Master's thesis

NTNU
Norwegian University of Science and Technology
Faculty of Social and Educational Sciences
Department of Geography

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Potential physical and societal impacts of glacial lake outburst floods in Hjelledalen, Stryn, Norway

Master's thesis in Geography
Supervisor: Irina Rogozhina
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Summary

Global warming is causing changes in the glacier environments all around the world. As well as in many other mountainous regions, the retreat of glaciers in Norway has promoted the formation of glacial lakes that often become hazardous and cause floods in downstream valleys. This happens in case glacial lakes get dammed by glaciers or moraines and suddenly release water through events that are called glacial lake outburst floods (GLOFs) or jøkullaups.

Tystigbreen in the Stryn municipality in western Norway has four glacial lakes. Of these four, two lakes are known to have suddenly drain on multiple occasions in the last decades. Although documented GLOFs in this area have not been on a scale that could have caused floods or harm in the valleys downstream, the behavior and hazardous activity of the two glacial lakes may well change in the future, with the glacier thinning and retreating at an unprecedented rate.

This thesis aims to investigate the potential of GLOFs from Tystigbreen to create floods in the downstream valleys, Videdalen, Sunndalen and Hjelledalen. Here I investigate a range of potential scenarios for GLOF speed and geography, estimating the consequences they will have on the downstream valleys and communities. This study discusses whether the downstream rivers can accommodate large future GLOFs without overspilling and flooding settlements and infrastructure. The means to investigate the impacts of GLOFs on valleys is through hydrological simulations with HEC-RAS, a software used to model the flow of water in creeks and rivers.

The results of these investigations show that there is a big potential for floods in the valleys connected to the glacial lake drainage paths, if glacial lakes drain rapidly. GLOFs with a duration of eight hours and especially two hours have a potential to significantly increase water levels in rivers and flood large areas in the main valley, Hjelledalen. In addition, rapid drainage of both glacial lakes will cause large floods in the upper valleys - Videdøla and Sunndøla in the worst-case scenarios. My model simulations show that infrastructure, buildings and agricultural land will be heavily damaged as a result of such GLOFs.

Future projections for GLOFs are still uncertain due to limitations in our understanding of their mechanisms. It is therefore unknown to which extent the scenarios modeled in this thesis are to occur. However, it is important to understand how future damaging GLOF scenarios might look like and how to prepare valleys downstream for such events.

Sammendrag

Global oppvarming skaper store endringer i karakteristikken av isbreer i verden og i Norge. Tilbaketrekningen til mange av Norges breer har økt dannelsen av glasiale sjøer. Bredemte sjøer skapes når isbreer eller morener blokkerer muligheten for at vannet kan drenere. Dersom de bredemte sjøene plutselig slipper ut vannet i de glasial sjøene, kalles dette for glacial lake outburst flood (GLOF) eller Jøkuhlaup. GLOFs har potensiale til å bli skape farlige hendelser og skape flom på mennesker, bygninger og infrastruktur nedenfor de bredemte sjøene.

Tystigbreen i Stryn kommune, har to bredemte sjøer. Disse bredemte sjøene har blitt plutselig tømt flere ganger de siste tiårene. Hittil har det ikke ført til flom eller skade på bygninger eller infrastruktur. Selv om det ikke har vært flommer som følge av GLOF på Tystigbreen så kan det fremdeles skje i fremtiden.

Denne masteroppgaven har som mål å undersøke hvor skadelig en GLOF kan potensielt være på de nedstrøms områdene i Videdalen, Sunndalen og Hjelledalen. Det blir undersøkt hvilke konsekvenser flere GLOF scenarioer kommer til å få. Studien vil diskutere og stille spørsmål ved hvor godt forberedt de nedstrømselvene; Videdøla, Sunndøla og Hjelledøla til å ta imot de vannmengdene som befinner seg i de bredemte sjøene. Metoden som skal brukes til å undersøke de ulike scenarioene er ved bruk HEC-RAS, et verktøy som brukes til å modellere vann i bekke- og elveløp.

Resultatene av undersøkelsen viser at det er stor fare for flom dersom de bredemte sjøene utløser en GLOF der de bredemte sjøene tømmes hurtig. Modellene viser at både to timers GLOF hendelser, og GLOF med varighet på åtte timer vil gi signifikant økning i vannmengden i elveløpene. Store flater spesielt i Hjelledalen vil ta stor skade ved det verste scenarioet, som er to timers GLOF. Dette gjelder både fra Lagune 1 som drenerer til Videdøla og Lagune 2 som drenerer til Sunndøla. Modellene viser at infrastruktur, bygninger, jordbruksområder, og potensielt menneskeliv kan gå tapt dersom en stor GLOF finner sted.

Fremtidige utsikter er uklare, og det er uvisst om de scenarioene som er modellert i denne oppgaven noen gang vil finne sted. Det er derimot viktig å vite hvordan et potensielt ødeleggende GLOF scenario kan se ut, og hvordan det vil påvirke områdene nedstrøms.

Acknowledgment

This thesis marks the end of my five years at NTNU Trondheim. My experiences as a student at the department of Geography has been fantastic, both academically and socially. The last two years has been especially difficult due to the lock-down caused by the COVID-19 virus, but I am happy that I have been able to finish, even with the troubles the virus has caused.

I would like to express my sincere gratitude to my supervisor at Department of Geography, NTNU, Dr Irina Rogozhina. The help and guidance I have received through the last years has been greatly appreciated. The guidance in the development of the thesis, the supervision during fieldwork, and the help and insight in writing the thesis has been key, and the Master's thesis would not have been possible without her.

I would like to give a special thanks to all the fantastic people on the GOTHECA team. Throughout the process of this thesis, they have been fantastic. Our fieldwork in Stryn have created memories I will never forget.

I would like to thank my family for the support during the entire five years I have studied at NTNU, Trondheim.

A special thanks for all the great moments with the gang at geography during my period as a student in Trondheim. Especially during the last year, where all of us have been struggling together to finish the thesis.

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List of abbreviations

GLOF – Glacial Lake Outburst Flood

DTM – Digital elevation model

HEC-RAS -

SHW – Shallow water equations

ELA – equilibrium line altitude

DW – Diffusion wave

LiDAR – Light detection and ranging

DEM – Digital elevation model

DSM – Digital surface model

ArcGIS - Aeronautical Reconnaissance Coverage Geographic Information System

NVE – Norges Vassdrags- og Energidirektorat

NVE NEVINA - Norges Vassdrags- og Energidirektorat, Nedbørfelt- og vannføringsindeksanalyse

HBV - Hydrologiska Byråns Vattenbalanssektions model

1. Introduction

The ongoing climate change is causing significant changes in Norwegian glaciers (Bosson et al., 2019; Hanssen-Bauer et al., 2015), finding its expression in the rapid retreat of the glacier front, ice thinning, and formation of glacial lakes either supraglacially, or englacially, or proglacially, often dammed by the glacier itself or by a glacial moraine (Jackson & Ragulina, 2014; Winsvold et al., 2014). Glacial lakes are gradually growing and being filled with meltwater from glacier ice, snow melt and precipitation (Bajracharya & Mool, 2009). The increased retreat in the glacier fronts is the cause why many glacial lakes has ceased to exist, it happens because the glaciers have retreated too far, and the glacier is no longer able to block the lakes (Jackson & Ragulina, 2014). This is inevitable for many of the world's glacial lake. The trend globally is however that there has been a rising trend in the development in glacial lake in the past decades (Carrivick & Tweed, 2016).

Meltwater from glaciers is generally considered an extremely valuable resource, since it provides freshwater used for both drinking and agriculture in many parts of the world (Yao et al., 2018). In Norway and many other high-relief countries it is also an essential part of the production of electricity through hydropower plants (Engelhardt et al., 2014). However, glacial lakes have the potential to suddenly drain into valleys downstream through a process known as a glacial lake outburst flood (GLOFs), or "jøkuhlaup" (Jackson & Ragulina, 2014). GLOFs are often unpredictable events that pose direct danger to populations and ecosystems downstream but can also act as triggers of other forms of natural hazards such as landslide and avalanches (Yao et al., 2018). They have been known to lead to numerous fatalities in many parts of the world, and have also caused damage to properties, buildings and infrastructure in Norway in recent years (Carrivick & Tweed, 2016). Due to attractive prices on the housing market and high potential for making a profit when building houses and cabins, and the increased construction of hydropower plants in the vicinity to glacial lakes, infrastructure and people are increasingly moving closer to areas that are prone to glacier hazards (Jackson, 2018). This combined with the rapid deglaciation and a widespread growth of glacial lakes has increased the likelihood of glacier-related incidents and hazards (Bendle, 2020). The presence of glacial lakes can become a source for a positive feedback mechanism for the glaciers and the ice sheets around the world. The glacial lakes will absorb more heat, which can thereby lead to an amplification in the ice loss by subaqueous melting of the glacier (Truffer & Motyka, 2016; Tweed & Carrivick, 2015).

In this study we have used Tystigbreen located in the Stryn municipality (Western Norway) as an example of GLOF-prone glaciers with multiple glacial lakes dammed by different counterparts of the glacier and causing regular disturbances in the river systems downstream. To the present day, glacial lakes have not posed a life threat to the inhabitants of the valleys, since sudden discharges of the glacial lakes have been marked by volumes and drainage velocities which are not hazardous. However, with the global warming causing a rapid retreat of the glacier counterparts and individual glacial lakes, it becomes more and more probable that the safety of private and public facilities in the valleys exposed to GLOFs will be compromised in near future. A sudden discharge of a large volume of water can have the potential to drastically alter the river flow and energy, exerting direct impacts on vulnerable portions of the infrastructure and population by altering landscapes through increased erosion, sediment transportation and deposition (Cenderelli & Wohl, 2003).

To predict potential impacts of different types of GLOFs on society and landforms, a hydrological analysis can be created with a use of hydraulic modeling enabled by a geoscientific model development or the use of commercial/public software such as HEC-RAS (Hydrologic Engineering Center's River Analysis System (Brunner, 2021b)) that can approximate the flow of water in rivers in response to external input from glaciers, including the amount of time water needs to pass through a river system. It can be used to reconstruct past floods or carry out future projections of possible flood scenarios. It can also help us specify when the peak of flood will occur, how the flood-impacted area will look like, and how well the downstream areas are prepared to receive massive GLOFs, since tools like HEC-RAS enable identification and analysis of the key areas that may be affected by potential floods (Brunner, 2021b).

This study is part of the GOTHECA (Glacier impacts On The Hydrological systems in Europe and Central Asia) project (GOTHECA, 2022). The project is a collaboration between several institutions such as Department of Geography at NTNU, Western Norway University of Applied Science (HVL), GRID Arendal, and NVE (Norwegian Energy and Water Directorate), among others. The GOTHECA project is a multidisciplinary project with focus on the effects of climate change on glaciers and glacier-fed hydrological systems by integrating various climate datasets and modeling of glacier runoff in Scandinavia, the European Alps, and Central Asia. As part of the GOTHECA project, this thesis will shed light on the hazards connected to glacial lakes and GLOFs on the downstream river systems.

1.1. Motivation for research

The glacial retreat, and the ongoing climate change is causing the formation of glacial lakes. From our fieldwork conducted in Vestland county, we encountered many people living downstream of glacial lakes. Tystigbreen, Folgefonna and Jostedalsbreen were some of the glaciers we visited, and talked to resident living downstream. Through our conversations and interviews, we learned that few of the residents downstream had knowledge of glacial lakes, proglacial lakes or GLOFs. The people had not received any information from governmental institutions on local, regional or national level. The motivation behind the research is to investigate the dangers associated with the proglacial lakes, and GLOFs. To investigate if the GLOFs should be something that the inhabitants downstream of the glacial lakes should be concerned about, and to see whether the governmental institutions should start informing the people living downstream of proglacial lakes of the hazards connected to them. There are a lot of gaps in the knowledge of how proglacial lakes drain. This is important for the motivation of the research since it leaves a question mark in how hazardous the GLOFs might become in the future. Modeling several scenarios of drainage gives a range of situation in which all of them can potentially become true future scenarios, since our knowledge of the drainage of GLOFs are limited. If the results of the thesis suggests that the glacial lakes in Tystigbreen can potentially become hazardous, then it can give an incentive to start monitoring the glacial lakes and implement measures for early warning systems for GLOFs. It can be implemented measures downstream protecting the society against hazardous GLOFs, for instance, how the society is structured, how and where infrastructure is built, placement of schools and governmental buildings, and implementation of plans of action in case of a large scale GLOF. It is a motivation to help the residents living underneath potentially hazardous glaciers to be aware of the dangers, and to help them understand how well prepared their community is if a hazardous GLOF should appear.

1.2. Research questions and objectives

The main objective of this study is to understand the danger GLOFs pose to downstream communities, proximal buildings, private properties, and infrastructure. We have selected Tystigbreen in the Stryn municipality as a case study site, since it has two large glacial lakes that have drained several times in the last decades and two growing smaller glacial lakes that have been first recognized as GLOF-generating through interviews with local people and remote sensing by the GOTHECA team in summer 2021. Because of the rapidly retreating glacier and currently lacking robust tools for reliable GLOF predictions, it is difficult to foresee how glacial lakes of Tystigbreen will behave in the future, and what magnitudes of GLOFs we should expect in the downstream areas. As opposed to many other GLOF-generating glacial lakes in Norway, these four lakes are not shielded by hydropower reservoirs and thus offer a direct exposure of people to potential hazards.

In the light of the above objective, this thesis will focus on answering two main research questions:

Are the two large glacial lakes of Tystigbreen capable of causing significant floods in the Hjelledalen area? How hazardous can GLOFs be in this area, how much material damage can they inflict, and what do their potential impacts depend on?

How well are different portions and communities in Hjelledalen prepared for large GLOFs? What are the key areas in danger under different GLOF scenarios?

Here we have designed a large suite of numerical experiments (See chapter 4) using HEC-RAS to address the above main objective and research questions of the thesis. It is a tool created for the purpose of numerical modeling and diagnostic projection of water flow in rivers and creeks. This thesis combines an exhaustive set of model simulations with a detailed account of historical floods through interviews and assessment of exposure and vulnerability of the downstream areas to a wide range of GLOF scenarios with different geographic settings and significant magnitudes.

1.3. Study Area

1.3.1. Tystigbreen as a pilot for studies of the glacial lake outburst floods in Norway

Tystigbreen is a glacier situated on top of Tystigen, a mountain on the eastern side of the Stryn municipality and on the western side of the Sjåk municipality, and at the divide of two counties – Vestland and Innlandet. Tystigbreen is situated at high altitudes, in a highly mountainous area, with altitudes ranging from approximately 1400 meters to 1900 meters above sea level. The cumulative size of Tystigbreen's diverse counterparts is roughly 16,5 km^2. Tystigbreen is located to the north of Jostedalsbreen, which is Europe's largest mainland glacier (Askheim, 2022). The area of Tystigbreen that is the main focus of this study is located just above the Stryn Summer ski resort. This part of Tystigbreen is only connected to the rest of the glacier via its southern part that acts as a natural ice bridge between two wings of the glacier. In other parts, it is separated from the rest of the glacier by natural topographic barriers, including high bedrock peaks. The above part of Tystigbreen has two large glacial lakes, known by the locals as Lagunene, or the Lagunes, which are dammed by the glacier and are frequent sources of GLOFs.

The glacial discharge from Tystigbreen flows in several directions: For example, the part of the study area where this thesis has its major focus has a discharge that drains into Videdalen, and from there further into Hjelledalen. In contrast, from the southwestern side of the glacier meltwater drains towards Sunndalen, later flowing into Hjelledalen. The river Hjelledøla flowing through Hjelledalen ends up in the Oppstryn lake, a fresh-water lake which is located to the west of Tystigbreen, while the Oppstryn lake is the last destination for the freshwater, before it enters the fjord, Innvikfjord, via the river Stryneelva.

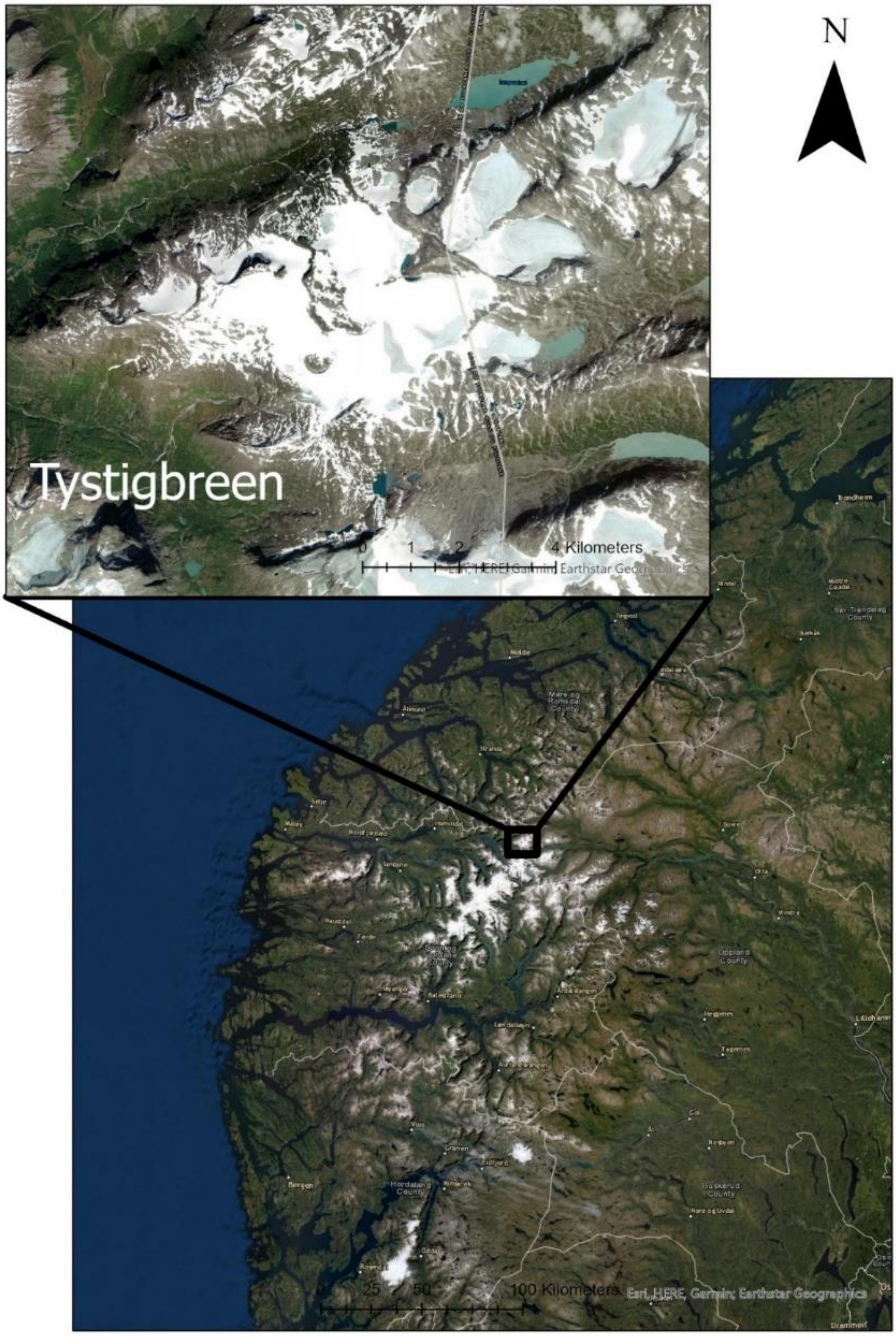


Figure 1: Tystigbreen, located in Stryn municipality. Map created in ArcGIS Pro.

Figure 2:The glacial lakes on Tystigbreen, located in Stryn municipality. Captured from Norgeibilder.no.

1.3.2. Glacier flood-exposed settlements and infrastructure

Hjelle is situated at the foot of the Stryn mountain range with mountains to the east. The river Hjelledøla is dividing the town into two parts - the southern side of the town that has a hotel and a local store, as well as most of the buildings and houses in Hjelle and the northern side where an elementary school from 1st to 7th grades, a kindergarten, SFO, and a cultural school are located. The northern side also includes several other buildings as well as the town's football pitch. Both sides of the town are connected through a simple bridge that is located in its eastern part. At the western side of the town is the lake known as Oppstryn or Oppstrynsvatnet where the river Hjelledøla eventually ends up draining. The area including Hjelledalen and Hjelle is particularly interesting since it has a great exposure to potential impacts of GLOFs.

Apart from Hjelle which is the major settlement, there are Hjelledalen consist of more than just this town. There are farms, with large areas of agricultural land, there is important infrastructure, such as the main road (Riksvei 15), and several bridges crossing the river.

There are multiple campsites in the close vicinity of Hjelledøla, as well as several private residents.

1.3.3. The drainage basin

The drainage basin of Hjelle can be seen in the figure below. The area marked in red is the watershed or drainage basin with a starting point in Hjelle. A watershed is a hierarchical system, where creeks and rivers only lead water to one spot in this watershed, and one spot in this picture. Therefore, all the water that either falls as precipitation or is produced through melting within this area becomes part of the same drainage basin, being transported on the surface to the only place where it can possibly move, because there is only one topographically-sound exit out of the drainage basin (Sulebakk, 2007). In the drainage basin shown in figure 3, the exit point of the watershed is right at the river delta, where the river Hjelledøla ends and where the lake Oppstrynsvatnet begins. The size of the drainage basin is 236 km^2. It is a watershed that is steep with tall mountains and widespread fell, it is a mountainous area above the tree line, with little to no vegetation often found in areas such as Scandinavian mountains, Iceland, and northern parts of Great Britain. 61,5 % of the drainage basin consists of the mountainous, nearly barren area, while 16,8% of the area in this watershed is covered by a glacier and 13,9 % - by forests. These are three largest and most significant land use types in this watershed.

According to NVE NEVINA's database, which is an automatic map service, for calculation of drainage basins, field parameters and indexes in Norwegian river system (NEVINA, 2022). the river in this watershed is 28,4 kilometers long, having a gradient of 51, 9 m/km and a slope of 23,9 degrees. A drainage density (D) in this drainage basin equals to approximately 1, where D is defined as D= L/A, where L is the total length of the river in the drainage basin, and A is the area of the drainage basin. There are uncertainties surrounding these estimates generated by the NVE NEVINA's website, since they are part of an automatic service for people rather than a phenomenon thoroughly investigated by NVE.

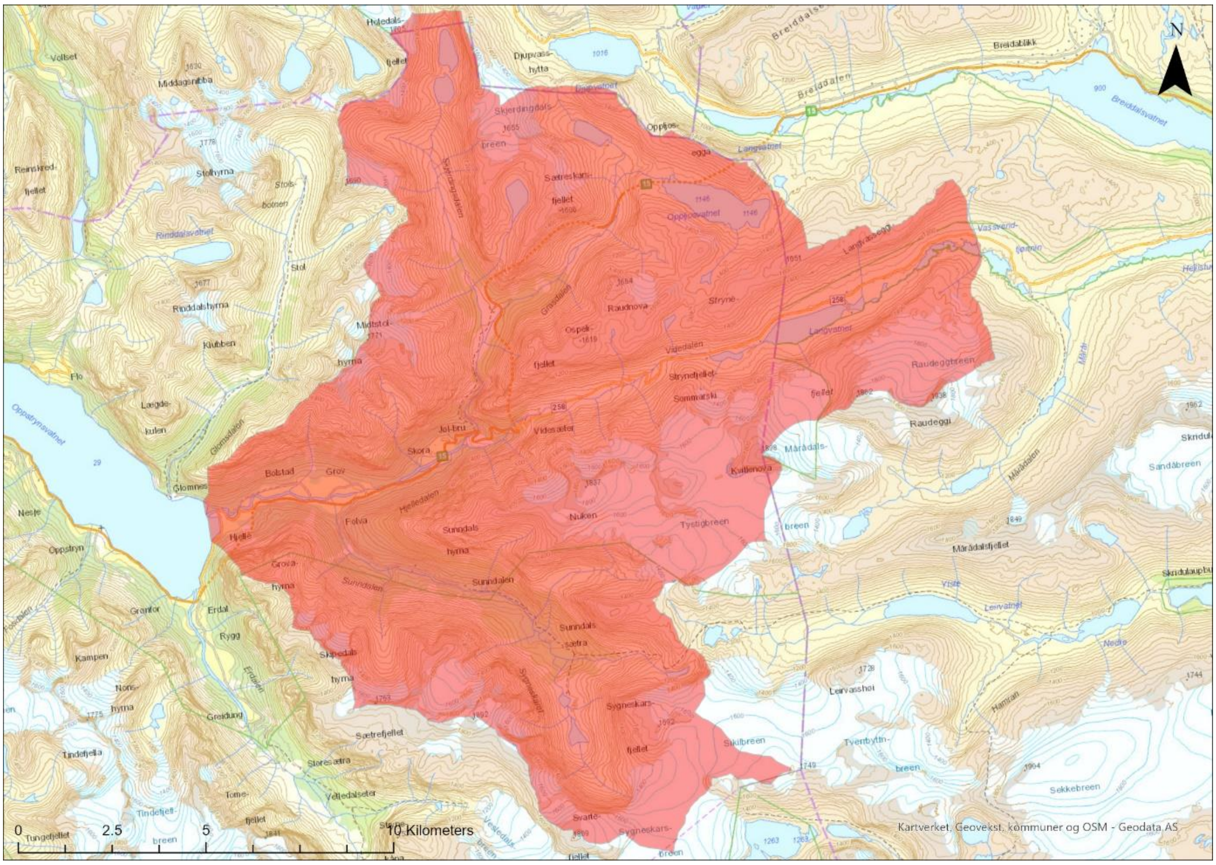


Figure 3: The drainage basin, from the beginning of Oppstryn lake, where the river Hjelledøla ends. Data from NVE NEVINA, and visualized through ArcGIS Pro

2. Theoretical framework

The theoretical framework consists of the analytical concepts and theory that is part of this thesis. It consists natural factors that are important for the thesis, such as the anatomy of floods, about glacier lake outburst floods, and the river processes, and how these can be affected by GLOFs. The next parts consist of more technical aspects of the theory, such as LiDAR, DTM and Planetscope satellite. It will hold important information about hydraulic modeling, HEC-RAS, and how the software computes hydraulic modeling. This consists of the 2D geometry, the unsteady flow modeling, parameters and computational intervals, the different equations the model uses, such as the shallow water equations the diffusion wave equations.

2.1. Anatomy of floods in Norway

Here we define a flood as natural process which occurs when the water level of a body of water, such as rivers, creeks and lakes, rises to until it overflow the barriers, which can be both artificial and natural, causing a submerging of areas that under normal circumstances would be dry (Luino, 2016). Floods can be driven by a wide range of processes such as storms, heavy rain events, big ocean waves, snow melting, breaking of dams, glacial lake outburst floods (GLOF) and excessive glacier melt. Flooding events can happen fast, or they can build up slowly over time, with the peak of the flood lasting for a longer period of time in some instances, while disappearing as fast as it happened in other instances (NOAA, 2022; NVE, 2021).

Floods are often driven by seasonal cycles: In Norway these are usually spring and autumn floods (Stenius et al., 2015; Stenius et al., 2014). In the spring, the snow stored in the high-altitude areas starts melting, and the water flows into river systems downstream. This process has an especially high probability of becoming a hazard, if the spring melting has a late onset, coinciding with rapid fluctuations from low to high temperatures (Hanssen-Bauer et al., 2015). In general, late springs are characterized by higher temperatures maintained over a longer period of time, triggering massive melting events, and feeding river channels with large amounts of meltwater. These are often combined with much precipitation and heavy rain events that will further increase the likelihood of hazards (Hanssen-Bauer et al., 2015; Stenius et al., 2015). The type of terrain is important when considering the basin's ability to experience a flood event, depending on the geographical settings, climatic conditions, as well as spatial variations in the terrain's height and slope within the watershed. All of these factors are important for the process in which melting of the snow in different stages and at different times during the spring impacts pre-existing channels and connectivity between them. With little variation in the terrain altitude within a watershed, snow and ice remaining at the end of the winter melt nearly simultaneously and thus provide an impulse water supply into river systems (Stenius et al., 2015) (NIWA, 2022). In contrast, autumn floods are not caused by melting of snow but rather by heavy rains that are typically of short duration and thus are the primary cause of flash floods (Marchi et al., 2010).

2.1.1. Drivers and processes of flash floods

Flash floods are usually classified as floods that occur within a short period of time, usually in a matter of hours after the triggering event that caused the flood (Gaume et al., 2009; Stenius et al., 2014). The response time for the flash flood is dependent on the size of the basin where it occurs. In most cases these are heavy rain events that are driven by locally produced convective precipitation with response times of a few hours or less and are therefore most common in basins with an area of less than 1000 km^2 (NOAA, 2022). Although statistically most of the flash floods are created by heavy rain events, other means can also contribute to their occurrence. For example, it can also happen that a dam or a levee fails or collapses (Gaume et al., 2009). Alternatively, it can be triggered by an ice dam that stops the natural flow of water and can cause flash floods and through a glacier lake outburst flood. Flash floods are very difficult to predict with certainty. Their short durations and local impacts make it difficult to issue reliable warnings before the event has already taken place, and it can therefore often come as an unwelcome surprise (NOAA, 2022; Stenius et al., 2015).

Flash floods constitute an important type of hazards due to the danger they pose to infrastructure and human life, and it is therefore of great concern to hydrological and natural hazard sciences (Gaume et al., 2009). About 40 % of the flood-related casualties that had occurred in Europe in the period between 1950 and 2006 were caused by flash flood events (Marchi et al., 2010). Flash floods are an increasing problem in the world, since the global warming is causing heavy rain events to become more frequent and more intense on both regional and global scales. There is also a bigger chance of damage to properties, infrastructure and human lives due to the ongoing expansion of private housing towards remote areas, and more intense use of land (Alfieri et al., 2015; Marchi et al., 2010; Wilhelm et al., 2012). Another issue that is common for the western coast of Norway is that many towns and cities are built close to rivers and hydrological systems and have short hydrological response times. This is due to steep mountainous terrain that makes flash floods fast and unpredictable in these regions (Stenius et al., 2015).

2.1.2. The making of glacier lake outburst floods (GLOFs)

Glacial lake outburst floods (GLOFs) are also known as a jøkullaup from the Icelandic words “Jøkull” meaning glacier and “hlaup” meaning flood burst. GLOF is a sudden release of water from a glacier that has a potential for a catastrophic flooding downstream and a high degree of geomorphological and socioeconomic impacts (Bendle, 2020). The source of the water in a GLOF can be from a glacial lake dammed by a glacier, or from glacial meltwater stored subglacially, englacially or supraglacially, or from a pro-glacial moraine-dammed lake (NVE, 2017).

Moraine dammed lakes form during warming climate intervals when glacier tongues retreat away from moraines formed during earlier, colder and more stable periods (Bendle, 2020; Harrison et al., 2018). When the glacier margin melts away and retreats, runoff from the glacier starts accumulating and being stored in the topographic lows in front of the glacier where moraines obstruct the further flow of the water and create dams (Harrison et al., 2018). The moraine types that tend to create moraine dammed lakes are often terminal moraines or lateral moraines. Many of the moraine dammed glacial lakes contain ice cores within the moraines that compromise the moraine stability in the long run (Østrem, 1959). Glacial moraines often consist of loose, unsorted permeable types of sediment, and when the sediment gets saturated with water, moraines weaken and fail due to melting of the ice inside the moraines (Bendle, 2020; Bennett et al., 2000). Even if the moraine dam collapse happens gradually over time, it still may trigger GLOF events through for example, displacement waves. This may happen when a lake-terminating glacier releases massive icebergs into a moraine-dammed lake, or similarly such waves can be created by large rockfalls, landslides or avalanches into a moraine-dammed lake. When a sudden input of material into the lake creates waves, they can overtop the moraine and produce a breach incision. In this case, water erodes sediments and creates channels at top of the moraine that will in turn initiate a positive feedback loop in that channels formed by displacement waves excavate surplus water, allowing it to further erode, widen and deepen the new channel and create a topographically constrained water flow during the upcoming drainage events. Through this channel, the water will eventually flow out of the pro-glacial lake, creating a potential for a GLOF (Bendle, 2020; Westoby et al., 2014).

Glacier-dammed lakes are formed when meltwater discharge from the glacier is blocked and dammed by the glacier itself (Carrivick & Tweed, 2013). Ice dammed lake formation is a gradual process, it is linked to the glacier mass balance, and climate forcings. However independently of the climate, sudden glacial advance can be the cause of the blocking of the usual channels for discharge, cause the drainage to halt, which can force the creation of a proglacial lake (Tweed, 2011). Drainage from ice dammed lakes occurs when the lake level is of level, which is high enough to overcome a barrier at the bed of the glacier, discharge will normally occur subglacially. The flood initiation both origins in the water level reaches the floatation level of the glacier, whilst other starts draining before reaches this flotation pressure, and the drainage of the glacier can be massively influenced by the state of the blocking glacier (Carrivick & Tweed, 2013; Tweed, 2011). Potential for drainage as a result of the GLOF happening on top of the glacier is possible (Jackson & Ragulina, 2014; Tweed, 2011). Glacially dammed lakes are more common in Norway, than in many other parts of the world. In most places the GLOFs occur as a result of drainage of moraine dammed lakes, while Norway receives most from glacially dammed lakes.

The two large lakes of Tystigbreen considered in this thesis are glacier-dammed lakes that formed because the Tystigbreen glacier counterparts block the drainage paths of both lakes. One side of the lakes is composed of a steep mountainside, while the other side is made of a steep glacier wall blocking the drainage path, trapping the lagunes between. There is a difference between glacial and moraine lake dams and how the process of GLOF occurs. For example, when water starts draining due to a breach in the dam, it does not require a collapse of the walls of the glacier-dammed lakes but rather a sudden opening of a drainage channel within or below the glacier. With moraine dams this process ends with a complete destruction of the dam and thus a one-time GLOF event, while glacier dams are likely to stay intact and create repeated hazards. The reason for the latter being a more hazard-prone environment is because lake water drains underneath or within the glacier through subglacial or englacial meltwater channels that close, once the water from the dam has flown through. One of the most probable mechanisms for the glacier-dammed GLOFs is the growing amount of water in the lake that causes the glacier body to float due to differences in densities of materials (ice versus water, Bendle, 2020) and lets the accumulated water escape subglacially (Tweed & Carrivick, 2015). Once the lake is emptied and the surplus water has escaped, the glacier can regain its contact with the ground. When the level of the glacial lake reaches 90% of the glacier dam height, the lake gains the potential to make the glacier float, lifting its base and connecting the lake to the active subglacial hydrological channels operating below glaciers (Bendle, 2020; Jackson & Ragulina, 2014). Since the glacier will stay intact after a GLOF event has occurred and the subglacial drainage system has closed up, it allows for a repeated storage of the runoff in the same lake basin and thus repeated GLOFs that can occur once in several years, or each year or even several times per year (Jackson & Ragulina, 2014). Still, GLOFs from glacier-dammed lakes can be considered to produce floods of lower magnitudes compared to the moraine-dammed lakes, because it usually takes a longer time for the water to drain sub-glacially, as opposed to typically rapid and sudden collapse of a dam that is associated with the moraine-dammed GLOFs. Due to the repeated cycles of GLOFs from glacially-dammed lakes, they create constant danger to the communities downstream, as opposed to more impactful but one-time events from moraine-dammed lakes (Bendle, 2020; Carrivick & Tweed, 2013).

Depending on regional settings, volumes of GLOFs can be enormous. In a remote past, the retreat of the Laurentide Ice Sheet in North America during the late Quaternary period resulted in a formation of enormous glacial lakes that drained catastrophically into the North Atlantic Ocean and partially collapsed the thermohaline circulation due to rapid input of freshwater (Klitgaard-Kristensen et al., 1998). In recent history, some of the Earth’s largest floods have occurred because of GLOFs, causing massive alterations in landscapes and numerous casualties (Bajracharya & Mool, 2009). Human activities have increasingly moved towards areas close to glaciated areas and catchments, and at the same time, many of the glacial lakes around the world have increased in size and volume due to climate change (Jackson & Ragulina, 2014). It is therefore important to carry out further research on both mechanisms and impacts of GLOFs, including potential damages they can create and the development of early warning systems for the mitigation of their adverse impacts. In the Stryn municipality, it is known that GLOFs from the lake of Tystigbreen have occurred several times. According to NVE’s reports, it previously happened in 2010, 2014 and 2018 (NVE, 2017). In addition, our team has witnessed the consequences of lake drainage during the fieldwork at Tystigbreen in summer 2021. We therefore identify this area as prone to natural disasters from glacial lakes, with a growing potential for higher impacts on society in the future.

2.1.3. River processes

Erosion, transportation, and sedimentation are constant processes that occur in rivers, streams and creeks (Kellerhals et al., 1976). The speed and amounts of water passing through a river system are essential for these processes that are in turn important for the development of fluvial depositional landforms, such as floodplains. Although floodplains have a high exposure to hazards, they are characterized by some of the richest soil types for agricultural use and have therefore historically represented land sectors where people settled and built communities (Fergus et al., 2010) (Sulebakk, 2007).

Fluvial erosion occurs when flowing water is removing more material from the surface than the water is able to leave behind (Fergus et al., 2010). In rivers, water detaches and transports materials in the form of sediments. In meanders, the speed of water flow and thus erosion are highest along the outer bends of the river.(NVE, 2015a; Sulebakk, 2007). The degree of degradation or vertical erosion depends on a range of controlling factors such as river length shear strength of the sediment material at the bottom of the river channel, as well as energy and volume of water flow hat all contribute immensely to the degree of erosion, with big floods leading to the highest degree of erosion in rivers (Fergus et al., 2010; Hooke, 1979; Sulebakk, 2007).

Sediment transportation occurs when water flow in a river entrains sediments and carries them downstream. Sediments typically include both organic particulate material and non-organic material. The non-organic material is sorted after particle size of sediment with clay, silt, sand, gravel, cobbles and boulders (Fergus et al., 2010; NVE, 2015c). There are three different ways for the sediment transport to happen: Saltation, suspension and dissolution. Saltation is a process through which larger pieces of sediment and rock get transported by a river channel. Cobbles and gravel either roll on the floor of the river channel or jump and slide. These fluvial actions smoothen the transported rock fragments and sediment particles and are important for the stability as well as for the shape of the river. Suspension occurs when sediments are light and buoyant enough to stay suspended in the river stream. The fine-grained sediments such as clay, silt and fine sand are the sediment types that are able to stay buoyant and kept afloat due to turbulence of the water in the river. Suspension is important for the biological conditions in and along the river and has a large influence on the water quality. Dissolution applies to easily dissolvable chemical substances that are transported in the river and eventually dissolve in the water (Fergus et al., 2010; NVE, 2015c).

Sedimentation happens when the energy of a river is insufficient to transport sediments, whether through suspension or saltation (Fergus et al., 2010). An example of sedimentation is in the inner bends of a river meanders, as opposed to the outer bends where water has enough energy to erode riverbanks. At the inner bends however the pace of the water slows down, reducing the energy and erosive power of the water, thereby resulting in an accumulation of sediments (NVE, 2015a).

