NTNU
Norwegian University of
Science and Technology

PRELIMINARY FLOOD RISK ANALYSIS FOR CLIMATE CHANGE SCENARIOS: THE CASE STUDY OF THE ORKLA RIVER SYSTEM

Francesc Llorach Paulo

Master's Thesis in Hydraulic Engineering

Submission date: December 2018

Supervisor: Oddbjørn Bruland, NTNU

Co-Supervisor: Tor Håkon Bakken, SINTEF Energi

Ignacio Escuder, UPV

Jessica Castillo, UPV

Norwegian University of Science and Technology

Department of Civil and Environmental Engineering

BACKGROUND

Nowadays, it is expected that climate change will increase the frequency and intensity of floods. This will influence both the likelihood and potential consequences and thus the risk of a flood event. To prepare for the future the society requires a better understanding of the risk and how this will be influenced by a changing climate.

To understand the consequence of floods either from a dam break or a natural flood, it is necessary to identify potential threats and damages. Rising water levels inundate land, infrastructure and buildings. Higher discharges increase water velocities and combined with higher water levels this leads to erosion with a damaging potential to infrastructure, properties and the built environment. The damaging potential is dependent on the flood characteristics.

This work will include the use of hydraulic and risk models to identify and quantify the potential damage of different natural flood events in the present. These models will serve as a preliminary study for future climate change scenarios. In addition, the software tool iPresas Flood will be used to compute risk, to evaluate and demonstrate how outcomes can be used to inform decisions on flood risk management.

The Orkla river system will be considered as the case study area in this work.

With this master thesis, the student hopes to contribute for present and future with a project which means to cover risk analysis for current vulnerable systems against the climate change in the future. Specifically, it will cover the aspects needed first to evaluate future scenarios for climate change.

- Regulatory context and references of interest for risk and flood management.
- Methodology that can be followed or modified to acquire system capacity.
- Flood study for different return periods of the system nowadays.
- Risk evaluation provide the software developed at UPV.
- Results comparison with Norwegian Water and Energy Directorate’s maps for flood areas.

PREFACE

This master thesis comes from the deep interest on the candidate in water resources, floods, river engineering, environment… and as a future hydraulic engineer, it is a duty to assure water is an ally and not an enemy.

Because of this, in hands of engineers stand the possibility to design, to build, to decide and to contribute for a safe society development.

Nowadays, we all are living in a changing climate change environment. Climate change has become part of our lives, despite it is being a dangerous phenomenon. It affects directly to climate, producing floods and droughts, water quality changes, sea level increase, ice melting...

Studying a Msc in Hydraulic Engineering and Environment in Universitat Politécnica de València, believed an exchange Erasmus in Norway, and becoming a NTNU member, could be a great opportunity to improve knowledge in the mentioned themes.

The audience of this thesis is technical personnel on a senior level, and therefore it was assumed that the reader has a good understanding of hydrological processes, geographical information systems and modeling, as well as about risk management and climate change.

Furthermore, many terms that are not common knowledge to the public were not defined or explained.

Explanations for such terms can be found in the glossary or easily found on the internet.

ACKNOWLEDGEMENTS

First, I would like to thank my supervisors in this wonderful country, Oddbjørn Bruland and Tor Håkon Bakken. Both of you made possible this case study, thanks for all the meetings you set up at the beginning and during the semester, your support and your trust till the end.

Thanks to Jessica Castillo, my supervisor in Valencia, who made me feel confident and helped me incredibly in this thesis. I will not forget her interest during my semester abroad, all the mails we have sent each other and her support.

To my friends at home, some of them came to visit me and we had a good time enjoying Trondheim, I thank you for your friendship.

To my friends in Valencia, you have listened my worries and supported me always. Thanks for all the laughs and conversations.

To my family, my parents and my brother, thank you so much for your effort and for making my experience in Norway possible. I love you.

And to Carla, for her trust and support during all this time, there are no words to explain how much you have done for me… and there are no words to say how grateful I am for being part of my life.

To all of you, my deepest and most sincere gratitude.

DISCLAIMER

I hereby verify that all work presented in this report is my own unless it is attributed to another source. All contributions from other sources are identified through citations during the reading, referenced in the last section or by other means.

TABLE ON CONTENTS

LIST OF FIGURES

LIST OF TABLES

GLOSSARY

Flood: *the temporary covering by water of land not normally covered by water. This shall include floods from rivers, mountain torrents, Mediterranean ephemeral water courses, and floods from the sea in coastal areas, and may exclude floods from sewerage systems.*

Flood risk: *combination of the probability of a flood event and of the potential adverse consequences for human health, the environment, cultural heritage and economic activity associated with a flood event.*

Flash Flood: *a flood that rises and falls quite rapidly with little or no advance warning, usually the result of intense rainfall over a relatively small area.*

River basin: *area of land from which all surface run-off flows through a sequence of streams, rivers and, possibly, lakes into the sea at a single river mouth, estuary or delta.*

Damage to people: *in principle, apart from loss of life, damage to people could also consider other aspects such as people injured with different degrees of gravity. However, due to the difficulty of quantification of wounded numbers, quantitative analysis usually focuses only on the first aspect.*

Direct economic damage: *damaged caused directly by the impact of the flood and the most visible type. It includes the cost associated with the damage suffered by the natural flood itself.*

Indirect economic damage: *damage happening after the event as a result of the interruption of the economy and other activities in the area.*

FN graph: *one of the most extended representations. Which is simply the cumulated form of fN graphs. In this way a curve is obtained instead of discreet points. In this curve, the horizontal axis represents the consequences (N) and the vertical axis the probability that these consequences (F) are exceeded.*[1]

Event tree: *is a representation of a logical model that includes all the possible chains of events resulting from an initiating event. The following figure shows an example of tree along with the notation used to refer to its*

[1] In this thesis will be used F-PAP and F-D curves, which work the same way than F-N curves

parts. Furthermore, in order to calculate the probability of occurrence of one of the chains of events the conditional probabilities in the branch must be multiplied. Since the rule requires the branches from a same node to be mutually exclusive and collectively exhaustive, the sum of the probabilities of all of them must be one.

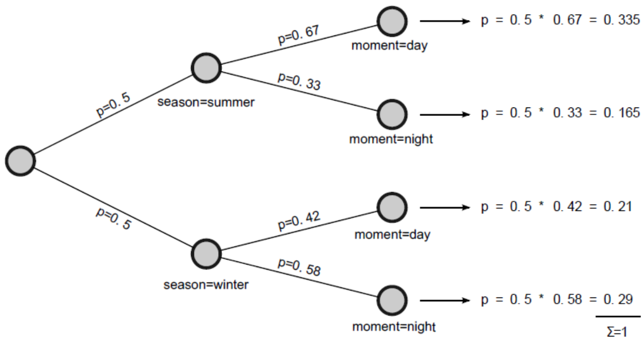

Figure 1: Example of calculations of the probabilities of all possible chains of events for an event tree.

Other damages: *related to environmental damage, social disturbing, loss of reputation, attachment to historical or cultural heritage, etc. All these aspects are difficult to quantify thereby they are usually treated in a qualitative way.* [1]

1 Introduction

1.1 Previous studies regarding river Orkla basin

The previous studies in the Orkla river system are focused on studies defining the hydropower production, but they are also tied to the salmon changes; regulation, temperature on growth of brown trout, annual loss of Atlantic salmon, etc.

Relevant to this case, there exist some articles that study the river system like routing, dampening and hydropower, like the following ones:

"A river routing model for Orkla river" Cao Tri Nguyen, June 2017

"Flood dampening in hydropower systems" Bendik Hansen, July 2018

"Modelling winter operational strategies of a hydropower system" Netra Timalsina, Felix Beckers, Knut Alfredsen, February 2016

In general terms for Norwegian rivers, there are also articles about climate change in regulated rivers for hydropower.

1.2 Project goals

In this project is pretended to study the current situation of flood risk in Orkanger (Study Area in chapter 4). To achieve this goal, it is used methodology based in theorical concepts explained in chapter 3.

Outcomes from two models will be analyzed:

Hydraulic simulations: maps from 1D and 2D calculations showing flooded areas due to different floods events. This allows the analysis of how flood areas are affected in extension, depth and velocity.

Risk models: to know how flood events affect in economical and societal terms.

Comparison of results with the Norwegian Water Resources and Energy Directorate's (NVE) maps for flood areas.

1.3 Historical floods

In earlier times Orkangerflata was considerably larger than it is today. Orkla has throughout the ages made strong use of this flat. We know that already in 1248, the river took a large part of flat. Other great floods were 1721, 1728 and 1773. The worst flood year, however, was in 1789 - the year of great life. The next flood was in 1812 and in 1828 the next big flood came. Before the flood in 1840 which also took a great deal of Orkangerflata, Fjordgata stretched a few hundred meters further towards Gjølme than now (*Elder historie, www.orkanger.info*).

The highest floods observed were in mid-June 1944 and in late August 1940 with daily discharges of 1256 and 1133 m^3/s, respectively (*Rivers of Europe*).

1.4 Justification

As it is possible to appreciate, the past antecedents demonstrate the justification to study the possible flood impact in the area. An impact that could be increased in the next years by climate change, increasing the probability of flooding and, furthermore, due to the urban development, larger potential damages, such as properties, schools, hospitals, etc.

So, there exist the interest to know which areas can be affected by flooding and the potential risk in economic and societal terms.

2 Basis and regulatory context

This chapter pretends to specify the remarkable laws and regulations from more general to more specific concerning flood risk management.

2.1 European application regulations

"*DIRECTIVE 2007/60/EC OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL of 23 October 2007 on the assessment and management of flood risks*."

This directive was approved based on the *"DIRECTIVE 2000/60/EC OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL of 23 October 2000"* [2] which objective is to achieve the good water status, its supply and ensure a good water policy.

Here, content of Directive 2007/60/EC is included:

"CHAPTER I
GENERAL PROVISIONS
Article 1

The purpose of this Directive is to establish a framework for the assessment and management of flood risks, aiming at the reduction of the adverse consequences for human health, the environment, cultural heritage and economic activity associated with floods in the Community."

"CHAPTER II
PRELIMINARY FLOOD RISK ASSESSMENT
Article 4

1. Member States shall, for each river basin district, or unit of management referred to in Article 3(2)(b), or the portion of an international river basin district lying within their territory, undertake a preliminary flood risk assessment in accordance with paragraph 2 of this Article.

2. Based on available or readily derivable information, such as records and studies on long term developments, in particular impacts of climate change on the occurrence of floods, a preliminary flood risk assessment shall be undertaken to provide an assessment of potential risks. The assessment shall include at least the following:

(a) maps of the river basin district at the appropriate scale including the borders of the river basins, sub-basins and, where existing, coastal areas, showing topography and land use

(b) (…)

(c) a description of the significant floods which have occurred in the past, where significant adverse consequences of similar future events might be envisaged."

"CHAPTER III
FLOOD HAZARD MAPS AND FLOOD RISK MAPS
Article 6

3. Flood hazard maps shall cover the geographical areas which could be flooded according to the following scenarios:

   (a) floods with a low probability, or extreme event scenarios;

   (b) floods with a medium probability (likely return period $\geq$ 100 years);

   (c) floods with a high probability, where appropriate.

4. For each scenario referred to in paragraph 3 the following elements shall be shown:

   (a) the flood extent;

   (b) water depths or water level, as appropriate;

   (c) where appropriate, the flow velocity or the relevant water flow."

2.2 Norwegian regulations

Applied to Norway, the Norwegian Water Resources and Energy Directorate is the responsible of determinate and make public the flood hazard maps and flood risk maps for the different return periods. Its regulation is *"PLANLEGGING OG UTBYGGING I FAREOMRÅDER LANGS VASSDRAG, SIST REVIDERT 5. MARS 2009" / "PLANNING AND DEVELOPMENT IN HAZARDOUS AREAS ALONG WATERWAYS, LAST REVISED 5 MARCH 2009"* [3]

"4.1 Introduction - Technical Regulation

Safety levels against floods along waterways are referred to NVE Guidelines No. 1/2007.

Flood safety levels in NVE's guidelines fulfill the safety requirements in TEK with related guidance. The security levels specified also fulfill the requirement in plan and building law on "adequate security", cf. section 688 of the Civil Code. TEK provides three safety classes for slots, broken down by consistency and largest nominal annual probability.

The guidelines provide a separate level of safety at risk of killing camp because it is in practice impossible to indicate the annual probability of vigilance cuts."

"4.2 Safety level against flood and icecap

The recommended flood and ice-level safety levels are specified by purpose and largest nominal probability of such events.

Safety class	Area use, buildings, technical installations	Highest annual probability
		Inundation, erosion, ice break-up
F 1	Small garages, boat-houses, storages	1/20
F 2	Houses, cabins, summer houses, industry, commercial activity, farming buildings, schools, infrastructure, etc.	1/200
F 3	Hospital, emergency institutions and critical infrastructure	< 1/1000

F 1: The class includes areas with buildings and facilities with a small amount of people and small ones economic or other social consequences, such as simple constructions like garages and warehouses.

F2: The class includes areas with most types of buildings with personal care, both housing, industry and office. The class also includes areas with farms in operation, schools and school's infrastructure. The financial consequences of damage to these buildings can be large. But critical social functions are not put out of play.

F3: The class includes areas with buildings for especially vulnerable social functions:

- area and buildings for particularly vulnerable groups of the population, orphanages and the like

- areas and buildings that will work in emergency situations, hospital, fire department, police stations, civil defense facilities and infrastructure of major social importance

- landfills (landfills that can lead to major pollution hazards) There will be great uncertainty about how large areas will be affected by a 1000-year flood. Therefore, it should be endeavored to add such features with a good margin water level of an estimated 1000-year event."

