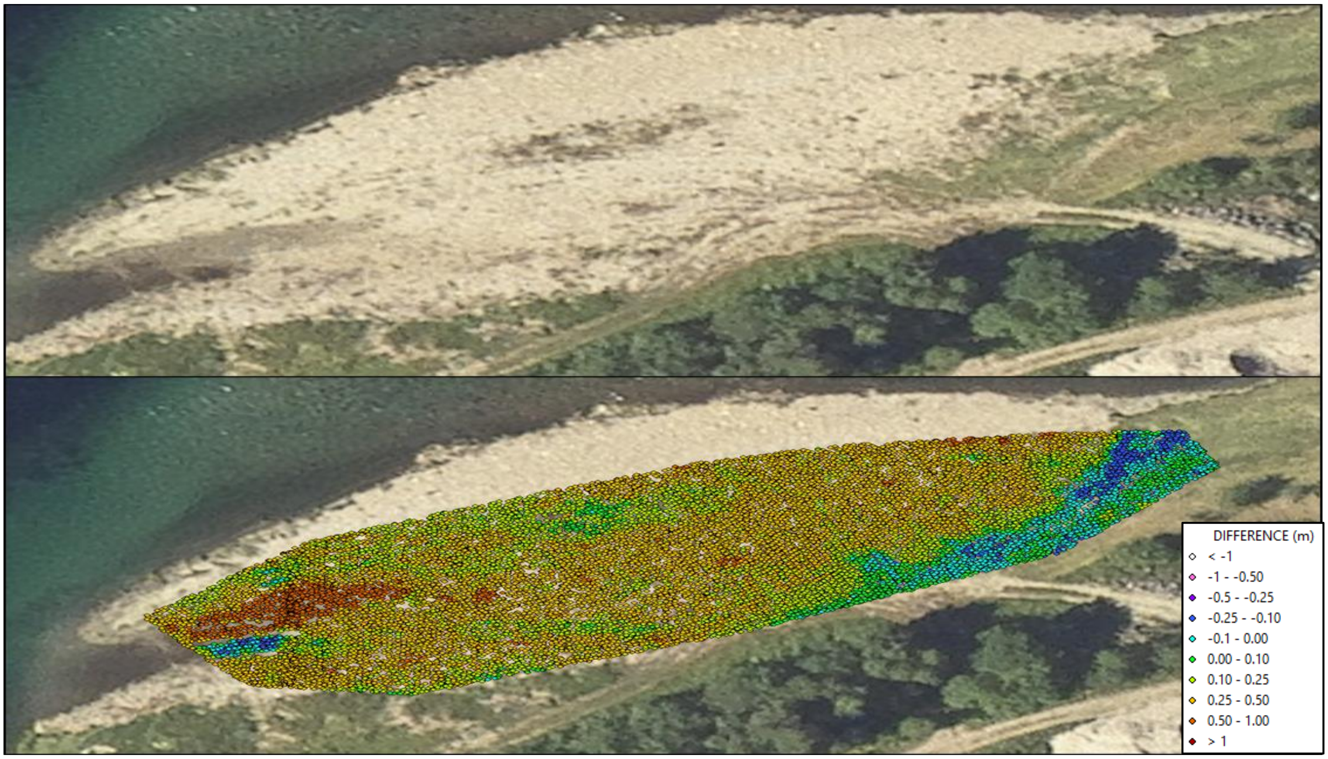


Figure F.3: Area classified as "Gravel 1"

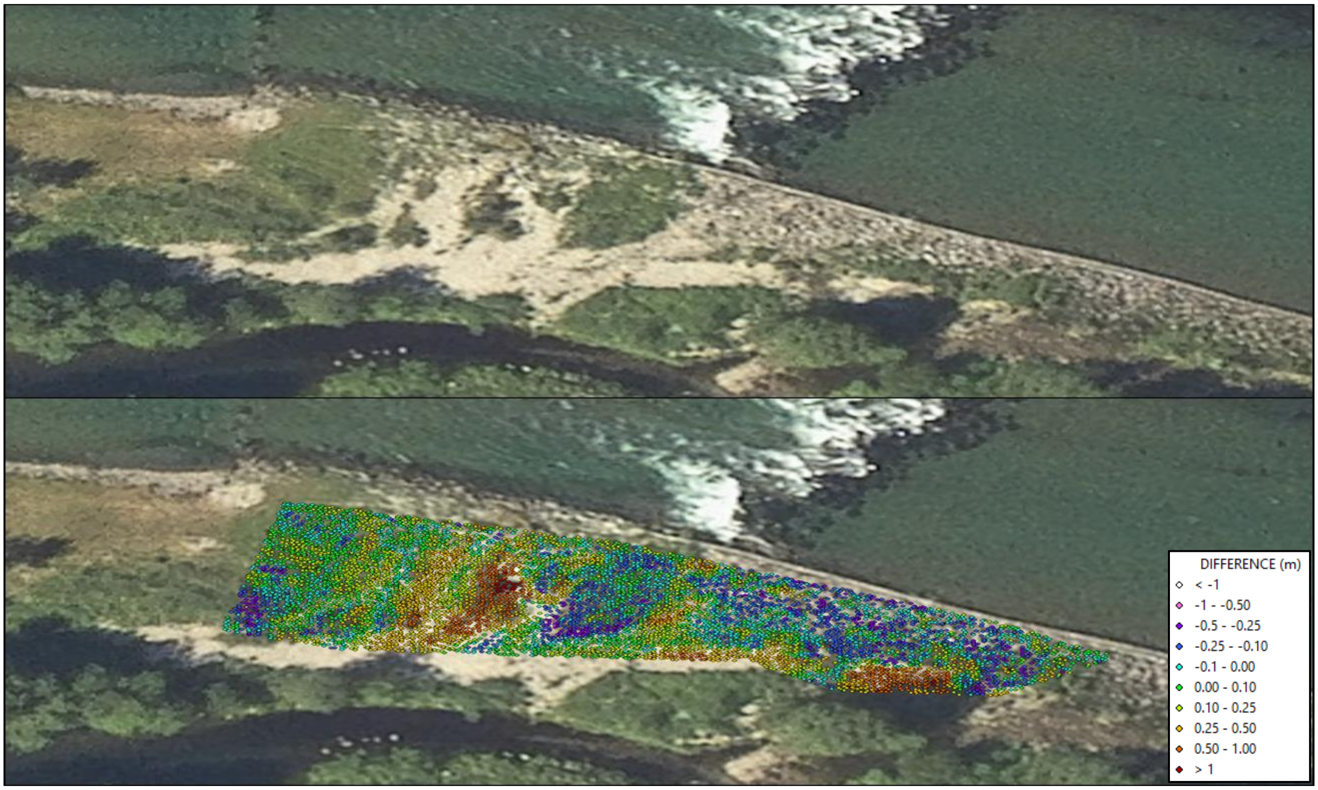


Figure F.4: Area classified as "Gravel 2"