The river processes are enhanced by GLOFs, leading to higher water volumes and more energy in the river. Under the influence of a GLOF, it can erode and transport materials with larger grain sizes. In this case, sedimentation can happen in areas where it would not usually occur. There are many variables that determine relative proportions of erosion, sediment transportation and sedimentation in a river. Their dependence on such variables can be easily visualized through the use of Hjulstrøm's diagram showing how erosion, transportation, and sedimentation of particles with different grain sizes depend on the speed of water.

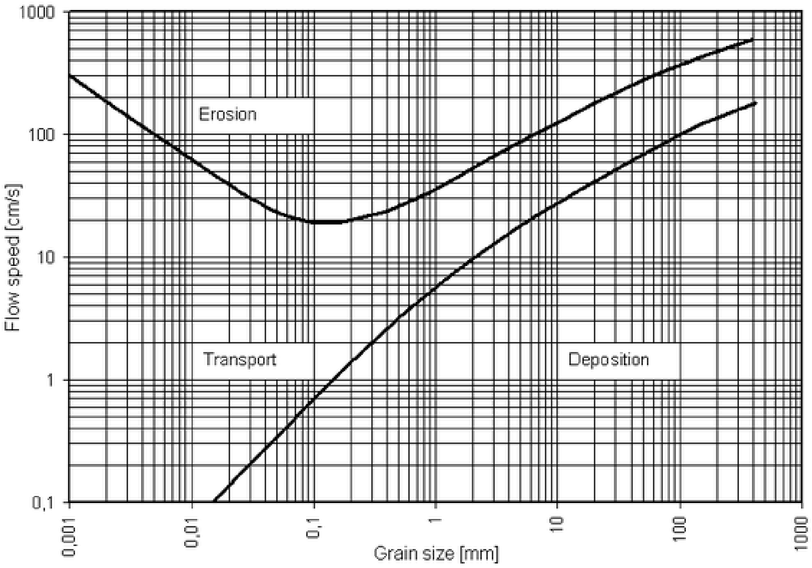


Figure 4: Hjulstrøm diagram, it shows at what flow speed different grain sizes of sediments erode, gets transported and deposit. The figure is captured from Wikiwand.

2.2. Background datasets for hydrological modeling and process understanding

2.2.1. Satellite imagery – PlanetScope

PlanetScope is a constellation of approximately 180+ cube satellites that are operated by Planetlabs (Planetlabs Inc). The PlanetScope satellites provide a large number of observations around the globe, delivering high-quality geospatial observations through their combination of coverage, frequency, and resolution. PlanetScope constellations orbit the poles every 90 minutes and are therefore able to capture the entirety of the Earth's landmasses in one day (Cheng et al., 2020). These satellites produce images with four spectral bands, i.e., blue (455-515 nm), green (500-590 nm), red (590-670 nm) and near infra-red (NIR, 780-860 nm), and deliver satellite images with a 3.7 m resolution. Compared to open-access satellite products such as LandSat and Sentinel, PlanetScope provides data with a good coverage and temporal and spatial resolution to study the evolution of glacial lakes, including potential GLOFs. This gives an opportunity to monitor when glacial lakes attain highest volumes of water and when they start draining. It can also give data on how long it takes for glacial lakes to drain partly or entirely (Cheng et al., 2020; Planetscope, 2022). PlanetScope is necessary in this thesis to monitor glacial lakes and estimate the amount of water contained in them during different stages of filling.

2.2.2. Terrestrial and airborne LiDAR observations

LiDAR was developed in the United States of America in the 1960s after the invention of the laser technology (Rød, 2015). The acronym LiDAR stands for "light detection and ranging" marking the method for an active remote sensing technology. The light used in the LiDAR technology is emitted through highly concentrated laser beams by the LiDAR scanner, that measures the time that it takes for one laser beam to hit and be reflected by the surface of an object and return to the scanner (Lim et al., 2003; Rød, 2009, 2015).

LiDAR offers a possibility to map the surface of the Earth with a high precision. The rate of the laser beams is known to be up to 300,000 pulses per second, but the more common instruments operate at around 50,000 to 150,000 pulses per second (150 kilohertz) (Carter et al., 2012). LiDAR observations create a point cloud that consists of a lot of points from every one of the laser beams from the LiDAR scanner, with points that are georeferenced in a XYZ coordinate system. The result is a very detailed and dense network of elevation points, which constitutes a 3D representation of the object it measures with a centimeter precision (Rød, 2009).

LiDAR instruments often operate in a near-infrared spectrum of light, around 1500 nm. This means that LiDAR instruments have the possibility to be effective during the night when it is dark, which can also be favorable because the air is often clearer during this time of the day (Carter et al., 2012). LiDAR observations collected with 1500 nm lasers do not have the ability to penetrate water surfaces such as rivers or lakes, as well as clouds and fog that will obstruct the signal if they are present during the scans. There are also dissimilar kinds of lasers mounted on LiDAR instruments that are suitable for performing measurements on more challenging materials. These include the LiDAR technology that operates at a wavelength of 1064 nm, making this type of a laser better at capturing snow and ice and thus at measuring glacier changes. In contrast, the blue-green LiDAR equipment can scan through water surfaces and therefore map the bathymetry of lakes and rivers. The LiDAR scanner with a blue-green wavelength operates at a wavelength down towards 532 nm (Carter et al., 2012).

Figure 5: Airborne LiDAR -scanner that scans the terrain below (Laser kartlegging (LiDAR), 2021).

Airborne LiDAR scans provide the most efficient way to capture topographic data over vast, continuous areas. Most commonly used platforms for airborne LiDAR are either airplanes or helicopter. LiDAR instruments are mounted inside a vehicle, plane or helicopter and are then flown over an area of planned observations. In contrast, terrestrial LiDAR instruments are mounted on the ground or on all-terrain vehicles. It has an advantage in places where airborne LiDAR has a limited reach as for instance, inside a cave or building and can be better at measuring smaller and more discrete features. Although terrestrial instruments are unable to map topography as far as airborne LiDAR, they are able to get really precise 3D models of smaller patterns from different angles. A weakness of using airborne LiDAR is that it creates more point measurements per square meter on flat surfaces such as an agricultural field and less points per square meter in steep terrain. This issue leads to an underrepresentation of points in complex, steep areas, and can lead to an overrepresentation of points on flat surfaces. If there are overhangs on steep mountain sides, these areas may be presented as blind spots in LiDAR scans. In this case a terrestrial scanner can be more useful on steep hills or mountain sides (Carter et al., 2012; Lim et al., 2003; Ruiz et al., 2004).

LiDAR data is an important part of the modeling of water flow and GLOFs, since it is essential for the creation of digital elevation models, which are necessary for hydraulic modeling, and hydrological analyses of the area. In addition, terrestrial LiDAR has been an important part of the fieldwork conducted in the Stryn municipality and the rest of western Norway used to create 3D models of the areas of interest.

LiDAR may also be an effective mapping tool for the Earth's surfaces hidden under vegetation due to the fact that laser pulses return to the LiDAR scanner multiple times during a scan. When scanning the terrain from an airplane, the laser pulse shoots towards the ground and will be returned to the scanner multiple times. When the light pulse reaches the top of a tree, it will be reflected and returned, but parts of the light pulse will continue towards the ground (Rød, 2009).

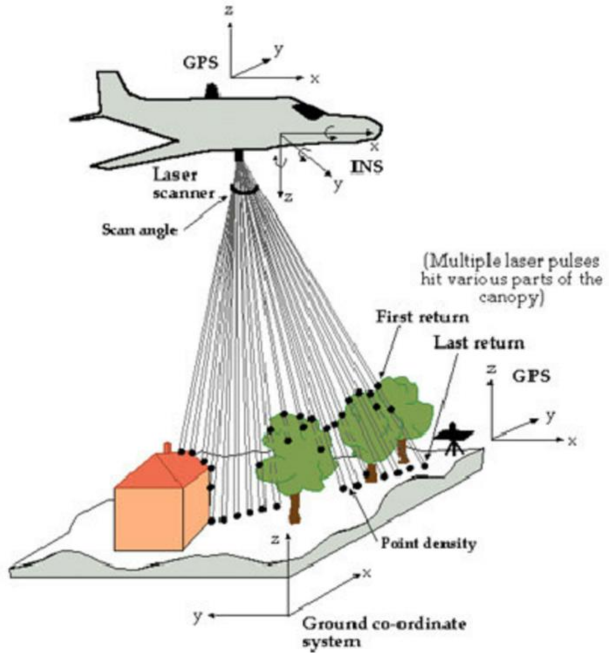


Figure 6: LiDAR scanner with multiple return points is able to scan the same object several times and at different angles (Dowman, 2004)

2.2.3. Digital elevation model

Digital elevation models (DEMs) are developed based on LiDAR data captured and turned into a digital model that represents the surface of an area with an elevation data added to the model (Mukherjee et al., 2013; Rød, 2009). A DEM shows the real height and terrain of the area in a model (Rød, 2015). DEMs are shown either as irregular vector data or in a shape of a regular raster-based data. Raster-based regular data contains data which is regular and consistent throughout the raster file. The data is shown as a grid where all the rectangular shapes are shown with equal size and spacing between them. The vector-based irregular elevation models on the other hand have different shapes and sizes for the elevation data (Hengl & Evans, 2009).

There are good reasons to use both types of the elevation models, but here we outline some advantages for using the vector-based models (Hengl & Evans, 2009):

- Raster-based grids can be less detailed and show less of the complexity of some types of topography. They can also show more of the areas with flat and even structures.
- Re-projection of grids can be a very slow process which will lead to a loss of accuracy.

In contrast, there are also several advantages for using raster-based grids:

- Grids have simple structures, and they are therefore easily reconstructed if need to be;
- Since there are even distances between cells and all the cells have equal sizes, coordinates can be easily calculated.
- Grid models are better suited for modeling, where the use of image processing and printing are necessary.

Even though there are good reasons to use both vector-based and raster-based elevation models, raster-based elevation models have become standard in science. The cell size of DEMs is crucial, when it comes to the creation of hydrological models. The cell size is imperative for the quality of a DEM and the detail of a hydrological model - the larger is the size of the cells, the less detailed the elevation data in the elevation model becomes and the less detailed the hydrological model becomes (Hengl & Evans, 2009). There can be a vast difference between the interpolated surface elevation and the actual physical land surface, meaning that if the resolution is too coarse, actual objects with the sizes below the resolution of the elevation map might disappear. Such objects as small rivers or creeks, bridges and culverts might be too small to be part of the elevation model, if the cell size is too coarse. The cell size is imperative for the quality of the DEM and the detail of a hydrological model(Brunner, 2021a; Hengl & Evans, 2009).

The cell size in a DEM is not only important for the details and the generalization of the model, but also crucial to the time required to process the data and to the size of the data file (Brunner, 2021a; Kenward et al., 2000). The higher is the resolution of the cell sizes in the elevation data, the longer time it takes to process the data and create hydrological models. It is a very important and difficult decision to decide when the resolution of the raster data is adequate. It is important to know if the data can lose some resolution and thus the detail of the underlying terrain to gain time to process and calculate the results and storage space on the computer (Hengl & Evans, 2009; Kenward et al., 2000).

2.3. Hydrological analysis

Hydrology is the science about the processes that drive the hydrological cycle and define the distribution of water on the Earth's surface (Tollan & Bakken, 2019). It is the essence of hydrology to study and understand how physical properties of water under the influence of gravity affect its interaction with the environment and surroundings. As part of hydrology, analyses of water levels and velocity in rivers and floodplains are designed to estimate the danger imposed by the water and hydrological systems to people, nature and manmade objects (Tollan & Bakken, 2019).

HEC-RAS is a software created by the United States army corps of engineers, the Hydrologic Engineering Center (HEC). HEC's River Analysis System (HEC-RAS) is one of the most popular programs for hydrological and hydraulic calculations and modelling (Brunner, 2021b). It is a common software used by both governmental organizations around the word as well as by private enterprises since its release in 1995 (Quirogaa et al., 2016). It has been developed for calculations of different parameters that determine the behavior of water in a hydrological system and has proven particularly useful for modelling water flows through systems of open channels and creating water surface profiles. The related software can calculate the possibility of floods in river systems, manage floodplains and execute tasks related to the evaluation of floodway encroachments, such as bridges, buildings, and natural obstructions along river pathways. It can be used to map and model the flow of dam- and levee breaks, including flash floods that occur when a dam breaches, as well as the flow of potential future GLOFs. Through the use of hydraulic modeling in HEC-RAS, it is possible to route the path of a GLOF and potential floods it may cause downstream, as well as visualizing its impacts on the buildings and infrastructure. In the HEC-RAS 6.1 software, it is possible to create both 1D and 2D hydrological models (Brunner, 2021b).

2.3.1. 2D hydrological analysis

A 2D geometry analysis is created through a network of cells named a 2D computational mesh, which is the most important part of the 2D flow area. In this 2D flow area, it is possible to define a perimeter for an area where hydrological model performs calculations; An example for such a perimeter can be a watershed or a part of the river that is of interest to the user (Brunner, 2021a). Inside the perimeter, one can determine a 2D calculational mesh and the number of computational cells inside this 2D computational mesh, defining a network of cells that is the basis for the 2D flow modelling. The two-dimensional model in HEC-RAS uses the network of cells to calculate the amount of water that flows from one cell to the next. Important aspects of the cells and the cell grid are the cell center, the cell face and the cell face point visualized in Figure 7 (Brunner, 2021a; Shrestha et al., 2020):

- The cell center is the computational center of a cell that does not have to be in the middle of the cell, but instead, it can be located anywhere in the cell. However, there can be only one cell center in each cell where surface elevation of the water is computed (Brunner, 2021a).
- The cell face is the area outlined by lines separating it from the neighboring cells. The simple grid architecture normally uses straight lines but can also benefit from introducing multipoint lines. This cell feature defines its boundaries, including borders with the adjacent cells. Each cell can have a maximum of eight adjacent cells, otherwise an error will occur and the simulation will be incorrect (Brunner, 2021a).
- Cell face points are the edges of the cell, where cell faces meet to form the corner of the cell. These points are important for connecting the 2D cell mesh to a 1D analysis, so cross sections are connected to the 2D cell mesh via the cell face points. This is also where the boundary conditions such as input upstream river and output downstream river are connected to the 2D cell mesh (Brunner, 2021a).

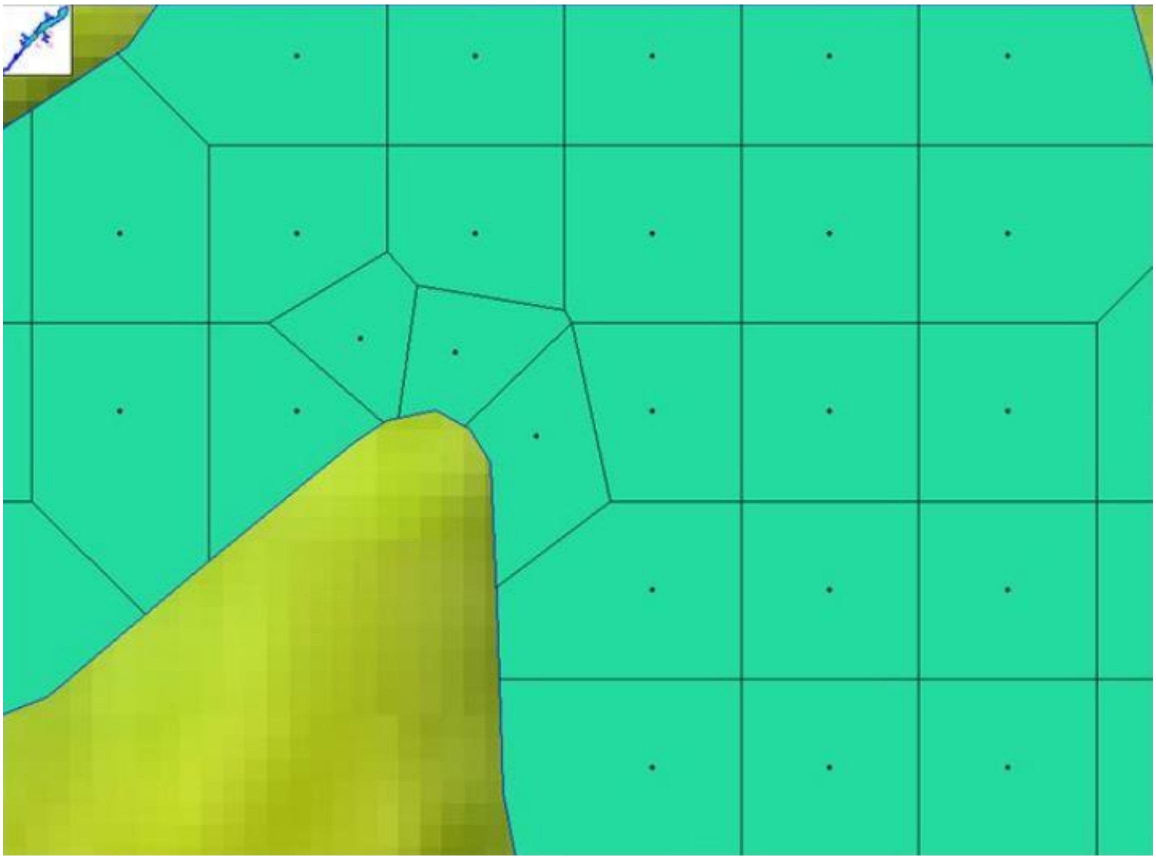


Figure 7: 2D computational mesh, with cell points, cell faces and cell face points (Brunner, 2021a).

The 2D computational mesh in HEC-RAS uses the representation from the underlying terrain, which is defined by a digital elevation model, to describe how water is routed from one cell to the next, by calculating the hydraulic properties and flow of water in the underlying terrain (Ongdas et al., 2020). The sub-grid model in the HEC-RAS software is commonly utilized to determine where and how the water flows in an open river system (Brunner, 2021a; Shrestha et al., 2020).

The advantage of using a 2D analysis is that it allows creating a flood analysis with inputs from several interconnected rivers which are being impacted by forces from different directions at the same time (Brunner, 2021a). In 2D, it is also possible to create precipitation analyses for the whole area and include many other features that are not permitted in 1D analyses. However, 2D models can be heavy to compute and process, depending on choices such as resolution and size of digital elevation data and 2D computational mesh, as well as the length of the hydrological system and of the simulation (Shrestha et al., 2020). 2D analyses require a higher computational power than 1D analyses, but it allows for more advanced models compared to 1D cases (Brunner, 2021a, 2021b).

Both 1D and 2D hydrological models use Manning's n roughness coefficient to calculate how much energy water in the river loses based on the roughness of the surface terrain (Brunner, 2021c). Manning's n coefficients are values assigned to different surface materials, such as asphalt, agricultural land, forest, or concrete, representing the roughness of each material and approximating the amount of internal energy the river will lose when flowing through such surface materials (Shrestha et al., 2020). In 1D analyses, roughness is only prescribed to the river channel, and it is only given where the cross-sections are located, which is drawn across the river at even intervals throughout a river in a 1D model, the cross sections calculates water flow by knowing the amount of water, the roughness of the water channel and elevation data from the DTM. And thus, defining the Manning's n values separately for different sections of the river. In 2D models, the Manning's n value is fed to HEC-RAS via a polygon map layer (Ongdas et al., 2020). If the user is in the possession of a land use map, it is possible to add several Manning's values to different kinds of surface materials. By using a 2D hydrological model, it is possible to not only have the roughness coefficient defined for the river channel and riverbanks, but also to utilized location-specific values within the area of interest that is included in the map (Brunner, 2021a, 2021b; Pappenberger et al., 2005).

2.3.2. Leaks in the 2D geometry

The presence of leaks in the computational mesh is a common error in HEC-RAS, if the computational mesh is not properly aligned with the underlaying terrain or if the cells of the computational mesh are too large (Brunner, 2021a). When HEC-RAS calculates water flow and faces a barrier or a high elevation obstacle in a cell, it might not detect the barrier, because the obstacle is contained within the cell. The result is that water is overtopped and streamed to both sides of the high obstacle or barrier, instead of staying on one side of the barrier (Goodell, 2015). The error occurs due to the software's way of calculating the relationship between height and volume. HEC-RAS uses the height for the entire cell to calculate the flow and motion of fluids. Therefore if heights are similar on both sides of the high ground object, both areas within the same cell with the same elevation are calculated as wet (Figure 8, Brunner, 2016; Goodell, 2015).

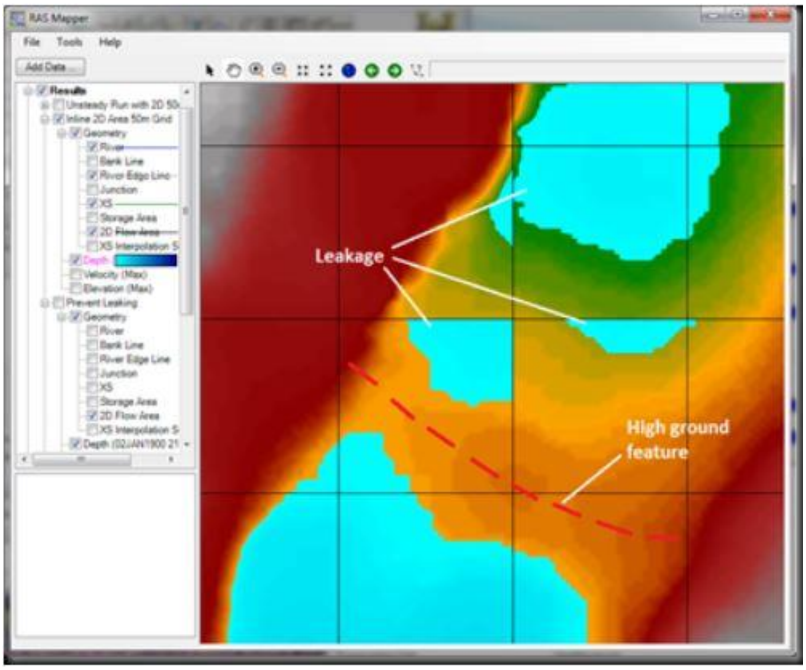


Figure 8: Image showing leaks in a 2D computational mesh (Goodell, 2015).

Figure 8 shows how the water can spill over the high ground feature, because the object is located diagonally across the 2D cell. It is therefore not identified by the simulation as an actual barrier that can hinder the water, while in reality the water would have been stopped by the barrier (Brunner, 2016; Goodell, 2015).

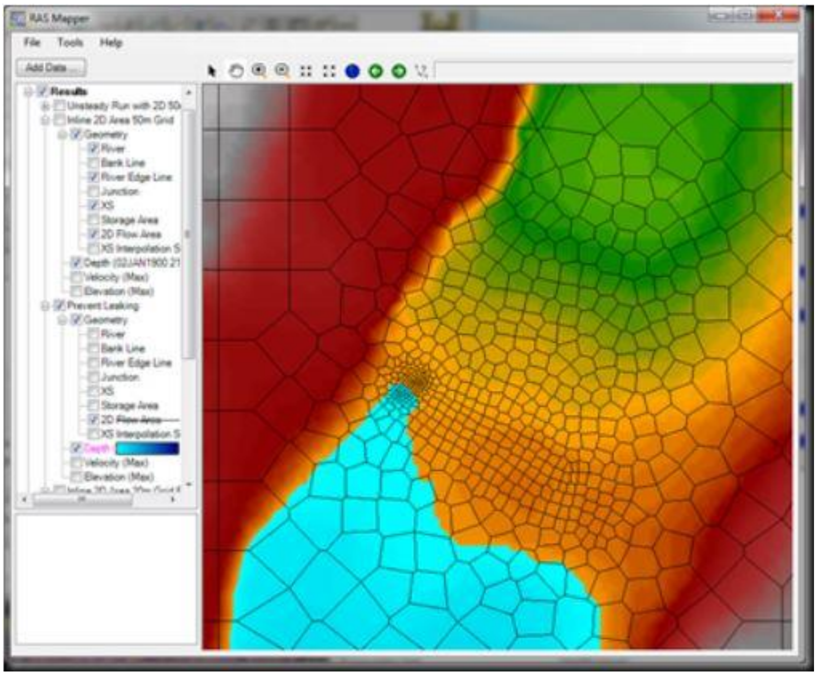


Figure 9: A solution to how a 2D computational mesh can be edited to stop leaks from occurring (Goodell, 2015).

The problem visualized by figure 8 is however possible to solve. In figure 9 the problem has been identified and a solution has been implemented. It has been specifically designed with a 2D computational mesh (and cell faces) which is perfectly aligned with the underlaying terrain (the contours of the digital elevation map). By altering the 2D computational mesh, water will not flow above the high ground feature, but will stop as it would have naturally done in the reality. This is a good example of problems that large 2D computational mesh networks can experience in HEC-RAS, when there are abrupt and big differences in elevation (Goodell, 2015).

This type of problems should not occur, if there is a relatively flat area with water flowing in a river. The 2D mesh can have big cells if the entire area has nearly the same elevation. Elevation is a key in how HEC-RAS calculates the flow of water in a 2D geometry (Brunner, 2021a; Goodell, 2015).

2.3.3. 2D unsteady flow and hydrodynamics

There are three different kinds of flow models and methods for their analysis that are used to approximate and resolve the flow of water - steady flow, unsteady flow, and quasi unsteady flow; they differ in the ways they introduce water and how water flows in the model. Though it is possible to use the three different analysis options, only two of them are widely used: namely, the unsteady flow and steady flow analyses. There are benefits with all the different flow models, but unsteady flow analysis is the most used in tasks of 2D hydrological analyses (Brunner, 2021b, 2021c; Brunner et al., 2020).

2D analysis with unsteady flow can approximate the water flow in an open river channel through a flow hydrograph that changes with time (Brunner et al., 2020). A flow hydrograph shows the water flow in a river or watershed through a certain amount of time, spanning a wide range of time intervals from seconds to hours to even years. It all depends on the amount of runoff data that is available and how long a hydrological simulation should be. A reference point in a watershed or river can be chosen to either coincide with the location where an input water flows into the hydrological model, or with the end point where the water flow exits the hydrological model in the downstream outflow area. Alternatively, but less conveniently, it can be placed at any location between the start and end points. There can also be several flow hydrographs if for instance there are more than one inflow locations where water enters the hydrological model, or if there are several rivers in the water catchment. For instance, a hydrograph can show how much water a glacier feeds into the river over a given time period. For Tystigbreen, it can potentially show the water flow in Hjelledøla during a 24-hour period. Unsteady flow models currently represent the best option for calculating and modelling a dam/levee break that results in a large input of water into a river over a limited period of time. This hydrograph can then be plugged into an unsteady flow analysis, while being modeled and visualized using HEC-RAS. In this study, the unsteady flow method is used to model GLOFs, because it is necessary for the models to have a hydrograph presenting different GLOF scenarios (Brunner, 2021c; Brunner et al., 2020).

2.3.3.1. Diffusion wave and Shallow water equations

There are two classical equations used for simulations of water flow in HEC-RAS with an unsteady flow analysis. These two methods are known in HEC-RAS as diffusion wave and shallow water equations. Shallow water equations are also known as Saint-Venant equations, but in HEC-RAS-related literature uses the term "shallow water equations" (Brunner, 2021c). The name Saint-Venant equations is adapted after the mathematician and mechanician Adhémar Jean Claude Barré de Saint-Venant. While the shallow water equations are derived from the simplified Navier-Stokes equations that describe the flow and motion of fluids in a 3D space, the diffusion wave equation is derived from the shallow water equations and is further simplified (Brunner, 2021c; Brunner et al., 2020; Pappenberger et al., 2005).

Both shallow water and diffusion wave equations rely on some simplifying assumptions. This is because the unsteady flow method varies the motion and flow of water in time and space through a preservation of mass, known as continuity, and speed of mass. These are amongst the laws that determine the flow of water. In a 2D unsteady flow method, these are expressed mathematically using partial differential equations that are based on the following assumptions (Astad, 2020; Brunner, 2021c):

- Fluid is incompressible, and the volume of the fluid is proportional to its mass. This is due to the fact that its density is assumed constant.
- The spread of the pressure distribution is assumed to be hydrostatic.
- The gradient of the river reach is less than 1:10.
- Friction coefficient is defined as for partially wet areas and can be described by the Manning's N value.

Mass conservation:

When the flow of water is assumed incompressible, the unsteady differential form of mass conservation (continuity) equation is:

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

Where: t = time; h = water depth; u and v = velocity components in the x and y direction respectively; and q = source/sink flux term (Brunner, 2021c).

The diffusion wave method is the default when trying to simulate with the behavior of an unsteady flow. This is due to the diffusion wave formula requiring less computational power and less of the user's time. This is the reason why it is recommended to model water flow with the diffusion wave equations before performing simulations with shallow water equations. A sensitivity test with shallow water equations should then reveal, if it is necessary to use shallow water equations instead of the diffusion wave equations. If they are considerably different, then the user should assume that the model created with shallow water equations is the best one.

Shallow water equations, or the Saint-Venant equations, are able to account for more of the water properties than the diffusion wave method. It can account for the Coriolis effect and for turbulence, which marks the change in the momentum (Kim et al., 2014). There are issues connected with the use of shallow water method, because it can lead to instabilities within the model in areas where the water flow alters along its path. This can however be solved by using a grid mesh network with a higher resolution and a lower number for the computational intervals (Brunner, 2021c).

Shallow water equations:

In the direction of x:

$$\frac{\partial u}{\partial t}+\frac{\partial u}{\partial x}+\frac{\partial u}{\partial y}-f_c v=-g\frac{\partial z_s}{\partial x}+\frac{1}{h}\frac{\partial}{\partial x}\left(v_{t,xx}h\frac{\partial u}{\partial x}\right)+\frac{1}{h}\frac{\partial}{\partial y}\left(v_{t,xx}h\frac{\partial u}{\partial y}\right)-\frac{\tau_{b,x}}{\rho R}+\frac{\tau_{s,x}}{\rho h}$$

In the direction of y:

$$\frac{\partial v}{\partial t}+\frac{\partial v}{\partial x}+\frac{\partial v}{\partial y}-f_c u=-g\frac{\partial z_s}{\partial y}+\frac{1}{h}\frac{\partial}{\partial x}\left(v_{t,xx}h\frac{\partial v}{\partial x}\right)+\frac{1}{h}\frac{\partial}{\partial y}\left(v_{t,xx}h\frac{\partial v}{\partial y}\right)-\frac{\tau_{b,x}}{\rho R}+\frac{\tau_{s,x}}{\rho h}$$

Where: u and v = velocities in the cartesian directions [L/T]; g = gravitational acceleration [L/T^2] ; z_s = water surface elevation [L]; $v_{t,xx}$ and $v_{t,yy}$ = horizontal eddy viscosity coefficient in the x and y directions [L^2/T]; $\tau_{b,x}$ and $\tau_{b,y}$ = bottom shear stresses in the x and y directions [M/L/T^2]; $\tau_{s,x}$ and $\tau_{s,y}$ = the wind stress in x and y direction [M/L/T^2]; R = hydraulic radius[L]; h = water depth[L]; andf_c = Coriolis parameter.

The diffusion wave method uses gravitation and friction at the bottom of the river as the main components to determine the flow and motion of fluids in the river channel (Brunner, 2021c). It leaves out the turbulence and Coriolis effects that the shallow water equations consider and is consequently a simplification of shallow water equations. Due to its simplicity, Diffusion wave is more computationally efficient than the shallow water method, but it also leaves out local and convective acceleration terms, which are important for calculations of flood events and for routing of fluids (Brunner, 2021c; Collier et al., 2011).

Diffusion wave equations (Brunner, 2021c):

$$\frac{n^2}{R^{4/3}}\backslash V\backslash V = -\nabla z_s$$

Where: V = velocity vector; R= is the hydraulic radius; ∇z = the water surface elevation gradient; and n = is the manning's roughness coefficient.

2.3.4. Computation settings

Computation settings include computation interval, hydrograph output interval, detailed output interval, and mapping output interval, which are among the most important settings in model simulations, when it comes to the amount of time required to complete the simulation. If the computation setting intervals are too high, it will lead to inaccurate results, and the model simulation will end up misrepresenting real-life scenarios. In contrast, if intervals are too small, simulations will require large amounts of computer power and processing time. It can also lead to numerical errors and instabilities, because the intervals are too small, and the processing time is too long (Brunner, 2021b).

Determining whether chosen intervals are too high or too low would never give a single answer. There are many factors that determine correct intervals. One such factor is the geometry of the river, namely its size and length; another factor is the intensity of water flow. If a long river is characterized by a heavy water flow and much hydraulic activity, it will be more time-consuming to simulate such processes and therefore more beneficial to use larger intervals in calculations (Brunner, 2021b).

The computation interval is the most important setting in the unsteady flow calculations that has a large influence on the model outcomes. Its selection should be based on several factors (Brunner, 2021b):

- The interval needs to be small enough to enable the best fit for the flow hydrograph. A general rule of thumb is to use an interval that is equal or lower than the time of the rise of the flow hydrograph divided by 20. If a flood wave rises from its base flow to a peak flow within 10 hours, then the computation interval should be 30 min, or less.
- The time step can either be fixed or adjusted based on the courant condition. An appropriate value for the computation interval can be chosen in a more simplistic way, using a fixed time step. In this option, the user can decide, if the computation interval with a standard time step of 1 second, 1 minute, 2 minutes, 1 day, 1 week, etc. This is useful, if the user just wants to have a standard interval in the computation, or to have a possibility to test the best solution. An adjusted time step based on the courant condition gives the opportunity to identify conditions that best fit the dynamic regime of the river that the user is modeling. The adjusted time step based on the courant condition can be counted by both minimum and maximum courant condition numbers. This gives the user a possibility to spend less amount of time on processing during the model simulation and obtain more accurate results. When using the courant condition, simulations can manipulate the computation interval through time based on the maximum and minimum courant condition numbers and the amount of hydraulic activity in the open river. With a high amount of hydraulic activity and high level of water flow in the river, a low courant condition number should be chosen as opposed to the case with low intensity of water flow and little hydraulic activity in the river. The choice of courant numbers will also depend on the method: while shallow water

equations should not have a courant number of more than 3, the diffusion wave method can set the courant number as high as 5 (Brunner, 2021b).

Courant equations (Brunner, 2021c):

$$\mathrm{C}= \frac{V_w \Delta T}{\Delta X}$$

$$T = \frac{\mathrm{C}\Delta X}{V_w}$$

Where: C = The courant number, V_w = The speed of water flow, ΔT = Calculation interval, and ΔX = The average size of the calculational mesh.

A hydrograph output interval is used to define the intensity and frequency of the interval for which the computed stage and flow hydrographs are written. It must be equal or larger than the computation interval and is selected to give the correct number of points to define the shape of the computed hydrographs. It also makes sure the information about the water volume and peak from the flow hydrograph is not lost (Brunner, 2021b).

A detailed output interval allows the user to produce profiles of the water surface elevation and flow at an interval specified in the model simulation and save them with a specified frequency. The selected detailed output interval must be equal or greater than the computation interval, although it is suggested that a choice of a larger interval reduces the amount of post-processing. An example can be provided for a simulation that is 72 hours long, where a detailed output interval is set to around six hours (Brunner, 2021b).

A mapping output interval is the option used to visualize the final result in the Ras-mapper. A chosen set of the outputs is written into a separate output file that corresponds to the plan file (Brunner, 2021b).

3. Methods

This chapter explains how and why we have made specific choices for the creation of the hydraulic model and how the underlying datasets have been collected. The datasets include elevation data, flow data, land use data, and interviews that were conducted in the field. A thorough description is provided for how ArcGIS Pro has been used to prepare these datasets for the Manning's roughness layer, and for the estimation of lake volumes. Then we describe the necessary chain of steps in HEC-RAS pro, including the bathymetric alterations, creation of 2D geometry, boundary conditions and calculation intervals. Furthermore, we include a description of the sensitivity tests conducted to understand how sensitive the model is to the alterations of major parameters and inputs.

3.1. Data collection and preparation

The dataset assembled for this thesis is important for the creation of numerical projections of GLOFs. For example, elevation data is important, because HEC-RAS uses the elevation data to calculate how the water flows. Also, the flow data provided by NVE is important to describe the drainage basin and its contents, information about the river system, and the mean annual runoff of the rivers. Land cover data and building data are necessary for the creation of the land cover layer that HEC-RAS needs for the Manning's roughness coefficient. Together with the GOTHECA team, the author of this thesis has also conducted interviews in the field, with this being important for the understanding of the area, the GLOF progression, and the general flood modes of the river system in Hjelledalen. Thus, the interviews are useful for the validation of the flood models in chapter 5.2, where remote-sensed constraints are sparse or absent.

3.1.1. Elevation data

Elevation data from the Stryn and Skjåk municipalities have been acquired from the website hoydedata.no created and maintained by Statens Kartverk, namely the official map agency of the Norwegian government. Data is downloaded from this website in the form of geotiff-files, which are DTMs (Digital Terrain Models) created with the aid of airborne LiDAR with a 1-meter resolution. To date, this elevation data has the best available resolution across the entire Hjelledalen area. Some areas in the Stryn area clearly have a better resolution, but since these only include parts of Hjelledalen, a decision was to have one DTM for the entire area, instead of dividing it into several sectors with different resolutions. Although a 1-meter resolution is not optimal for routing water flow, it provides the possibility to incorporate the most important objects and features of the river and surrounding area into the model. The decision of choosing a DTM over a DSM (Digital Surface Model) was motivated by the necessity to deal with the vegetation cover in the latter, so that water can be routed along the ground without vegetation obstacles causing errors in the flow models.

3.1.2. Drainage basin data and river data

NVE NEVINA is an automatically updated map service created by NVE with the purpose of generating drainage basin geometries and field parameters. In this thesis, it was used to find the mean annual flow of the rivers Hjelledøla and Sunndøla. The NVE NEVINA software also provides the possibility to estimate the amount of water that would be part of for example, a 100-year or 200-year flood. It is also able to provide a general information about the area, how steep and extensive the slope is in the drainage basin and the size of the river within the drainage basin. Since this website is automatically updated, the user should not rely on the data downloads as 100 percent correct. Instead, they should be supplemented with analyses and other kinds of hydrological evaluations. The model is an adapted version of the Swedish HBV-model that uses a structure based on a simplified mathematical presentation of the hydrological elements and processes in nature. It calculates precipitation minus evaporation rates and changes in the water layer/content stored in snow/soil. The webservice is a good starting point for the hydrological modeling (NVE, 2015b) although NVE NEVINA cannot be directly used to generate the flow data for GLOFs that will be calculated using ArcGIS Pro (see chapter 3.2.2).

3.1.3. Building data and land use map

The land use data has been acquired from NIBIO through GeoNorge. NTNU has a partnership that makes it possible to get hold of the FKB-data, which is part of the Felles KartdataBase, a national database with the map data. Here we combined two maps - FKB-AR5 and building maps - for the two municipalities Stryn and Skjåk. FKB-AR5 data shows the land use types in municipalities, such as for example, cultivated soil, rivers, and forests. The FKB-AR5 map is in the form of a shapefile and shows different land use areas as polygon layers. The building data shows buildings as polygons in the two municipalities. Both land use and building data are needed for the calculations of the roughness in the HEC-RAS software that enable realistic modeling of the waterflow and floodplains. The process of creating a land cover layer is described in chapter 3.3.1.

3.1.4. Interviews collected in the field

On-site observations assembled in this thesis have created a better understanding of the area. Most of the data collection was made possible by the fieldwork conducted by the GOTHECA team in Stryn and other parts of Western Norway, first in August and later in September, 2021.