"*5.2.1 Municipal plan and municipality plan*

The assessment of flood hazard at municipal level is intended to clarify whether there is a land area potential flood hazard in areas where development may be relevant and how to do it consider hazardous areas in the plan. Flooding means both flooding, erosion and shedding events in steep waterways.

A. Identification and marking of all rivers, streams and lakes in the plan area

B. Marking of any known danger zones

C. Assessment of potential hazards beyond known danger zones

D. Potential hazard areas and known hazards are incorporated into the municipal plan"

3 Project’s methodology

This chapter describes the methodology used for this master thesis.

As it is explained in the background, the thesis includes a preliminary analysis for flood risk as an input for the analysis of future climate change scenarios. So, the main objective is to define the current situation about flood risk.

For this objective was needed to:

Justify the need for such study due to historical events that have put in potential risk Orkanger’s population by flooding.

Research for previous studies.

Perform a study area about general themes, then physical characteristics about the catchment and compilation of demography information. This allows to know better the emplacement and prepare the geographical information, such as inflows for the following hydraulic model, location of vulnerable areas and buildings, etc.

Research for relevant information to build the hydraulic model: Digital Elevation Models 1m*1m, and land cover information.

The results obtained by 1D and 2D calculations are then used along with a geographical system again to determinate the land area affected and estimate then the economic consequences and potential affected population.

Then, it is needed to establish the different phases of the project in a scheme, including the references to each chapter or annexes of this document (Figure 2).

The methodology was based in theorical concepts referenced in chapter for as [7]–[12].

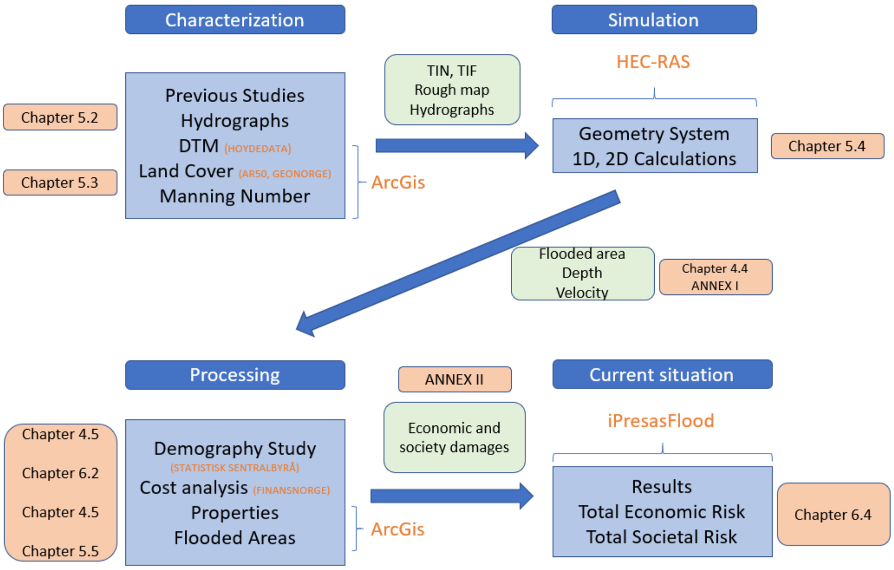

Figure 2: Diagram of the applied methodology for flood risk analysis

4 Study area

4.1 Location

The area will be focused in the Orkla river at his pass for Orkanger city, which is the main coastal city in the catchment and located in Orkdalsfjorden (60º 17' N, 9º 50'E). It is situated in Sør Trøndelag, from Trøndelag county in Norway.

With 18848 km^2, Sør-Trøndelag receive the precipitation for the river Nidelva, Gaulaand Orkla and Røros.

The river Orkla is situated in the counties Oppdal, Hedmark, and Trøndelag in central Norway. The river stretches across 172 km and has a catchment area of 3053 km^2 at its outlet in Orkdalsfjorden.

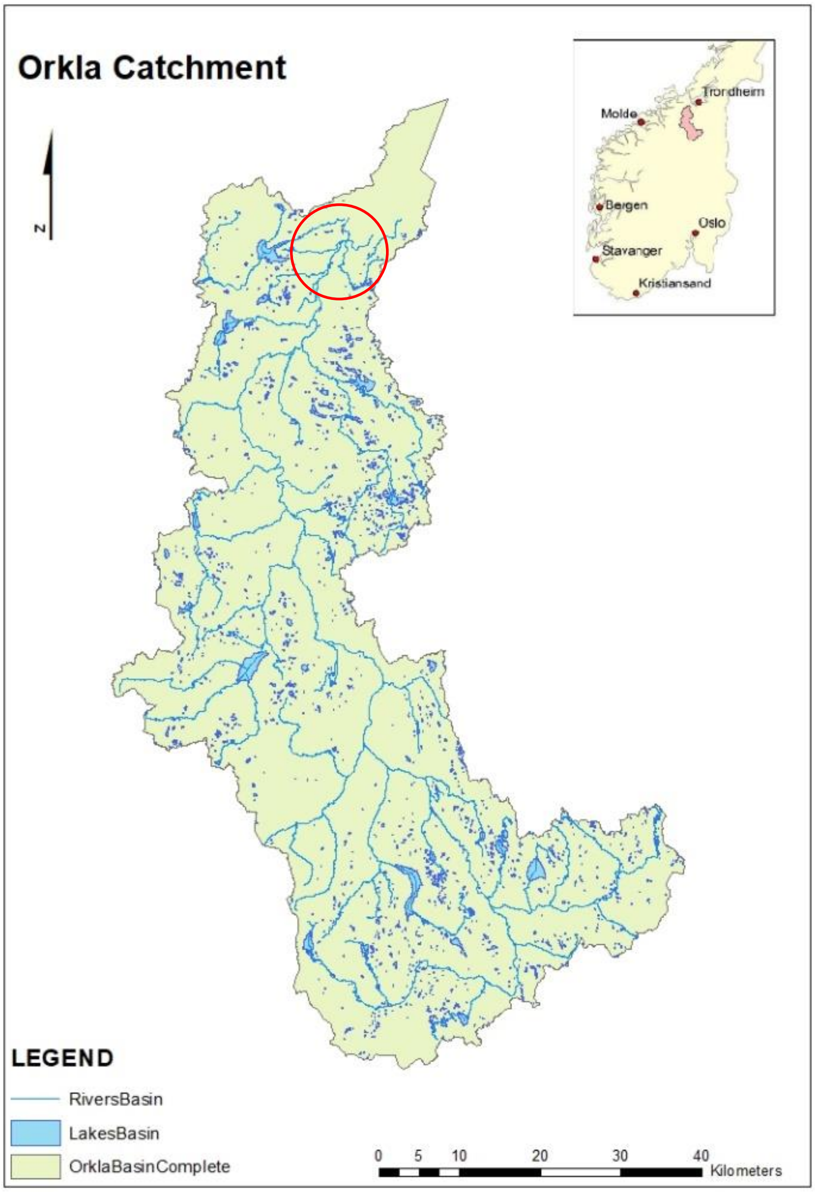

Figure 3:The Orkla river catchment

Figure 4: Orkanger aerial photography

4.2 Catchment general description

Due to the lack of natural lakes in its main river, Orkla has a limited potential to dampen floods. As it is possible to observe after, it comes from the slope in the catchment. There are 5 large hydropower stations in the system: Ulset (35MW), Litjfossen (75MW), Brattset (80MW), Grana (75MW), and Svorkmo (55MW) with an average annual production of 1371GWh (*Toldnæs and Heggstad 2017*).

Focused in this study, the last gauge in the catchment is at the Bjørset Dam, built in 1983 and 98m fall height. All the reservoir regulation happens upstream of that point, and Bjørset gauge has a long timeseries both before and after regulation. (*https://tronderenergi.no/produksjon/kraftverk/svorkmo*).

The Bjørset Dam catchment area is 2317 km^2 with an elevation ranging from 130 masl. to 1640 masl. It contains all the reservoirs and power plants mentioned above and has a total reservoir storage capacity of 426 million m^3. The average gauged flow since 1912 is 48,4m^3/s (1.526 mm^3) (according to NEVINA the annual runoff is 679 mm, 49,9 m^3/s).

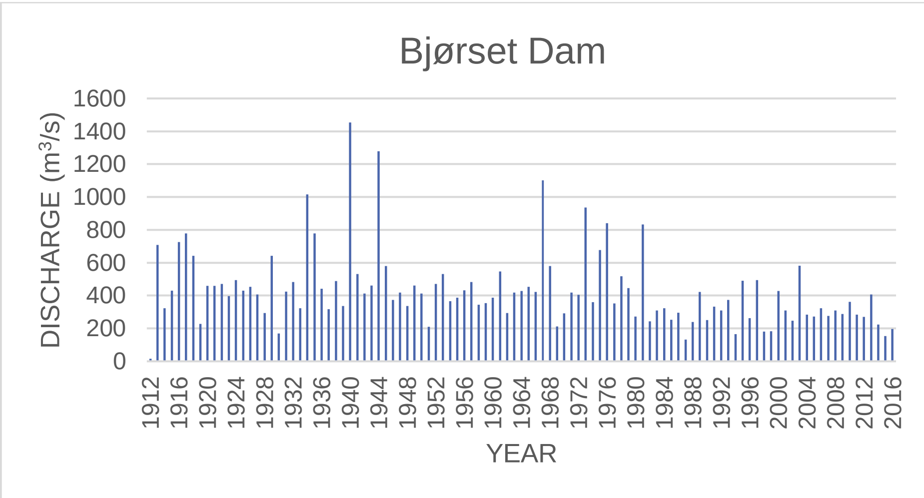

Figure 5: maximum historical discharge at Bjørset Dam till 2016

It is relevant to know the maximum discharge of the dam due to the proximity to the study area, which is downstream of the dam, and there are short number of reaches incorporated later. Also, the inflow designed in the hydraulic model.

Later, it will be used for the hydrographs, a recompilation of flow registered downstream and close to Orkanger city, once all the reaches have arrived to the Orkla river.

4.3 Physical characteristics of the study area

The catchment physical characteristics define how the flow acts. So, it is important to study some aspects of the catchment. In this part there are some morphological parameters that could be calculated with ArcGis using geographical information. In the following table is summarized the basic parameters.

Table 1: Parameters in the river Orkla catchment

PERIMETER (Km)	496.35
AREA (Km2)	3053.02
HIGHEST ELEV (m.a.s.l)	1603
MINIMUM ELEV (m.a.s.l)	0
GRAVELIUS COEF.	3
RIVER SLOPE	0.003

- Gravelius coefficient: It defines the relation between the perimeter and the circumference with the same area as the catchment.

$$Kc = \frac{P}{2\pi R} = \frac{0.28 * P}{\sqrt{A}}$$

Where P is the perimeter, R is the radium circumference and A is the area's catchment.

A coefficient above 2 means an oblong catchment. Oval and oblong catchments use to get flash floods more easily than the ones with a minor Gravelius coefficient.

- Hypsometric curve: defines the relation between the elevations and area.

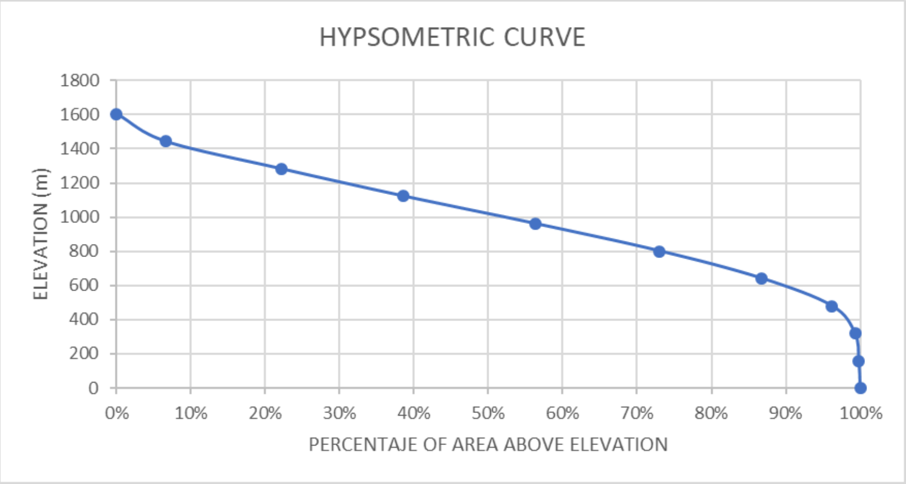

Figure 6: Hypsometric curve for river Orkla catchment

4.4 Demography

As it is known, the object of the study is to calculate the flood risk for a natural flood to prevent the population and to know the possible economic damages. So, it is priority to acquire information about the demography in the study area.

In the following tables it is possible to appreciate the number houses and how many people lives in Ørland, which is the region of the villages in the relevant area. The information available exists only for 2001 and 2011 so, it is going to be compared and studied the development for this decade to know how it is growing or decreasing.

On one hand, the development that it is appreciate it is not significant, in fact, it is practically the same, because the total number of people is 10 people less than the last decade.

On the other hand, it is possible to observe an increasing number of houses with a household size of 1 and 2 persons significantly.

Due to that numbers, the development of society about population is growing slowly or not even growing, but it is observed the number of homes is increasing.

