The floor is Q-LavHA

A study about Hafnarfjörður and the rising volcanic activity on the Reykjanes peninsula, Iceland

Fagradalsfjall with its crater (mountain in the middle) and lava flow

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Abstract

The 2021 eruption in Fagradalsfjall might have activated a new era of volcanic activity on the Reykjanes peninsula. To study possible eruptions and its impact, one way of simulating lava flow using QGIS is through the plugin *Q-LavHA*. To validate the method, a reference flow from Fagradalsfjall was digitized and showed accuracy when simulating a new flow with parameters in Manhattan Length, lining up with the reference flow. *Manhattan Length* is a Q-LavHA parameter for simulating a lava flow line following the *travel distance*. This validates the method of the plugin enough to line up with the original flow from Fagradalsfjall. The same parameters for Fagradalsfjall were then used on a fissure south of Hafnarfjörður, to simulate a potential lava flow. However, it does have a different topography than Fagradalsfjall and could therefore mean a different outcome.

The method after simulating a possible flow in Hafnarfjörður from the reference flow in Fagradalsfjall was to simulate a "worst-case scenario" using the plugin but changing and using FLOWGO as a parameter. This was simulated with a flow similar to water, to get a longer extent that reaches Hafnarfjörður to analyze how the town could be affected and the possible lava flow pathway. This was done on both Fagradalsfjall and Hafnarfjörður, to see how the plugin would use the new parameters in FLOWGO compared to each other. It did show a longer extent and that the topography has an important role in the simulated flow, as Hafnarfjörður is flat while Fagradalsfjall has a variety of heights. The worst-case scenario flow on Fagradalsfjall did not reach the nearest town Grindavík, according to Q-LavHA, while the worst-case scenario for Hafnarfjörður reached the town.

The next step was to change topography using the previous flow and add it to the *Digital Elevation Model (DEM)*, then simulate a new flow and a worst-case scenario flow on top of that near Hafnarfjörður. This was also done for Fagradalsfjall but with the new DEM with changed topography already added from the real outbreak. The last step was to visualize a barrier to see that the plugin could stop the flow at a certain barrier height. This resulted in barriers reaching heights of 30-40 m for the lava flow to stop, and a relatively long barrier.

Keywords: *Q-LavHA, volcanic activity, lava flow pathway, Iceland, Hafnarfjörður, Fagradalsfjall*

Sammanfattning

Det vulkaniska utbrottet i Fagradalsfjall 2021 kan ha aktiverat en ny era av vulkanisk aktivitet på Reykjaneshalvön. För att undersöka möjliga utbrott och dess effekt har simuleringar av lavaflöden utförts i QGIS genom pluginet *Q-LavHA*. För att validera metoden har ett digitaliserat referensflöde på Fagradalsfjall använts för att jämföra det med det nya simulerade flödet skapat med Manhattan Length parametrarna. *Manhattan Length* är en Q-LavHA parameter som simulerar en lavaflödesväg som följer färdsträckan mellan två punkter. Detta validerade metoden då plugin-programmet var tillräckligt för att komma i linje med det ursprungliga flödet från Fagradalsfjall. Samma parametrar för Fagradalsfjall applicerades längs en spricka sönder om Hafnarfjörður för att simulera ett potentiellt lavaflöde, men på grund av olika topografier på platserna gentemot varandra kan det innebära ett annat resultat.

Efter att ha simulerat ett potentiellt flöde i Hafnarfjörður med referens till Fagradalsfjall, skapades ett värstafallsscenario genom pluginet. Detta gjordes genom parametern FLOWGO, då simulationen av flödet efterliknade vatten för att skapa en längre utsträckning som nådde Hafnarfjörður för vidare analys på dess påverkan och undersöka potentiella riktningar på lavaflöden. Simulationen appliceras både på Hafnarfjörður och Fagradalsfjall för att jämföra resultatet med varandra. Som resultat fick de både ett längre lavaflöde, men visade också att topografin har en viktig roll i simulationen då det påverkade resultatet. Hafnarfjörður har en mer plan yta med sluttning norrut, medan Fagradalsfjall är mer kuperad. Enligt Q-LavHA's värstafallsscenario för Fagradalsfjall, kommer lava inte att påverka staden Grindavík som befinner sig i närheten, medan det värstafallsscenariot i Hafnarfjörður nådde staden.

