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SCENARIO-BASED MODELLING OF GLACIAL LAKE OUTBURST FLOOD AND ASSESSMENT OF ITS IMPACT IN DOWNSTREAM AREA

A Case Study of a glacial lake in Jostedalsbreen Ice Cap, Norway

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Abstract

With the increased melting and retreat of glaciers as an effect of climate change, the number and size of glacial lakes are increasing, putting the downstream communities in the Arctic region at risk. Jostedalsbreen Ice Cap in Western Norway is facing a similar problem where new lakes are formed, and existing lakes have been found expanded in recent years. In recent decades, the number of Glacial Lakes Outburst Flood (GLOF) events have also been recorded to increase in number and some lakes are expected to be potentially dangerous. That is why it is important to assess the impact of potential GLOFs in such areas so that the planners and local authorities can make plans accordingly and prepare the downstream communities to avoid or reduce potential disasters.

In this context, this study utilizes the 2-dimensional Hydrodynamic modelling tool, HEC RAS to model the dam breach and inundation flood generated due to GLOF in a potentially dangerous moraine-dammed lake in Jostedalsbreen region. The study also utilizes the empirical formula to derive mean depth, total volume, drainage volume, and peak discharge of lake water from the lake surface area. The outburst duration, peak discharge and manning's roughness coefficient are varied in a way to assume three different scenarios (Optimistic, Intermediate and Pessimistic) to assess the impact of flood (2-meter water depth) in downstream area.

The result of the study showed least impact in Optimistic scenario with 23 buildings, 4.80 km of river section and 2.64 km2 of land surface area affected under flood. However, the highest impact was observed in the Intermediate scenario where 35 buildings, 6.47 km of river sections and 3.68 km2 of land surface area were affected by the flood rather than in Pessimistic scenario. This could be because of the change in water course due to terrain feature, roughness coefficient, and difference in the velocity of flow which avoided some buildings, river sections and land surface area in Pessimistic scenarios.

This method is very economical because of the use of open-source software like HEC RAS, QGIS, and empirical formula and it at least helps the planners and local authorities to anticipate the range of impact different scenarios could create in downstream areas. Nevertheless, it is crucial to study the geomorphology of glacial lakes, moraine dam and potential flow path to model the impact with higher precision.

Language: English

Key Words: Climate change, Glacial Lake Outburst Floods, scenarios, modelling, HEC RAS, and impacts

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Acronyms

GLOF	Glacial Lake Outburst Flood
NVE	Norwegian Water Resources and Energy Directorate
HEC RAS	Hydrologic Engineering Center's River Analysis System
DEM	Digital Elevation Model
QGIS	Quantum Geographic Information System
SI	International System of Units

1. INTRODUCTION:

1.1 Background:

Among the most sensitive indicators of climate change are glaciers, which are losing their mass at an astounding rate resulting in a rapid increase in the number and size of glacial lakes all-round the globe with more than 50% than that of 1990 (Shugar et al., 2020; Zheng et al., 2021a). In recent years, new lakes have emerged in glacier forefields, and surface areas and volumes of many proglacial lakes are reported to be growing in many mountain areas due to climate-induced glacier melt (Carrivick & Quincey, 2014; Song et al., 2017; Wang et al., 2015). Due to a continuing increase of summer temperatures predicted for western Norway until the end of this century, it is likely that the current trend of the accelerated mass loss of Norwegian glaciers will continue and one consequence of this development, new lakes will emerge within the formerly glaciated and newly exposed terrain (Laute et al., 2020; Laute & Beylich, 2021).

Especially in mainland Norway, where glaciers and glacier-fed streams have a high importance for hydropower production, tourism, and climate research it is essential to gain a better understanding of the possible impacts of glacial lakes for being prepared for risks but also advantages arising from these newly emerging landscape elements (Laute et al., 2020).

Ice-dammed lakes, some called proglacial lakes can cause catastrophic Glacier Lake Outburst Floods (GLOFs) (or jökulhlaups in Norwegian) when these dams fail (Harrison et al., 2018; Liestøl, 2008; Reynolds, 1999; Veh et al., 2018; Zheng et al., 2021b). This has increased threat to the communities residing downstream from the glacial lakes with potential Glacial Lake Outburst Flood (GLOF) events causing loss of lives and properties. Until 2022, more than 2,800 GLOF events have been recorded globally (Veh et al., 2022) and more than 12,000 deaths are accounted to such events until few years back (Carrivick & Tweed, 2016). It is recorded that 158 events have occurred since 1760 in Norway alone, half of which have occurred since 2000. About twice a dozen events have been recorded around Jostedalsbreen, the largest glacier in the mainland Europe (Norwegian Water Resources and Energy Directorate, 2023). In a recent inventory, it was confirmed that new lakes are being formed in the area, while the size of existing glacial lakes is increasing (Andreassen et al., 2022) which indicates the possibility of GLOF events in near future.

1.2 Research problem and rationale of the study

With increasing impact of global warming on glacier and glacial lakes, the frequency of GLOF events and the magnitude of their impact on downstream communities is expected to increase in coming years (Jackson & Ragulina, 2014). Therefore, inventory of glacial lake surface area both in regional and national level has been conducted in some years intervals in Norway to monitor the changes (Nagy & Andreassen, 2019)and are updated in the official glacier atlas website of Norwegian Water Resources and Energy Directorate (NVE), the Breatlas. Besides lake surface area, the atlas includes updated records of sites (lakes) with history of GLOF events and potentially dangerous sites (*NVEs Breatlas*, 2023). However, it is also necessary to assess potential impacts of GLOF events when they occur in the future to prevent damages due to potential hazards. Therefore, this study aims to conduct 2D dam-breach modelling in HEC RAS (stands for Hydrologic Engineering Center's River Analysis System) of a potentially dangerous glacial lake at Jostedalsbreen to assess potential impact downstream in case of outburst at present and in future.

1.3 Glacial Lake Outburst Flood (GLOF)

The movement of glaciers erodes the landscape under them, leaving depressions and ridges behind them. These ridges which in fact are made up of unconsolidated earth materials of rocks and dirt are called moraines. Most of the glacier lakes are formed as a result of filling of the depression made by melt water from glacier retreat and hold back by the moraine dam. Such lakes are very common and are in fact called moraine-dammed lakes (AntarcticGlaciers.org, n.d.-b).

GLOF is generally a sudden release of water from a glacial lake due to dam failure. The duration of this process may range from few hours to many days, and it might also occur in certain cycles meaning that certain volume of water gets discharged from the lake at certain intervals instead of discharging at once. However, moraine dam failure occurs mainly because of two factors. They are integrity of dam and type of trigger mechanisms. Dam failure process begins with the introduction of trigger factor such as huge chunk of ice calving causing a displacement wave on the surface of glacial lake. This initiates the overtopping of moraine dam and consequently formation of incision. The water discharge from the lake keeps on increasing as the incision gets bigger and finally slows down after certain point (AntarcticGlaciers.org, n.d.-a) (Fig. 1).

