Master's thesis

NTNU
Norwegian University of Science and Technology
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Department of Geography

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Alternative pathways of water

A GIS analysis

Master's thesis in Natural Resources Management
Supervisor: Jan Ketil Rød
Co-supervisor: Hans Ola Fredin

May 2021

NTNU
Kunnskap for en bedre verden

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Abstract

Extreme weather events and natural disasters can lead to destructive consequences when they interact with the natural and human environments. Increased frequency and more severe floods are posing a threat to humans, communities and infrastructure. In the coming decades, it is expected that climate change will increase the probability of occurrence of more frequent natural hazards, leading to continuously more vulnerable communities (Allen et al, 2012). The compensations due to natural hazards for the period 2010-2019, have costed Norway 29,4 Billion NOK from which 3.649 Billion NOK are because of flood events (Finans Norge, 2020).

Flood events however are not just the outcome of climate change, but in accordance with high density human environments that create impenetrable surfaces, result in surface water. Flash floods are caused from surface water following an extreme precipitation, usually in small watersheds and they are hard to predict.

A large flash flood in Utvik that took place during the summer of 2017, was caused by extreme precipitation and it led to extensive damages to buildings, bridges, infrastructure and property (Bruland, 2018). The reason for the damages was possibly that the water paths were blocked by debris and sediments, and the water flow was forced to take alternative paths. Knowledge of what extend the surface runoff can reach, will allow us to identify potentially exposed areas after heavy precipitation events.

This study is focused on Utvik’s neighbouring village, Innvik, which has similar characteristics as Utvik. In the future, it is possible that a similar flash flood might take place in Innvik. The target is to identify with the use of a GIS, alternative pathways that the water might take in the case of 16 different combinations of closed and open culverts and bridges. The research shows, that the methodology used for modifying the DEM in potentially exposed infrastructure such as bridges and culverts, is one way to identify spots where possible changes might occur in the water flow. However, knowledge about technical information regarding the infrastructure, would be essential for a better evaluation.

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1. Introduction

Natural disasters, extreme weather and climate events and failure of climate change mitigation and adaptation are today risks with the highest likelihood of occurrence, and largest with global impact (World Economic Forum, 2017), and can be disastrous if they interact with vulnerable human and natural systems. According to the Norwegian Natural Perils Pool, which is the national insurance arrangement regarding damages to buildings caused by natural events including storms, storm surges, floods, landslides, earthquakes and volcanic eruptions, the direct compensations for the years 2010-2019 owing to natural hazards, have costed Norway alone 29,4 billion NOK and the public sector even more (Finans Norge, 2020). On both national and international levels, increased frequency and more severe floods will cause a threat to humans, livelihoods and infrastructure. The climate change scenarios reinforce the reality of this threat in the coming decades. Climate change increases natural hazards' probability of occurrence, the communities are more vulnerable and thus it is challenging to cope with such events (Allen et al, 2012).

1.1 Norway; topography & climate change

Norway is a mountainous country with over half of the total area being at least 1,600 feet above the sea level. The Kjolen Mountain Range constitutes a natural boundary along the Swedish border as far south as about 62° north latitude. In northern Norway exist lower mountains compared to the area south of the county of Trøndelag where there are several mountain ranges with height of up to 2.469 meters. The slopes are steep particularly in western Norway and are often rising sharply several thousand feet from the sea. In the far south and in eastern Norway the country is sloping and in the far north exist few plateaus. Norway in general is nowhere flat, except from the Eastern part of Norway located south of Oslo and close to the Swedish borders and Jæren, which is located far south in western Norway. The land use in Norway is as follows: forest land 21,4%, agricultural land is 3,4%, urban settlements 1%, unproductive land consisting of mountains, mountain pastures, lakes, glaciers, swamps and other is 71% and inland water is 4,1% (Aune-Lundberg & Strand, 2010).

According to the 2010 report «Adapting to a Changing Climate», the future conditions in Norway will be shorter snow seasons, less snow in lower elevation areas but also in mountain areas, more precipitation during all seasons and more heavy rain all around the country. It is also expected a projected raise of the temperature between 2.3-4.6 ºC, 5-30 percent increase in precipitation and particularly in the frequency and intensity of heavy rainfall events due to global warming. It has to be mentioned that some areas particularly in western Norway, will experience seasonal increases of up to 40 percent (Hanssen-Bauer et al. 2017, Huntington, 2006). The expected increase in precipitation, is one of the main challenges related to climate change and some of the main impacts of the anticipated climate change effect due to higher precipitation, is damage on infrastructure (roads, bridges, railway, manholes and culverts) by water accumulating due to inadequate drainage, such as deterioration of roads. The damage can be caused due to higher risk of flooding and erosion from rivers and sea. Among other risks, is potential water-borne pollution such as sedimentation ponds, together with increased frequency of landslides and rock fall, as well as flash floods and debris flows. Debris flows displays one of the most common geological hazards in mountainous areas, usually carrying large volumes of sediment threat to roads, farmlands, settlements, human life, and property. Operational problems might come forward in the event of heavy rain or heavy snowfall, such as reduced accessibility on the road network and thus higher demands is being placed on road operation and preparedness (Norwegian Public Roads Administration, 2019). Studies show that short duration high intense rainfall events are expected to increase (Westra et al., 2014).

1.2 Natural perils

The natural peril types recognized by the National Perils Pool are storms, floods, landslides, storm surges, volcanic eruptions, and earthquakes (Opach & Rød, 2019). The impacts of climate change have already been imprinted on certain natural disasters and modelling of different scenarios with higher atmospheric greenhouse gas concentrations predicts further climate change and therefore more extreme weather events, some of them are intensified heat waves, increased flooding and drought, and more severe storms. Therefore, four of the natural peril types recognized by the National Perils Pool are related to climate change and these are floods, storms, storm surges and landslides (Allen et al., 2012).

1.2.1 Landslides

Landslides and avalanches are responsible for over 2000 deaths in Norway for the last 150 years, of which snow avalanches have caused more than 1500 deaths and they have mostly affected western and northern Norway. Western Norway and Troms county are places where area are common large rock slides and avalanches are common and such events can generate tsunamis in the fjords, lakes and reservoirs (Blikra et al., 2006). Higher frequency of landslides and higher exposure of infrastructure leads to an increase in the landslide-related costs. The historic observations show a pattern of increasing precipitation and the InfraRisk project (NGI, 2013) documented this tendency for the historic data on daily extreme rainfalls. According to climate research, the average temperature will increase in Norway, having as a result more precipitation in the future. Extreme rainfall constitutes one major trigger for the weather-triggered landslides, which are therefore expected to increase in the future. Anthropogenic activities, uncontrolled urbanization, changes in land use and climate change, are factors that increase the vulnerability both of the population and the infrastructure and they contribute to a changing landslide risk (Kalsnes et al., 2016).

1.2.2 Storms & storm surges

Storms from the southwest are common along the Norwegian coast and they push water towards the shore. A storm is a low-pressure system, often accompanied by winds that set the seawater in motion, through friction. The higher water level associated with an individual storm is known as a storm surge (Breili, Simpson, Klokkervold & Ravndal, 2020). "Storm surges are temporary increases in sea-level, above the level of the tide, caused by low atmospheric pressure and the force exerted on the sea surface by strong winds" (Lowe & Gregory, 2005). Storm surges with the effects of low pressure, ocean tides and winds might lead to extreme sea levels arise above the normal (Hanssen-Bauer et al., 2017). Due to the effect of the weather dominating the astronomical tide in southern Norway, storm surges are more likely to have consequences regardless of the tides, while a storm surge taking place in northern and western Norway during low tide, has no or little impact and that is due to the storm surge height being lesser than the amplitude of the astronomical tide. The continental uplift in Scandinavia, is expected to mitigate the global increase of the sea level height along the Norwegian coast. However, sea level rise due to climate change, will lead Norway to a high absolute increase in expected annual damage and number of people exposed to coastal flooding by 2100, with the annual damages expected to increase to between 1.7% and 5.9% of GDP. According to Insurance data from 1980 to 2018 from the Norwegian Natural Perils Pool, a total of EUR 140 million has been compensated for damages from storm surges (Vousdoukas et al., 2018).

1.2.3 Floods

Floods are the second most damaging natural hazard in Norway following storms (Rød, 2013) and they are one of the most common and largely distributed natural risks to life and property. Good farmland was located on the flood plains and constituted the basis for therefore follow the valley floor and they are accordingly subject to flooding (Lawrence & Hisdal, 2011; Peereboom et al., 2009). Norway is a country with terrain and weather conditions that produce floods regularly, caused by snowmelt and/or rainfall. Norway's northern position features long winters with low runoff as well as snow accumulating in the mountain areas, elements leading to higher runoff in the spring and resulting in a regime with the highest floods occuring during the spring. Autumn and winter floods dominate in the western coastal area. The climate is milder in that region due to influence of the ocean and the catchments are small in general, leading to short runoff periods. In many areas of Norway, the topography is mountainous. Compared to European standards, Norwegian river basins are relatively small (Lawrence & Hisdal, 2011). The initial conditions in the upstream basin are highly affecting the magnitude of a flood and severe flooding has not been caused always by intensive rainfall events due to unfavorable initial conditions.

Rainfall floods can be either caused by local rainfall events of high intensity that is happening due to local convective storms, or by long duration rainfall (Roald, 2008). The weather type and the occurrence of intensive rainfall and rainfall floods are strongly related varies regionally around Norway. Snowmelt is especially relevant to floods occurring during springtime. Snowmelt occurs if sudden increase in temperature happens and simultaneously with heavy rainfall events might lead to river flooding. A combination of melting and rainfall usually causes large snowmelt floods, but snowmelt alone can cause large floods in inner Finnmark. The amount of the accumulated through the winter snow mass, in accordance with the melting conditions during the flood, are both factors that affect the snowmelt floods. Consequently, that type of floods is dependent on the shifting weather conditions throughout the winter months and it cannot be associated to specific types of weather (Roald, 2008). Flooding due to heavy precipitation is a hydrological hazard dependent on the weather, has effects on the society and the ecosystem and can lead to human fatalities and great economic losses (CRED, 2009). The magnitude of the hazard and the area's vulnerability are the main factors that form the risk of the hazard and therefore the impact on the society (Špitalar et al., 2014).

1.2.4 Surface water flooding & flash floods

A further problem that could be treated as a climate change related natural hazard in addition to landslides, storms, storm surges and floods, is surface water flooding. Surface runoff occurs when the drainage capability of the soil is smaller than the amount of rainfall (Vatne, 2013). In areas where the population density is higher, the ground is absorbing less amount of water than in other types of surfaces and as a result, that water becomes surface water. In an urban environment especially, surface water flow will meet along its way infrastructure and different types of properties and consequently might lead to an increased number of damages (Allen et al., 2012). In high relief small catchments, the water accumulates in streams and during high intensity rainfall events the water level raises rapidly, leading to a type of floods known as flash floods (Vatne, 2013). A Flash flood occurs suddenly, escalates rapidly and it is hard to predict and warn (Viréhn, 2014). Climate change is expected to make smaller watercourses more vulnerable towards violent flash floods caused by local rain events, which are expected to be more frequent and more extreme in the future (Lawrence & Hisdal, 2011; Bruland, 2018). Flash floods in Europe represent 40% of the total flood damages (Barredo, 2007), and they have the highest rate of mortality compared to other natural hazards (Jonkman, 2005). In steep rivers this causes rapid changing discharges and large waterforces, conducing to erosion and rivers taking new courses (Pavlíček & Bruland, 2019). These events are also associated with sediment transport. In steep catchments both flash floods and debris floods are dangerous (Lawrence & Hisdal, 2011). Sediments that are deposited in culverts increase the possibilities to have blocked culverts and therefore the natural water ways and eventually force the water to find alternative paths (Vatne, 2013).

In areas with steep slopes, natural hazards occasionally take place, particularly floods which can lead to the destruction of communities, loss of human lives, loss of property and in general might cause extensive damages on the social and economic network (Rimba, 2017). In order to assess the impacts caused by a flash flood, one must consider a number of weather-related factors, aspects of the hydrological hazard, as well as the local characteristics of the area. Flood events in urban areas and in coastal or riverine flooding differ from each other, while it is observed that in urban areas there is an increased flood risk and the damages depend more on demographic and anthropogenic factors. The social impact a weather event will cause, depends on how populated an area is. The population density constitutes a factor that shows the number of people exposed (Amaro et al., 2010) and the continuous land development is another factor, because it is obstructing the water absorption and therefore it increases run-off (Du et al., 2015). The type of urbanization and the land use are directly associated with the impacts caused after a flood (Llasat et al., 2009; Papagiannaki et al., 2015).

In a future climate, there will be large floods due to raining and less ‘spring floods’ caused from melted snow and additionally, coastal Norway will be affected by the rise of sea level (Norwegian Public Roads Administration**,** 2019). Of the estimated yearly precipitation of 1600 mm, over 1100 mm results to runoff, while a little less than 500 mm evaporates. The observed warming has broadly led to increased runoff in winter and spring and earlier snowmelt. The average of all projections indicates relatively small change in total annual runoff for Norway for the next 50 years (Hanssen-Bauer et al., 2017). Changes between the different seasons are considerably growing, with reduced runoff during the summer season and increased runoff during the winter season (Hanssen-Bauer et al., 2017). It has been observed that floods are taking place earlier in the springs and that this is caused by increased temperatures. Rain floods are more frequent during recent decades and there is a tendency to increase more. The magnitude of rain floods is estimated to incline, while meltwater floods will decline over time (Hanssen-Bauer et al., 2017). The future increase in local and heavy precipitation, could increase the occurrence of severe floods in small catchments (Lawrence & Hisdal, 2011). In river systems where snowmelt floods prevail, it has been expected a reduction of up to 50% in spring floods. In river systems where rain floods prevail, it has been expected a raise by up to 60% in the magnitude of floods (Hanssen-Bauer et al., 2017).

Nationally, the Natural Hazards-Infrastructure, Floods and Slides project (NIFS), addressed the cause and effect of floods on infrastructure (Myrabø et al., 2016). NIFS was a national commitment that took place between 2012 and 2016, involving Norges Vassdrag- og Energidirektorat which is the Norwegian Water Resources and Energy Directorate (NVE), the National Rail Administration (Jernbaneverket) and the Norwegian Public Road Administration (Statens vegvesen). NIFS covered a broad range of aspects related to floods and built a strong platform for further research in the area. NIFS also identified the following knowledge gaps for future projects; uniform management of catchments, data coordination, social and economic analyses, follow-up after events and skills development. According to NIFS, there is an uncovered need for adaptation strategies regarding steep terrain watersheds with downstream settlements, infrastructure, farmland or other economic activities.

1.3 Importance of rivers

Rivers maintain a large percentage of the earth's population through their supply of water for consumption, their provision of ecosystem services, food production, energy generation, and industrial processes, as well as their cultural significance. Natural resource managers require efficient means of monitoring river flows in large and smaller scale, as well as documenting and projecting long term changes to the rivers flow regime, in order to assist expecting changes in the increasing frequency of extreme events (Zeng, Bird, Luce, & Wang, 2015). Human activities such as water supply for municipal and industrial use, reservoir inaugurations, irrigation schemes and fish farms, have a great impact on river runoff (Scholz, 2018). Human made interventions in the river catchments, as well as possible hydrological impacts of climate change, demand a continuous assessment of water resources and monitoring. Water resources management is vital to be supported, due to the uncertainties related to water quality, degradation caused by pollution and the continuously increased flood risks (United Nations, 2011). Climate change necessitates governments, organizations and individuals to make changes in order to adjust to the new reality. In the case of floods, it is vital to know which areas are likely to be affected after a heavy precipitation and/or snowmelt and thus we will know which areas will be possibly exposed to flooding. As mentioned before, increased floods are one of the major risks in a future climate (Alfieri, et al., 2017; Arnell, 2016) and if we are able to identify flood-prone areas, then we can calculate the flood risk and that is essential to support the decision making process towards risk management, starting from planning proposals and leading to detailed design (Balica, Popescu, Beevers, & Wright, 2013).

1.4 Significance and aims of the study

On the 24th of July 2017, a thunderstorm caused a large flash flood in Utvik, a village located in the municipality Stryn (see Figure 1), western Norway on the southern shore of the Nordfjorden. The river Storelva in Utvik flooded together with three other rivers nearby. The flood itself was larger than the amount of precipitation that could be tolerated and resulted in major damages to man-made environments. The flood that took place in Utvik in 2017 is an example of a violent flash flood caused by extreme precipitation (Bruland, 2018). The reason for the damages was most likely that the naturally water paths were blocked by debris and sediments, and the water flow was forced to take different paths. The flood caused extensive damages to buildings, bridges, infrastructure and property in general.

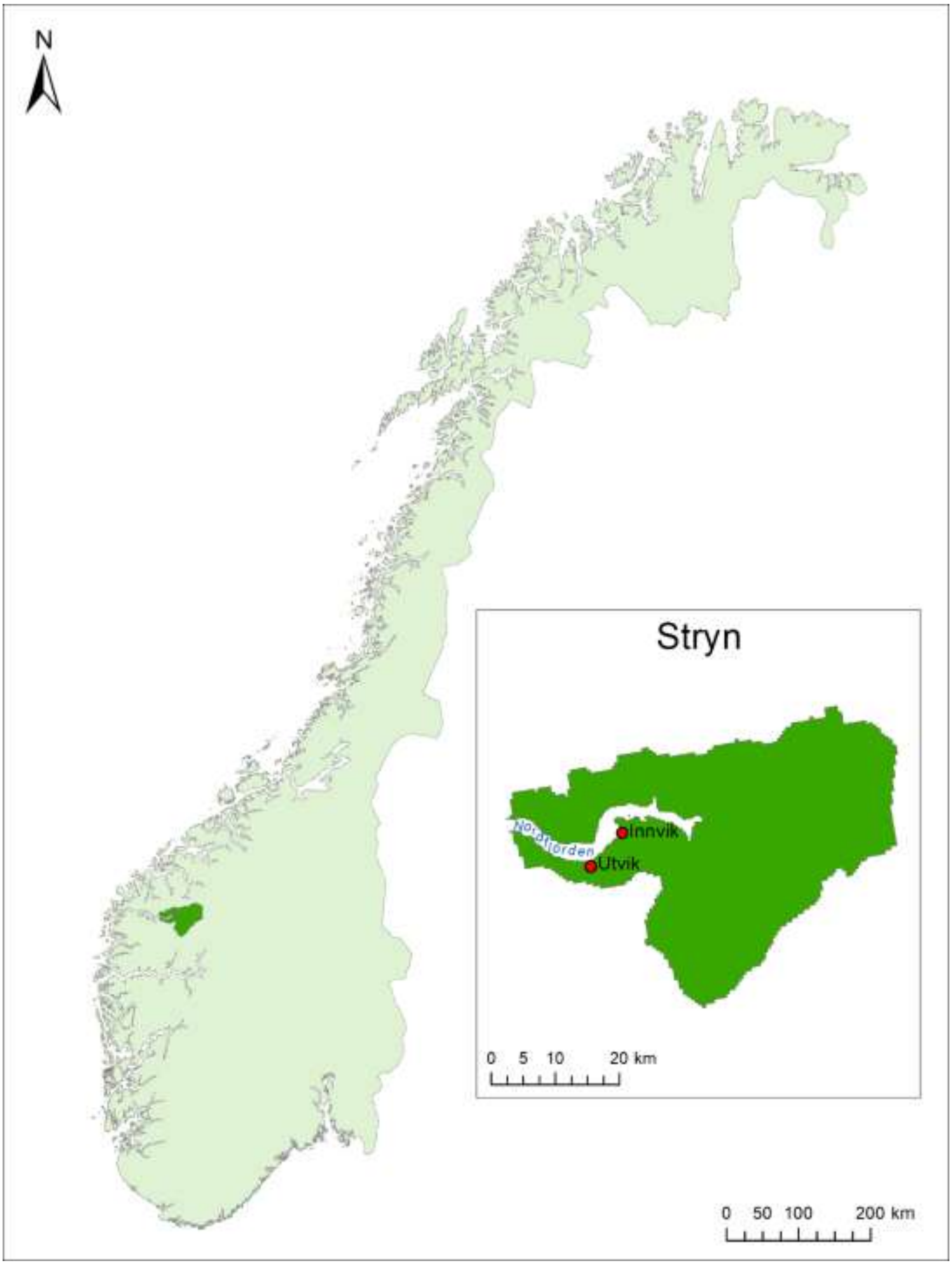

Figure 1: Map of Norway and inset map of Stryn municipality indicating Innvik

In the neighboring village Innvik (see figure 1), a large amount of precipitation occurred but it did not flood during that time. Even though that event did not fully affect Innvik, the characteristics of the other rivers in the area that flooded are very similar to the one in Innvik. This study examines the possible water paths in case a similar scenario of heavy rainfall would take place there in the future. Using Storelva river catchment in Innvik as study area and GIS modelling as main methodological approach, the main research questions (RQs) for this study are as follows:

RQ1: How to identify and represent critical spots that make surface water runoff to take alternative pathways?

In order to predict the path of the water flow, one has to know all the critical spots that can lead the water to turn in other directions. Therefore, these critical spots can create many possible combinations of the water directions. Consequently, it is clear that predicting where the water will flow is a quite complex matter (Viréhn, 2014). It is important to obtain knowledge about critical spots where the water might take alternative pathways and ideally add in a database that can be used for further research in the future. A resulting second research question is:

RQ2: How can the flow direction be manipulated in critical spots?

The objective is to make changes in the flow paths when the drainage system is closing in small watersheds. Bridges and culverts have been used as critical spots in this project. Gravity is forcing surface water to take the direction of the steepest gradient according to the slope, and therefore the flow will go along the lowest path in the terrain (Gruber & Peckham, 2009; Viréhn, 2014).

Surface runoff modelling is about finding the low paths and surface water is considered. If the results of hydrological modelling of surface runoff water should be used as a decision basis for where adaptation measures such as drainage dimensioning and/or maintenance are most needed, the validation of the runoff modelling is necessary. For validation of possible flood prone areas, the susceptibility maps from NVE will be used. These maps do not show which areas are likely to flood, however they show areas where the danger of flooding may need to be further assessed (Peereboom, 2011). Therefore, a third research question has been formed:

RQ3: Can the flood susceptibility maps from NVE be used as validation for identifying flood prone areas?

The research questions will be answered with the use of hydrological tools incorporated in a Geographical Information System. These hydrological tools use as a basis an elevation model, a gridded DEM, whose quality determines the quality of the analysis (Murphy et al. 2008; Viréhn, 2014). The elevation model is used to define which cells flow into other cells, using the flow direction algorithm (ESRI, 2014). The results will be presented as static GIS data in the form of maps.

This study, by providing knowledge will hopefully support the local community and the municipality in Stryn, regarding possible targets of a future flood and eventually might help to prevent any negative consequences as well as contribute to adaptation in the area.

1.5 Describing the study area

Innvik is a village belonging to Stryn municipality in Sogn og Fjordane county, located in the region of western Norway and it is laying on the southern coast of the Nordfjord (figure 1). In western Norway it is anticipated a seasonal increase in precipitation of up to 40 percent (Hanssen-Bauer et al. 2017). The 0.71 km² village has a population of 431 inhabitants and a population density of 607 inhabitants per km² (Statistisk sentralbyrå, 2019). Innvik is located 7 kilometers northeast of the village of Utvik. Innvik and Utvik both lie on river plains, with steep rivers that go down the hill and through the village. In Innvik, the river in many places is in higher level than the surrounding terrain (Bruland, 2018). The river channel in Innvik and Utvik is steep (ca. 3-17%) and rough sediment, rocks and boulders are settled in the riverbed (Pavlíček & Bruland, 2019).

On the 24th of July 2017 a thunderstorm caused a large flash flood in Utvik. The flood caused extensive damages to buildings, bridges, infrastructure and property in general. The catchment area of the main river, which is around 25 km², modified its cause in the downstream part of the village (Dam, 2018). “The results show that towns build in deltas are particularly flood prone due to the additional sedimentation effect” (Dam, 2018). The flood that took place in Utvik in 2017 is an example of a violent flash flood caused by extreme precipitation (Bruland, 2018). “Over a period of 4 hours the flow in river Storelva in Utvik, increased from less than 5 m^3/s to around 200 m^3/s. With a catchment of 25 km² this corresponds to a specific runoff of at around 8000 l/s, km² which is considered extremely high. Estimates indicate that a precipitation causing the flood to be 80 to 100 mm over 4 hours” (Bruland, 2018). Moreover, the sediment accumulated in the downstream part of Storelva, due to a decreased river slope and velocity, caused the water levels to raise further and led to additional flooding (Dam, 2018). The riversides close to the fjord up to about 14 meters over sea level had been protected by NVE. Some of the flood’s aftermath was extensive damages to water supply, sewages, electrics, roads, bridges, houses. (Live, 2017).

According to NVE post-flood report, after the flood in Utvik NVE started with crisis mitigation (Live, 2017). In the period between January 2018 and June 2019 NVE conducted major constructions in Utvik and in the aftermath of the 2017 event in Utvik, Stryn municipality assessed the need for mitigation measures in Innvik as well and therefore, applied to NVE for support.

Table 1 presents the yearly income for the year 2019 of the main companies based in Innvik and the number of the employees. From Table 1 one can see the importance of the area in numbers, while a future disaster might have negative consequences to the human resources and to the local economy.

Table 1: Companies based in Innvik (Proff The Business Finder, 2019)

Company	Income 2019	Employees
Legekontor Innvik	NoData	1471
Innvik Sellgren AS	73.941.000 NOK	60
Skogstad Sport Innvik	NoData	47
Innvik Fruktlager SA	55.797.000 NOK	15
Innvik Fjordhotell Misjonsheimen	5.668.000 NOK	10
Viking Camping Og Kro Grethe Grøsvik Hilde	NoData	6
Vikane barnehage avd Innvik	NoData	21
Innvik Rekneskapsservice AS	3.431.000 NOK	7
Matkroken Innvik	NoData	8
Nordfjord Monumentservice Tøsse	NoData	3
Innvik Vassverk	NoData	6
Wald Lyslo	NoData	3
Skogen AS	1.379.000 NOK	8
Bruland Maskin AS	4.556.000 NOK	3
Vagstad AS	914.000 NOK	1
Gjendebu AS	5.766.000 NOK	2
Snorre AS	633.000 NOK	1
Hilde Fellesfjøs DA	627.000 NOK	1
Innvik Næringspark AS	2.113.000 NOK	NoData
Fri Stil AS	2.570.000 NOK	NoData
O R Haugen AS	208.000 NOK	NoData
Gamle Innvik Ullvarefabrikk	227.000 NOK	NoData
Stiftinga Liatunet	89.000 NOK	NoData
Haugen Rådgivning AS	33.000 NOK	NoData
Sacco Of Norway AS	6.531.000 NOK	NoData
Skogstad Eigedom AS	990.000 NOK	NoData

1.6 NVE work for floods in steep catchment

NVE has done several projects regarding areas which are particularly vulnerable to flooding and in general the extent and possible consequences of floods in large watercourses are mapped in a wide scale (NVE, 2018). However, flood hazard mapping has been done for major river catchments but has not yet been completed for the whole country (Rød, Opach, & Neset, 2015). In NVE's 2011 report "Hydrological projections for floods in Norway under a future climate", they have been assessed possible changes in hydrological floods by applying precipitation and temperature data based on 13 regional climate scenarios. Between the 115 modelled catchments around Norway, some of the steepest compared to those in other regions of the country, have been found in Møre and Romsdal, Sogn and Fjordane and Hordaland. Most of the modelled catchments show an increased flood magnitude and some of the largest projected increases for Norway are found in in Sogn and Fjordane with some of them having a projected increase of over 40%. These large increases in the area mirror the effect of increased precipitation in autumn and winter in an area which is rainfall-induced floods already prevail (Lawrence & Hisdal, 2011).

Historically, the focal point has mostly been on floods located in larger watercourses (Bruland, 2018). However, the hazards in small and steep catchments are not adequately mapped. The faster response and the forces caused by high water velocities generate another risk dimension that is significantly more challenging to encounter" (Pavlíček & Bruland, 2019). In small and steep catchments, local events of intensive convective precipitation (Vatne 2013; Viréhn, 2014), in conjunction with blocked drainage paths are often the reason of the flood (Myrabø, 2013; Viréhn, 2014). Therefore, the water level and its conveyance route during a flood is difficult to foresee, and thus the predicted water covered area would be inaccurate (Lawrence & Hisdal, 2011). The surface run-off is likely to damage along its path and cause erosion. Natural features such as trees and rocks, in accordance with anthropogenic features such as buildings and infrastructure, will be possible obstacles to the regular water path and might be possible damage points. Consequently, when it comes to the risks associated with floods in steep rivers, there is a lack of approach and methodologies to handle this analysis (Pavlíček & Bruland, 2019).

1.7 National framework for adaptation to climate change

It is important to understand the reasons why societies are more vulnerable to climate change and consequently to assist in the adaptation process. Climate change has different effects depending on the type of the human and physical environment. «Adapting to a Changing Climate» report was carried out and published in 2010, it included all sectors and management levels in Norway 2010, and it is the first national survey of vulnerability to the impacts of climate change. Part of the above national vulnerability study was conducted and published in 2009 and updated in 2015, the report "Climate in Norway 2100" which provides the official basis for adaptation in Norway. The report offers an overview of the Norwegian climate of the past and the present, presents the observed trends, as well as the outcome of the modelling of climate change towards the end 21st century (Norwegian Public Roads Administration, 2019).

The need for a common decision basis for all sectors in Norway that will be used for adaptation to climate change, as a well the existence of climate data that can be practically used, lead to launching the Norwegian Centre for Climate Service in 2014. NCCS includes overviews, impacts and anticipated risks of climate change for every administrative region. In addition, NCCS communicates updated data for applications in climate change adaptation, since new features are added continuously, such as the 2017 introduced maps of monitored and modelled short-term precipitation (Norwegian Public Roads Administration, 2019). The "Climate Adaptation in Norway" white paper published in 2013 emphasised the importance of common knowledge, cooperation and shared responsibility, between the individual and the organisational level, and the importance of knowledge and cooperation. In 2017, the Ministry of Climate and the Environment divided officially the responsibilities between the state, the counties and the municipalities. The municipalities are responsible for their own infrastructure (such as roads, bridges, culverts etc.). Among a large number of topics related to the environment being discussed in the report, the government appointed a commission to study the impacts of climate change, as well as necessary mitigation and adaptation measures. NVE is responsible for administration of the nation's water and energy resources. NVE is therefore the main actor in prevention and mitigation of damages from floods and other natural hazards and is in charge of implementing the Flood Directive in the country. NVE is therefore responsible for securing settlement against flood and avalanches (Lillestøl & Rykkja, 2016).