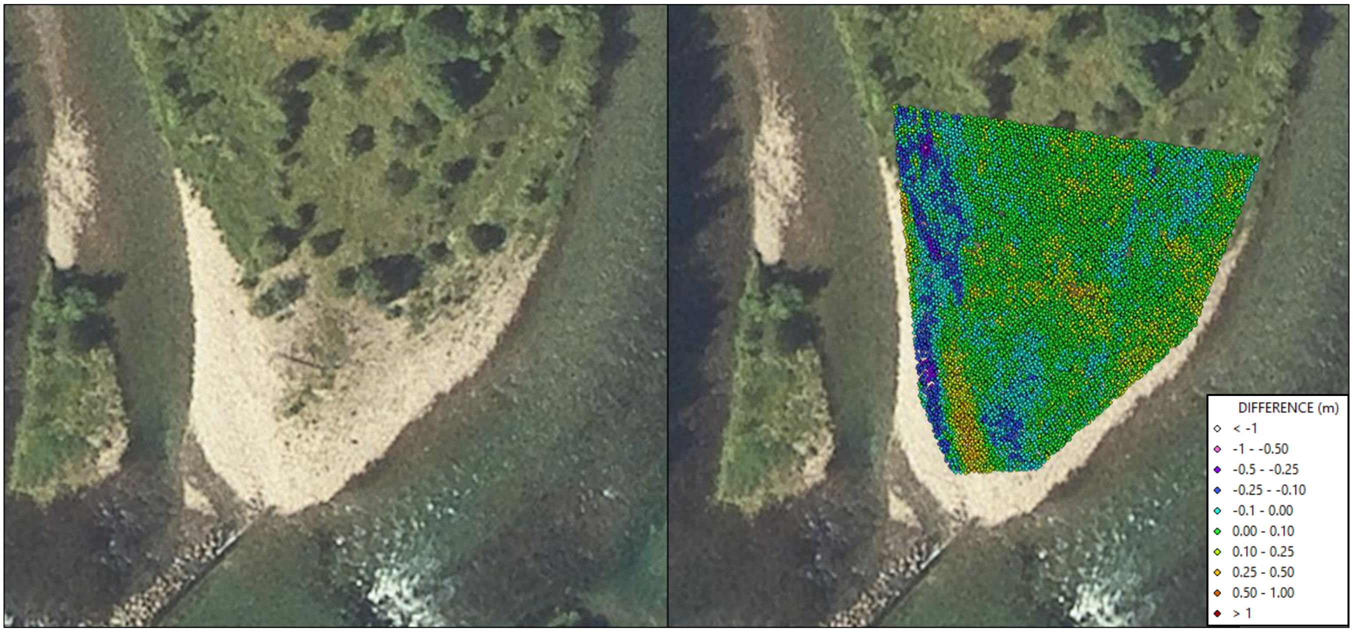


Figure F.5: Area classified as "Gravel 3"

b) Roads

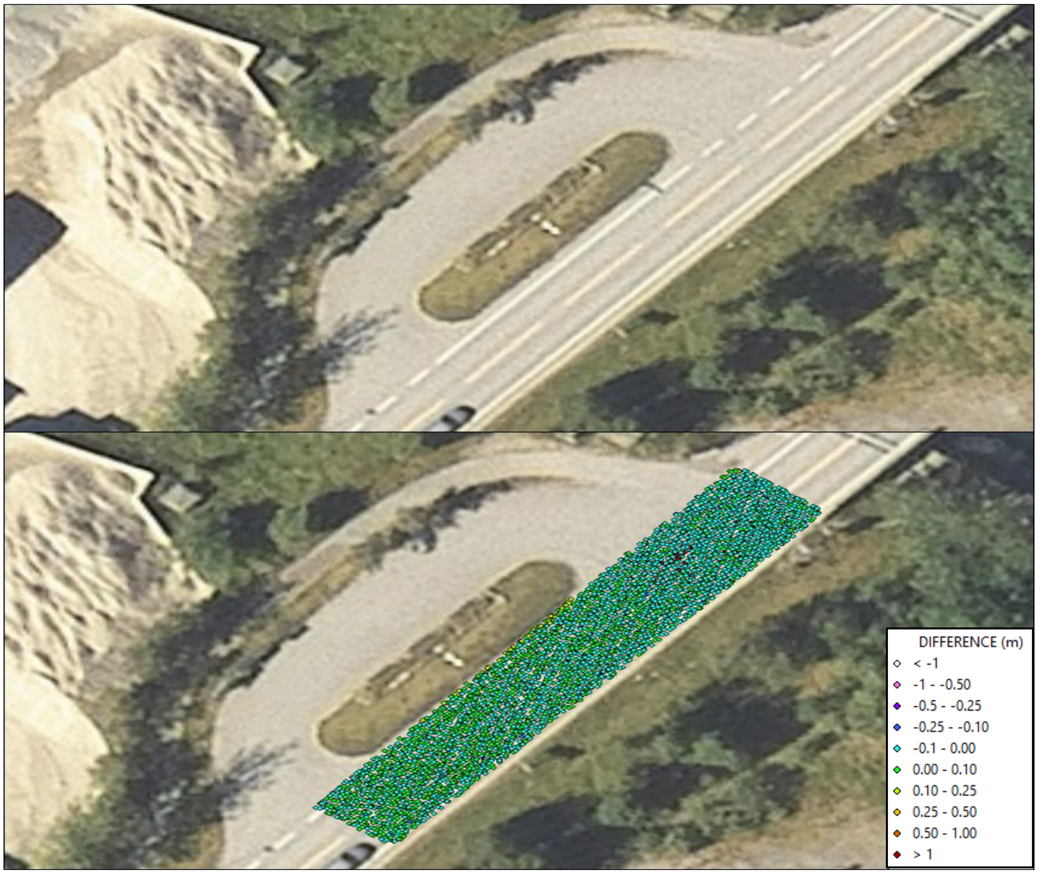


Figure F.6: Area classified as "Road 1"

Figure F.7: Area classified as "Road 2"

Figure F.8: Area classified as "Road 3"

c) Open land

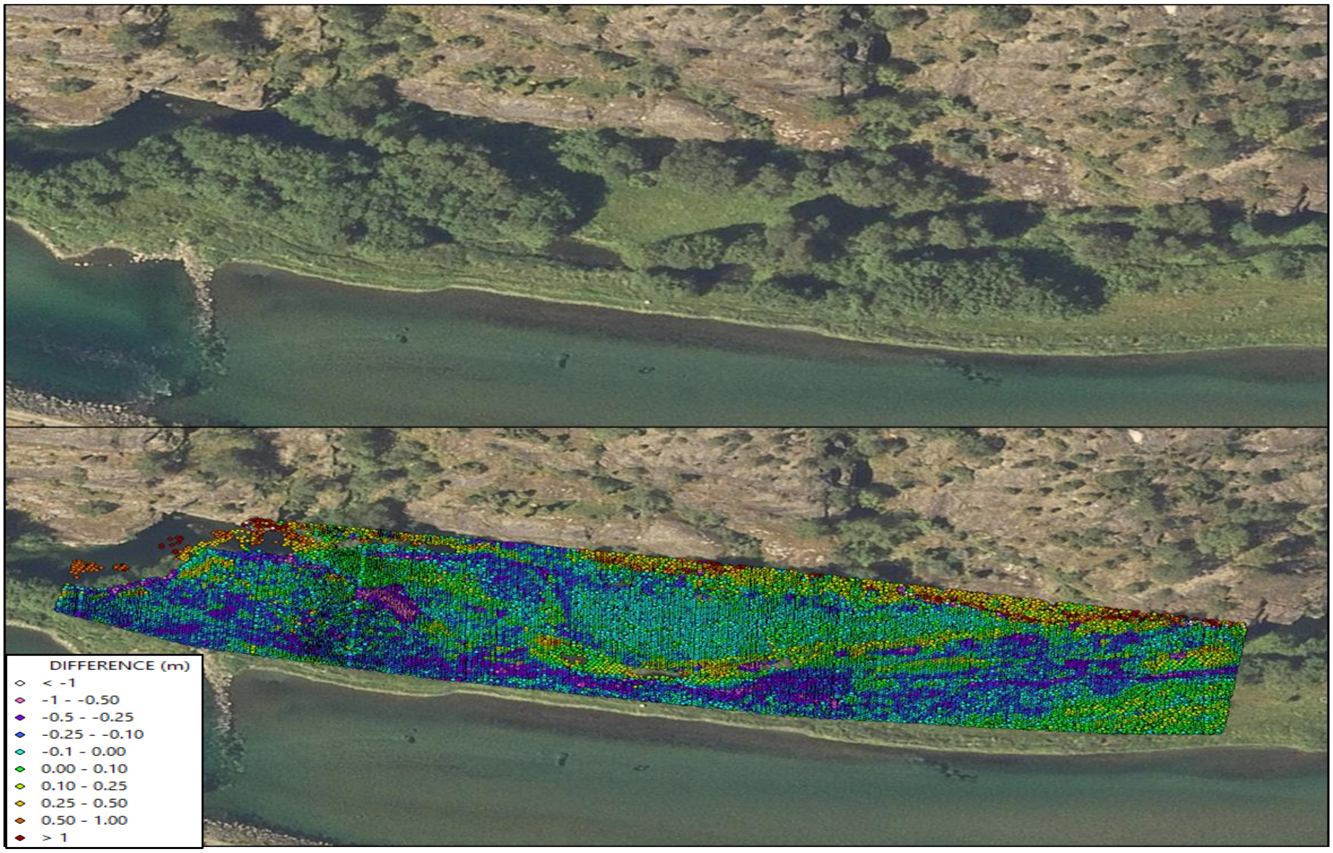


Figure F.9: Area classified as "Open land 1"