As part of this process, we carried out interviews with several people in Hjelledalen, including two people from the school in Hjelle, two residents who have lived most of their lives in the Hjelledalen area and a brief interview with a former employee of the Stryn municipality. These were supplemented by general conversations with other people in the area. Qualitative interviews were conducted to understand the extent to which people in Stryn are prepared to a large-scale GLOF if it suddenly happens. We have also explored the depth of their knowledge about GLOFs and historical accounts of any danger or damage caused by glacier-related incidents. Finally, we wanted to know how much information they receive about GLOFs and glacier-related hazards from local, regional and national governmental institutions. Besides the information about GLOFs and glacier-related hazards, it was also necessary to learn about past flood events in the river and thus validate models (see chapter 5.2).

3.2. Methodical approaches in ArcGIS Pro

ArcGIS Pro is an important tool for the analysis of models in HEC-RAS. It is necessary for preparing maps and input datasets that will be used to create flow models. The Manning's roughness coefficient is prepared in ArcGIS Pro in advance to be able to get the proper values for different soil layers. DEM needs editing in order to be useful in HEC-RAS. Also, estimating the lake volume can be done in ArcGIS Pro, because it is compatible with PlanetScope satellite images. For the visualization of GLOFs, ArcGIS Pro is used to create layouts, with a north arrow, scale bar and legends.

3.2.1. Manning's roughness coefficient

In HEC-RAS, it is necessary to create a map layer to plug into the hydrological model to be able to estimate the energy loss from different materials and soil types. In the ArcGIS Pro software, I created a map layer with the data from the Norwegian FKB-data (Felles kartdatabase, section 3.1.3), including the land cover data for the area, which shows different soil types and how the land is being cultivated, and the building data that has been edited into the AR5 data, so that each building in the area of interest is added to the AR5 map. This is done with the ArcGIS Pro tools "erase" and "merge". Here, "erase" is used to remove the areas where the buildings are in the AR5 layer so that the building can be added later to that exact position. This is because buildings are not represented as buildings in the AR5 layer but as built-up areas. This is something that must be created and added to an already existing AR5 map.

In the next step, I added numbers for the Manning's N coefficient corresponding to the correct land use type from Chow (1959) and Brunner (2021c) that assign values to several different soil types and materials. I have used satellite images, aerial photographs from Norgeibilder.no, google maps, and the google maps streets view function to choose values that belong to specific soil types. Additionally, I have also used pictures and observations from the fieldwork when we conducted fieldwork in the area. All different land use areas are given by distinct codes between 11 and 99, which are referred to as NIBIO codes. NIBIO is the institute responsible for creating the AR5 maps of Norway.

- Number 11 represents built-up areas that contain many different materials and places. It is not easy to prescribe any single value to these specific areas, but it is reasonable to believe that most of these places have a lot of asphalt. Therefore, these places have been proscribed a value for asphalt (rough, 0.016).
- The Nibio code 12 is assigned to transportation and essentially covers all main roads in Hjelle and eastern Stryn. These roads are made of asphalt and thus also receive a value of 0.016.
- The Nibio code 15 corresponds to the buildings that I added to the AR5 map. When it comes to buildings, it is not easy to determine correct Manning's N coefficients, since many buildings are made of a combination of different materials, with diverse shapes and sizes of both buildings themselves and their composites. There are also different methods for how water flows, when it encounters buildings; for example, it is possible to account for the water flow around a building or into buildings through doors, windows and other weak points in a building's construction. To reconcile these dissimilar scenarios, there are different approaches in the hydrological modelling, in particular, how to best represent the Manning's N value for the buildings. Different hydrological models use different Manning's N values for buildings - from 0.08 to up

to 20. Still, the value of 0.3 is the most used value for buildings and is the one that I have chosen for the hydrological modelling experiments carried out in this thesis (Syme, 2008).

- The Nibio code 21 represents fully cultivated soil used for either growing crops or grass. Since the production of grass is more common than production of crops in this area, the Nibio code 21 is assigned the Manning's N value of 0.03, which is typical for cultivated areas with little to no crops.
- The Nibio code 22 is prescribed in areas with surface cultivated soil (overflatedyrka jord), which is given the same Manning's value of 0.03 as in the previous area.
- The Nibio code 23 represents the areas with pastures (inmarksbeiteområde) used by the animal livestock for grazing which are again given a Manning's N value of 0.03 typical for pasture with no bush or short grass.
- The Nibio-code 30 represents forests covering some of the largest areas in the whole catchment. However, a large fraction of the forests is a sufficiently away from the river and the hydrological systems, with limited anticipated effects from river flooding. Still, in our simulations, we prescribe a Manning's N value of 0.1 to the forested areas under the assumptions of heavy stands of timber, a few downed trees, little undergrowth, and flood stage below branches that best fit local forest conditions.
- The Nibio code 50 represents areas with open land (åpen fastmark), including places with low vegetation, as well as mountains and plateaus. It is difficult to determine which value to prescribe to this soil type, but here a Manning's N value of 0.06 has been chosen, corresponding to light brush and trees in the summer.
- The Nibio-code of 60 is used for the few marsh areas in the catchment that are that are given the Manning's value of 0.1. Such value is typically prescribed to areas that have very weedy reaches, deep pools, or floodways with heavy stands of timber and bush.
- The Nibio code 70 is typically prescribed to glaciers, which are not part of the roughness map in our simulations and are thus not represented in the hydraulic modelling.
- The Nibio code 81 marks areas that are covered in fresh water, including both lakes and rivers, with the latter being the central aspect of this master's thesis. The Manning's N coefficient value prescribed to the rivers in this thesis is 0.05, which is typically chosen for stony, meandering rivers with some pools and shoals.
- The Nibio code 99 is the code prescribed to land areas that lack observations with the airborne LiDAR and therefore have an unknown soil type. However, these represent

areas that are most remote areas in the water catchment and are located at very high altitudes. They are therefore given a Manning's value of 0.025, representing barren land, including bedrock and glacial till.

Figure 10: AR5 layer, with the Nibio codes given a separate color, and is connected to a Manning's N roughness value.

3.2.2. Volumes of glacial lakes

When estimating volumes of the two glacial lakes discussed in this study, we intended to use terrestrial LiDAR observations that can be used to create very precise measurements and 3D models. The GOTHECA team spent about 10 days on Tystigbreen in Stryn in the summer of 2021, first in June, then in September, and collected LiDAR scans of the glacier and one glacial lake. Learning how to use the LiDAR scanner and interpret the data was an intense experience, although the results were not easy to incorporate into this study, since the LiDAR scanner could only derive quality observations over distances of approximately 200 meters on ice, as opposed to 1000+ meters over the bedrock. This means that LiDAR scans were neither able to capture the whole lake, nor the surrounding ice walls. Since the observational component of the GOTHECA project is new, our team was not aware of such limitations for this particular scanner, even though there was an experienced technician on the team, and did not realize the impacts of such limitation on observations prior to the analysis of the scans at

NTNU. We also encountered the limitations of the LiDAR when it is being used in fog, which was mentioned in chapter 2.2.2. Tystigbreen, has rapidly changing weather, and we encountered several days where scanning was impossible due to sudden occurrence of fog. This made it too dangerous to walk on the glacier, and also made it impossible to see anything on the scans that were captured. Fog on the lens was a recurring limitation that occurred because the LiDAR was not completely waterproof, and therefore we needed time for it to dry off. All of these reasons are why this thesis only includes the interpretation of LiDAR scans for the sake of the demonstration of its limitations in the areas central to our investigations, because we were unable to capture the entire lake and thus could not use them to estimate the volume of the lake. However, this experience has been beneficial for the entire GOTHECA team that will use the LiDAR scanner differently in the future or will employ a LiDAR scanner that better captures ice and snow.

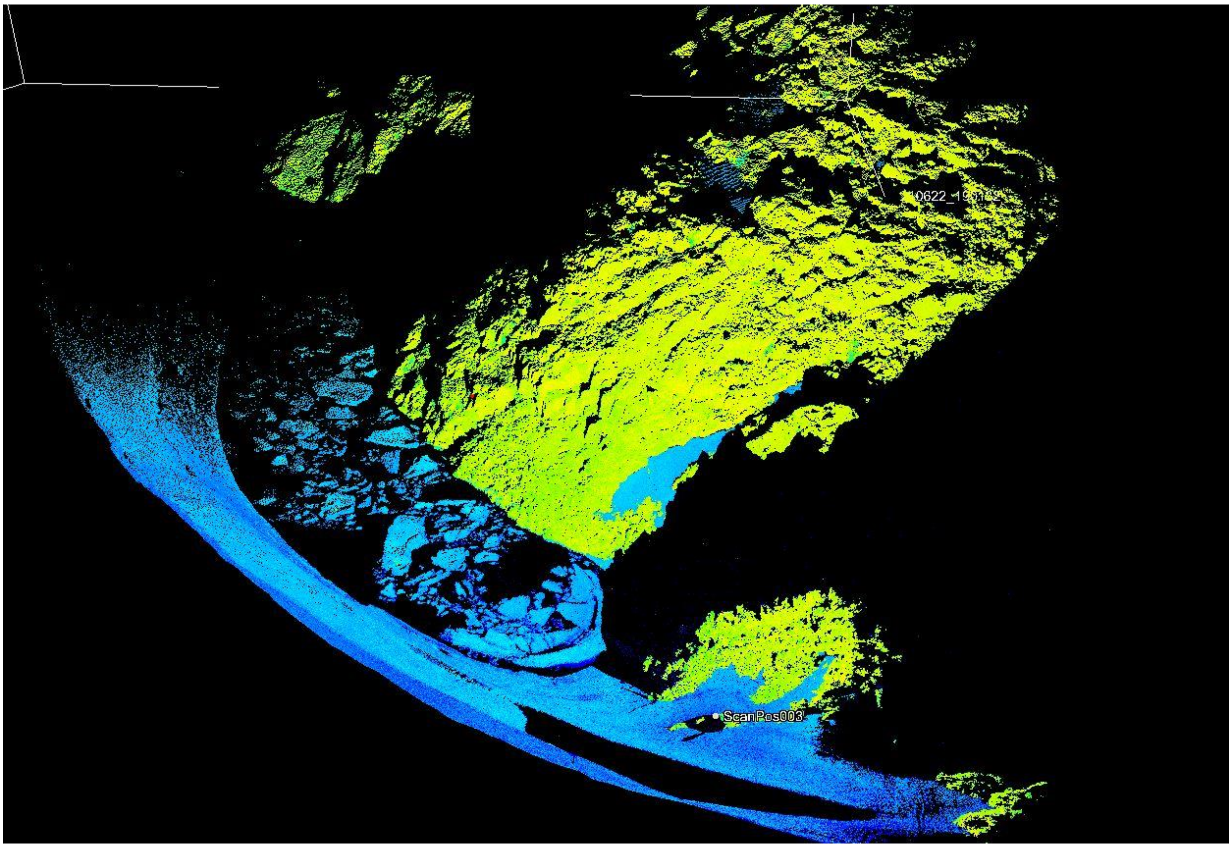


Figure 11: LiDAR scan of Lagune 1

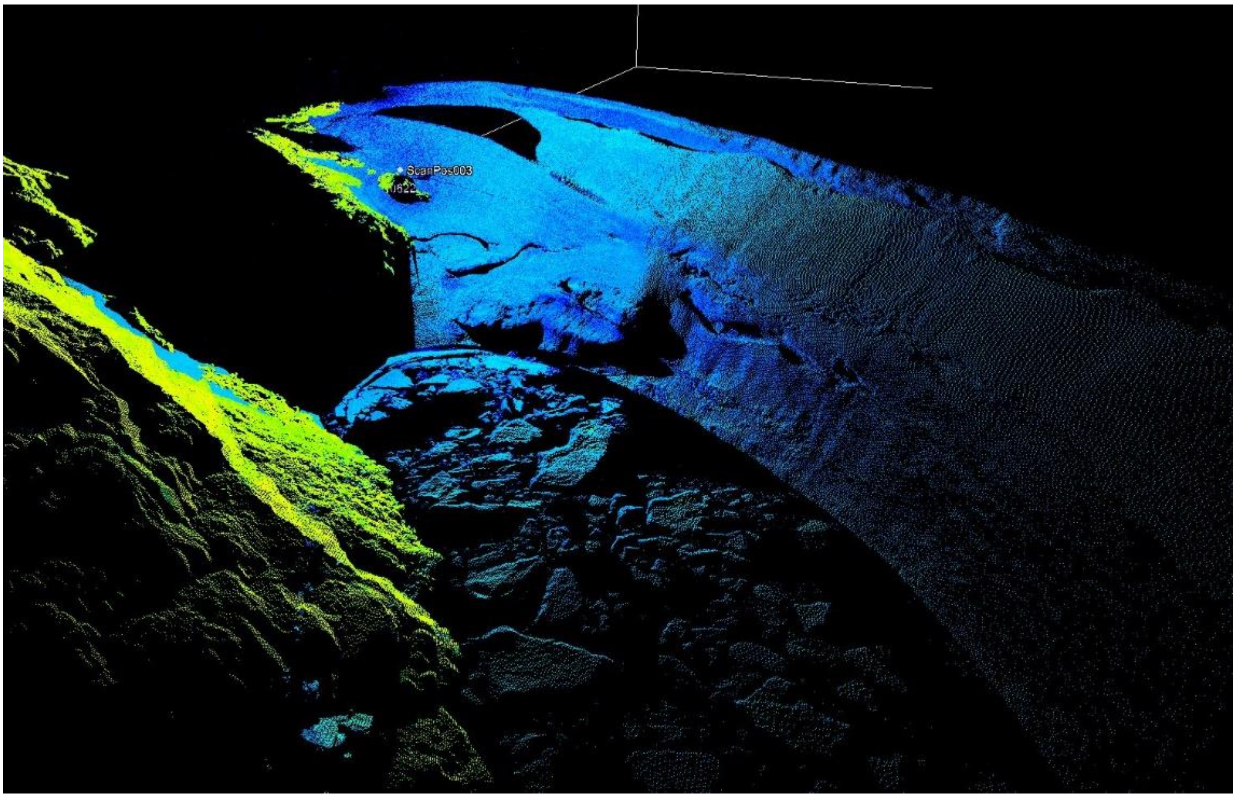


Figure 12: LiDAR scan of Lagune 1

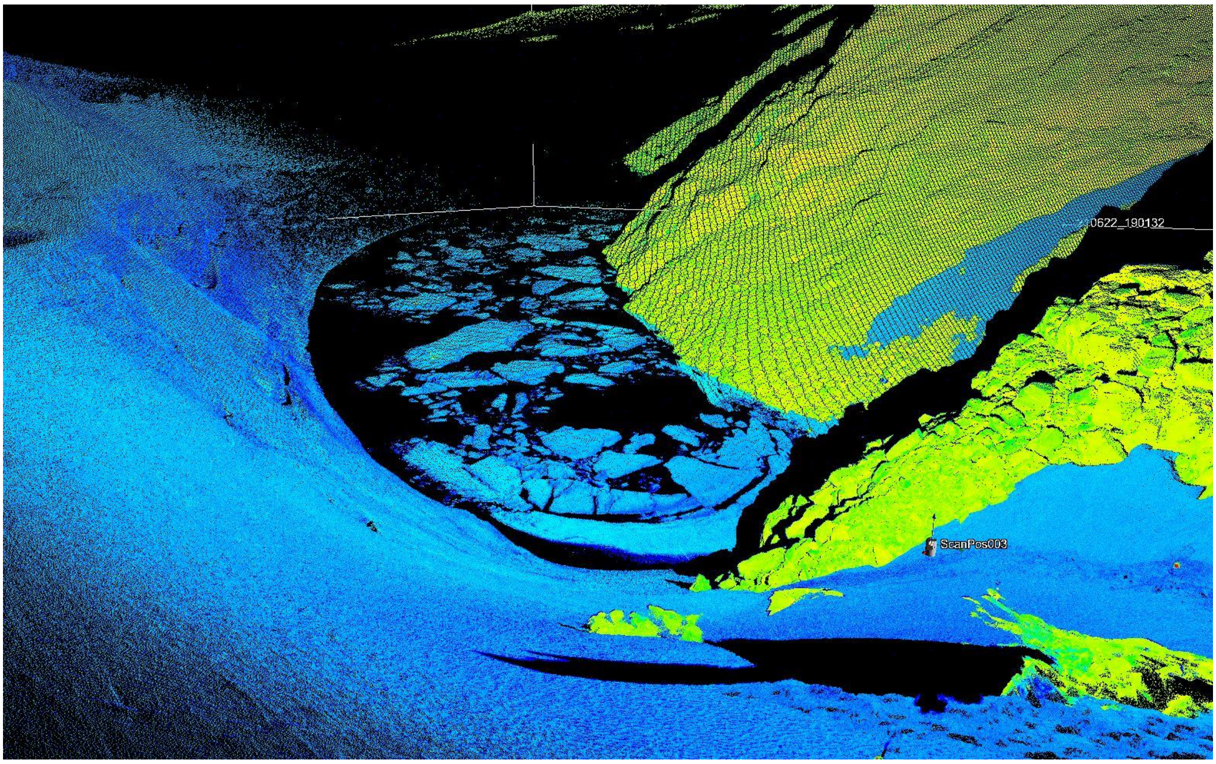


Figure 13: Scan inside of Lagune 1.

As seen in the figures above, the scans from the terrestrial LiDAR has great resolution, the problem is that it was not able to capture the entire glacial lake.

Since LiDAR was not an option to be used in the estimation of the amount of water in the lake, it was decided that remote sensing should be used. Satellite imagery from the PlanetScope satellites was the best option. Through the satellite images it was discovered when the lakes were at the fullest, then the two glacial lakes were outlined with the use of ArcGIS Pro.

When finished tracing the outline of the lakes, the area of the lake was known through the ArcGIS Pro program. It was then necessary to learn the depth of the glacial lakes, to estimate the lake volume. To estimate the depth, our own experience in the fieldwork has been important. It has also been through the people working at the ski center in Stryn, they are often in the area. They estimate the lake to be very deep, and that it can possibly deeper than 50 meters. Our own estimations are also that the depths of the glacial lakes are around 50 m. The ground penetrating radar results that will not be a part of this thesis, show that the glacier itself is quite thick in the area, around 80 to 90 meters. The actual depth can be deeper than 50 m, but 50 m has been decided to be the depth used in the modeling. The estimation of the glacial lakes volumes should be considered a rough estimation.

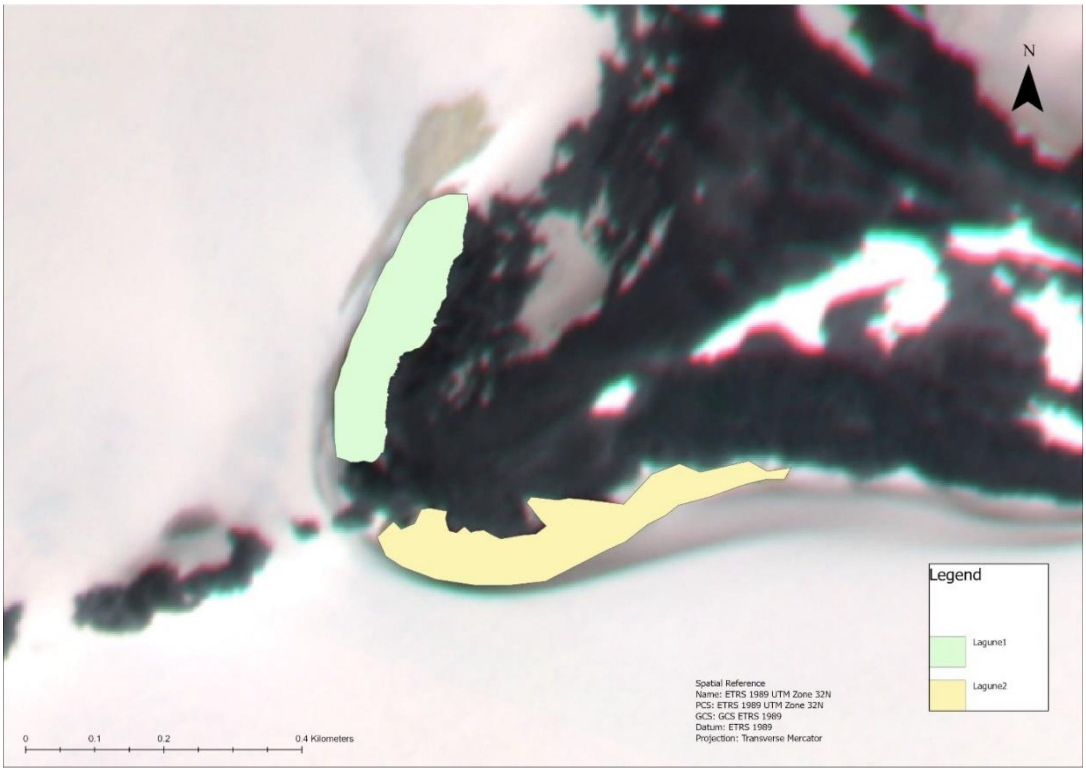


Figure 14: The outline of the glacial lakes at Tystigbreen. The layout is created in ArcGIS Pro.

When having both the area of the lakes and the depth of the lakes. The estimation for the lake volume was done by multiplying the area of the lake with the lake depth.

- For lagune 1 is it: 33 394 m^2 x 50m = 1 669 700 m^3
- For lagune 2 is it: 38 364 m^2 x 50 m = 1 918 200 m^3

The calculation of a GLOF is shown underneath. The example shown beneath is for a 24-hour GLOF from Lagune 2.

- 1 918 200: 24 : 60 : 60 = 22 m^3/s

This calculation is for the calculation of a 24-hour GLOF. In the flow hydrographs in HEC-RAS the water flow is plugged in to the models as cubic meters per second, m^3/s. 1 918 200 : 24 is to divide the lake volume into 24 hours. Then divide it by 60 to get it into minutes. Then divided by 60 once more to get the result in seconds. The answer is 22 m^3/s, which is the number of cubic meters of waters that drains from the glacial lake per second, during a 24-hour GLOF.

This thesis visualizes a range of different GLOF scenarios. Four scenarios for each glacial lake. 48, 24, 8, 2-hour floods for both lagune 1 and lagune 2. There will also be a model showing the mean annual flood in the thesis, with the data given by NVE NEVINA. The example shown above with a 24-hour GLOF needs to be repeated for every of the scenarios to get the cubic meters of water every second for all the scenarios.

The calculations for the scenarios are:

Lagune 1:

48-hour GLOF in Lagune 1:

- 1 669 700 : 48 : 60 : 60 = 9,6 m^3/s

24-hour GLOF in lagune 1:

- 1 669 700: 24 : 60 : 60 = 19 m^3/s

8-hour GLOF in lagune 1:

- 1 669 700 : 8 : 60 : 60 = 58 m^3/ s

2-hour GLOF in lagune 1:

- 1 669 700 : 2 : 60 : 60 = 230 m^3/s

Lagune 2:

48-hour GLOF in Lagune 2:

- 1 918 200 : 48 : 60 : 60 = 11 m^3/s

24-hour GLOF lagune 2:

- 1 918 200 : 24 : 60 : 60 = 22 m^3/s

8-hour GLOF in lagune 2:

- 1 918 200 : 8 : 60 : 60 = 66 m^3/ s

2-hour GLOF in lagune 2:

- 1 918 200 : 2 : 60 : 60 = 266 m^3/s

3.3. Methodical approaches in HEC-RAS

HEC-RAS is the software used to produce hydraulic models. It will be used in this thesis to create various ranges of GLOF scenarios, based on different drainage times. To make the models, the setup of the model parameters is important. It is necessary to manually alter the bathymetric data, to make the river channel realistic. The process of creating a 2D geometry in HEC-RAS must be done, to model the flow of water. Boundary conditions must be introduced to the model at the correct places, in order to plug the GLOFs in the model where it naturally would occur in the valleys. Sensitivity tests will be conducted in order to see how sensitive the model is to changes.

3.3.1. Alterations of the bathymetric data

The LiDAR scans captured from airborne flights in Stryn are not able to capture the full extent of the river. LiDAR scans captured with laser beams that are in the near infrared spectrum will not be able to penetrate the water surface. To create LiDAR scans able to recreate the river channel the LiDAR must be with a blue/green laser (Carter et al., 2012). Because the laser is unable to capture beneath the surface of the water, there will be problems when trying to simulate the flow of the water in the river. Since the bathymetry of the river in reality is lower in the actual terrain than the digital elevation map shows, the river channel inaccurately represents the actual river channel. Since the surface of the water will be interpreted by HEC-RAS software as the riverbed, this will cause the water to flow over the edges of the river more easily. HEC-RAS offers a solution to how this potential problem can be fixed. By creating a 1D river geometry in the river, it will be possible to edit the bottom of the river channel into a more realistic riverbed. When creating cross sections in a 1D river geometry and then edit their values, the HEC-RAS software will interpolate the terrain between the cross sections in the river.

The method for the creation of the river bathymetry has been introduced by Krey H. Price, the director of surface water solutions and his youtube channel, The Ras Solution (Price, 2022), where he creates training videos on how to create models in HEC-RAS, and teaches smart ways to solve hydrological problems in the software.

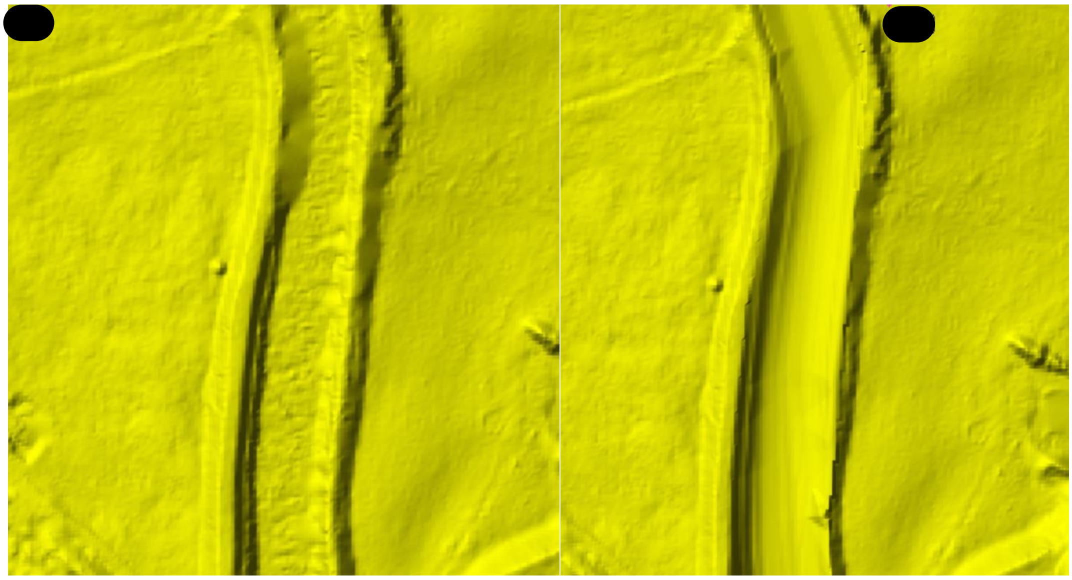
First step in creating the bathymetry is to open Ras-mapper, which is a workspace inside HEC-RAS. When opening Ras-mapper I can add the digital elevation map, which is essential to create the bathymetry of the river. When the digital elevation map is added to the workspace, the next step is to make sure the DTM has the correct map projection, and that the map is correctly georeferenced.

To alter the river bathymetry a 1D geometry of the river is required. Firstly, the center line of the river was created. The center line should be placed in the middle or the deepest part of the river. The river center line is created from the upper reach of the river to the river delta. Bank lines must be placed on both riverbanks of the river. There is also a need to create flow path lines. Flow path lines are created on the outside of the riverbank lines. This is created for computing the reach length between the cross sections in the left to the right overbank.

Creating the cross sections are the most important part of the 1D geometry model. The alteration of the bathymetry occurs at the position of the cross sections, the bathymetry for the remaining areas of the river will be interpolated from the cross sections. The bathymetry needs the right number of cross sections to interpolate the river bottom correctly, the entirety of the river needs to be covered. The cross sections must cross all the five lines already created, the center line, bank lines and flow path lines. In straight parts of the river without many bends or elements that can disturb the flow of the water, there is no need for the cross sections to be drawn with a high frequency down the flow path of the river. When there are more bends and more details and elements to consider that can disrupt the water flow, the cross sections should be drawn closer to each other so that the details in the river will be better preserved. In this thesis the cross sections are located further apart on the straight parts of the river, and there are more cross sections closer together when there are shoals, turns in the river and more elements that needs more detail. These details are very important to cover properly with the river bathymetry so that the interpolation process does not smooth or eliminate the details.

When creating cross sections, it is possible to see the cross sections as plotted data in a grid. This grid shows the cross sections from the sides, with the river bathymetry plotted with points. These points are representing the river channel and the riverbanks. It is in this grid that the alteration of the river bathymetry has happened. The bottom of the river channel is shown as a relatively flat surface in the calm areas of the river because the water is flat when it is flowing in the river channel. The flat areas of the river, is the water surface, but is interpreted as the riverbed in the digital elevation model. Therefore, it is necessary to change it. This is manually done by changing the points at the cross sections. This is then done at all the cross section, so that it will change along the entire river. When changing it at the cross sections, the HEC-RAS program will interpolate the terrain for the parts of the river located between the cross sections.

When changing the cross-section altitude values manually it is important to know what the actual difference between the river floor and the height of the flowing water in the river channel. The use of satellite images, aerial photographs, google street view, and in-situ observation has been very important in understanding the real depth of the river channels. However, the created difference in the bathymetry has been created conservatively. This has been done to be sure not to make the river channel deeper that they actually are in the real world. If I were to dig the river bathymetry too deep, then a big flood might not be visible as a flood in the simulated model, because the river channel is able to hold much more water than it can in reality. It was attempted to create a conservative estimate.



[redacted] [redacted]

Figure 15: The ordinary bathymetry on the left, and the changed bathymetry on the right. The edited bathymetry on the right side is much smoother than the original one. Captured from HEC-RAS.

3.3.2. 2D Geometry

The calculations in the software HEC-RAS are dependent upon the 2D computational mesh, this cell grid will capture the information about the underlaying terrain, and how the hydrological flow of water will act upon the underlaying terrain. After the creation and the implementation of the digital elevation model with the edited bathymetric properties, a 2D computational mesh needs to be created (Brunner, 2021a).

When the area of interest has been determined and the perimeter has been set, the computational mesh can be built. The first computational mesh was created with 60x60 meters, which is a large size for the cells in a computational mesh, but it is good to start with. It is usual to create a large grid mesh network in the beginning to get a sense of how the water acts upon the terrain, and see where it is necessary to have a smaller mesh, and to create refinement regions and break lines where it is necessary (Brunner, 2021a).

Break lines are drawn at the riverbanks along the entirety of the river system. The break lines are created at the riverbanks, so that the cells are facing the same way along the edges of the river, also it is important to have the cells at the top of the riverbanks to stop cell leaks from occurring in the computational mesh. At both the river banks it was created bank lines with the cell size of 5x5 meters. It is recommended to have a break line in the area somewhere between 5 to 10 meters size cells (Brunner, 2021a). The smaller the size of the break lines the more detailed the cells will become. It is important that the cell size is small enough not to ignore the potential barriers that can disrupt and be an obstacle to the flow of water. Break lines are drawn at the location of bridges. Since bridges is not a part of the terrain model, the bridges are drawn in with a break line at both sides of the river. This is done to get better understanding of how the flood will affect the bridge., but bridges are still not implemented in the model.

A refinement region is smaller 2D computational mesh, inside the already existing 2D computational mesh (Brunner, 2021a). It is created in HEC-RAS, where there is need for more detail and smaller cells. Furthermore, it can act as a middle ground between the normal grid area, where there are 60x60 meters for the not so interesting parts of the model, and the very fine 5x5 meters cell size of the break line areas. If there is a break line inside a refinement region, and a 60x60 mesh outside of the refinement region, it will automatically adjust the sizes of the cells in the grids at the border where they meet. If there is just a break line along the river and a 60x60 cell mesh, a lot of errors will occur. Errors occur because a cell can only have 8 adjacent cells. Since the size of the beak lines are 5x5 meters, and the grid network is 60x60 m, the big cells will meet the smaller cells, and there will be many small cells that is adjacent to the big ones, and it will be a lot more than 8 adjacent cells for the big cells. It will result in manually adjusting of every cell in HEC-RAS where the break lines and the grid mesh network collides. Which can be a substantial job, when the perimeter of the work area extends over a large area. By having refinement regions, one eliminates this substantial job, and the grids will automatically adjust to different sizes of the cells. The refinement region is created along the river and further onto the areas where the water can flood. It is built with 5x5 meter cells. When the creation of the 2D computational mesh was complete, the 2D geometry consisted of 215 348 cells.

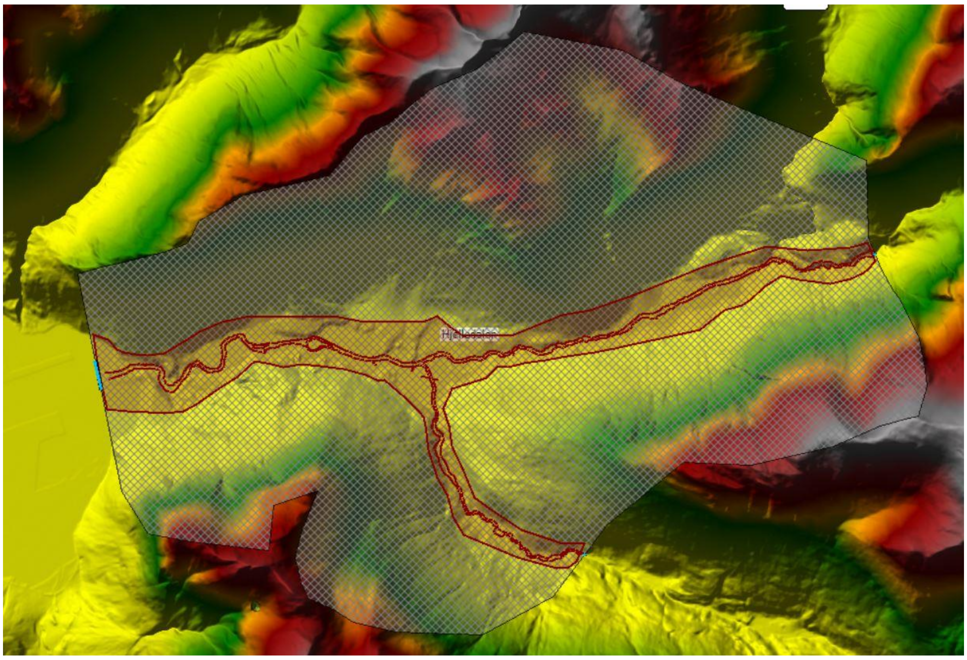


Figure 16.: The 2D geometry covering the study area. It has 60x60 cells at the outer, most remote areas, then a refinement region of 5x5 cells in the areas of interest, break lines are created at the riverbanks. Image captured from HEC-RAS.

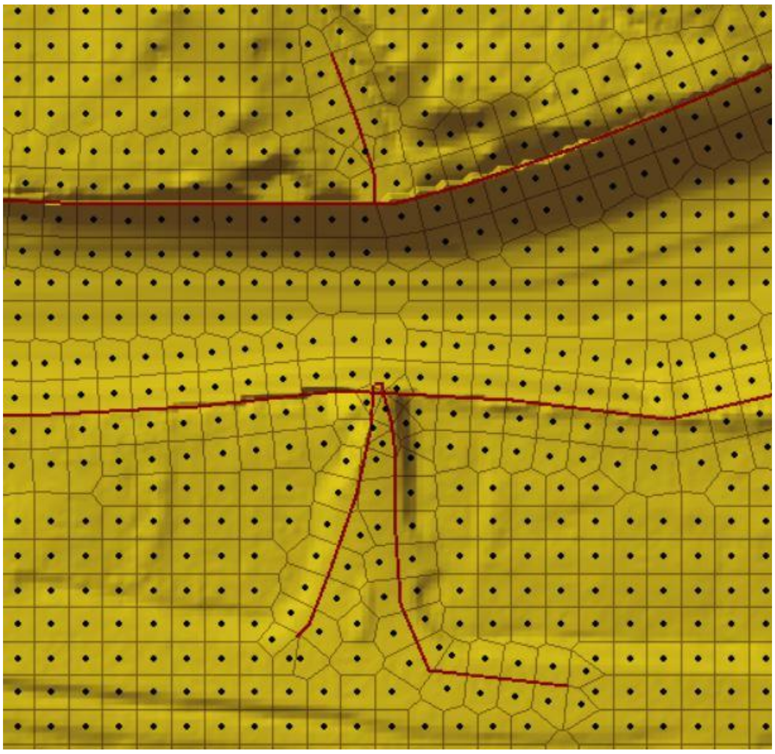


Figure 17: Editing of break lines on top of a bridge. Image captured from HEC-RAS

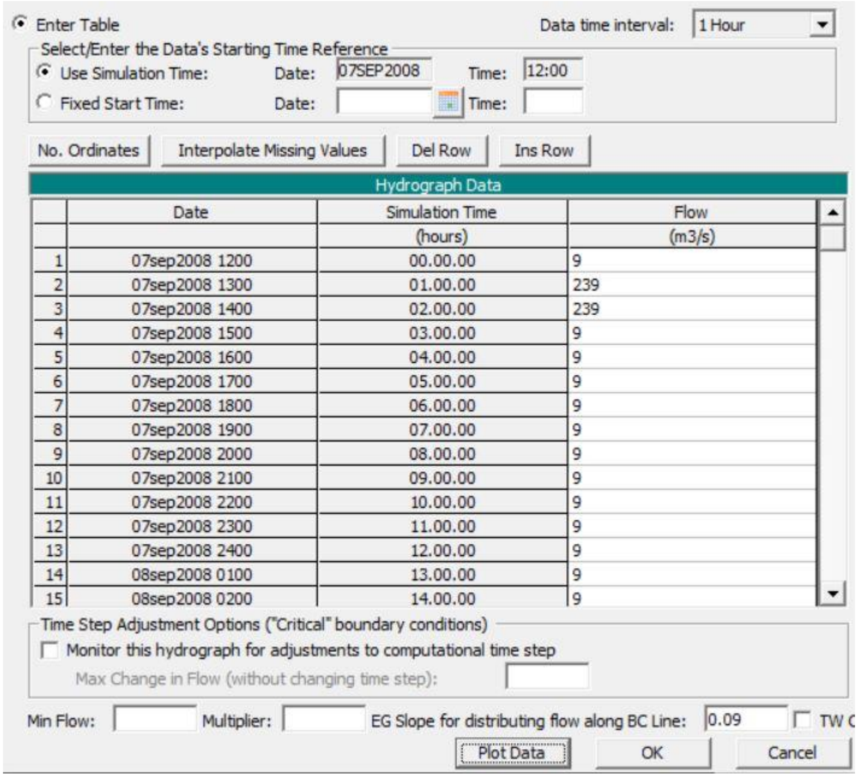
3.3.3. Boundary conditions

The boundary conditions are the location where water is introduced into the model, and taken out of the model. The water is introduced to the model in form of a flow hydrograph. The flow hydrograph plugs the water into the model as cubic meter each second (Brunner, 2021b). For this thesis the boundary conditions are placed three places. Two boundary conditions plug water into the model, and one that takes water out of the model. There is one in Videdøla, close to the ski center then another one in Sunndøla. The reason for the two boundary conditions is because there are two glacial lakes, with Lagune 1 draining into Videdøla, and Lagune 2 draining into Sunndøla. The boundary condition in Videdøla is located at the point where the GLOF enters the river. The energy gradient is plotted into each boundary condition. For Videdøla the boundary condition is 0,09. The energy gradient can be found by measuring the slope of the river in HEC-RAS. The energy gradient for Sunndøla is 0,06. There is also a boundary condition located where the water exits the model, this is located in the Oppstryn lake. The boundary condition in the bottom of the river is known as normal depth, and it is necessary to let the water exit the model. The energy gradient used for the normal depth boundary condition is 0,01.