In the climate adaptation strategies for Norwegian counties presented by the Norwegian Climate Service Centre, increased flooding in small and steep rivers is considered central issue for all regions of Norway and an increase in small catchment flash floods is to be expected (Hanssen-Bauer et al., 2017). High intensity local convective rainfall is usually resulting to the most extreme peak flows in small catchments (Ogden & Dawdy, 2003). Most studies are concerned with large rivers and large-scale assessments. Since larger catchments have been always in the focus for data collection and monitoring, most existing flood estimation methods are seldomly including data from small catchments. Methods of flood estimation methods developed on catchments of larger size, are usually not suitable for smaller ones. The features of the catchment, such as the geomorphology of the area, land use, land cover, infiltration capacity of the soil and groundwater storage, in accordance with the rate of precipitation and variability between space and time, are shaping the catchment's peak discharge response to precipitation. The importance of every one of these factors depends on the extent of the catchment and on the runoff producing process (Ogden & Dawdy, 2003). Flood estimation in small catchments can be difficult because of the flood peaks being more subjected to the effect of local features, such as flow diversions, field drainage, or the storage of flood water behind bridges, culverts and embankments (Environment Agency, 2012). Another reason that complicates the flood estimation in small catchments is that local extreme precipitation events might result in higher peak flows relatively similar to the average flow of larger catchments, so that comparison with larger neighboring catchments might offer little information (Fleig & Wilson, 2013). In small urban catchments are present artificial flow structures such as pipes and culverts and in rural or mountainous areas infrastructure such as roads and railways can be frequently damaged by local flood events. Although Norway is sparsely populated, most urban activity is concentrated along the valley floors. Further development and infrastructures consequently follow the valley floor, and thus they are exposed to flooding. In addition, flood estimation in small catchments in rural areas of Norway is important as well, because parts of infrastructure might often be damaged by local flood events (Fleig & Wilson, 2013). Statens Vegvesen is responsible for the maintenance of such infrastructure as bridges and culverts and any operations related to them (NGI, 2013).

1.8 GIS tools and climate change adaptation strategies

The factors shaping the climate as well as the manifestation of its effects are geographic in nature. Geographic Information System (GIS) are essential in registering, monitoring, analyzing, and predicting these dynamic activities and interdependencies.

GIS tools have been used in Norway for modelling hydrological scenarios. Larsen (2010) in Denmark, demonstrated how hydrological modelling in GIS can help to adapt the infrastructure to the future climate and has created and applied to different climate scenarios a GIS model based on elevation data from LiDAR in order to identify areas with high water accumulation close to the road system. Bratlie (2013) used elevation data to identifying surface water runoff during an intensive flood that took place in south Norway in 2012, where very intense precipitation was above the capacity of the drainage functions and had as result the water to flow in other directions. In that study, had been used as validation data from a previous storm event (Bratlie, 2013). Another study in Norway, is that of Viréhn (2014) and it examines three study areas in Gudbrandsdalen that flooded in 2013. Using as basis an elevation model and by manipulating it in certain points (for example culverts), it showed that hydrological modelling can suggest possible surface water ways. Viréhn (2014) used damage points of a previous flood as validation, based on the concept that if the flow accumulation is notably increasing in a damage point, then it is possible that an alternative water way has caused the damage before.

1.9 Definitions

According to Knighton (1998), a watershed is defined as land area that contributes flow by precipitation, to a common outlet as concentrated drainage. Affected by the terrain, the water accumulates within a geographic area, and leads into the river network. The watershed might change in case of erosion or existence of obstacles in the river system (Knighton 1998).

Culverts are a common type of hydraulic structure and they are primarily used in the facilitation of drainage through roadway systems and other obstacles (Kells, 2008). Culverts are major parts of infrastructure that allow water sourcing from a river or a stream usually, to flow underneath a road, a railway, a bridge, a trail or other similar obstruction, without interrupting the flow of traffic. Several culverts were designed and built in the past and they might not be sufficient anymore for the current circumstances. Whether outdated or insufficiently designed, culverts can become "blue spots" (i.e. sinks in the terrain where water may accumulate) during storm events. That means that their capacity of water and debris may not be enough to support the current conditions that recent storm events create. There is a likelihood they might lead to flooding of surrounding areas or have important consequences to the transportation system. In some cases that culverts have the capacity for high floodwaters, but they are too narrow for that amount, they may increase the velocity of water moving below the roadways, and therefore increasing downstream erosion in some river systems. Properly positioned culverts that allow a large amount of water to flow through, can reduce flooding and protect adjacent properties, as well as minimizing the disruption to the transportation system. A bridge is a structure leading either a railway or a road above a water course (Li et. al, 2013).

In this master thesis, closed culverts and closed bridges means culverts and bridges that block water because of debris or other natural obstacles (for example trees) that block the water by entering and flowing through. Similarly, open culverts and open bridges means that water is flowing unobstructed through or below. Culverts are manufactured from various materials and can have different shapes and characteristics according to their utility (Schall et al., 2012). The capacity of a culvert depends on a combination of factors, with the most important being the inlet characteristics such as the inlet geometry, culvert shape, wingwalls configurations, and extent of bevelling (Schall et al., 2012). The inlet shape of a culvert is affecting the capacity of the culvert during sediment transport and different shapes of inlets can result to different capacities (Faqiri, 2014). In this master thesis, the capacity of the culverts is not taken into consideration and only the width and length which is necessary to create a buffer around the line representing the length of the culvert is considered.

2 Methodology

2.1 Introduction

In this section I describe the methodology that I followed to perform the hydrological analysis and every process conducted that led to the results, which will be presented in maps. The software I used is ArcMap10.6 for Desktop which is freely available from my institution and is one of the most competitive software for hydrological analyses.

In this master thesis, I follow the methodology of Sui & Maggio (1999) which supports that hydrological tools implemented in a Geographical Information System (GIS) are efficient and use the DEM as a basis. “Grid DEMs consist of a matrix data structure with the topographic elevation of each pixel stored in a matrix node and they are simple to use”. That is the reason grid DEM have been widely applied to the analysis of hydrology related problems (Moore et at., 1991). A simple definition of the DEM is “any digital representation of the continuous variation of relief over space” (Burrough 1986; Moore et al. 1991). One of the most used definitions is that the DEM is a representation of (a subset of) the Earth’s surface excluding natural or artificial features (Burrough, 1986; Hutchinson and Gallant, 1999). A raster layer consisting of pixels representing the elevation of the terrain is usually used in geomorphologic analyses (Pike et al. 2009; Viréhn, 2014).

2.2 Data

For conducting this study, several datasets have been used and will be mentioned in this section as well as their source.

Detailed elevation data are available free of charge for download at the website of the Norwegian Mapping Authority (Kartverket, 2019). The Norwegian Mapping Authority is a public agency under the Norwegian Ministry of Local Government and Modernisation. The Norwegian Mapping Authority is the nationwide coordinator of geodata of Norway and one of its responsibilities is geographical information. One can find national elevation models with a resolution of 1, 10 and 50 meters. For this project it has been used a terrain model (DEM) in grid format (USGSDEM raster) with 1 meter resolution.

FKB data are used, whose source is the national spatial data infrastructure in Norway (GeoNorge, 2019). From these data I used the vector layers of the road network, the river network, other water surfaces and buildings. I was unable to find culvert data in any topographic datasets, neither in FKB or from the Stryn municipality, so NTNU PhD student Mikal Pavlicek whose work is related to the area and he has done field work there, provided me with point features of the coordinates of the culverts. All of the processes in ArcMap were performed after all the layers being set in WGS 1984 UTM Zone 32N.

2.3 Study area

The purpose of this research is to show the changes in the water flow having as input a modified DEM at the locations of the culverts and bridges and thus, the culvert and bridge data are used in order to delineate the study area. NVE provides layers with the watershed boundaries around Norway and in this master thesis a combination of three neighboring watersheds is forming the study area. The number of obstacles that have been taken into consideration in the next steps of the workflow is a total of 11, of which six are culverts and five are bridges along the river (figure 2).

Figure 2: Map of locations of bridges and culverts in the study area

In order to make the visualization easier, the culverts and bridges have been numbered and presented on maps as it can be seen in figure 3, while figure 4 shows images of the bridges and culverts, so that the reader can be able to assess how critical they are. The numbering has been maintained throughout this research.

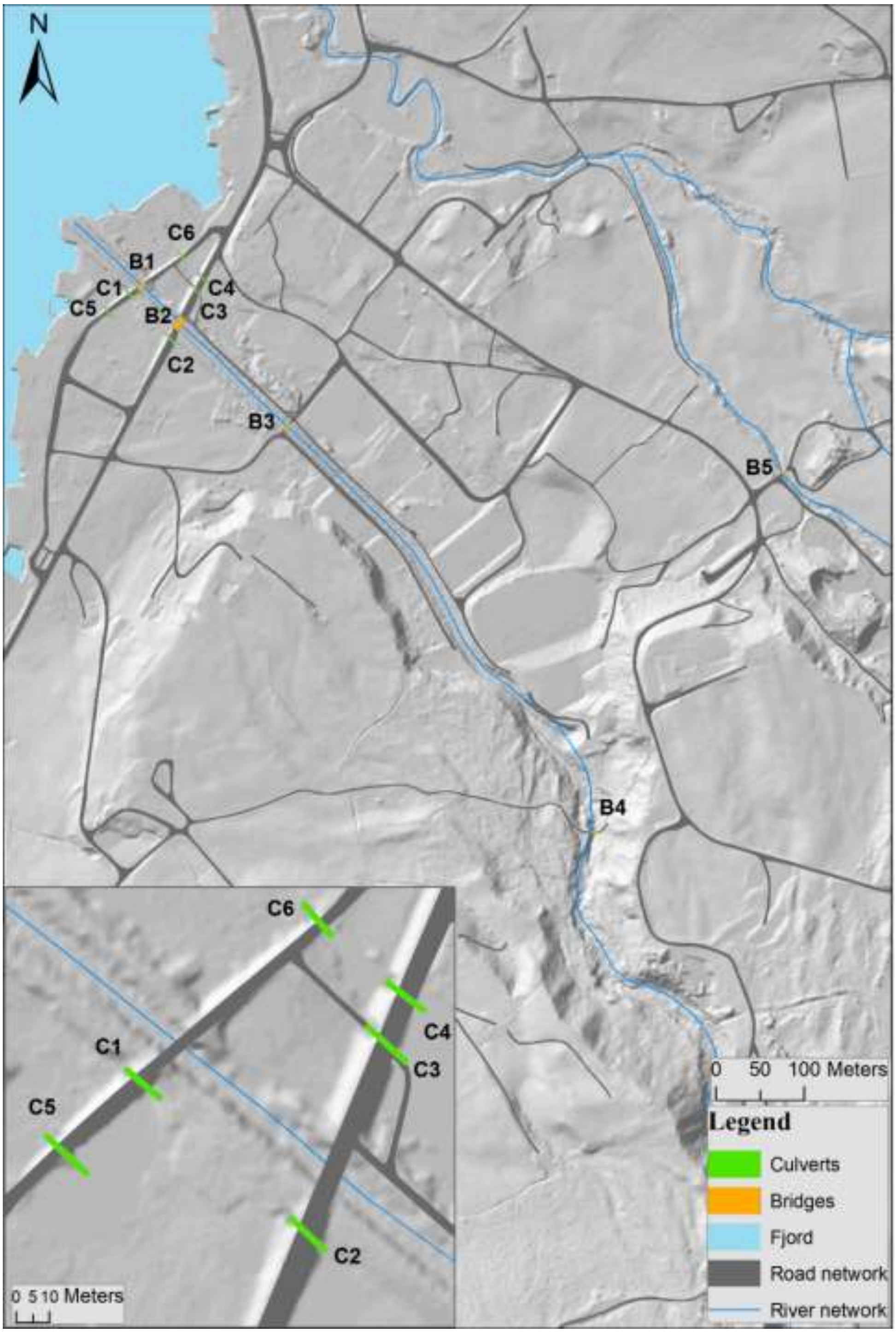

Figure 3: Map of the bridges and culverts in the study area with numbering

Figure 4: Bridges B1, B2, B3 and culvers C1, C2, C3 (Photo: Michal Pavlíček)

2.4 Preparation of the DEM

The purpose of this project is twofold. Firstly, it aims to find where the water will flow under normal conditions, i.e. through open culvers and under bridges. Secondly, it aims to find where the water will flow under different scenarios of surface water resulting from a heavy rain event with much debris closing culverts and blocking bridges. In the study area, different kind of infrastructure exist, such as roads, bridges, culverts and buildings. The problem is that usually DEMs derived from LiDAR, reflect the ground's topographic features and as a result, ground features such as culverts might be modeled as "digital dams", affecting the modeled drainage passage (Li, et al. 2013). That means that the LIDAR pulse detects the road and not the culvert that is located under the road and whose purpose is to guide the water. Therefore, performing a process to obtain the water flow direction on the original DEM, will cause the water to follow the lowest path along the road or along the various infrastructures, instead of through the culverts, as it does in reality. The target is to model the water flowing through the culverts and that can be achieved by hydrologic conditioning of the DEM. Hydrologic conditioning is the process of modifying a DEM to change flow routing and drainage.

One common way of removing "digital obstacles" that block the waterflow is to trench the DEM by "burning" the stream through the obstruction to force flow downstream. In order to "burn" the DEM, specialized GIS tools are used to reduce the elevation of DEM grids corresponding to the drainage structures, such as DEM Reconditioning in the Arc Hydro plug-in for ArcGIS, which is based on the AGREE algorithm. The AGREE algorithm reduces the elevation of the DEM cells according to the defined drainage structures. The drainage structure dataset has to be created, which demands the coordinates of the inlets and outlets of culverts, the start/end points of the bridges and their geometrical characteristics such as diameter of the culvert pipe, bridge span and depth, but it is also possible to add other parameters such as materials and culvert design (Li, et al. 2013).

In this master thesis, the DEM has been modified at the culvert locations by making a toolbox in order to manipulate the pixels at these locations, to represent the heights of the foot of the culverts. The bridges on the other hand, are not affecting the water flow in the original DEM because they are not visible and therefore the water is going under them similarly as in reality, but in this project I wanted to test different scenarios of what paths the water will take in case a bridge is blocked. That means the DEM has to be modified similarly in this case as well, but in this case the pixel heights will be raised to the height of the bridges.

To make a hydrologically correct DEM it is common to use existing hydrological features such as vectorized streams with elevation values (Murphy et al. 2007). I used the point data of the culverts as a layer and by visually assessing the hillshade of the area and comparing with the coordinates of the culverts point data, one can see the culverts exact location (figure 5).

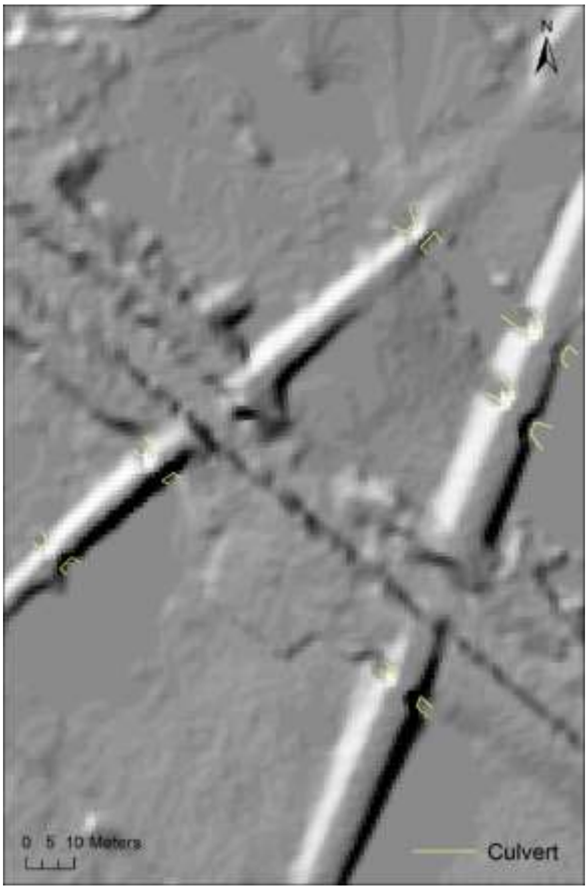

Figure 5: Culverts represented as polylines

The next step was to make line features representing the culverts. Each culvert was digitized as a line feature starting with a point above the obstacle (for example a road) and ending in a point beneath the obstacle. The same was done with the bridges, but while digitizing them I had to find the start and end points of the bridges' lines and therefore I used as reference the polygon shapefile with the bridges. Following the manipulation of the DEM, it has been created a new raster of the area with pixels whose values represent the elevation of bridges and culverts, according to the scenario applied and that raster has been used to build a hydrologically correct DEM. Figure 6 presents the profile of culvert C6 before and after manipulation, while figure 7 presents the profile of bridge B1 before and after manipulation and the pixels along the purple line are those manipulated.

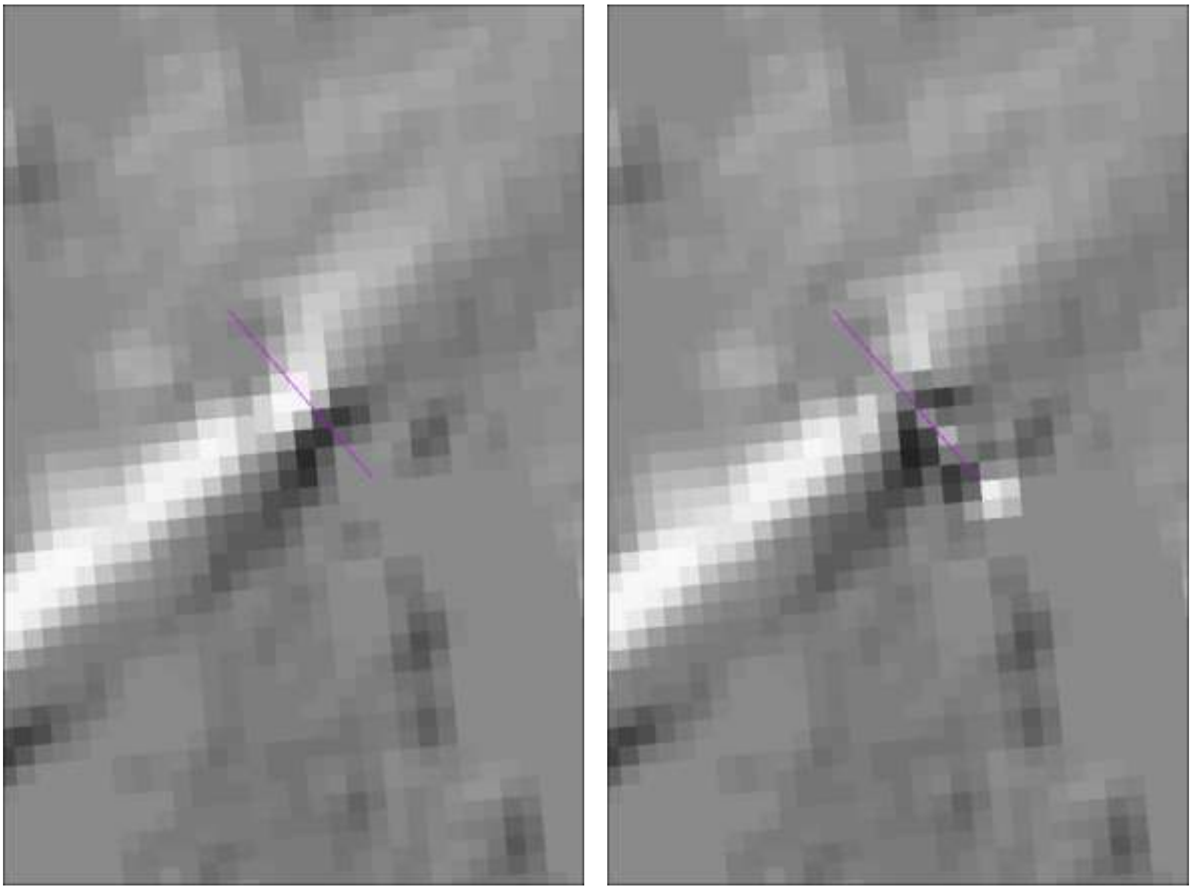

Figure 6: Profile of culvert C6 before (left) and after manipulation (right)

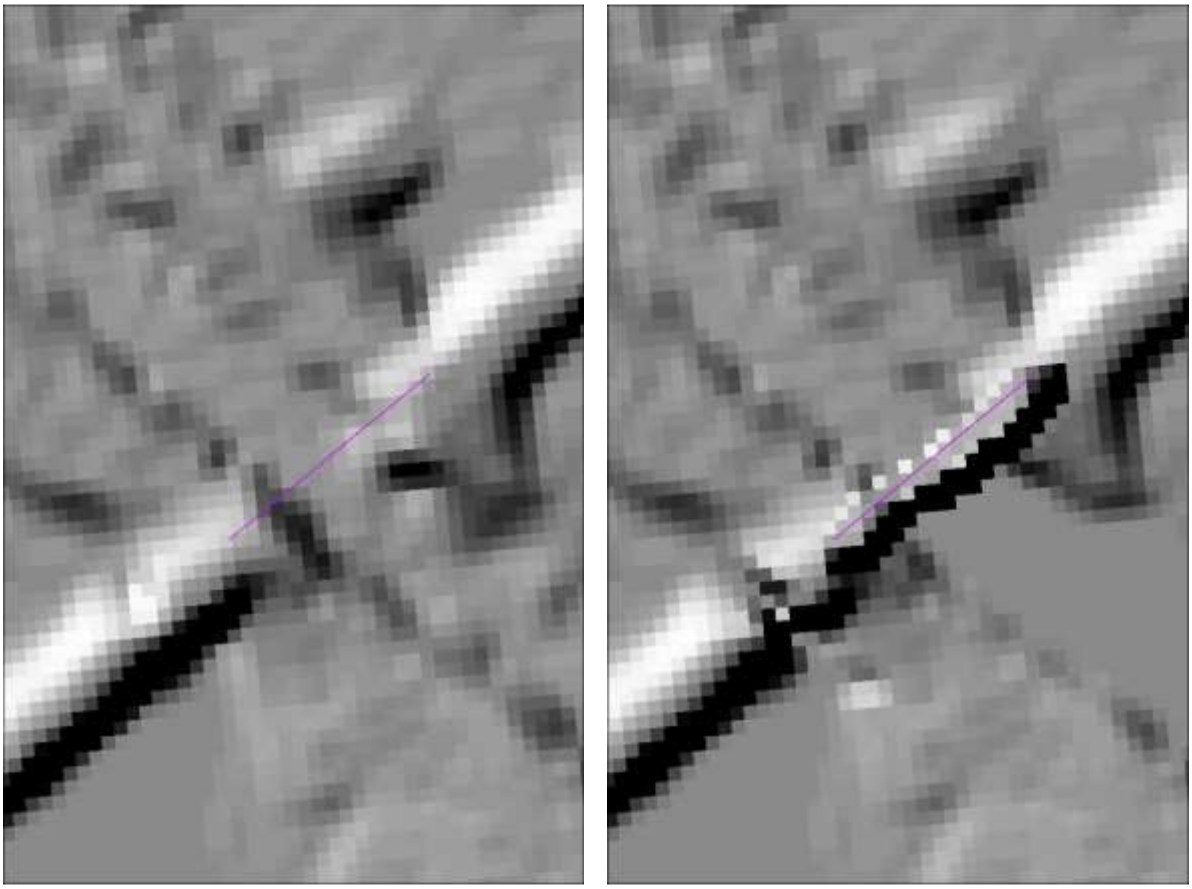

Figure 7: Profile of bridge B1 before (left) and after manipulation (right)

2.5 Manipulation of the digital elevation model

In order to manipulate the DEM, ModelBuilder in ArcMap was the tool that helped to make the process easier and faster. ModelBuilder is an application for creating, editing, and managing models. A model is representing the workflow that links together sequences of geoprocessing tools and it is using the output of one tool as input to another tool. In this research, the same processes had to be repeated many times and therefore using ModelBuilder made the process faster. Model elements are the basic building materials of models. Four main types of model elements are included in ModelBuilder: geoprocessing tools, variables, connectors and groups. One can set input and output for tools, which are visualized in ModelBuilder as yellow rectangles. Geoprocessing tools can be any tool that exists in a system toolbox, as well as special tools such as iterators, utilities and logical tools. Variables are the elements that contain a value or a reference to data. Data variables represent the input data, they are visualized with blue oval shape and they include the workspace, feature class and raster dataset. Derived or output data are those data created by a tool in the model and are visualized with green oval shape (ESRI, 2014). Figure 8 is showing a generalization of the model used to modify the DEM and the different inputs and outputs will be explained below.

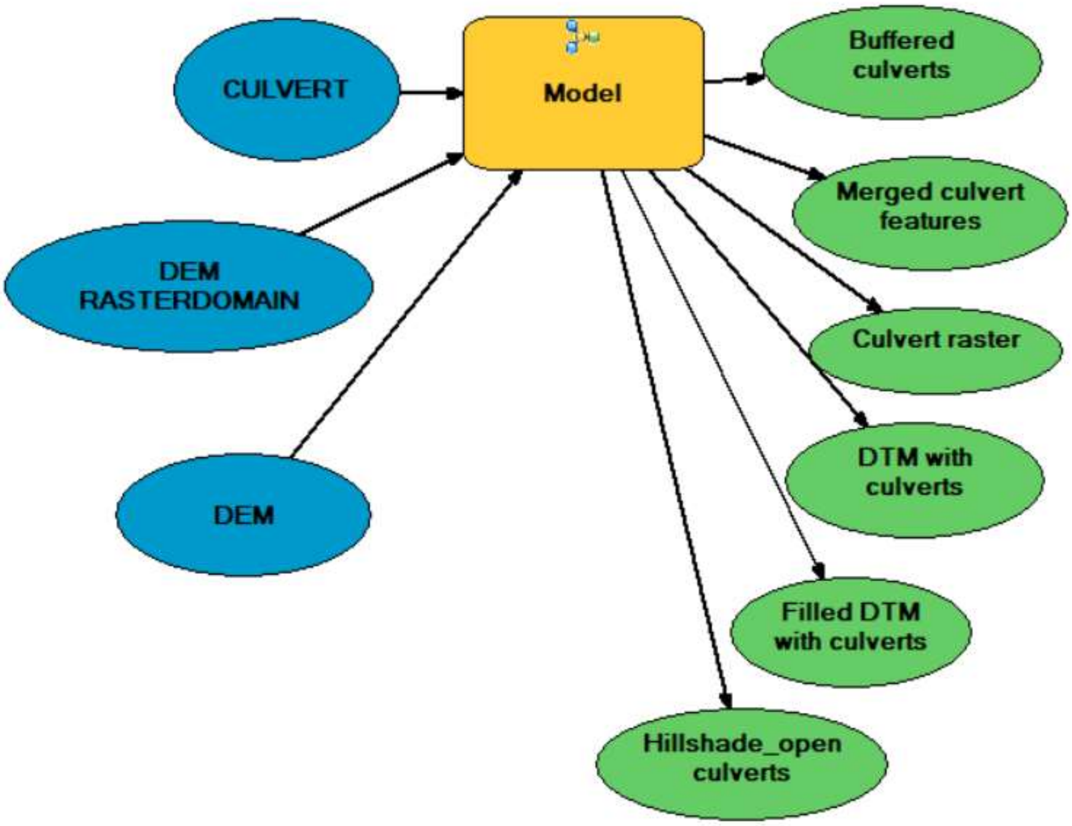

Figure 8: Input and output resulting from the model used to modify the DEM

2.5.1 Application of the model

To begin with, it is necessary to define the raster extent to be the same as in the digital elevation model in the model properties. The model is using as inputs three different parameters;

- CULVERT: A polyline feature class containing the culverts, on which we add a new field with elevation value (the name "Z" was used). Then we give every culvert a value used to increase or subtract DEM height, for instance 10, to the new field holding z-values
- DEM RASTERDOMAIN: The extent of the DEM; The tool Raster Domain uses as input the DEM and the output is a polyline footprint of the data portions of the DEM. 3D polygons contain elevation values only along the perimeter of the features, which

means the inner portions of the polygon will not contain any vertices. That is important as it will allow us to manipulate the elevation values by adding a Z field with value 0. The name of the field has to be the same as in the culverts layer, because it will be used from the model in later steps to manipulate the DEM and the wanted spots.

- DEM: The Digital Elevation Model (DEM) clipped to fit the study area.

The first step is to buffer the culverts layer. Buffer (Analysis) tool combines multiple input datasets and turns them into a single output dataset. Euclidean buffers work well when analyzing distances around features in a projected coordinate system, which are concentrated in a small area, such as in a single UTM zone, like in this case. The buffer distance of the culverts will be 2 meters (figure 9), because that is approximately the width of all the culverts in the study area. The width of 2 meters can be validated by the length of the car above C3, as it appears in figure 4.

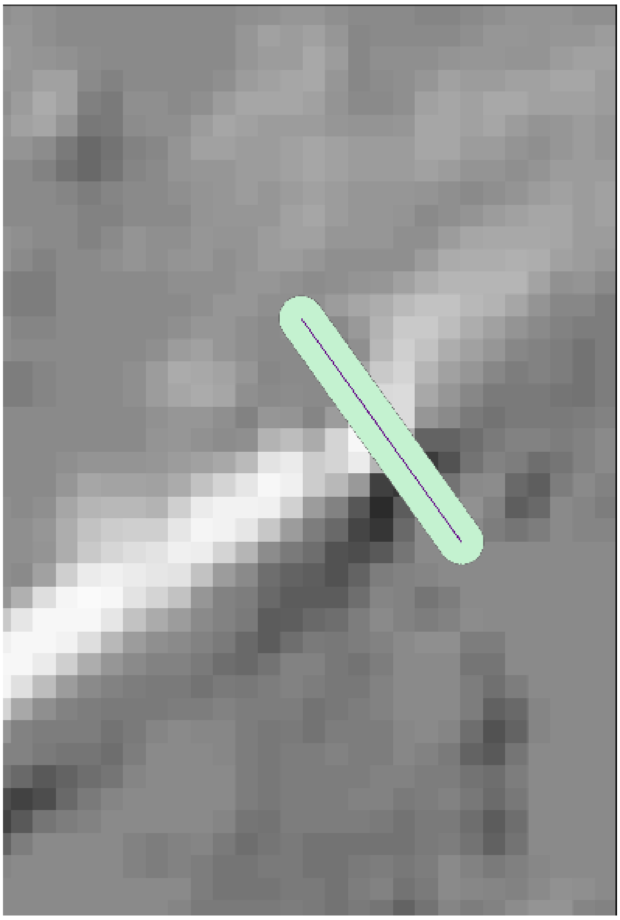

Figure 9: Profile of 2 meters buffer around culvert C6

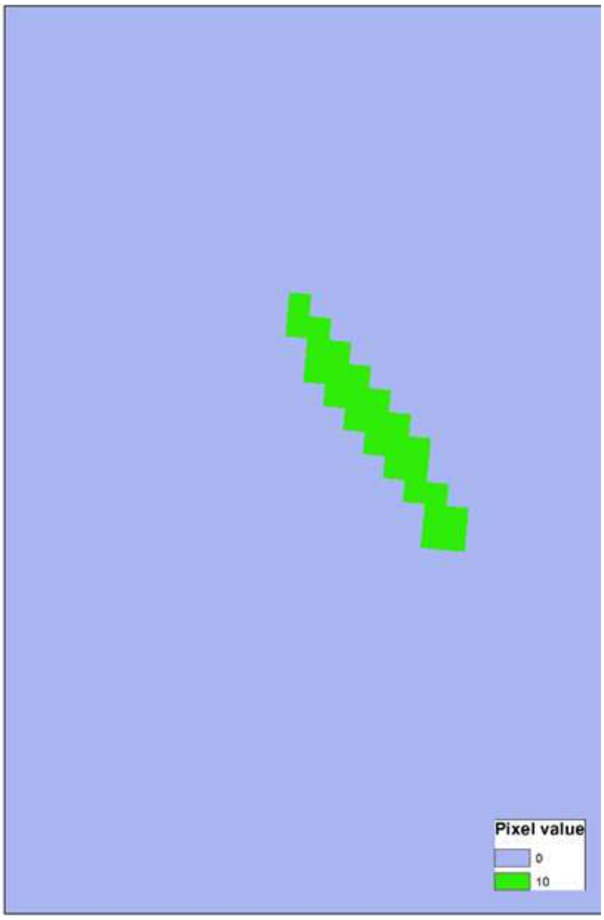

Figure 10: Rasterization of culvert C6

The DEM extent and the buffered culverts are combined using in the Merge tool (Data Management) which combines multiple input datasets of the same type, into a single output dataset. That step will give an output that will contain all the combined input datasets, therefore a polygon layer with value 10 for culverts and 0 for other areas in the extent of the raster.