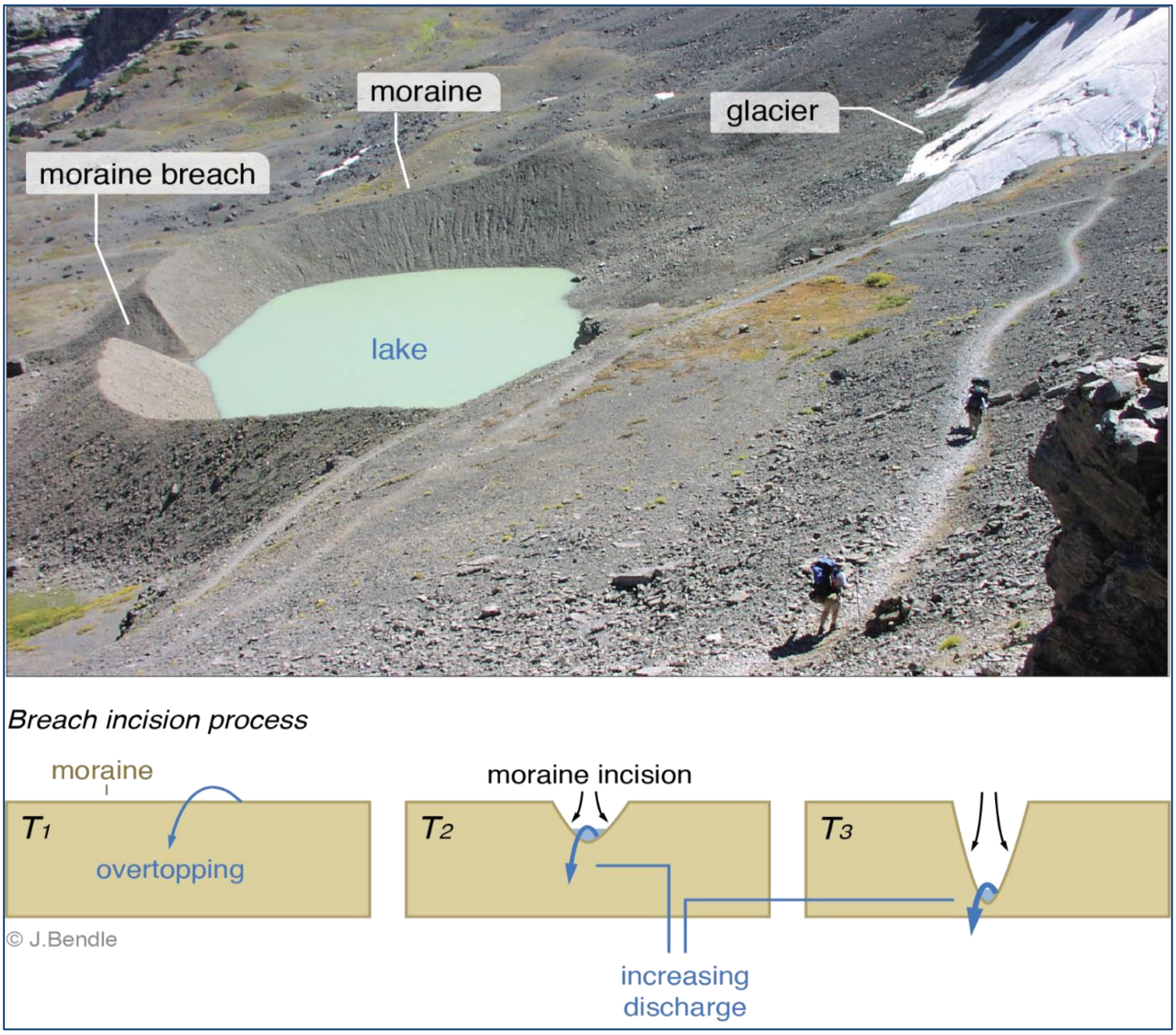


Figure 1: Breach incision process in a moraine-dammed glacial lake (source: (AntarcticGlaciers.org, n.d.-a)

In recent years, the number and size of glacial lakes in mountain regions have increased worldwide associated to the climate-induced glacier retreat and thinning (Laute et al., 2020). Hence, climate change is making GLOF a more urgent problem as glaciers melt more quickly due to rising temperatures, leading to more glacial lakes that could potentially cause a flood (Laute et al., 2020). The average surface temperature of the earth has increased between 0.30 C° and 0.60 C° over the past hundred years and the increase in global temperature is predicted to continue rising during the 21st century (Bajracharya et al., 2007). Due to the predicted increase in summer temperatures for western Norway until the end of this century, it is very likely that the current trend of an accelerated mass loss of Norwegian glaciers will continue (Laute et al., 2020). Therefore, it is essential to understand the causes and effects of GLOFs in order to create practical mitigation methods that will safeguard ecosystems and vulnerable populations.

1.4 Dam-breach and inundation flood modelling

One of the most widely used software for modelling flood water is the HEC RAS which stands for Hydrologic Engineering Center River Analysis System and is capable of performing various hydrologic analysis including 1-Dimensional (1D) steady flow and 2-Dimensional (2D) both steady and unsteady flow analysis (USACE Hydrologic Engineering Center, 2023a). Since the GLOF is an example of an unsteady flow velocity, pressure, and cross-section changes with time during the flow, this study utilizes 2D unsteady flow analysis process to model the flood. The basic principle under which the HEC RAS functions is the principle of continuity combined with the Digital Elevation Model (DEM) meaning that the product of cross-sectional area of water flow and its flow velocity at one point is equal to that at another point along the flow path (Xu et al., 2019). Apparently, the software requires the user to delineate the storage area (lake) and flow area (downstream flow area) and set up some parameters to establish initial and boundary conditions. The initial conditions include flow and stage of lake water, and the boundary conditions include friction slope and lateral inflow hydrograph (USACE Hydrologic Engineering Center, 2023a). In addition, the entire flow area should be divided into small grid cells (2D mess) so that the modelling results are computed for each cell (USACE Hydrologic Engineering Center, 2023a).

2. OBJECTIVE AND RESEARCH QUESTIONS:

The objective of this study is to model the dam-breaching and inundation of GLOF based on different scenarios and assess their impacts in downstream area. In line with the objective, this study answers the following questions.

- What is the extent, and depth of flood water in downstream areas at certain time after the start of dam breach at the glacial lake upstream?
- How many buildings, what length of streams and what area of land surface are impacted under different scenarios of GLOF?

3. MATERIALS AND METHODS:

3.1 Study area:

Stryn municipality lies at the north-western part of the largest glacier in mainland Norway, Jostedalsbreen covering an area of 1,382 km^2. The municipality extends from the ridge of Jostedalsbreen Ice Cap towards the fjord including the 12 glacier arms. However, the area of interest for this study is a beautiful tourist-attracting valley called Oldedalen which lies along the Oldenelva river and a glacial lake in its upstream. There is no specific name found for this glacial lake, but it is a proglacial lake situated at the northern edge of Melkevollbreen glacier (Glacer ID: 2324) (Visit Nordfjord, 2023). The glacial lake is a moraine-dammed lake with a surface area of 0.0432 km^2 measured on 26th August 2021 and it lies at an altitude of 1404 meter from the mean sea level (Pariyar, 2022b). Geographically, the lake is located at a latitude of 61.638394° and a longitude of 6.841653°. The lake has an outlet with natural drainage at the moraine formed towards north (Pariyar, 2022b).

Oldedalen valley has a number of things to offer to the tourists such as beautiful sceneries cabins, hotels, campsites, hiking trails, grocery stores, and cafes (Visit Nordfjord, 2023). For the sake of this study, the study area is delineated with an imaginary rectangle extending from just above the glacial lake all the way to the Oldevatnet lake downstream and covering the ridges on either side of the valley. Therefore, the total number of buildings that come inside the area of interest is 213. Similarly, total of 59.15 km river section and 49.65 km^2 of land surface fall within the study area as shown in (Fig. 2).