The location of the boundary conditions is ideally placed for the GLOFs, but not ideally placed for the rest of the water in the river. The water is plugged into the river from the top of the rivers, where the GLOF enters the river, but much of the water that flow in the river comes from other sources. Many smaller streams bring water to the river, but since the focus of the thesis is on the GLOFs all the water will be plugged in where the GLOFs are plugged in. The mean annual flow of the river will be entered into the river, will be plugged into the river from the same location. The flow will only come from two sources, from Videdøla and Sunndøla, in reality the water would originate from many places in the catchment.

The GLOFs are added in addition to the already flowing water in the river system, which is the mean annual flow. This water amount is known by NVE NEVINA web service. For Videdøla this is 9 m^3/s, and for Sunndøla is it 6 m^3/s. Then the GLOFs will be added in addition to this amount.

All the models have been run with a simulated duration of 12 hours. After running some sensitivity tests, they have shown that the simulation for 48 hours does not show any difference when using 12, 24 or 48 hours. 12 hours has been used since it saves process time. For the 2-hour period it was strictly not necessary to use 12-hour simulation, since the flood only lasts for 2 hours, but it gives a clearer picture of how the water acts upon the terrain when it retreats.



● Enter Table

Data time interval: 1 Hour

Select/Enter the Data's Starting Time Reference

● Use Simulation Time: Date: 07SEP2008 Time: 12:00

○ Fixed Start Time: Date: Time:

Hydrograph Data

	Date	Simulation Time (hours)	Flow (m3/s)
1	07sep2008 1200	00.00.00	9
2	07sep2008 1300	01.00.00	239
3	07sep2008 1400	02.00.00	239
4	07sep2008 1500	03.00.00	9
5	07sep2008 1600	04.00.00	9
6	07sep2008 1700	05.00.00	9
7	07sep2008 1800	06.00.00	9
8	07sep2008 1900	07.00.00	9
9	07sep2008 2000	08.00.00	9
10	07sep2008 2100	09.00.00	9
11	07sep2008 2200	10.00.00	9
12	07sep2008 2300	11.00.00	9
13	07sep2008 2400	12.00.00	9
14	08sep2008 0100	13.00.00	9
15	08sep2008 0200	14.00.00	9

Time Step Adjustment Options ("Critical" boundary conditions)

☐ Monitor this hydrograph for adjustments to computational time step

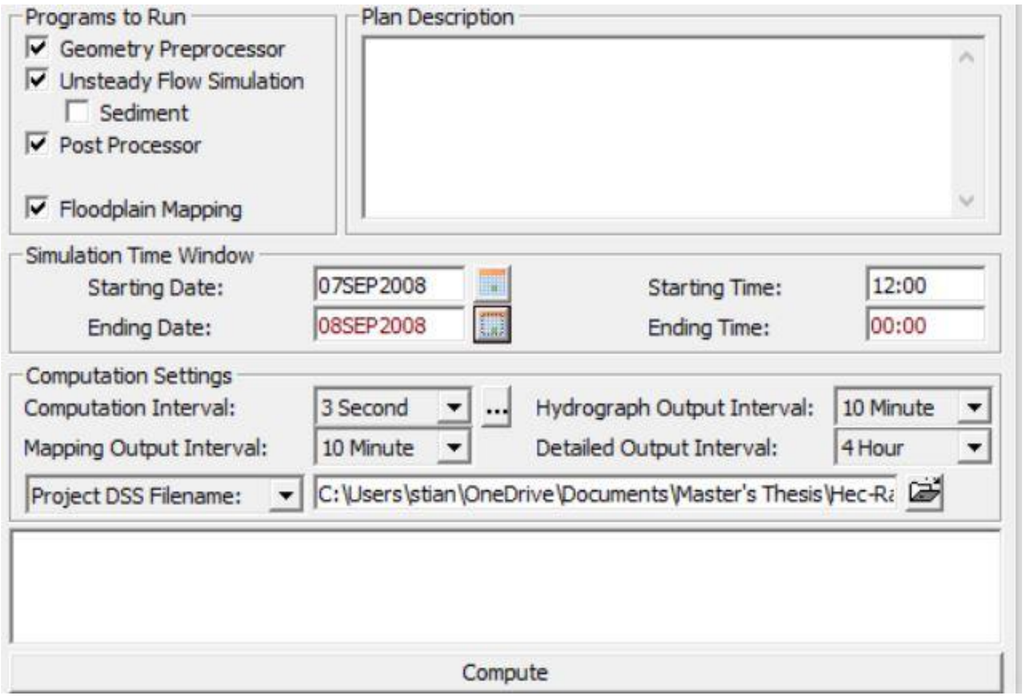
Max Change in Flow (without changing time step):

Min Flow: Multiplier: EG Slope for distributing flow along BC Line: 0.09 ☐ TW C

Figure 18: An example of how a hydrograph with a 2-hour GLOF in Videdøla may look. image captured from HEC-RAS

3.3.4. Calculation intervals and parameters

The calculation intervals and parameters used in the model is key for how the model functions. The computational interval for this thesis has been set to 3 second. It has a hydrograph output interval of 10 minutes, a mapping output interval of 10 minutes, and a detailed output interval of 4 hours. During the stress tests it was attempted to use a variable time step based on courant. This alternative was too time consuming, and a 12-hour simulation would have required more than 48 hours to complete, which was too time consuming. The computational interval was therefore set to 3 seconds, which took approximately 4 hours to complete a simulation.



☑ Geometry Preprocessor
☑ Unsteady Flow Simulation
☐ Sediment
☑ Post Processor
☑ Floodplain Mapping

Starting Date: 07SEP2008
Starting Time: 12:00
Ending Date: 08SEP2008
Ending Time: 00:00

Computation Interval: 3 Second
Hydrograph Output Interval: 10 Minute
Mapping Output Interval: 10 Minute
Detailed Output Interval: 4 Hour
Project DSS Filename: C:\Users\stian\OneDrive\Documents\Master's Thesis\Hec-R

Figure 19: Settings and parameters for the creation of hydraulic models. The figure is captured from HEC-RAS

It was decided to use shallow water equations rather than diffusion wave. To use diffusion wave's simplified equations of water flow would make it possible to save some time and processing power. Shallow water equations which have more advanced equations of water flow, will require more time. It is however recommended to use shallow water equations to model dam breaks, which is similar to GLOFs, this is why the choice fell upon the shallow water equations.

The warmup of the model is a very important part of the process. The initial conditions time was set for 6 hours, with the initial conditions ramp up fraction was set to 0,5. The warmup is essential in wetting the river system before the water is introduced into the model. Without it the model starts the simulation on a dry riverbed. The initial condition time is the number of hours the warmup should last, and the initial condition ramp up fraction tells how long time of the warmup should be used to gradually increase the amount of water before it reaches the first value of the flow hydrograph. When it is set to 0,5 that means 50 %, so the warmup is reaching the first value of the flow hydrograph after 3 hours, when the initial conditions time is set for 6 hours (Brunner, 2021a). During a test the initial conditions time was set to four hours, it turned out that this did not leave enough time for the water to flow through the model. By setting the time period to 6 hours it solved the problem, and the water was able to flow down the entirety of the river system.

3.4. Sensitivity test of the model

There has been created several sensitivities analyses to see how well the model react to changes in input data and the changes in parameters and settings. Without sensitivity test the model will have to be considered less accurate because the robustness of the model has not been clarified, and parts of the uncertainties of the model might not become clear to the modeler. The model is sensitive to the sizes of the cells in 2D calculational mesh, especially in the areas of the terrain that has steep areas, or that has areas that have altitude changes inside a cell. Too big cells in the calculational mesh will create leaks and floods that in a mesh with smaller cells would not occur, in areas with steep altitude or obstacles with different heights inside the cells. The sensitivity tests have therefore revealed that the model is sensitive to the placement of break lines in the calculation mesh. There are places along the river that showed floods would occur, but through more testing showed that leaks occurred due to too big cells with changing altitude obstacles in the middle. The riverbanks were therefore not as efficient in the model at keeping the water in the river channel as it would have been in a real scenario. Through the use of smaller cell size calculation mesh and strategically placing bank lines along the riverbanks, which made it possible to have alle the cells along the riverbanks to face the same way, this solved most of the problems with leaking in the 2D mesh.

The amount of time it takes to process the simulation of the model is not very sensitive to changes. Through the sensitivity tests they showed that the peak floods do not change when calculating the GLOFs with durations of 24 and 48 hours. This meant that I could run the simulation for shorter periods of time, and still receive the same result, when it comes to the velocity and depth of the water. For instance, the test showed the same result when simulation a model of a GLOF, where the drainage of the lake lasted for 48 hours, the flood peak was the same if the simulation lasted 12, 24 or 48 hours. It was possible to save processing time and computational power by reducing the duration of the flow hydrograph. I could run a 48-hour GLOF with a simulation time of 12 hours, and get the same result as a 48-hour GLOF with a 48-hour simulation.

It was tested several scenarios using different values for the Manning's N roughness. This sensitivity test was not part of the calibration of the roughness layer, or to find the correct n value. The purpose of the sensitivity test was to find how sensitive the roughness layer is to changes in the Manning's N coefficient value. Simulations were made by testing different Manning's N values in the river channel, to test the sensitivity of the Manning's number. It became clear that the model is very sensitive to the choice of Manning's n value. The tests were made with 0,06, 0,05, 0,04. The results turned out to have a massive influence in how the flood behaved. The flood peak became significantly higher in 0,06 Manning's value, than in 0,05. Also 0,05 was significantly higher than 0,04. This means that the choice of which n-value to choose in the model will have a big impact on the flow of water and the potential floods.

3.4.1. Sensitivity of diffusion wave and shallow water equations

Figure 20 show the comparison between the flow of the river with diffusion wave and shallow water equations. The differences look very small in figure 20. The map shows the water flow model with shallow water equations as the blue color of the river. The diffusion wave model is shown as a red flow in the river channel. The red and blue is almost identical, but the red color is wider in some locations. The differences are not visually big, there are still quite big differences in the depth of the river in the two different models. The maximum depth using the shallow water equations are at 2,24 meters. While modelling in diffusion wave simulates a depth of the water flow in the river at maximum 3, 41 meters. This means that the differences at the maximum point of depth is 1, 17 meters. This is a substantial difference and will cause the river to erode more sediments in one model than the other, and gives the river more force to suspend sediments in the river and also to transport larger rocks and stones downstream. Even though it does not look like it is much difference in figure below there is actually a quite big difference. This is because the shallow water equations are more complex than the diffusion wave equations. Diffusion wave is built upon the equations from the shallow water equations, but simplified to save processing time and power. Where the shallow water equations include turbulence and the Coriolis effect as driving forces for the river, does the diffusion wave equations exclude these driving forces to simplify the complexity of the model. It is recommended to use shallow water equations if there are substantial differences in the two methods, and it is also recommended with dam breaks. This is why the final decision fell on the shallow water equations when computing the models.

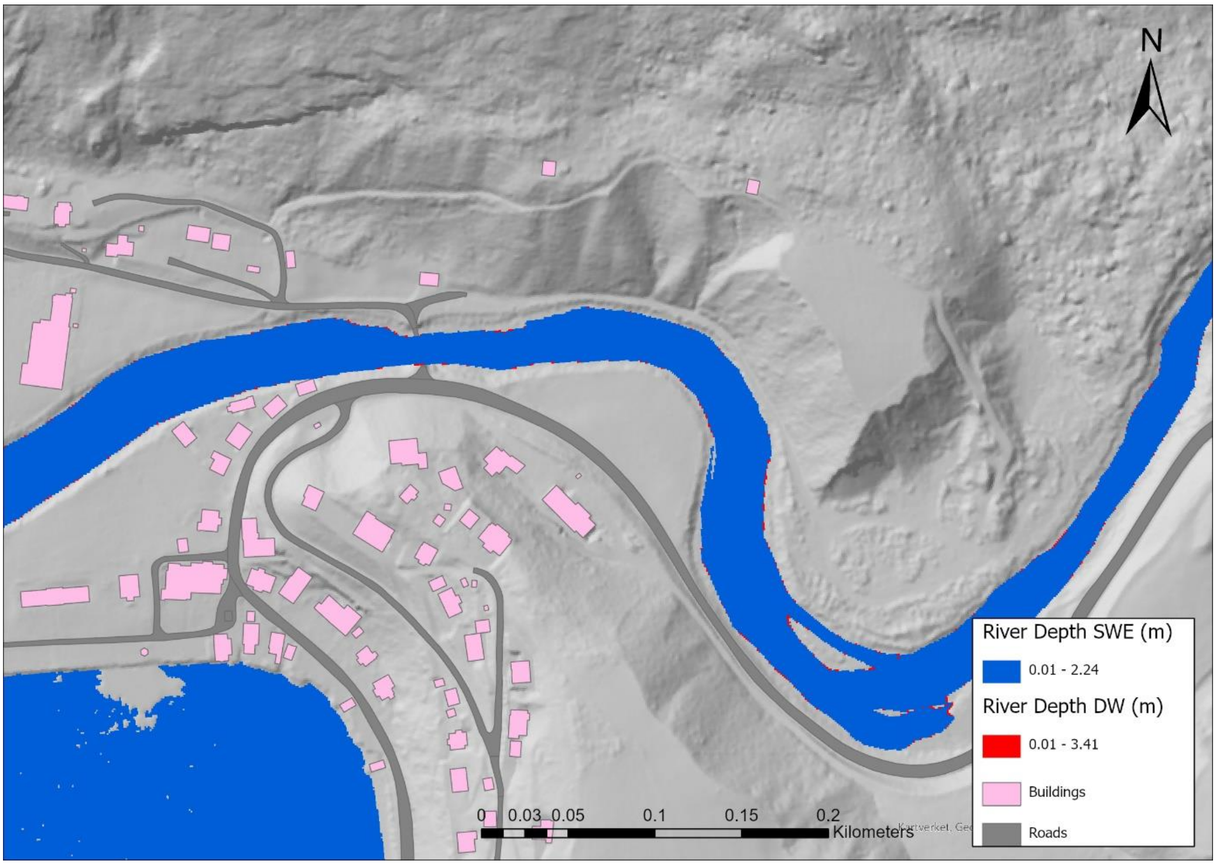


Figure 20: comparison of the two different flow methods shallow water equations and diffusion wave. Created in HEC-RAS.

4. Results

This chapter aims to answer the two main questions of this thesis and assess relative hazardous potentials of GLOFs in the Hjelledalen area using models under different scenarios in HEC-RAS. These models evaluate the duration of the drainage from glacial lakes that is needed to make these events hazardous and cause damaging floods. A range of model simulations has been created with GLOF durations of 48, 24, 8 and 2 hours. I have created scenarios for both Lagune 1, which drains into Videdøla, and Lagune 2, which drains into Sunndøla. Runoff from both rivers eventually ends up in Hjelledøla, even though it comes from different locations. These results clearly demonstrate that the risk of hazardous GLOFs is present and significant, since there are damaging scenarios from both glacial lakes and risks of floods in both valleys, Videdalen and Sunndalen. However, the area which is most prone to floods is located in Hjelledalen. The valley of Hjelledalen has a gentler slope than the two valleys connected to it at the upper reaches, which are very steep. Hjelledalen is the main valley, and the place with most objects that can be damaged including important infrastructure, buildings, farms, and educational institutions. The results presented in this thesis also show that as long as the duration of the drainage is slower than 24 hours, the river is able to contain water within its limits. Although water levels generally increase, leading to higher erosion in the river, they do not cause hazardous floods.

4.1. Simulated flow of the mean runoff

Figure 21 visualizes runoff in Hjelledøla, where mean runoff has been calculated using the NVE NEVINA software (see Section 3.1.2). According to NVE, the mean annual runoff in the river Hjelledøla is 16 m^3/s. Figure 21 (and figures thereafter) visualize river flow in blue color, with the lightest blue color symbolizing areas with the shallowest areas in the river. This particular layout of the simulation shows the last sector of the river close to its mouth, where it flows into the Oppstryn lake. It features the town Hjelle, which is the largest populated area along the river and is the place where the river can do most of the harm to people, buildings and infrastructure.

Figure 21 shows that the river itself is capable of holding the average water flow well. There is no sign of flooding, and there is no place along the river, where it overflows its banks, which is also a general case for the entire river. The simulation forecasts that water in the river is 2,24 meters deep at its deepest. Even though the river is safe and can easily contain the average annual amount of waterflow, it is still possible to identify locations along the river that might act as areas of accumulation that may represent flood-prone zones. One area that stands out in Figure 21 is the area with the deepest water to the east of the bridge in the Hjelle town where the river channel is getting narrow. This might cause river to expand and create a risk of flood, when water levels increase. This bridge is a crucial part of the infrastructure in Hjelle – one needs to cross the bridge to get from one side of the town to the other. The school and kindergarten are for instance on the northern side of the bridge, and a lot of private houses in Hjelle are on the southern side of the river.

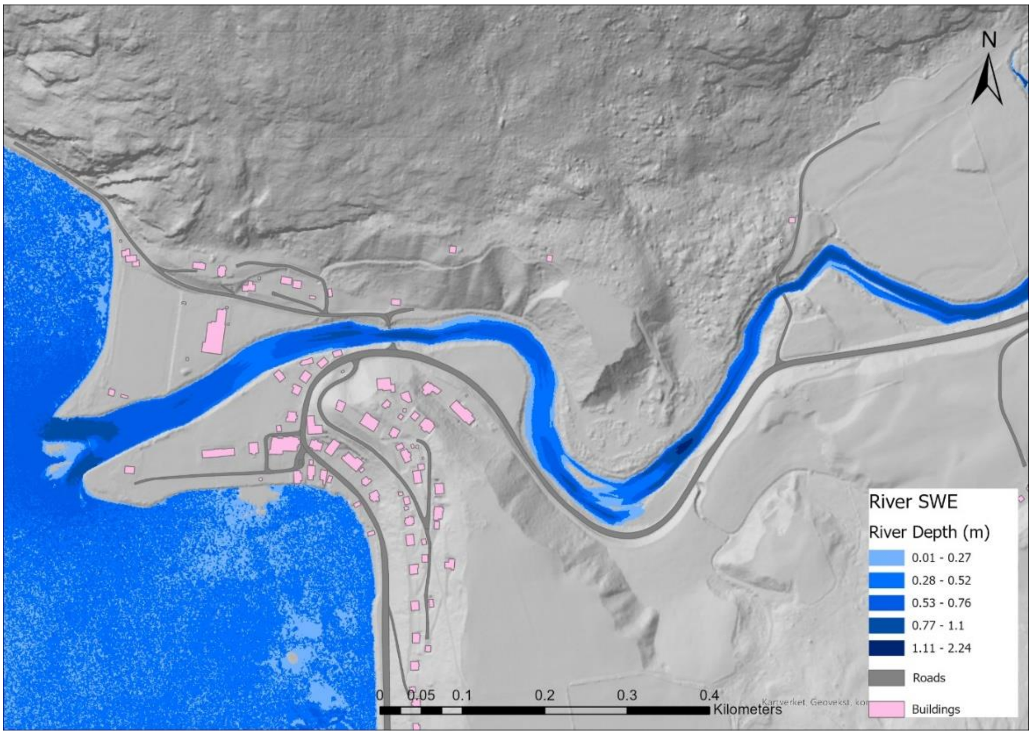


Figure 21: Mean annual flow in Hjelledøla. Created in HEC-RAS, layout created in ArcGIS Pro.

4.2. Modelled scenarios for glacial lake outburst flood

Videdøla is the river that is flowing along the road in Videdalen. Most of the water in this river comes from glacial meltwater as well as from snow melt and precipitation. The river Videdøla transforms into the river Hjelledøla, where rivers Skjerdingsdøla and Videdøla meet. Videdøla receives water input from GLOFs from the Lagune 1. Modeling of GLOF events is initiated at the starting point where GLOF water escapes from beneath the glacier in real-life scenarios, namely downstream of the Stryn summer ski center. This is where the water from the GLOF is inserted into the model and is streamed towards the lake Oppstryningen.

Sunndøla is the river that flows through the valley Sunndalen, starting high up in the valley in a very mountainous area and being very steep, partially a canyon, in this sector. At the end of the river, Sunndøla transforms into Hjelledøla. At the last stretch, where the farmland begins, the river slope becomes quite gentle. It is still not certain where exactly in Sunndalen the glacial lake drains, but it is supposed to be close to the location where I have entered it into the model - quite far up in the valley. In this study, GLOFs are visualized with the depth of the water as the maximum depth that occurred in the river during the simulations of the GLOFs. Figures show GLOFs in blue color, with the light-blue color corresponding to the shallowest water depth and the darkest showing the deepest parts of the water. Building polygons are presented with pink color, and the roads are shown with black color.

4.3. Low risk scenarios (not hazardous)

4.3.1. Upper part of the river

Figures 22 and 23 show GLOF events occurring with a duration of 48 hours, while the following two figures - 24 and 25 - are from the same location but with a GLOF lasting over 24 hours. These four figures show the upper part of the reaches from both the rivers, where the GLOFs are plugged into the model. The location where the water is plugged in is the place, where the model is least stable, and there is a bigger chance of having errors in the model.

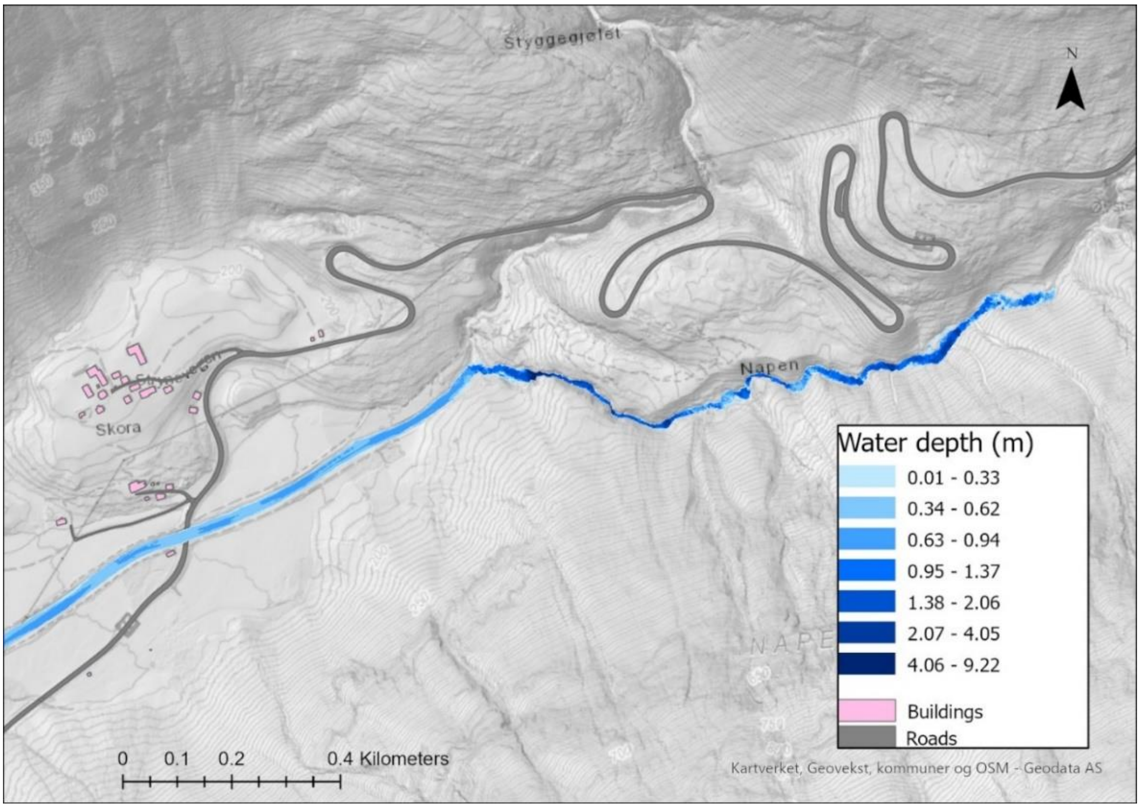


Figure 22: 48-hour drainage in the upper part of the river, from Lagune 1.

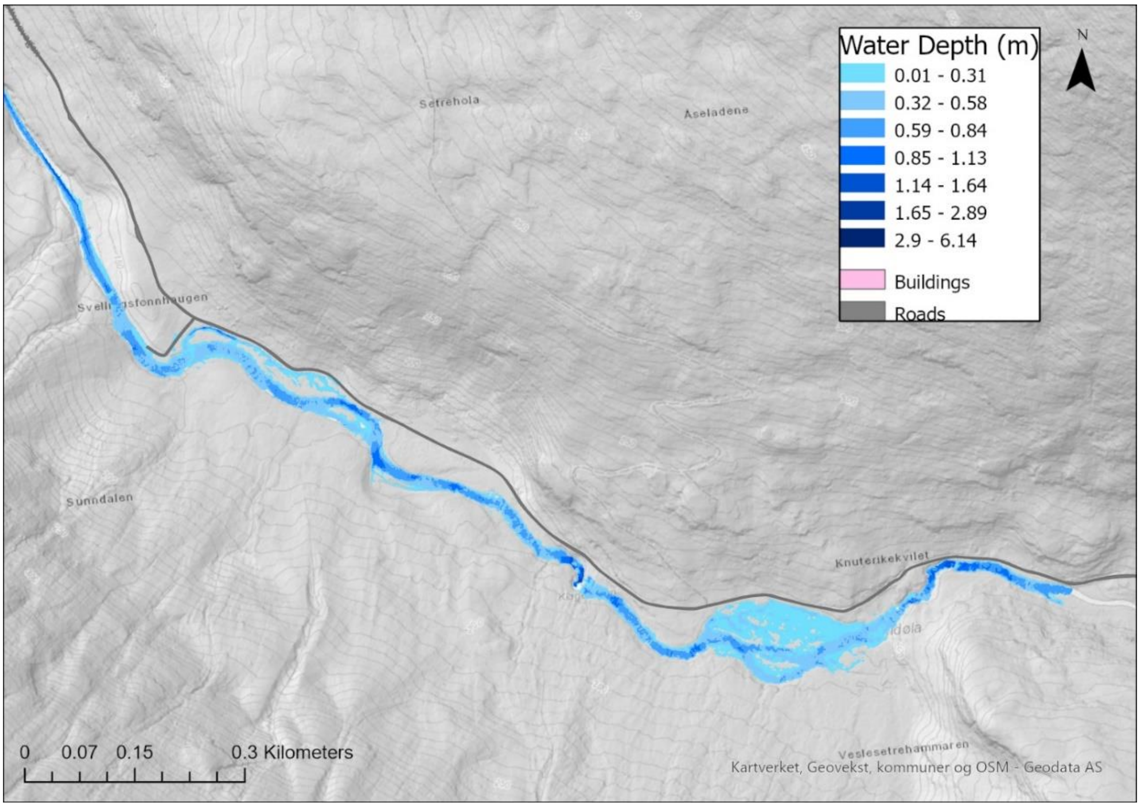


Figure 23: Upper part of Sunndøla with 48-hour drainage from Lagune 2.

The model suggests that 48-hour GLOFs are not able to cause any kind of flood in the upper part of the river, when Lagune 1 drains at a speed of 9,6 m^3/s. This is twice as much as the amount of water that is located in the river during the mean annual flow. For Lagune 2, which drains into Sunndøla in Sunndalen, the amount of water released in a period of 48 hours is 11 m^3/s that is significantly more than the usual mean annual flow speed of 6 m^3/s. To conclude, GLOFs with a duration of 48 hours does not cause any floods and are unlikely source of hazards in the upper part of the river. However, it should be noticed that the modeled maximum water depth is deeper than during a mean annual flow, with GLOFs causing a 9,22-maximum depth in Videdøla and 6.44 in Sunndøla.

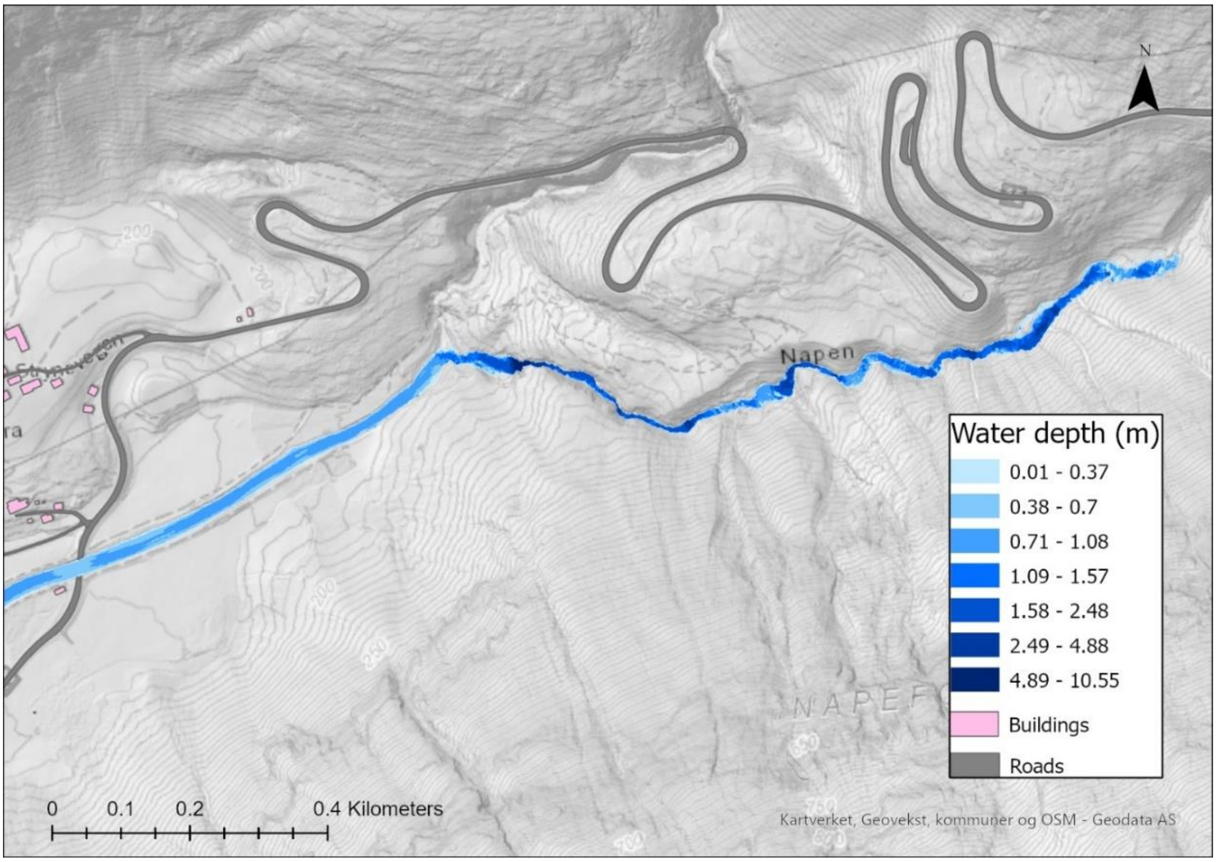


Figure 24: Upper part of the river with 24-hour drainage of lagune 1.

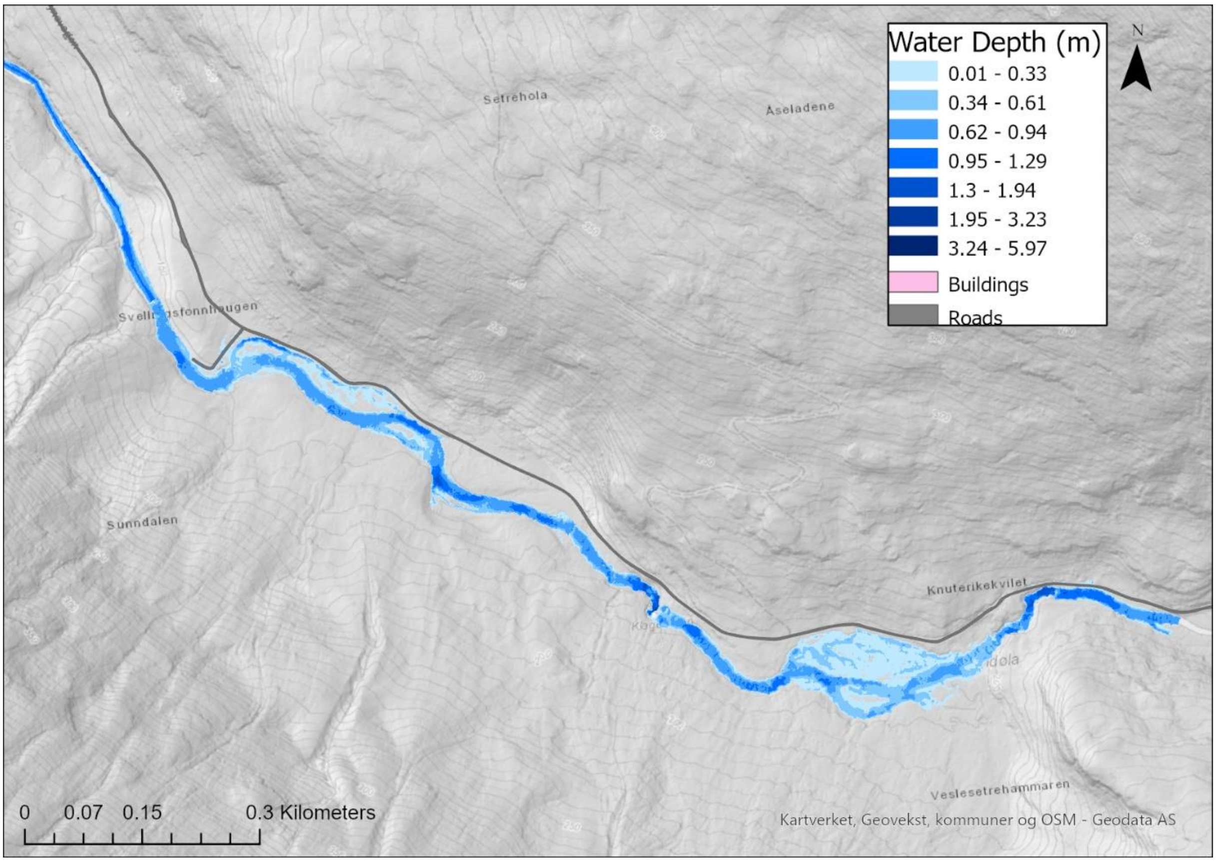


Figure 25: Upper part of the river Sunndøla, with a 24-hour GLOF from Lagune 2.

Figure 24 stretches along the river Videdøla and the beginning of the river Hjelledøla, while Figure 25 features the river Sunndøla. These two models show responses of the respective rivers to GLOFs with a duration of 24 hours, suggesting such slow GLOFs are not viable causes of floods either. There is a large increase in the water volumes from 48-hour GLOFs to 24-hour GLOFs - for Lagune 1, it adds 19,22 m^3/s to the mean annual flow while for Lagune 2 reaches a discharge of 22 m^3/s. In the figures it is a clear rise in the water level. Both the minimum depth and the overall depth have increased. One thing that is strange is that Sunndøla has a lower maximum depth for the 24-hour GLOF than for the 48-hour GLOF. While the reason for this is unclear, it might be due to sinks in the DTM. The general depth of the water flow in the river is deeper for the 24-hour GLOF than the 48-hour GLOF.

4.3.2. Junction

The junction is visualized with four figures. The junction is where the river Sunndøla is coming in from the south, and flows into Hjelledøla. Sunndøla coming in from the south in the model, while Hjelledøla is entering from the east. Figures 26 and 27 show the GLOFs with a 48-hour duration. The modeled GLOF from Videdøla is entering the junction from the east (figure 26). This Junction is after the merger where Videdøla and Skjerdingdøla merge and creates Hjelledøla. The 48-hour GLOF in Sunndøla is modeled, and is entering the model from the south (figure 27). It is no floods caused by these GLOFs, when the drainage of the glacial lakes is happening at this pace.