The next step is to convert the above feature class (figure 9), into a raster dataset (figure 10). The Feature to Raster (Conversion) tool requires to define the field value, which is the field from the feature dataset's attribute table used to assign values to the output binary raster. In this case this is the field Z that will assign the value 10 for cells representing culverts and the value 0 for the cells representing all other areas (figure 10).

Raster Calculator (Spatial Analyst) allows to create and execute a Map Algebra expression, in order to calculate the raster which will be the DEM with its original values but modified at the cells representing the culverts. That can be simply achieved by using as inputs the original DEM and the raster of the culverts and then subtract from the initial DEM the original values of the culverts and replace them with the new value which is -10. The outcome is a DEM on which all other areas are above the height of the culverts. The result of the expression is therefore a raster that represents the final modification of the DEM with the culverts being “carved” in. The same process applies for the bridges, the zvalue is -10 which after processing it attributes the value of +10 for the bridges and that means that the bridges are above other surrounding areas and thus they represent a barrier or a blocked bridge.

2.6 Sinks & Hillshade

A sink is a cell whose drainage direction has not been defined, it occurs when all surrounding cells are higher than that cell or when two cells flow into each other and it is given a value deriving from the sum of their potential directions. The tool Fill (Spatial Analyst) can remove small imperfections in the above raster output by filling the sinks and that is achieved by gradually raising the height level of the sinks until the level of the lowest out flow is reached (figure 11) (ESRI, 2019c).

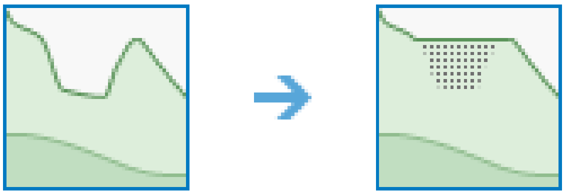

Figure 11: Profile of Fill Sinks tool (ESRI, 2019c)

This method is the most common method for this particular purpose (Graham, 2012) because filling the sinks may not always be suitable, particularly where the water is held in depressions and evaporated or in the case of extensive tile drainage. For Standardized Precipitation Index (SPI) creation, which is one of the indexes used for assessing changes in drought episodes, filling pits is most appropriate process for landscapes with steep slopes and less suitable for areas with low relief (Galzki, et al. 2011).

The Hillshade tool will use as input raster, the fifth output raster and will create a shaded relief raster with integer values ranging from 0 to 255. That is calculated by considering the illumination source angle and shadows. The illumination source is considered to be at infinity. The Hillshade is used as a background layer for illustrative purposes, as it is illustrating well the terrain variations after the DEM manipulation. Figure 12 illustrates with Hillshade the effect of modifying the DEM in accordance with the scenario of making openings in all of the six culverts' locations.

Figure 12: Hillshade before and after manipulating the culverts

2.7 Different Scenarios

In this research 16 different scenarios are tested, 16 different combinations of open and closed culverts and bridges. That means that the DEM has to be modified 16 times accordingly. There are more than 16 combinations but in this research it has not been made scenarios for all. There are 6 culverts and 5 bridges that can either be open (1) or closed (0) and it has to be calculated how many possible variations exist of open or blocked culverts and bridges.

Variations are arrangements of selections of objects, where the order of the objects is important. To calculate k number of variations of n number of objects, we have to choose a k-element combination and then a permutation of the selected objects. Thus, when repetition is not allowed, the number of k-element variations of n elements is calculated by equation (1)

$$V_{n,k} = P_{n,k} = \binom{n}{k} \cdot k! = (n)_k \qquad \textbf{(1)}$$

There is also the number of ways of putting k distinct elements into n distinct cases such that each case receives maximum one element, in other words the number of one-to-one functions from a group of k separate elements into a group of n separate elements. When

$$V_{n,k} = n^k \quad \textbf{(2)}$$

repetition is allowed, the amount of k-element variations of n-elements, is calculated by equation (2).

Equation (2) calculates the number of all ways of putting k separate elements into n separate cases and is also the number of all functions from a group of k separate elements into a group of n separate elements (Bussey, Orgill, & Crippen, 2013). In order to calculate how many possible variations exist of open or blocked culverts and bridges, equation (2) is applied and n stands for the possible outcomes, while k stands for the total number of times, so in this case the formula will be 2^{11} =2048, where 2 stands for the possible outcomes in each bridge/culvert (1 or 0) and 11 stands for the total number of culvert or bridges.

The reason of making the decision of simulating 16 scenarios (out of 2048 possible), is because the aim of this research is to find the possible maximum extent of the water paths and therefore assess which buildings are in the way of the water. If bridge number 1 is blocked by trees or boulders, that will not affect bridge number 4 that is situated in a higher elevation or bridge number 5 that is situated on the neighboring stream. If culvert number one is blocked by debris, that is likely affecting culverts 5 and 6 but not bridge number 3 that is situated far behind and in a higher elevation, and so on. Consequently, there are several scenarios that can be excluded. Nevertheless, the aim of this research is not to portray all the possible combinations that equation (2) is suggesting, but to use some of those possibilities in order to simulate different scenarios and identify buildings and infrastructure that might be on the way of an alternative water path during a flood. That is being achieved with the following 16 scenarios;

1. All culverts are closed & all bridges are open.
2. All culverts are open & all bridges are open.
3. All bridges are closed & all culverts are open.
4. All bridges are closed & all culverts are closed.
5. Bridge 1 is closed & all culverts are open.
6. Bridge 2 is closed & all culverts are open.
7. Bridge 3 is closed & all culverts are open.

8. Bridge 4 is closed & all culverts are open.
9. Bridge 5 is closed & all culverts are open.
10. Culverts 2, 3, 4 are closed & all bridges are open.
11. Culverts 1, 5, 6 are closed & all bridges are open.
12. Culverts 1, 5, 6 are closed & bridge 1 is closed.
13. Culverts 2, 3, 4 are closed & bridge 2 is closed.
14. Culverts 1, 5, 6 are closed & bridge 2 is closed.
15. Culverts 2, 3, 4 are closed & bridge 1 is closed.
16. Culverts 2, 3, 4 are closed & bridge 3 is closed.

2.8 Hydrological modelling

The challenge of the hydrological modelling is to produce the surface runoff. For that purpose I used the hydrology tools from the spatial analyst extension in ArcGIS. The hydrology tools have as basis the parameter of flow direction. Figure 13 visualizes the process of creating a depressionless DEM.

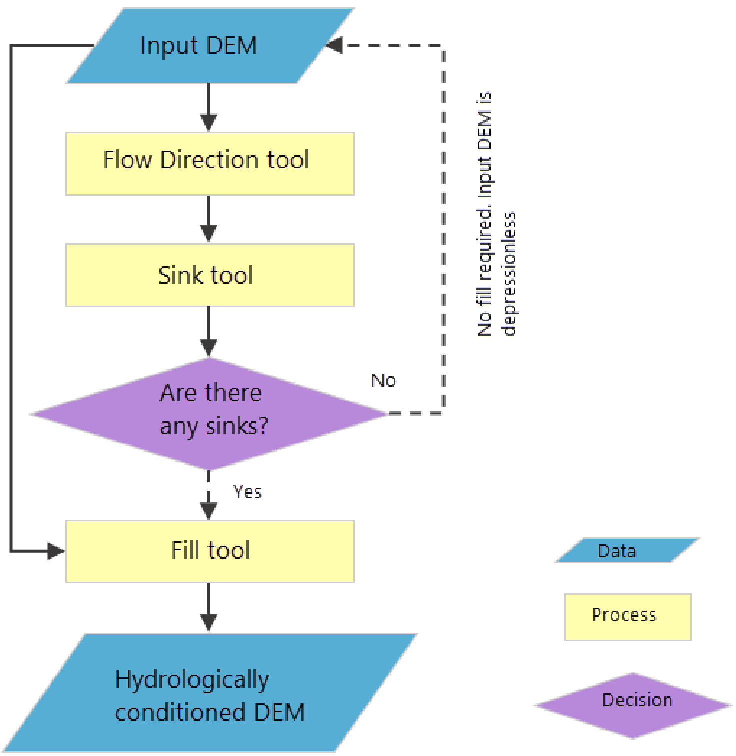

Figure 13: Hydrologic conditioning flowchart (ESRI, 2019b)

The Flow Direction function takes as input a DEM surface raster and creates a raster of flow direction from every pixel to its steepest downslope neighbor. ArcGIS supports three flow modeling methods: the D8 algorithm, Multi-Flow Direction (MFD) algorithm, and D-Infinity (DINF) algorithm.

The Multiple Flow Direction algorithm divides into parts the flow from a pixel to every downslope neighboring pixel. A flow-partition exponent is created based on topical terrain conditions and is used to define the fragment of flow draining to every downslope neighboring pixel (Qin, 2007). The output is not easily visualized because the flow directions of MFD algorithm might have several values attached to every pixel, with every value corresponding to flow segments towards its downslope neighbors (ESRI, 2019b).

The D-Infinity algorithm was proposed by Tarboton (1997) and it defines flow direction as the steepest down slope on eight triangular facets which are centered at the pixel of interest and are presented in a 3x3 pixel window. DINF was created in an attempt to calculate the contributing area more accurately on divergent hillslopes (ESRI, 2019b). The output of DINF "is a floating point raster represented as a single angle in degrees, progressing counterclockwise from 0 (due east) to 360 (again due east)" (ESRI, 2019b).

The method D8 has eight flow directions and it is the most common and simplest method for identifying flow directions (Tarboton, 1997). It works by specifying the flow from every cell to one of its eight neighboring cells, that is the steepest downslope cell of all its eight neighbors (O' Callaghan and Mark, 1984). The result of the Flow Direction tool run with the D8 algorithm, is an integer raster with values ranging from 1 to 255. There are eight valid output directions relating to the eight adjacent cells into which flow could travel. This approach is referred to as an eight-direction (D8) flow model and follows an approach presented in Jenson and Domingue (1988). One disadvantage of the D8 method is that it's considering that the water flows into only one of the eight possible directions, separated by 45° (figure 14), which means that the modelled flow can only have these 8 azimuth directions: 45, 90, 135, 180, 225, 270, 315 and 360 degrees (Tarboton, 1997). This means that D8 allows to model just these 8 directions of drainage, while in reality, the water is possible to flow in an infinite number of azimuth directions (ESRI, 2019b).

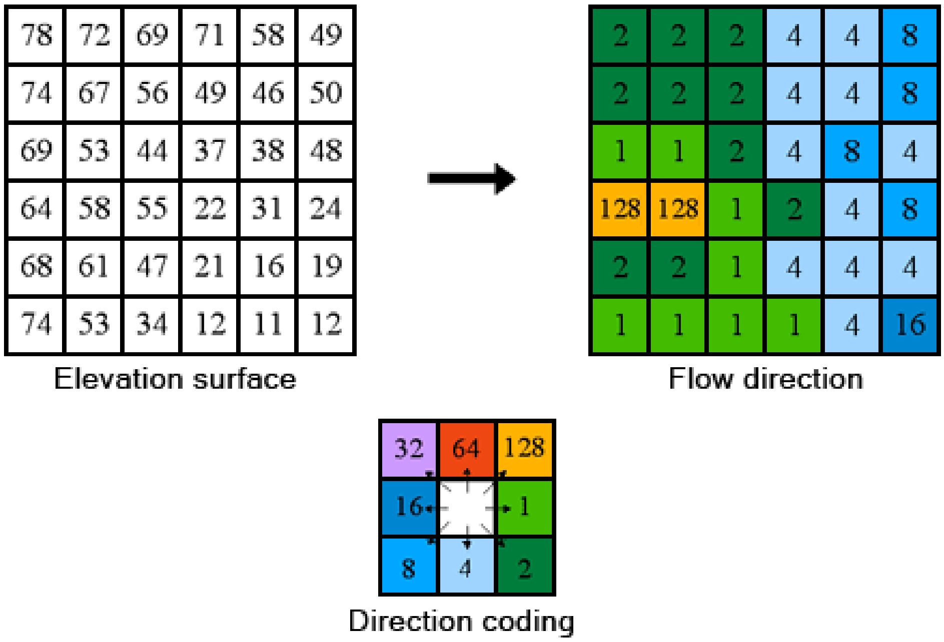

Figure 14: The coding of the flow direction (ESRI, 2019b)

The method allows modelling of convergent flow, that is several cells that drain into one cell, but does not allow modeling of divergent flow, accordingly that one cell drains into several cells (Gruber & Peckham 2009). The elevation values corresponding to neighboring pixels, usually have similar values because of the smooth variation of the terrain (high autocorrelation), but the D8 algorithm is generally suitable for small drainages in areas of high relief (Jones 2002). The increase of the quality and resolution of the elevation data will minimize the error due to ambiguous flow (Olivera et al. 2000). The study area of this research is steep (ca. 3-17%) and the DEM is of high resolution, therefore the use of D8 algorithm for assigning the flow direction is a suitable method.

Flow direction has to be executed once in order to create the hydrologically conditioned DEM and once more, to generate a flow direction output which differs from the first one since it has filled several sinks and that one is used for the flow accumulation.

2.9 Flow accumulation

Flow Accumulation is the next step in the process. Based on the flow direction raster, the Flow Accumulation tool calculates how many upstream cells are draining to each cell. Each cell is given a value corresponding to the total number of upstream cells (Figure 15).

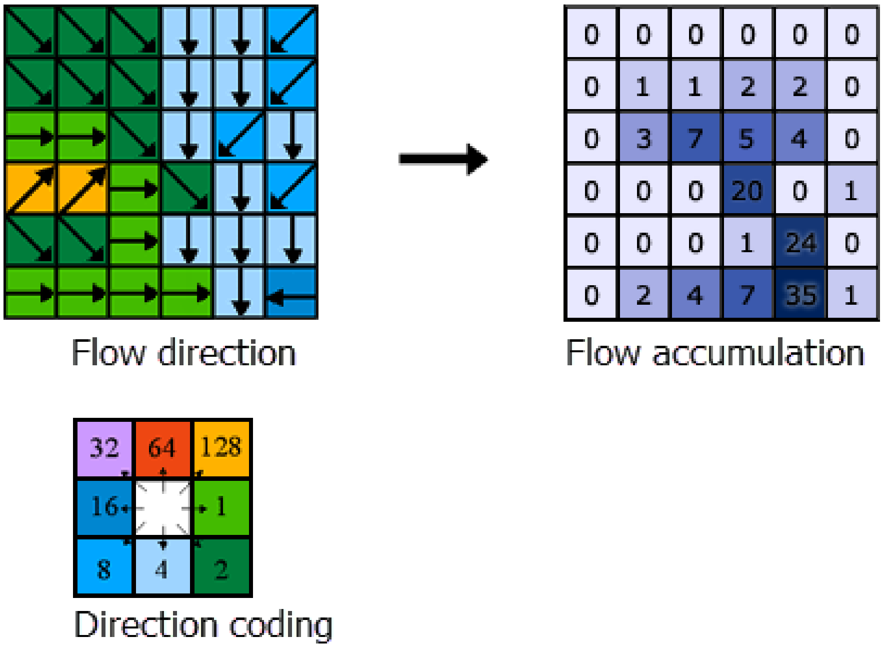

Figure 15: Determining the accumulation of flow (ESRI, 2019a)

The result of the flow accumulation process is a grid in which the cells with the highest value create a network of drainage channels, and cells having a value of "0" represent ridges (Jenson, 1988). Each pixel value represents the number of upstream pixels that are contributing water into it. High numbers mean that there is a large upstream drainage area. A pixel value of 0 indicates that there are no other pixel in the raster that flow into it. A value of 1 indicates that 1 pixel flows into it. These values can be translated to sub-catchment areas feeding into each pixel, whose sizes can be found by multiplying the pixel value with the pixel value's surface area (Jenson, 1988).

In addition, a threshold or cut-off is chosen to separate the drainage channel cells from the rest of the cells. This threshold will set all cells with values above the threshold to "1" and all values below the threshold to "0". According to Jenson (1988), "because all cells in a depressionless DEM have a path to the data set edge, the pattern formed by highlighting cells with values higher than some threshold delineates a fully connected drainage network. As the threshold value is increased, the density of the drainage network decreases". In other words, the threshold value symbolizes the minimum number of cells that flow into a cell of the flow accumulation grid. If the threshold number is too high or too little, the flow accumulation will not represent accurately the drainage network. In this research, four different thresholds were tested in order to find the most appropriate and the results were compared to NVE's river layer of the area. The four thresholds tested were the following: 2,500, 5,000, 7,500 and

10,000 cells. A threshold of 2,500 was too fine and detailed, showing channels that did not exist on NVE's river network layer. A threshold of 10,000 cells was too coarse and the threshold of 7,500 cells was not that coarse but did not coincide with the river layer. The most appropriate threshold for this research is that of 5,000 cells, which presented enough detail and was the closest to the river network layer. However, determining a threshold value that demonstrates where a stream or stream channel begins is also affected by climate, slope, and soil attributes (Tarboton, Bras & Rodriguez–Iturbe, 1991).

I visualized the above as a classified color scheme with only 2 classes, one class is the river channel and one class is what is not the river channel which got a NoData value. The cut off is at 5.000, so what is below 5.000 is just a spot on the hillslope and is represented with no color, and what is above 5.000 is the modelled river channel and is represented with blue color. The tool delineated all the river channels and the pixels with high accumulation that are actually in the riverbed are blue, while everything else is clear. However, under different circumstances there would come to surface a couple of big issues. When the original DEM is used as a basis, without any changes in the points of the culverts, the river is directed to hit the road and get deflected down the road. In that case, there is a culvert going under the road, or a bridge perhaps that should make the channel continue under the road and through the culvert. Therefore, the topography of the map has to be inspected. What could have happened in such a case is that by running the Fill operation, the starting point of the culvert would be recognized as a sink and thus it would be filled up behind the road. Then the river would spill out at the closest downslope cell and actually end up flowing down the road until it would join the river. The water would flow down the road and in that case there would be a culvert that is going under the road there. It is important to not misuse the flow accumulation tool and always make sure the result is reasonable. In this master thesis, the DEM has been manipulated at the locations of the culverts and bridges and the modelling indicates what may happen if critical points (culverts and bridges) become impedance for the flow of water, forcing it to deviate from its normal course and make damages to properties and infrastructure.

In order to better visualize the range of the contributing area, I took the log of the flow accumulation values. In the raster calculator I performed a map operation log10 of the flow accumulation grid and on the output I changed the color map starting from yellow to blue as flow accumulation values increase. In that grid exist some NoData values. This goes up to the very finest parts of the hillslopes and sometimes hillslope processes may dominate over fluvial processes so the transition from hillslope to fluvials is right at some critical contributing area.

In raster calculator I used the conditional evaluation Con of the log grid of the previous step and calculated the expression Con("log grid" >= 2, "log grid") which means that where it is true that log grid is bigger or equal to 2 then it will return that log grid, otherwise the cells are assigned as NoData. The output is a more realistic looking drainage network with a more persistent structure and on which I gave the same color map as on the previous step.

To identify the exposed buildings and infrastructure and rank the most exposed areas using the Zonal Statistics tool. Zonal Statistics summarizes the values of a raster within the zones of another dataset which can be either raster or vector and reports the results to a table (ESRI, 2019a). As input feature zone data is used the buildings feature class and the roads feature class and as input value raster I used the flow accumulation raster that contains the values on which to calculate the mean or average of all cells in the value raster that belongs to the same zone as the output cell. Zonal statistics was repeated for every scenario and the output presents buildings and road segments being exposed, as well as ranking them based on the possible amount of water that can "hit" the buildings and road segments.

2.10 Study limitations

This study was subject to a variety of limitations which I will describe in this section. The first limitation experienced was the difficulty to find English literature about the study area. However, that was expected when I chose my topic and the solution to this was to hire a translating service to help me translate all the necessary official documents and relevant literature. Another limitation related to the language, was the contact with officials from Stryn municipality. Contacting with the project managers of flood related matters in Stryn, helped me gain insight in the management after the disastrous flood of Utvik in 2017 and in understanding prevention measures taken in case of repeating a future event and was vital for my research. In this case the communication was challenging for both parts, the municipality officials and me, but it was successful in the end. One more limitation was that I did not conduct fieldwork myself, something that wasn't really necessary for this research but it was impossible to find data on culverts otherwise. This difficulty was overcome with the contribution of PhD candidate Michal Pavlíček, who was conducting his field work in the area at the same time and provided me with the data in need. However, even though not necessary to be in the field, it would be useful to be present and observe in person in order to gain a better understanding of the geography of the area. In addition, issues coming from the ArcGIS usage had to be dealt with during the workflow. The large amount of data I analyzed resulted the processes to run slowly and occassionally caused the program to crash. Despite these limitations described above, the credibility and quality of the current project was not affected.

3 Results

This chapter focuses on the findings of the research which are presented in the form of static maps for each individual scenario tested. In order to describe the results optimally, it has been used for every scenario an illustration of the flow accumulation. The flow accumulation is presented with a logarithmic scale to demonstrate the smaller flow paths as well, applying a gradually increasing colour scale from low to high values, where lighter color indicates smaller accumulation values and it increases gradually to darker color which indicates higher accumulation values. In addition, are included illustrations that show the changes in the flow based on the functional or dysfunctional culverts and bridges, in comparison with the main river channel when everything is functional. Eventually, are included illustrations of the classified ranking of the exposed buildings and roads based on the possible water accumulation.

3.1 All culverts are closed & all bridges are open

In this scenario, the original DEM has been used, with no modifications at the culverts and bridges location. Figure 16 illustrates the flow accumulation in the study area when all culverts and all bridges are functional. The inset map of figure 16 together with figure 17, are focused on a part of the river and they show that when the culvert is closed, the water is flowing along the road or other infrastructure, because in this case the water has no other path to follow since the culverts are not functional and thus it follows the downhill direction provided, which is along the road in this case. Figure 18 shows the rate of exposure of the buildings and road segments based on the possible water accumulation, ascending from low to high. Low exposure level indicates low values based on the flow accumulation raster, while high exposure level indicates high values from the flow accumulation raster.

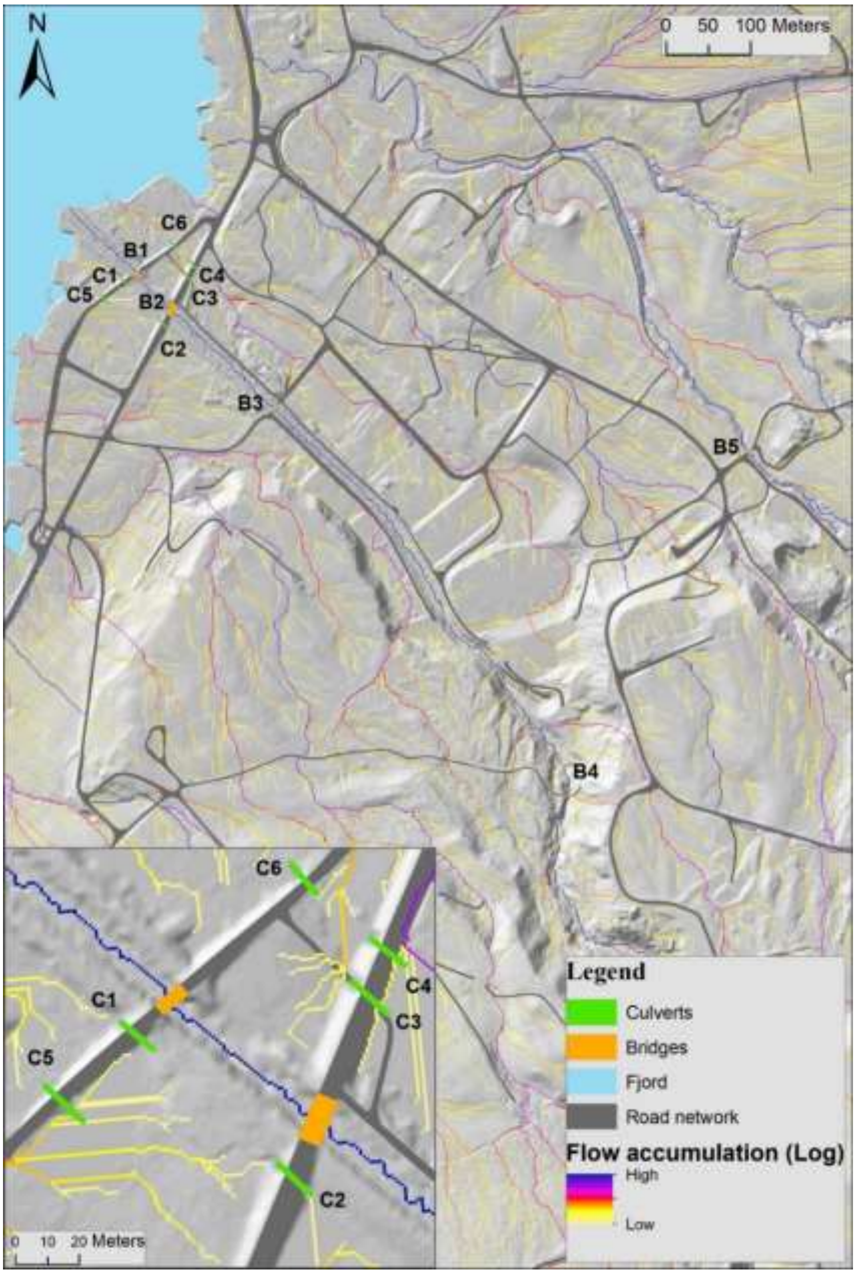

Figure 16: Flow accumulation in the case all culverts are closed & all bridges are open

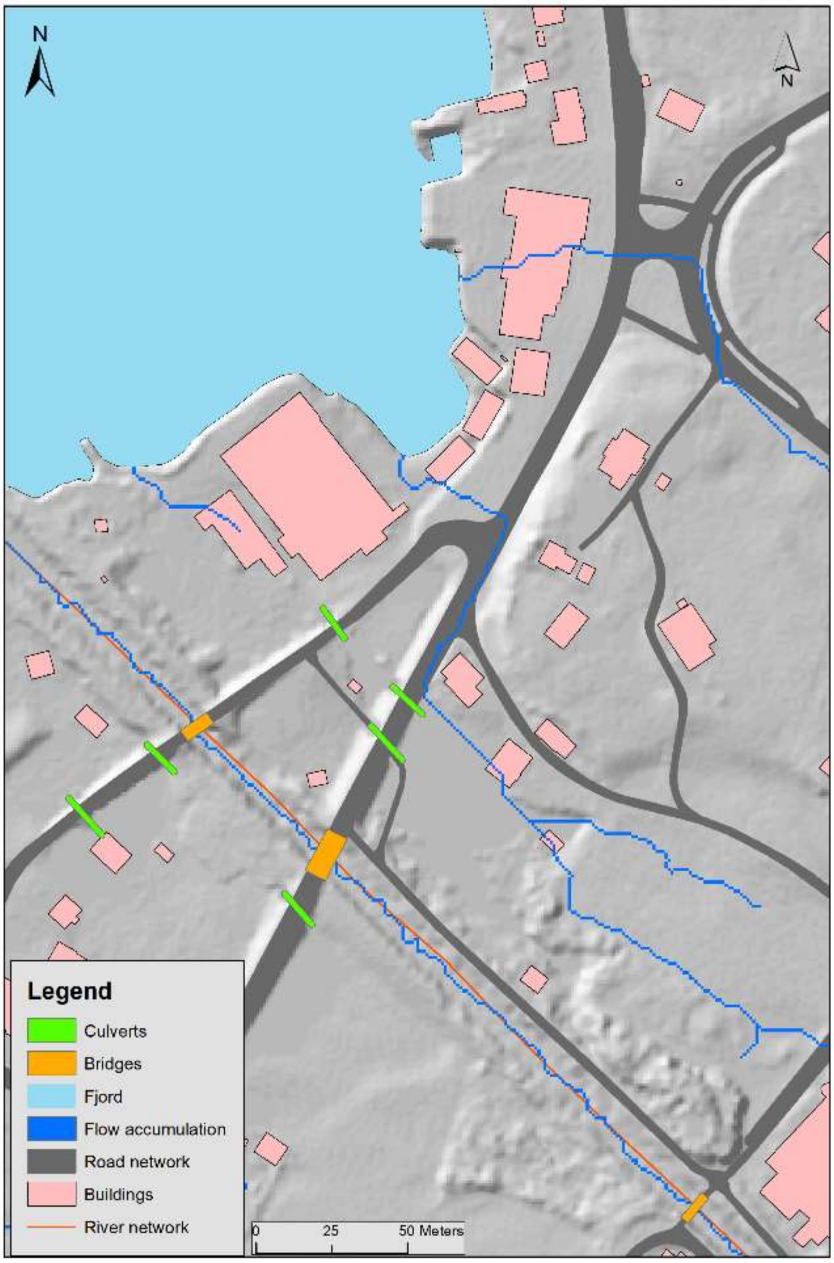

Figure 17: Water flowing along the road in the case of a blocked culvert

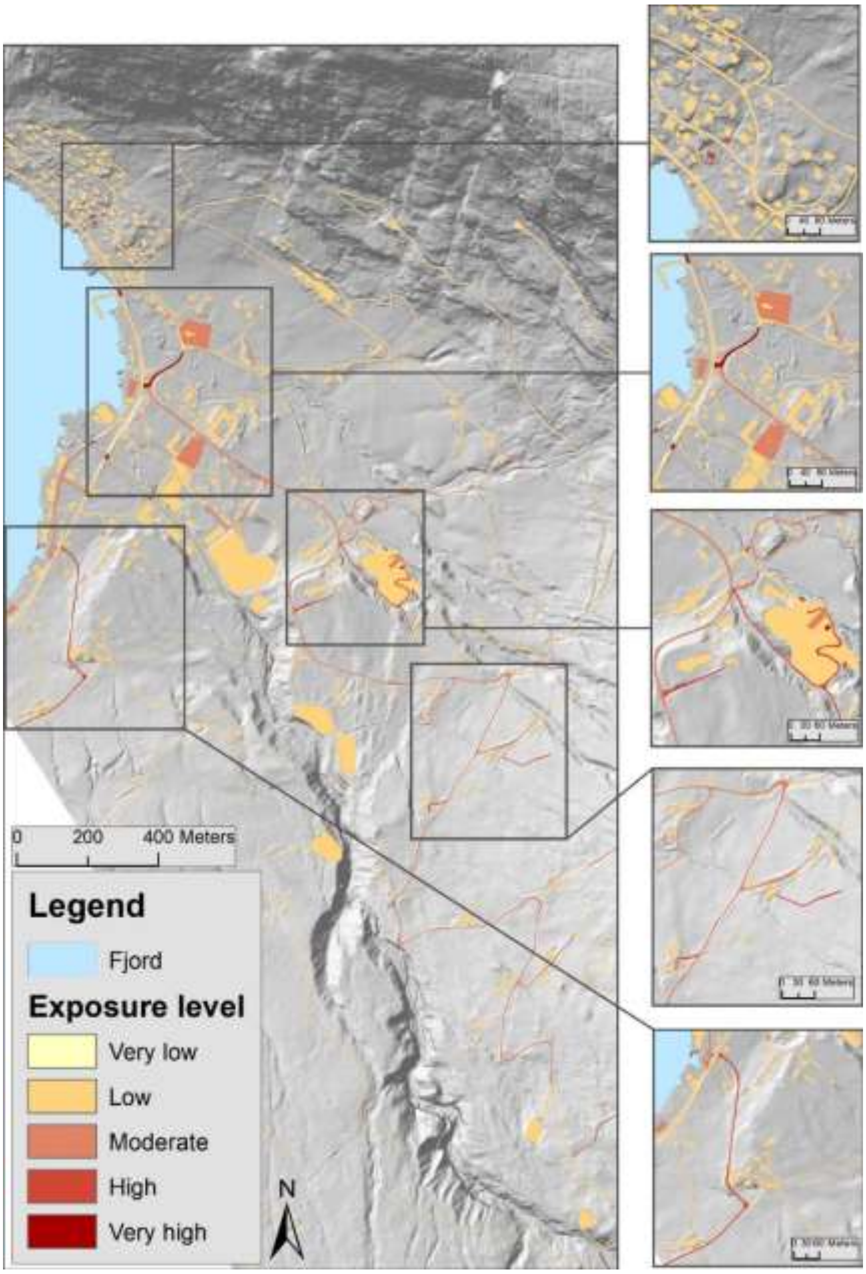

Figure 18: Exposure level of buildings and road segments based on the possible water accumulation in the case all culverts are closed & all bridges are open

3.2 All culverts are open & all bridges are open

In this case the culverts have been represented in the DEM and the result clearly shows that the water flows through the culverts when it is functional. This scenario represents the case of every culvert and bridge being functional and in general the highest accumulation values coincide with the river system. Figure 19 demonstrates the flow accumulation and in the inset map is represented how the water follows the path towards the culverts when the

DEM is modified, instead of following the road or any other low path along the existing infrastructure. Figure 20 shows the level of exposure of road segments and buildings, which in contrast to the first scenario (figure 16), the water flows normally through the culverts and is not exposing neither roads nor buildings.