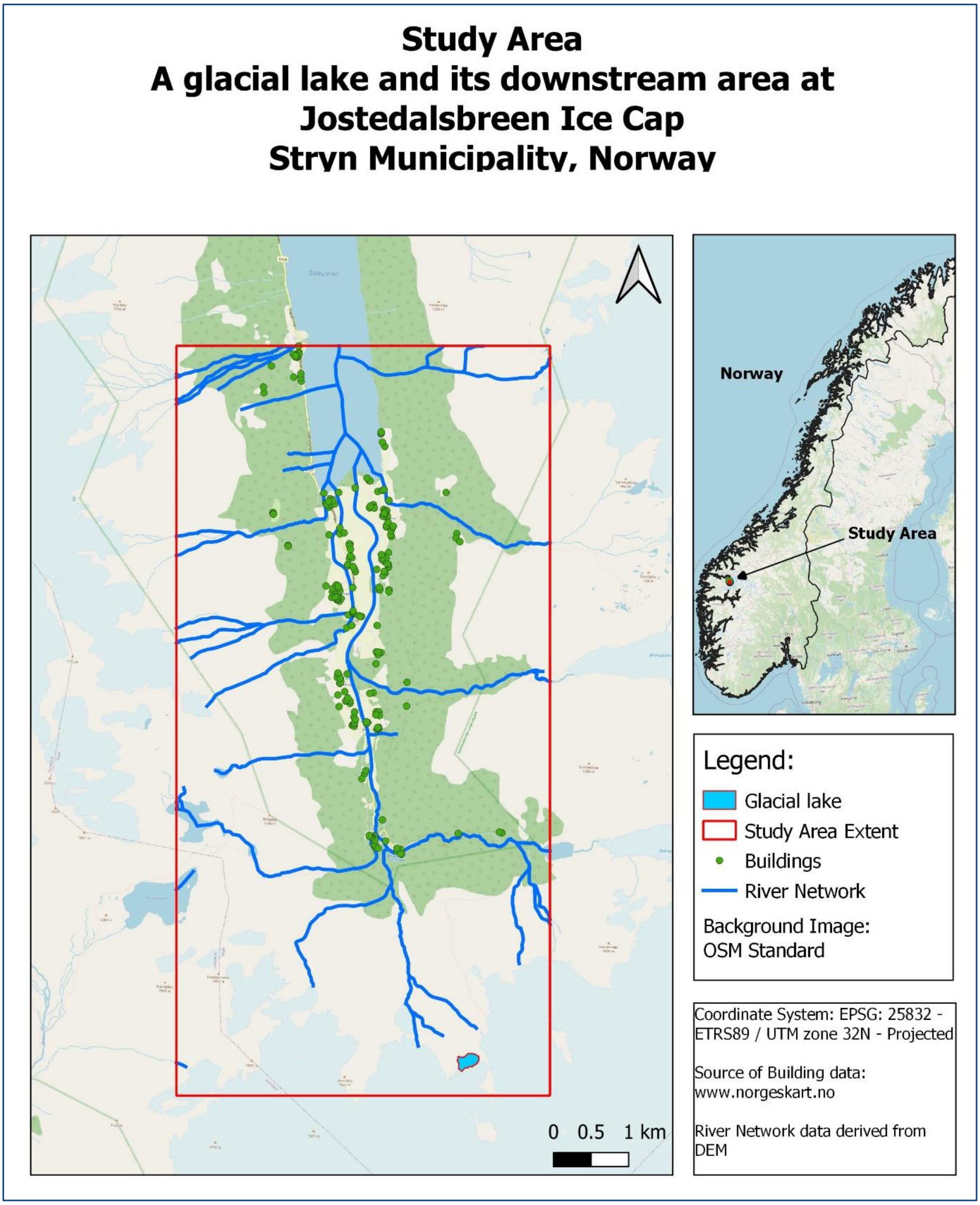


Figure 2: Study Area

The reason behind choosing this lake for this study is the gradual expansion in the lake extent in recent years and significant chance of overtopping because of displacement wave caused due to ice-calving. With increase in regional surface temperature, the lake is expected to expand even more in near future which might have higher impact downstream in case of outburst (Pariyar, 2022a).

3.2 Research design:

The study is designed to model GLOF events in three different scenarios at present context. However due to unavailability of actual field data on certain parameters, empirical derivative equations feasible for the study area are used to derive the data for required parameters. The illustration of procedure of this study can be observed in the (Fig. 3).

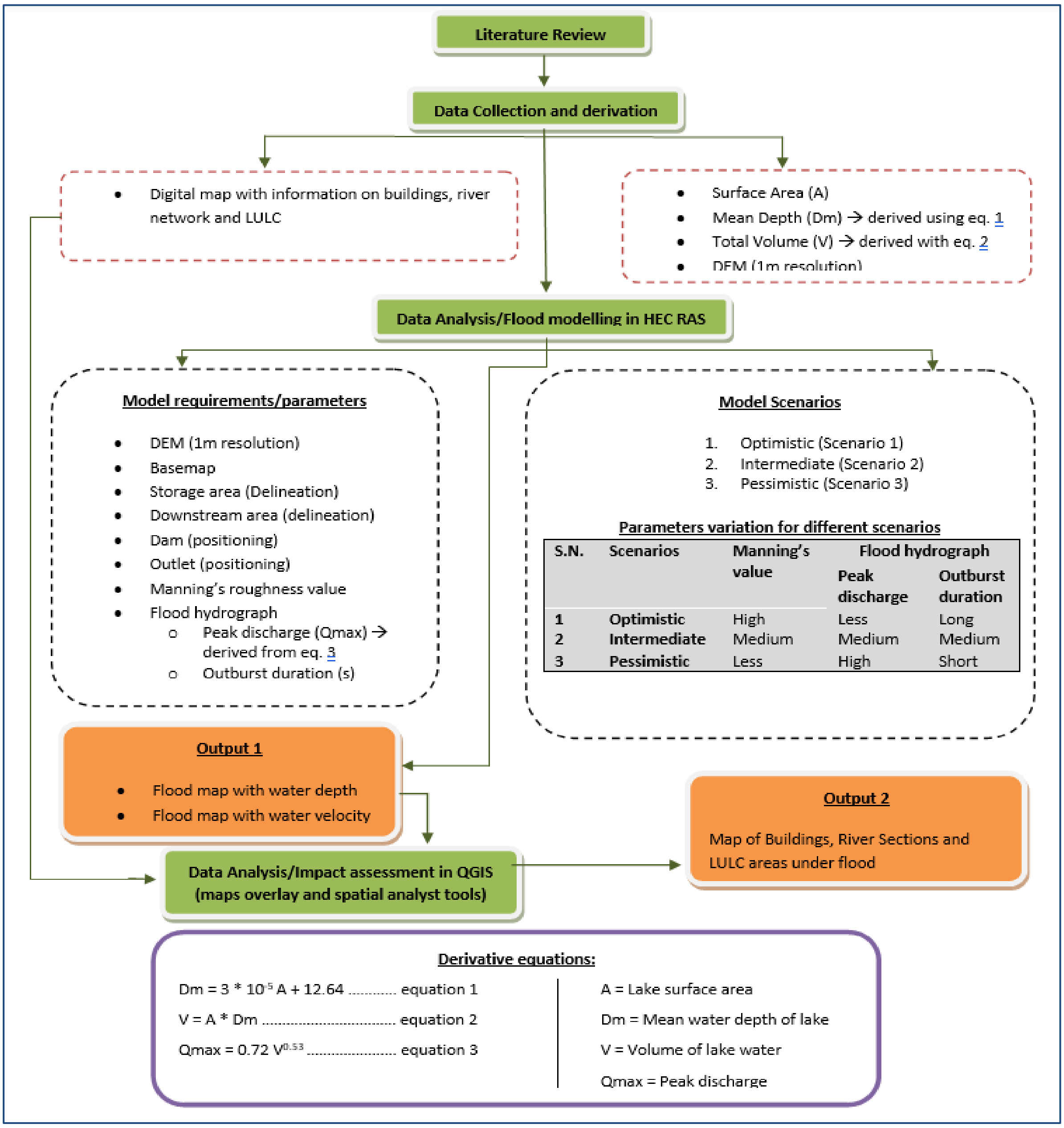


Figure 3: Research Design

The study begins with literature review on already published articles and reports on glacier, mass balance, glacial lakes, and impacts of climate change on them in Norway and in other regions. Even if there have been many GLOF events in Norway, it was found that there are few studies associated with modelling of GLOFs conducted in Norway. Due this and a lack of actual field data, I chose to approach this study with the help of empirical derivative equations used in other parts of the world with similar geographical situations. Hence, the primary data to begin with the modelling process in HEC RAS, which is the surface area of glacial lake, was delineated from the Sentinel 2 Imagery obtained from Copernicus Satellite Services (*Copernicus Open Access Hub*, 2023; Pariyar, 2022a). The following empirical equations were used to derive other parameters.

$Dm = 3 * 10^{-5} A + 12.64$ ………… equation 1 (Cook & Quincey, 2015a)

$V = A * Dm$ ……………. equation 2

$Qmax = 0.72 V^{0.53}$ ……………… equation 3 (Evans, 2011)

Here, A is lake surface area, Dm is mean water depth of lake, V is volume of lake water, and Qmax is peak discharge of lake water.

Three different scenarios are developed in this study where the parameters are varied to make them optimistic, intermediate, and pessimistic. The main parameters varying in these scenarios are discharge volume, peak discharge, outburst duration, and Manning's roughness value (roughness coefficient) which make the scenarios different from each other. Basically, the optimistic, pessimistic, and intermediate scenarios are the conditions where the impact on downstream area will be less, high, and medium respectively given other factors constant, meaning that less number of buildings, land surface area and length of river sections come under the flood in less impact scenario (Optimistic scenario) and more in high impact scenario (Pessimistic Scenario). However, the actual results of these modelling scenarios indicates how the magnitude of the impact. With climate change, the extents of glacial lakes are also showing variations, so these scenarios could also be tested for future condition of the lake. Once the flood maps containing water depth and velocity for different scenarios were obtained, they were exported to QGIS where they were overlaid on digital maps (shapefiles) with information on buildings, river sections, and land surface areas. Eventually, spatial analyst tools were used to assess the impacted elements in downstream area.