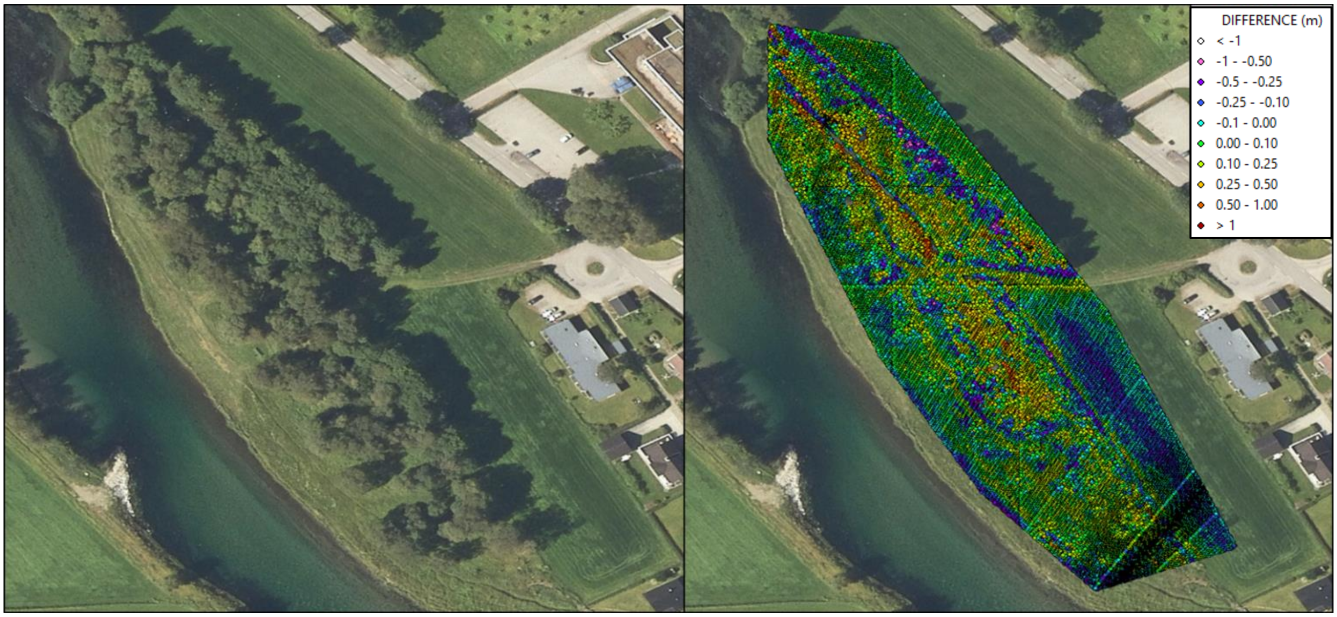


Figure F.10: Area classified as "Open land 2"

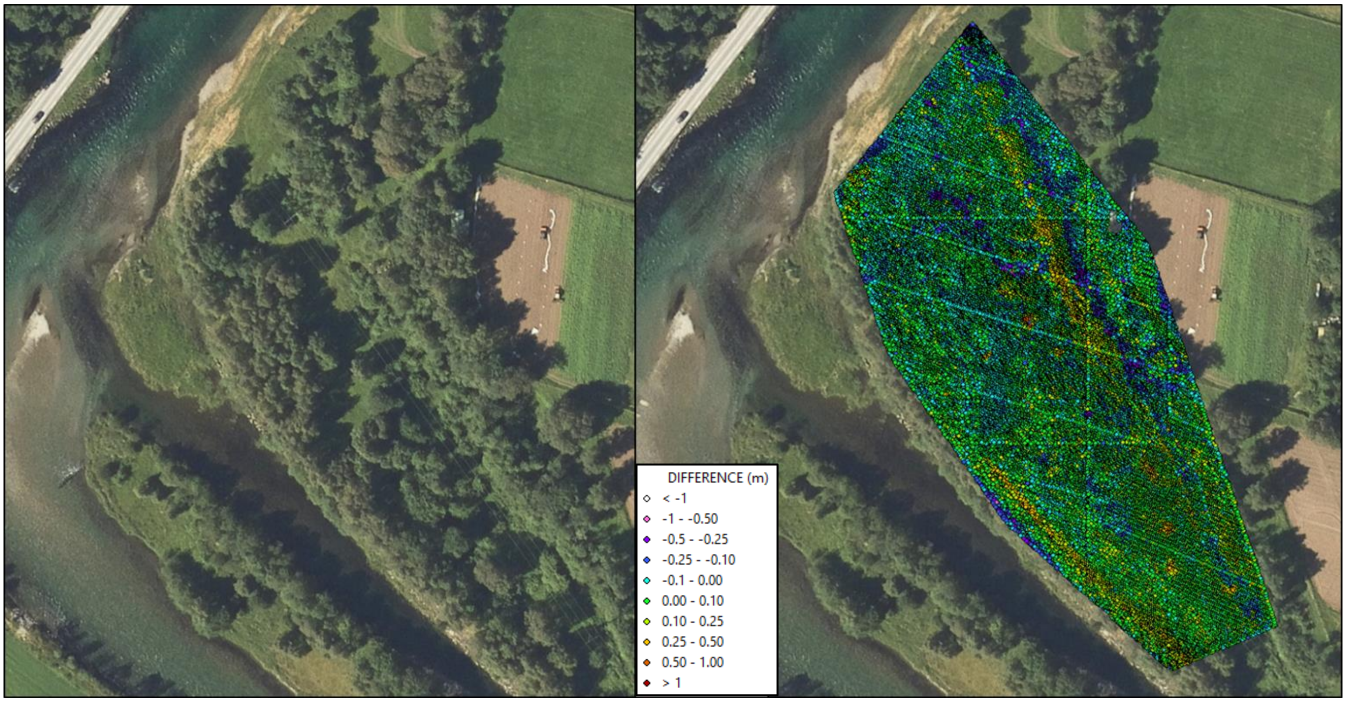


Figure F 11: Area classified as "Open land 3"

d) Grass

Figure F.12: Area classified as "Grass 1"