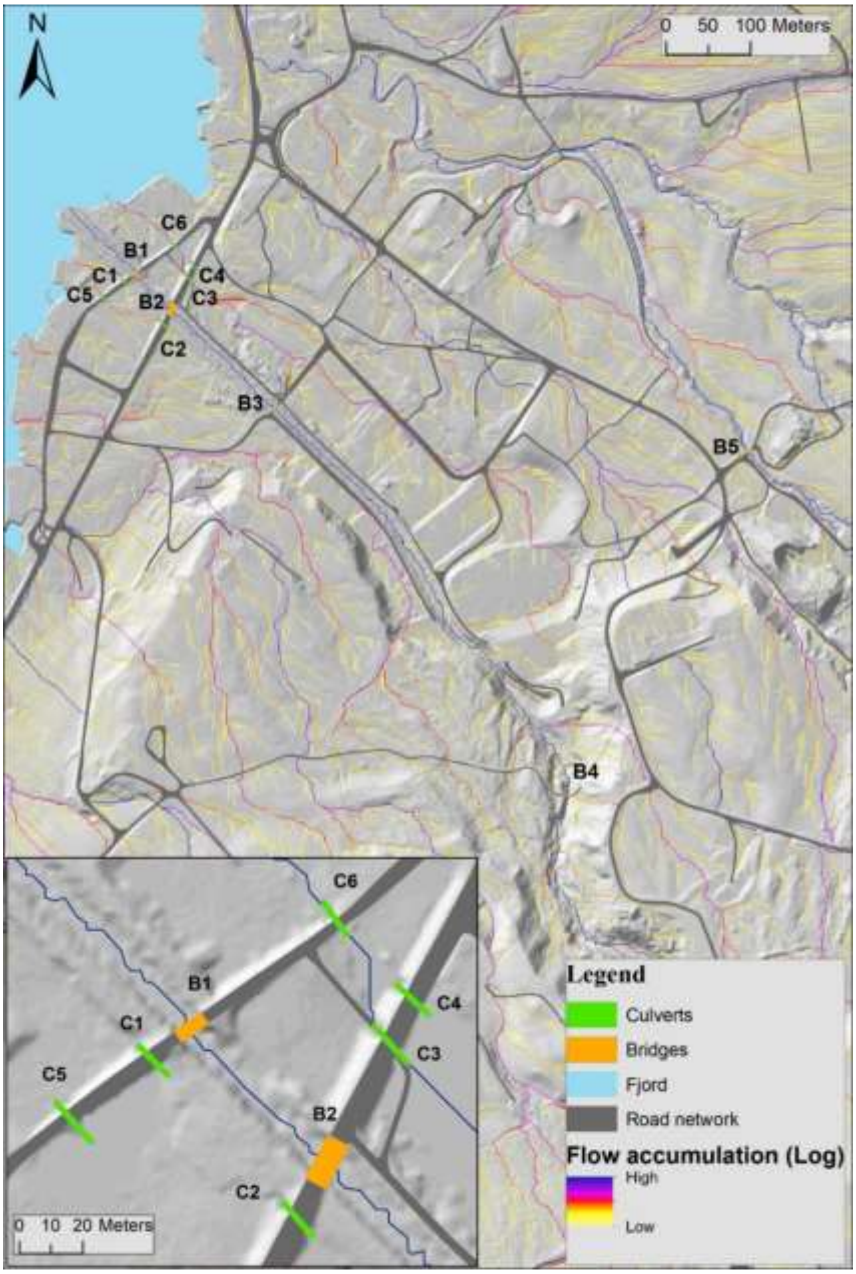

Figure 19: Flow accumulation in the case all culverts & bridges are functional

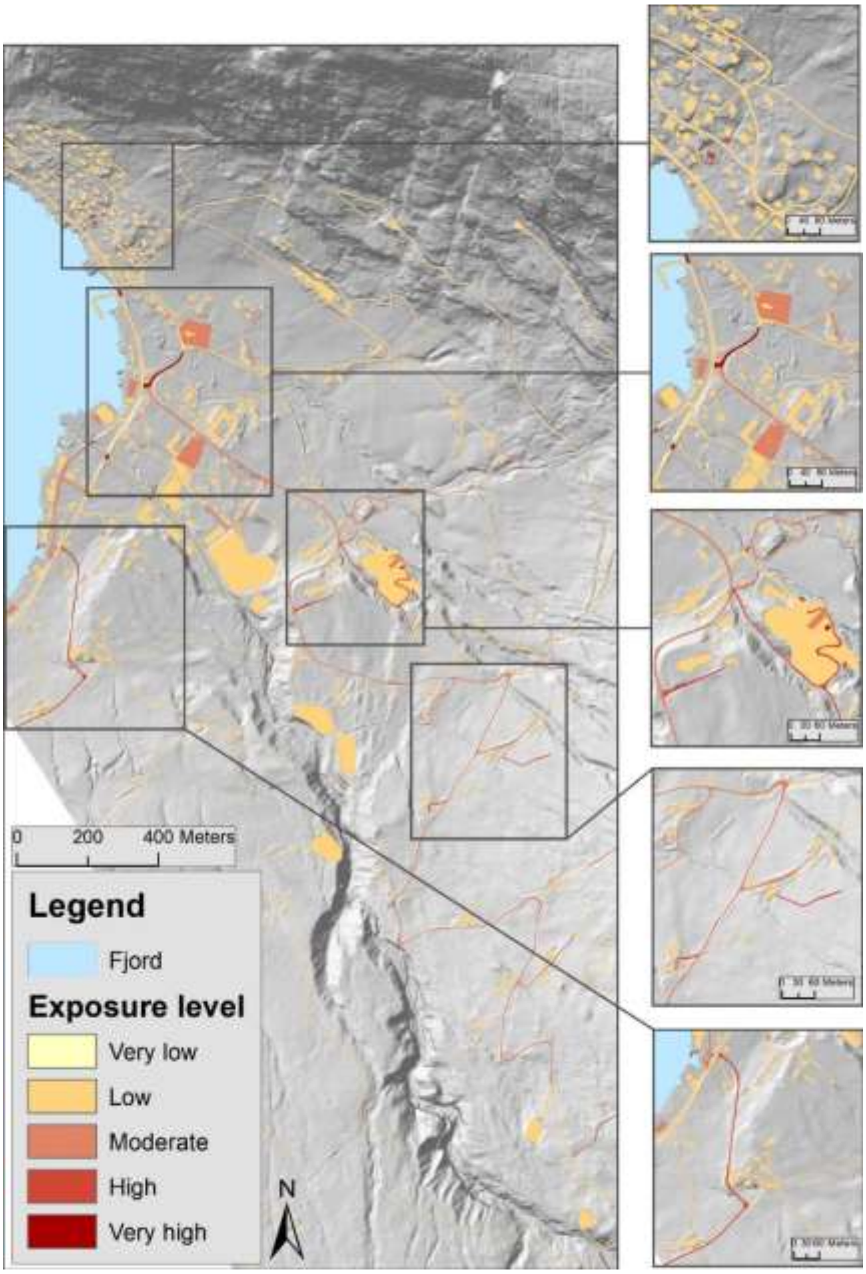

Figure 20: Exposure level of buildings and road segments based on the possible water accumulation in the case all culverts & bridges are functional

3.3 All bridges are closed & all culverts are open

In this scenario, the DEM has been modified at the culverts locations, making openings and allowing the water to flow through the culverts. At the bridges' location however, I have created barriers in order to block the water and force it to take other paths. The water flow was not affected by the blocked bridges B4 and B5 (see figure 22), where in both cases it followed the path around the bridge and continued right after on the main flow path. Before bridge B3 however, in the case that is blocked, the water goes around, meets the road and continues to the direction of the road until it makes a turn downhill following the path that eventually meets and flows in a row through culvert C3 and C6 (see figure 21).

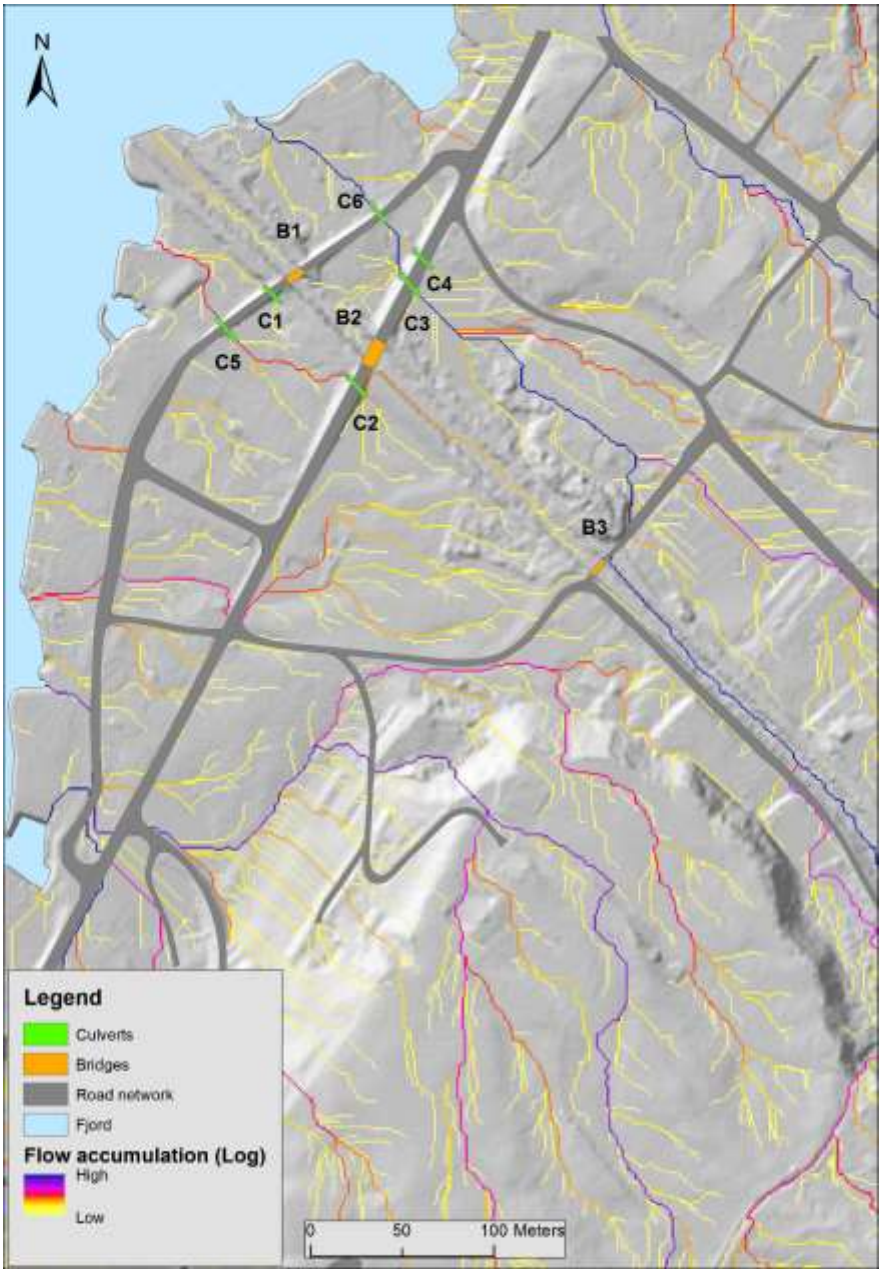

Figure 21: Flow accumulation when every bridge is closed & every culvert is open

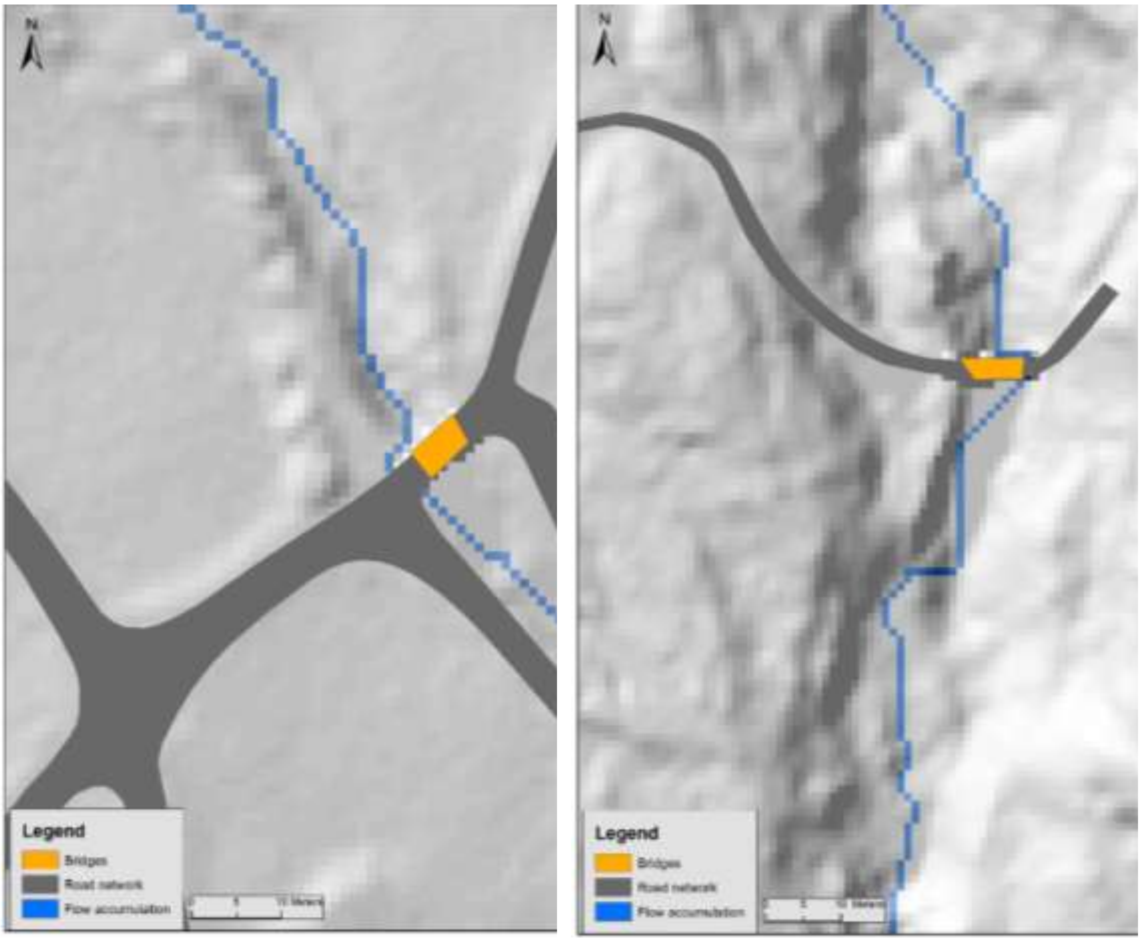

Figure 22: Water path when B5 is closed (left) and B4 is closed (right)

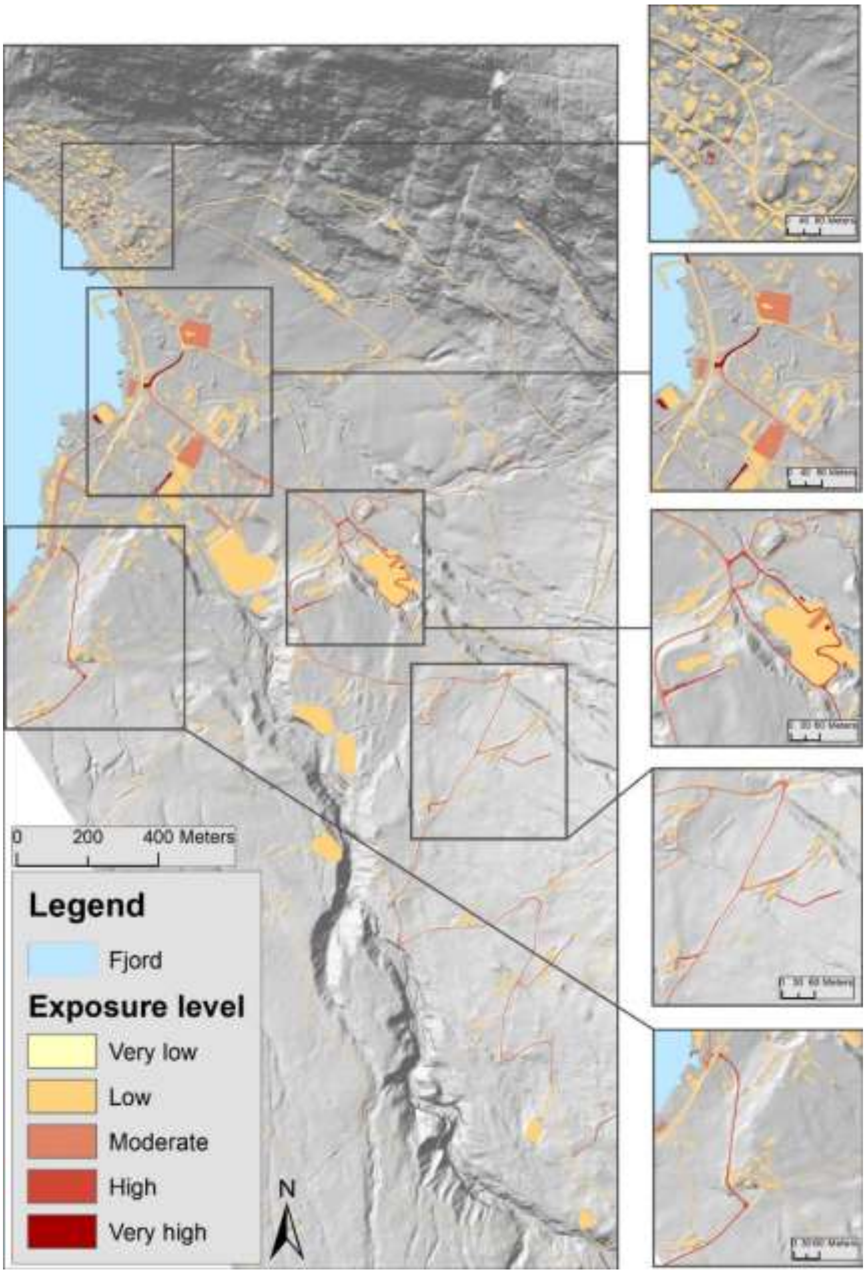

Figure 23: Exposure level of buildings and road segments based on the possible water accumulation when every bridge is closed & every culvert is open

3.4 All bridges are closed & all culverts are closed

For this scenario, the original DEM has been modified at the locations of all of the bridges by making barriers and all the culverts are closed. In figure 24 below, one can see that before bridge B3, the water is following the road, goes down the lowest path until it meets another road, similarly to the previous scenario up to this point (figure 21). After that however, the water turns at the point where the culvert should be open and follows the road again and therefore it meets on its way with buildings and road segments close to bridges B2 and B3, which as a result are highly exposed (see figure 25).

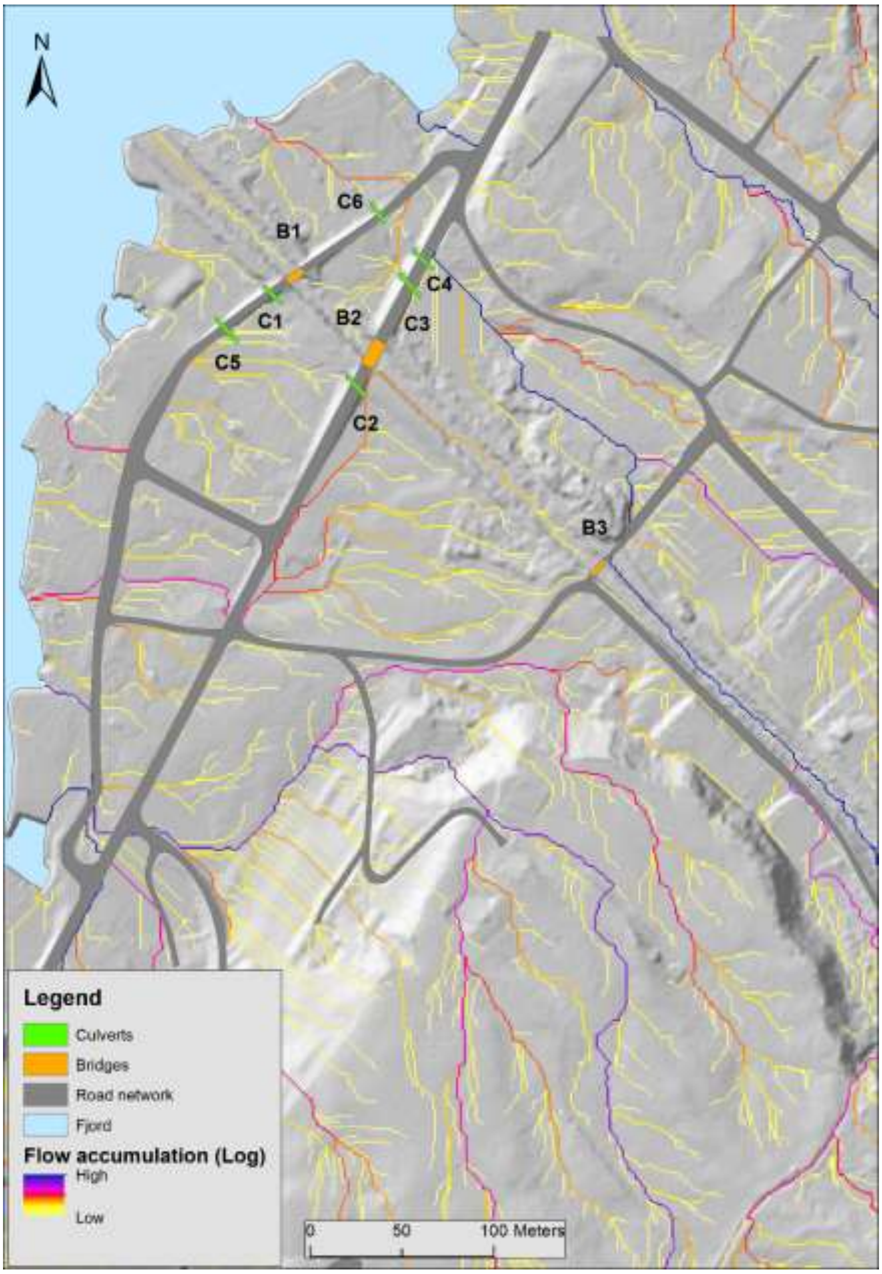

Figure 24: Flow accumulation when all bridges & culverts are closed

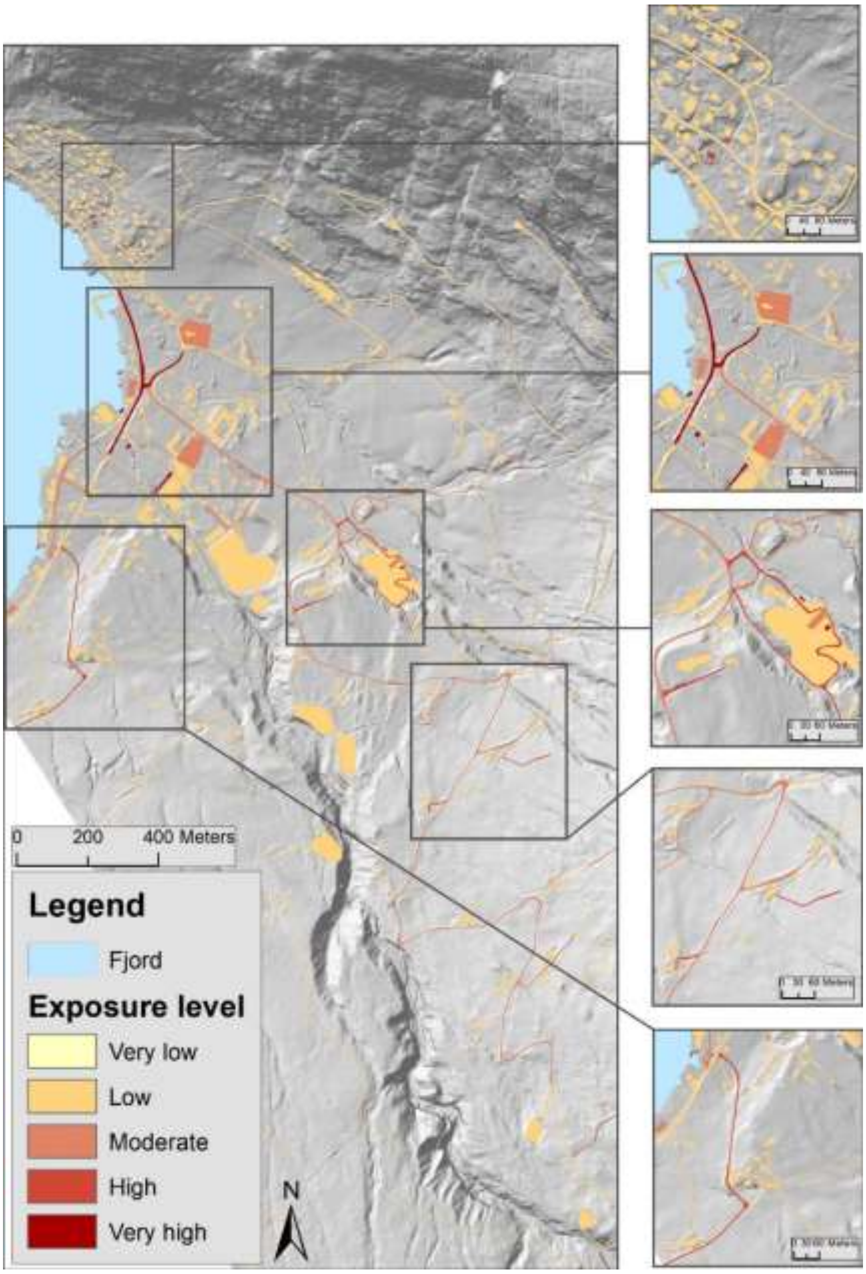

Figure 25: Exposure level of buildings and road segments based on the possible water accumulation when all bridges & culverts are closed

3.5 Bridge B1 is closed & all culverts are open

In this scenario, the DEM has been modified at the locations of the culverts by making openings and at the location of bridge B1 by making a barrier and results to the water flow of high accumulation to change its original flow after bridge B2, hit a small road and eventually flow through the culvert C6, as figure 26 shows. In figure 27 is shown that the water accumulates in different part of the area compared to figure 25 and it hits buildings and roads around the culvert C6.