Nästa del av metoden var att förändra topografin genom att använda föregående flöde och addera det med digitala höjdmodellen (DEM) och sedan simulera ett nytt flöde, samt ett värstafallsscenario ovanpå i Hafnarfjörður. Samma metod applicerades på Fagradalsfjall, men i stället för att addera manuellt användes ett nytt DEM-lager som redan hade en inräknat förändrad topografi med det riktiga utbrottet. Sista steget var visualiseringen av barriärerna för att se om pluginet kunde stoppa lavaflödet med en viss höjd på barriärerna. Resultatet visade att det krävs 30-40 m höga barriärer, samt relativt långa för att kunna stoppa lavaflödet.

Nyckelord: *Q-LavHA, vulkanisk aktivitet, lavaflöde, Island, Hafnarfjörður, Fagradalsfjall*

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Glossary

QGIS - QGIS is a free Open-source Software and GIS application. It supports data in vector, raster and database formats and functionalities (QGIS, n.d).

Q-LavHA - Quantum-Lava Hazard Assessment is a free QGIS plugin that makes it possible to simulate basaltic lava flow probability on a digital elevation model from eruptive vents (Vrije Universiteit Brussel [VUB], n.d).

Fissure - Large cracks or fractures in a rock, such as extrusion of lava or pyroclastic material that can lead to becoming a volcanic vent (Keller & DeVecchio, 2012, p.533).

Fissure swarm - Fissure swarms are areas that have many fractures or cracks in the ground and are usually near a central volcano. They are activated through dike intrusion due to seismic activity (Hjartardóttir, Einarsson & Björgvinsdóttir, 2016).

Vent - Is the passage which the magma passes through to the surface of the earth. This is what leads to a volcanic eruption (Keller & DeVecchio, 2012, p.533).

Crater - Is the cone shaped like a circle on the volcano, which is created after a volcanic eruption (Keller & DeVecchio, 2012, p.533).

Magnitude - A local magnitude scale based on 10 logarithms, determined by seismic activity released from an earthquake. The higher on the scale, the higher the intensity (GNS Science, n.d).

Manhattan Length - Q-LavHA parameter for simulating the length of a flow line. It is the travel distance that is covered by the flow line. Recommended for users with less knowledge about the data (VUB, n.d).

Euclidean Length - Q-LavHA parameter for simulating the length of a flow line. Represents the crow fly distance between the simulation start and flow line stop. Recommended for users with less knowledge about the data (VUB, n.d).

Decreasing Probability - Q-LavHA parameter for simulating the length of a flow line. Determine the flow from mean and standard deviation of historical lava flow (VUB, n.d).

FLOWGO - Q-LavHA parameter for simulating the length of a flow line. Uses 1D cooling-limited thermorheological models. The slope is of importance and influences the lava flow line due to cooling and velocity rates (VUB, n.d).

1 Introduction

Due to the most recent eruption in Fagradalsfjall the 19th of March 2021 on the Reykjanes peninsula, speculation around a new active volcanic period causing frequent eruptions has taken place. With earlier active periods lasting for almost 300 years, having more than ten eruptive outbreaks, there is reason to believe that history will repeat itself. Whether the volcanism will spread to the closest volcanic system is unclear, but there is a relatively similar pattern that seems to have occurred throughout history. Lava shield volcanoes such as Fagradalsfjall have a pattern of active periods reaching over several decades and can build up flat mountains due to the properties of the lava, as it easily flows over and fills sinks (Sturkell & Stockmann, 2021).

With this recent event, the seismic activity on the Reykjanes peninsula has become more active. On the 19th of April 2022, there was seemingly more activity as the subsidence of the ground caused earthquakes with magnitudes between 2-3.5. These earthquakes hit east-northeast from the island Eldey on the Reykjanes Ridge, but it is still unsure if there is any accumulation of magma in the area. There will be increased surveillance to see if the seismic activity will enhance in the days after, but as mentioned earlier, since the eruption in Fagradalsfjall there has been seemingly more activity on the peninsula. The activity will probably continue in the area or slightly further east, according to natural hazard specialist Salóme Jórunn Bernharðsdóttir. Only 6 days prior, the 13th of April 2022, a stream of earthquakes hit the tip of the peninsula with magnitudes reaching 3-3.9. The area was measured 30 km west of Fagradalsfjall (Hafstað, 2022a; Hafstað, 2022b). If we are now entering a new era of active periods, it is of interest to study possible eruptions to see how it will affect and how large the damage might be on Iceland.