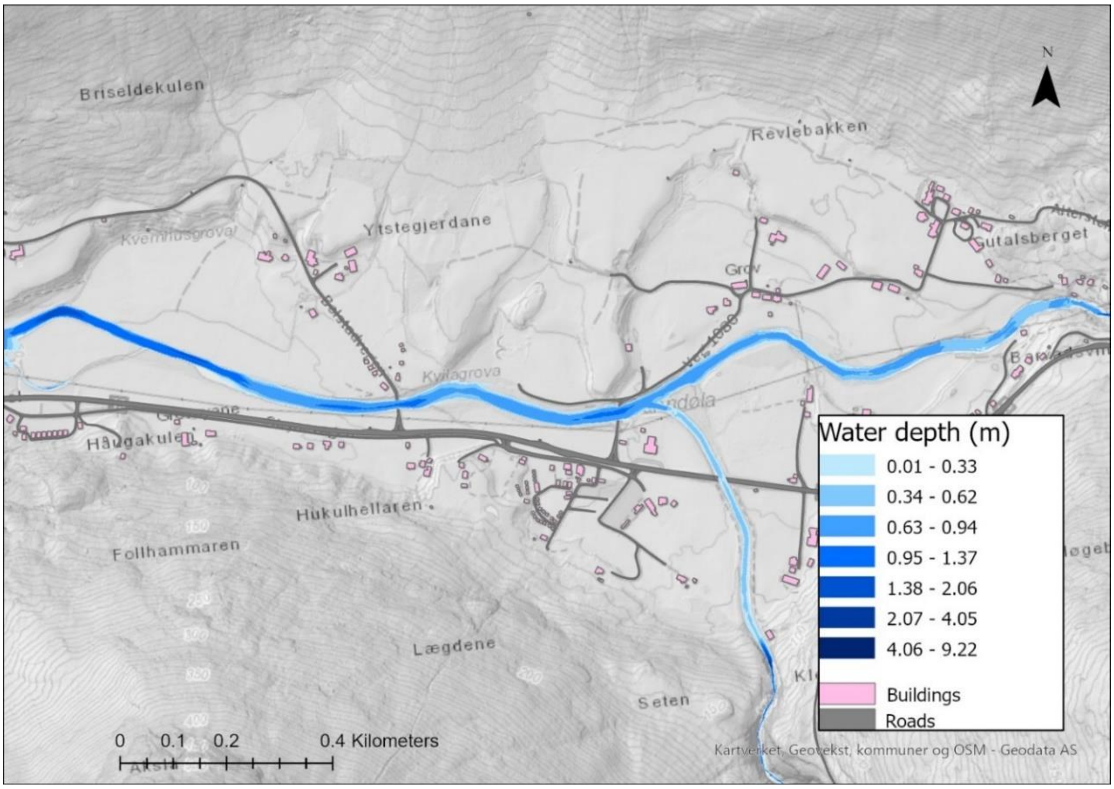


Figure 26: The junction where Hjelledøla meets Sunndøla, a GLOF with duration of 48h from Lagune 1

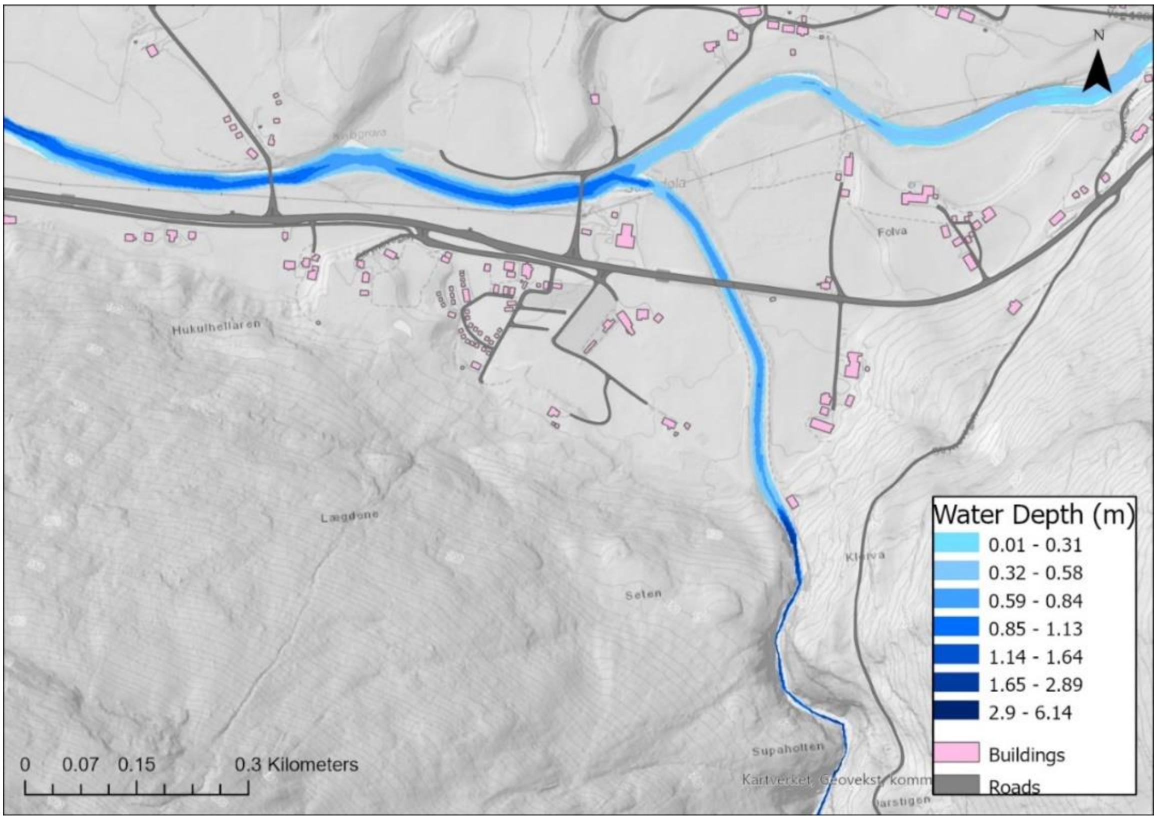


Figure 27: The junction where Sunndøla flows into Hjelledøla, in Hjelledalen in Stryn municipality, with a GLOF lasting 48h from Lagune 2.

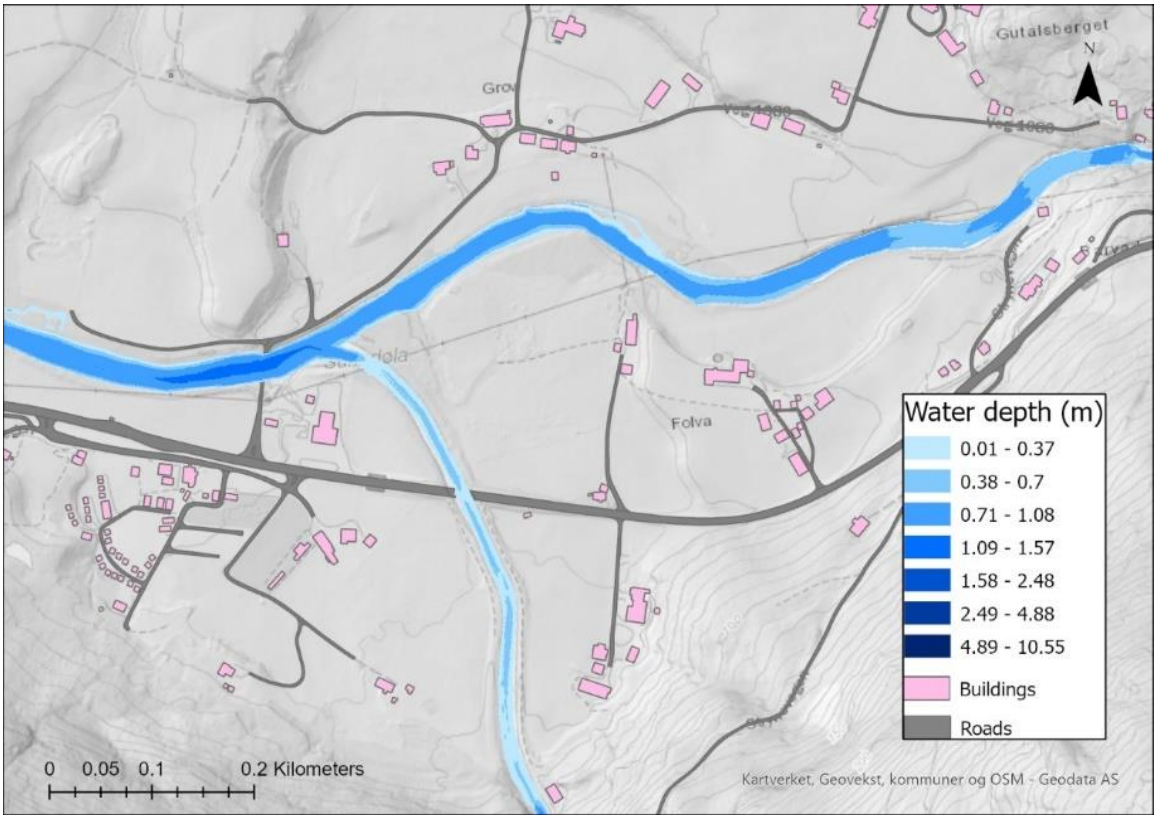


Figure 28: Hjelledøla and Sunndøla meets at the junction, with a 24-hour GLOF event, from Lagune 1.

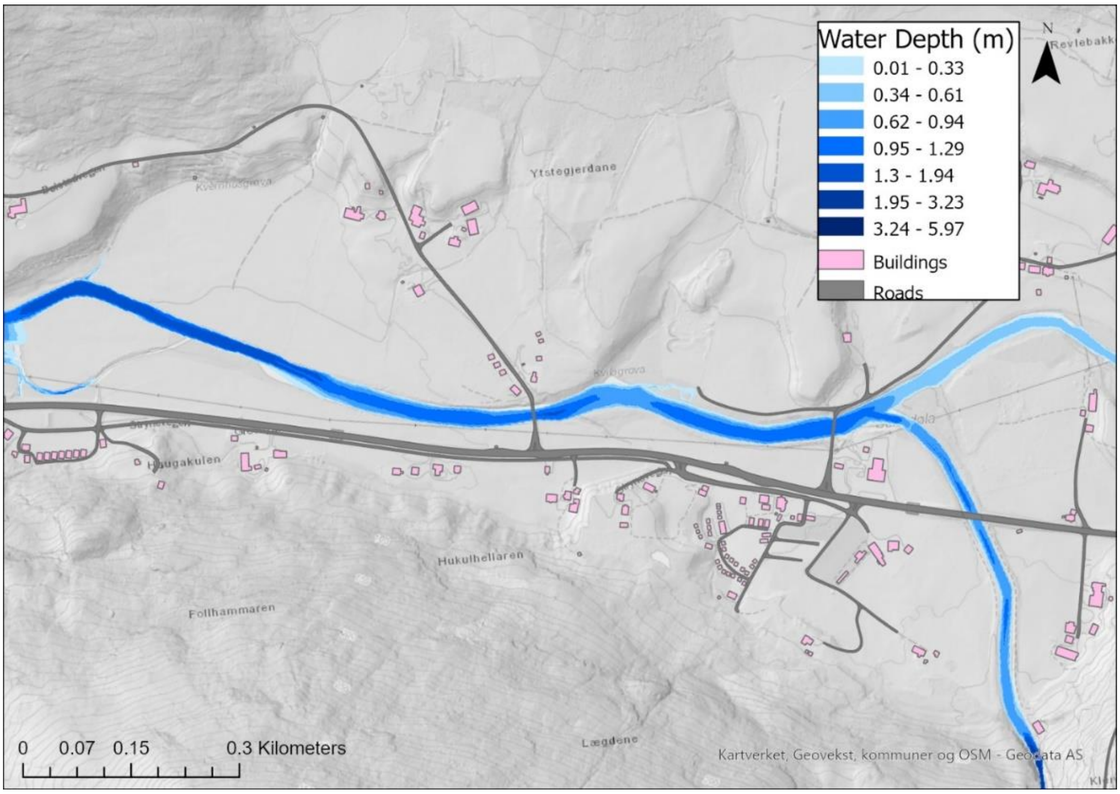


Figure 29: Sunndøla 24-hour GLOF.

Figure 28 show the modeled GLOF from Videdøla. Figure 29 Show the modeled GLOF from Sunndøla. Neither of these two have signs of floods. Both of them have elevated water levels in the river. More than they usually have, during the mean annual flow. It goes to show that the river is able to hold the water within its barriers, when the GLOF is of a duration of 24 hours, or more.

4.3.3. Hjelle

Hjelle is the largest populated area along the rivers and the only town. Hjelle has the school, kindergarten, and the cultural school. It has a hotel, a store, football pitch and many residential homes. It is very important and one of the places where the river potentially can do a lot of damage. This is also the location where the river ends, Hjelledøla flows into Oppstryn lake.

Figures 30 and 31 show the GLOF in Hjelle with a 48-hour GLOF. It is clearly visualized in the models. That a 48-hour GLOF is not enough to cause the GLOF to flow beyond its natural and artificially created boundaries.

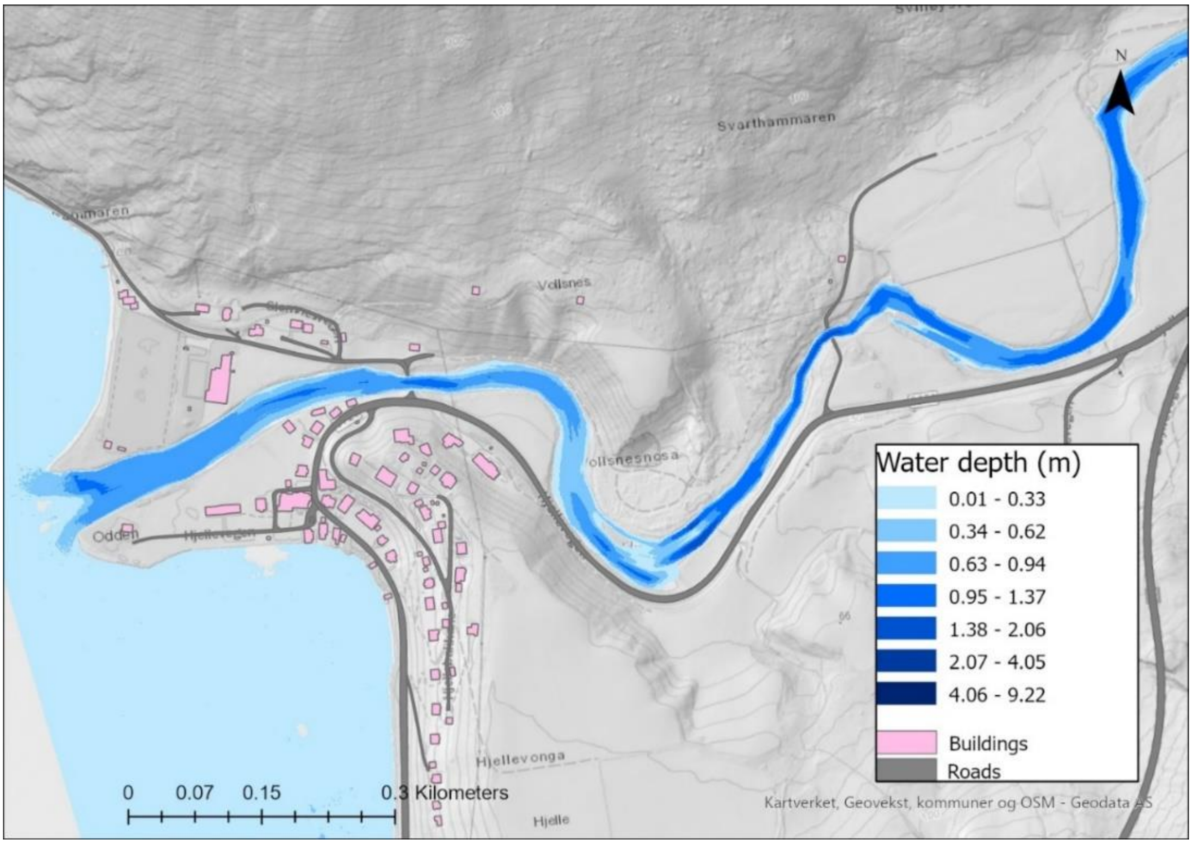


Figure 30: 48-hour drainage seen from the bottom of the river Hjelledøla where the river flows into the lake. From lagune 1.

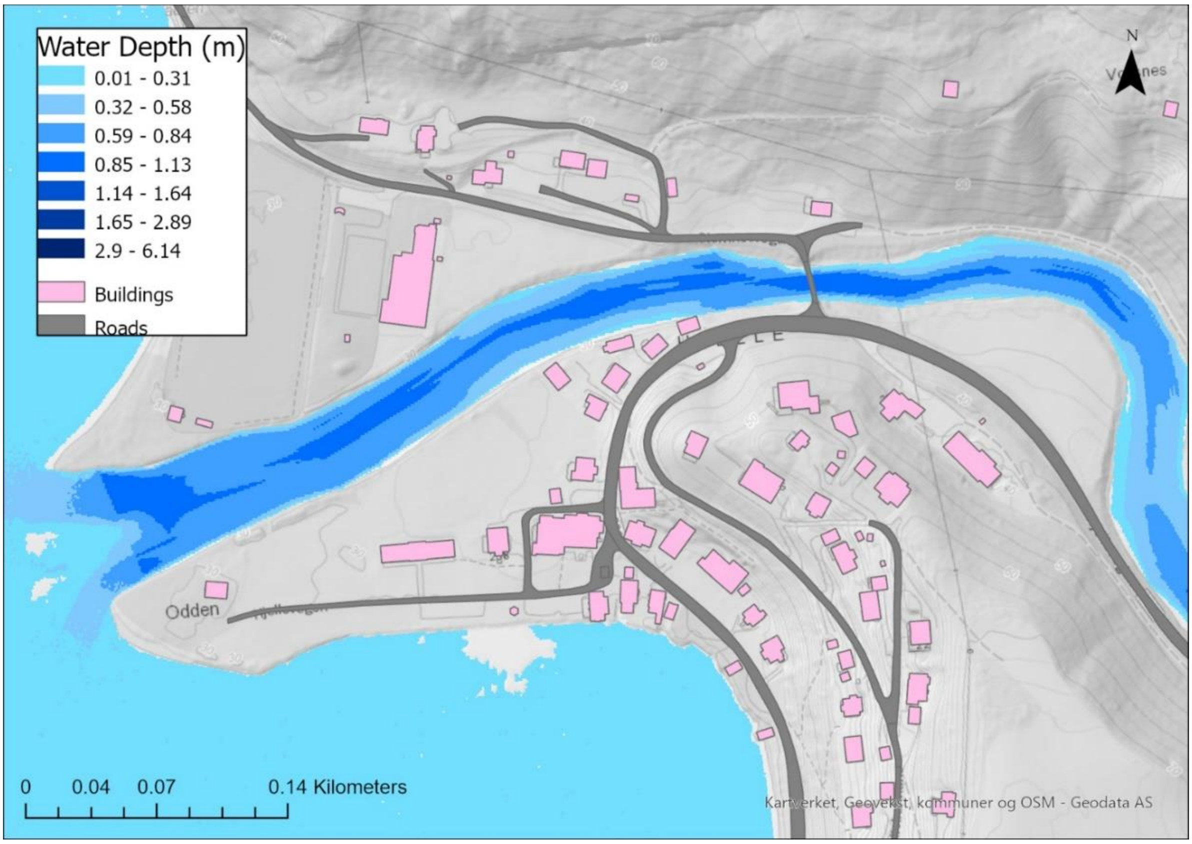
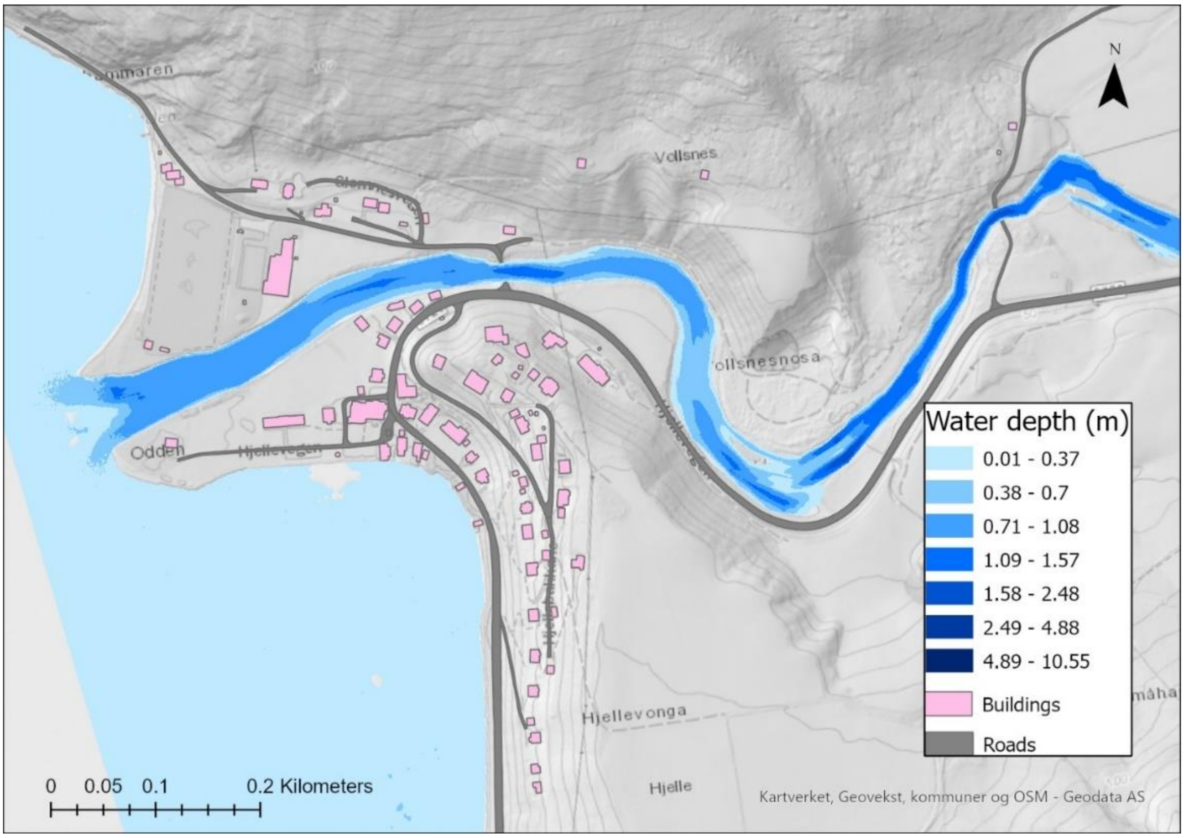


Figure 31: Hjelle town, where the river flows into the lake, with a GLOF from Lagune 2, lasting 48 hours.



Kartverket, Geovekst, kommuner og OSM - Geodata AS

Figure 32: The river flows in the lake Oppstryn in the town Hjelle in Stryn municipality, 24-hour GLOF from Lagune 1.

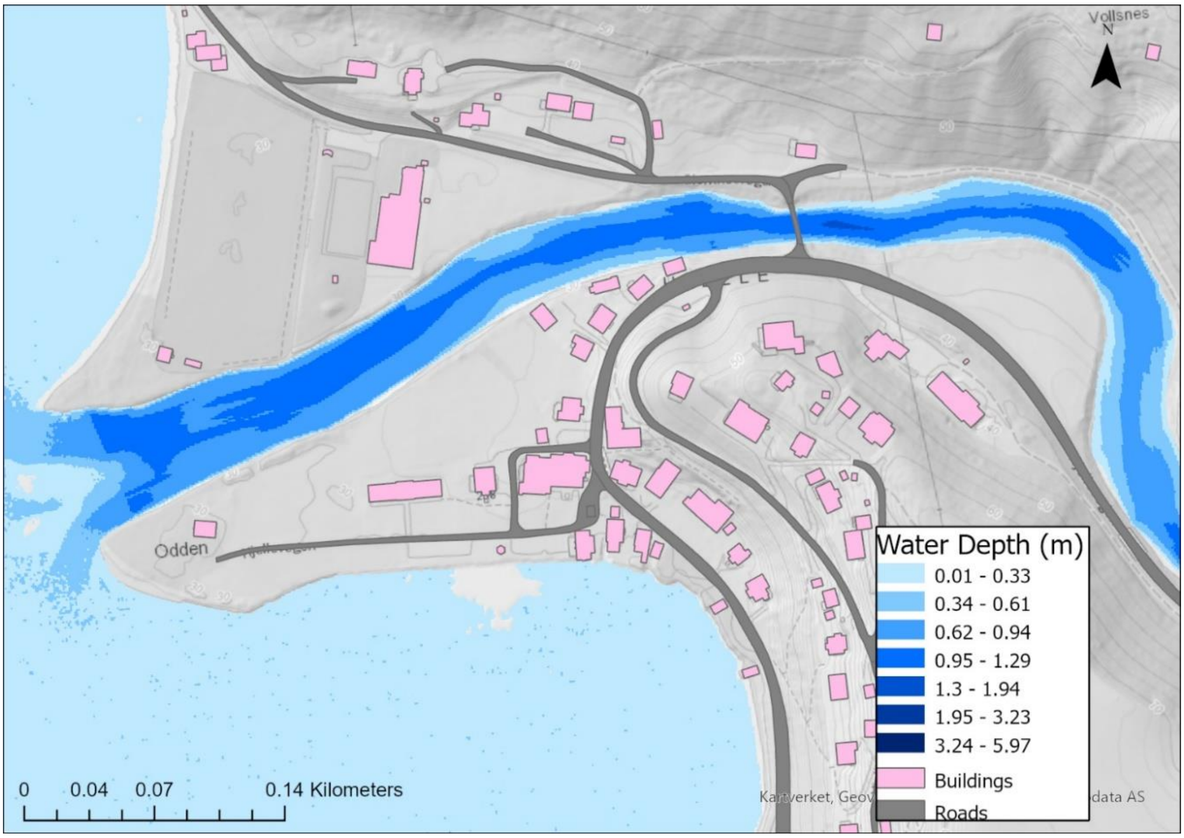


Figure 33: Hjelle in Stryn municipality, with a GLOF lasting 24 hours

The GLOFs lasting for 24 hours is visible in figures 32 and 33. It shows elevated water levels in the river. The elevated water levels are still not enough to flow past the riverbanks. There is no danger for the school, situated on the north side of the river. The bridge is also fine, and will not be in danger when the glacial lakes drain at this pace.

4.4. High risk scenarios (Hazardous)

4.4.1. Upper part

Scenarios described in this section have the capacity to cause an overspilling of the water flow past riverbanks, as a result of GLOF events happening at a fast pace. Here we have tested scenarios for GLOFs with a duration of eight hours, and in the worst-case scenario considered in this thesis, two hours.

Figures 34 and 35 show GLOFs with a duration of 8 hours draining at a speed of 58 m^3/s into Videdøla and 66 m^3/s into Sunndøla, respectively. In both locations water in the river has become significantly deeper than for the scenarios with 24-hour GLOFs. In the GLOF occurring in Videdøla the during the 8-hour GLOF, the river starts branching (figure 34). Although it would naturally branch at this location, this would not usually happen at the scale we see in this picture. However, the river is for most part contained within riverbanks. In comparison, the model with the GLOF in Sunndøla (Figure 35) shows a large expansion of the river that starts flowing onto a private road, likely causing damages to it and making it unusable during this event.

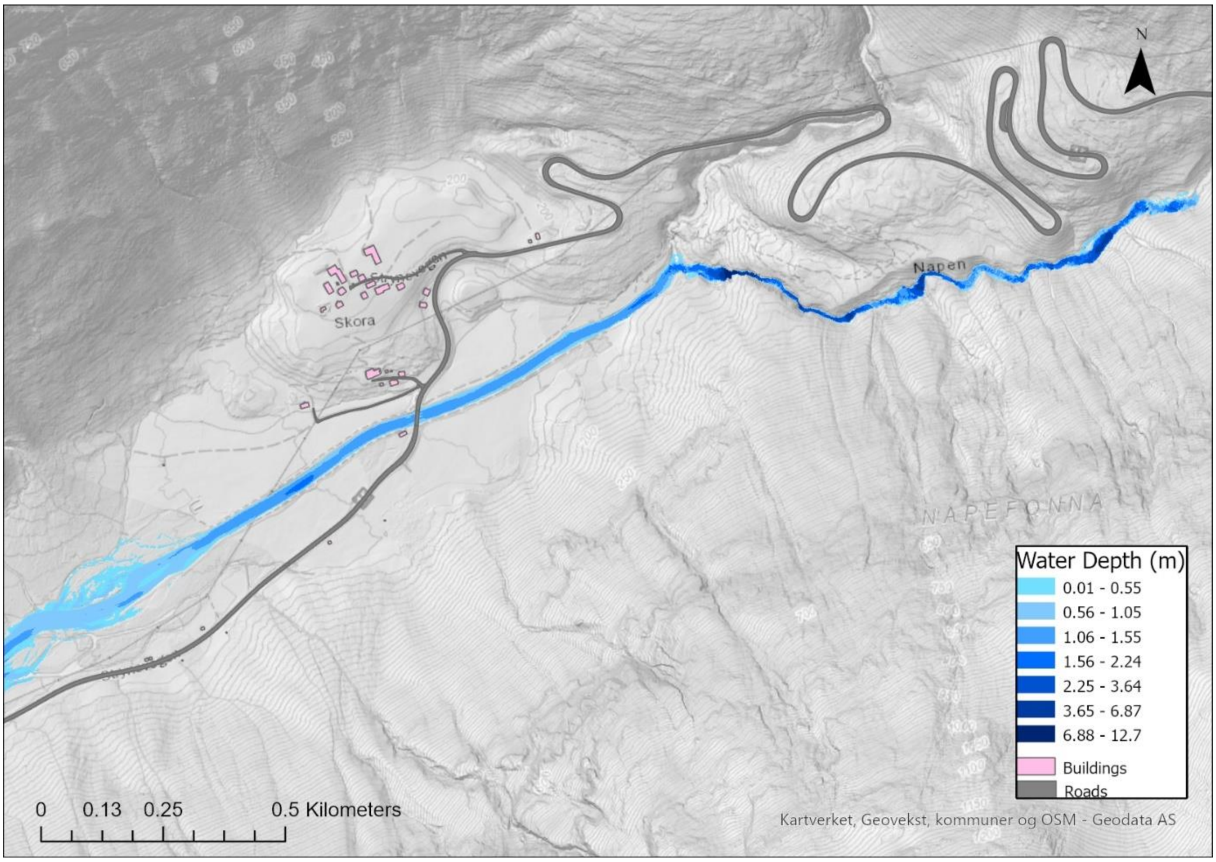


Figure 34: 8 hours drainage in the upper part of the river Videdøla.

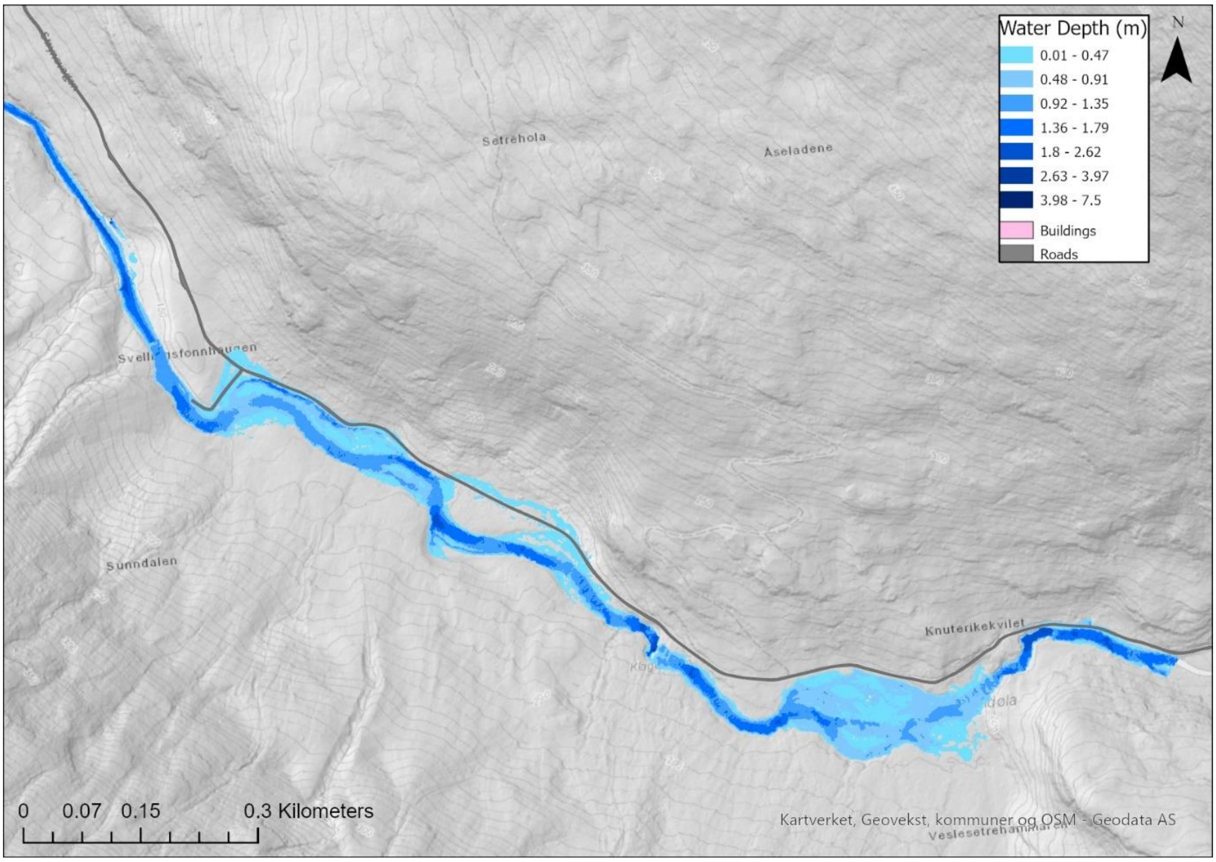


Figure 35: Upper part of Sunndøla with an 8-hour GLOF.

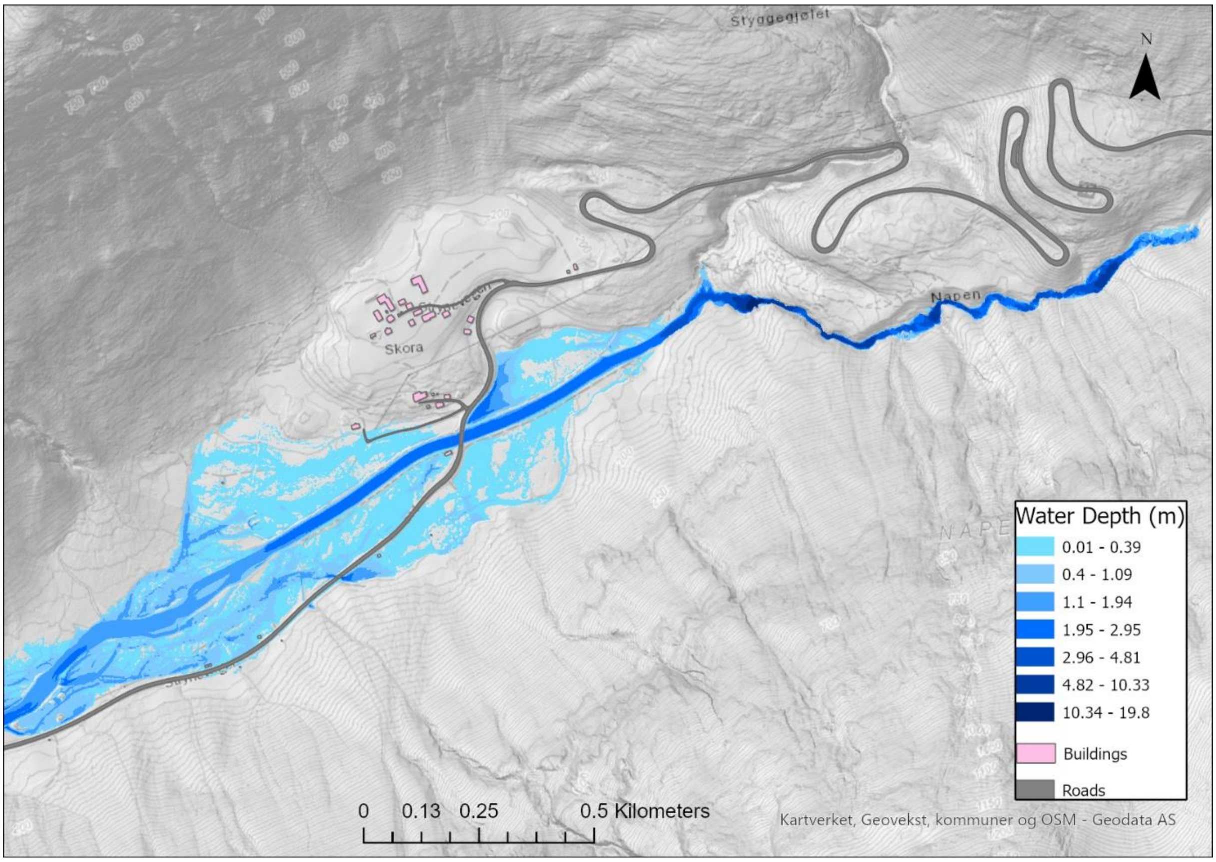


Figure 36: 2-hour GLOF event in the upper part of the river Videdøla.

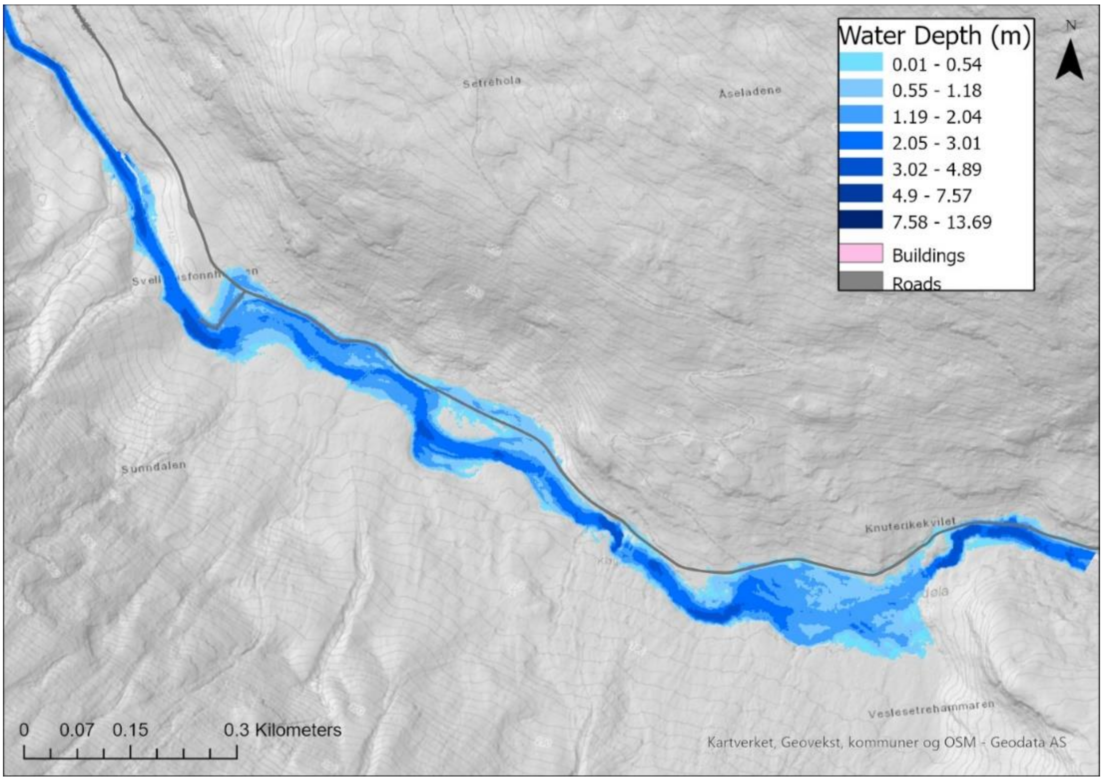


Figure 37: A 2-hour drainage of the Lagune 2, viewed from the location where the GLOF is introduced into the model.

Figures 36 and 37 zoom in on the GLOFs with durations of two hours within the river sectors where excessive water associated with GLOFs is plugged into the model. GLOF events in these rivers carry more than enough water to flood several larger areas within the regions of our analysis. Figure 36 shows the GLOF in Videdøla that carries 230 m^3/s of water during the duration of the GLOF. Excessive water in the river overspills riverbanks, causing large floods on both sides of the river. It also causes floods on both sides of the main road (Riksvei 15), which is the road connecting Stryn and Sjåk across the mountains. The behavior of the water flow showcases a limitation in the model, where the spreading water flows under the road in a culvert (which is not included in the model), instead of flowing across the road. In contrast, in another location, water is flowing onto the road, but not completely covering it.

Under a similar scenario, the river Sunndøla experiences a discharge of 266 m^3/s of water from the glacial lake (Figure 37). This GLOF results in a submerging of the dirt road, with water flow being able to cause large permanent damage to its integrity. It is likely that under this scenario, the dirt road will need repairs.

4.4.2. Junction

The junction where Sunndøla and Hjelledøla meet is a location that will receive large amounts of water from GLOFs on either side of Tystigbreen. Figure 38 shows the GLOF from Lagune 1 that causes a limited flooding at the outer bend of the river, upstream of the river junction. It flows atop the riverbanks on the southern side before the merger of the rivers and causes a significant flood on its northern side.

In Figure 39 the river Sunndøla comes from the south to merge with the river Hjelledøla, with the junction marking an important location, where the valley slope becomes gentler downstream. The model shows puddles of flood on the western side of Sunndøla. Following the merger between rivers, the flood on the northern side is visibly larger in the eight-hour GLOF from lagune 2.