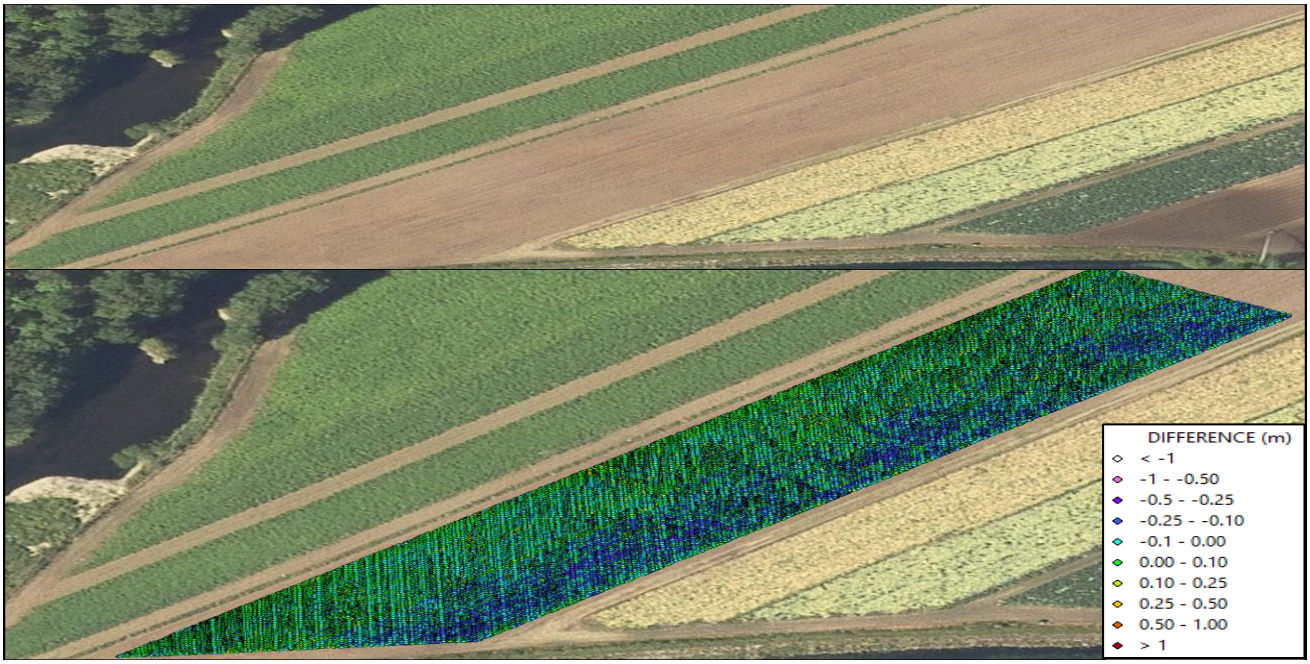


Figure F.13: Area classified as "Grass 2"

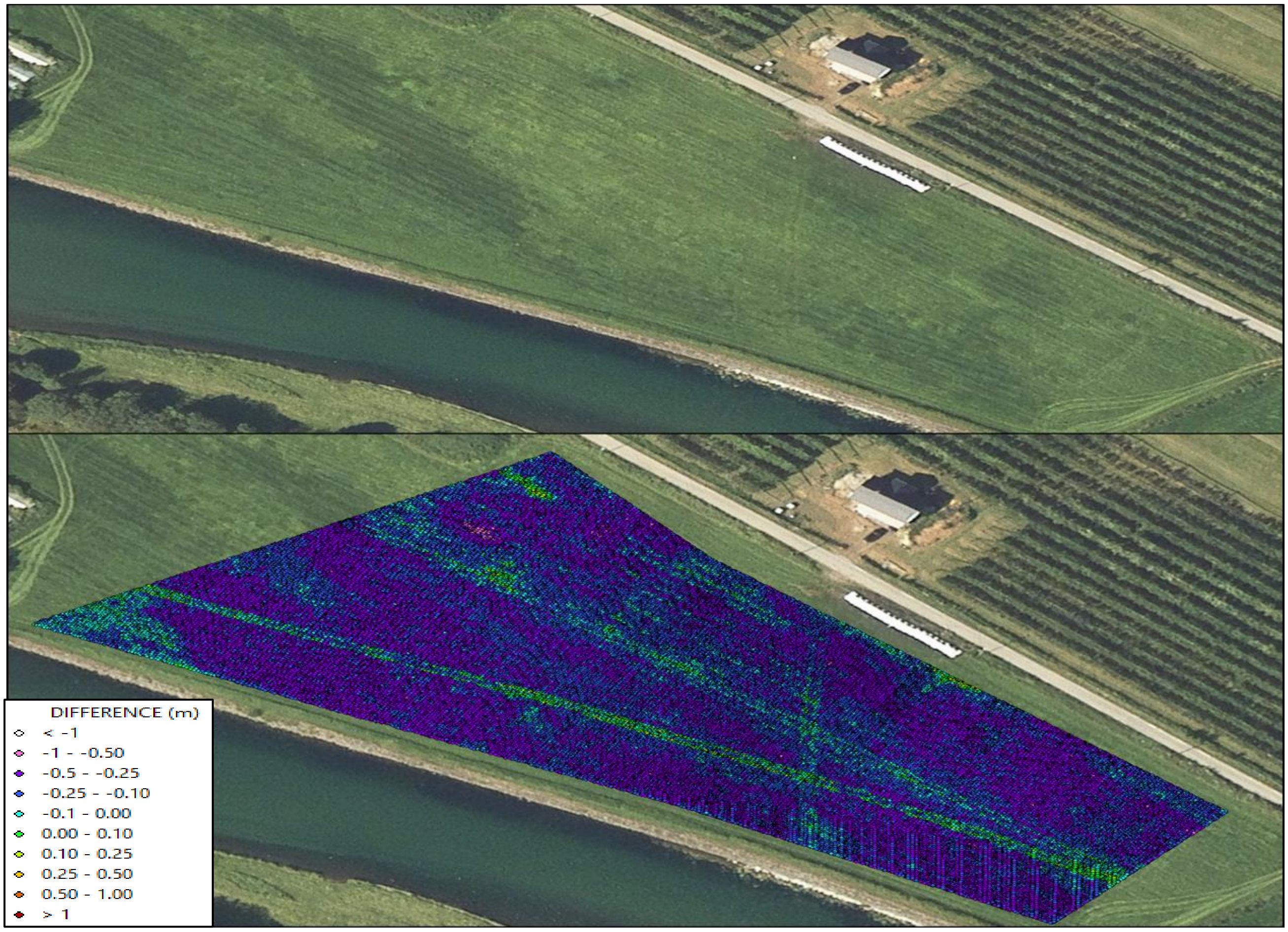


Figure F.14: Area classified as "Grass 3"