Details on dam breach scenarios are shown in the following table (Tab. 1) where surface area is obtained from outline mapping done on Sentinel 2 imagery of the lake on 26th August 2021 (Pariyar, 2022b). Mean depth (Dm), total volume (V), and Peak Discharge (Qmax) are derived from above-mentioned equations (1), (2) and (3).

Table 1: Details of dam breach scenarios

Area (m2)	Mean Depth (m)	Volume (m3)	Qmax (m3/s)	Scenarios	Outburst duration (m)	Manning's value	Drainage Percentage (in decimals)	Total Discharge Volume (m3)	Qmax (m3/s)
43200	13.94	602035.2	832.78	Optimistic	60	0.05	0.2	120407.04	354.88
				Intermediate	40	0.04	0.5	301017.60	576.75
				Pessimistic	20	0.03	1	602035.20	832.78

GLOF events are unpredictable because of different factors. Out of them, the most common are geomorphology of the dam and trigger mechanisms. Similarly, volume of flooded water and duration of outburst are unpredictable (Cook et al., 2016; Cook & Quincey, 2015b; Kougkoulos et al., 2018). However, in general, we can assume that higher volume of water flooded in short period of time will cause higher impact and vice-versa. Therefore, in Optimistic scenario, outburst duration is assumed longer time (60 minute) with just 20 % of total lake water volume to be flooded and in Pessimistic scenario, outburst duration is assumed shorter time (20 minute) with just 100 % of total lake water volume to be flooded. In Intermediate scenario, outburst duration is 40 minute and flooded water volume is 50 % of total lake water volume. Peak discharge (Qmax) for each scenario is calculated with respective volumes of flooded water using equation 3. The Manning's roughness coefficient represents the loss of energy of flooded water causing less harm downstream (USACE Hydrologic Engineering Center, 2023b), however due to lack of field observation, it was not possible to assess the actual materials on the flow path to find exact Manning's roughness coefficient value. Nevertheless, observation from Google Earth helped to confirm that it's a mountain stream with no vegetation in the stream channel but trees along the banks. As per the table of Manning's roughness (n) values for Channels proposed by Chow (1959), such mountain streams could have a value range from 0.03 (minimum) to 0.05 (maximum), 0.04 being normal (Oregon State University, n.d.). Therefore, Manning's roughness coefficients for Optimistic, Intermediate and Pessimistic scenarios were assumed to be 0.05, 0.04 and 0.03 respectively in this study which were also used in similar study in Bolivia (Kougkoulos et al., 2018).

3.2.1 Data collection and analysis:

The primary data needed for conducting the modelling are geomorphological details of lake, DEM, and flood hydrograph. The details of lake include its geographic location, elevation, surface area, water depth (mean depth), volume of lake water, drainage percentage (based on scenario), total discharge volume (based on scenario), peak discharge volume (based on scenario) and Manning's roughness coefficient value. The location, elevation, surface area, and DEM can be obtained from the US Geological Survey website, the EarthExplorer (https://earthexplorer.usgs.gov/) (United States Geological Survey, 2023). However, the DEM for this study was obtained from website https://www.kartverket.no/ which is developed by the Norwegian national mapping agency, The Norwegian Mapping Authority (The Norwegian Mapping Authority, 2023a, 2023b). The DEM hence obtained is of 1 meter resolution. Since it is not possible to obtain water depth due to lack of bathymetry data, the empirical formula (eq. 1) was used to derive mean depth (Dm) from surface area (A). The mean depth hence obtained was multiplied to surface area to get total volume (V) of water in lake (eq. 2). As per the scenario, the drainage % determines the actual drainage volume, which was used in eq. 3 to derive peak discharge. Due to lack of actual flood hydrograph, an anticipated outburst duration was paired with peak discharge value obtained from the derivation in a way that they represent three different flood hydrographs corresponding to three different scenarios. Basically, a low peak discharge and long outburst duration determines an optimistic scenario and opposite for pessimistic scenario. Medium peak discharge and medium outburst duration determine an intermediate scenario. Manning's roughness coefficient values are also set in a similar fashion meaning higher for optimistic and lower for pessimistic scenarios.

Secondary data needed for this study was the digital maps of buildings, river network, and land surface which were obtained from the website https://www.kartverket.no developed by Norwegian Mapping Authority. These maps were combined with flood maps in QGIS for assessing the impact.

3.2.2 Flood hydrograph

A hydrograph is a simple chart or graph showing the discharge of water at certain point of a channel against time (Willis, 2011). Discharge is the rate at which water flows out from a water source, and it is expressed in cubic meter per sec (m^3s^{-1}) (Misra et al., 2011). Since discharge can be measured at any point of time during the flow, the time duration can be either seconds, minutes, hours, days, or other units. Therefore, the unit of hydrograph can be m^3 per -seconds, -minutes, -hours, and so on (Misra et al., 2011; Willis, 2011). Generally, the shape of the hydrograph is triangular with a rising and a falling limb with a peak discharge in between but it is difficult to predict an exact shape of a hydrograph due to numerous factors, so it was assumed as a perfect isosceles triangle where the peak discharge lies exactly at the mid-point of total outburst duration as in fig. 2 (Kougkoulos et al., 2018). Based on the variations in scenarios they formed different isosceles triangles.

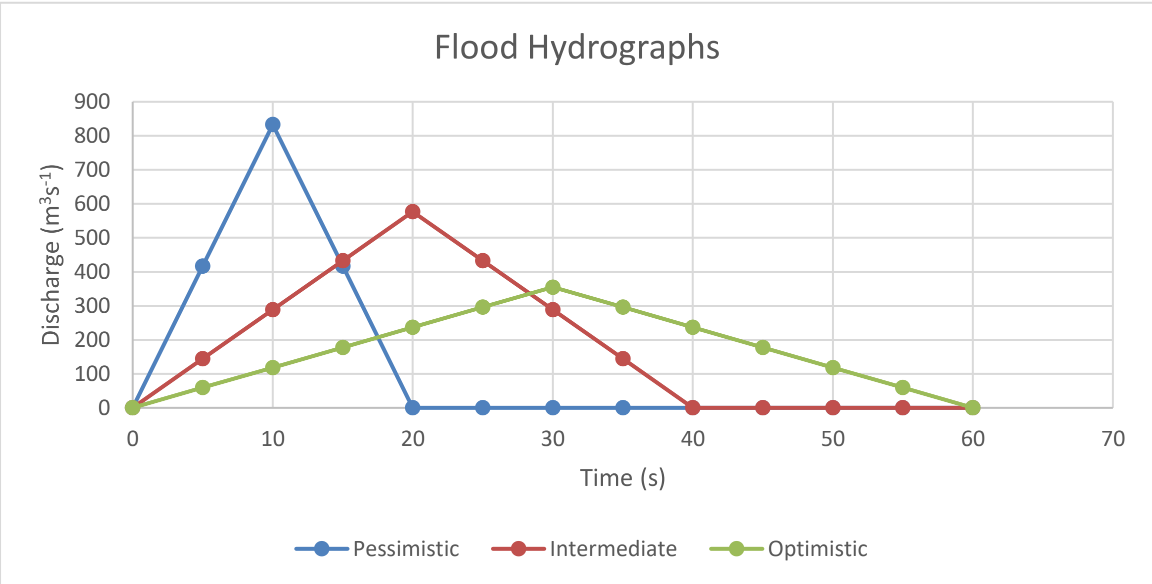


Figure 4: An illustration of flood hydrographs showing three different scenarios.

3.2.3 Digital Elevation Model (DEM)

Digital Elevation Model (DEM) is a graphical representation of land surface without including vegetation, buildings, and other elements on the surface of earth (U.S. Geological Survey, n.d.). It is the base surface over which the flow of flood water is modelled. DEM with spatial resolution of 1 meter is used for this study to optimize the accuracy of the model. The DEM required for this study is freely downloadable from the official website of The Norwegian

Mapping Authority (https://hoydedata.no/LaserInnsyn2/) (The Norwegian Mapping Authority, n.d.).