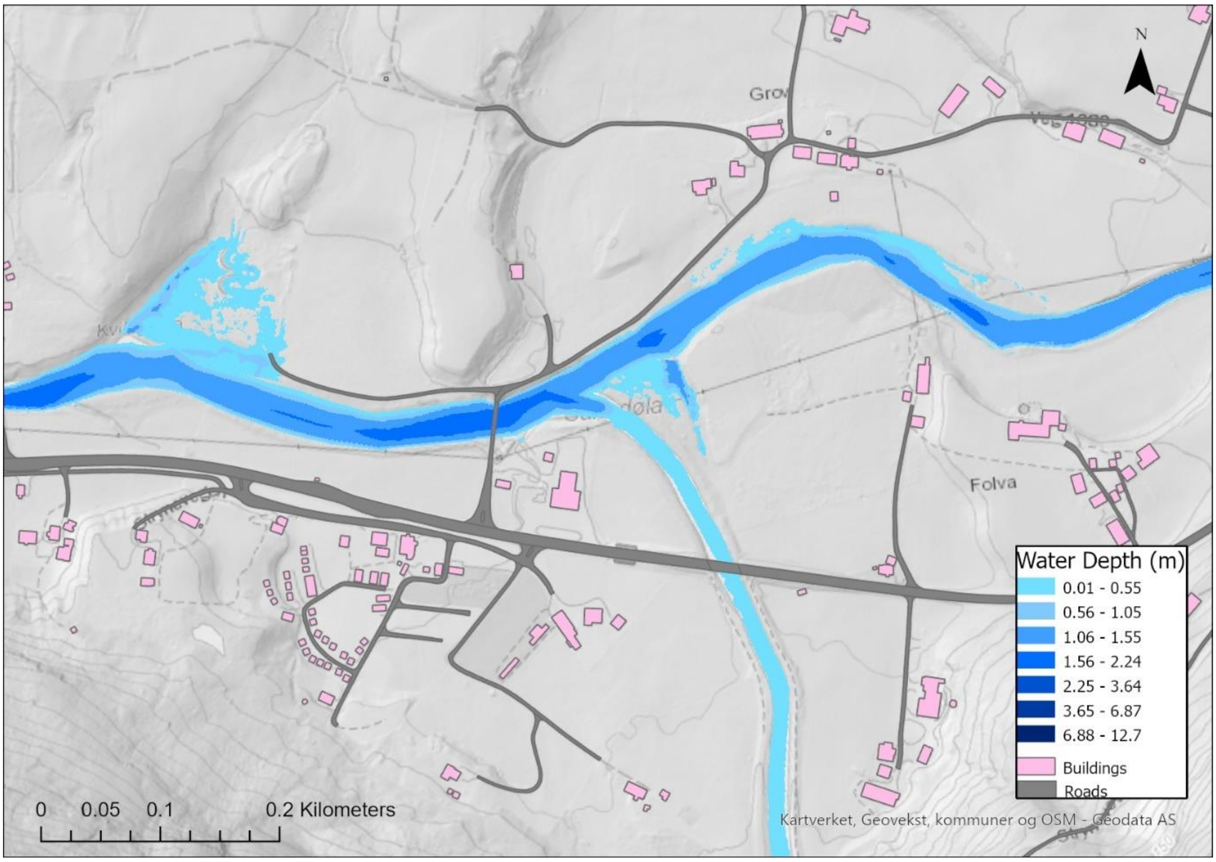


Figure 38: Eight-hour drainage at the junction where Hjelledøla and Sunndøla meet, from lagune 1.

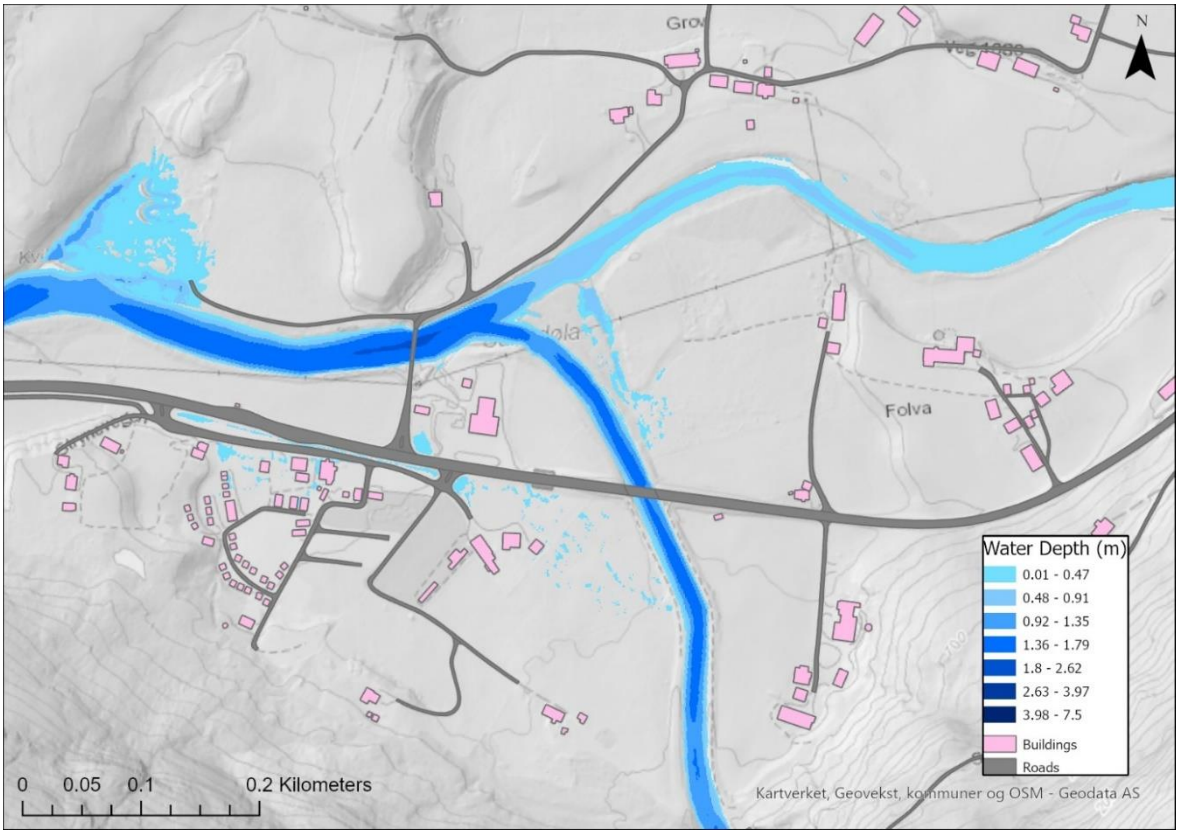


Figure 39: The junction where Sunndøla ends, and flows into Hjelledøla in Stryn municipality, from lagune 2.

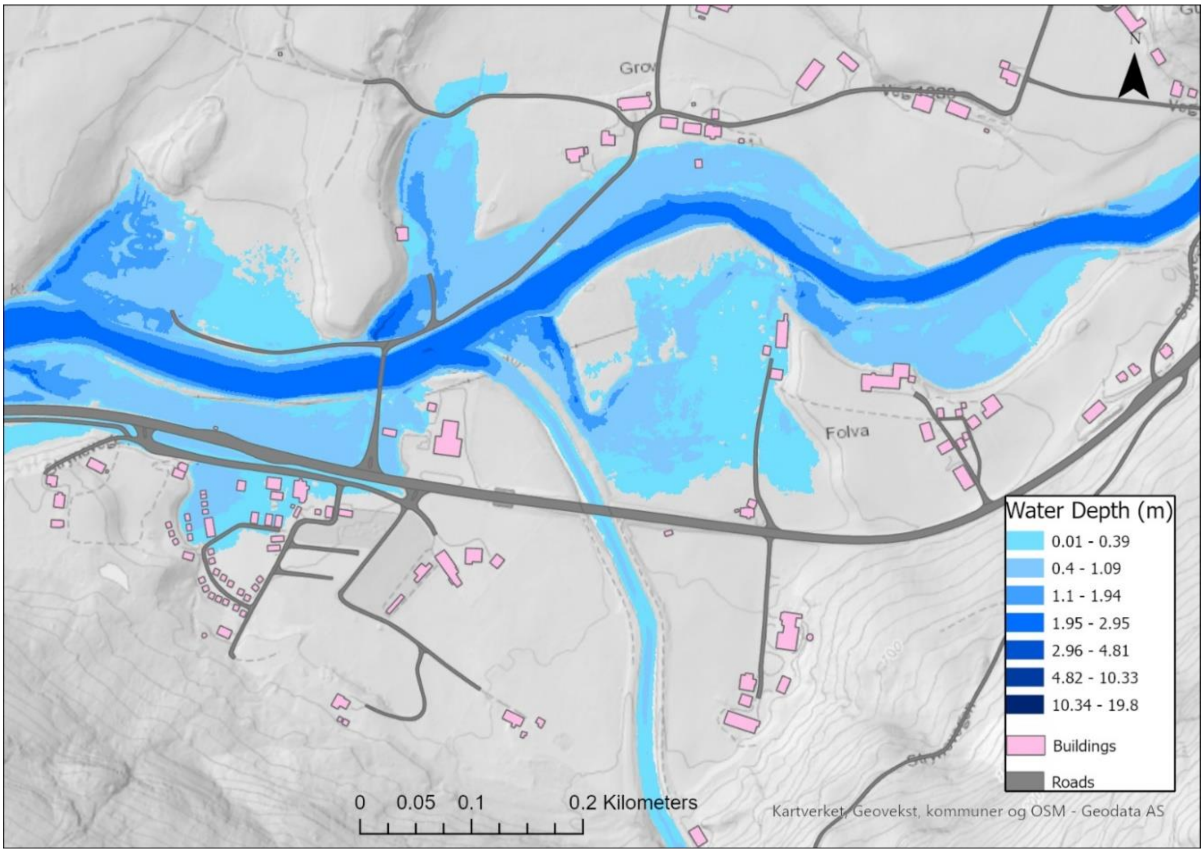


Figure 40: Massive flood at the junction where Hjelledøla and Sunndøla meets, if a 2-hour flood occurs, from lagune 1

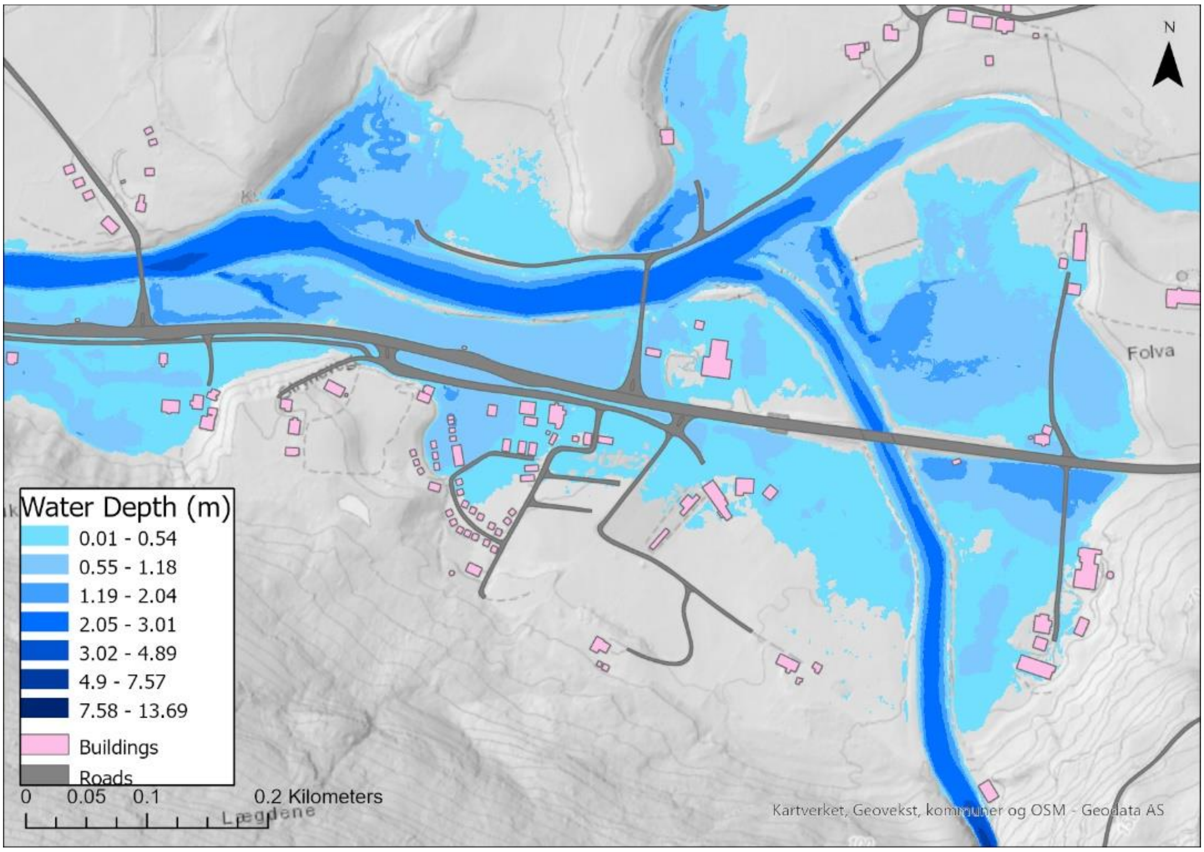


Figure 41: Massive floods can be seen when the GLOF has a duration of two hours, this image shows the junction where Sunndøla flows into Hjelledøla

The two-hour GLOFs visualized in Figures 40 and 41 bring a lot of water into the river systems downstream, with the floods from both Videdøla and Sunndøla overflowing riverbanks. The rushing water does not only submerge large areas of agricultural land, but also floods several houses, farms, and the bridge, next to the petrol station. Finally, they also submerge the Folven adventure camp, located southwest of the bridge. Compared to the GLOF entering from the side of Videdøla, much larger areas are flooded to the south of the river systems, if we analyze the consequences of the GLOF entering from Sunndøla, while little differences are observed in the extent of the flooding along the northern flanks of the river junction section. The larger extent of flooding in this latter scenario implies that farms, agricultural land and several houses are submerged on both sides of the river, the petrol station is flooded, and the bridge next to it also finds itself below water.

4.4.3. Flood prone, gently sloping area in Hjelledalen

Next we are analyzing the relative impacts of GLOFs from the two sides of Tystigbreen on the area of a straight river stretch downstream of the river junction and upstream of Hjelle. This area containing shoals and an island is indicated by the model to be prone to flooding. When we look at the areas affected by eight-hour GLOFs, both simulations result in substantial floods in this area, submerging farmlands on both northern and southern sides of the river (Figures 42 and 43). The flood gets dangerously close to the house on the southern side of the river located on the northern side of the road. In contract, two sheds on the agricultural land get flooded, and the flood propagates towards the location of the island on the north side of the river.

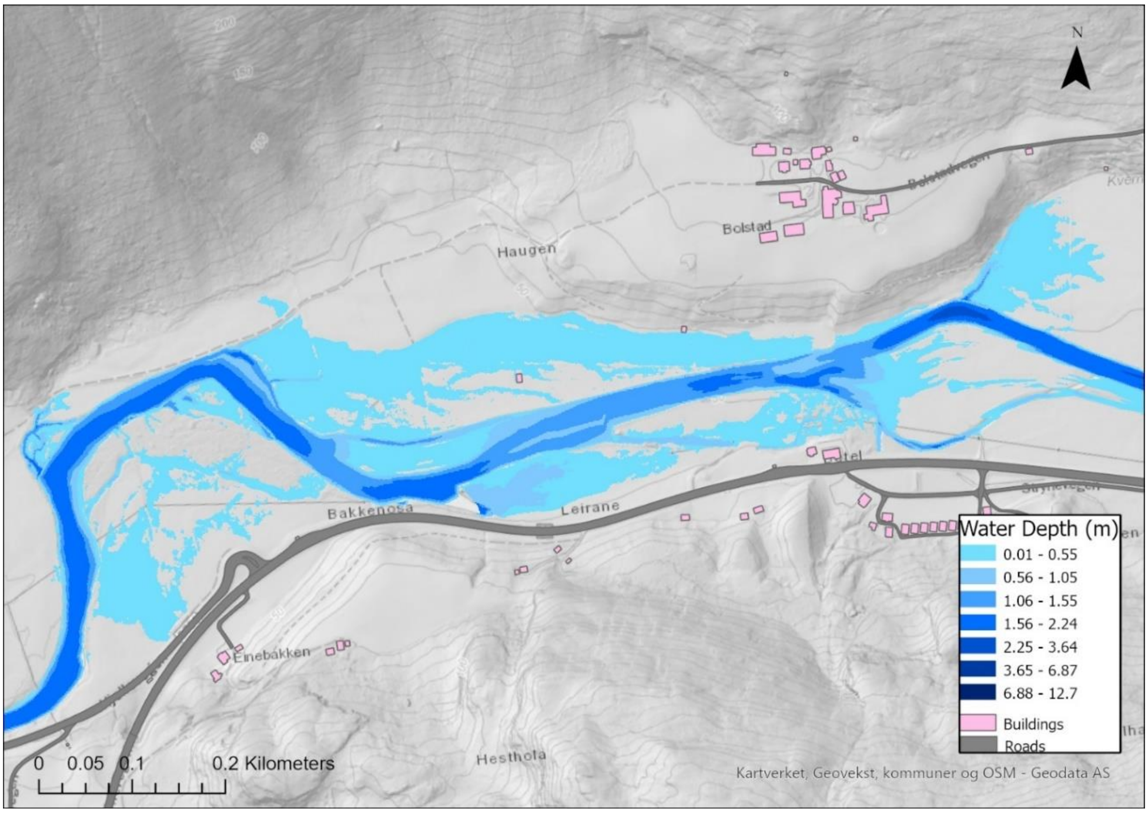


Figure 42: A key area between the river junction and Hjelle town, eight hours from lagune 1.

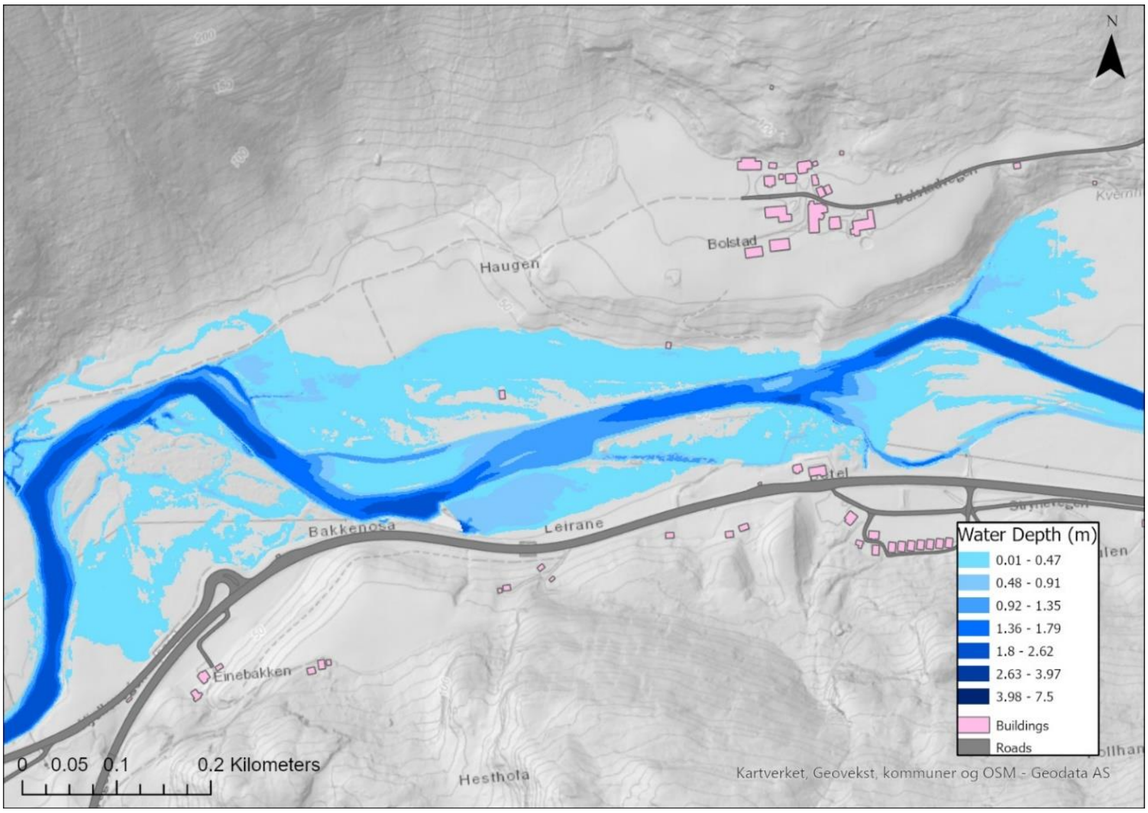


Figure 43: Flooded area east of Hjelle town, in Stryn municipality, 8-hour GLOF from Lagune 2.

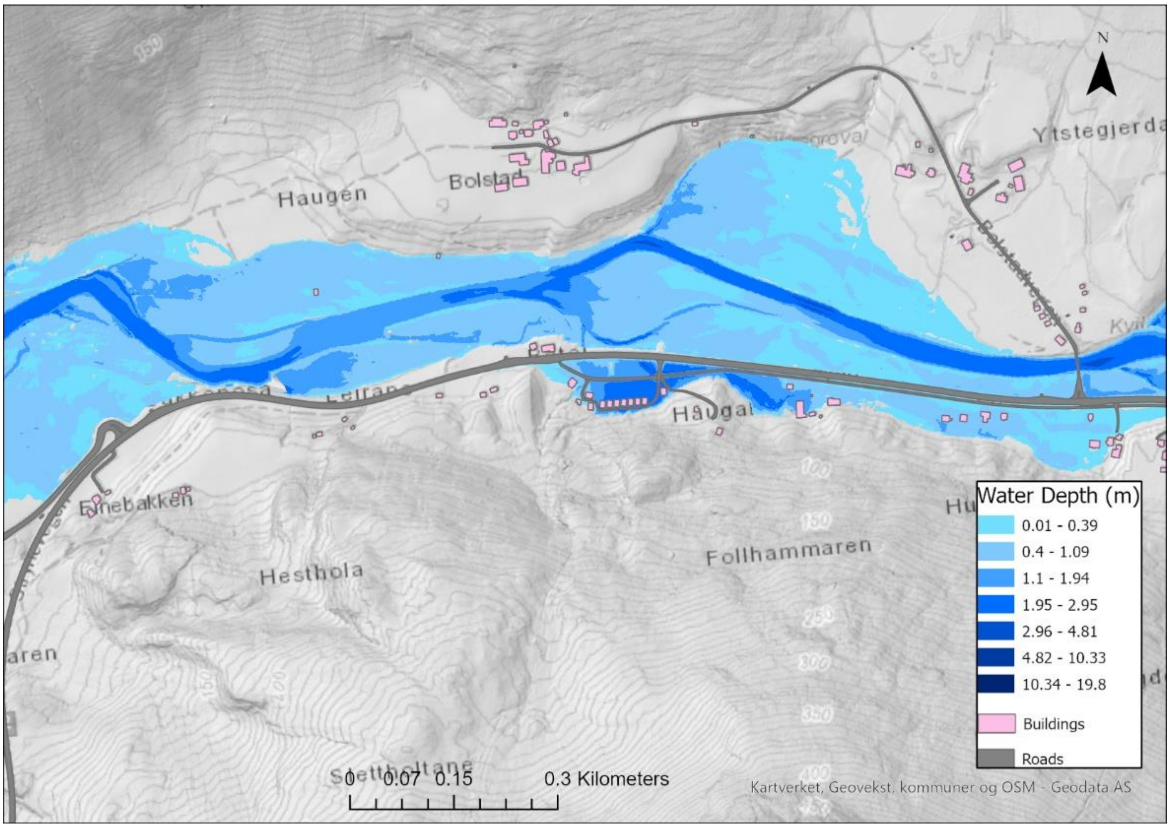


Figure 44: 2-hour drainage, located west of the junction, lagune 1.

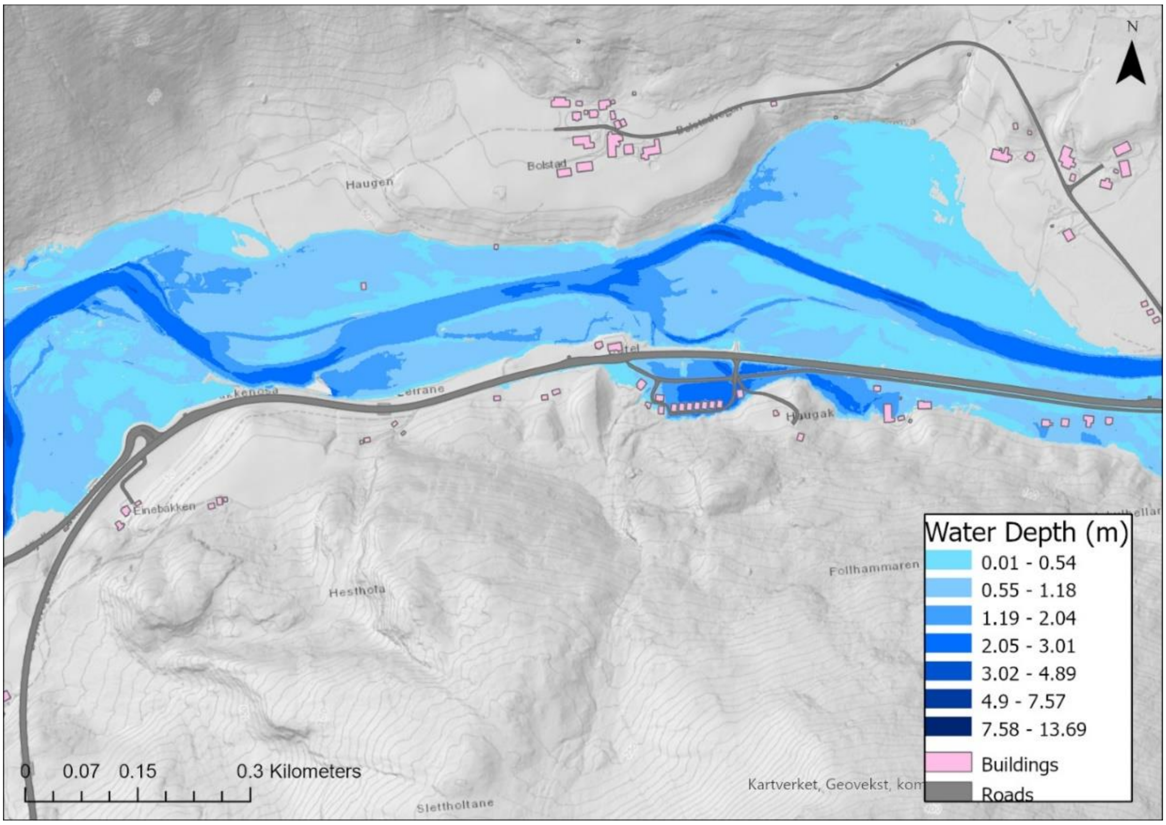


Figure 45: a 2-hour GLOF between the junction and Hjelle town. The result of the model is a massive flood.

The drainage of the glacial lakes lasting 2 hours completely submerges most of the area, including large areas of farmland, both to the north and south of the river system. Water overspills riverbanks in both scenarios (Figures 44 and 45), and the vast flood covers most of the main road, making its use impossible during such event. The cabin rental place known as Hjelledalen Hyttesenter gets submerged under water to a maximum water depth of 3 meters. Several houses get flooded on the southern side of the road, especially in the eastern sectors of the areas shown in figures 44 and 45.

4.4.4. Hjelle

As the most populated area in Hjelledalen, Hjelle is a principal area for the flood risk assessments in this thesis. Our model simulations infer that regardless of the large impacts of the eight-hour GLOFs on the river sectors upstream, the town its will not suffer from any floods during such GLOF events. This is a common result for both GLOF events entering from Sunndalen and from Videdalen. From these assessments we can conclude that the river at Hjelle is able to contain excess water within the riverbanks.

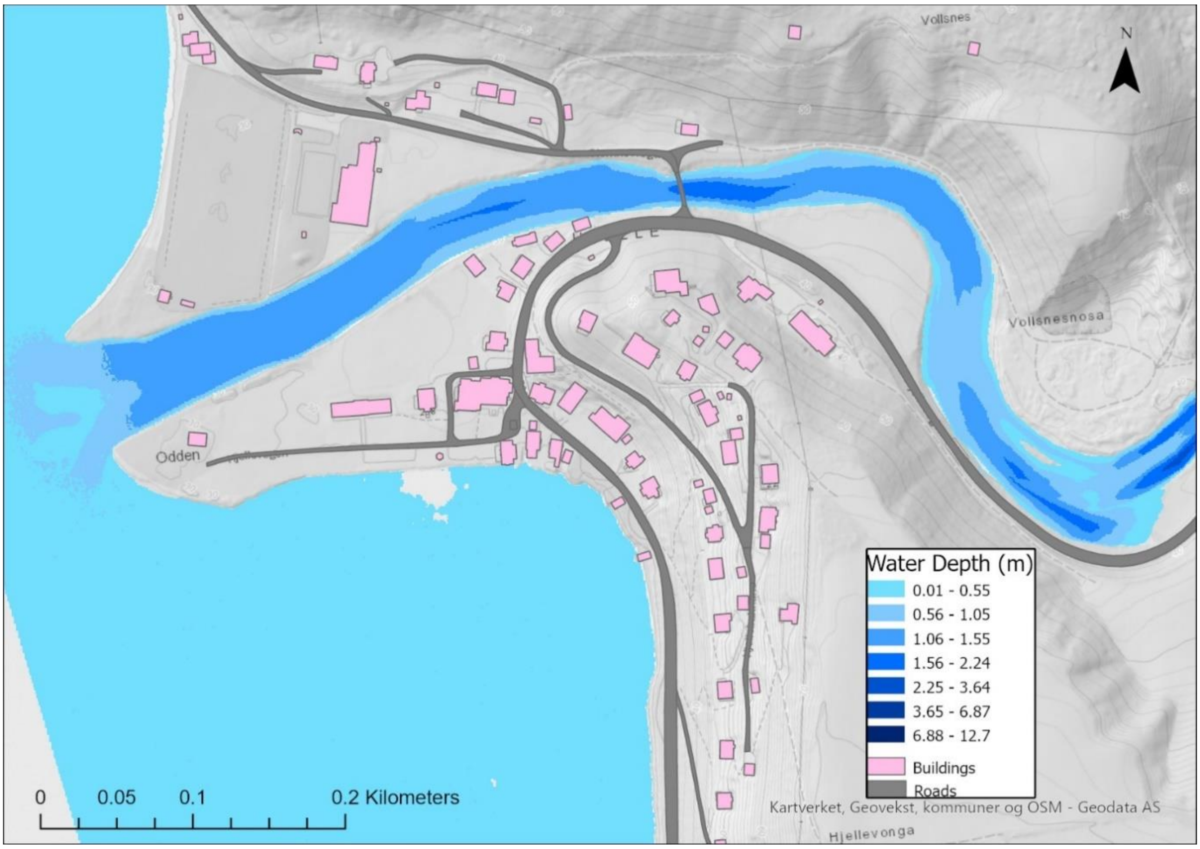


Figure 46: Hjelle town with a GLOF lasting eight hours, Lagune 1.

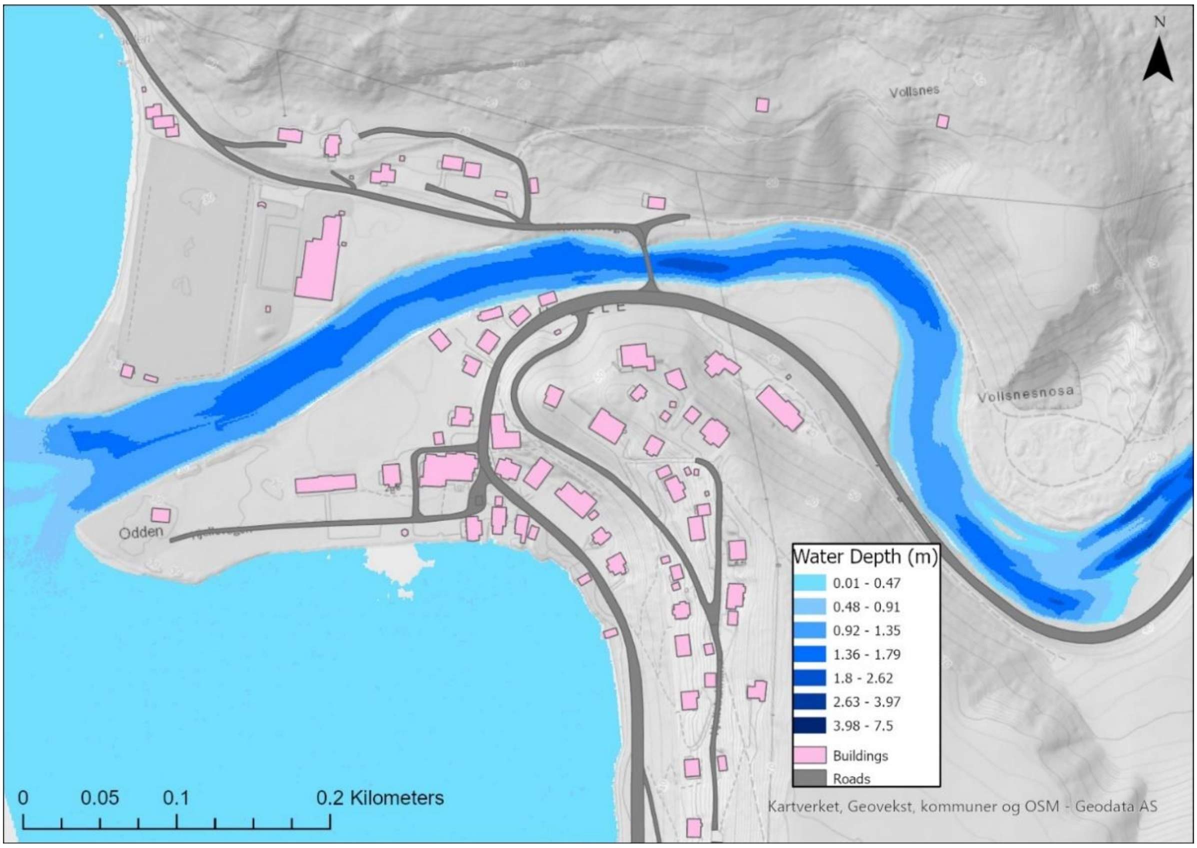


Figure 47: 8-hour drainage of Lagune 2 in Hjelle town, in Stryn municipality.

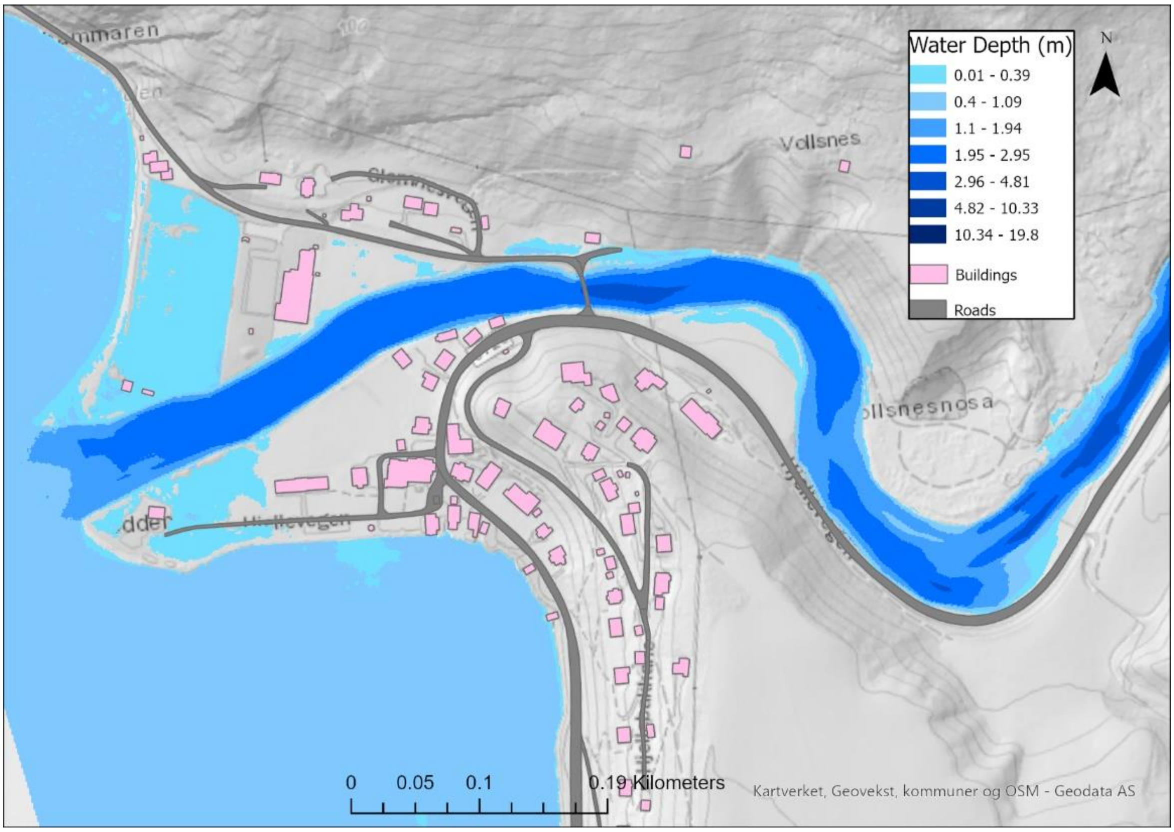


Figure 48: 2-hour GLOF event in Hjelle, from Lagune 1.