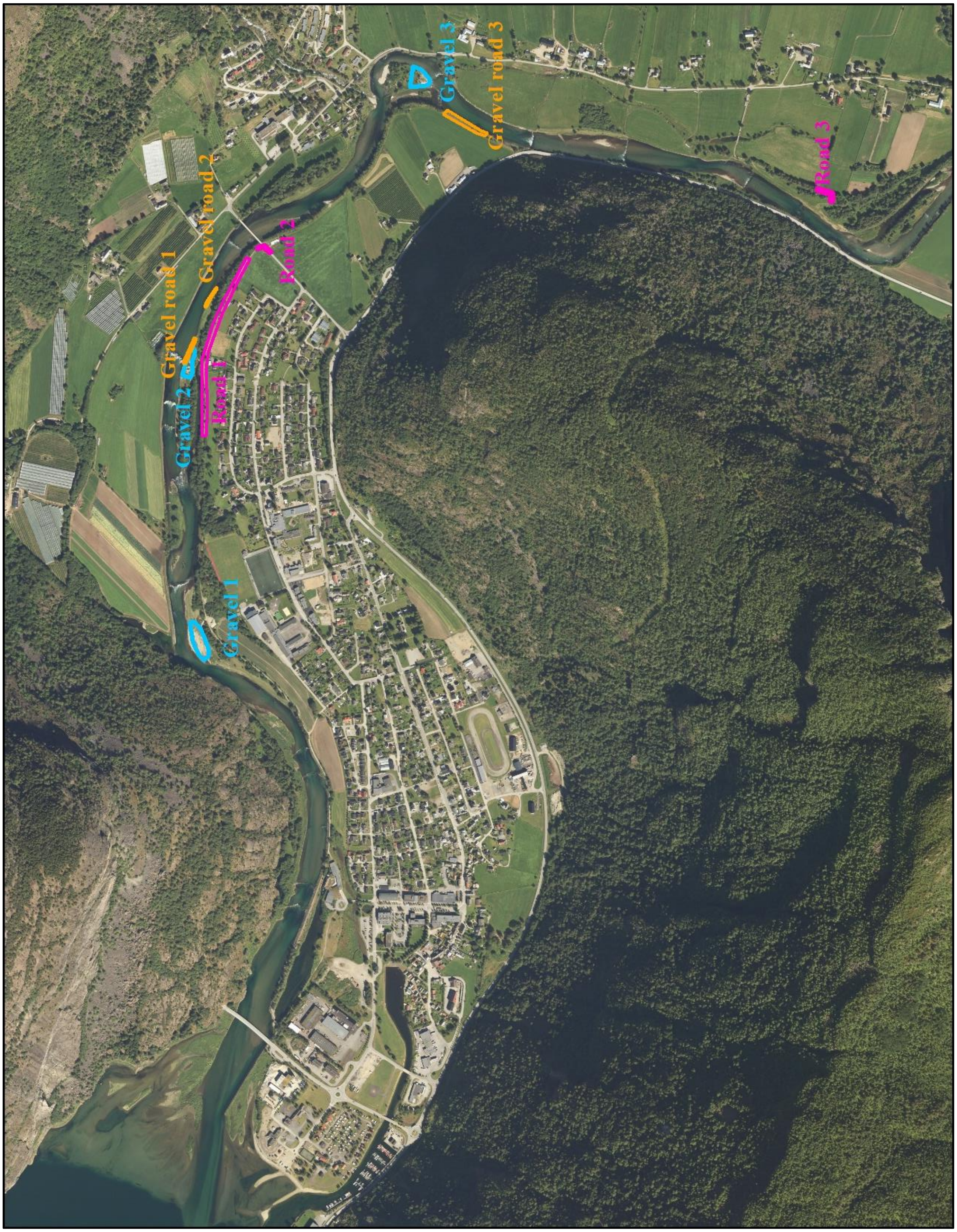


Figure F.15: Location of the areas selected for the GPS-green LiDAR comparison

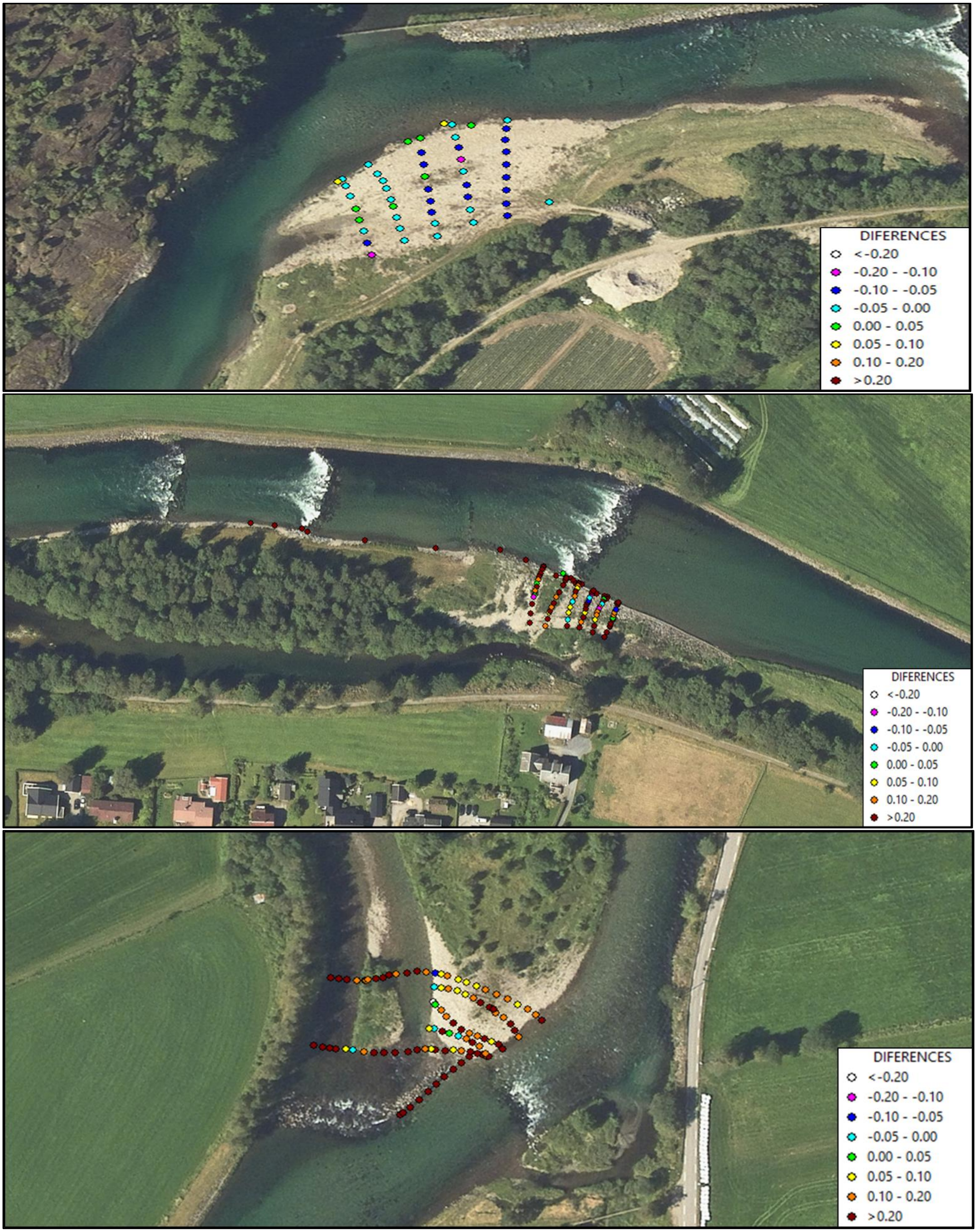


Figure F.16: Areas classiffied as "Gravel A, Gravel B, Gravel C"