Table 2: Population and household size in 2001 for Ørland (Statistisk Sentralbyrå)

2001						
TOTAL HOUSES	HOUSEHOLD SIZE					TOTAL PEOPLE
	1 PERSON	2 PERSONS	3 PERSONS	4 PERSONS	5 PEOPLE OR MORE	
2147	782	575	299	290	201	4994

Table 3: Population and household size in 2011 for Ørland (Statistisk Sentralbyrå)

2011						
TOTAL HOUSES	HOUSEHOLD SIZE					TOTAL PEOPLE
	1 PERSON	2 PERSONS	3 PERSONS	4 PERSONS	5 PEOPLE OR MORE	
2224	847	624	303	270	180	4984

But what is most important is where that homes are located. With GEONORGE information it was possible to stablish location points at home addresses, this includes industry, farms and all kind of properties. So, in the next figure it is observed their proximity or not to the river Orkla.

Figure 7: Properties location close to the river Orkla

As a conclusion, it is observed a high number of properties are located next to the river, which means they are under the influence and risk of floods. It is needed to make a special mention in the last reach of the river, in the entrance of the fjord, which contains many properties (industry and homes).

Before that, lots of fields and orchards are in the vicinity of the river. That would decrease the economic costs of a flood in case it shall happen.

Furthermore, it is needed to explain the area showed is the most relevant in property aspects because of the number of them that includes. Due to the difficulty to represent hundreds of properties, it is easily to show the relevant areas with high density of buildings and influence.

4.5 Protected areas, environment and cultural spots

In this section is tried to make a list of possible places of interest affected. For this purpose, there is a search done for places such as nature reserves, places of cultural interest, highways or high traffic roads, hospitals, etc.

The fact is to stablish places with a superior vulnerability in flood case.

Buildings	St. Olavs hospital - Orkdal sjukehus/ with a capacity of 110 beds
	Amfi Orkanger - Shopping mall/ 13.200m^2 opened 12h a day
	Orkla camping/ with a tenant capacity of 90 people
Roads and highways	fv460/ Primary County Road
	fv710/ Primary County Road
	fv462/ Primary County Road
	fv65/ Secundary County Road
Cultural interest	Bårdshaug stasjon - Train museum
	Little Norway Thamspaviljongen Orkdal/ Norway's stave church

No nature reserves are situated in or close to the study area. The environment is quite urbanized or at least used to farm.

5 Hydraulic model

5.1 Introduction

The hydraulic model was focused in obtaining the pluvial flood event due to the discharge of the Bjørset dam upstream. There was no included any event to study the dam break and its associated flow. The model analyzes the flood events of different return periods based in the results of the hydrographs of discharge of the dam for each flood.

To simulate the different floods, it is needed to stablish a hydraulic model which allows the calculations to now the flood area. The software used is HEC-RAS 5.0.5, and in this part, it is going to be explained how the computational scheme works and the equations used to define the results.

5.1.1 Computation scheme

- Equations
  - Full 2D Saint-Venant
  - Diffusive Wave Approximation
- Solutions
  - Coupled 1D and 2D
- Computational Engine (64 bits)
- Multiple Processors
- Mesh
  - Structured (explained in 5.4)

5.1.2 Equations

The unsteady flow requires the Saint-Venant equations:

$$C = \frac{V \Delta T}{\Delta X} \leq 1.0 \quad (with\ a \max\ C = 3.0)$$

Or

$$\Delta T \leq \frac{\Delta X}{V} \text{ (With C = 1.0)}$$

Where C is the Courant Number, V is the Flood wave velocity in ft/s, ΔT is the computational time step in seconds and ΔX is the average cell size in feat.

The Diffusion Wave Equations:

$$C = \frac{V\Delta T}{\Delta X} \leq 2.0 \quad (with\ a \max\ C = 5.0)$$

Or

$$\Delta T \leq \frac{2\Delta X}{V} \ (\text{With C} = 2.0)$$

Where the parameters mean the same as in the Saint-Venant equations.

And the Conservation of the momentum:

$$\frac{\partial U}{\partial t} + U\frac{\partial U}{\partial x} + g\frac{\partial v}{\partial x} - g(I_b - I_f) = 0$$

Where each parameter represents by order: local acceleration, convective acceleration, pressure gradient, bed slope and friction slope. [4]

5.2 Hydrographs

The hydrographs used for modeling the hydraulic system were provided by SINTEF (NTNU). SINTEF is one of the largest independent research organizations in Europe, carrying out several thousand projects for customers. The hydrographs come from the study of flood dampening in the Bjørset dam as a hydropower system. In the following paragraphs it is mentioned how they were calculated, and the methodology that was used:

- <u>Reservoir release capacities and transfer capacities</u>: The potential releases were estimated using release gate dimensions and elevations supplied by TrønderEnergi and a basic orifice flow equation:

$$Q = B * h * C_d * \sqrt{2 * g * H}$$

where Q is the maximum potential release through the opening, B is the width of the gate in meters, h is the height of the gate in meters, Cd is the discharge coefficient, g is the force of gravity, and H is the head of water above the center of the gate in meters. Cd was assumed to be 0.61 due to lack of data on the gates.

- WEAP: Water Evaluation and Planning System (*www.weap21.org*) is a water resources planning tool that lets the user assess the effects of both supply characteristics (streamflow, groundwater, etc.) and demand characteristics (water use pattern, efficiency, allocation priority, etc.). The system integrates the simulation of both natural processes (e.g. rainfall runoff models) and engineered components (e.g. reservoirs and powerplants). It also has integrated GIS functionality, and utilizes a graphical user interface where components can be added and arranged in a user-friendly manner.

- HBV rainfall-runoff simulation: The standard HBV-model is divided into 4 routines: the snow routine, the soil routine, the upper zone, and the lower zone. The snow routine is divided into 10 elevation zones for the catchment in question, to more accurately simulate differences in snow processes due to elevation changes. It uses a degree-day model to simulate snow-melt. The soil routine uses a non-linear soil- moisture equation to generate surface flow, and the upper and lower zone use linear tanks with varying numbers of outlets which shape the hydrograph.

- PINE HBV: The benefit of the HBV model is the relative ease with which it can be set up and calibrated for a catchment with limited data. Inputs consist of fixed catchment characteristics, such as area and elevation zones; regional parameters, typically only potential evapotranspiration; and temperature and precipitation time series. All the remaining parameters, such as snowmelt temperature and linear tank outlet coefficients, are calibrated based on observed flow timeseries. It is very helpful to have an auto-calibrator for this process, as doing it manually can be challenging. An already developed HBV model called PINE HBV with an integrated PEST auto-calibrator was initially used. The scaling was done based on both area and annual runoff (in mm) compared to the catchment the flow was calibrated for by using the following equation:

$$q_{local} = q_{total} * \frac{A_{local} * Q_{local}}{A_{total} * Q_{total}}$$

Where q is the flow on a given day, A is the area, and Q is the annual runoff to the catchment.

- Multi-catchment HBV model: The benefit of utilizing the distributed data for each catchment was deemed to warrant the creation of a separate HBV model (henceforth referred to as EXCEL HBV) that could simulate all catchments simultaneously and automatically combine the results for comparison with observed flows. All flood simulations were done using the EXCEL HBV output, as it was found to give approximately the same fit as the best simulation from PINE HBV but with the added benefit of presumably representing local phenomena more accurately.

- Scaled observed runoff: There were certain observed floods which were not captured by any of the HBV simulation. Furthermore, the HBV simulations only extend back to 1957 due to the availability of climate data. Therefore, the poorly simulated floods and the floods that occurred in the period before climate data is available were replaced with runoff scaled from the observed values. For those floods, all catchment runoff was scaled from the runoff timeseries does not extend far enough back in time to cover all the floods, and the scaling was done based on area and annual runoff using the last equation.

- Flood simulations: Floods with a simulated (using EXCEL HBV) unregulated peak greater than 800m3/s were selected for investigation and run through the WEAP model setup, as an appropriate number of floods were available above that threshold. The initial reservoir level was set before each flood simulation depending on the time of year, with values for realistic filling obtained from NVE's observed reservoir filling curves for the region. The median filling was used to represent a realistic value.

Each flood was simulated three times: with full reservoirs, with empty reservoirs, and with reservoir at a realistic level. Due to the lack of lake routing and hydraulic constraints on outflow, the full reservoirs scenario is identical to a scenario with no reservoirs at all, and this represents unregulated conditions. For these simulations there was no outflow from the reservoirs unless they were full and spilled. The results were compared to the results from an existing model setup in nMag, a hydropower and reservoir operation simulation. The nMag model was not made for flood simulation, but it was run with and without reservoirs for comparison of the runoff generation and flood peak reduction.

- Flood dampening: The flood dampening of a system was defined as the percentage that the daily peak flow was reduced by. This was done by finding the peak flow during the flood period with and without reservoirs in the system and then calculated using the next equation:

$$\%\ dampening = 100 * \frac{(Q_{peak_{unreg.}} - Q_{peak_{reg.}})}{(Q_{peak_{unreg.}}}$$

where Q_{peak_unreg} is the simulated unregulated peak, and Q_{peak_reg} is the simulated regulated peak with “realistic” initial reservoir filling. [5]

Applying the methods, it is possible to find the results in the document mentioned in the references below.

In this case, the hydrograph used is the result downstream of Vorma river, which is the last affluent river in Orkla river before his arrival to Orkanger. It is possible to see the location in *Geometry system*. The inflow that is used in the hydraulic simulation begins in this spot.

Table 4: Peak flow in Orkla before Vorma’s pass for different return period

Q_5 (m^3/s)	Q_{10} (m^3/s)	Q_{20} (m^3/s)	Q_{50} (m^3/s)	Q_{100} (m^3/s)	Q_{200} (m^3/s)	Q_{500} (m^3/s)
540	627	950	1257	1536	1816	2095

The hydrographs were defined to simulate a peak flow for 24h, increasing from 50 m^3/s to the peak in the first 8 hours and then coming back to the normal flow in 16 hours. The simulation continues for 24h more to see the result after the flood.

The following figures represent the hydrographs used to simulate the floods.

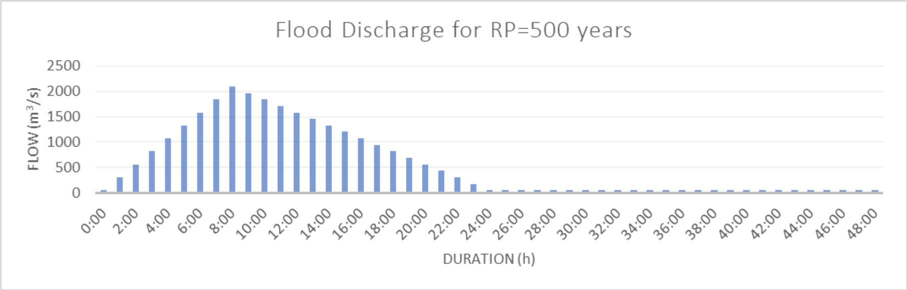

Figure 8: Hydrograph used to simulate 500 years return period flood

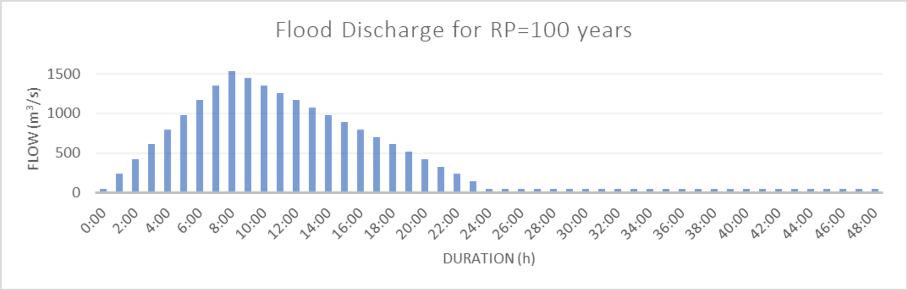

Figure 9:Hydrograph used to simulate 100 years return period flood

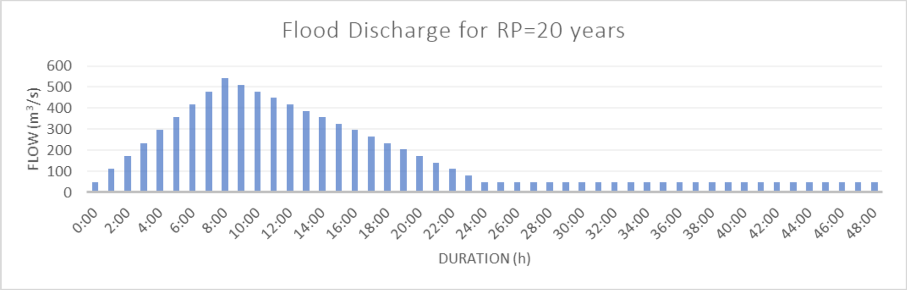

Figure 10: Hydrograph used to simulate 20 years return period flood

As it is seen, the flow increases to the peak at 8:00 and how decreases till the average after 16 hours in each hydrograph.

5.3 Land Cover and Manning number

To model the geometry correctly, it was necessarily to stablish a land cover, which is completed by the Manning number.

The land use was obtained in GEONORGE, which is the map catalog to search for, look at or download the official Norwegian geodata (https://www.geonorge.no/). Using the catalog available, it was possible to define the areas in the study area, as it is shown in Figure 11 with ArcGis.