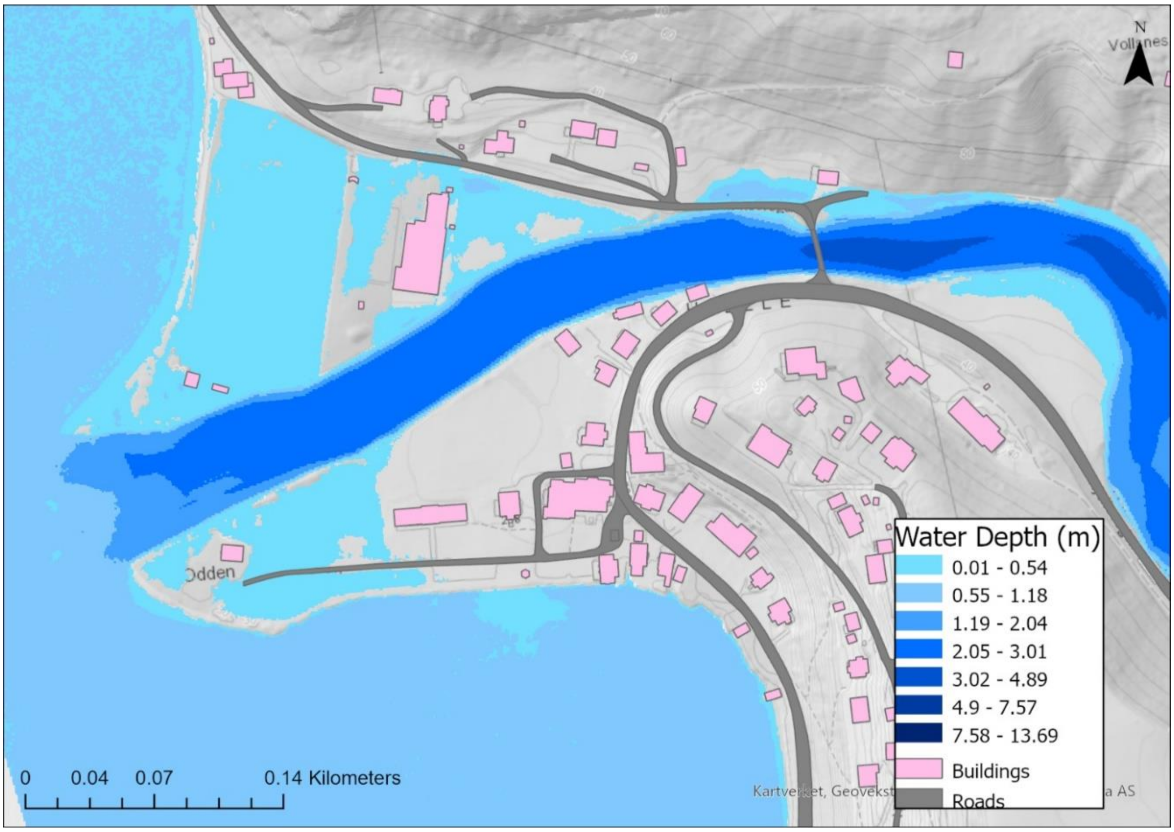


Figure 49: 2-hour GLOF from Lagune 2 in Hjelle.

As opposed to the eight-hour GLOFs that were unable to cause floods and hazards in Hjelle according to our model simulations, 2-hour GLOFs tell a completely different story. It is clear from both Figures 48 and 49 that parts of the town of Hjelle get flooded in both scenarios, although in the case of the GLOF from Videdøla and Lagune 1, it will have a lesser extent than from Sunndøla and Lagune 2. In both model scenarios, the football pitch gets submerged in water, and the southern side of the river is equally flooded. The largest differences are observed at the bridge and around the school. The school and the playground around the school are less submerged under water in the Lagune 1 GLOF scenario (Figure 48), as opposed to the Lagune 2 scenario where large floods impact the school buildings and the surrounding playground (Figure 49). Here the bridge is also more damaged by the flood, although it is not fully submerged in either of the two models.

5. Discussion

Through the model simulations presented in Chapter 4, I attempted to answer the main research questions central to this thesis (see Section 1.2). One of the questions has been whether GLOFs from glacial lakes at Tystigbreen have a potential to cause significant floods downstream. My results suggest that under certain circumstances, GLOFs are able to cause large and even severe floods to the downstream areas, including the possibility of damage to properties and infrastructure. This brings us to another research question that focuses on the identification of some key areas along the river, where such floods can cause severe damage to infrastructure and buildings. The extent to which key areas can be affected by GLOFs and the most important objects to be flooded in these key areas are discussed in this chapter.

Validation of the model results is also an important part of the discussion. We need to investigate how well our model experiments reproduce real scenarios or if they potentially portray unrealistic scenarios. Their reliability is important when considering protective measures that must be implemented to avoid adverse consequences of large GLOFs presented in the results section (Chapter 4). Given that these valleys are often affected by seasonal floods related to excessive snowmelt or rainfall, a governmental institution or a civil society downstream may choose to implement measures to counteract possible floods, including those from GLOFs. In this case, the results of simulations need to be validated showing that the scenarios presented can indeed become true scenarios.

There will be a further discussion of whether the scenarios presented are likely or not, what types of GLOFs this area has experienced so far, and how they might develop in the future. We will also discuss what there is to learn from the models presented in the results of this study and that such models should not be considered with a 100% certainty, but rather as a representation of how the impacts of a rapid GLOF event might look like. These simulations are meant as a way to map places that might be affected by floods and guide mitigation of damage by glacial floods.

Within the analysis carried out in this study, I will also discuss the uncertainties and limitations that are present in its methodology and simplifying assumptions, such as associated with the choice of parameter settings and options, lake volume estimates, digital terrain models, and bathymetry of the river channel.

5.1. Validation of the models

The results of this master's thesis show different scenarios how the river and downstream areas of the glacier lakes are being affected if a GLOF should occur. The different scenarios of the two different lagunes, that flows into respective valleys, which are Videdøla in Videdalen and Sunndøla in Sunndalen, and from there the rivers flows into Hjelledalen in the river Hjelledøla. With the different scenarios of 2-, 8-, 24- and 48-hour duration GLOFs it is possible to visualize how such flooding event will look in a real scenario, and how the GLOF will affect the downstream river, buildings, infrastructure and the whole area in general. What the models suggests are that the possibility for floods, if the glacial lakes are drained within a short time period can become significant. With a time period of 2-hour drainage for both Lagune 1 into Videdøla and for Lagune 2 into Sunndøla can have devasting consequences. The validation of the models is essential, and it is necessary to know if the models can be trusted.

Validation of the HEC-RAS models consists of surveying if the presented models portrays realistic results (Vedmani & Vinay, 2020). Calibration is necessary, and is the iterative process of comparing the model's results with the real scenario, revising, and comparing until the model gets validated (Brunner, 2021b). Data for validation of models can be pictures of past floods, maps, measurements of previous water levels, stories from people that experienced the previous flood events.

The data used for validation and calibration of this model are:

- Pictures from the past flood in 1995. The pictures were given to me by one person we interviewed.
- Anecdotical interviews, and their experience with previous floods, and GLOFs.

There are issues with validating the results of this thesis. First of all, the result simulated in HEC-RAS is not easy to validate, since a glacier lake outburst flood has not happened in the scale that the models portray. Since GLOF of this magnitude has not happened, the scenarios created are still only models, and not real scenarios, it is difficult to know how it would look in real life. It is impossible to test the HEC-RAS model with a 2-hour GLOF to a real scenario of a 2-hour GLOF, because it is something that has not occurred in this area. Therefore, it will be an issue to get a good validation of such a flood event. The validation of the model will be compared to flood events not caused by GLOFs.

Pictures can be good indications for the water level of the river during the past flood. It is a good source of data for the moment when the picture was captured. There is however a problem with using pictures as it difficult to know when the peak of the flood was during the flood. As the pictures only captures one moment, it is hard interpreting the flood from that moment alone. If the flood peak was before, after or at the exact moment the picture was captured, is difficult to know for certain.

For the validation it is a problem that I am currently only in the possession of pictures captured by one person for a flood event from 1995. This was the only flood event that I was able to get pictures from. It would be ideal to have satellite images or aerial photographs from the flood scenario, but I have not been able to acquire it. Satellite data from 1995 are very few, and the ones that exist have a very poor resolution, it is not possible to recognize the flood from those pictures. There has also been attempted to acquire satellite images from 2018, but it has not been possible, mostly due to clouds blocking the view from the satellites. This leads to problem in the process of validation of the models created in HEC-RAS. To completely validate the model, the best scenario would be to have satellite and aerial photos, and to have pictures from several floods that has occurred in this river system through the years, and not just the flood in 1995.

Since I only have the pictures from the one flood event, much of the validation will rest upon these pictures for validation. The other forms of validation that I have is the interviews with local inhabitants done while the GOTHECA team was conducting fieldwork in Stryn municipality. It is interviews with people that have lived most of their lives in the area, as well as a brief interview with a former employee in Stryn municipality.

5.1.1. Picture validation

The two figures beneath, figures 50 and 51, shows a flood in Sunndøla, before the river flows underneath the main road (Riksvei 15), and before it merges with Hjelledøla. This flood was from the large flood in 1995, that caused flood on several farm, a campsite, the main road, and the gas station. The flood also caused the death of several farm animals, and heavy damage on agricultural land. Figure 50 show the flood on the eastern side of the river, with the farm circled in green. Figure 51 is captured from the eastern side of the river, looking at the western side. With two farms circled in yellow and red colors. The colored circles make it easier to recognize the same farms in the models. The same farms have also been circled with the same color in the model figures (figures 52 and 53).

Figure 50: Eastern side of Sunndøla, during the flood in 1995.

Figure 51: Flood seen looking from the easter side, looking at the flood on the west side of the river.

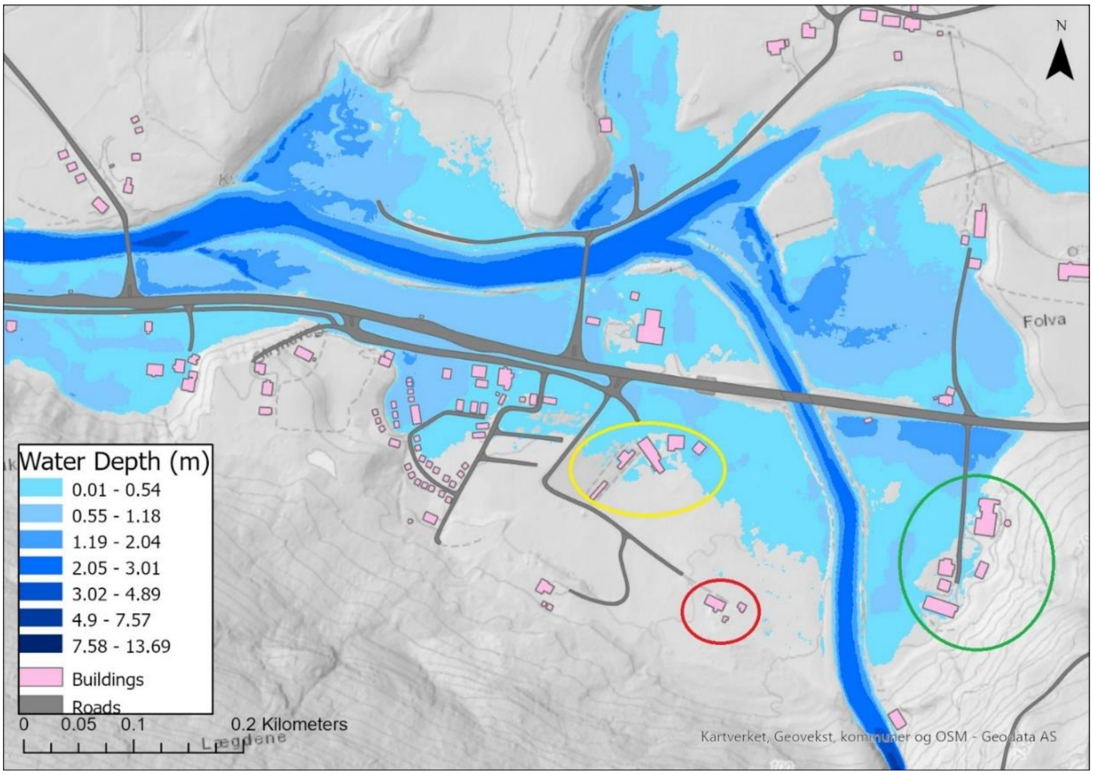


Figure 52: Modeled flood during a 2-hour GLOF.

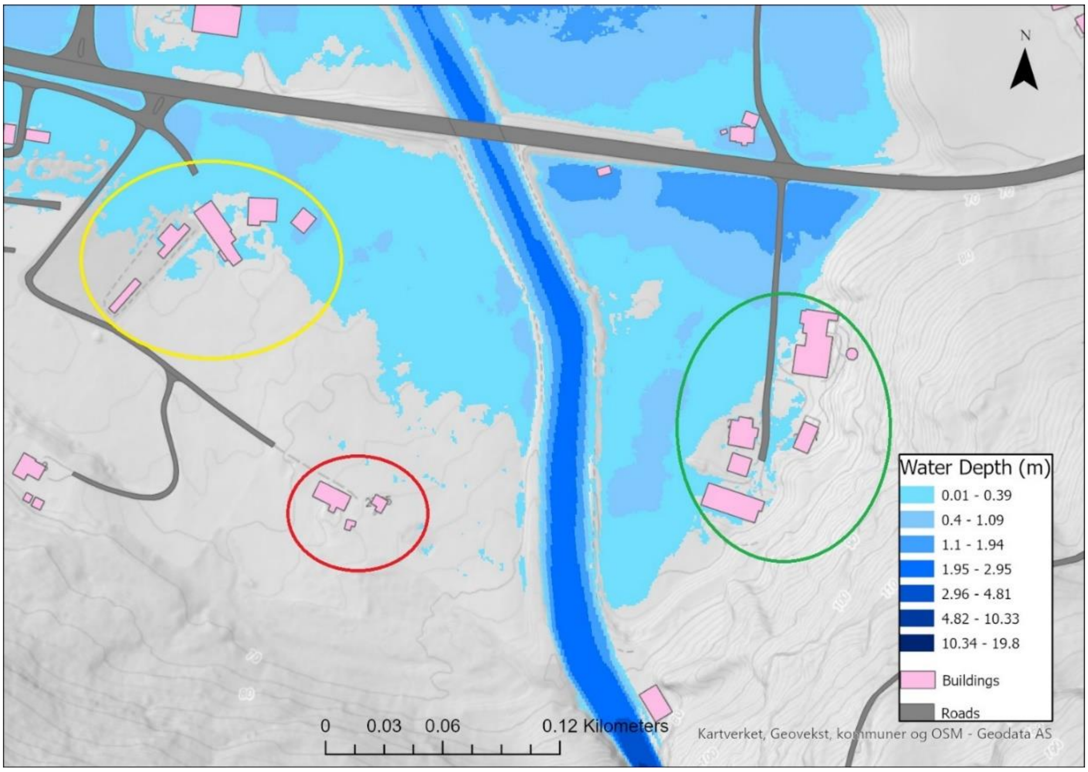


Figure 53: A 2-hour GLOF from Sunndøla, zoomed in to the same area that has been flooded in the pictures from 1995.

The modeled flow from a GLOF with a duration of 2 hours has been modeled (figures 52 and 53). The same locations are visible on the modeled flow of the junction in Hjelledalen, as the pictures from the flood in 1995.

Figure 54: The flood in Sunndøla in 1995, the farm on the west side of Sunndøla.

Figure 55: Looking from the main road up toward Sunndalen and Sunndøla, where the flood originated.

Figures 54 and 55 show how the flooded area look after the flood peak has passed. They show the west side of the Sunndøla, with the pictures being captured from the main road. Figure 54 show the farm that was located in the middle of the flood. With massive amounts of flood water entering the buildings. In figure 55 Sunndalen is visible, the valley where the flood originated. The amount of sediments left behind from the flood is visible, and it has also eroded sediments with smaller grain sizes. A heavy clean up job was required for the agricultural land. It is likely that this flood generated a high cost for the insurance companies, and for the owners of the land and buildings. The power of the flood is visible, where all the fence posts are bent, most of them in close to a horizontal position (figure 54).

The flood events shown in the model, and the real flood events from 1995 has several comparable similarities. The similarities are presented on the eastern side of Sunndøla when the flood is covering the farmland next to the river, until it reaches the main road (figure 50). At the at the western side of Sunndøla, the flood is flowing on the farm on the western side of the river, and almost flooding the farm located to the south (figure 51). The flood then continues to flow to the main road and cover it in water. From there it flows to Folven adventure camp and floods that as well. The petrol station across the road was also flooded similar to the model. This is similar to how the flood behaves in the modeled flow as well. The depth of the water also looks to be similar to the depth shown in the model flow (figure 52), where the water depth is shallow for most areas, but reaches depths of up to 1,18 m on the farmer's fields, especially on the western side of the river. It looks like the depth on the pictures are at roughly similar depths, however it is difficult to see with the water being muddy and brown in color.

A difference is that the water flow on the western side does not start as far to the south as it did in the real flood, the farm circled in red, was much closer to the flood in 1995 than it is presented in the model. Another difference is that the flood stops after Folven adventure camp, and the flow does not continue further down the valley. On the eastern side of the river, the water is only on the southern side of the main road, and it looks to be either very little or no water at the north side of the road. While in the model, the flood is covering the road on the eastern side of the river.

A difference between the modeled flood, and the one in 1995, is the way the floods originated. While the floods that have been modeled in this thesis is caused by sudden drainage of glacial lakes. This is not the case for the flood in 1995. This flood was caused by avalanches and landslides. The debris created a dam that lasted for three hours. When the dam breached a flood occurred. The flood has similarities, but they are still different in origin. The reason to validate the modeled flood with the flood from 1995 is really to see how the water would flow on the landscape, and how the water acts and behaves with the manmade and natural obstacles in the terrain. As seen in both the figures the water behaves in a similar fashion, on both the real scenario from 1995 and in the scenario created in HEC-RAS. It is possible to tell from the how a potential GLOF might act upon the land, by looking at the similarities of the past flood in 1995 and the modeled GLOF.

5.1.2. Validation through interviews

There were several interviews conducted by the GOTHECA team through the course of the several fieldworks in the area. Through the interviews we learned that there had been floods in the area in the past. The floods were in 1953, 1995, and once in 2018. GLOFs regularly occur in from Tystigbreen, but has not caused floods.

The flood in 1953 was big and brought down several buildings on both sides of the river Sunndøla, but also on smaller side rivers coming from Videdalen that brought damage to roads. This was a typical autumn flood that had little to do with the glacier or glacial lakes.

In 1995 the there was another big flood. It occurred because of avalanche and landslide dammed up the river. It flooded both sides of the river Sunndøla. The river was dammed for approximately three hours, mostly dammed by trees and debris from the landslide, and also from snow from the avalanche. When the dam breached the water came and flooded the area. This is the flood I have pictures from.

The flood in 2018 occurred in Hjelledøla and was of such size that the school was evacuated. This was mostly due to the river was so large that there was a fear of the bridge in Hjelle would collapse, and the school was evacuated because of this event. This event also caused the Oppstryn lake to fill more than usual, this caused football field to become submerged by the lake.

An interview with a former employee in Stryn municipality was conducted during the fieldwork, we talked about a GLOF from 2016. It was reported by several people living along the river Hjelledøla that the river was brown and dirty. A campsite along the river used the river as a source for fresh water, they complained that the water in their faucets had turned brown. After the municipality had investigated, they found that there had been a GLOF from Tystigbreen. It was Lagune 1 that had drained in to Videdøla and continued into Hjelledøla. The GLOF was not big in size, and was nowhere near of causing a flood. The water in the glacial lake was released slow enough not to cause any measurable elevation of the river level, but the water that the GLOF brought with through the bottom of the glacier had a lot of sediments in it, and was dark in color. GLOFs has happened from Tystigbreen several times, often without anyone notices, and there has never been GLOFs big enough in this river system to cause any flood, we know GLOFs has occurred in 2010, 2014, 2016 and 2018, and also in the summer of 2021.

The interviews suggests that floods rarely occur in these river systems. The people that have been interviewed also has the perception that the river is able to contain much water. Though through the interview it has become clear that it can happen, and it has happened. Many of the people that was interviewed was under the impression that there is no real danger for flood in the area, but even though it does not happen very often, does not mean that it is impossible for floods to occur in a place like this.

It is difficult to use these interviews as a tool to validate and calibrate the model. The interview was more a tool for information about the place, how prone it is to flood, and their experience with glacial lakes and GLOFs. Still the knowledge they provided has been great in understanding how the floods have happened in the area, where some of the key areas of the river is located, and which areas along the river that can be in danger or can be affected by the river. Many of the stories they told, fits with what the models suggests. Especially with the flooding in 1995, where the farms, the main road, the campsite, and the petrol station ended up damaged by the flood. The football pitch was under water in 2018, and they were afraid that the bridge would collapse, so they had to evacuate the school.

5.2. Key areas in danger of getting flooded

Through the models created in HEC-RAS, it has become clear that there are some areas along the river that are more prone to flooding and related damage than other areas. Both rivers get more prone to flooding in the sectors proximal to Hjelledalen, where the terrain slope becomes gentler. In this discussion we will go through the following four key areas (1 - 4) that are most exposed to GLOF dangers:

1) The first bridge in Hjelledøla, located right after the merger between Videdøla and Skjerdingdøla.
2) The junction between Sunndøla and Hjelledøla.
3) The area where the cabin rental place is located, including a vast agricultural land.
4) The town of Hjelle with the bridge, school, and football pitch.

5.2.1. Key area 1

The bridge marked as key area 1 is placed at the location where the rivers Videdøla and Skjerdingdøla meet and create Hjelledøla (Figure 50 - 51) and is the first element of infrastructure that can be damaged by a GLOF. According to our model simulations, the bridge will not be completely flooded under any of the considered scenarios, but the water depths on the northern side of the river (or on the eastern side of the bridge) will reach 2,96 – 4,81 meters, resulting in the flooding of the area around. This is a key area since the bridge is an essential part of the main road, and under such large amounts of water surrounding the bridge, local authorities will have to consider closing it for the time of the event. Looking at the results of the simulations, I recognize that the solution might be impacted by a numerical artifact in the form of a leak in the 2D model solution discussed in Section 2.3.2, causing water to flow above the boundaries of the river. Even though it looks like a leak is present at the western side of the main road, on the northern side of the river, and possibly also at the southern side of the river, numerical simulations make it certain that most of these areas will be flooded with or without numerical artifacts under the scenario demonstrated in Figure 50. Although it looks like there are numerical artifacts at all locations on the southern side of the river, this is clearly not the case, since the height of the river and the way floods develop within the software HEC-RAS suggest that the water can easily flow above the riverbanks.

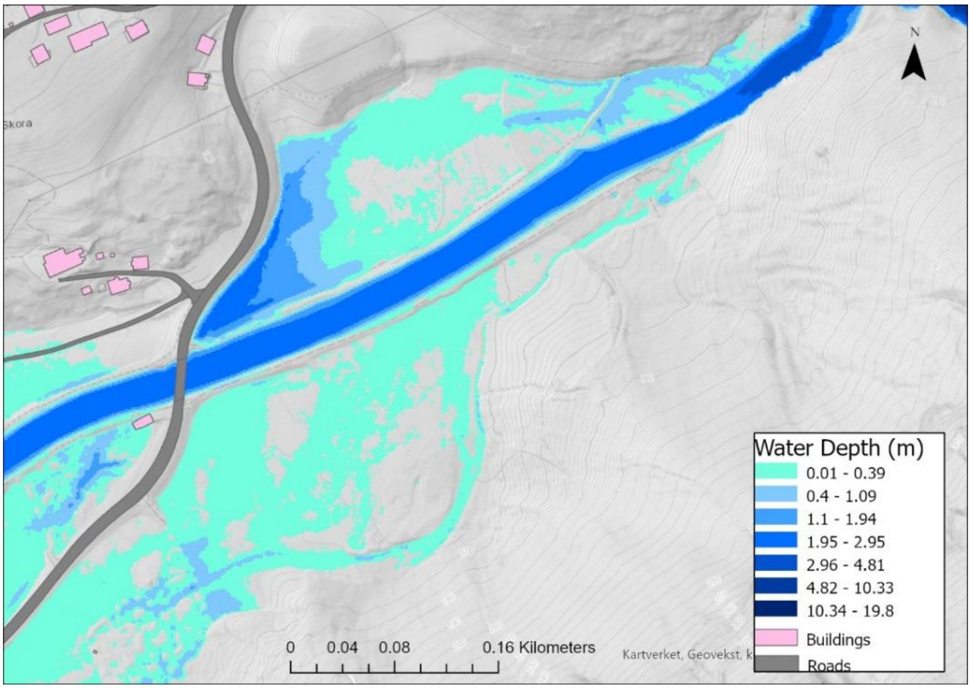


Figure 56: The first bridge after Videdøla turns into Hjelledøla, with a modeled flow of a 2-hour GLOF from Lagune 1. Layout is created in ArcGIS Pro.

Figure 57: The first bridge after Videdøla turns into Hjelledøla, with a 2m GLOF. Captured from Norgeibilder.no

5.2.2. Key area 2

The second key area in our modeling domain is the junction where the river Hjelledøla and the river Sunndøla meets. According to the model simulations with rapidly draining lakes (2-hour events, from Lagune 1 and Lagune 2), this area can be prone to flooding. According to the model several farms on both side of the river Sunndøla will be affected by the flood. When the GLOF is of a duration of two hours. There will be a large flood submerging the main road over a large area. Agricultural farmland, on both sides of the river, will be flooded by the GLOF, there is a high potential for permanent damage to the topsoil of the agricultural land, due to erosion and sedimentation. Finally, the petrol station and the general store located in the same building and the Folven adventure camp will be flooded, if a GLOF with a 2-hour duration hits this area.

Figure 58: The river junction, where Hjelledøla and Sunndøla merges, is prone to flood. Captured from Norgeibilder.no

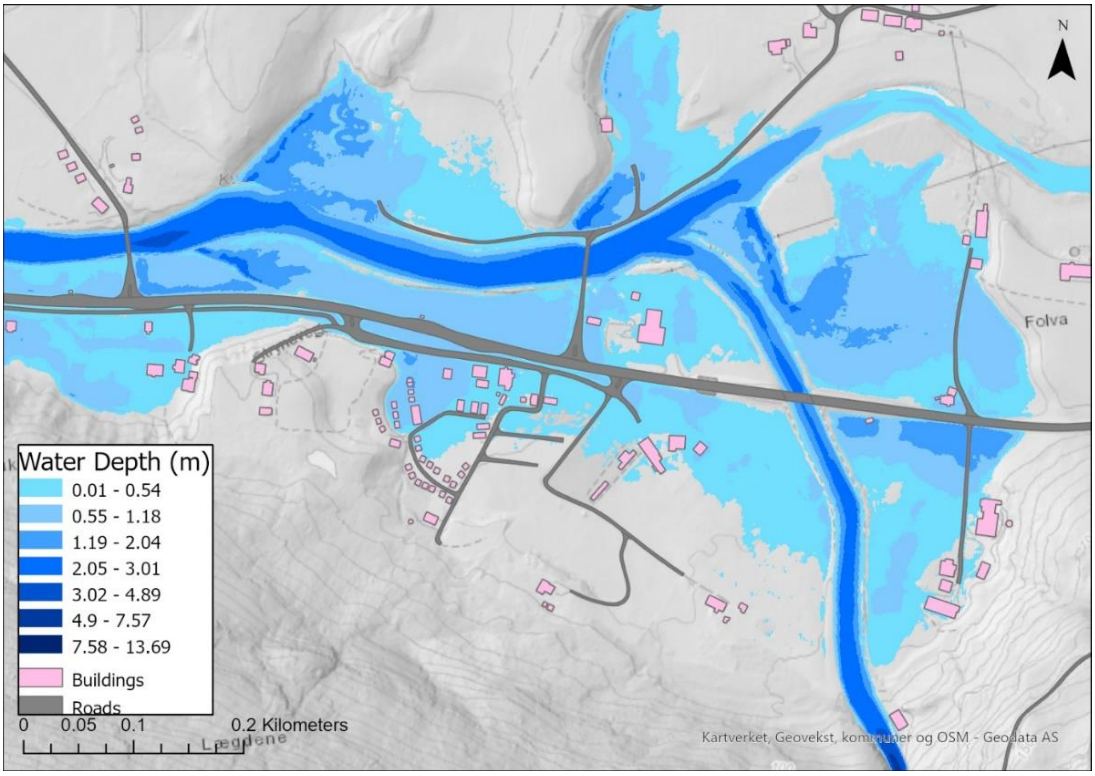


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Figure 59:The river junction, modeled in HEC-RAS with a 2-hour GLOF into Sunndøla.

Figure 60: Close up of a farm, Folven adventure camp, and the petrol station. Captured from Norgeibilder.no

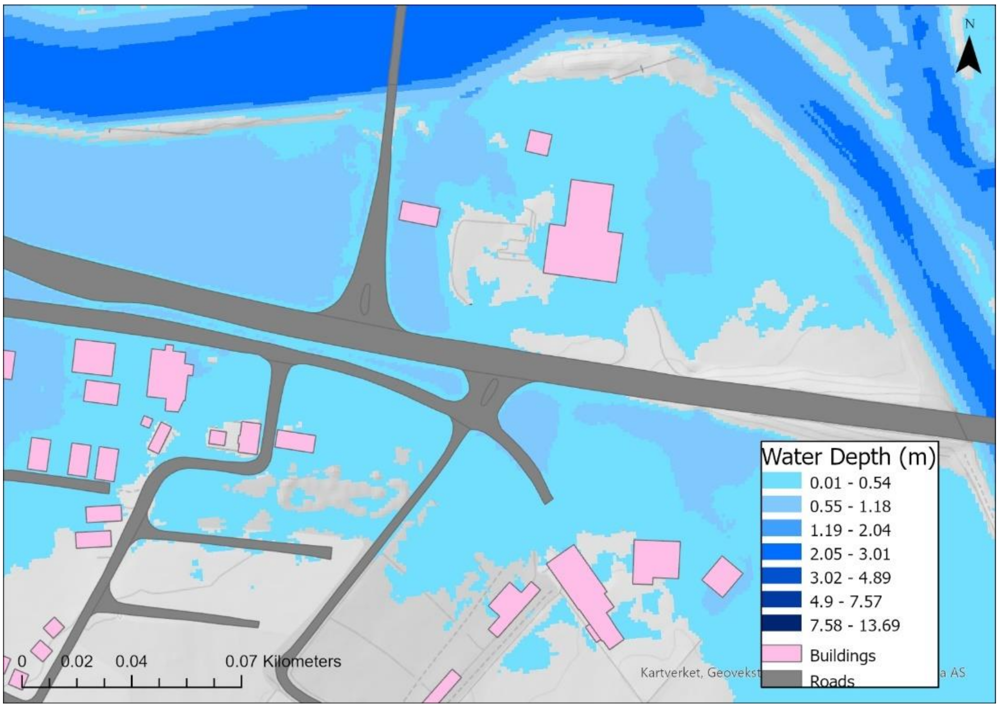

Figure 61: the same cutout that can be viewed in figure 54, with the petrol station, Folven adventure camp and a farm.

Figure 62: The petrol station and store, which was flooded in 1995. Picture captured from Google Street view.

Figure 63: Folven adventure camp has previously been flooded, last time in 1995. Picture captured from Google Street view.

Figures 62 and 63 show the petrol station, the general store, and the Folven adventure camp. As discussed above, our modeling suggests that both of these places will be flooded by a 2-hour GLOF, with the depth of the water around the main buildings rising up to 0,54 m and at some other locations on their properties up to 1,18 m.

5.2.3. Key area 3

The third key area is a stretch of the river with an island and shoals, which the model suggests being prone to flood, with Hjelledalen hyttesenter as part of this key area. Hjelledalen hyttesenter is a cabin rental site next to the main road, south of the river Hjelledøla. The model predicts that when a 2-hour GLOF from Lagune 1 and Lagune 2, this location is poorly located. The site is located at a gentle slope down from the main road. This means that water will have the chance to flow down to the cabin rental site and the flood will accumulate and potentially become deep in this location.

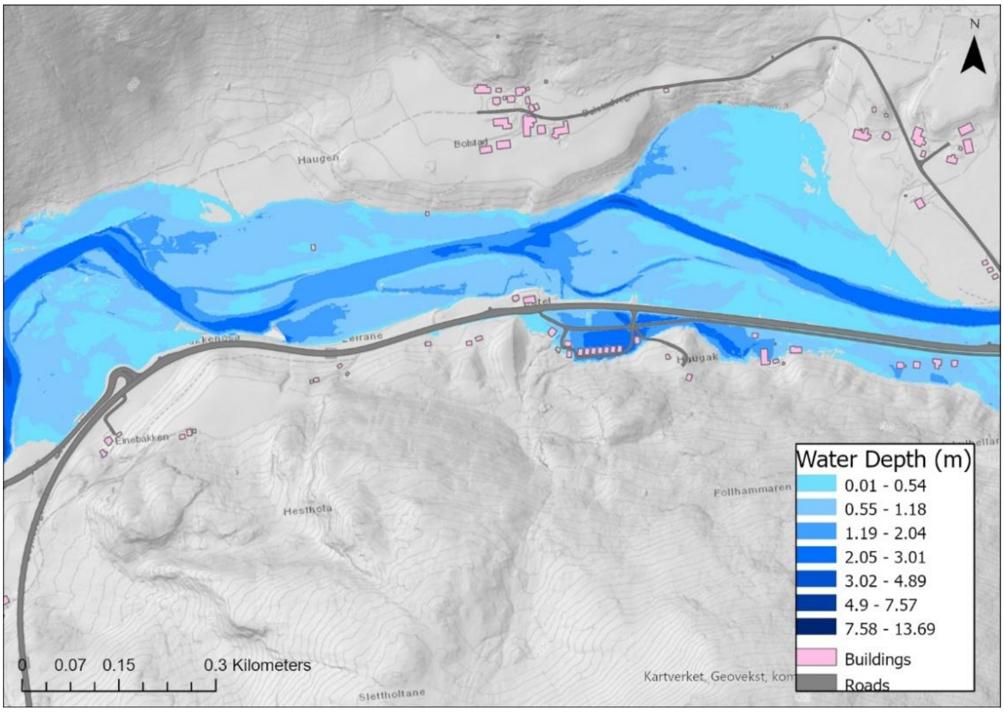

Figure 64: Hjelledalen hyttesenter is shown to be flooded with a 2-hour GLO, from Lagune 2.

Figure 65: Hjelledalen hyttesenter has potential to become flooded. Captured from Norgeibilder.no

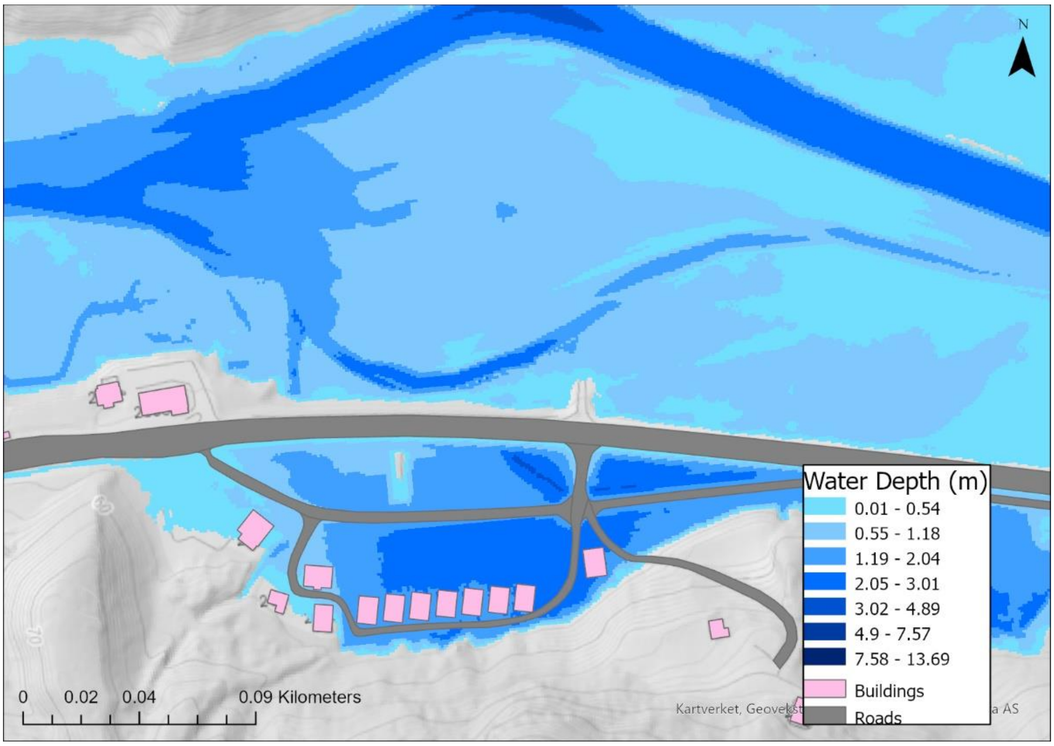

Figure 66: Hjelledalen hyttesenter with a modeled 2-hour GLOF from Lagune 2.

The close up of the Hjelledalen hyttesenter show how the water builds up depths of up to 3 meters in this site. This is one of the sites that has the worst locations in terms of water depth in relation to buildings. It is likely if a scenario like a 2-hour GLOF becomes true that the Hjelledalen hyttesenter will become heavily damaged by the flood. The buildings on the western side of the campsite will have a better chance of survival than the cabins on the eastern side. Figure 67 show how the cabins look from the main road. The cabins are located on a downslope from the road.

Figure 67: A view of Hjelledalen hyttesenter from the road.

Located north of Hjelledalen Hyttesenter is a stretch of river with agricultural land on both sides of the river. This stretch of the river is according to the model an area of the river that will have water flowing over the riverbanks, both in an 8-hour GLOF and a 2-hour GLOF. Figures 68 and 69 show the same stretch of the river. Figure 69 show the river with an eight-hour flood, causing damage to two sheds on the north side, with big floods on the agricultural soil. The flood can bring with it large a number of sediments, and cover the soil in sediments from the river. It can also lead to erosion of the topsoil, causing permanent damage to the farmland.

Figure 68: An area of farmland, that has the potential of being affected by floods. Captured from Norgeibilder.no

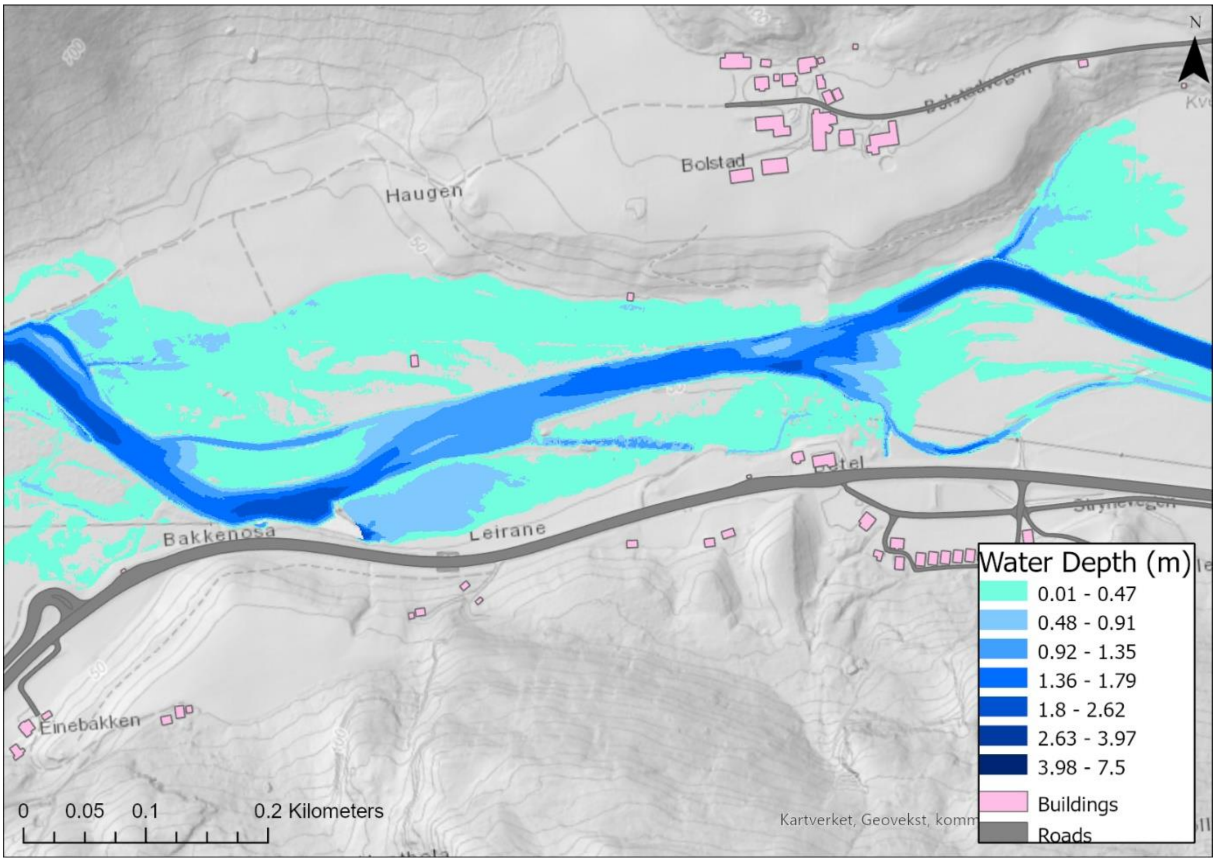

Figure 69: The same area shown in figure 68, modeled with an 8-hour GLOF.