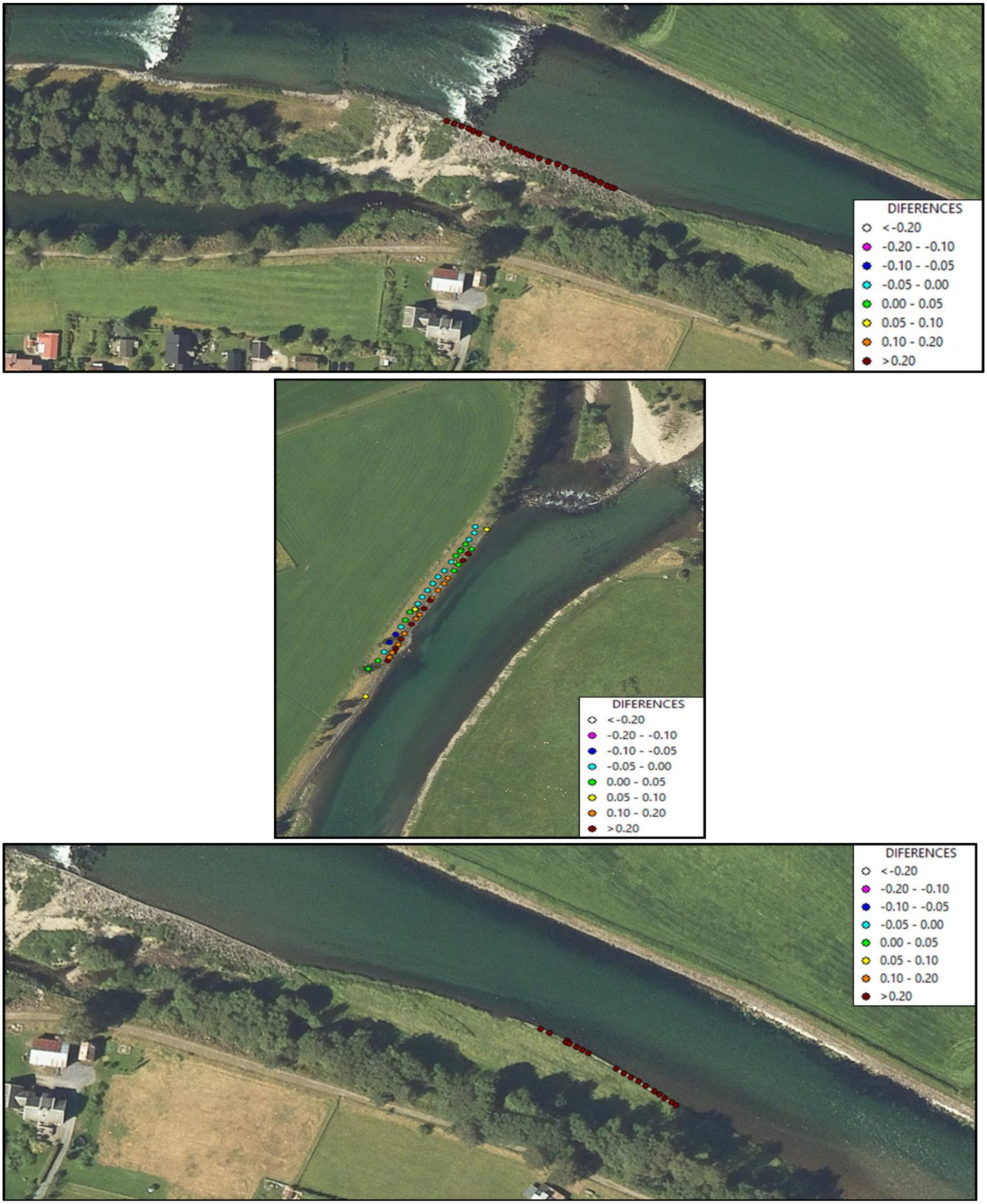


Figure F.17: Areas classified as "Gravel Road A, Gravel Road B, Gravel Road C"

Figure F 18: Areas classified as "Road A, Road B, Road C"

APPENDIX G. PROFILE LINES OF THE RESULTS OF THE SIMULATIONS

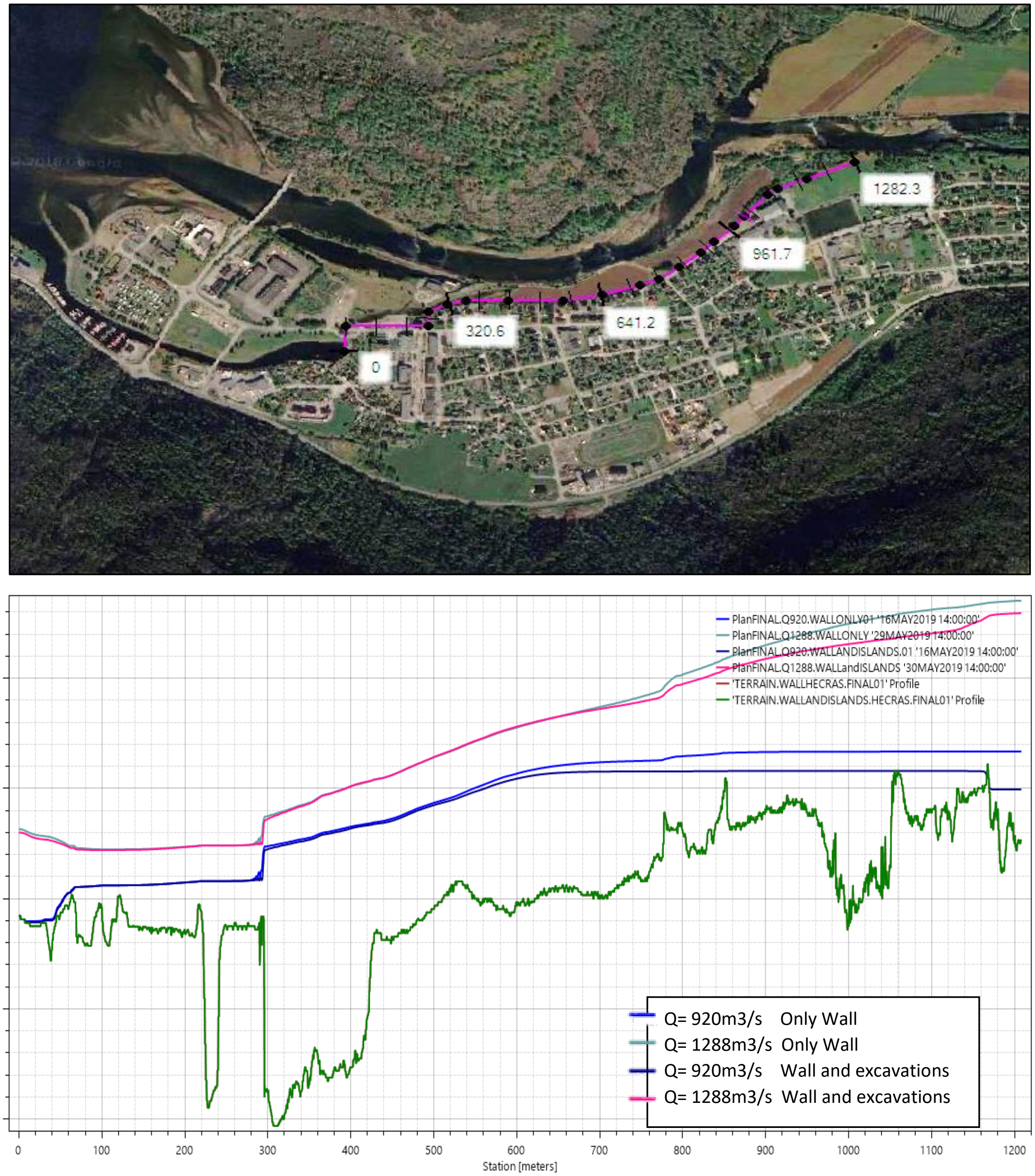


Figure G 1: Profile line along the sections just before the wall in the lower part of the village (see figure on the top). Green line represents the elevation of the terrain in this area.