3.2.4 2D Dam-breach and outburst flood modelling using HEC RAS:

There are different methods available for modelling the outburst floods based on the purpose of study and parameters available for the models but there are basically two modelling approaches; 1-dimensional (1D) and 2-dimentional (2D) modelling approaches that can be used in HEC RAS (USACE Hydrologic Engineering Center, 2023b). Since I was interested in finding the extent, depth, and velocity of flood water, 2D model was best fit for this study as it is capable of modelling multi-directional and multi-dimensional flows, which are the basic aspects of GLOFs (Kougkoulos et al., 2018; USACE Hydrologic Engineering Center, 2023b). Therefore, the HEC RAS 6.3.1 version of software was used for this study as it is freely available.

At first, a project was created in HEC RAS setting the field specific projection and SI unit and the DEM layer covering the study area is added in the geometry section. Once the DEM was added, the geometry was edited to locate and delineate the lake area (Storage Area), inundation area (2D Flow Area), dam (Weir/Embankment), and outlet. A 2D mess of specific cell size was generated in the 2D Flow Area and then a breach in the Weir/Embankment was planned with data on its final bottom-width, elevation and slope, breach formation time, and starting water surface elevation. The data on Normal Depth – Friction Slope and Lateral Inflow Hydrograph were filled in to fulfil Boundary condition. The Normal Depth-Friction Slope denotes the slope of downstream area which is almost flat, so it was kept 0.01. Likewise, the Initial Elevation of Storage Area (lake water) was filled in Initial Condition. After setting the breach starting time, ending time, model computation interval and mapping output interval, the model was run. The model run time was set to 3 hours after the starting time so that the flooded water in could be fully captured well in the downstream. When the process was successful, the flood maps representing the changing extent, depth, and velocity of flood water after outburst were obtained.

3.2.5 Impact analysis using QGIS:

The flood maps hence obtained was exported to QGIS software where it was overlayed with other digital maps including households, river network and land surface. Both the maps were analysed for impact assessment using spatial analyst tool. The QGIS 3.22.13 version which is freely available was used for this study.

4. RESULTS:

4.1 Scenario 1 (Optimistic Scenario)

The following figure (Fig. 5) shows the result of optimistic scenario of GLOF modelling where the pink-coloured area represents the extent of the flood with water depth above 2-meter as well as the land area affected by it. In this scenario, 23 buildings (red), 4.80 km of river section (blue) and 2.64 km^2 of land surface (pink) fall into the flood.

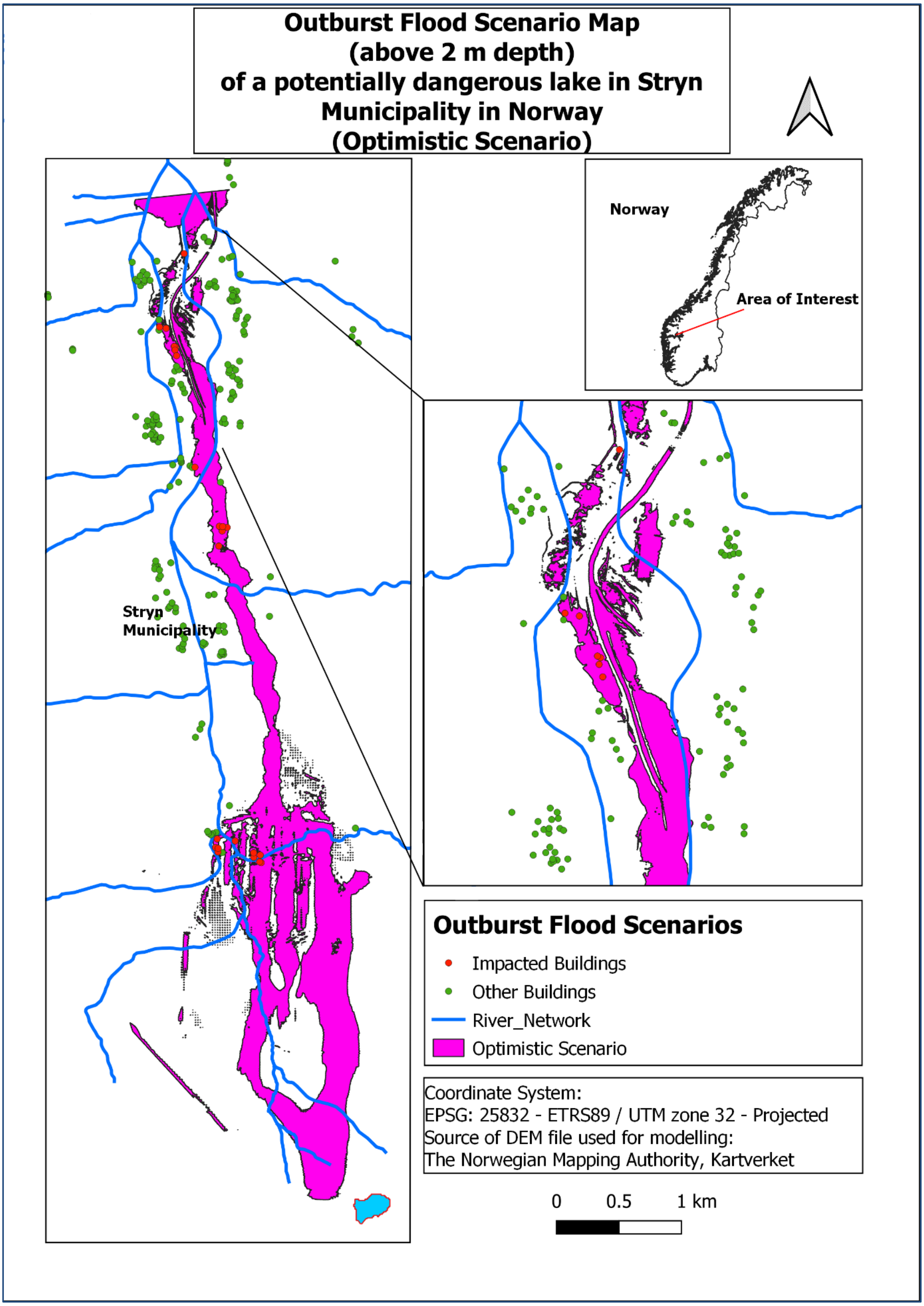


Figure 5: Scenario 1 (Optimistic Scenario)

4.2 Scenario 2 (Intermediate Scenario)

The following figure (Fig. 6) shows the result of intermediate scenario of GLOF modelling where the yellow-coloured area represents the extent of the flood with water depth above 2-meter as well as the land area affected by it. In this scenario, 35 buildings (red), 6.47 km of river section (blue) and 3.68 km^2 of land surface (yellow) fall into the flood.