1.1 Intent and questions at issue

Purpose of this study is to validate the plugin Q-LavHA, by using Fagradalsfjall´s eruption as a reference. If validated, a prediction of a possible lava flow pathway on the fissure near Hafnarfjörður, Iceland, can be simulated as the same behavior might occur. Production of maps will illustrate the potential future risks that can occur according to the plugin connected to a volcanic eruption in the selected study area. A worst-case scenario will be tested in the method, to force the lava flow simulation to reach Hafnarfjörður (where the lava flow follows the steepest path). By also adding barriers and changing the topography through calculating the first simulated lava flow into the DEM, it might be possible to see changes to the lava flow pathway with a new simulation. The main goal is to see how well the plugin can be used in simulating lava flows, even if it is just for testing the method.

Questions at issue

- How accurate is the Q-LavHA plugin in regard to simulating a lava flow pathway?
- What pathway does the lava flow take in a simulation projected from possible craters?
- Which areas would be affected by a simulated eruption according to Q-LavHA in the study area when simulating a worst-case scenario?
- How will a changed topography affect the lava flow pathway in a simulation?

1.2 Background

The volcanic system Krýsuvík-Trölladyngja has been vastly active in the last 8000 years, with the most recent eruption occurring on the 19th of March 2021 in Fagradalsfjall after 870 years of a moderately active period. Before this, the two latest eruptions occurred in the 12th century separated by 37 years. The Krýsuvík volcanic system (figure 1) has no central volcano but is part of a 50 km long fissure swarm, combined with a 30 km long eruptive fissure swarm. Preceding this, there are two eruptions well known before the 12th century in the same system occurring about 2000 and 3000 years ago. Therefore, intervals and frequency between eruptions may vary between 400-1000 years, averaging approximately over 750 years. During periods with no eruptive episodes, there can still be seismic activity around the tectonic boundaries that extend through the peninsula, with earthquakes reaching magnitudes of 4-6 and some minor explosions due to steam pressure. The seismic activity also influences the subsidence and uplifts that occur, relating to the area having geothermal activity. 15 months prior to the Fagradalsfjall eruption, observations on activities such as earthquakes and intrusions were noticeable, then becoming more central to Fagradalsfjall closer to the eruption date. Even though earthquakes reached magnitudes of 5 in the months preceding, just hours before the eruption there was only minor activity recorded (Einarsson, 2019).