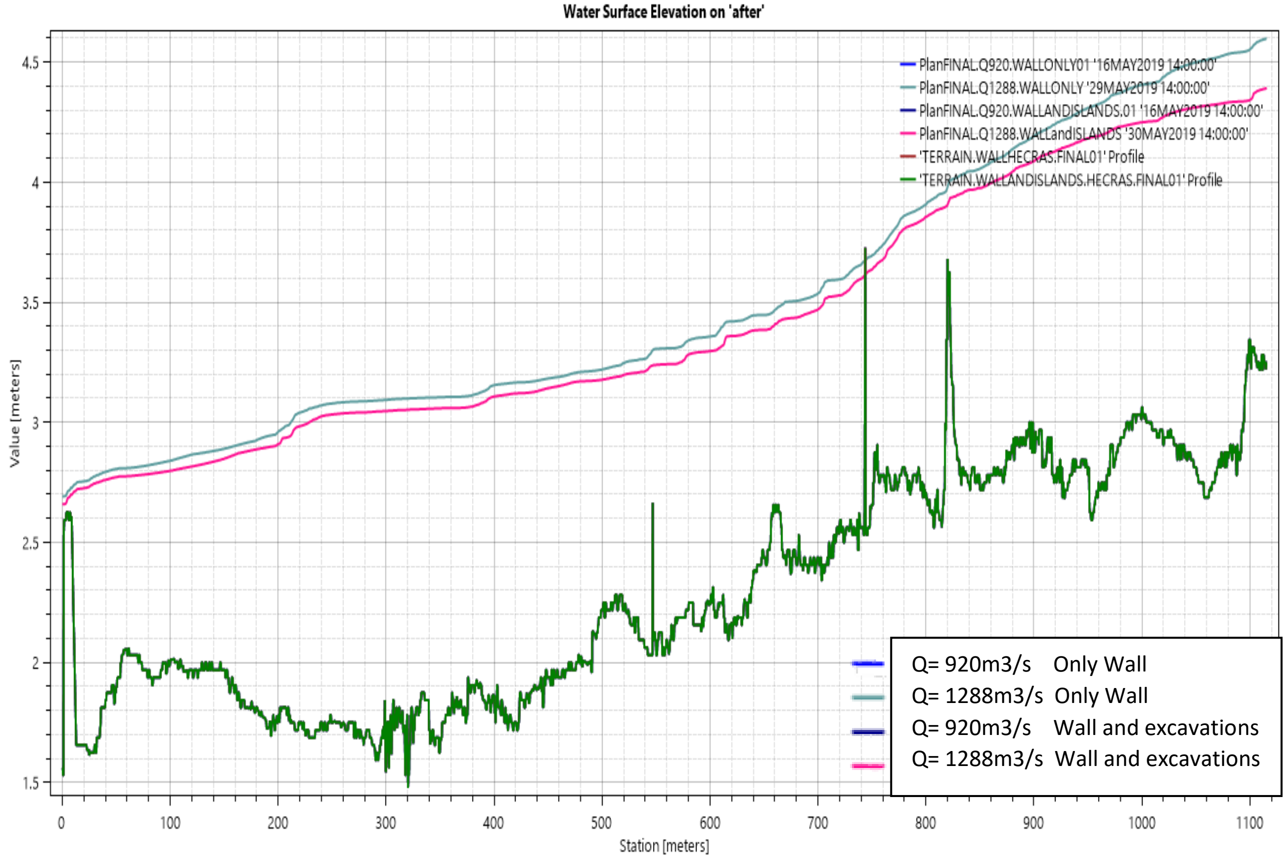


Figure G.2 Profile line along the sections just after the wall in the lower part of the village (same line as in figure G.1 but a few meters further into the city). Green line represents the elevation of the terrain in this area. This figure shows that water does not appear anymore after the wall when the effect of climate change is neglected, i.e. when the discharge value is 920m3/s.

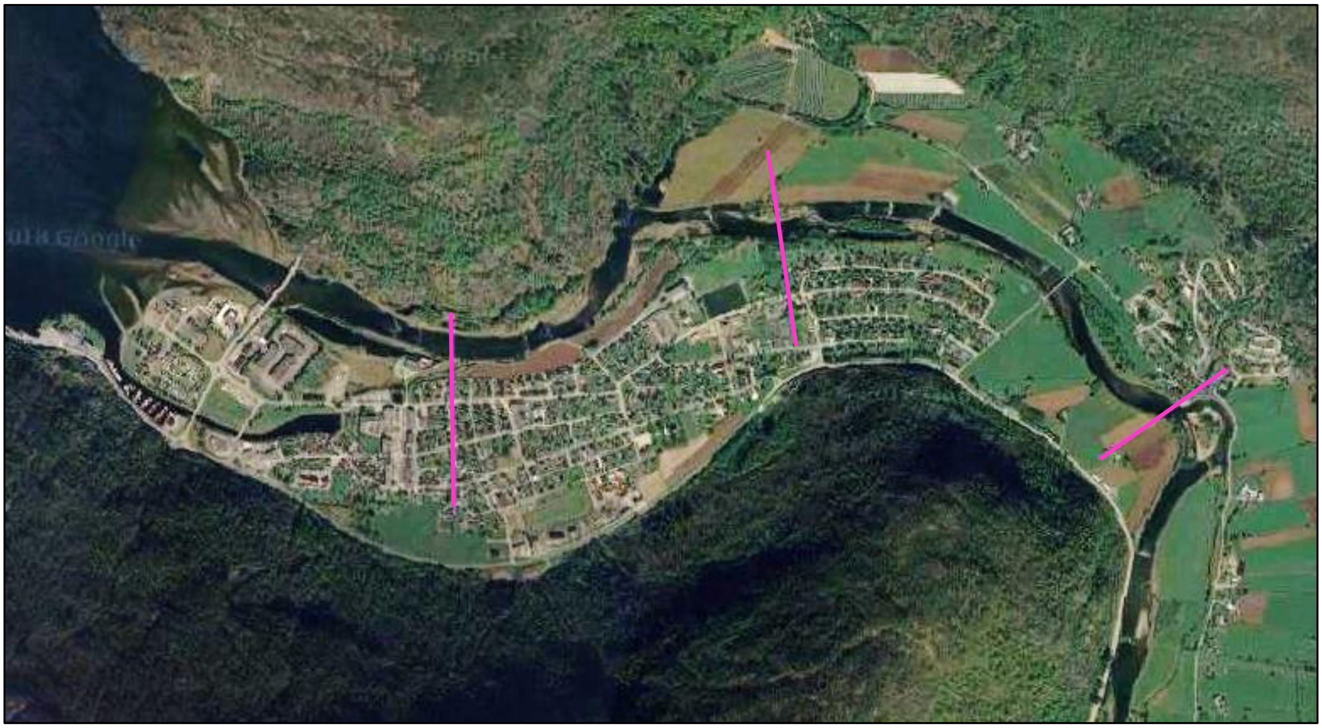


Figure G 3: Profile lines selected to check the WSE and the effect of the wall in some cross sections

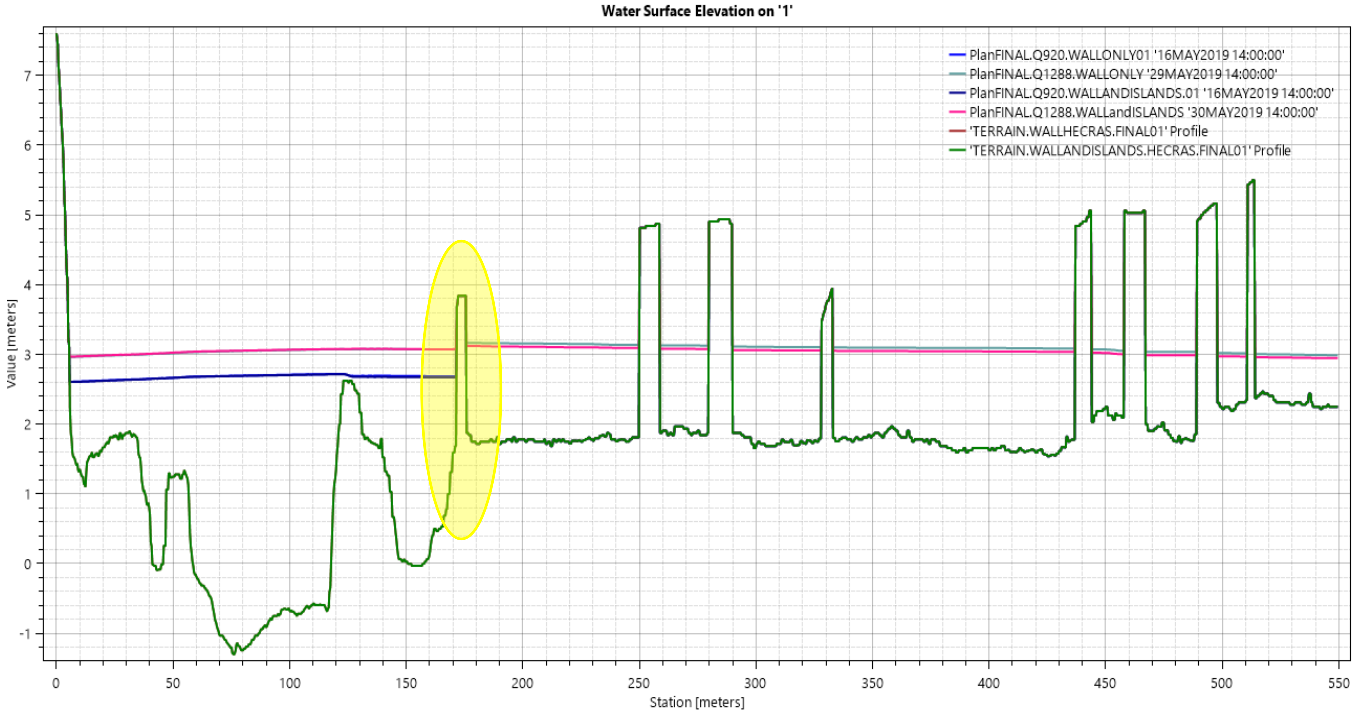


Figure G.4: Terrain (green) and WSE for the profile line on the left. The peak on the terrain marked in yellow represents the wall The rest of the peaks appearing in the terrain are buildings. The figure shows that the wall stops the city to get flooded when the discharge value is 920m3/s.