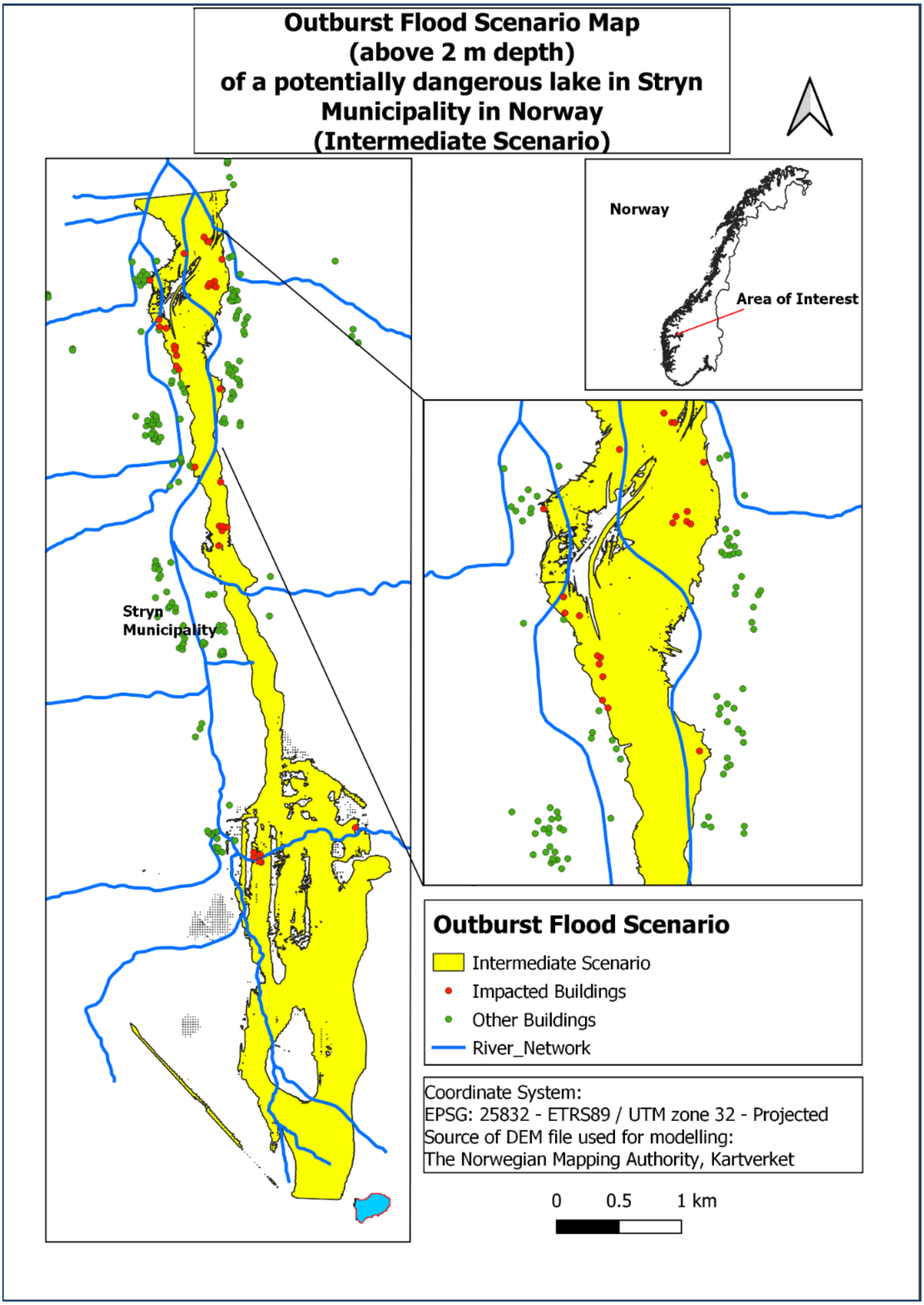


Figure 6: Scenario 2 (Intermediate Scenario)

4.3 Scenario 3 (Pessimistic Scenario)

The following figure (Fig. 7) shows the result of intermediate scenario of GLOF modelling where the red-coloured area represents the extent of the flood with water depth above 2-meter as well as the land area affected by it. In this scenario, 32 buildings (red), 6.29 km of river section (blue) and 3.56 km^2 of land surface (red) fall into the flood.

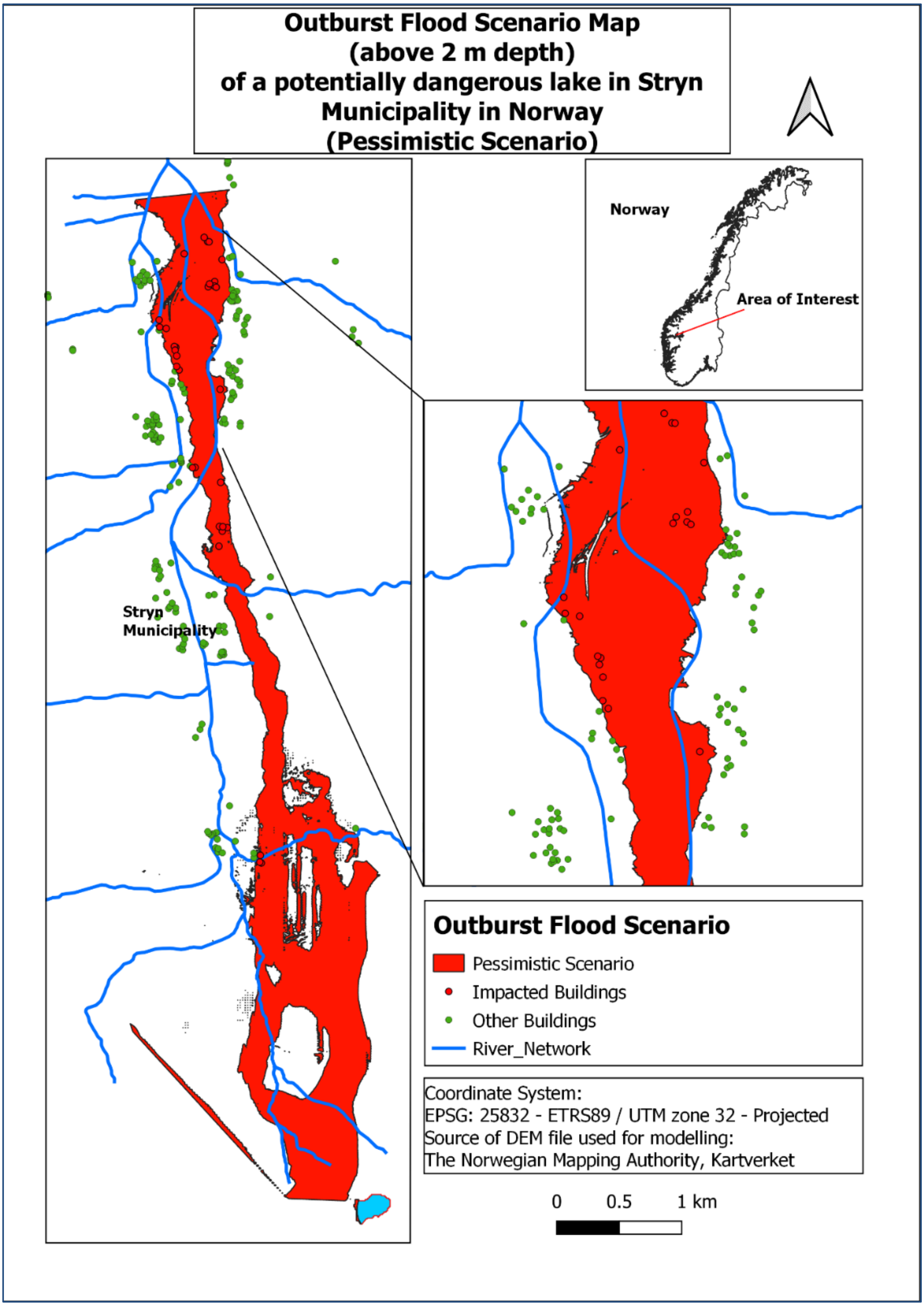


Figure 7: Scenario 3 (Pessimistic Scenario)

4.4 Comparison between scenarios

The following figure (Fig. 8) shows the result of all three scenarios of GLOF modelling overlaid on top of each other where pink, yellow and red areas represent Optimistic, Intermediate and Pessimistic scenarios respectively.