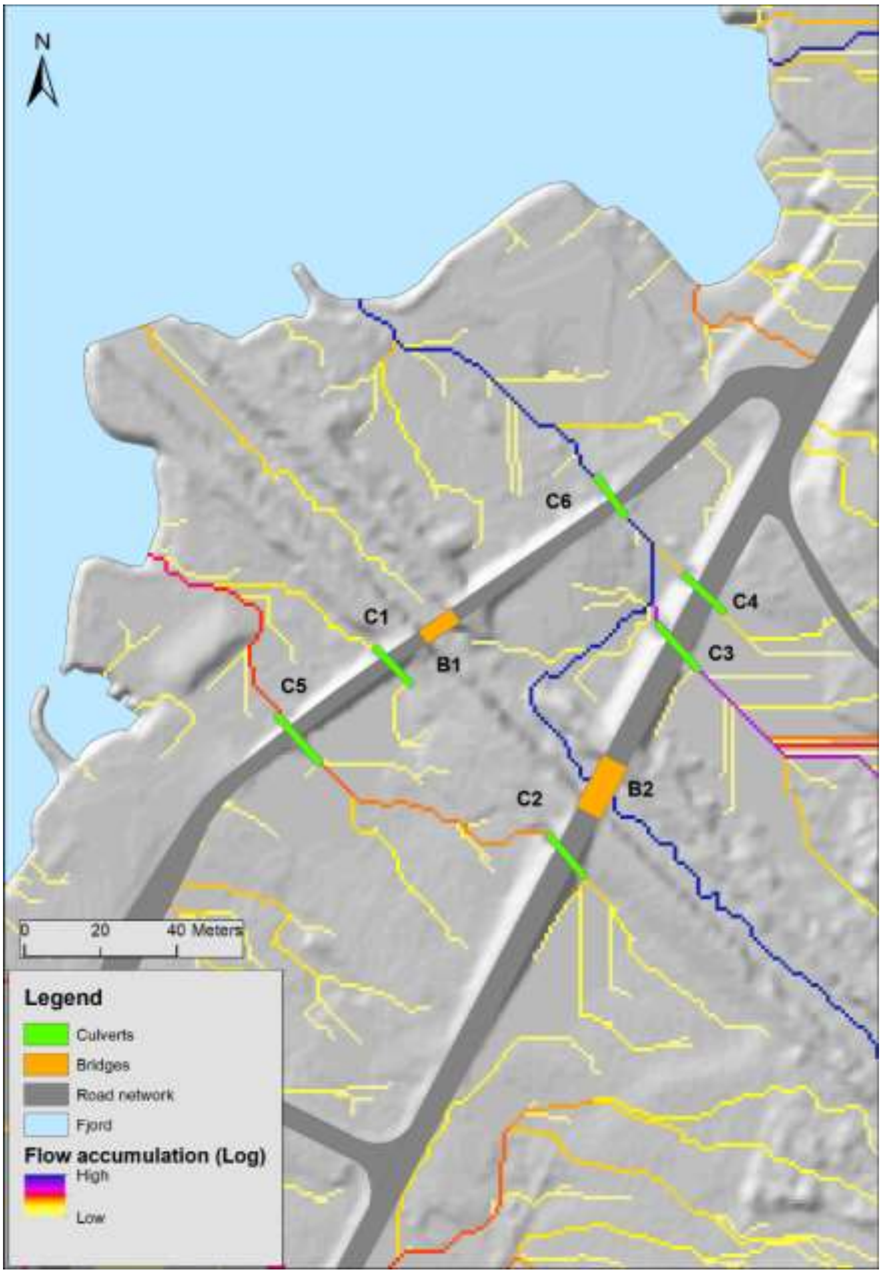

Figure 26: Flow accumulation when B1 is closed & all culverts are open

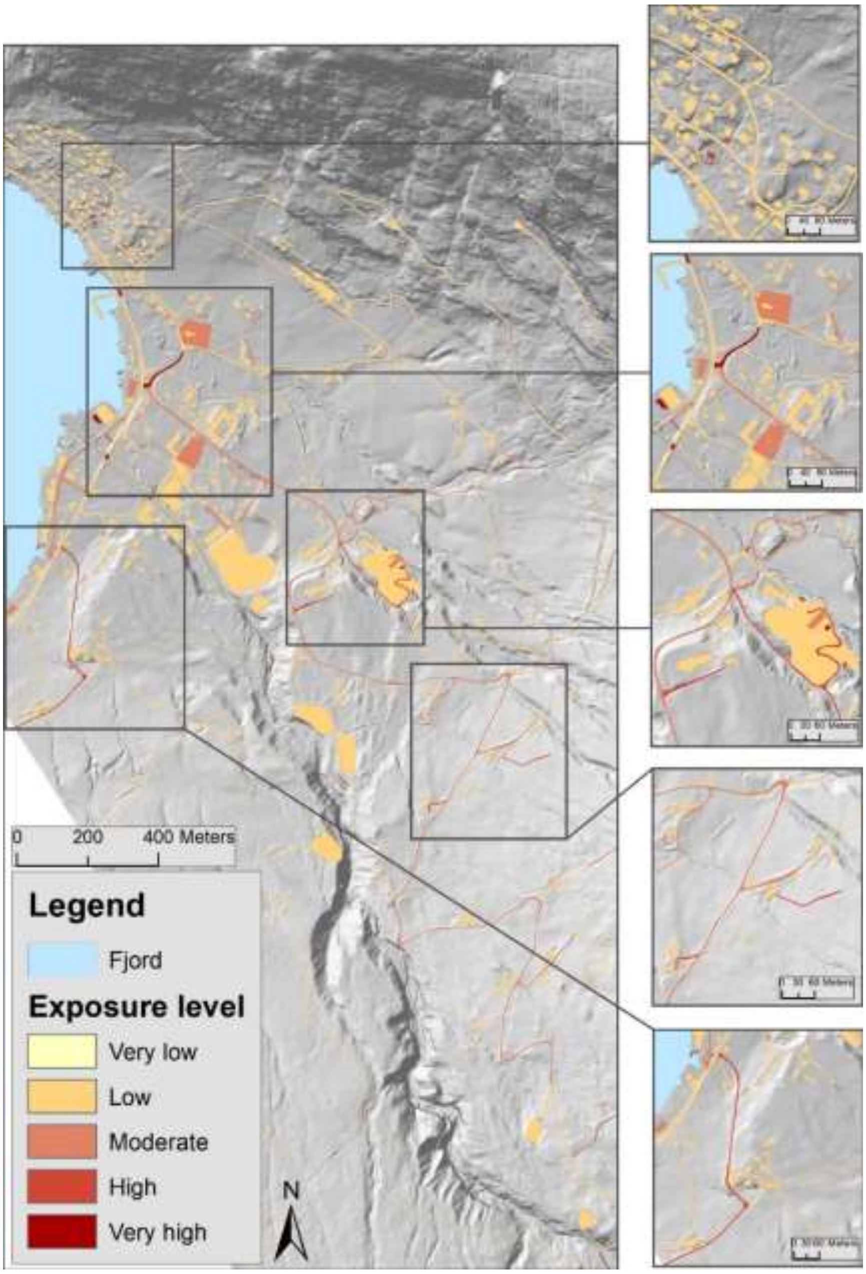

Figure 27: Exposure level of buildings and road segments based on the possible water accumulation when B1 is closed & all culverts are open

3.6 Bridge B2 is closed & all culverts are open

In this occasion, the DEM has been modified at the locations of the culverts by making openings and at the location of bridge B2 by making a barrier. Compared to the initial river channel, the flow has moved left in this case and as figure 21 shows, the river flows through the bridge B3, but right before the blocked bridge B2, it turns left and goes around the bridge B2, follows the road and is forced to flow through the culvert C2 and from there is going downwards and through the culvert C5. Figure 29 presents that one building right before the culvert C5 is on the water way, as well as that the roads on the left side of the bridges B1 and B2 have accumulated higher values.

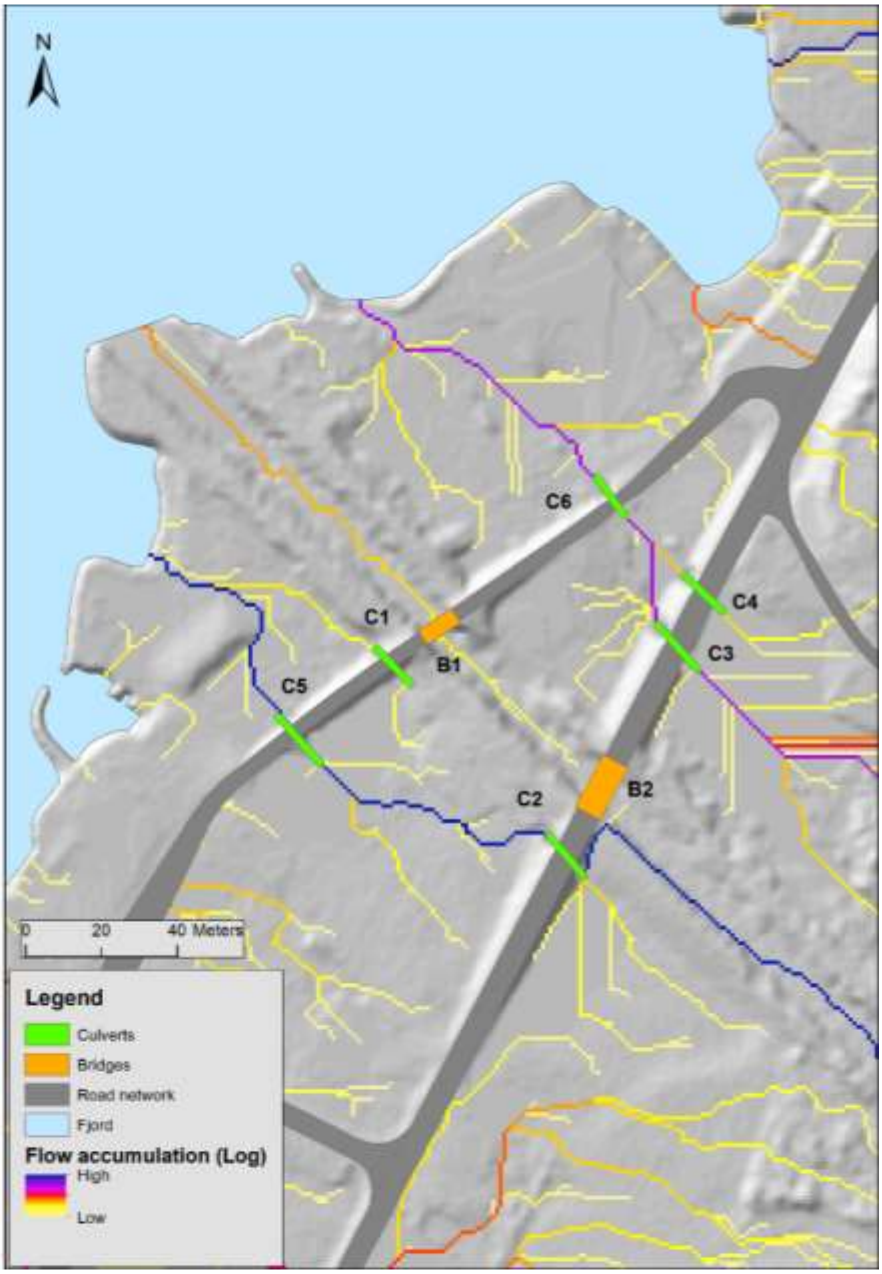

Figure 28: Flow accumulation when B2 is closed & all culverts are open

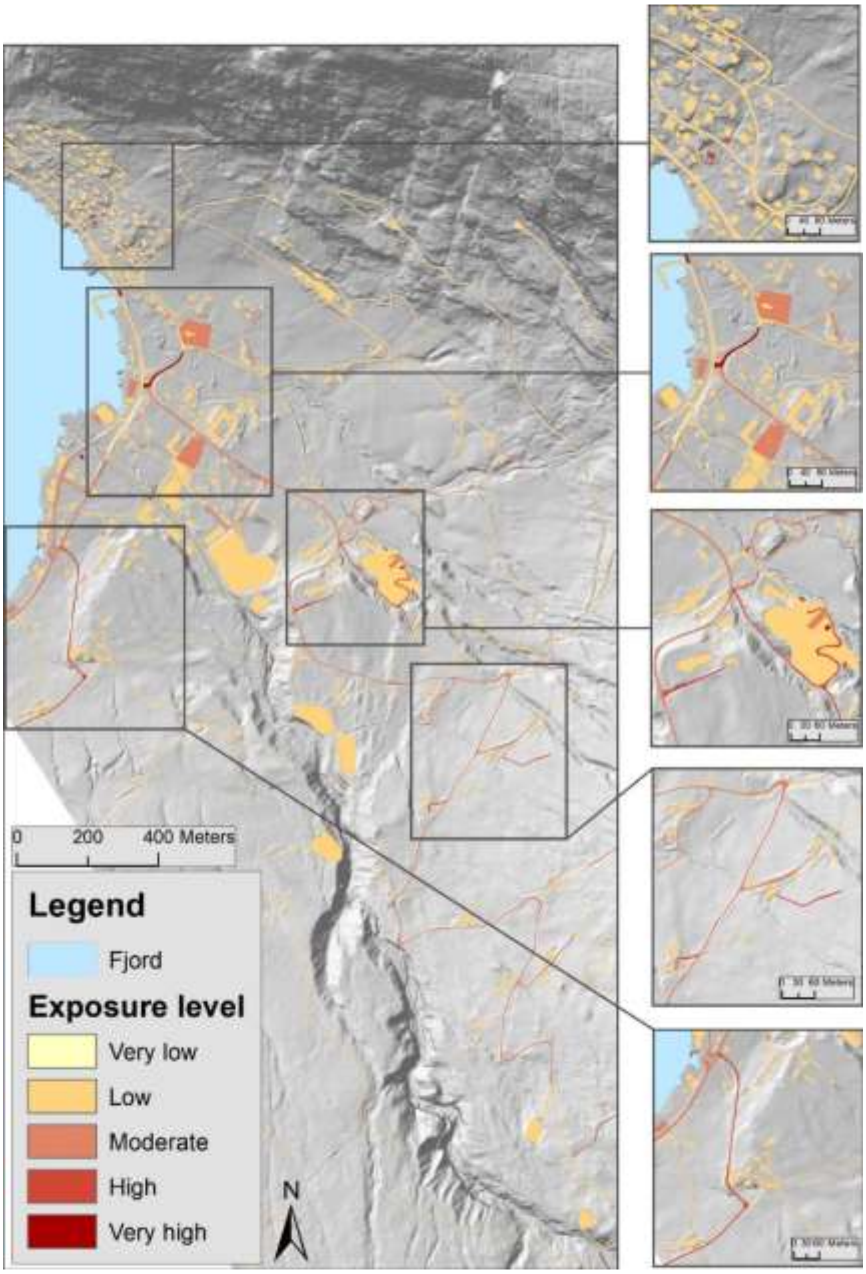

Figure 29: Exposure level of buildings and road segments based on the possible water accumulation when B2 is closed & all culverts are open

3.7 Bridge B3 is closed & all culverts are open

In this scenario, the DEM has been modified at the locations of the culverts by making openings and at the location of bridge B3 by making a barrier. Figure 30 shows that in this case the highest accumulation has moved before the bridge B3 to the right and around it and from there it continues until the culvert C3 and then through the culvert C6. In figure 30 one can also observe that the main river has taken a very different path than the initial river from the point that it hit the blocked bridge B3.

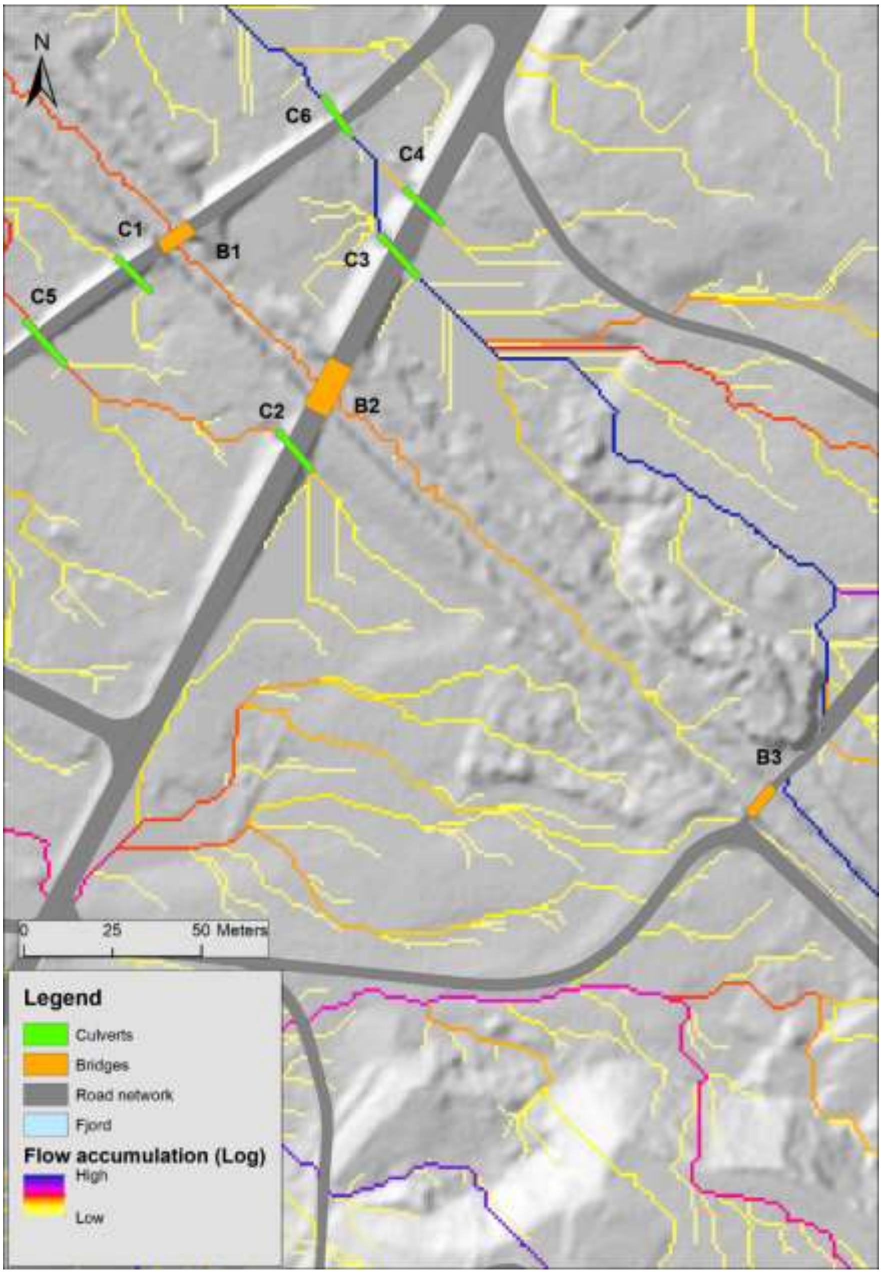

Figure 30: Flow accumulation when B3 is closed & all culverts are open

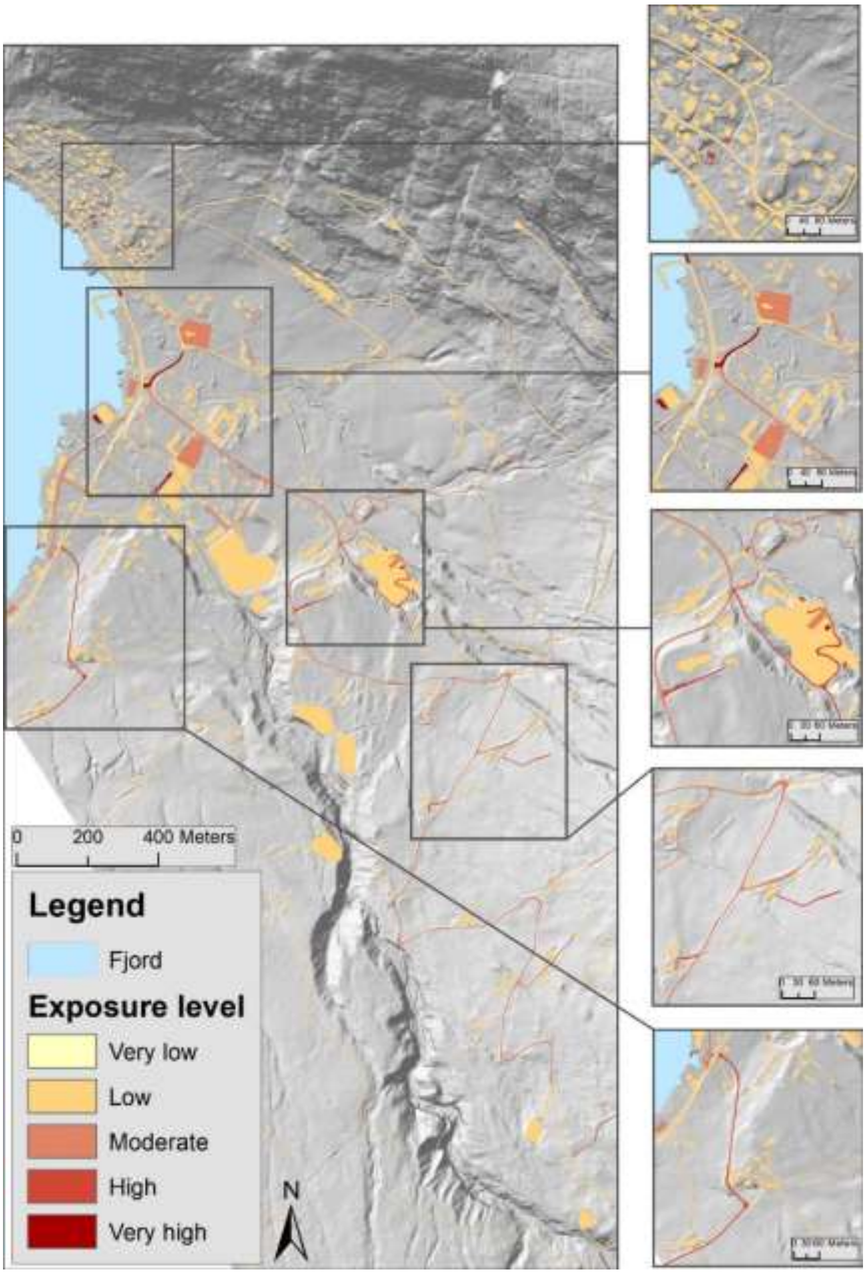

Figure 31: Exposure level of buildings and road segments based on the possible water accumulation when B3 is closed & all culverts are open

3.8 Bridge B4 is closed & all culverts are open

In this occasion, the DEM has been modified at the locations of the culverts by making openings and at the location of bridge B4 by making a barrier. Figure 32 shows that the water goes around the bridge and directly continues to the same path it originally flows with no differences. One possible reason that this is happening, is because the elevation is high enough to force the water downwards the main path even though the bridge is blocked, or that during the DEM modification should have been used bigger z-values when creating the barrier. However, this could be better evaluated if there would be pictures available of that particular bridge and the surrounding area. In any case, this is one of the two bridges that failed to "block" the water. As a result, the buildings and road segments affected (figure 33) are the same as when all the bridges and culverts are functional (see figure 20).

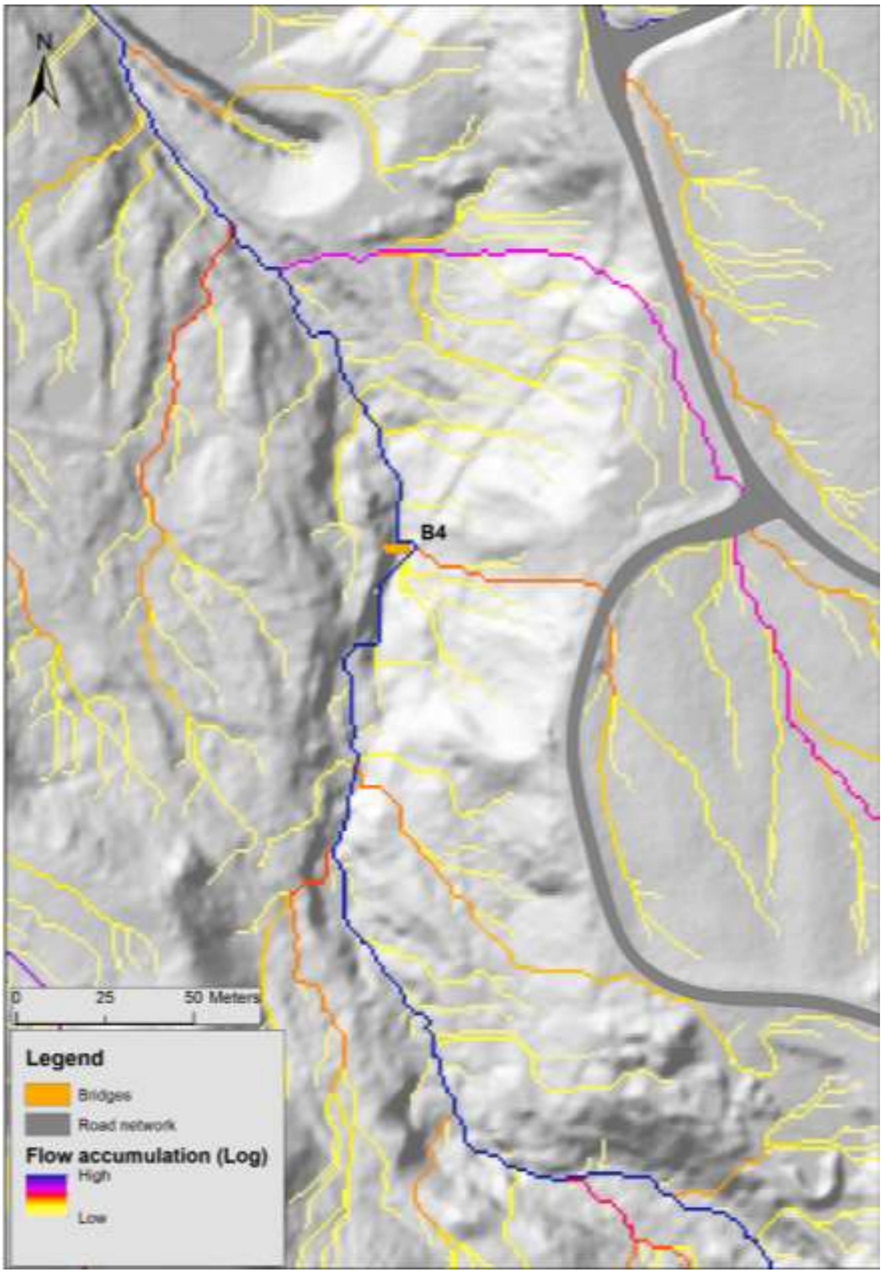

Figure 32: Flow accumulation when B4 is closed & all culverts are open

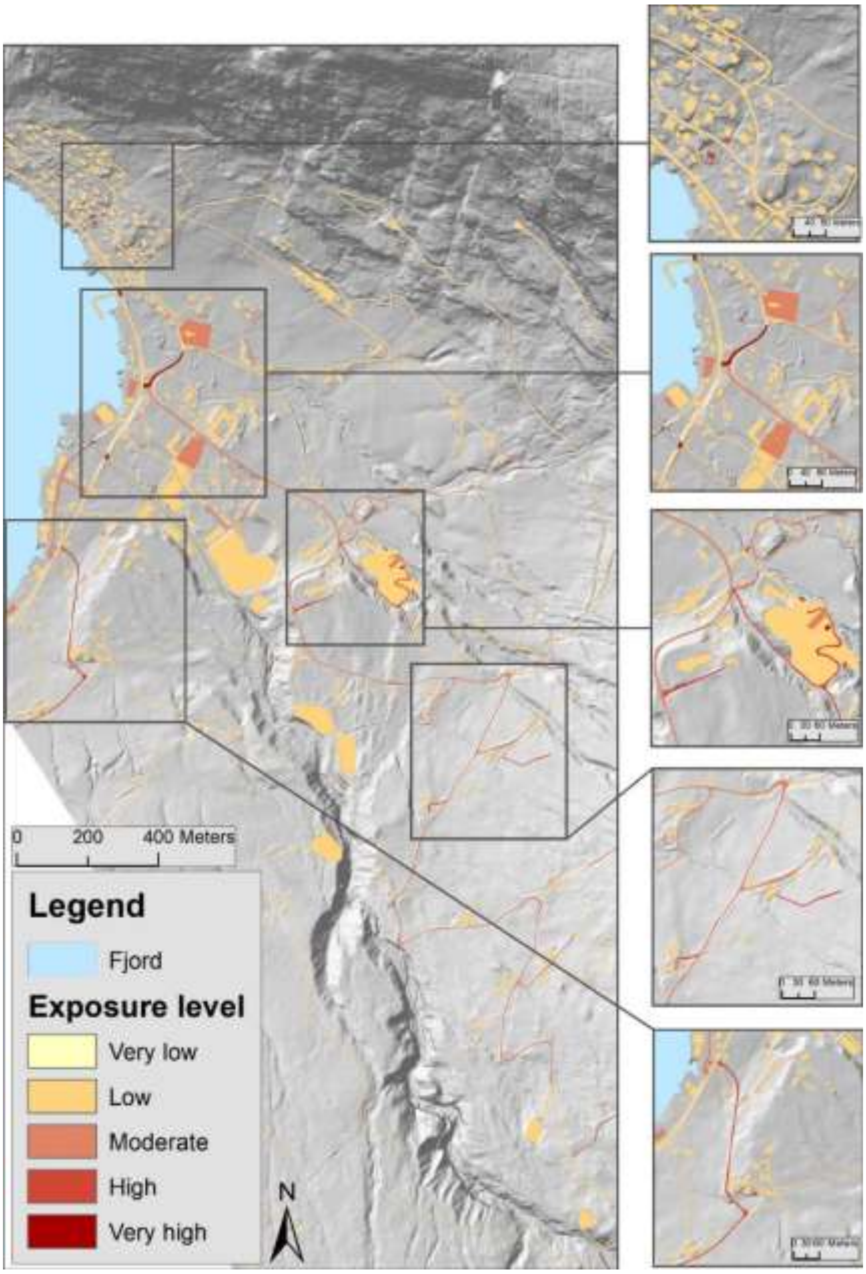

Figure 33: Exposure level of buildings and road segments based on the possible water accumulation when B4 is closed & all culverts are open

3.9 Bridge B5 is closed & all culverts are open

The DEM has been modified at the locations of the culverts by making openings and at the location of bridge B5 by making a barrier. Similarly as the eight scenario, figure 34 shows that the water hits the blocked bridge, goes around it and takes the same path it flows with no alterations, resulting to the outcome presented at figure 35 which is the same as in the eighth scenario and as when all the bridges and culverts are functional (see figure 20).