Depending on the land use, rugosity can be modelled by defining different values for the Manning coefficient. With HEC-RAS, and the Ven Te Chow classification, Table 5 represents those types of use and the number assumed. [6]

Table 5: Land Use and Manning number used in the simulations (AR50, GEONORGE)

LAND USE and MANNING		
AREATYPE_1	**USE**	**MANNING**
10	City (all)	0.013
20	Agriculture	0.04
30	Wood	0.1
50	Terrain	0.05
60	Terrain2	0.035
70	Ice	0.02
81	Channel	0.035
99	Not registered	0.05

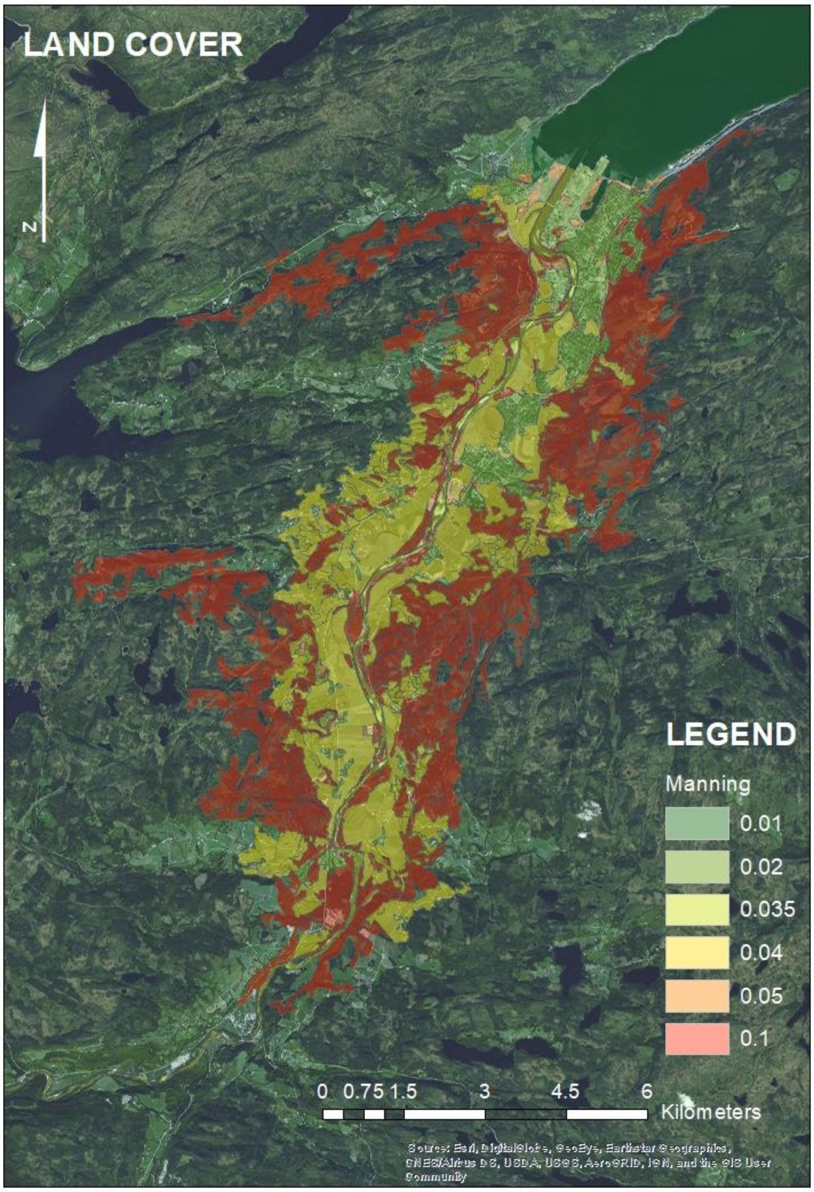

Figure 11: Study area land cover

5.4 Geometry system

In this part is shown the geometry used to define in 1D and 2D the simulations.

First, figure 12 shows the geometry of the Orkla river in this model, using RAS Mapper to define cross sections. It was also necessary to define the geometry editing the bank stations and levees. Using the editor, from the main menu in HEC-RAS in Figure 13 and 14.

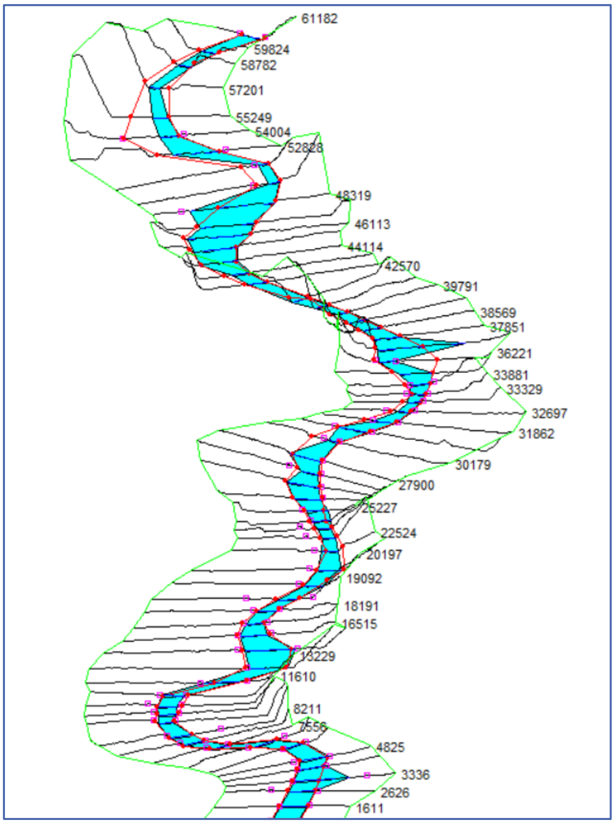

Figure 12: Geometry defining the river Orkla in Orkanger with 20 years return period flood (HEC-RAS)

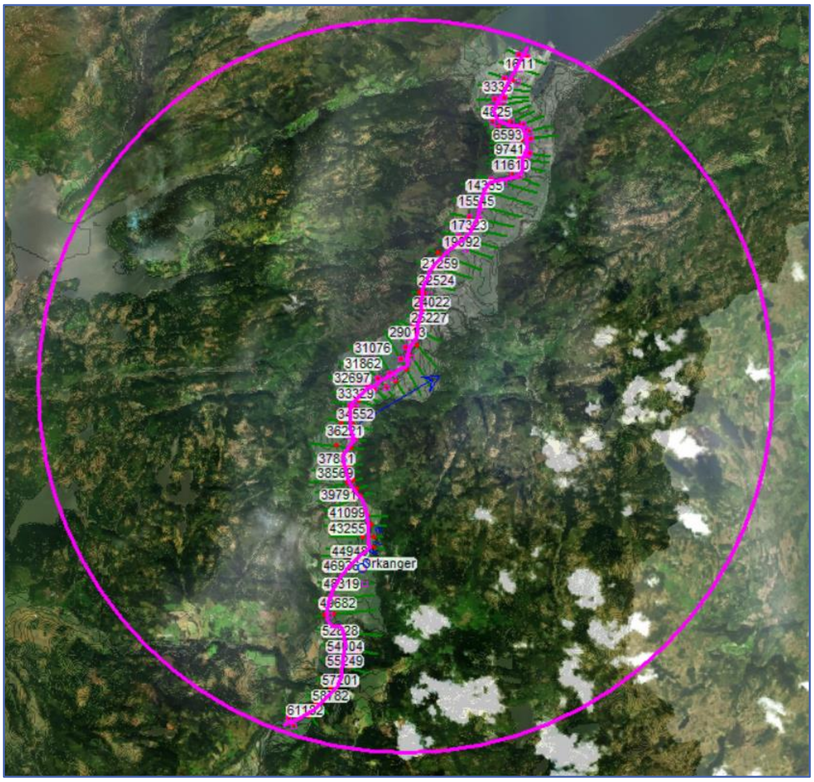

Figure 13: River Orkla cross sections in the edition menu (HEC-RAS)

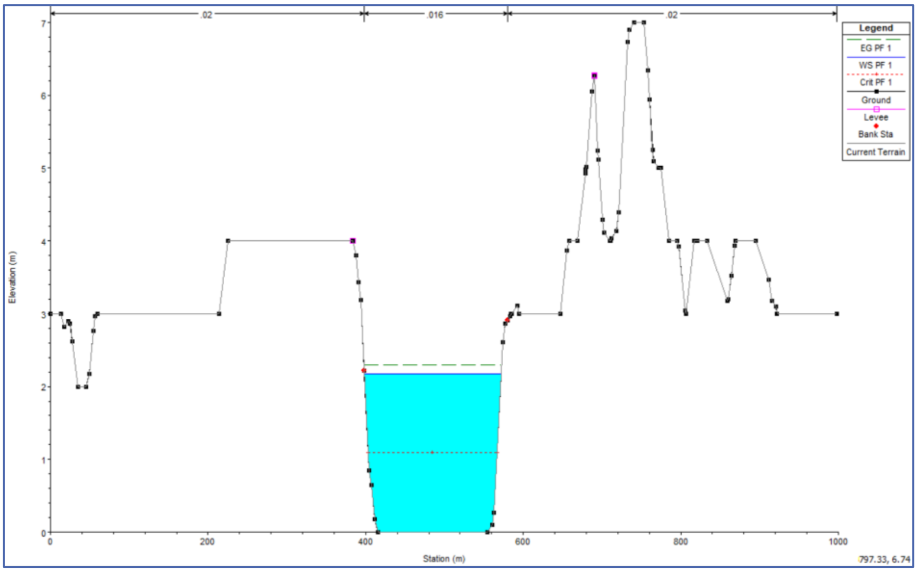

Figure 14: Cross section example in the edition menu (HEC-RAS)

Second, it was defined the 2D model, which needs to be edited in the RAS Mapper.

The model shown in Figure 15 includes: Flow area, Storage areas, Manning values, Perimeter and Break lines, and Boundary condition lines.

The flow area was defined with a 15m*15m mesh that contains 231699 cells, with an average of 225.69 m^2 each one.

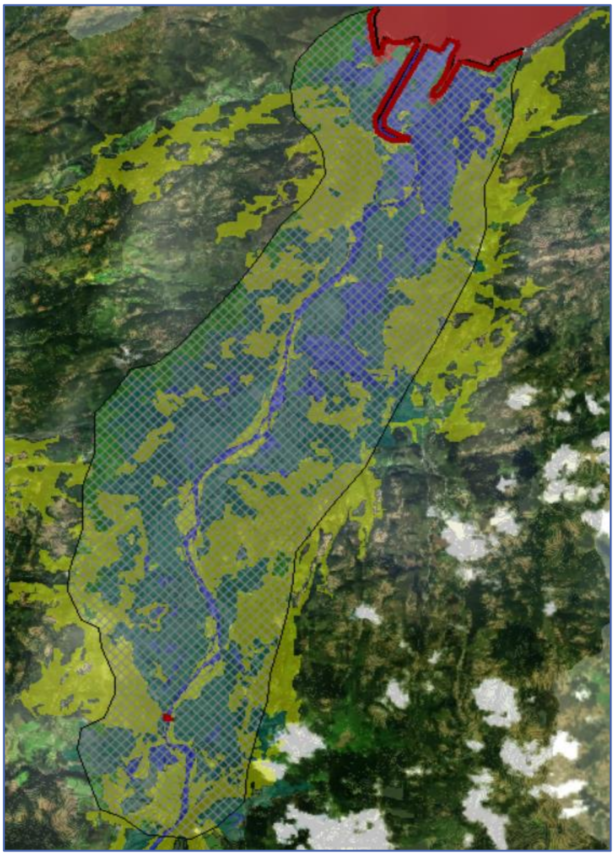

Figure 15: 2D Model edition for Orkla river (HEC-RAS)

5.5 Results

After the simulations for 20, 100 and 500 years of return period with all the mentioned before, it is showed the flood boundary for each one. In Annex I, it is also possible to see conditions for the same returns period for depth and velocity.