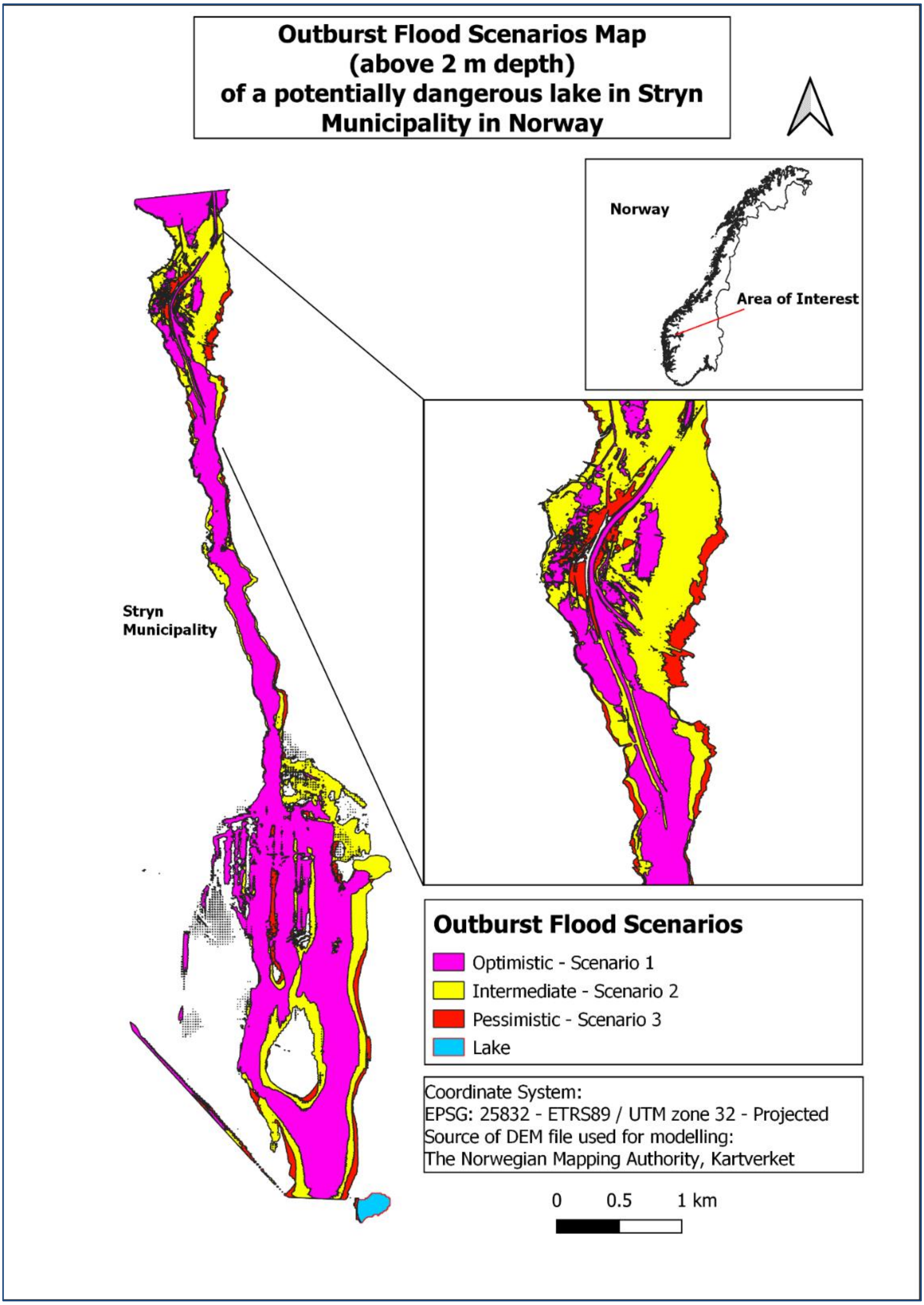


Figure 8: Outburst Flood Scenarios

The following table (Tab. 2) summarizes the impacts of GLOF in different scenarios. As expected, the number of buildings, sections of river network and area of land surface flooded are more in Intermediate and Pessimistic scenarios as compared to Optimistic scenarios. However, the impact is slightly higher in Intermediate scenario as compared to Pessimistic scenario which suggests that the parameters values used in Intermediate scenario are capable of generating higher impact in the study area.

Table 2: Impacts of different scenarios

Scenarios	**Impacts**		
	Number of buildings affected	**Section of river network crossed (in km)**	**Area of land surface affected (in sq.km.)**
Optimistic-1	23	4.80	2.64
Intermediate-2	35	6.47	3.68
Pessimistic-3	32	6.29	3.56
NOTE: Flood depth over 2m is considered hazardous			

5. DISCUSSIONS:

According to the result of the outburst, more buildings, river sections, and land surface areas are impacted in the intermediate scenario than in the pessimistic scenario. This could be because of the change in water course due to terrain feature, roughness coefficient, and difference in the velocity of flow. Since the pessimistic scenario has shorter outburst duration, higher peak discharge, and lower roughness coefficient, the velocity of flow is higher which could result in change in direction of water course and cover lesser buildings, river sections and land surface in its path (Fig. 9).

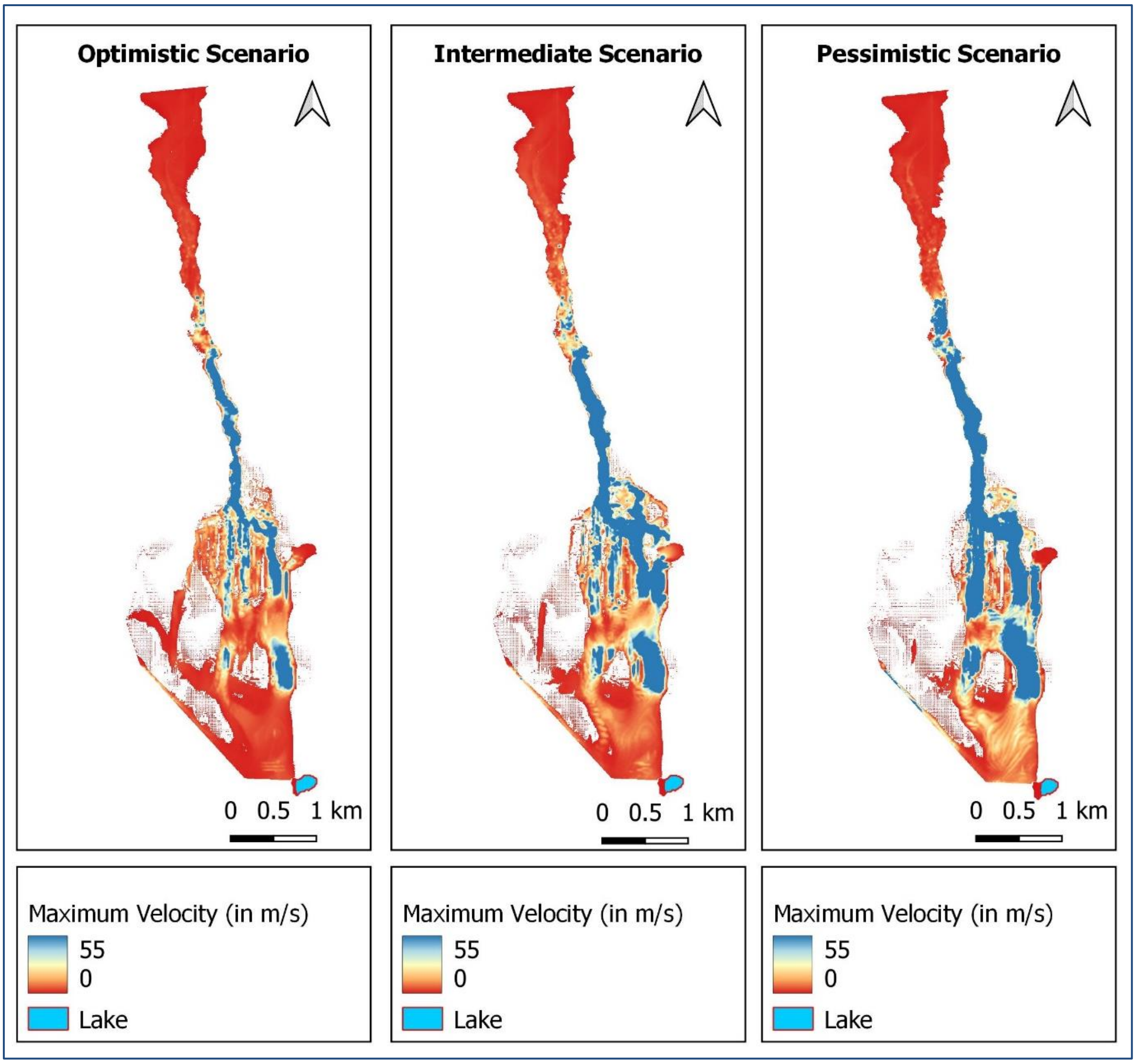


Figure 9: Maximum velocity of flood water in m/s in different scenarios

The major problem while performing such modelling is the validation of the results. Since there has been no GLOF events happened in the study area (glacial lake) in the past, it is difficult to validate the results produced in this study. However, there has been few studies of GLOF events happened in other glacial lakes around the Jostedalsbreen Ice Cap in the past so we can at least compare the applicability of the empirical equation to derive the parameters values to model the possible outburst in the study area. For the context, there was an outburst event occurred in the year 2004 in a similar moraine-dammed lake situated at other side of the glacier in Fjærland, Western Norway. The glacial lake is situated at an altitude of around 1000 m.a.s.l. The study conducted at the site (Breien et al., 2008) suggests that the surface area of the lake before the GLOF event was around 10,000 m^2 which when used in the empirical equations gives a total water depth of 12.94 meter and a total water volume of 129,400 m^3. According to the study by

(Breien et al., 2008), there was a difference of 6 to 10 meter in the elevation in the lake area and the lake was not fully drained. This suggests that the total depth of the lake could be near around the derived value (12.94 meter) and thus favours the applicability of the empirical equations for the glacial lake in our study. The study by (Breien et al., 2008) also identifies that the decrease in water level was 5 meters from the initial water level which is 38.6 % of the estimated total water depth (12.94 meter) and the volume of water drained was at least 50,000 m^3 which is also 38.6 % of the estimated total water volume (129,400 m^3) by coincidence. However, it is fact that due to curved lakebed surface, the volume of water is higher in upper section of the lake (Fig. 10) and the estimate made in the study by (Breien et al., 2008) also suggests that the volume of water drained out could be more than 50,000 m^3. In this sense, we can say that the empirical equation for deriving total volume of lake water in our study area is also doing a good justice.