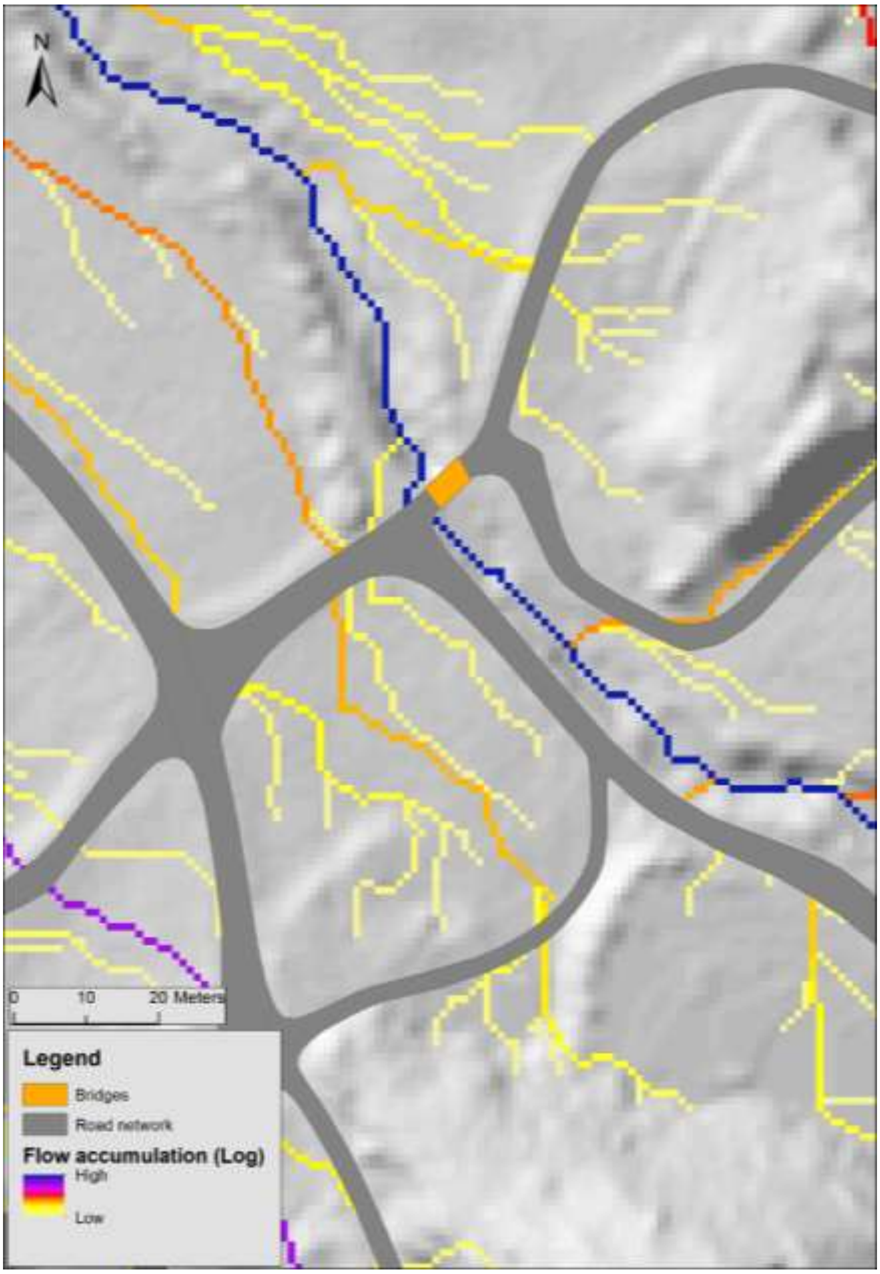

Figure 34: Flow accumulation when B5 is closed & all culverts are open

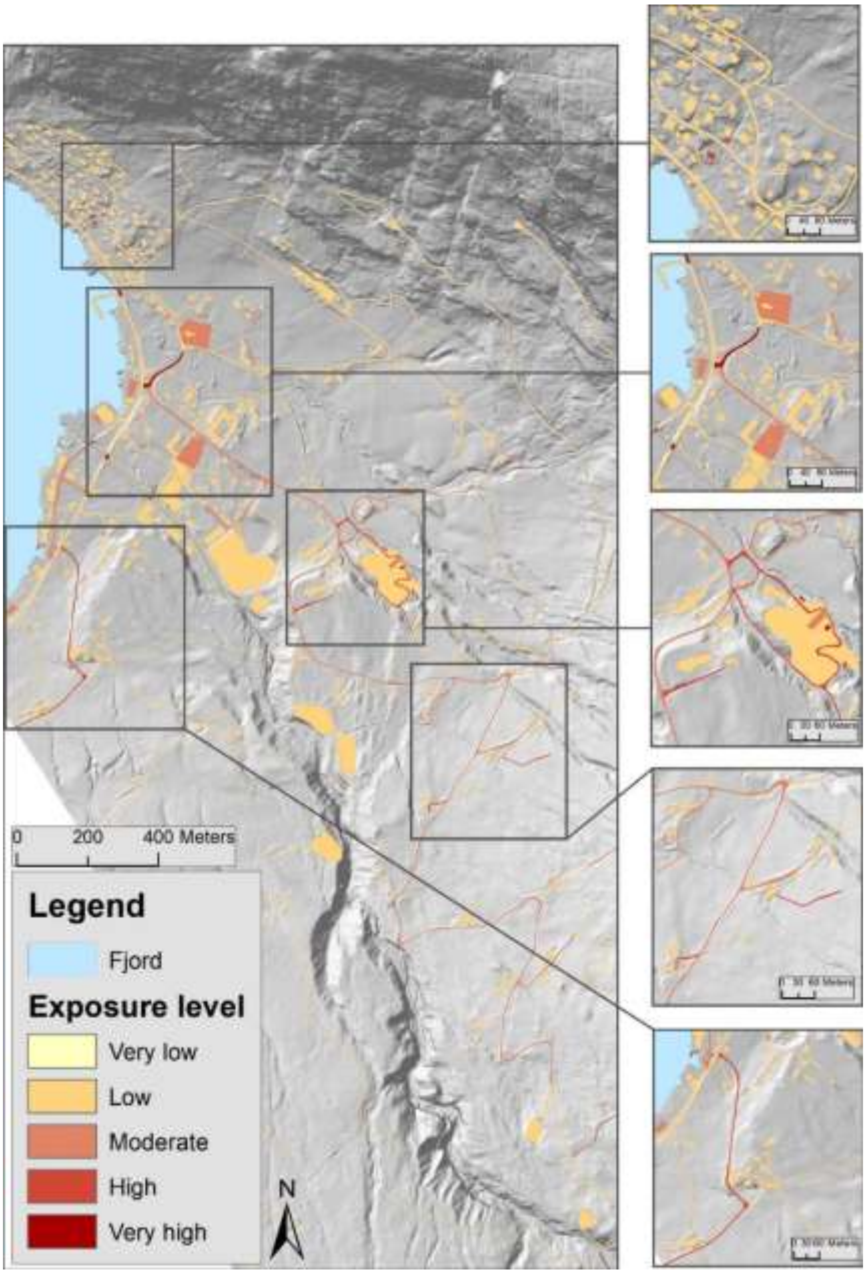

Figure 35: Exposure level of buildings and road segments based on the possible water accumulation when B5 is closed & all culverts are open

3.10 Culverts C2, C3, C4 are closed & all bridges are open

For this scenario the DEM has been modified just at the locations of culverts C1, C5 and C6 by making openings. Figure 36 shows that in case of high water accumulation between bridge B1 and B2, culverts C2, C3 and C4 will lead it through if their capacity is efficient. Figure 37 demonstrates the buildings exposed in this case and they are the same as in the scenario when everything is functional (see figure 20). The same applies to the exposed road segments where the results are almost the same (see figure 37).

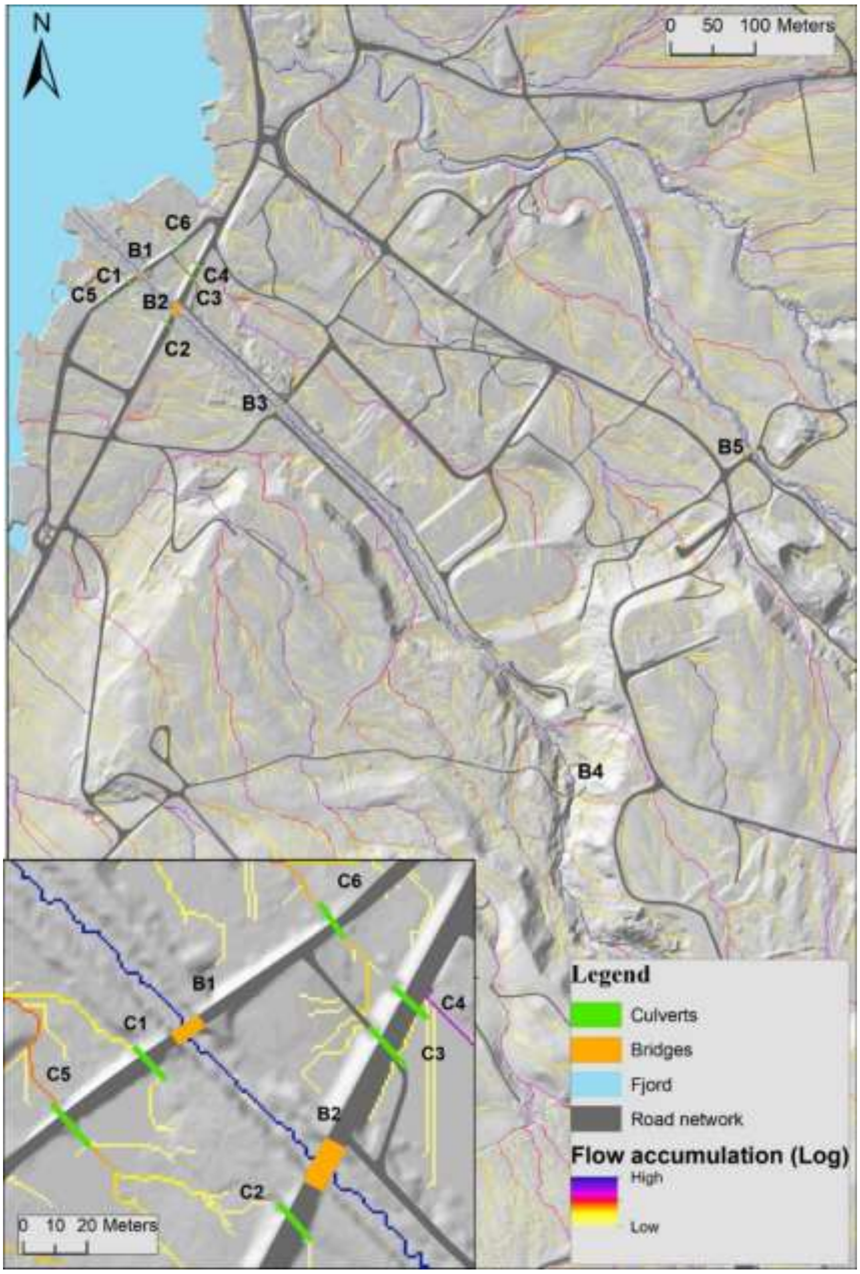

Figure 36: Flow accumulation when all bridges are open and C2, C3, C4 are closed

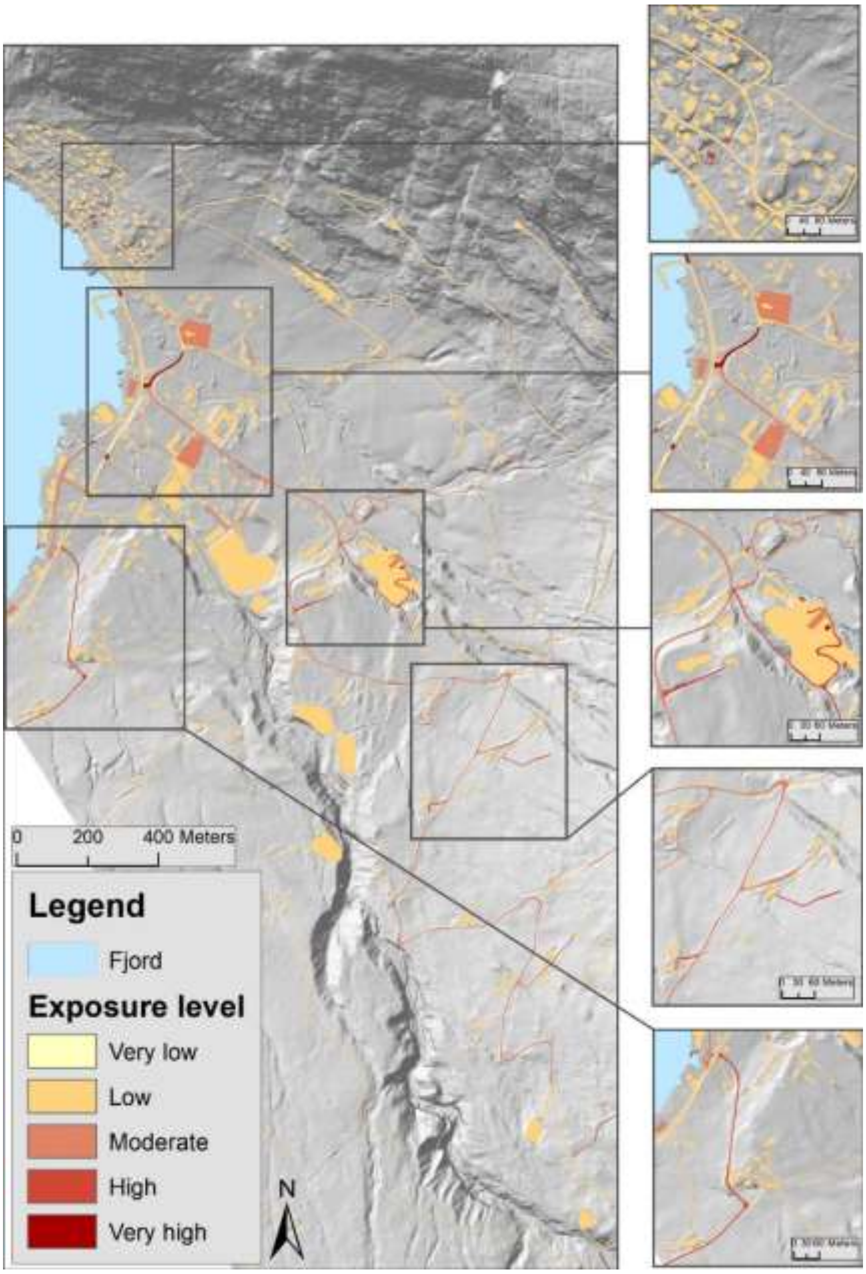

Figure 37: Exposure level of buildings and road segments based on the possible water accumulation when all bridges are open and C2, C3, C4 are closed

3.11 Culverts C1, C5, C6 are closed & all bridges are open

In this case, the DEM has been modified just at the locations of culverts C2, C3, C4 by making openings. Figure 38 shows that from the bridge B2, the water partly flows to the left through the culvert C2 and since culvert C5 and C1 are blocked it follows the road and gives to it a high accumulation value (see inset map of figure 38) and similarly to the right where it flows through culvert C3 and C4, it finds that culvert C6 is blocked and so it hits the road, as well as the buildings and road segments portrayed with dark red color in figure 39.

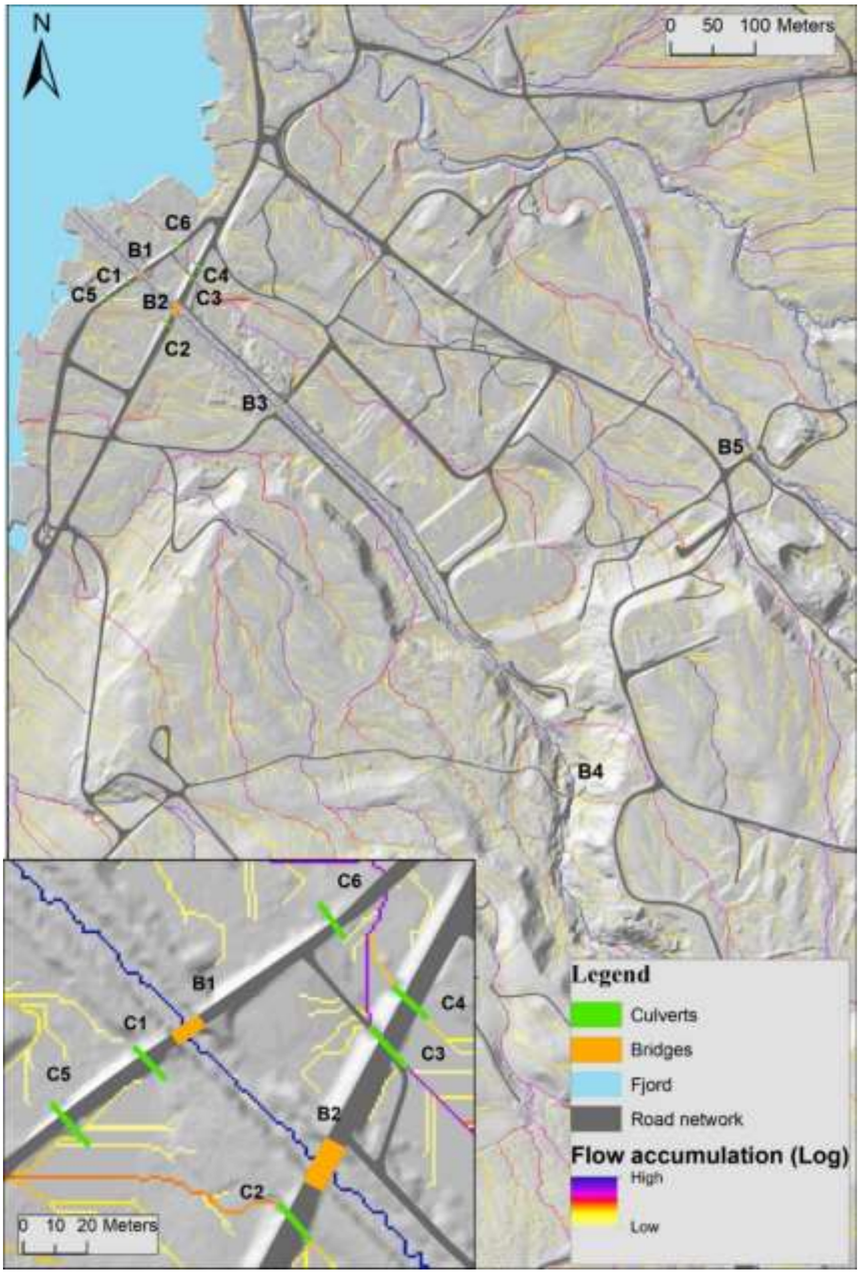

Figure 38: Flow accumulation when all bridges are open and C1, C5, C6 are closed

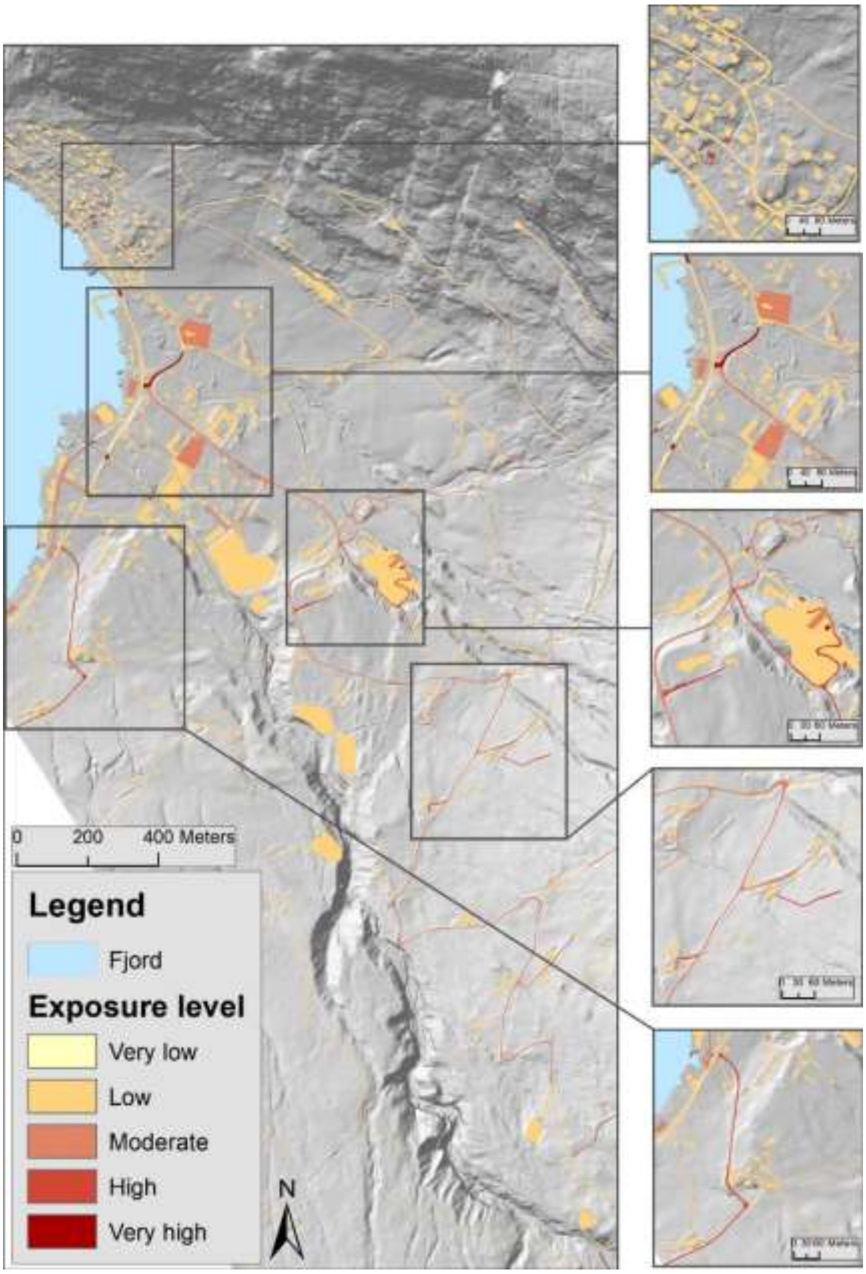

Figure 39: Exposure level of buildings and road segments based on the possible water accumulation when all bridges are open and C1, C5, C6 are closed

3.12 Culverts C1, C5, C6 are closed & bridge B1 is closed

In this case, the DEM has been modified just at the locations of culverts C2, C3, C4 by making openings and at the location of bridge B1 by making a barrier. Figure 40 shows the water leaving the main network before the bridge B1, turning right and hitting the road because of the culvert C6 being closed, as well as from the left side of the bridge B2 the accumulated water is higher due to the blocked bridge and because of the blocked culverts B1 and B5, results to hit the road and giving to it high exposure value (see inset map of figure 40). Figure 41 presents those buildings and road segments on the way on both sides that have high water accumulation values.

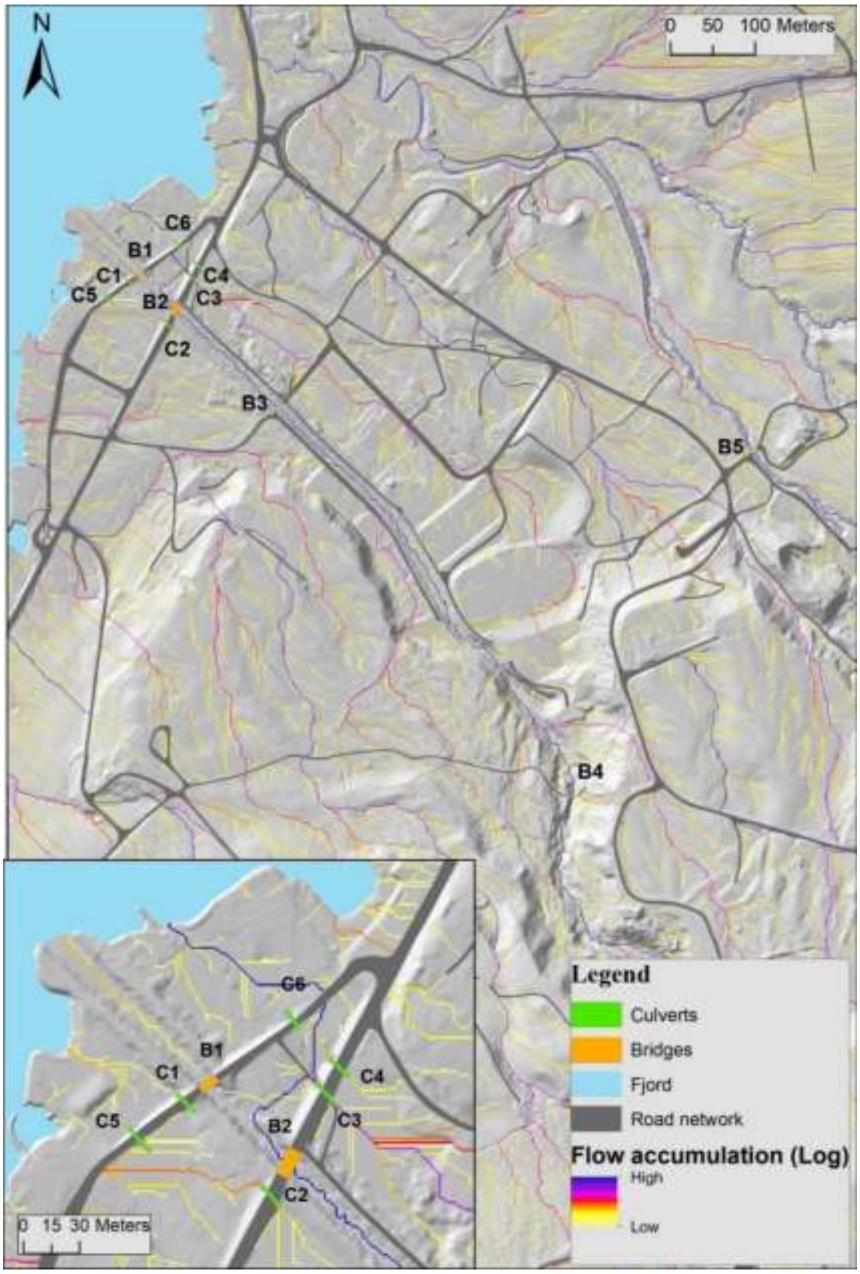

Figure 40: Flow accumulation when C1, C5, C6 are closed & B1 is closed

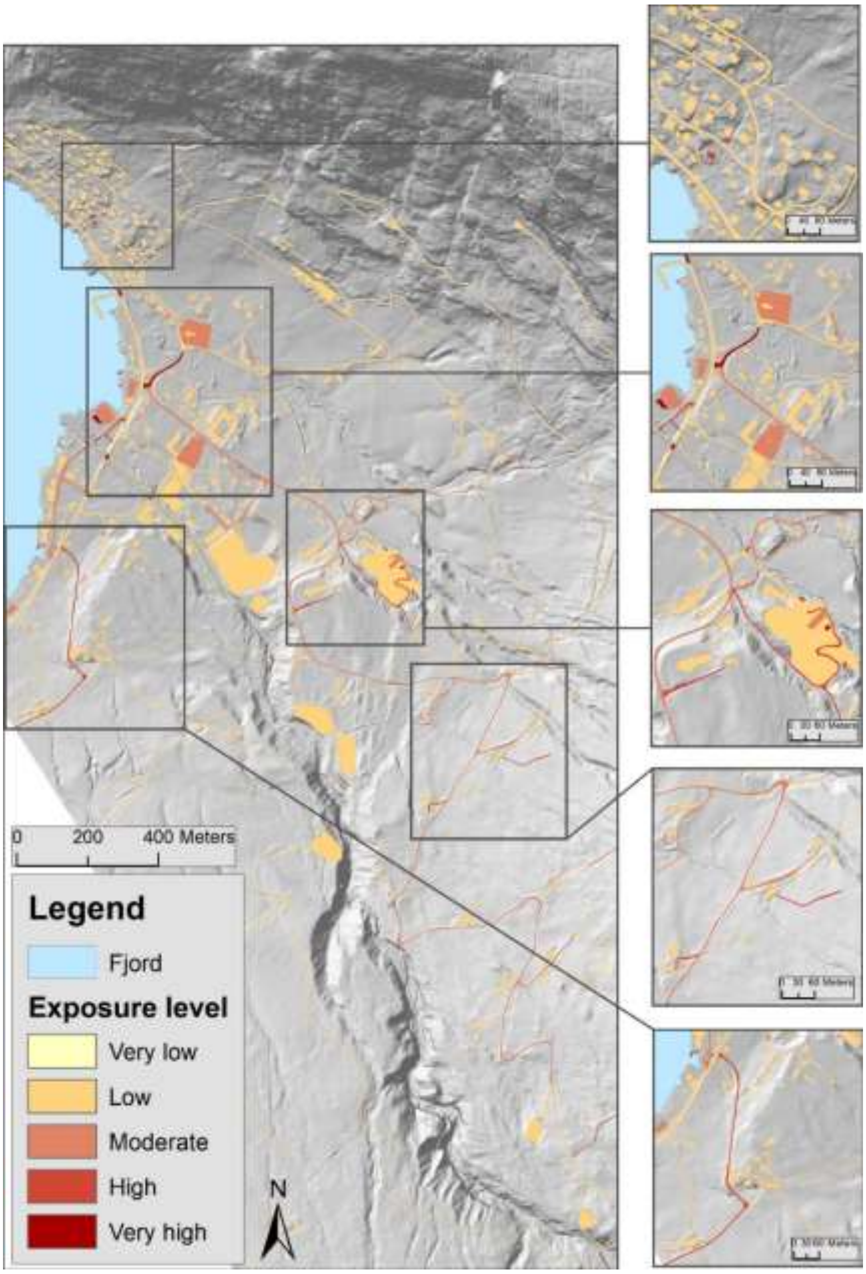

Figure 41: Exposure level of buildings and road segments based on the possible water accumulation when C1, C5, C6 are closed & B1 is closed

3.13 Culverts 2, 3, 4 are closed & bridge 2 is closed

In this scenario the DEM has been modified by making openings just at the locations of culverts C1, C5, C6 and at the location of bridge B2 by making a barrier. Figure 42 represents the flow accumulation values being the highest before the bridge B2 where the main river hits it and changes its path towards the left and along the road. It is observed that more road segments in that area have high accumulation values because the water along that road intersects with more road segments. In this scenario the accumulation in this left part of the area is the highest compared to the previous cases, however in figure 43 it is shown that buildings are not affected there. At the right side of the river on the other hand, the accumulation is high because of the blocked bridges B3 and B4, the water flows along the road giving it a high exposure, but in this case also the same buildings are exposed (see figure 43).