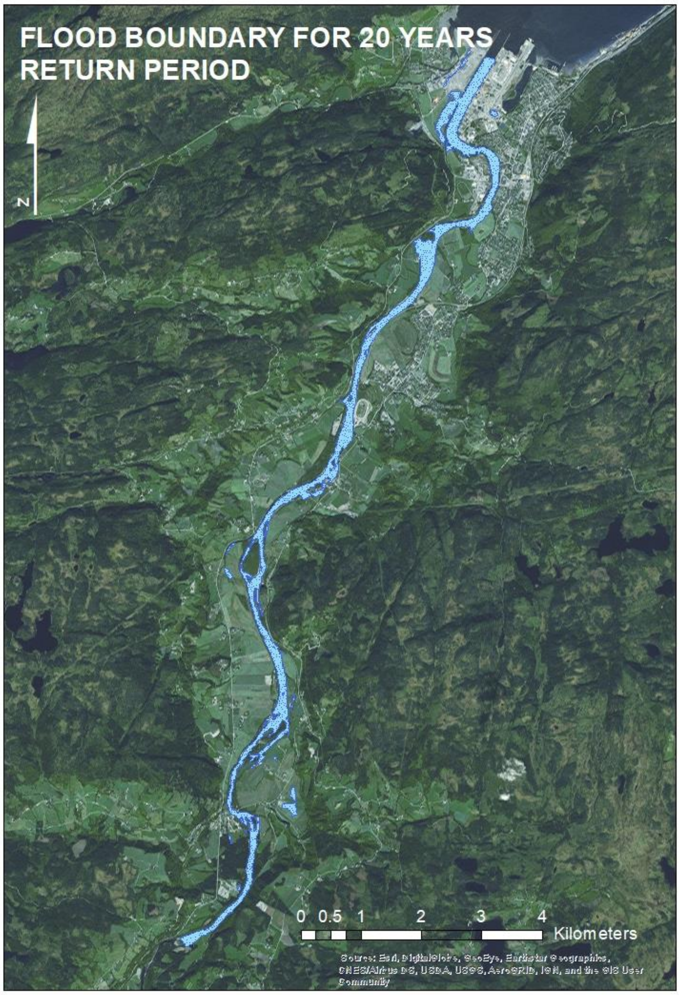

Figure 16: Flood boundary for the river Orkla at Orkanger pass with a RP of 20 years

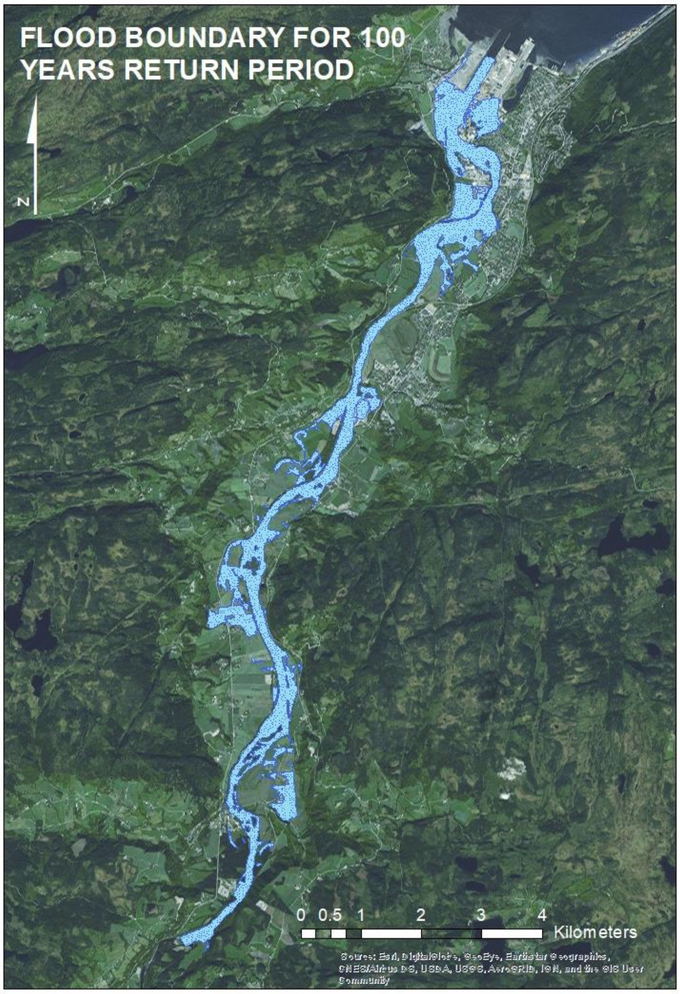

Figure 17: Flood boundary for the river Orkla at Orkanger pass with a RP of 100 years

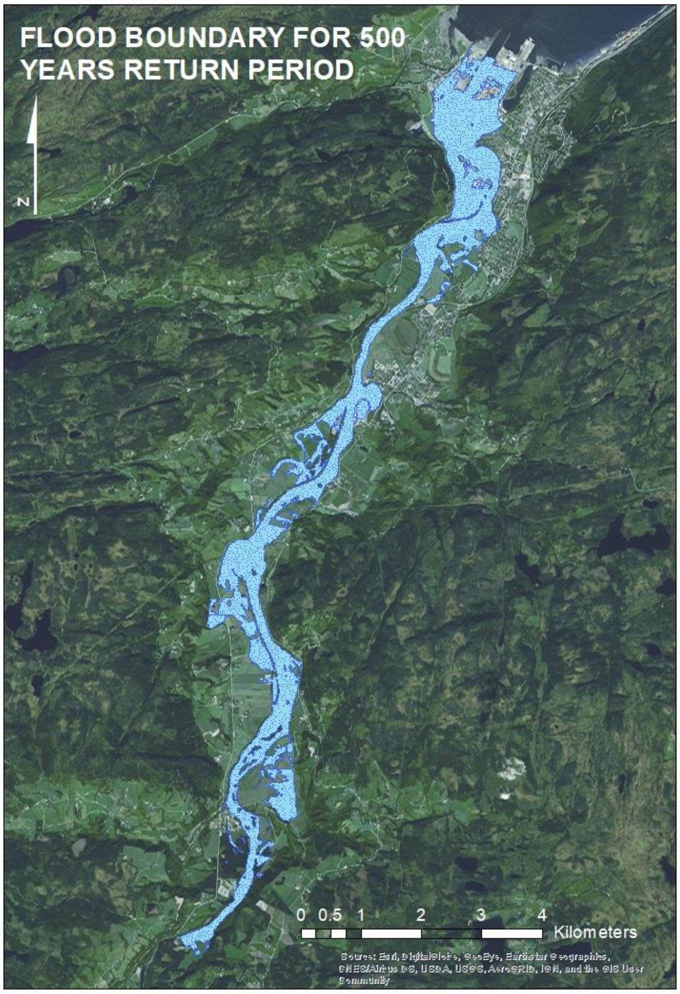

Figure 18: Flood boundary for the river Orkla at Orkanger pass with a RP of 500 years

These boundaries will be used in the next chapter to define areas and buildings affected by the different floods. The risk analysis will be based in these layers and the information from the Statistisk Sentralbyrå.

6 Risk model

6.1 Description

A flood is a non-permanent natural phenomenon, part of the territory is temporarily occupied by the waters. The risk caused by floods in a specific area of the territory is obtained by the combination of danger and vulnerability in the space, as it is outlined in figure 19.

Figure 19: Concept of flood risk

The risk is, therefore, the average damage that floods can potentially produce, and will be greater to the extent that vulnerability and dangerousness are also.
It is defined as vulnerability, to the damage that can potentially occur at a point in the territory and at a certain time of year. In this sense, vulnerability depends on land use (either current or well planned) and varies with the magnitude of the flood.

The dangerousness will be given in turn, by the combination of the frequency and magnitude of the flood.

The most common definition of the frequency of a given flood is the probability that in any year the flow that produces it will be exceeded at least once. However, most of the time it is talked about the return period in years, which is the inverse of this probability of exceeding. The frequency limits that are used in this work for the evaluation of the impact are those of 20, 100 and 500 years.

On the other hand, the magnitude of the flood depends on the amount of precipitation, the characteristics of the watershed at the point considered (mainly its size and the infiltration capacity of the land), and finally the drainage conditions of that point concrete. In such a way that if the drainage capacity is insufficient for the magnitude of the flows collected by the watershed, a flood occurs.

Once the results from the hydraulic model have been obtained for different flood events, risk analysis is carried out using the iPresas Flood software.

Previously to risk calculations, an estimation of economic and societal consequences is required to obtain input data for the risk model, whose results in economic damages and potentially affected population, respectively, will be incorporated into the corresponding nodes.

Flood maps for each event are compared with GIS data on population to know the number of properties affected. Due to the number of properties affected, it was needed to study the economic damages and potential affected people, which is explained in the next chapter.

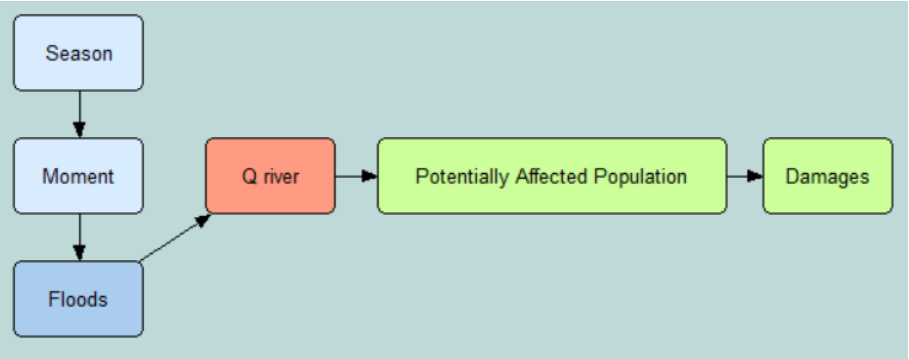

Figure 20: Influence diagram used for risk calculation

Table 6 describes the information included in each node of the diagram. The inputs are described in Annex II (Risk model inputs).

Table 6: Node definitions for the influence diagram

NODE	DESCRIPTION
SEASON	Divides the year in summer and winter periods and includes their probabilities
MOMENT	Includes the probabilities of the flood occurring during the day or at night
FLOODS	Defines the return period of each analyzed flood
Q RIVER	Includes input data on peak flow discharges for a series of return periods within the range given in the previous node. Therefore, this node includes a relationship between annual exceedance probabilities and peak flow discharges of the river at the study site
POTENTIALLY AFFECTED POPULATION	Used to estimate population affected due to river flooding using the peak river discharges computed in the previous node.
DAMAGES	Estimates the economic consequences of flooding and introduces a relation between economic consequences (Damages) and river discharge (QMax).

6.2 Estimation of economic consequences

The review of costs of past flood events has been considered to estimate cost per building affected by flooding.

To define the average cost, it was necessary to find information about water and flood damages. In Finans Norge (*https://www.finansnorge.no/statistikk/*) it is found the number of cases and the reparation cost every year in Norway.

The flood characteristics of the flood event have an influence on the degree of damages.

Based on the Direktoratet for Byggkvalitet (*https://dibk.no/byggeregler/tek/2/7/7-2/*), safety class F3 is considered for areas where the depth is greater than 2 m and the product of depth and water velocity (in m/s) is greater than 2 m^2/s.

The following tables show the information about the recent cases in the last decade. It was considered a case of flood the ones which were above the 2 m^2/s and disaster the ones with the product lesser than 2 m^2/s.

Table 7: Number of cases of flood in Norway and its cost (x1000NOK) for the decade 2008-2018

YEAR	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	TOTAL
CASES	851	374	1135	4207	2421	3842	1937	3277	822	2678	1458	23002
COST	49929	27344	78474	558044	390634	474976	396333	570433	63487	431987	140480	3182121

Table 8: Number of cases of water disaster in Norway and its cost (x1000NOK) for the decade 2008-2018

YEAR	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	TOTAL
CASES	5760	4881	7863	11089	6649	9830	8305	8280	8874	11592	8420	91543
COST	210535	166768	278121	454307	259010	424058	339558	342784	585374	469692	261840	3792047

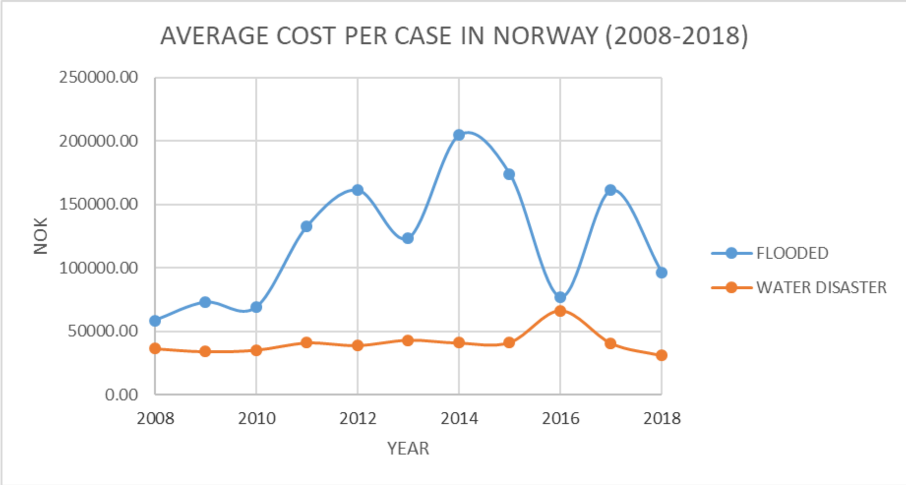

Figure 21: Average cost in NOK for flood cases in Norway during the last decade (2008 - 2018)

The averages of each disaster are the following ones:

- Flooded buildings (>2m^2/s): 138,341.06 NOK
- Affected buildings (<2m^2/s): 41,423.67 NOK

The total cost was calculated by multiplying the number of buildings for the different flood events simulated, which have different flood areas and buildings under the influence of the event. It is possible to see with more detail the calculations in Annex II.

6.3 Estimation of potential affected population

Potential affected population was defined by using the flooded areas for different simulations and by the attributes in ArcGis. Then, it was possible to stablish the number of potentially affected buildings by flood. So, assuming the distribution of potentially affected people follows the same distribution as the following (explained in chapter 4.4 Demography), it is defined the total of affected people.

Table 9: Distribution followed to calculate the number of potentially affected people in flood events

2011						
TOTAL HOUSES	HOUSEHOLD SIZE					TOTAL PEOPLE
	1 PERSON	2 PERSONS	3 PERSONS	4 PERSONS	5 PEOPLE OR MORE	
2224	847	624	303	270	180	4984

Table 10: Count of houses and people potentially affected

RETURN PERIOD	HOUSES AFFECTED	1 PERSON	2 PERSONS	3 PERSONS	4 PERSONS	5 PEOPLE OR MORE	TOTAL PEOPLE AFFECTED
20	2	0	0	1	1	0	7
100	103	39	29	14	13	8	231
500	208	79	58	28	25	17	466

6.4 Results

The risk model allows the quantitative risk estimation. The results of the calculation can be represented in curves such as F-PAP and F-D, where F is the cumulative annual probability of exceedance of a certain level of flood consequences, expressed in Potentially Affected Population (PAP) or economic costs (D).

Economic and societal risk are obtained by multiplying probabilities and consequences of all branches of the event tree resulting from the influence diagram that represents the case study.