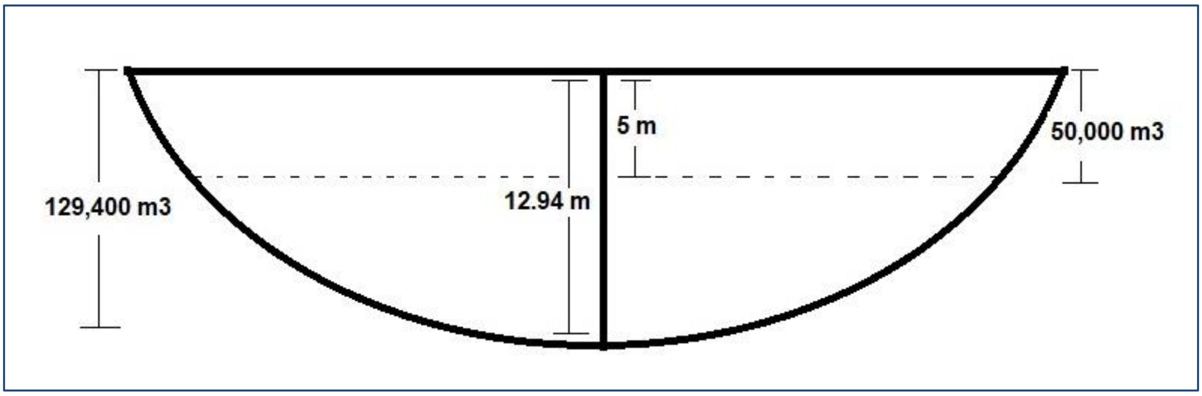
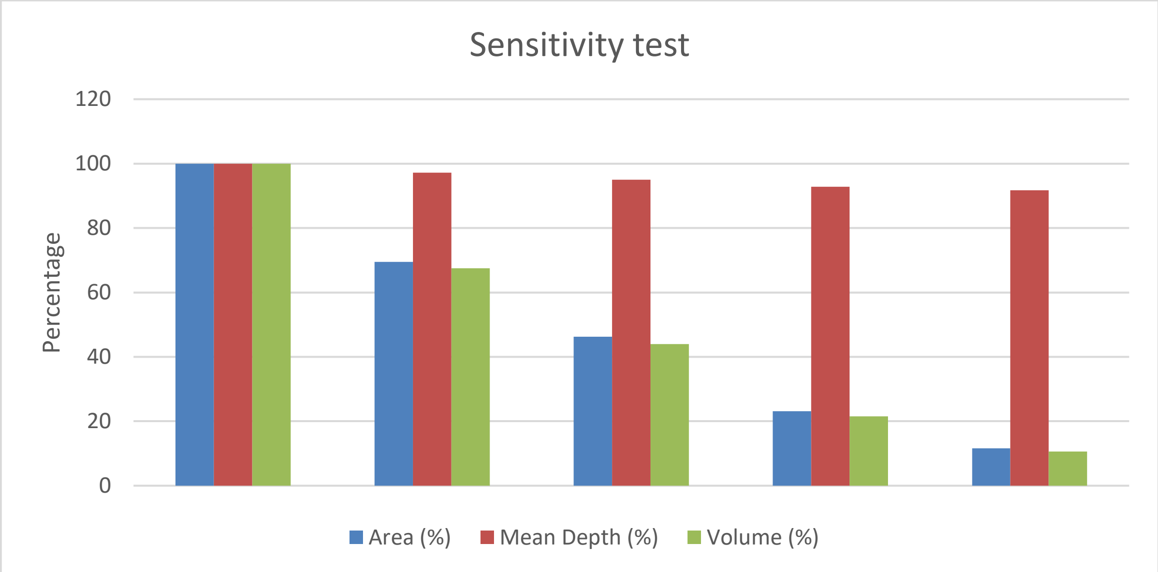


Figure 10: Illustration of lake depth-volume relation

According to the eyewitness mentioned in the study by (Breien et al., 2008), the total GLOF event took about 35 minutes until the debris was finally deposited on the farmland 3 km from the lake. This suggests that the event was a sudden outburst and the peak discharge at the incision could have reached in less than 15 minutes if we assume the flow hydrograph to be triangular. This justifies that the flow durations assumed in our study area are also reasonable. In addition, the area of glacial lake in our study area is more than 4 times the size of the lake in Fjærland, so we can also expect the debris flow to reach to the Oldevatnet lake which is about 7.8 km far from the lake and the magnitude of debris flow could be even more than that generated in Fjærland (240,000 m^3). However, it largely depends on the quantity of unconsolidated material lying at the incision of the moraine dam and along the path of the flow.

Despite having the usefulness of this method for predicting flood inundation due to GLOF, there are uncertainties regarding the values used in parameters in this method. As mentioned earlier, the flood hydrograph, peak discharge and outburst duration are unpredictable due to unpredictable nature of the glacial lake outburst. The outburst could be either an abrupt event taking just a few minutes, or it could last for hours, or it could occur in a cyclic order, draining out water in certain time intervals. Meanwhile, as a principle, a high peak discharge and a short outburst duration could have a higher impact as compared to that with low peak discharge and a long outburst duration and this is what the study is based on to find a range of impacts creating varied scenarios. Furthermore, there is no GLOF events occurred at this lake in the past, so it is not possible to compare the model results with the actual event's result and validate the parameters values used in this study. However, the mean depth and volume of water in such lakes are primarily important factors that could influence the impact downstream so we can at least perform a sensitivity test on initial parameter (area) based on the empirical formula used to derive the mean depth and volume. The result of sensitivity test is as follows:

Table 3: Sensitivity Test on initial parameters using empirical formula



Area (m^2)	Percentage	Mean Depth (m)	Percentage	Volume (m^3)	Percentage
43200	100.0	13.94	100.0	602035	100.0
30000	69.4	13.54	97.2	406200	67.5
20000	46.3	13.24	95.0	264800	44.0
10000	23.1	12.94	92.9	129400	21.5
5000	11.6	12.79	91.8	63950	10.6

The above table (Table 4) shows that there is not much difference in the mean depth even if the area is reduced significantly. For example, when the area is 20,000 m^2 (46.3 % of initial area), the mean depth is reduced by 0.7 meter and when it is 10,000 m^2 (23.1 % of initial area), the mean depth is reduced by 1 meter. Meanwhile, the volume follows the similar pattern as the area in the process. The relation between the lake surface area and depth seems unrealistic as the area decreases so this suggests that the empirical formula is only applicable to certain range of lake surface area. The similar study from Bolivia uses this empirical formula in lakes with surface area ranging from 34,000 m^2 to 699,200 m^2. Since, the lake area of our study area is within this range, the use of the empirical formula could be justifiable.

6. CONCLUSION:

Despite the uncertainties, the study is highly effective in places where there is lack of data on lake water depth, volume, and flow hydrograph. This is even more effective in places where there is a history of GLOF event in the past and records of lowering of water level in the lake, flow path and extent of flood water, amount of unconsolidated materials swept away from the incision of moraine dam and amount of debris collected at the downstream. These information helps us compare and anticipate any other scenarios in the future event of GLOF. This enables the planners to at least anticipate the range of impacts (high or low), prepare a zoning map based on levels of hazard and make plans accordingly. Since, this method is based on empirical formula, necessary assessments on local geographical and geological features is highly recommended.

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