5.2.4. Key area 4

Hjelle is one the places along the river system where the river can cause the biggest damage to both property and people. The school, hotel, stores, and it is also the most densely populated area. This makes it important to analyze the results carefully in this area. The biggest flood is caused by the 2-hour GLOF from Sunndøla, which according to the model will cause flooding at the bridge, the area around the school, the football pitch, and at the small area south of the river (figure 70).

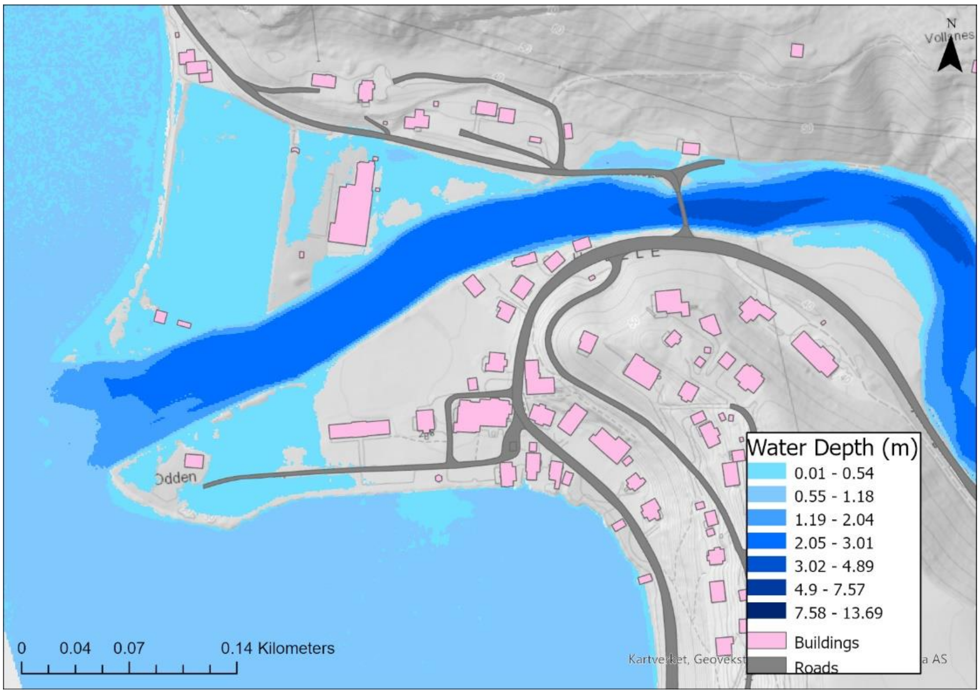

Figure 70: Hjelle town with 2-hour GLOF.

The bridge in the eastern part of Hjelle is a key area in this town (figures 71 and 72). The bridge is the only way to get from the north side of the town to the south side. The model with a 2-hour GLOF from Lagune 2, show that the bridge will get flooded on the north side of the bridge. The bridge is lower on the north side than it is on the south side (Figure 72). A flood like the one shown in the model will make the bridge unusable while the flood is ongoing, and the bridge will need to be checked for any structural damage. During the flood in 2018 the school was evacuated because they feared that the bridge could have collapsed due to the amount of water that was in the river at that time. A two-hour GLOF will bring more water, and cause a bigger flood than the flood in 2018. We know this because the north side of the bridge was not submerged in water then. If they feared the flood back then would cause the bridge to collapse, then they will probably think the same if this happens, because this flood can be bigger. The bridge is also important for the evacuation of the school children and the children in the kindergarten because the bridge is the only way from the north to the south of town. If the bridge is flooded than it will be impossible to evacuate the school and kindergarten across the bridge.

Figure 71: The bridge in Hjelle, is a key structure in Hjelle town. Captured from Norgeibilder.no

Figure 72: Hjelle bridge seen from the norths side of the river.

Figure 73: The view from the bridge, looking at the school.

This view from the bridge in Hjelle (Figure 73) show the school in the distance on the north side of the river. The school is placed on a site that is located lower in the terrain than the bridge, but the river is wider at that specific location, which is positive for the flood situation at the school. The model of a 2-hour GLOF from Lagune 2 will partly hit the school, by water flowing from the area between the school and the bridge, from there the water will flow down toward the school. The school building and the surrounding playground will be partly submerged in water.

Figure 74: The football field, which has previously been flooded. Captured from Norgeibilder.no

The football pitch, which is where the football team play football, and also is an important area for the school. This area will according to the 2-hour GLOFs, be flooded. This has also occurred before. In 2018, the same year as the school was evacuated because there was a fear that the bridge would collapse by the amount of water, the football pitch was also submerged in water. The football pitch was according to the model (figure 70), submerged in shallow water, from 0,01 to 0,54. Still it will cause the flood to be big enough to potentially drown the grass on the football field making the football pitch unusable for a while. It can also leave rests of sediment on the pitch. The most dangerous part of the flooding of the football pitch however is the that is located in the direct vicinity to the school and kindergarten.

Figure 75: The football pitch, as seen from the road north of the pitch.

5.3. Likelihood of hazardous GLOFs

This thesis presents the modeled glacial lake outburst floods with different scenarios of 48, 24, 8 and lastly 2-hour GLOFs. This has been for both of the glacial lakes. We know that glacial lake outburst floods occur in the lagunes quite frequently. It happened in the summer of 2021 with lagune 2, and it happened in 2010, 2014 and 2018 according to NVE (NVE, 2017). From the interview with the former employee Stryn municipality, I learned that a GLOF occurred in 2016. For now, the GLOFs has not been of a magnitude that has caused floods or damage. The drainage of the glacial lakes has been too slow to cause floods. The GLOF from lagune 2 in 2021 drained in approximately 15 days, we know this from PlanetScope satellite monitoring. As shown in the models of this thesis, a GLOF with a discharge of 15 days will have no potential for flood in the river. Since the model show that a 48-hour flood can occur without a flood event, a GLOF lasting 15 days will have no potential to cause a flood. The interview with the former Stryn municipality employee revealed that the GLOF from 2016 was described as being very brown water saturated with sediments. This likely also occurred in the summer of 2021, it was reported by one person we interviewed, as being very brown, which is unusual for these rivers. This can become a recurring issue for the campsite that complained about the brown water during the GLOF in 2016, which uses water from the river in their campsite. Every time a GLOF occurs the water they pull from the river can become filthy, and can cause damage to water pumps and filters.

With the global warming and the rapidly shrinking glacier on Tystigbreen, it is possible that the GLOFs may become different, and more dangerous than they have been in the past. With the changing of the glacier appearance, with frontal retreat and thinning of the ice, the drainage of the glacial lakes may become more hazardous in the future. It is not given that since the GLOF has taken 15 days to drain in the past, that all GLOFs from lagune 2 will happen in a duration of 15 days in the future. Drainage of glacial lakes and GLOFs are still subjects we do not know enough about.

The models can never be replacement for the real events, but is useful in identifying the key areas. If a GLOF with a duration of two hours occur in either Lagune 1 or Lagune 2, it is probable that the flood will not be identical to the floods created in the models. The models in HEC-RAS should be used as a tool to identify key areas to where the flood might become a risk, and key areas that might be in danger if a flood at this size occurs. Through these models it can be suggested that the valley downstream is not prepared to receive a large GLOF. There are several key areas downstream that will according to the model be heavily flooded. In the thesis four key areas has been presented as places where the floods can become hazardous, and which have important infrastructure and buildings. The four key areas (chapter 5.2) are the places most prone to flood. One of the initial aims that was in the introduction of this thesis, was to investigate how hazardous a GLOF might be on the downstream areas, the models suggest that the valleys downstream is not well prepared for a 2-hour GLOF. Measures should be implemented, so that the valleys can be better prepared to receive a large GLOF in the future. Information to the population is probably the easiest, and cheapest measure. Everyone living underneath glaciers with potentially hazardous activity should know about it. Our conversations and interviews with the people living underneath the glacier, revealed that very few know what a glacial lake is, and what a GLOF is, no one knew that GLOFs could be hazardous for them. Information about the risks and hazards should be provided. Other measures can be implemented downstream, to make it less likely for the water to flow past the natural and artificial barriers of the rivers. Moving or raising buildings and other infrastructure could be a possibility to mitigate dangers of floods. An example can be the school building, to have it in a location less likely to be affected by the flood. Bridges, and roads can be lifted to be less affected by GLOFs. Measures are possible to mitigate floods, but it is probably not possible to terminate all risk from GLOFs. If a really big GLOF that drains faster than two hours, or if the two glacial lakes start draining at the same time, it will be hazardous. The population in the downstream areas will never be a 100 % safe, but it is important to always make the area safer. A monitoring system, and an early warning system for the glacial lakes would be beneficial. To have warnings sent to the people living downstream when the glacial lakes start to drain is something that should be considered by the governmental institutions.

5.4. Limitations and uncertainties

Limitations are the shortcomings of the study; it is necessary to recognize and document the limitations and uncertainties of the thesis (Price & Murnan, 2004). The uncertainties are a measurement of how much something is known. The uncertainties are important in science since it lets the researcher communicate the findings better, by revealing how many uncertainties, how big the uncertainties are, and how they are associated with the results (Price & Murnan, 2004). There are multiple sources of limitations and uncertainties in this thesis. The experience of the person doing the modeling, there are uncertainties in the input of water from the boundary conditions and the data for the water flow, the interpolation and resolution of the river channel and digital elevation has some limitations, the land surface layers have a source of uncertainty there are also limitations in the parameter settings and options for the model.

5.4.1. The past experience of the person doing the modeling

No prior experience with use of HEC-RAS or any other software developed to model flow of water and floods, are reasons why it should be noted that the modeler should be considered an uncertainty. Since I started working with the modeling for this thesis in 2021, I had never tried using HEC-RAS, or flood modeling with other software. Everything that I have learned have come from scholarly articles, the HEC-RAS user manuals, master theses from previous students, lectures, videos on youtube and forums during 2021 and 2022. It would have been an advantage if I had a background from hydrology or more knowledge about hydraulic processes. By having a professional modeler do the modeling, the uncertainties and limitations of the models would be reduced.

5.4.2. Boundary condition and flow data

In the model water is entered into the model at the boundary conditions. These boundary conditions are located close to where the GLOFs will enter the rivers in reality. All the other water in the river is also entered at the same location. Water falling as precipitation will fall on the entire drainage basin, and not enter at the top where I have it plugged in the model. The precipitation will enter the river as smaller streams, but not in this model. The reason is that to have everything plugged in at just two locations requires less computational force, and it will reduce time. When having rainfall as part of the model, it would require a calculational mesh network to have much smaller cells over the entire cell mesh. During the calculations it has been 215 348 cells in the 2D computation mesh. By adding a rainfall layer, it would require much more cells. The reason is that the models produced in this thesis have a refinement region. Refinement region allows for areas in the 2D geometry where the cells can be smaller. In these models there is a refinement region surrounding the river system, and the flood prone areas. This makes it possible to drastically reduce the time and power required to model water flow. In the refinement region, there are 5x5m size computational cells, outside of the refinement regions the computational cells are the size 60x60m. This is because the area outside is not of interest, because that area cannot be affected by GLOFs. By having precipitation layer the entire 2D geometry would have needed to be 5x5 meters. That would require much more time, and much more computer power. And it is therefore plugged into the model from where the glacial lake outburst floods are plugged into the model. This gives an error, and becomes a limitation in the model.

The data for the mean annual flood is collected from NVEs web service called NVE NEVINA. Their flow data they provide is automatically calculated runoff data, based on precipitation, snow and ice melt, minus the evaporated water. This is not actively measured data from the rivers. This means that since it is automatically runoff data, the data is not 100 % correct. The actual mean annual runoff for the rivers will likely differ some from the NVE NEVINA data. Though it is assumed that the flow data is not too much off the actual river runoff.

5.4.3. Land surface layer and Manning's coefficient

Manning's N roughness coefficient is a large uncertainty, and instability in the models created in HEC-RAS (Pappenberger et al., 2005). Too low values will make the river shallower than it actually is, while too high value will cause the river to have a higher water level, and a potentially bigger flood (Brunner, 2021c). The choice of which Manning's N it becomes an uncertainty in this model because it is no true answer for what Manning's value that is the correct value. The values for the roughness layer has been provided by (Chow, 1959), and the HEC-RAS reference manual (Brunner, 2021c), where they provide different sets of Manning's N values for different soil types. The examples they provide should be given to the soil types as starting points and thereafter should be calibrated to find the proper Manning's N value. The number they provide should be considered an estimated range of values rather than that exact value. For instance, was 0,05, used for the river channel in the models, but that could mean that the range is somewhere between 0,04 and 0,06 as the realistic roughness value. Calibration of the roughness layer is a time-consuming task. It requires the user to run several hours long simulations to compare the different result. There has been a focus in the thesis to test different Manning's N values and compare them for the river channel. This was essential and the final result would have felt incomplete if that would have gone untested, but to evaluate all the different soil types would be a task that would have been too time consuming. Some of the Manning's N values are therefore a limitation in this thesis, because they are not calibrated at all places. This can affect the flow of water, and how big or small the flood is in the models of this thesis. It has also been difficult to calibrate the models, because the lack of pictures to be used in calibration and validation of the models.

5.4.4. Resolution and interpolation of the river channel and digital elevation model

For many rivers in Norway bathymetric datasets has been created, this is not the case for the rivers in this thesis. Without being able to obtain the actual bathymetric data I had to manually create it. This is a cause for uncertainties because the bathymetric data has not been measured with proper tools, like LiDAR or GPS measurements. The bathymetric alterations have been made by looking at aerial photographs, satellite images, google street maps and the observations made from our field work in Stryn. Through these observations I believe that the bathymetry has been recreated and altered to the best of my abilities, however there are uncertainties and limitations, and the river channel will likely have errors. If the bathymetry is unrealistic then the results of the thesis will become unrealistic. It was important not to make the river channel too deep. It was also important to be careful to not dig out the riverbanks, and by this way making the river channel wider. The river channel can be considered to be a conservative estimate of the bathymetry.

The bathymetry is created through creating a 1D geometry of the river channel. Then adding cross-sections at several locations in the river. The alteration of the river is happening at these cross-sections. Then the rest of the river that is not covered by river stations, will be interpolated results from the alterations at the river station. This interpolation process creates a source of uncertainty. This is because if the river stations are too far apart, the interpolations will not be able to capture obstacles and other elements that otherwise would disrupt the flow in the river. For instance, if there would be a shoal in between two river stations, and have no river station at the shoal. The shoal might be smoothed or eliminated from the bathymetry. Still if there has been placed a reasonably amount of river station it is no guarantee that the interpolation will work perfectly, and this is a limitation. In the first attempt at creating an altered bathymetry I realized that the cross sections were located too far apart from each other. They were not able to interpolate the area between the cross sections correctly, and an important section of the area was not being identified. It was solved by creating more cross sections. There will always be some imperfections in the interpolation process, which is a limitation.

5.4.5. Parameter settings and options in HEC-RAS

There are various options and settings that can be used in the modeling of floods. Important settings are the computational settings which can have several different adjustments and options. For the study area the best option of choosing a computational interval based on courant was too time consuming. My experience was that too run a flow simulation for the entire area for 12 hours would take more than 48 hours, if I were to choose the interval based on courant. In the final results the time intervals have been adjusted to 3 seconds. There are also several other settings and parameters, such as the initiation condition, which is the warmup of the model, how the warmup should last, and the initial conditions ramp up duration. Computational time steps are a possible limitation in the thesis, however through the sensitivity test, I do believe that that the uncertainty will be small. When using 3 seconds as I have done in the models, it is a low time step. According to the user's manual the time step when modeling a dam break should be lower than five seconds (Brunner, 2021b).

6. Conclusion

In this work, I have investigated how modeling of glacial lake outburst floods (GLOFs) can be performed with a software such as HEC-RAS to identify most vulnerable locations in valleys located downstream of a GLOF-generating glacier. The objectives of this thesis have been shaped by interviews and discussions with local inhabitants of Hjelle and the surrounding area in Hjelledalen. Through such conversations, I got an impression that glacial lake outburst floods, which have frequently occurred in the area in the last decades, are considered as not hazardous for the inhabitants downstream and that the river would be able to handle the amount of water released by glacial lakes. These conversations also revealed that most of the inhabitants did not know of the existence of glacial lakes at Tystigbreen, and that they are unaware of the possibility that these GLOFs may inflict damage and cause floods in the downstream areas. These facts have shaped my decision to investigate the pre-conditions for possible hazardous impacts of future GLOFs using HEC-RAS, a software developed by the armed forces in the United States of America to specifically model the flow of water in rivers and creeks.

The results of the model simulations presented in this thesis show that glacial lakes have a potential to create large floods leading to an extensive damage of buildings, agricultural land, roads and important infrastructure. Neither of the rivers Sunndøla, Videdøla or Hjelledøla will be able to contain water released by a GLOF in a short period of time of 2 to 8 hours, with these resulting in very extensive floods in many sectors of these rivers. Although these rivers are characterized by a steep topography, with strong vertical gradients in the altitude between their sources and mouths, there are gently sloping areas located in Hjelledalen that are especially prone to floods. It is in these areas that bridges will become unusable, roads will be flooded, and many farms and buildings will suffer high reparation costs as a result of large parts of the valley being submerged under water.

For the time being no GLOF events has caused damage to the river or the surrounding area. It is not certain that a GLOF in this river system will ever cause damage to people, buildings or infrastructure. The usual scenario that occurs in this area is that the drainage of the glacial lakes happens slow enough so that the water level is not visibly elevated, with dark water, saturated with sediments, when the GLOF occurs. It is still important to know what kind of hazards that is connected with glaciers and glacial lakes. This thesis has answered some question of the potential for hazards connected to glacial lakes. The thesis suggests that the potential for floods from GLOFs are significant, if the duration of the discharge occurs in a short period of time. Both two and eight hours will flood large parts of the areas next to the river in Hjelledalen. The GLOF has according to the models created in HEC-RAS potential to flood large areas, and damage buildings and infrastructure.

The validation process of the thesis has shown that the flatter areas of the river system, are prone to flooding, and that it has happened before. The flood in 1995, share several similarities as the modeled GLOF of Lagune 2 with a duration of 2 hours. With similar areas being flooded on both the western and eastern side of the river. Both the fields on both side of the river, a farm, the petrol station, and Folven adventure camp. All of these areas were flooded in 1995, and in the model that visualizes a two-hour flood from Lagune 2. This suggests that the scenario simulated in the model, is not an impossible scenario or an unlikely scenario, such a flood has already occurred in the past. The circumstances surrounding the origin of the flood can also be claimed to be similar, because both of the floods are characterized as a kind of a dam or levee break. Though they are different because one is caused by landslides which dammed up the river, and the other is a GLOF. The interviews with people in Hjelle have shown that the football pitch and the bridge in Hjelle has been affected by floods before, this is similar to the models. This happened during a period of highly elevated level of water in the river, in 2018. This event was however not completely similar because the flooding of the football pitch was happening because the lake was flooding, and not as a result of the river flooding. This event is not as easy to compare to the models, as the flood in 1995 is. The models show that the glacial lakes are capable of creating heavy damage downstream, which shows that measures for reducing the risk of damage by GLOFs should be looked into, and information about the danger of hazards from glacier and glacier lakes should be better communicated to the public.

There are presented large floods in the models, but there are still large uncertainties in the model. There are still elements of the modeling that is based on unknown or uncomplete knowledge. When modeling floods and the flow of water, the experience of the programmer is something that should not be overlooked. It would always be best if an experienced modeler conducted the research. This is not the case in this thesis, since this is my very first-time using HEC-RAS, and the first-time modelling water flow. The roughness of the terrain was revealed during the sensitivity tests to have a considerable influence in the flood level. The Manning's roughness values are chosen to the best of my ability, but there are uncertainties tied to the values. Bathymetric data is another limitation of this research. If there had been real bathymetric data available to download, that would be beneficial. That would remove one cause for uncertainty, which is the manually altered river bathymetry. The estimation of the amount of water in the glacial lakes is also a rough estimation, which is a limitation. The limitations and uncertainties are why the models should not be viewed as the exact models for how the GLOFs will become in the future. It presents some key areas, with locations of vulnerable areas, which should be investigated closer, to see if it is necessary with measures to counteract the damage a GLOF might bring in the future.

6.1. Suggestion for further work

This thesis is developed using HEC-RAS. There are several other methods and tools that is possible to use in order to model floods. A good way to further validate the danger from the GLOFs would be to test it with another modeling software. This thesis has some uncertainties, and an interesting suggestion for further work would be to create a better model, with accurate measurement of the bathymetry of the riverbed.

It is planned to improve some of the areas downstream, where the main road (Riksvei 15) goes across Sunndøla, to better secure it for floods. This work is supposed to begin in 2022, and it would be beneficial to create a new flood analysis of the area when this work is completed.

This thesis can be used to investigate possible measures and solutions to mitigate the flood hazards in the area.

Sources:

Alfieri, L., Burek, P., Feyen, L., & Forzieri, G. (2015). Global warming increases the frequency of river floods in Europe. *Hydrol. Earth Syst. Sci.*, *19*(5), 2247-2260. https://doi.org/10.5194/hess-19-2247-2015

Askheim, S. (2022). *Jostedalsbreen*. Store Norske Leksikon. Retrieved 29. 04. from https://snl.no/Jostedalsbreen

Astad, A. H. (2020). *Flomsonekartlegging av Bismo, Skjåk: En hydraulisk analyse gjort i HEC-RAS* [Master's, NTNU]. Trondheim.

Bajracharya, S. R., & Mool, P. (2009). Glaciers, glacial lakes and glacial lake outburst floods in the Mount Everest region, Nepal. *Annals of Glaciology*, *50*(53), 81-86. https://doi.org/10.3189/172756410790595895

Bendle, J. (2020). *Glacial Lake Outburst Floods*. https://www.antarcticglaciers.org/glacier-processes/glacial-lakes/glacial-lake-outburst-floods/

Bennett, M. R., Huddart, D., Glasser, N. F., & Hambrey, M. J. (2000). Resedimentation of debris on an ice-cored lateral moraine in the high-Arctic (Kongsvegen, Svalbard). *Geomorphology*, *35*(1), 21-40. https://doi.org/https://doi.org/10.1016/S0169-555X(00)00017-9

Bosson, J.-B., Huss, M., & Osipova, E. (2019). Disappearing World Heritage Glaciers as a Keystone of Nature Conservation in a Changing Climate. *Earth's Future*, *7*(4), 469-479. https://doi.org/https://doi.org/10.1029/2018EF001139

Brunner, G. (2021a). HEC-RAS River Analysis System 2D Modeling User's Manual Version 6.0 Beta. In (Version 6.0 ed.): US Army Corps of Engineers Institute for Water Resources Hydrologic Engineering Center (HEC).

Brunner, G. (2021b). HEC-RAS River analysis system user's manual. In (Version 6.0 ed.). 609 Second Street, Davis, CA 95614-4687: US Army Corps of Engineers, Institute for Water Resources.

Brunner, G. (2021c). HEC-RAS, River Analysis System Hydraulic Reference Manual. In U. A. C. O. ENGINEERS & H. E. C. (HEC) (Eds.). 609 Second Street, Davis, CA 95616-4687: US ARMY CORPS OF ENGINEERS, HYDROLOGIC ENGINEERING CENTER (HEC).

Brunner, G., Savant, G., & Heath, R., E. (2020). *Modeler Application Guidance for Steady vs Unsteady, and 1D vs 2D vs 3D Hydraulic Modeling.* In US army corps of Engineers, Institute for Water resources, Hydrological engineering center (HEC). https://www.hec.usace.army.mil/publications/TrainingDocuments/TD-41.pdf

Brunner, G., W. (2016). HEC-RAS, River Analysis System 2D Modeling User's Manual Version 5.0. . In: US army corps of Engineers, Institute for Water resources, Hydrological engineering center (HEC).

Carrivick, J. L., & Tweed, F. S. (2013). Proglacial lakes: character, behaviour and geological importance. *Quaternary Science Reviews*, *78*, 34-52. https://doi.org/https://doi.org/10.1016/j.quascirev.2013.07.028

Carrivick, J. L., & Tweed, F. S. (2016). A global assessment of the societal impacts of glacier outburst floods. *Global and Planetary Change*, *144*, 1-16. https://doi.org/https://doi.org/10.1016/j.gloplacha.2016.07.001

Carter, J., Schmid, K., Waters, K., Betzhold, L., Hadley, B., Mataosky, R., & Halleran, J. (2012). *Lidar 101: An Introduction to Lidar Technology, Data, and Applications.* Retrieved from https://coast.noaa.gov/data/digitalcoast/pdf/lidar-101.pdf

Cenderelli, D. A., & Wohl, E. E. (2003). Flow hydraulics and geomorphic effects of glacial-lake outburst floods in the Mount Everest region, Nepal. *Earth Surface Processes and Landforms*, *28*(4), 385-407. https://doi.org/https://doi.org/10.1002/esp.448

Cheng, Y., Vrieling, A., Fava, F., Meroni, M., Marshall, M., & Gachoki, S. (2020). Phenology of short vegetation cycles in a Kenyan rangeland from PlanetScope and Sentinel-2. *Remote Sensing of Environment*, *248*, 112004. https://doi.org/https://doi.org/10.1016/j.rse.2020.112004

Chow, V. T. (1959). *Open channel hydraulics*. McGraw-Hill Book Company, inc.

Collier, N., Radwan, H., Dalcin, L., & Calo, V. M. (2011). Diffusive Wave Approximation to the Shallow Water Equations: Computational Approach. *Procedia Computer Science*, *4*, 1828-1833. https://doi.org/https://doi.org/10.1016/j.procs.2011.04.198

Dowman, I. (2004). Integration of LiDAR and IFSAR for mapping. *International Archives of Photogrammetry and Remote Sensing*, *35*.

Engelhardt, M., Schuler, T. V., & Andreassen, L. M. (2014). Contribution of snow and glacier melt to discharge for highly glacierised catchments in Norway. *Hydrol. Earth Syst. Sci.*, *18*(2), 511-523. https://doi.org/10.5194/hess-18-511-2014

Fergus, T., Hoseth, K. N., & Sæterbø, E. (2010). *Vassdragshåndboka: Håndbok i vassdragsteknikk*. Tapir akademisk forlag.

Gaume, E., Bain, V., Bernardara, P., Newinger, O., Barbuc, M., Bateman, A., Blaškovičová, L., Blöschl, G., Borga, M., Dumitrescu, A., Daliakopoulos, I., Garcia, J., Irimescu, A., Kohnova, S., Koutroulis, A., Marchi, L., Matreata, S., Medina, V., Preciso, E., . . . Viglione, A. (2009). A compilation of data on European flash floods. *Journal of Hydrology*, *367*(1), 70-78. https://doi.org/https://doi.org/10.1016/j.jhydrol.2008.12.028

Goodell, C. (2015). *2D mesh "leaking"*. The Ras Solution. Retrieved 14.03 from https://www.kleinschmidtgroup.com/ras-post/2d-mesh-leaking/

GOTHECA. (2022). *GOTHECA*. Retrieved 26.04 from https://www.gotheca.com/

Hanssen-Bauer, I., Førland, E., Haddeland, I., Hisdal, H., Mayer, S., Nesje, A., Nilsen, J. E. Ø., Sandven, S., Sandø, A. B., Sorteberg, A., & Ådlandsvik, B. (2015). Klima i Norge 2100, Kunnskapsgrunnlag for klimatilpasning oppdatert 2015. *NCCS report*, *no. 2/2015*.

Harrison, S., Kargel, J. S., Huggel, C., Reynolds, J., Shugar, D. H., Betts, R. A., Emmer, A., Glasser, N., Haritashya, U. K., Klimeš, J., Reinhardt, L., Schaub, Y., Wiltshire, A., Regmi, D., & Vilímek, V. (2018). Climate change and the global pattern of moraine-dammed glacial lake outburst floods. *The Cryosphere*, *12*(4), 1195-1209. https://doi.org/10.5194/tc-12-1195-2018

Hengl, T., & Evans, I. S. (2009). Chapter 2 Mathematical and Digital Models of the Land Surface. In (Vol. 33, pp. 31-63): Elsevier Science & Technology.

Hooke, J. M. (1979). An analysis of the processes of river bank erosion. *Journal of Hydrology*, *42*(1), 39-62. https://doi.org/https://doi.org/10.1016/0022-1694(79)90005-2

Jackson, M. (2018, April 01, 2018). *Glacier Floods and Hydropower - curse or blessing?* https://ui.adsabs.harvard.edu/abs/2018EGUGA..2018871J

Jackson, M., & Ragulina, G. (2014). *Inventory of glacier-related hazardous events in Norway*.

Kellerhals, R., Church, M., & Bray, D. I. (1976). Classification and Analysis of River Processes. *Journal of the Hydraulics Division*, *102*(7), 813-829. https://doi.org/doi:10.1061/JYCEAJ.0004583

Kenward, T., Lettenmaier, D. P., Wood, E. F., & Fielding, E. (2000). Effects of Digital Elevation Model Accuracy on Hydrologic Predictions. *Remote Sensing of Environment*, *74*(3), 432-444. https://doi.org/https://doi.org/10.1016/S0034-4257(00)00136-X

Kim, B., Sanders, B. F., Schubert, J. E., & Famiglietti, J. S. (2014). Mesh type tradeoffs in 2D hydrodynamic modeling of flooding with a Godunov-based flow solver. *Advances in Water Resources*, *68*, 42-61. https://doi.org/https://doi.org/10.1016/j.advwatres.2014.02.013

Klitgaard-Kristensen, D., Sejrup, H. P., Haflidason, H., Johnsen, S., & Spurk, M. (1998). A regional 8200 cal. yr BP cooling event in northwest Europe, induced by final stages of the Laurentide ice-sheet deglaciation? *Journal of Quaternary Science*, *13*(2), 165-169. https://doi.org/https://doi.org/10.1002/(SICI)1099-1417(199803/04)13:2<165::AID-JQS365>3.0.CO;2-#

Laser kartlegging (LiDAR). (2021). https://radioh.no/kartlegger-distriktet-med-laser/

Lim, K., Treitz, P., Wulder, M., St-Onge, B., & Flood, M. (2003). LiDAR remote sensing of forest structure. *Progress in Physical Geography*, *27*(1), 88-106. https://doi.org/http://dx.doi.org/10.1191/0309133303pp360ra

Luino, F. (2016). Floods. In P. T. Bobrowsky & B. Marker (Eds.), *Encyclopedia of Engineering Geology* (pp. 1-6). Springer International Publishing. https://doi.org/10.1007/978-3-319-12127-7_126-1

Marchi, L., Borga, M., Preciso, E., & Gaume, E. (2010). Characterisation of selected extreme flash floods in Europe and implications for flood risk management. *Journal of Hydrology*, *394*(1), 118-133. https://doi.org/https://doi.org/10.1016/j.jhydrol.2010.07.017

Mukherjee, S., Joshi, P. K., Mukherjee, S., Ghosh, A., Garg, R. D., & Mukhopadhyay, A. (2013). Evaluation of vertical accuracy of open source Digital Elevation Model (DEM). *International Journal of Applied Earth Observation and Geoinformation*, *21*, 205-217. https://doi.org/https://doi.org/10.1016/j.jag.2012.09.004

NEVINA, N. (2022). NVE NEVINA. In NVE (Ed.). nevina.nve.no: nevina.nve.no.

NIWA, N. I. o. W. a. A. R. (2022). *What is a return period?* NIWA, National Institute of Water and Atmospheric Research. Retrieved 21.02 from https://niwa.co.nz/natural-hazards/faq/what-is-a-return-period

NOAA, N. S. S. L. (2022). *Severe Weather 101: Flood basics*. NOAA, National Severe Storms Labaratory. https://www.nssl.noaa.gov/education/svrwx101/floods/

NVE. (2015a, 2021). *Erosjonsprosesser*. NVE. Retrieved 01.03 from https://www.nve.no/vann-og-vassdrag/vannets-kretslop/erosjon-og-sedimenttransport/erosjonsprosesser/

NVE. (2015b). *HBV-Modellen*. NVE. https://www.nve.no/vann-og-vassdrag/vannets-kretslop/analysemetoder-og-modeller/hbv-modellen/

NVE. (2015c). *Sedimenttransport*. NVE. https://www.nve.no/vann-og-vassdrag/vannets-kretslop/erosjon-og-sedimenttransport/sedimenttransport/

NVE. (2017, 14.01.2022). *Jøkulhlaup (GLOF)*. NVE. https://www.nve.no/hydrology/glaciers/jokulhlaup-glof/

NVE. (2021). *Hva er en flom?* NVE, Norges Vassdrags og Energidirektorat. Retrieved 18.02 from https://www.nve.no/naturfare/laer-om-naturfare/hva-er-flom/

Ongdas, N., Akiyanova, F., Karakulov, Y., Muratbayeva, A., & Zinabdin, N. (2020). Application of HEC-RAS (2D) for Flood Hazard Maps Generation for Yesil (Ishim) River in Kazakhstan. *Water*, *12*(10), 2672. https://www.mdpi.com/2073-4441/12/10/2672

Pappenberger, F., Beven, K., Horritt, M., & Blazkova, S. (2005). Uncertainty in the calibration of effective roughness parameters in HEC-RAS using inundation and downstream level observations. *Journal of Hydrology*, *302*(1), 46-69. https://doi.org/https://doi.org/10.1016/j.jhydrol.2004.06.036

Planetscope. (2022). *imaging the earth daily*. Planet. Retrieved 16.03 from https://www.planet.com/products/planet-imagery/

Price, J. H., & Murnan, J. (2004). Research Limitations and the Necessity of Reporting Them. *American Journal of Health Education*, *35*(2), 66-67. https://www.proquest.com/scholarly-journals/research-limitations-necessity-reporting-them/docview/212630719/se-2?accountid=12870

Price, K., H. (2022). *The Ras Solution* Youtube. https://www.youtube.com/channel/UClJ0otLhqayjbYDwSewctdg

Quirogaa, V. M., Kurea, S., Udoa, K., & Manoa, A. (2016). Application of 2D numerical simulation for the analysis of the February 2014 Bolivian Amazonia flood: Application of the new HEC-RAS version 5. *Ribagua*, *3*(1), 25-33. https://doi.org/10.1016/j.riba.2015.12.001

Ruiz, A., Kornus, W., Talaya, J., & Colomer, J.-L. (2004). Terrain modeling in an extremely steep mountain: A combination of airborne and terrestrial LiDAR. *The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences*, *35*.

Rød, J. K. (2009). *Innføring i GIS og statistikk*. Fagbokforlaget.

Rød, J. K. (2015). *GIS: Verktøy for å forstå verden*. Fagbokforlaget.

Shrestha, A., Bhattacharjee, L., Baral, S., Thakur, B., Joshi, N., Kalra, A., & Gupta, R. (2020). Understanding Suitability of MIKE 21 and HEC-RAS for 2D Floodplain Modeling. In *World Environmental and Water Resources Congress 2020* (pp. 237-253). https://doi.org/doi:10.1061/9780784482971.024

Stenius, S., Glad, P. A., Wang, T. K., & Væringstad, T. (2015). Veileder for flomberegninger i små uregulerte felt. *Veileder nr 7-2015*.

Stenius, S., Glad, P. A., & Wilson, D. (2014). Karakterisering av flomregimer In *Naturfareprosjektet Dp. 5 Flom og vann på avveie*. Oslo: NVE.

Sulebakk, J., R. (2007). *Landformer og prosesser*. Fagbokforlaget.

Syme, W. J. (2008). *Flooding in urban areas - 2D modelling approaches for buildings and fences* Engineers Australia, 9th National Conference on Hydraulics in Water Engineering, Darwin Convention Centre. https://tuflow.com/media/4997/2008-flooding-in-urban-areas-2d-modelling-approaches-for-buildings-and-fences-syme-hwe-aus.pdf

Tollan, A., & Bakken, T. H. (2019). Hydrologi. *Store Norske Leksikon*. https://snl.no/hydrologi

Truffer, M., & Motyka, R. J. (2016). Where glaciers meet water: Subaqueous melt and its relevance to glaciers in various settings. *Reviews of Geophysics*, *54*(1), 220-239. https://doi.org/https://doi.org/10.1002/2015RG000494

Tweed, F. (2011). Ice-Dammed Lakes. In V. P. Singh, P. Singh, & U. K. Haritashya (Eds.), *Encyclopedia of Snow, Ice and Glaciers* (pp. 619-621). Springer Netherlands. https://doi.org/10.1007/978-90-481-2642-2_637

Tweed, F. S., & Carrivick, J. L. (2015). Deglaciation and proglacial lakes. *Geology Today*, *31*(3), 96-102. https://doi.org/https://doi.org/10.1111/gto.12094

Vedmani, R. K. P., & Vinay, K. P. (2020). Calibration and Validation of HEC-RAS Model for Minor Command in Coastal Region. *Int.J.Curr.Microbiol.App.Sci*, *9(2)*. https://doi.org/https://doi.org/10.20546/ijcmas.2020.902.082

Westoby, M. J., Glasser, N. F., Brasington, J., Hambrey, M. J., Quincey, D. J., & Reynolds, J. M. (2014). Modelling outburst floods from moraine-dammed glacial lakes. *Earth-Science Reviews*, *134*, 137-159. https://doi.org/https://doi.org/10.1016/j.earscirev.2014.03.009

Wilhelm, B., Arnaud, F., Enters, D., Allignol, F., Legaz, A., Magand, O., Revillon, S., Giguet-Covex, C., & Malet, E. (2012). Does global warming favour the occurrence of extreme floods in European Alps? First evidences from a NW Alps proglacial lake sediment record. *Climatic Change*, *113*(3), 563-581. https://doi.org/10.1007/s10584-011-0376-2

Winsvold, S. H., Andreassen, L. M., & Kienholz, C. (2014). Glacier area and length changes in Norway from repeat inventories. *The Cryosphere*, *8*(5), 1885-1903. https://doi.org/10.5194/tc-8-1885-2014

Yao, X., Liu, S., Han, L., Sun, M., & Zhao, L. (2018). Definition and classification system of glacial lake for inventory and hazards study. *Journal of Geographical Sciences*, *28*, 193-205. https://doi.org/10.1007/s11442-018-1467-z

Østrem, G. (1959). Ice Melting under a Thin Layer of Moraine, and the Existence of Ice Cores in Moraine Ridges. *Geografiska Annaler*, *41*(4), 228-230. https://doi.org/10.1080/20014422.1959.11907953

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