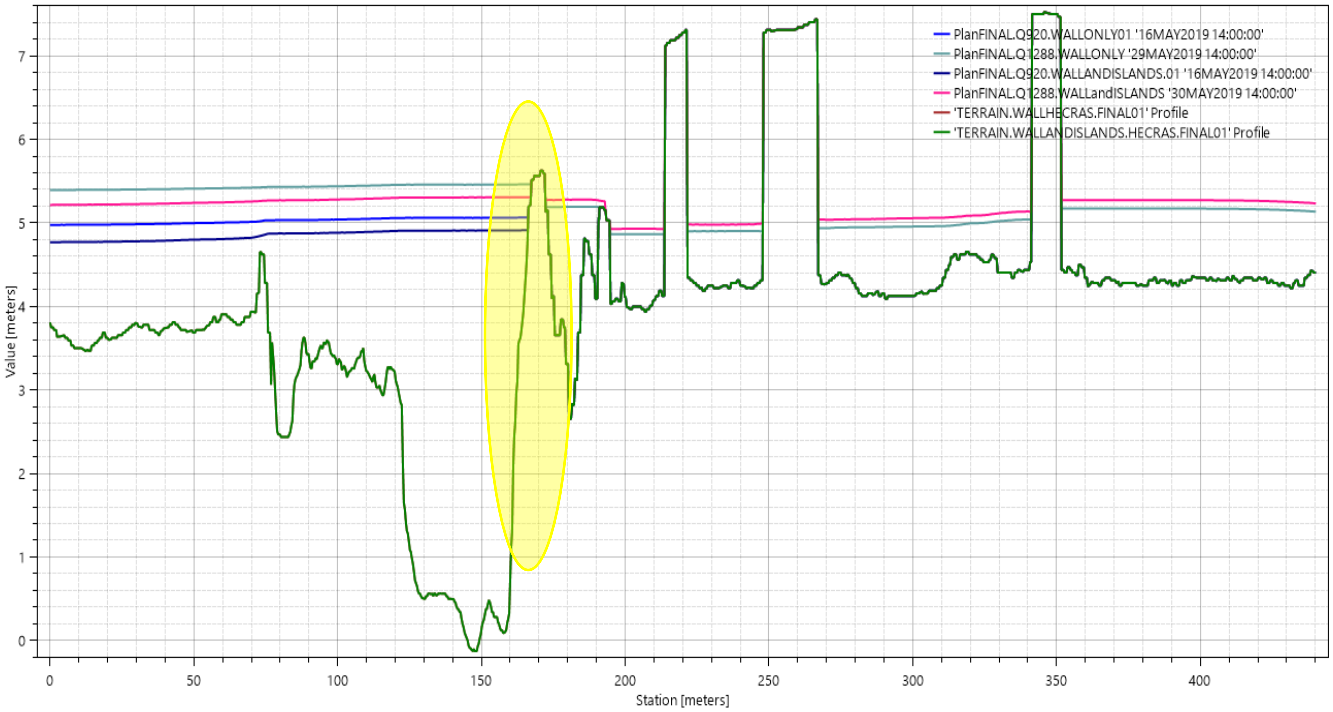


Figure G 5: Terrain (green) and WSE for the profile line on the middle. The peak on the terrain marked in yellow represents the wall. The rest of the peaks in the terrain are due to some buildings of the city. The figure shows that the wall stops the city to get flooded when the discharge value is 920m3/s.

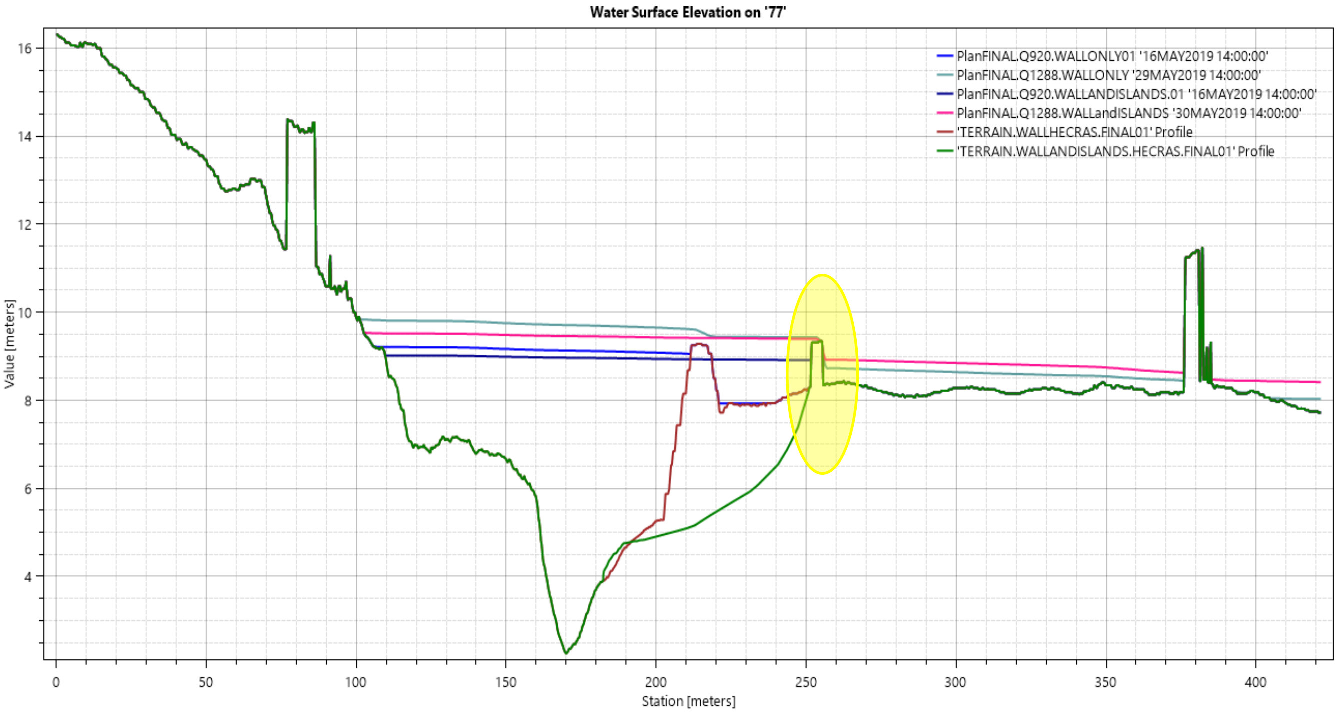


Figure G.6: Terrain (green) and WSE for the profile line on the right. The peak on the terrain marked in yellow represents the wall. The rest of the peaks on the terrain are due to some buildings of the city. The red line indicates how the terrain was in this area prior to the excavation of the river. The figure shows that the wall stops the floods when the discharge value is 920m3/s.

APPENDIX H. FIELDWORK IN LÆRDAL (06-07 MAY 2019)

Figure H.1: Picture of Lærdaselva

Figure H.2: Pictures of the river. The discharge that day was around 38m3/s

Figure H.3: Area classified as Gravel 2. It is in this location where the highest differences between the GPS and the green LiDAR values were obtained

Figure H.4: One of the parts that would be excavated to widen the river if the NVE plans are carried out

Figure H 5: Ortophotomosaic of two parts of Lærdaselva. The picture on the top corresponds to Øye and it has a total error of 5cm. The figure on the bottom corresponds to Ofta and it has a total error of 7cm

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