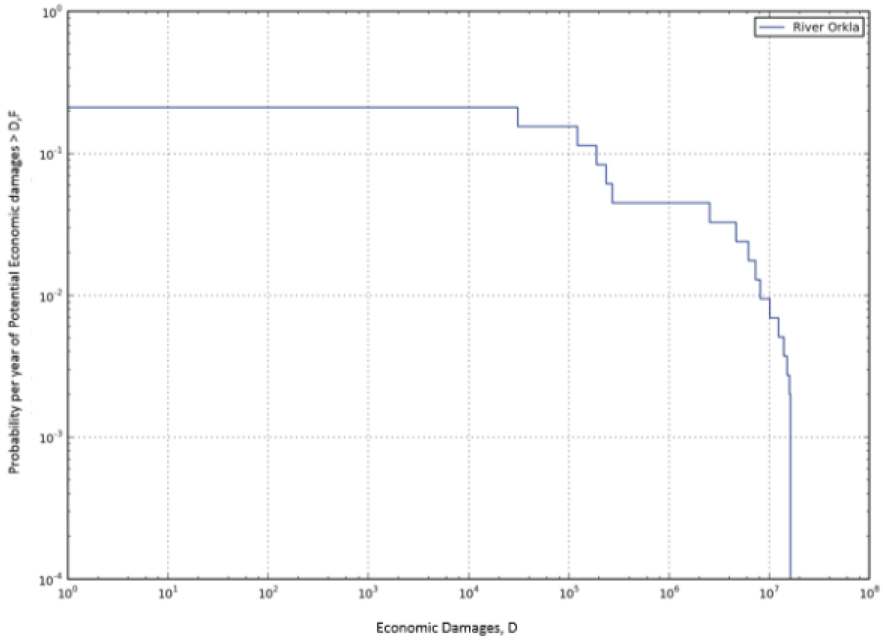

Figure 22: F-D curve for the river Orkla study

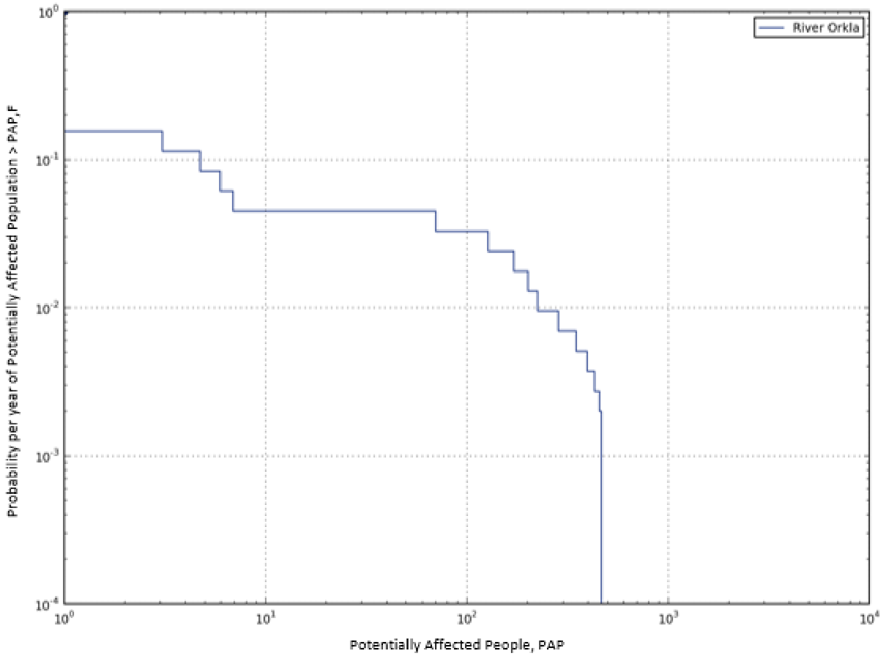

Figure 23: F-PAP curve for the river Orkla study

Due to the discretization, the total risk is the area below the F-PAP or F-D curve.

Results for the Base Case are shown in Table 11, where economic risk is expressed in NOK/year and societal risk in affected people/year.

Table 11: Total risk calculated for the river Orkla system

Total economic risk (NOK/year)	320992.87
Total societal risk (AP/year)	9

It must be explained, the results shown just show the total economic risk and societal risk calculated for a return period of 500 years.

7 Results comparison and conclusions

7.1 Comparison

First, results are compared with the Norwegian Water Resources and Energy Directorate's (NVE) maps. These maps are available at *https://www.nve.no/map-services/*.

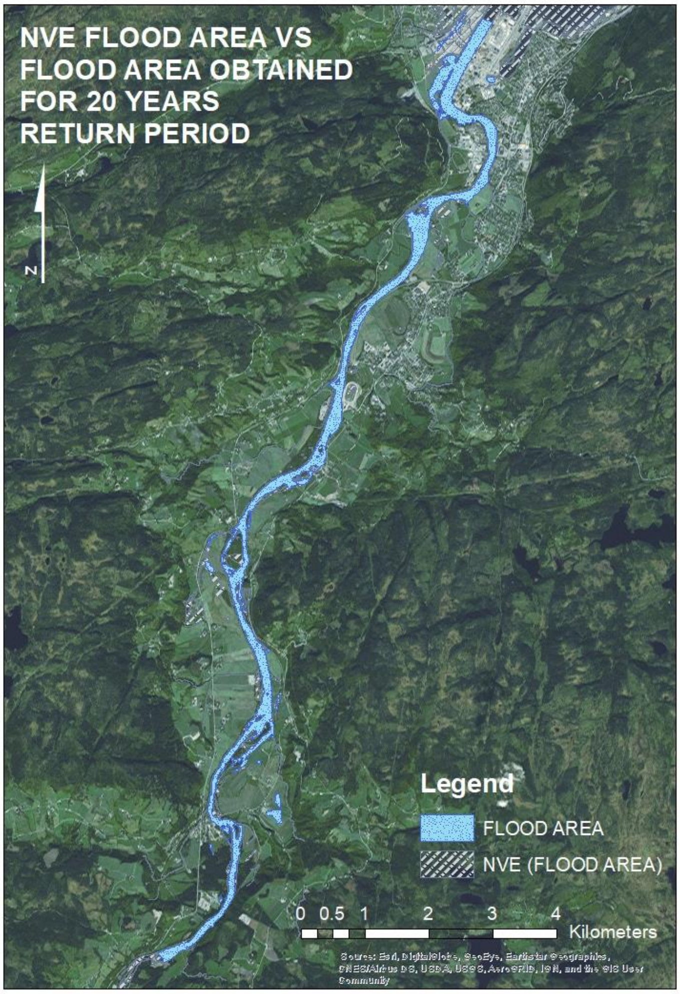

Figure 24: Comparison between the flood area obtained in this thesis and the flood area of NVE for 20 years return period

As can be observed in figure 24, flooded areas are quite similar. Near the river mouth exist a variation because of a storage area near to the coast at the right bank of the river which was not considered in the model due to its low relevance for this return period.

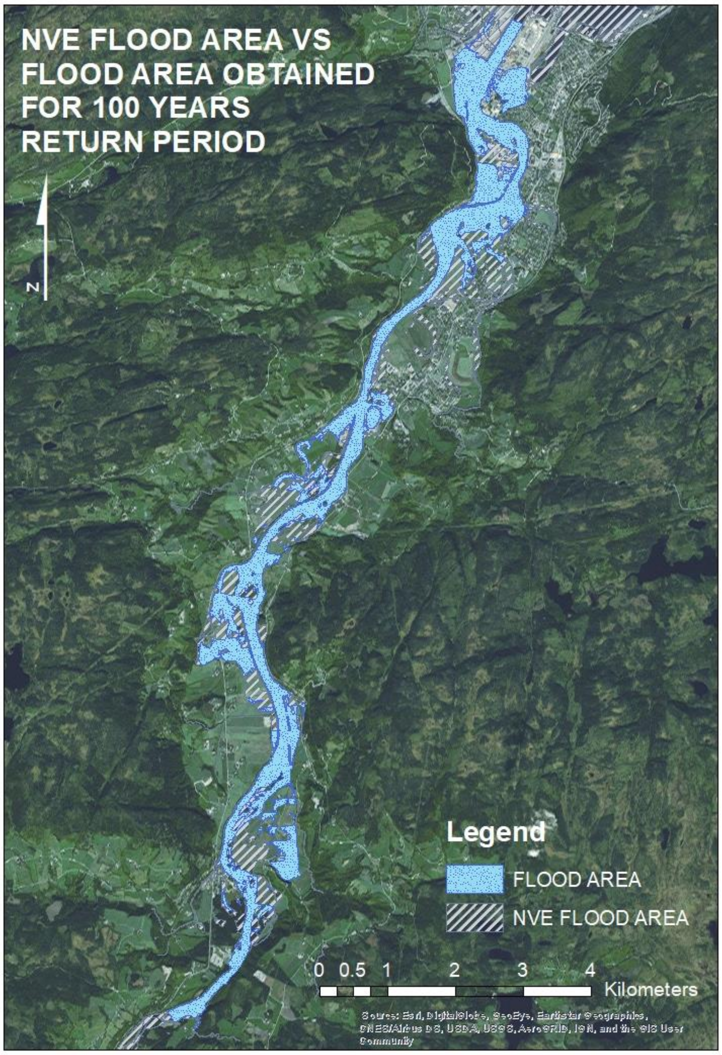

Figure 25: Comparison between the flood area obtained in this thesis and the flood area of NVE for 100 years return period

In Figure 25 it is shown that the difference between the results obtained and the NVE's has increased when compared with the previous case. The main stream continues fitting one to each other.

However, the extension of the flooded area shown in NVE map is larger. That could increase the potential affected people and the economic consequences but, differences between both sources are mainly areas where there are no households neither buildings.

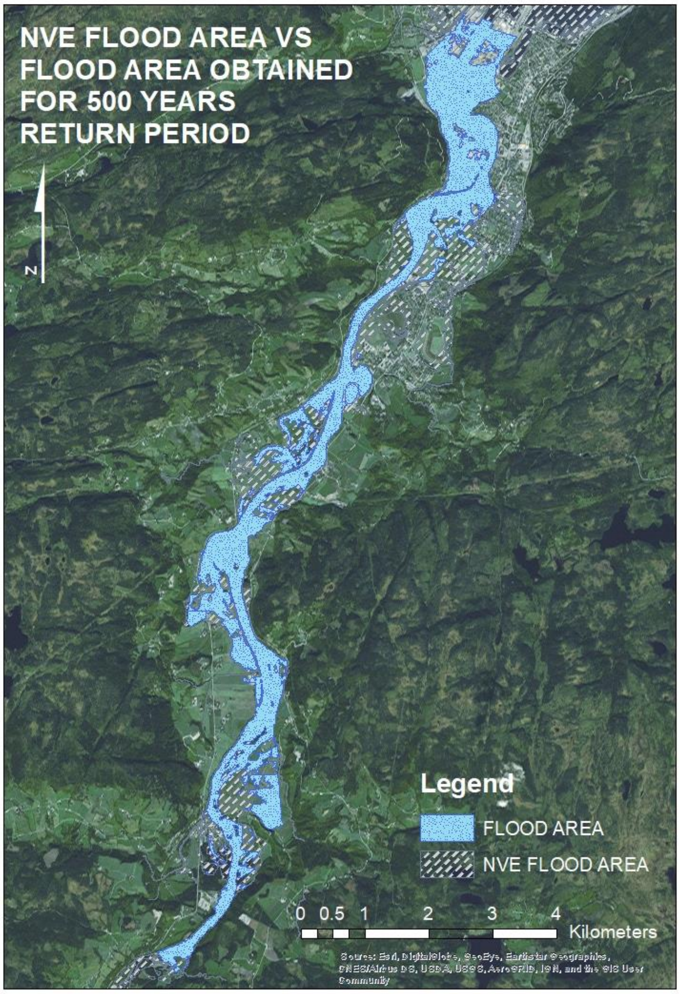

Figure 26: Comparison between the flood area obtained in this thesis and the flood area of NVE for 500 years return period

As previously mentioned, the NVE's system provides larger area for the flood event of 500 years return period than the results obtained from the hydraulic model. This time the right bank of the river is more exposed to the flood risk, and there are also some building areas in there. So, for the case of 500 years of return period, it could be a difference between number of potential affected people and the economic consequences, being increased by this new flood area.

The Norwegian Water Resources and Energy Directorate dispose a gigantic data base useful for studies like this one. However, it is not possible to know the depth and velocity in the flood areas, and this thesis covers both and estimates the economical and societal risk.

The atlas and the maps services have several layers with relevant information about floods and hydrological data. These comparison helps to let know there is no a far conclusion for the flood area, and the risk calculations made in chapter 6 make sense.

7.2 Conclusions

To sum up, it is possible to define vulnerable areas, as it is the case. It is shown in the following figure that exist an area where the buildings are completely exposed to floods, from the first ones with 20 years of return.

Figure 27: Most exposed buildings to flooding in the area of study

In conclusion, it is appreciated that the reason of the potential risk is the location of the properties close to the banks of the river in flat lands. Some of them are clearly exposed and too close to the river, which allows no reaction time for flash floods or heavily. This has a potential economic risk above the 320.000 NOK/year and 9 affected people per year.

As far as it is studied, the thesis covers the preliminary and the first needs to study future climate change scenarios, where the hydrology, and most probably the number of potentially affected properties and buildings will increase.

7.3 Proposals for future work

As it is said at the beginning of the document, this master thesis goal is to stablish the preliminary flood risk for future climate change scenarios.