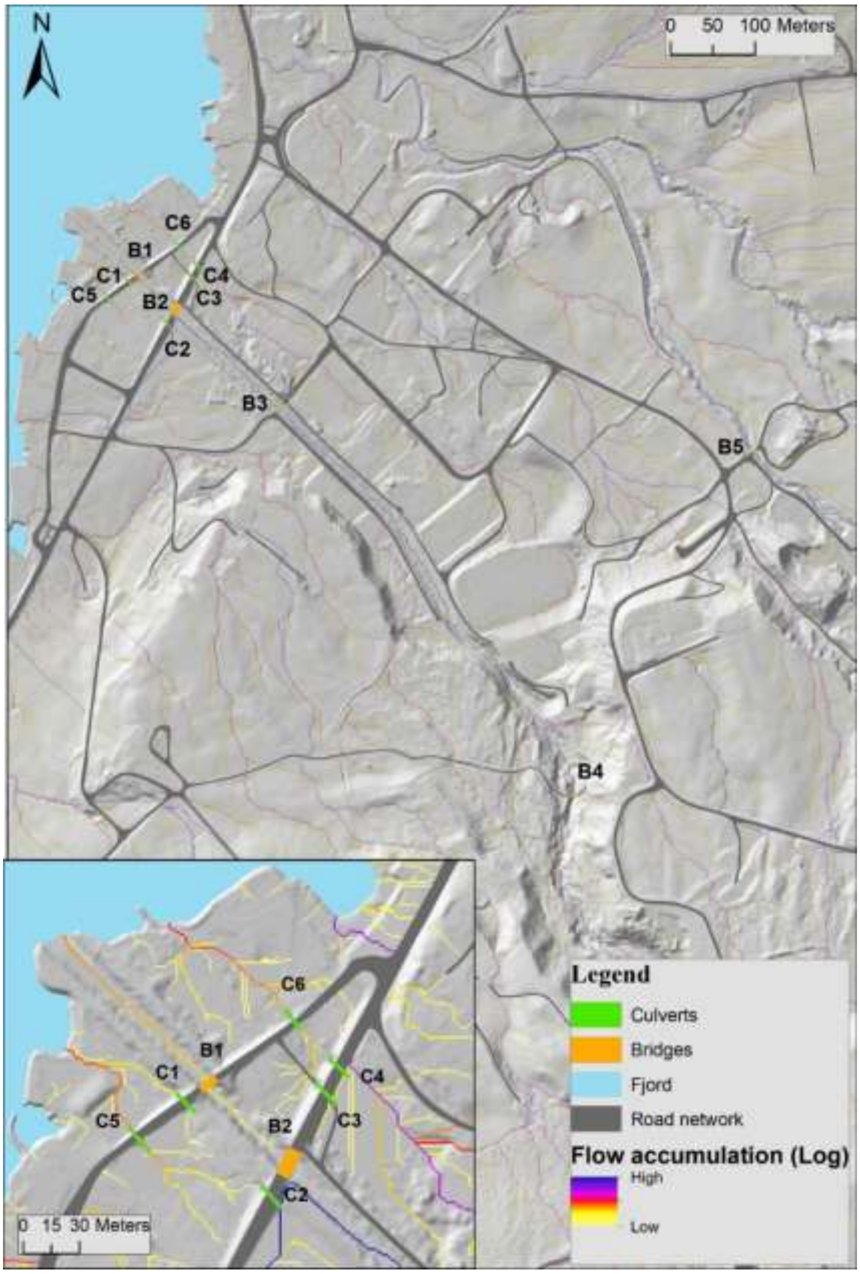

Figure 42: Flow accumulation when C2, C3, C4 are closed & B2 is closed

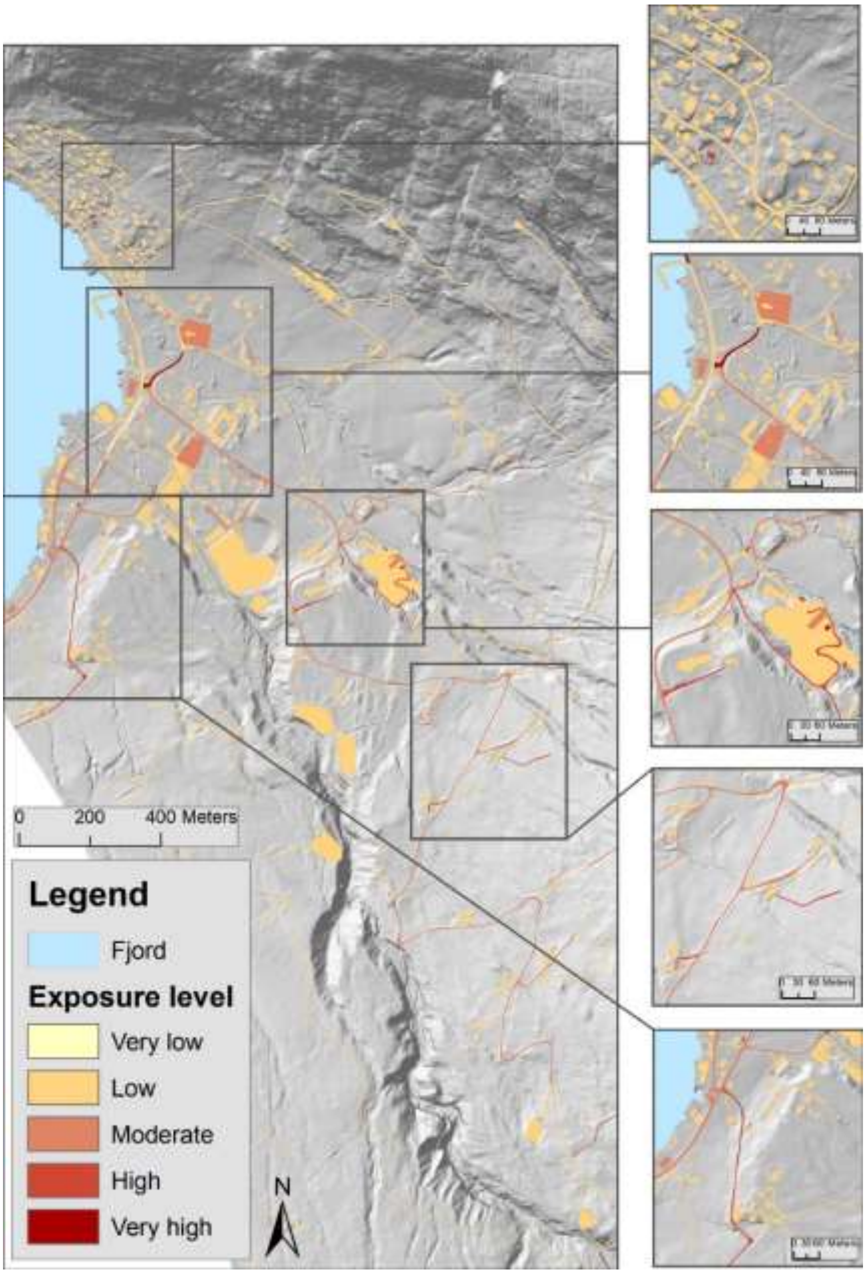

Figure 43: Exposure level of buildings and road segments based on the possible water accumulation when C2, C3, C4 are closed & B2 is closed

3.14 Culverts 1, 5, 6 are closed & bridge 2 is closed

Here, the DEM has been modified at the locations of culverts C2, C3, C4 by making openings and at the location of bridge B2 by making a barrier. Figure 44 demonstrates how the flow variates from before the bridge B2 and is divided to the right and left side of it. Figure 44 also shows the high flow accumulated at the left of the blocked bridge B2 where the water goes through the culvert C2 and directs to the road next to the bridge B1 where it hits it and gives an increased exposure value to it as demonstrated in figure 45, without hitting any buildings on the way. From the right side of the river the water flows through the culverts C3 and C4 and meets the closed culvert C6 (see inset map of figure 44) and from there follows the road and continues downwards to expose buildings (see figure 45).

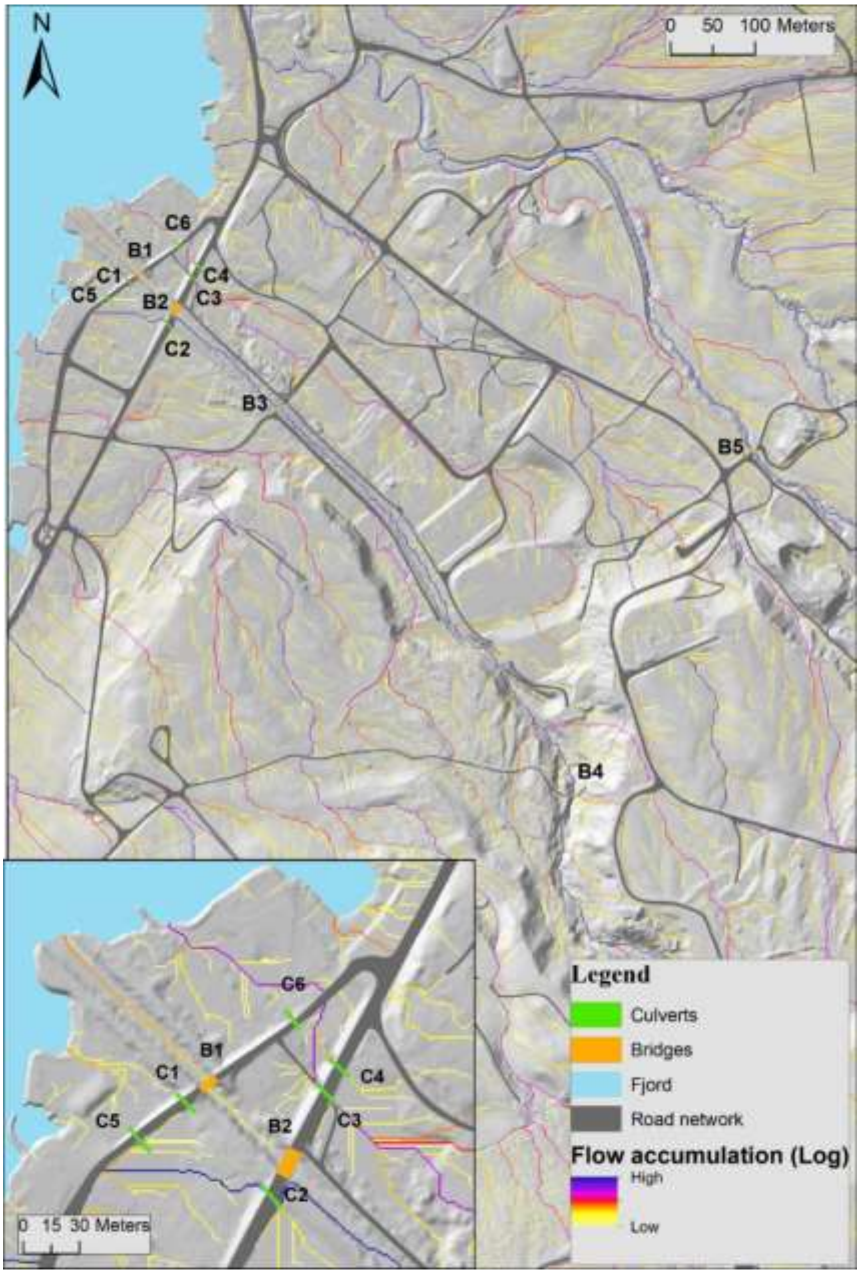

Figure 44: Flow accumulation when C1, C5, C6 are closed & B2 is closed

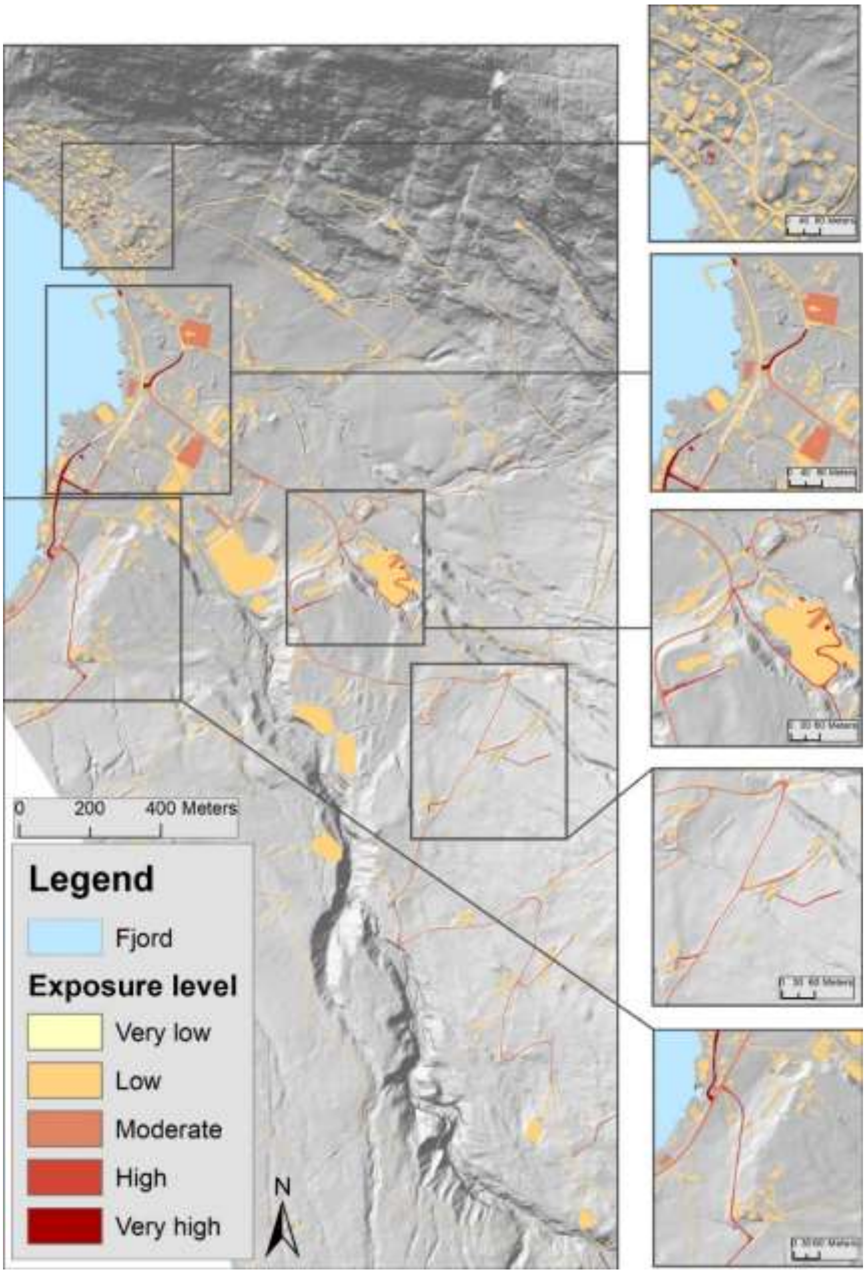

Figure 45: Exposure level of buildings and road segments based on the possible water accumulation when C1, C5, C6 are closed & B2 is closed

3.15 Culverts 2, 3, 4 are closed & bridge 1 is closed

In this scenario the DEM has been modified just at the locations of culverts C1, C5, C6 by making openings, and at the location of bridge B1 by making a barrier. In figure 46 it is observed that the flow with high accumulation turns after the bridge B2 and before the blocked bridge B1 to the right and goes through the culvert C6. The water accumulation value is high and that can be seen in figure 47, at the high exposure of the buildings and road segments presented with dark red color below the culvert C6.

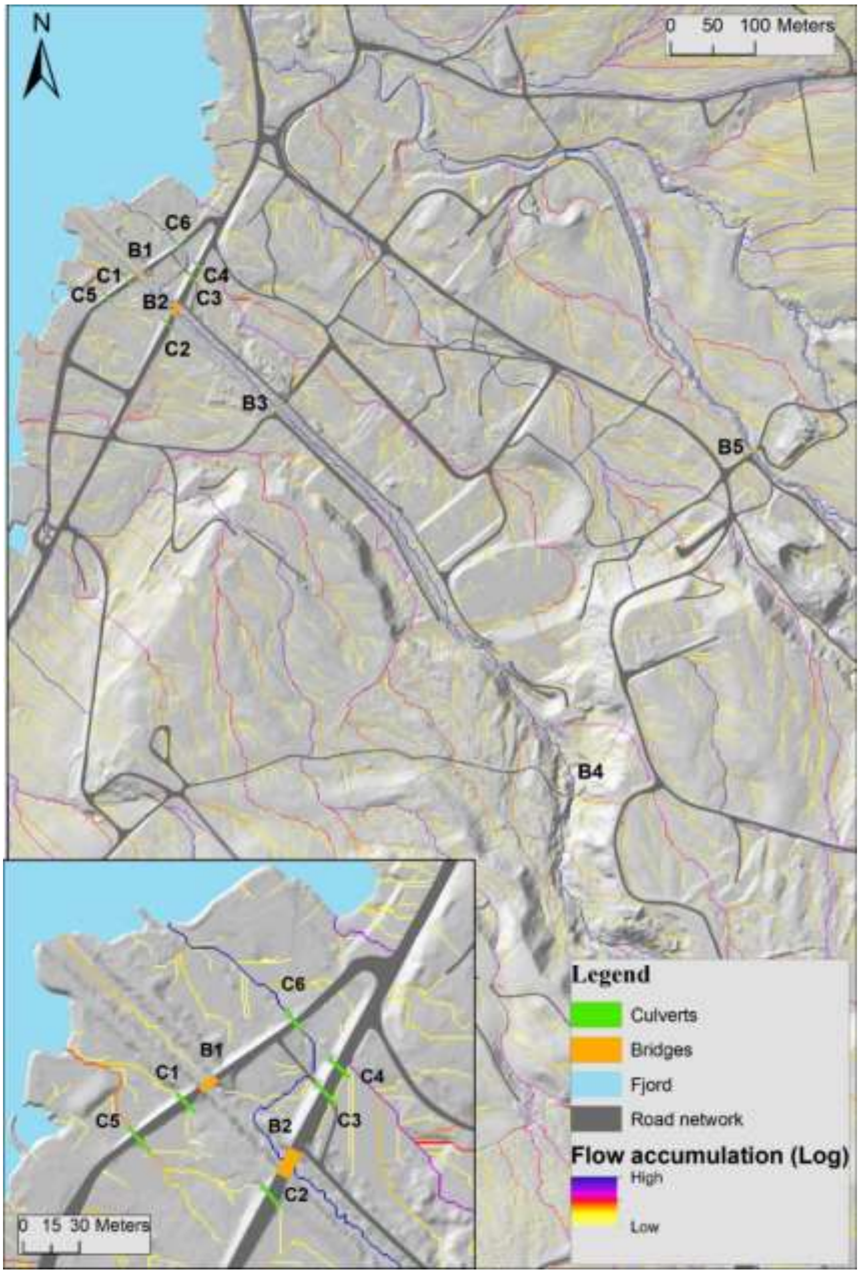

Figure 46: Flow accumulation when C2, C3, C4 are closed & B1 is closed

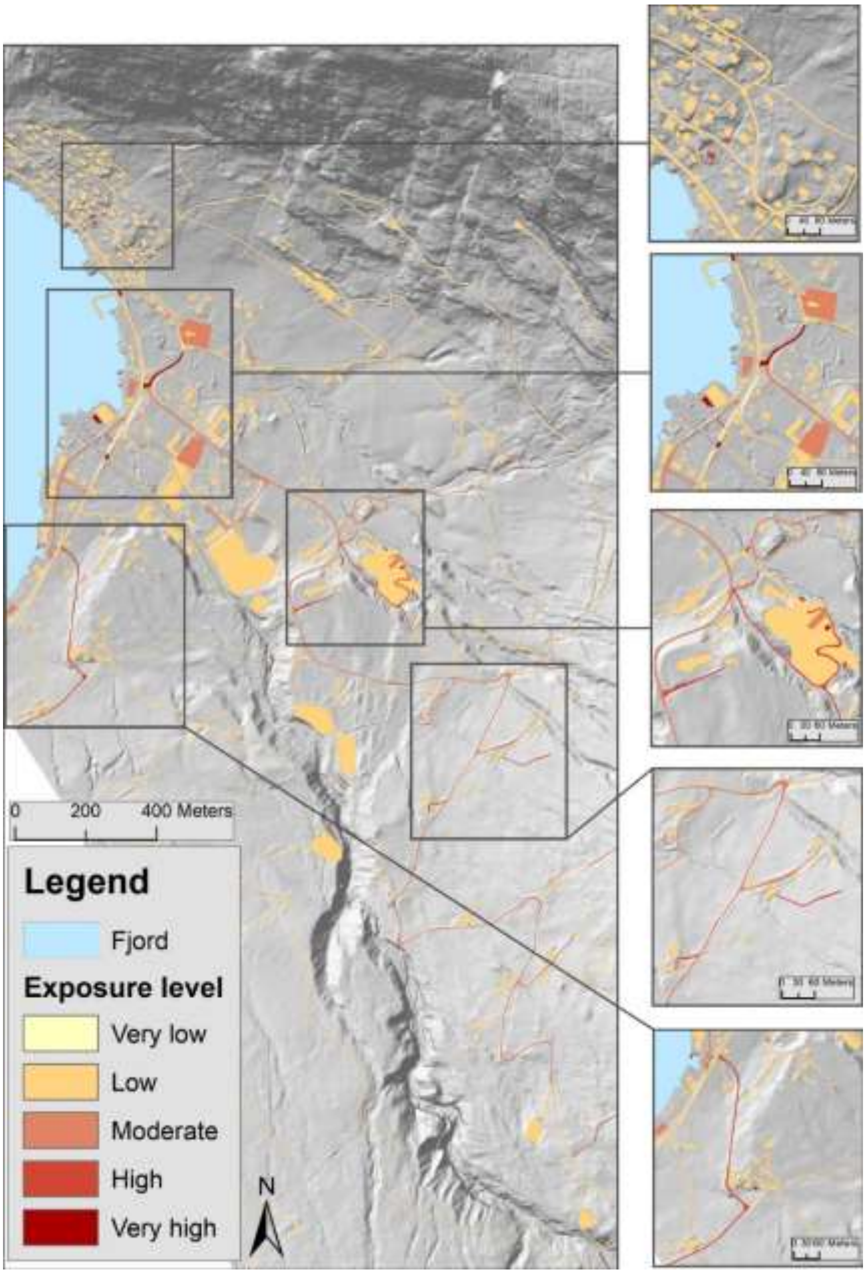

Figure 47: Exposure level of buildings and road segments based on the possible water accumulation when C2, C3, C4 are closed & B1 is closed

3.16 Culverts 2, 3, 4 are closed & bridge 3 is closed

The DEM has been modified at the locations of culverts C1, C5, C6 by making openings, and at the location of bridge B3 by making a barrier. Figure 48 presents that the water with the highest accumulation hits the blocked bridge B3, hits the road on the right side and flows downhill where it hits another road and follows the low path of it. The flow path is quite different than the initial river flow that applies when everything is functional as demonstrated in figure 19 earlier in the text. The result is to hit buildings along this path and to give very high accumulation values to the two roads that it intersects with (see figure 49).

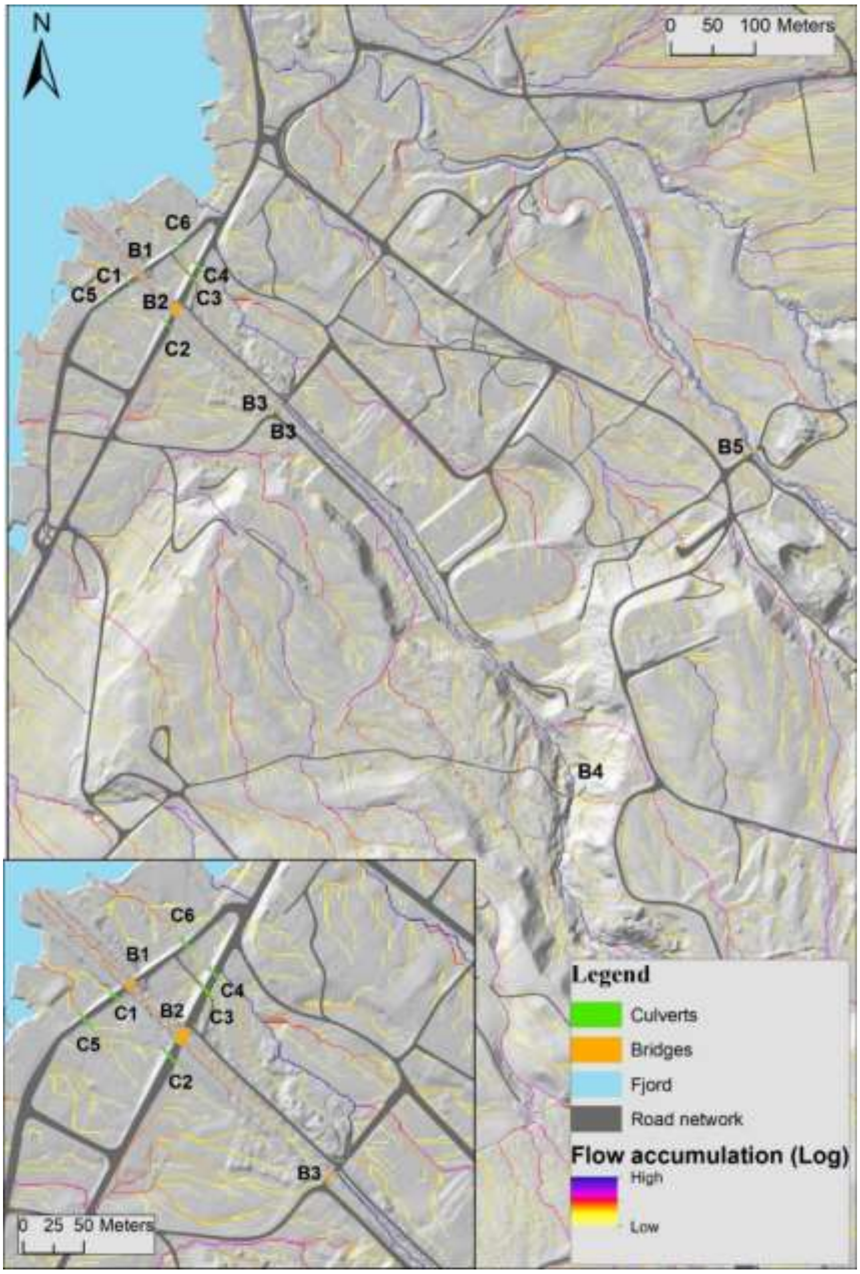

Figure 48: Flow accumulation when C2, C3, C4 are closed & B3 is closed

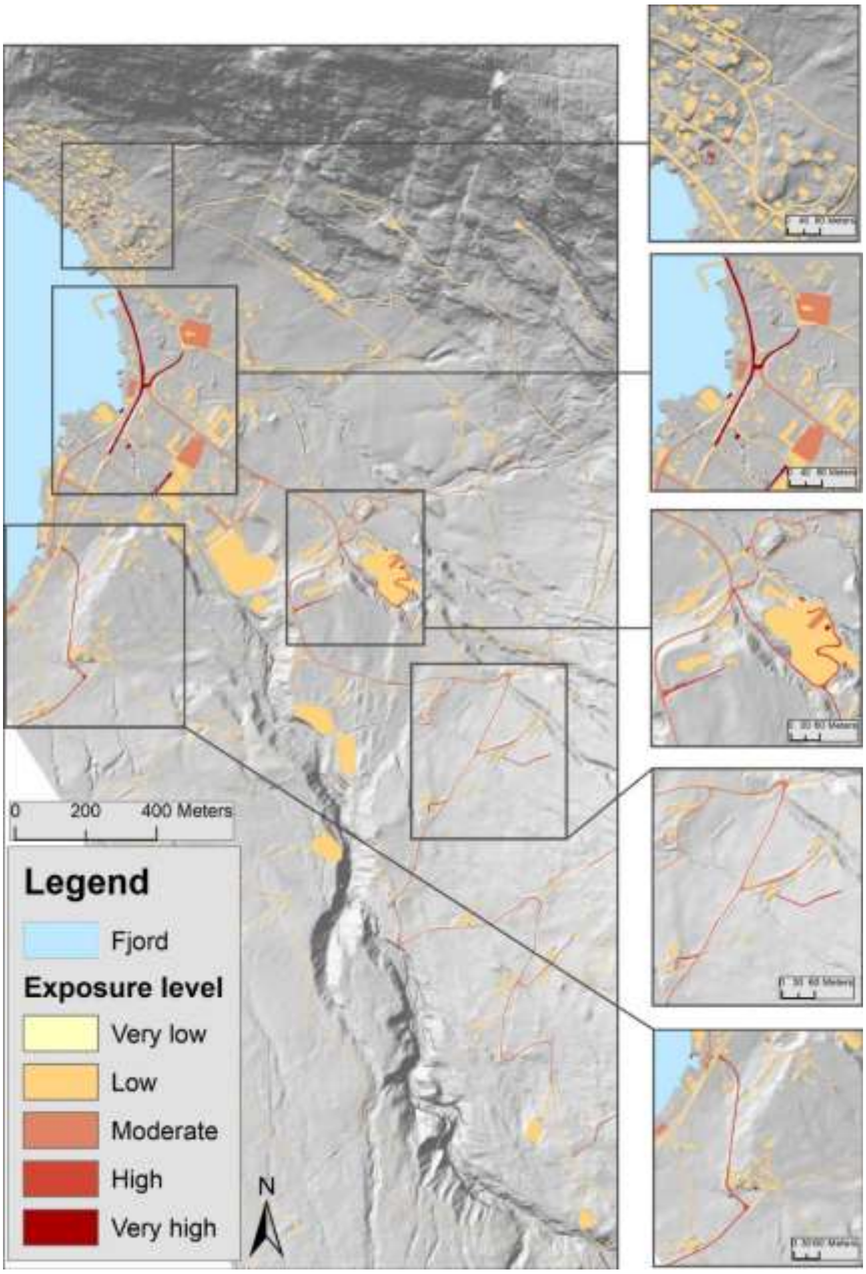

Figure 49: Exposure level of buildings and road segments based on the possible water accumulation when C2, C3, C4 are closed & B3 is closed

3.17 Comparison between the different scenarios

In scenario 1 and scenario 4 all the culverts are closed and it is observed that road segments and buildings on the right side of the river are more exposed (figure 50). In the case that bridges are blocked (scenario 4), elements with high exposure values are located close to B1, B2 ad B3 (Figure 50).

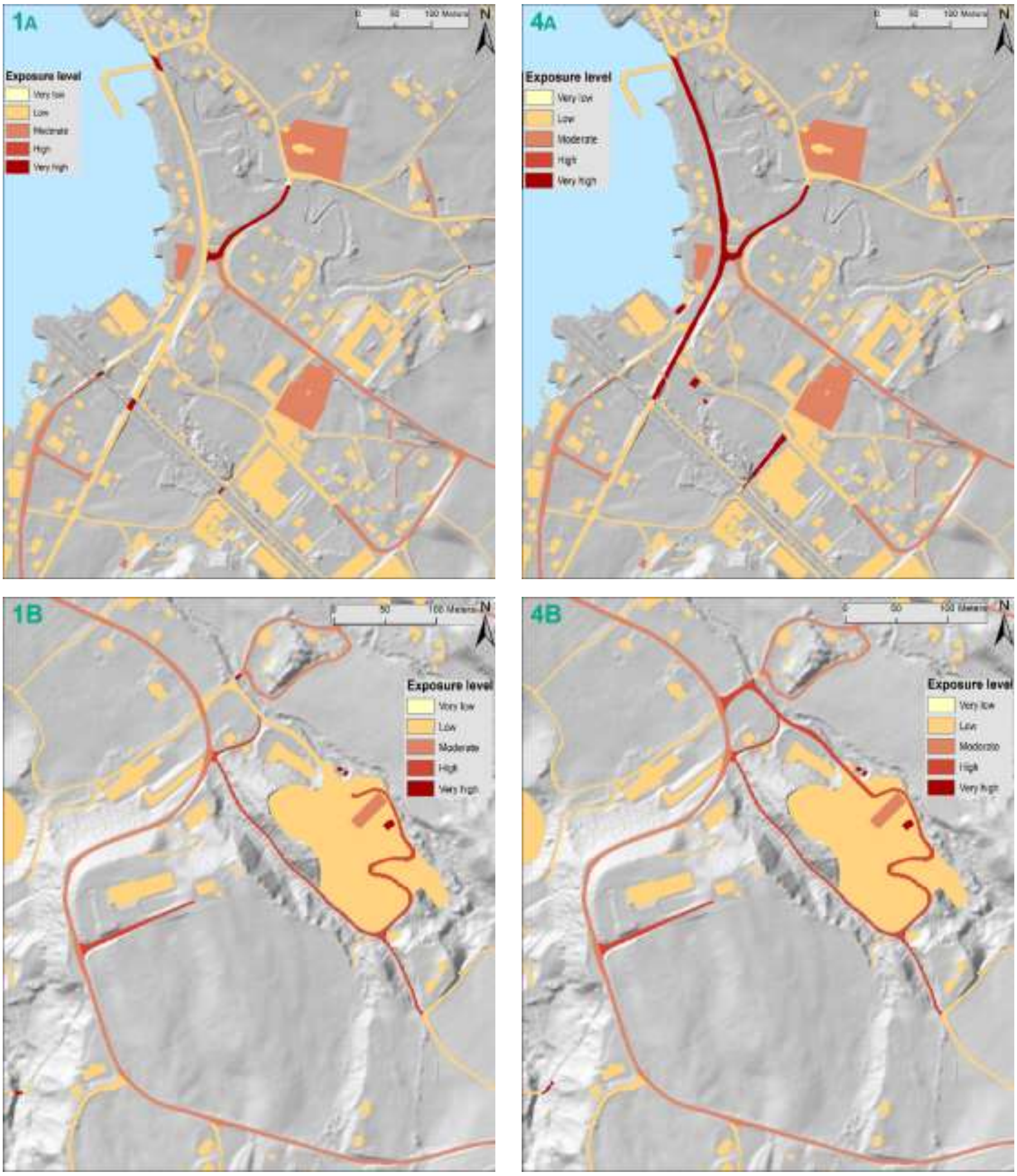

Figure 50: Comparison between scenarios 1 and 4

Similarly, it is observed that the same area is affected when the bridges are blocked in the third and fourth scenario, but in this case the values are increasing around the lower part of the river and some other buildings and road segments are also highly exposed. Even though the culverts are open in the third scenario, some elements are highly exposed around B1 and B3 (figure 51).