For future work, it is needed to stablish and study the climate change scenarios that will change the flood events and their characteristics. The result will give a completely flood risk analysis for the Orkla river system, allowing to know the new flood events and providing the new potential economic cost and affected population.

8 References

[1] SPANCOLD, “Risk analysis as applied to dam safety. Technical Guide on Operation of Dams and Reservoirs,” *Rep. Tech. Guid. Dam Safety, Vol. 1*, vol. 1, p. 153, 2012.

[2] A. U. Schratter-Sehn, W. F. O. Schmidt, R. Kielhauser, H. Langer, and K. H. Karcher, “Pravention Lokaler Schleimhautlasionen Wahren Oropharynx-Bestrahlung Durch Einen Plombenschutz,” *Strahlentherapie und Onkol.*, vol. 168, no. 1, pp. 35–38, 1992.

[3] NVE, “Retningslinjer for planlegging og utbygging i fareområder langs vassdrag,” 2007.

[4] US Army Corps of Engineers, “HEC-RAS 5.0 Reference Manual.” p. 960, 2016.

[5] B. Hansen, “Flood dampening in hydropower systems,” no. July, 2018.

[6] O. Flæte *et al.*, *Adapting to a changing climate: Norway’s vulnerability and the need to adapt to the impacts of climate change*. 2010.

[7] A. Morales-Torres, A. Serrano-Lombillo, I. Escuder-Bueno, and L. Altarejos-GarcÃ-a, “The suitability of risk reduction indicators to inform dam safety management,” *Struct. Infrastruct. Eng.*, vol. 12, no. 11, pp. 1465–1476, 2016.

[8] A. Morales-Torres, I. Escuder-Bueno, L. Altarejos-García, and A. Serrano-Lombillo, “Building fragility curves of sliding failure of concrete gravity dams integrating natural and epistemic uncertainties,” *Eng. Struct.*, vol. 125, pp. 227–235, 2016.

[9] A. Instanes, V. Kokorev, R. Janowicz, O. Bruland, K. Sand, and T. Prowse, “Changes to freshwater systems affecting Arctic infrastructure and natural resources,” *J. Geophys. Res. G Biogeosciences*, vol. 121, no. 3, pp. 567–585, 2016.

[10] J. T. Castillo-Rodríguez, I. Escuder-Bueno, L. Altarejos-García, and A. Serrano-Lombillo, “The value of integrating information from multiple hazards for flood risk analysis and management,” *Nat. Hazards Earth Syst. Sci.*, vol. 14, no. 2, pp. 379–400, 2014.

[11] J. T. Castillo-Rodríguez, J. T. Needham, A. Morales-Torres, and I. Escuder-Bueno, “A combined risk analysis approach for complex dam–levee systems,” *Struct. Infrastruct. Eng.*, vol. 13, no. 12, pp. 1624–1638, 2017.

[12] A. Serrano-Lombillo, A. Morales-Torres, I. Escuder-Bueno, and L. Altarejos-García, “A new risk reduction indicator for dam safety management combining efficiency and equity principles,” *Struct. Infrastruct. Eng.*, vol. 13, no. 9, pp. 1157–1166, 2017.

https://nve.no/maps-services/

ANNEX I

Hydraulic model results

This annex pretends to cover the hydraulic modelling by the maps disposed. As it is possible to perceive, the different return periods (20, 100 and 500) are mapped for depth and velocity. This comes from the European regulations exposed in chapter 2.

The information is detailed in chapter 5, including the hydrographs, the geometry or model in 2D applied and manning number and land cover respectively.

Furthermore, there is a comparison of results with the NVE in the last chapter of the contents.

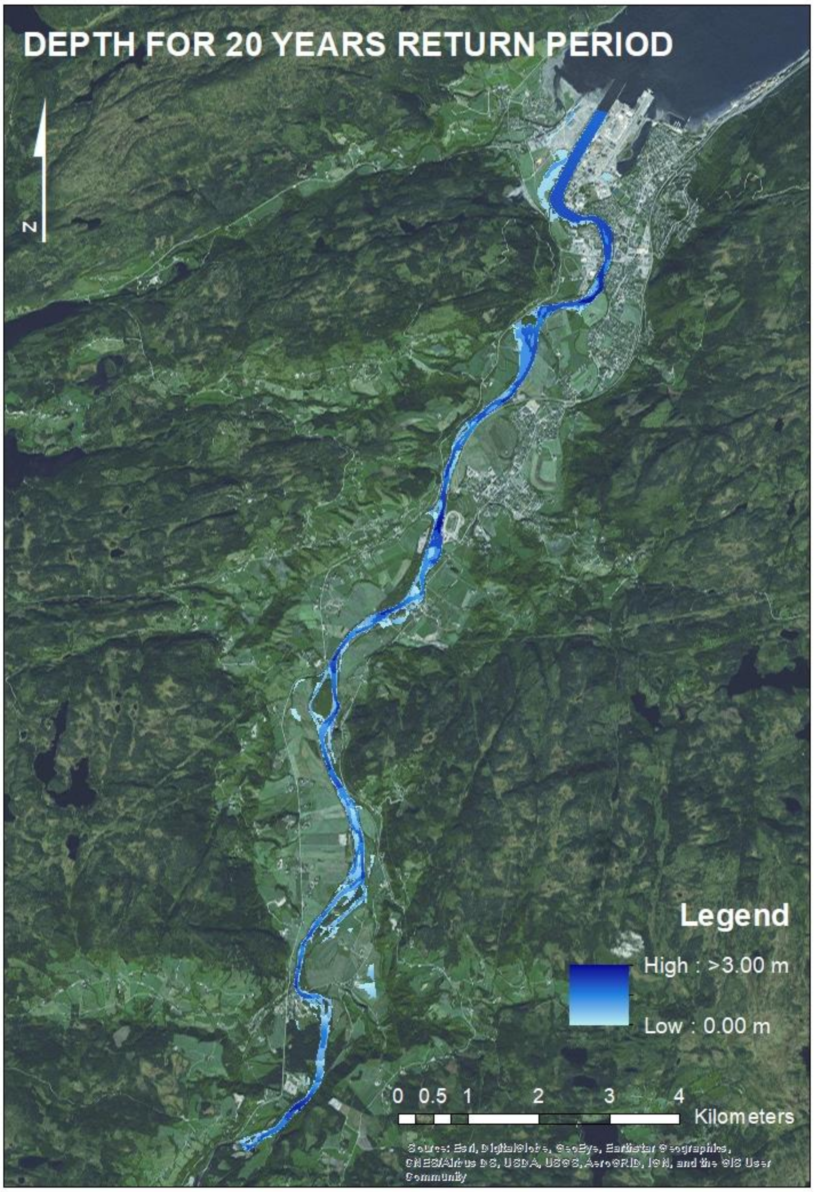

Figure 28: Depth for 20 years return period in Orkanger

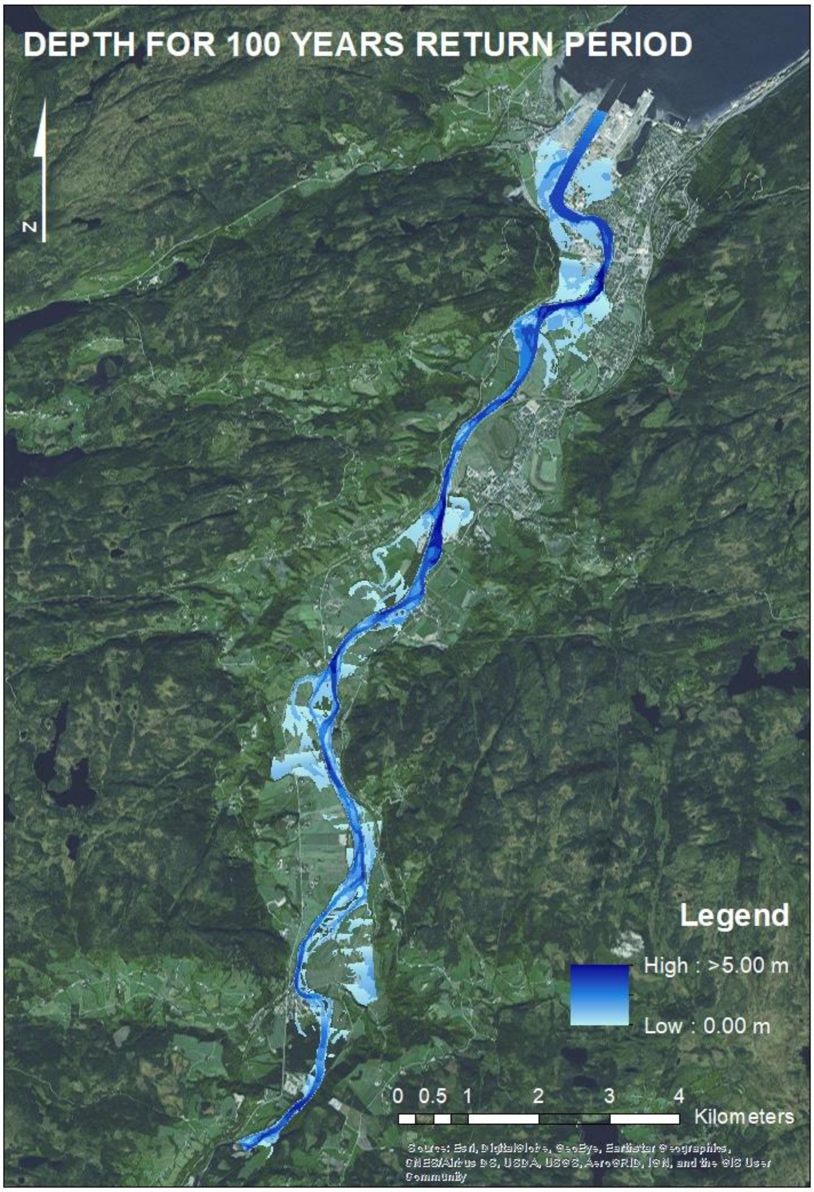

Figure 29: Depth for 100 years return period in Orkanger

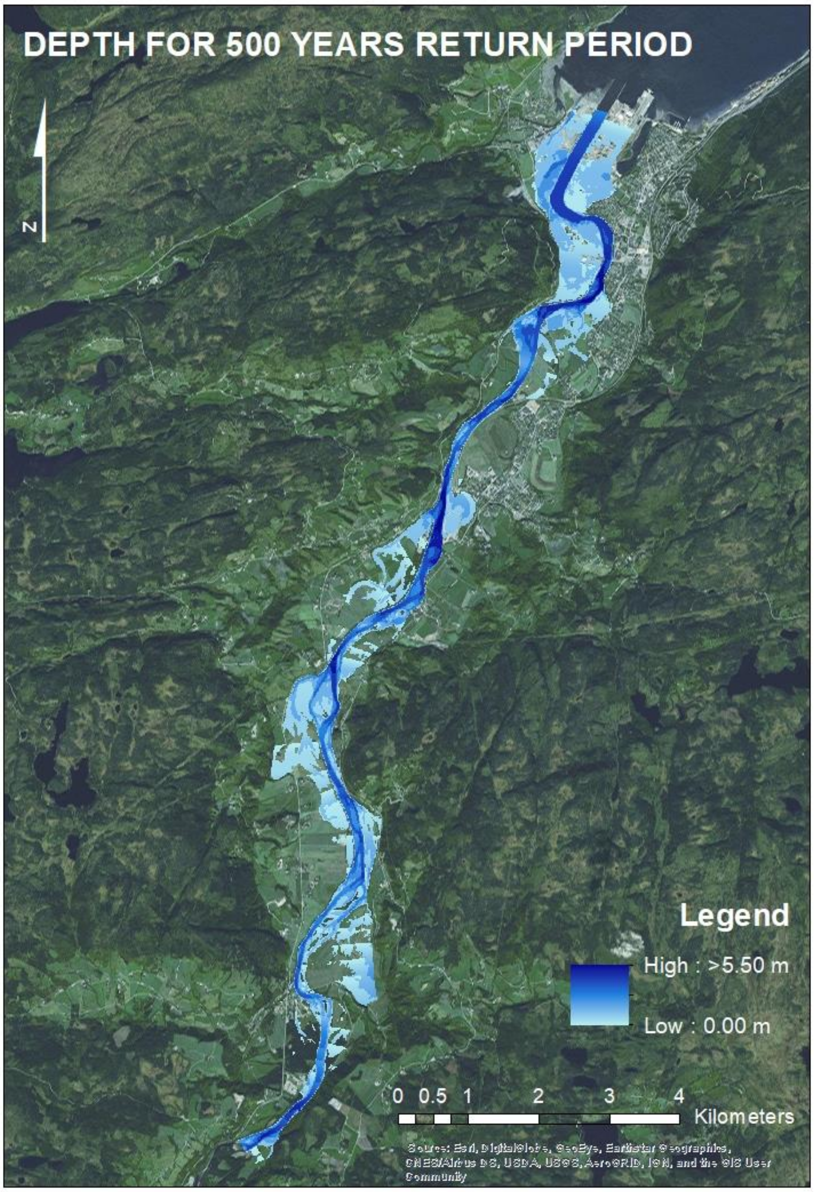

Figure 30: Depth for 500 years return period in Orkanger

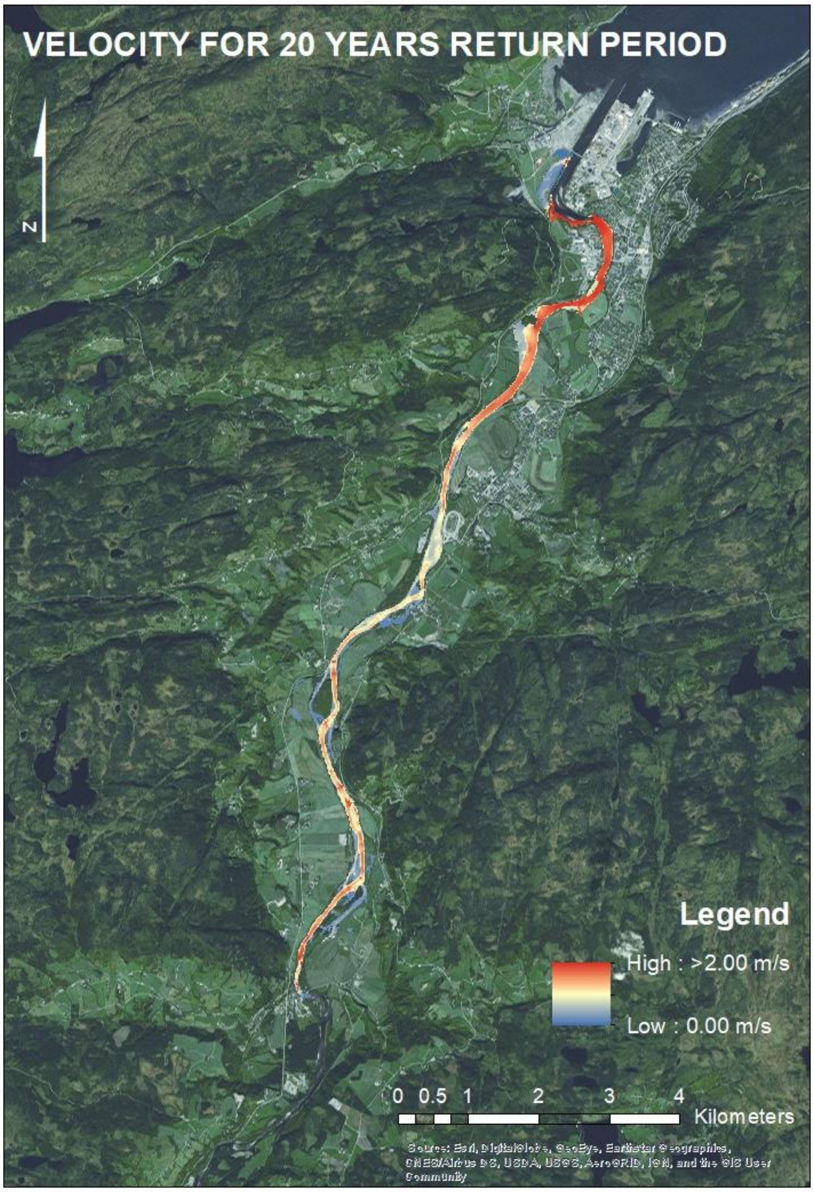

Figure 31: Velocity for 20 years return period in Orkanger

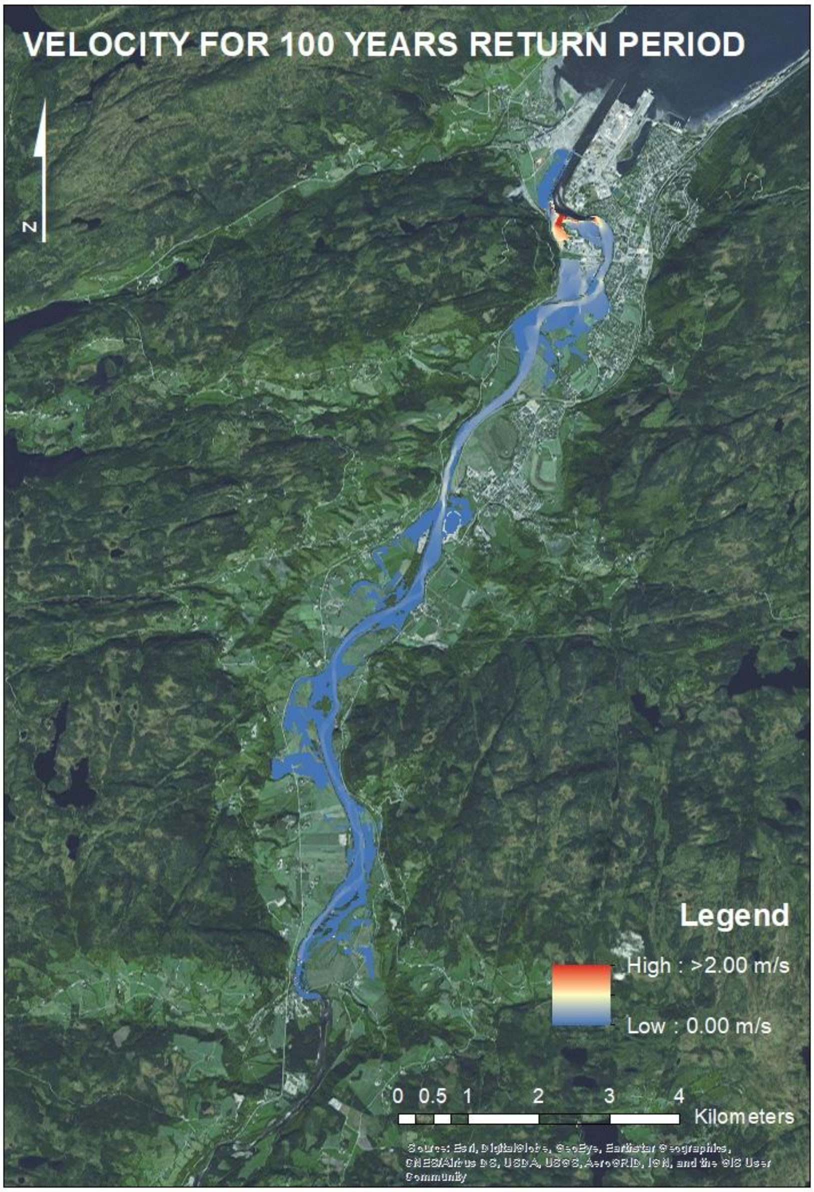

Figure 32: Velocity for 100 years return period in Orkanger

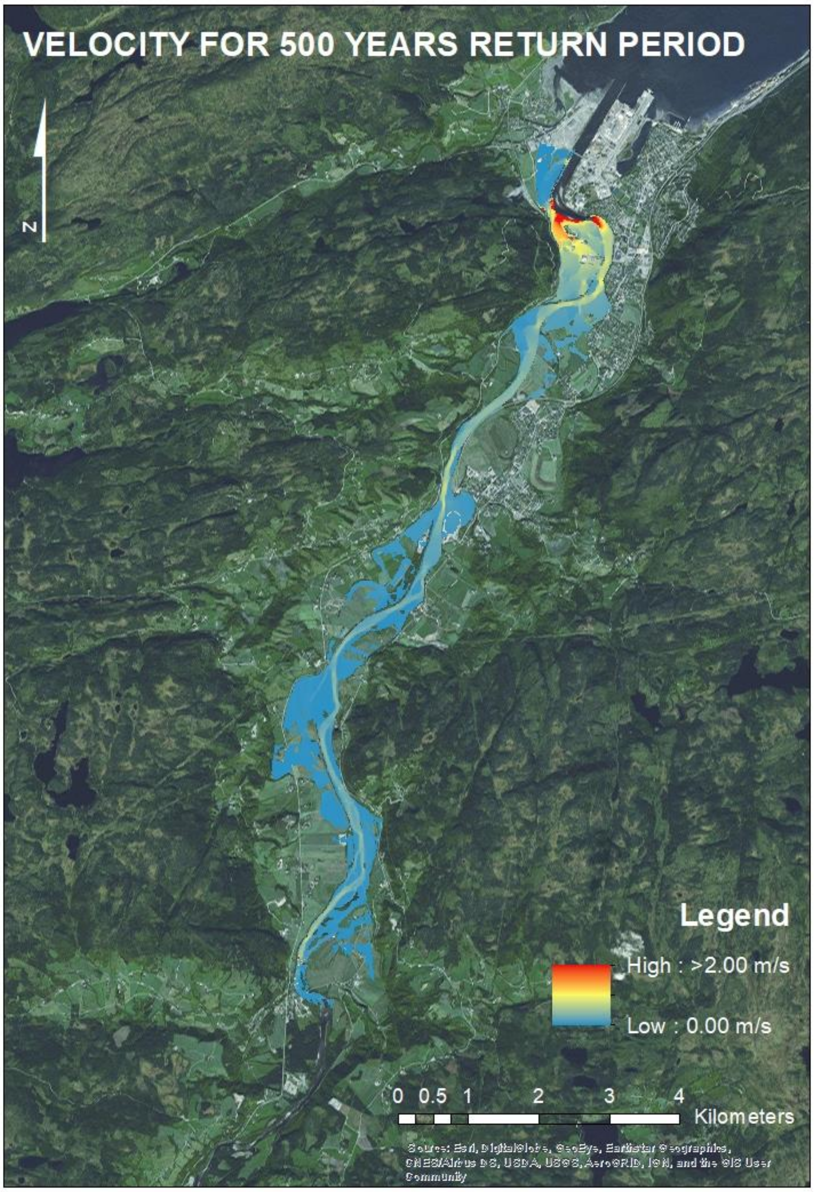

Figure 33: Velocity for 500 years return period in Orkanger

ANNEX II

Risk model calculations and inputs

In this annex is going to be explained and included the parameters and inputs applied to the risk model.

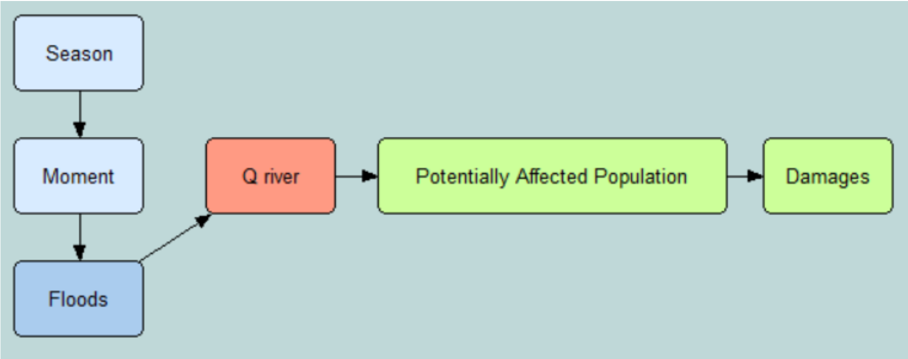

Figure 34: Influence diagram used for the analysis

The model is composed by six nodes, as follows:

For the Season node, it was defined a probability of 50% in each season (summer and winter).

For the moment node, it was assumed a probability of day in summer season of 75% and 25% night. On the other hand, it was defined as the inverse the probability moment for night and day for winter, 75% night and 25% day.

These nodes are used to incorporate into the model the effect of daily or seasonal variation on population at risk. For this case study, population downstream is assumed constant, which means same potentially affected population during the day or at night, and during the year.

For the Floods node includes the minimum and maximum return period. For this case study, the minimum return period was defined as 1 and the maximum as 500.

The Q river node includes the excel sheet file with the flow by return period which is defined in the next table.

Table 12: Input for Q river node defining Qmax for different T

T	AEP	QMax
500	0.002	2095
100	0.01	1536
20	0.05	950
5	0.2	540
1	1	418

The Potentially Affected Population node and the damages were defined by using the flooded areas for different simulations and by the attributes in ArcGis. Then, it was possible to stablish the number of potentially affected buildings by flood and with that, people and economic damage.

Assuming the distribution of potentially affected people follows the same distribution as the following in Table 13 (explained in chapter 4.4 Demography), it is defined the total of affected people.

Table 13: Distribution followed to calculate the number of potentially affected people in flood events

2011						
TOTAL HOUSES	HOUSEHOLD SIZE					TOTAL PEOPLE
	1 PERSON	2 PERSONS	3 PERSONS	4 PERSONS	5 PEOPLE OR MORE	
2224	847	624	303	270	180	4984

Table 14: Count of houses and people potentially affected

RETURN PERIOD	HOUSES AFFECTED	1 PERSON	2 PERSONS	3 PERSONS	4 PERSONS	5 PEOPLE OR MORE	TOTAL PEOPLE AFFECTED
20	2	0	0	1	1	0	7
100	103	39	29	14	13	8	231
500	208	79	58	28	25	17	466

Table 15: Input for Potentially affected people by season and moment (permanent residents)

QMax	PAP
418	0
540	0
950	7
1536	231
2095	466

Knowing houses affected by the product of depth and velocity more than 2 m^2/s or less as it is explained in chapter 6, it is possible to calculate the economic cost for the different floods calculated in the hydraulic model.

- Flooded buildings (>$2m^2$/s): 138,341.06 NOK
- Affected buildings (<$2m^2$/s): 41,423.67 NOK

Table 16:Total cost calculation for different RP

	TOTAL ACCOUNT	COUNT < $2m^2$/s	COUNT > $2m^2$/s	COST < $2m^2$/s	COST > $2m^2$/s	TOTAL COST (NOK)
RP500	208	129	79	41423.67	138341.06	16272596.92
RP100	103	61	42	41423.67	138341.06	8337168.26
RP20	2	0	2	41423.67	138341.06	276682.11

With the total cost calculated, it is possible to define the last node.

Table 17: Inputs for Damage node depending on the different flow for each RP and the total cost in NOK

QMax	Damages
418	0.000
540	0.000
950	276682.11
1536	8337168.26
2095	16272596.92

Notes