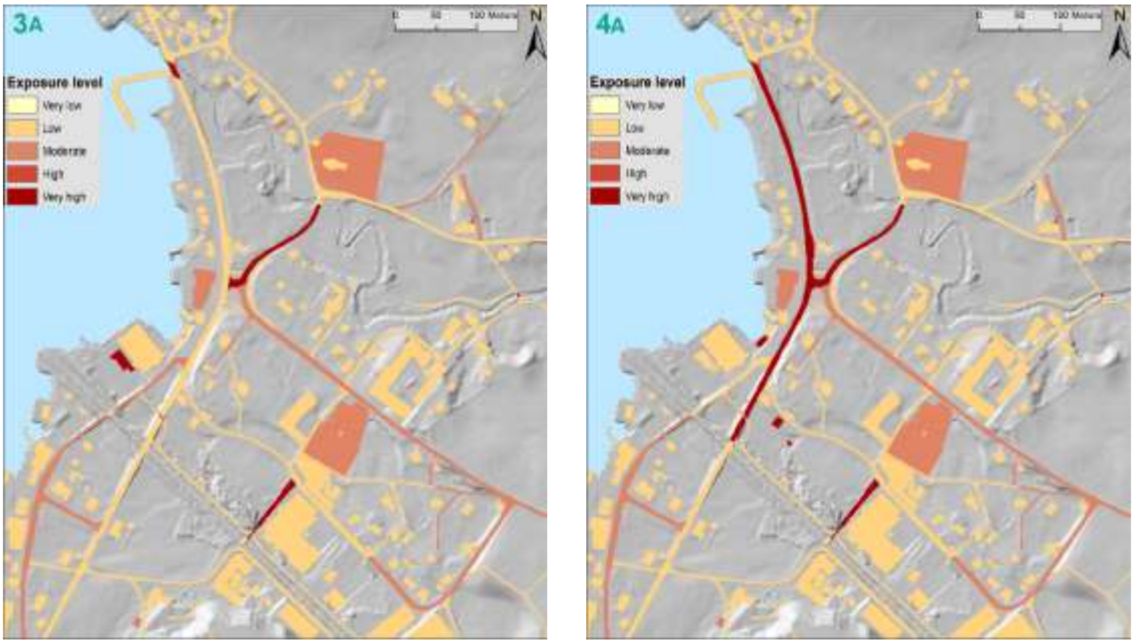

Figure 51: Comparison between scenarios 3 and 4

The second scenario represents the case of a normal function of the bridges and culverts, however in this case also exist elements moderately to highly exposed (figure 52). When B1 or B2 is closed it is observed that the elements around them are exposed, even though the culverts are open (figure 52, figure 53). When B3 is closed, it is observed that some elements in the lower part are more exposed than in the other scenarios, even though B1 and B2 are open (figure 53). There are no significant changes in the exposure level when B4 and B5 are closed (figure 53).

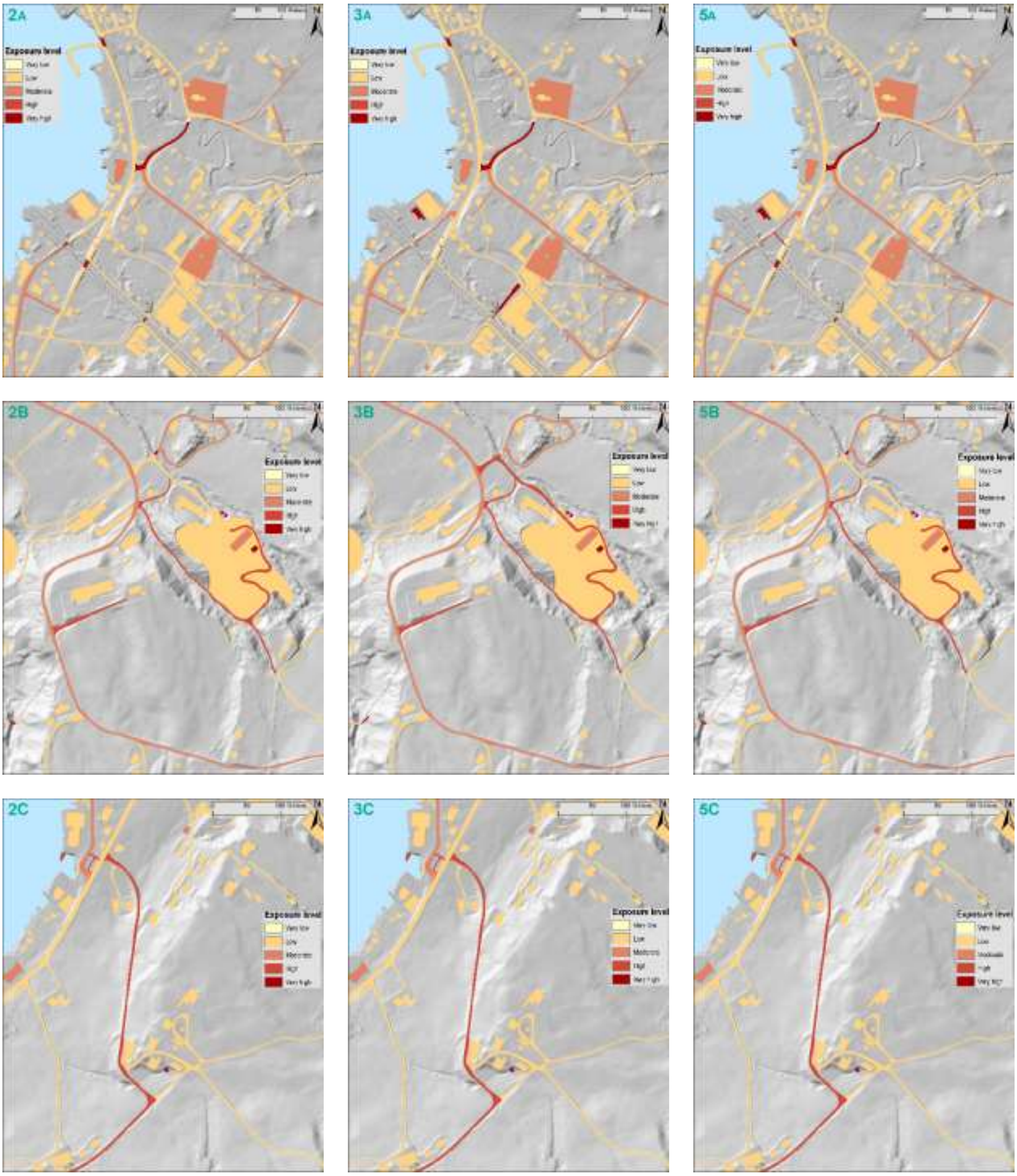

Figure 52: Comparison between scenarios 2, 3 and 5

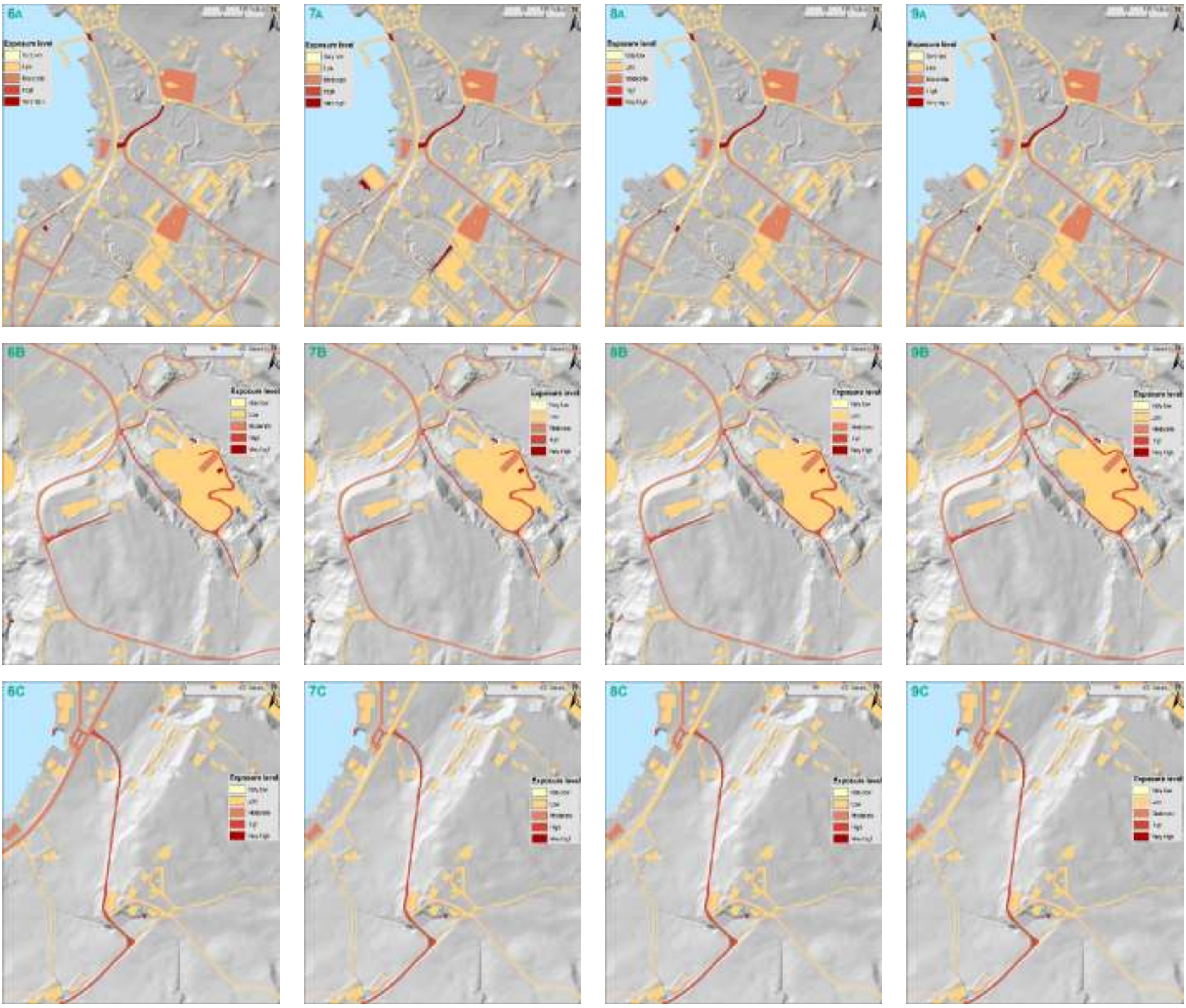

Figure 53: Comparison between scenarios 6, 7, 8 and 9

When both the bridges and culverts are open in the second scenario, some elements are more exposed than when the culverts are closed in the first scenario (figure 54). Differences in the exposure level can be spotted when C2, C3, C4 or C1, C5, C6 are closed around the culverts' location on the right side of the river (figure 54).

Figure 54: Comparison between scenarios 1, 2, 10 and 11

When B1 is closed and the culverts are open, again it is observed that elements around B1 are exposed and their number increases when C1, C5, C6 or C2, C3, C4 are closed (figure 55).

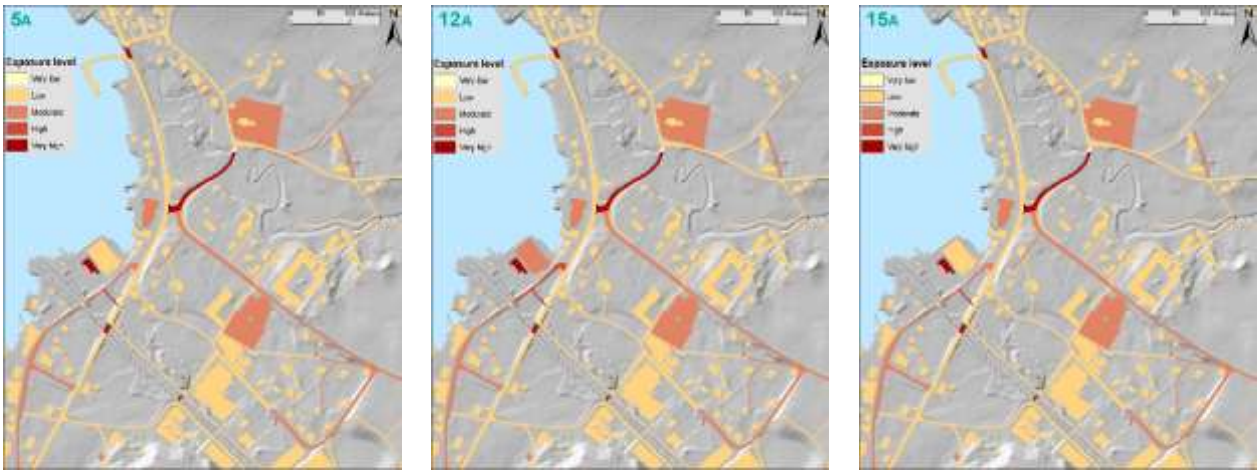

Figure 55: Comparison between scenarios 5, 12 and 15

When B2 is closed and the culverts are open (sixth scenario), again there are exposed elements around B2 and B1 but also in areas not directly next to the bridges (figure 56). When C2, C3, C4 or C1, C5, C6 are closed, the same area is affected but in the second case is more exposed the lower part located on the left side of the river (figure 56).

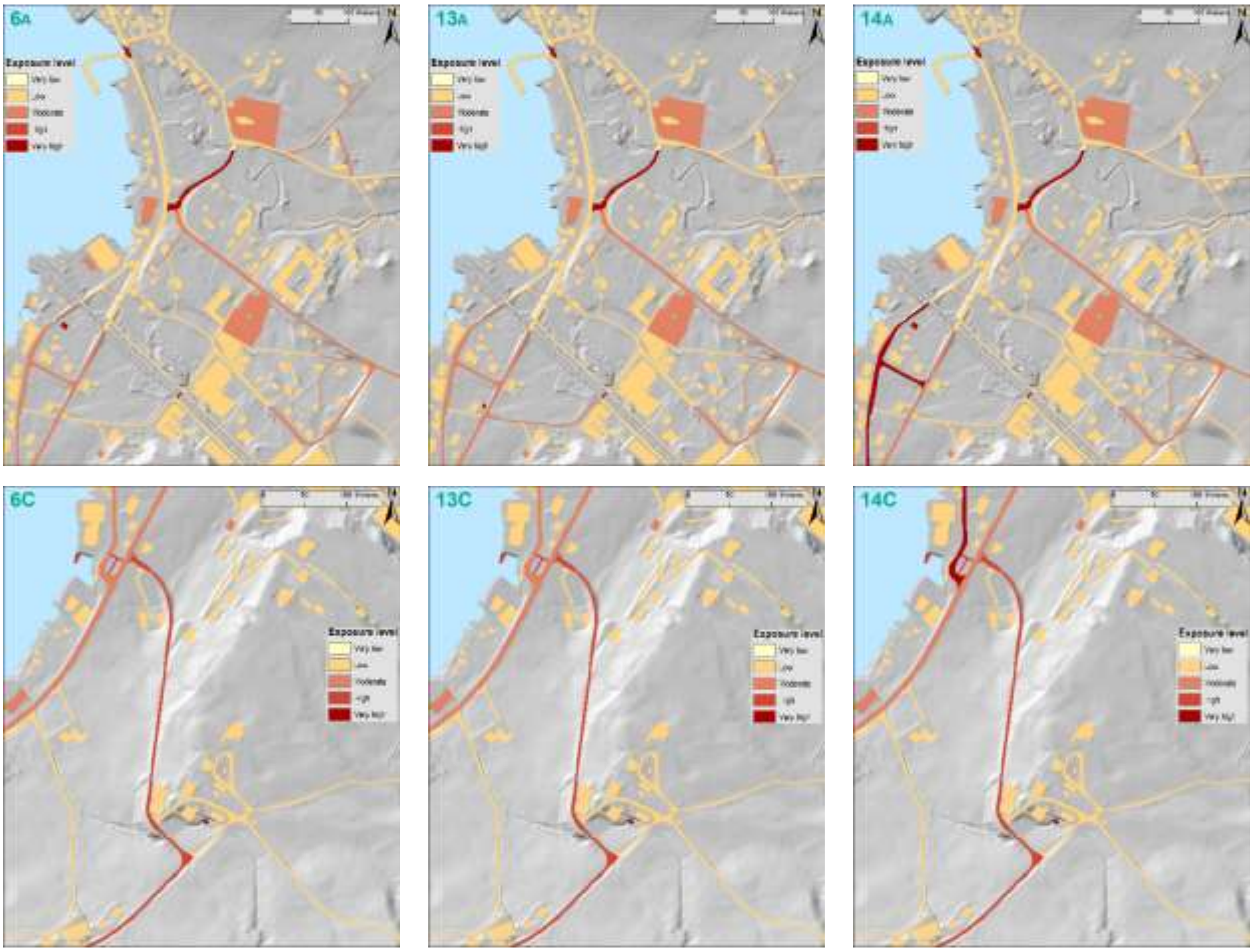

Figure 56: Comparison between scenarios 6, 13 and 14

When B3 is closed there is a significant increase in the level of exposure when C2, C3 and C4 are closed in the sixtinth scenario, located in the right side of the lower part of the river (figure 57).

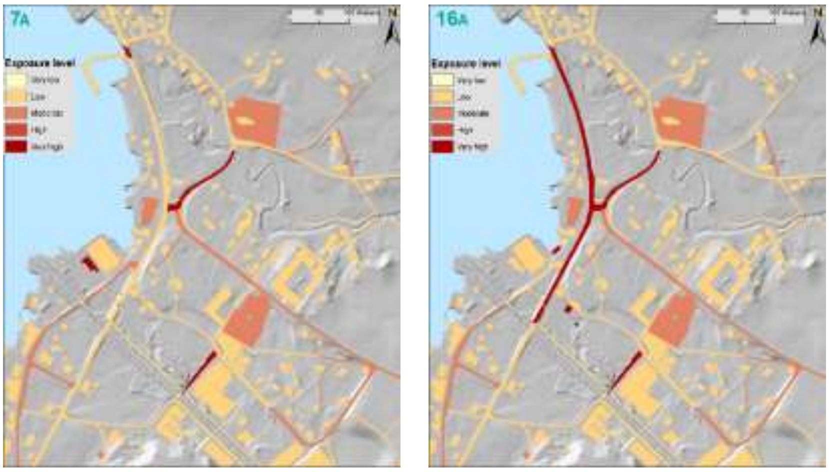

Figure 57: Comparison between scenarios 7 and 16

In the case where C1, C5, C6 are closed the outcome varies depending on which bridges are open. When B1 is closed the right lower part is affected the most (scenario 12), while when B2 is closed the left lower part close to B1 is affected the most (figure 58).

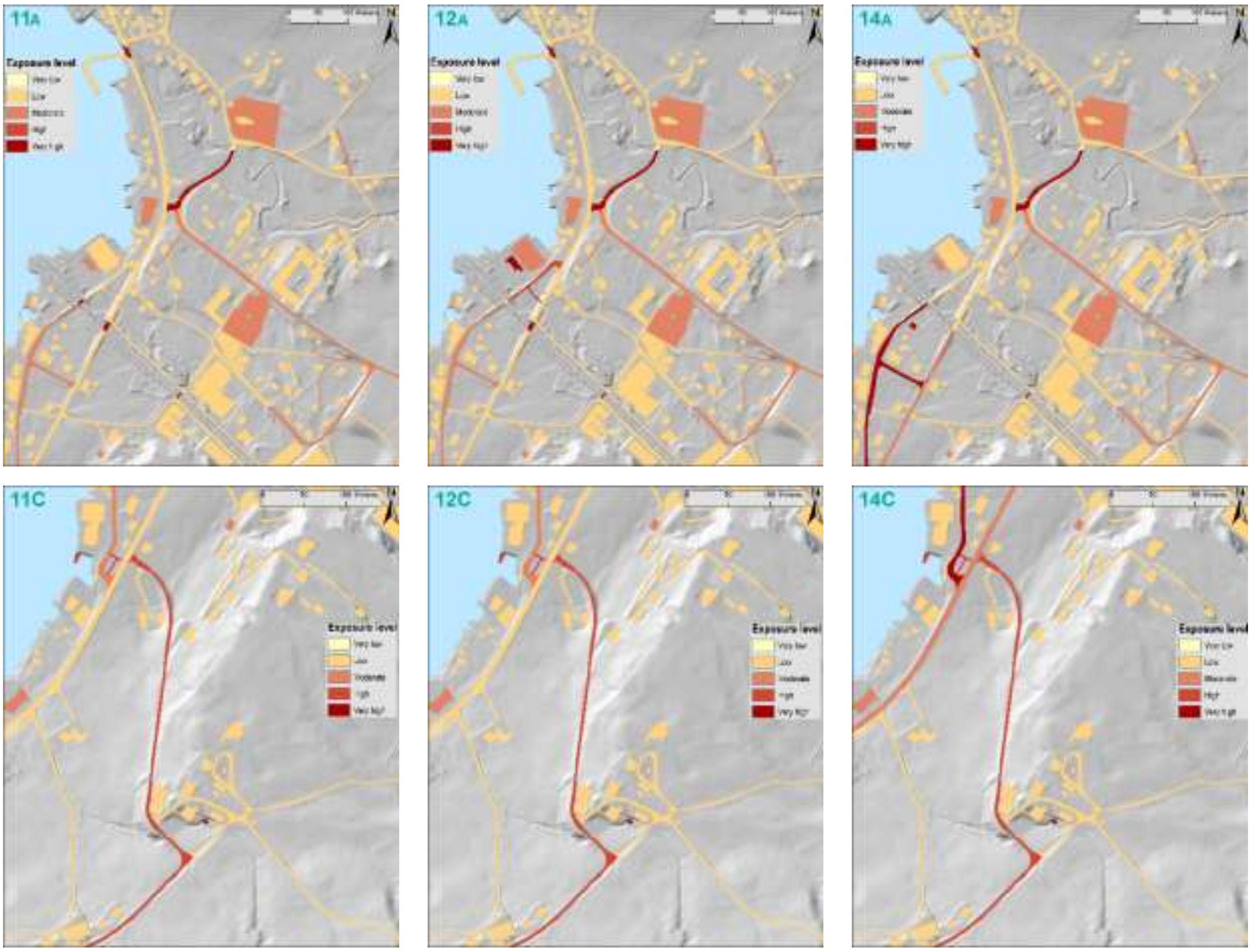

Figure 58: Comparison between scenarios 11, 12 and 14

Similarly, in case C2, C3 and C4 are closed the result varies depending on which bridges are open. In the thirtinth scenario where B2 is closed, road segments are affected on the left side of the river and close to B3, B2 and B1 (figure 59). When B1 is closed, the lower part around B1 is affected and when B3 is closed much higher values are accumulated on the right side around B3 and B2 (figure 59).

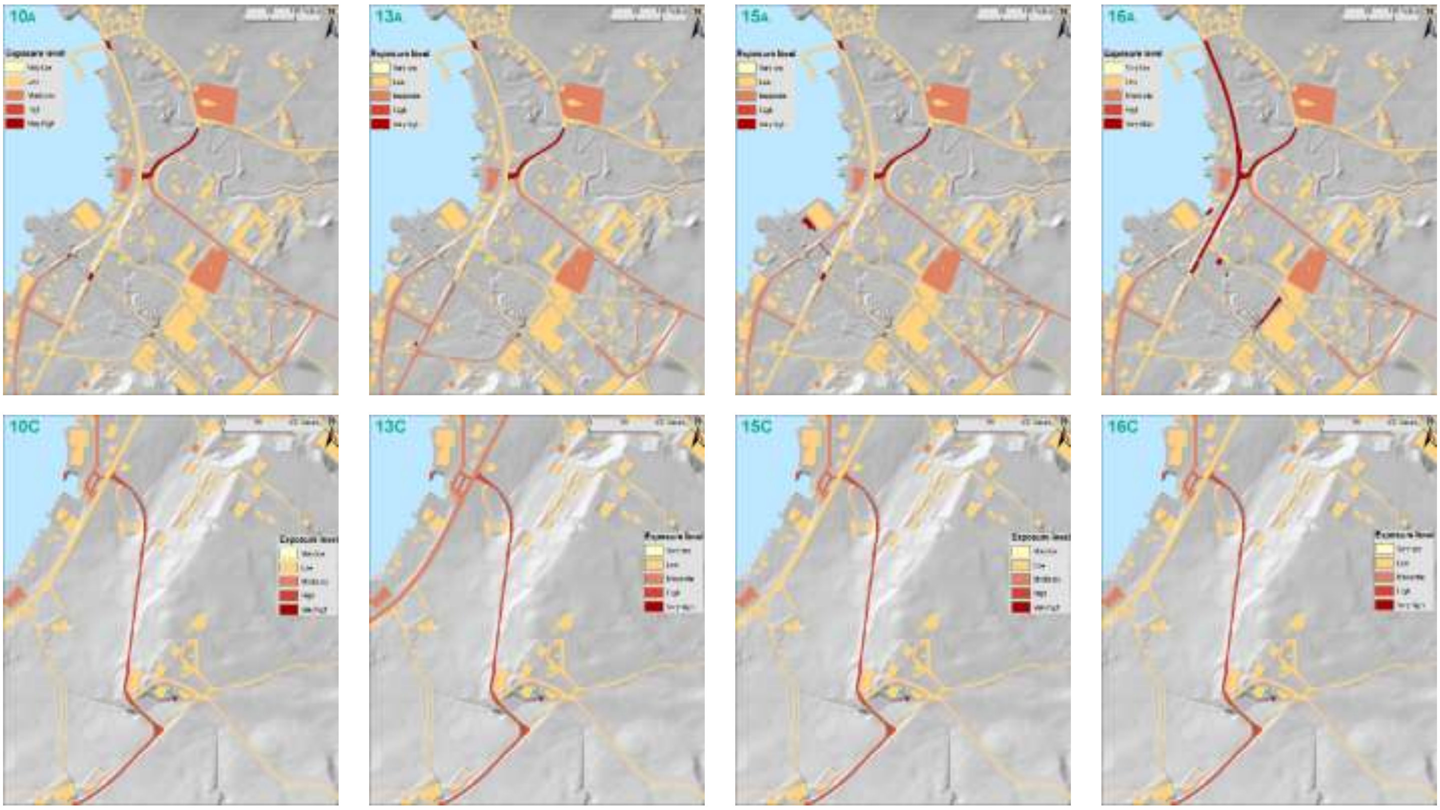

Figure 59: Comparison between scenarios 10, 13, 15 and 16

3.18 Results in comparison to NVE's susceptibility map

In order to validate the possible flood prone areas, susceptibility maps from NVE were compared with the results of this research. In order to summarize the information of the 16 scenarios, has been calculated the mean accumulation values for each building and road segment of the 16 maps. Thus, is provided a clearer picture of which of the buildings and road segments are most exposed to any scenario.

Figures 60 and 61 demonstrate maps where the classification of buildings and road segments accordingly based on their flow accumulation values, are compared for every scenario with the flood susceptibility map from NVE. In every case, the borders of the flood susceptibility map do not coincide with the exposed buildings and road segments which are spreading in a bigger extent.

Figure 60: NVE susceptibility map compared to the resulted mean building exposure map of all scenarios

Figure 61: NVE susceptibility map compared to the resulted mean road segments exposure map of all scenarios

4 Discussion and Conclusion

Gravity always leads the water to flow towards the steepest downslope in a terrain. This research has demonstrated a GIS-based method of surface flow mapping in small and steep catchments. This research has used a terrain model (DEM) in grid format with high precision (1 meter resolution). The estimation of the flow has been achieved with the D8 algorithm which specified the steepest downslope flow from every cell to its neighbors and the calculation of the flow accumulation showed which areas tend to accumulate water and potentially are exposed to flash floods, following an event of heavy precipitation. Regarding RQ1 "How to recognize alternative pathways of surface water in the small catchment of Storelva river in Innvik, with the use of a GIS based method?" the methodology used for modifying the DEM in potentially vulnerable infrastructure such as bridges and culverts, in accordance with the output in the form of static maps is one way that allows us to identify spots where potential changes might occur in the water flow. Further developing of that approach could include making these static maps interactive, by creating an online version of the map where the user may select a certain scenario and the map would update accordingly with the surface flow paths, along with a classification of the exposed buildings and road segments.

Knowledge about technical information regarding the infrastructure and understanding of the complexity of the study area, would possibly lead to a better evaluation of methods. In this research have been tested 16 different combinations of open and closed culverts and bridges. As mentioned in the methodology, there are more possible scenarios and thus, the total number of possible combinations of flow modelling with open and closed bridges and culverts could be studied thoroughly for an improved evaluation of the possibly exposed to floods areas. By combining the 16 scenarios of open and closed culverts and bridges, there have been identified buildings and road segments that are exposed, whatever scenario has been applied (figure 60, figure 61). Comparison between scenarios with something in common has shown differences in the exposed areas.

The surface runoff modelling studied in this master thesis has been based on the simple algorithm D8. Regarding RQ2 "How can the flow direction be manipulated in critical spots ?", the model used to modify the DEM in specific locations, was effective on making changes in the flow paths, by digging "openings" in the DEM which are the culverts in this case and by raising the elevation in the case of the bridges, in order to manipulate the water flow accordingly.

The third research question is concerned with NVE's existing flood susceptibility maps. RQ3 "Can the susceptibility maps from the NVE be used as validation?" will be answered negatively because in the findings of this research by all the scenarios compared, the locations of the most exposed buildings and road segments do not coincide with the susceptibility map of the NVE. One reason that might happens, is due to the methodology of Peereboom (2009), which is not used to produce a flood inundation map, but to produce a susceptibility map instead, that demonstrates areas where the danger of flooding needs to be evaluated further and it does not show which areas are likely to flood. Another reason might be because the study area is a steep, small catchment and the results can vary depending on how steep the catchment is. Nevertheless, as mentioned in the methodology, it is common to use damage registrations from previous events as validation, which could not be found in this case.

This study has shown that for the scenarios applied, the highest accumulation values and thus exposed buildings and roads, are mostly located in the lower part of the catchment, with also some of them located higher in the catchment area and on the right side of the river. This research has also found that these buildings and road segments located in the lower part of the watershed, differ in their level of exposure and some of them are exposed only by some few scenarios while others are exposed by many. In the third, fifth, seventh, fifteenth and sixteenth scenario are observed the most exposed elements higher in the catchment area. The lower right side part of the river is more exposed when the third, fourth and ninth scenarios are applied. Regarding the lower left side part of the river, it is observed that more exposed elements exist in the sixth, thirteenth and fourteenth scenario, with the latest having elements with the highest accumulation values. From the results it is observed that when a bridge is blocked, the accumulation values around rapidly incline, therefore it is vital to ensure the culverts are effectively operating. Around bridge B3 are not installed any culverts and the surrounding area is highly exposed in case that bridge is blocked. In conclusion, what is happening before the flow reaches the lower part of the watershed matters and a blocked bridge will affect the total water flow that will reach the watershed.

This GIS method could be further developed with the use of more advanced hydrological modelling. It would be useful to know more technical information that form the capacity of the culverts and bridges, such as material, shape and any flaws that could lead a heavy rainfall event to develop into flood. Information regarding the capacity of the drainage system would promote the research as it is important to know what is the amount of rainfall that the drainage system can tolerate. In addition, precipitation data could be implemented from a potential future heavy rainfall event that would lead into a flood. Such implementation would offer knowledge about critical spots and information about the actual flood areas. Additionaly, registering of any existing damage points, could offer an increased validation to this research. Thus, we would learn more about the critical spots and how much water they can endure. Based on this study and further research in the infrastructure of the area, could be identified potentially critical locations and action may be taken, such as replacement of “weak” structures and installation of additional culverts in areas in need.

In conclusion, this research will hopefully support the decision making in the local community in Stryn, regarding possible targets of a future flood and hopefully will contribute to prevent any negative outcomes as well as to adaptation.

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