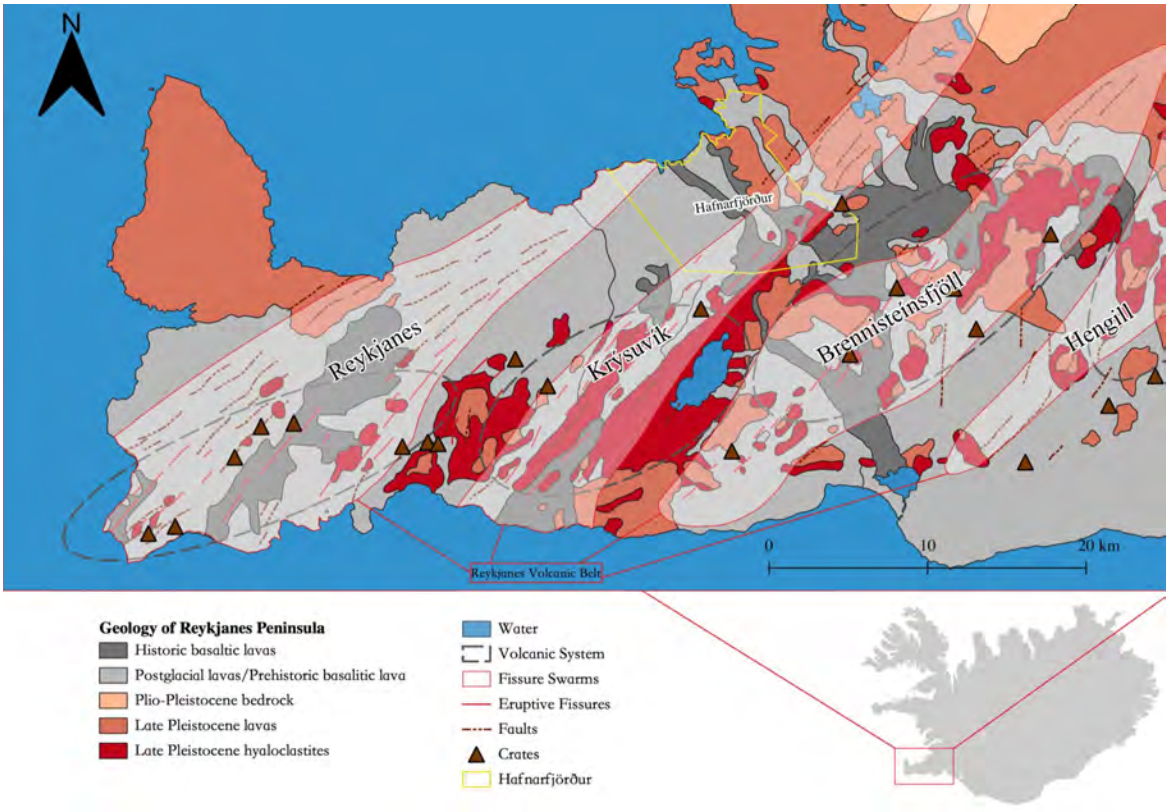


Figure 1*. Geology of the Reykjanes peninsula. Fissures, faults, craters, historic lavas and volcanic systems. Names for the four volcanic systems on the peninsula (includes both the volcanic system and fissure swarms) and the Reykjanes Volcanic Belt (RVB). Created 2022-04-16 with the projection ISN2016/Lambert 2016 EPSG:8088 (Icelandic Institute of Natural History, n.d; íSOR, n.d).*

Figur 1*. Geologin på Reykjaneshalvön. Sprickor, sänkor, kratrar, historisk lava och vulkaniska system. Namnen på de fyra vulkaniska systemen på halvön (inkluderar både de vulkaniska systemen och spricksvärmar) och Reykjanes Vulkaniska Bälte (RVB). Skapad 2022-04-16 med projektionen ISN2016/Lambert 2016 EPSG:8088 (Icelandic Institute of Natural History, n.d; íSOR, n.d).*

1.2.1 Current research

It is a difficult matter to foresee a volcanic eruption. It can happen in a few moments, in two years or even in a few decades. One way of foreseeing volcanic eruption and warning of volcanic activity is to monitor seismic activity, ground uplift and subsidence, and volcanic and geothermal gases (Gudjónsdóttir et al., 2018). Even if precise predictions are not always possible, it is important to know the risks and consequences to reduce and prepare for possible severe impacts. One way of doing that is through simulating different scenarios using GIS. These predictions are not always accurate and can give a false image of an actual lava flow. Iceland has a plethora of different volcanic activities and systems, and even if the activities have been moderate for hundreds of years it might have awoken once more. By using the DEM from Iceland´s Landmælingar, future scenarios have been created which illustrate possible areas such as important infrastructure that might be affected by a possible eruption from the Q-LavHA plugin.

Craters such as the one in Fagradalsfjall, are common in fissures which is why it is of interest to simulate lava flow from fissures near Hafnarfjörður. These are called *spatter cones*, and some can reach great heights in a small period of time. It is still unclear how long the eruption will last in Fagradalsfjall, but if there is more magma coming from underground it can go on for months or years. There is a sense that this eruption will spark a new era of volcanic activity on the peninsula. The eruption in Fagradalsfjall started in a fissure, only 500 m long, and the magma flow was about 5 m/s. In the first days of the eruption, there was an analytical silence between scientists. First, they assumed the lava would be 1000°C, but later came to realize it was actually 1200°C, meaning that the magma came from the deeper mantle, around 20 km deep. When eruptions go that deep, it could mean that the eruption can last a longer time since the magma from the mantle is almost infinite. It is presumed that the fissure might open more to the north and develop a few kilometers in the months to come while all the scientific data directs to the eruption lasting a long time. The effusion rate started at 4-8 m^3/s, and later increased to 8-13 m^3/s in the later stages of the eruption. The evolution of the effusion rate in Fagradalsfjall is rare according to previous studies of Icelandic eruptions (Andrews, 2021; Pedersen et al., 2021; Svavarsson, 2021).

1.2.2 Area of study

The area of study includes Hafnarfjörður, as this is the area for risk assessment. Fagradalsfjall is used as a reference for lava flow to assess how accurate the method is. The study area shown in figure 2 is mostly to show the reader the approximate operational space that the method will take use of. The administrative area of Hafnarfjörður is shown within the red line and is part of the study area as well. As mentioned, there are no central volcanoes in the Krýsuvík volcanic system, so there will not be a specific volcano for the study. The fissures and existing craters will be used to simulate a flow and also where to create new craters, since the volcanic system can cause eruptions without a central volcano. Furthermore, as seen in figure 1, there are several eruptive fissures southeast of Hafnarfjörður and figure 2 illustrates one of those fissures which will be used further in this report to simulate lava flow and create possible craters to see how this might affect Hafnarfjörður (see appendix 1 & 2).

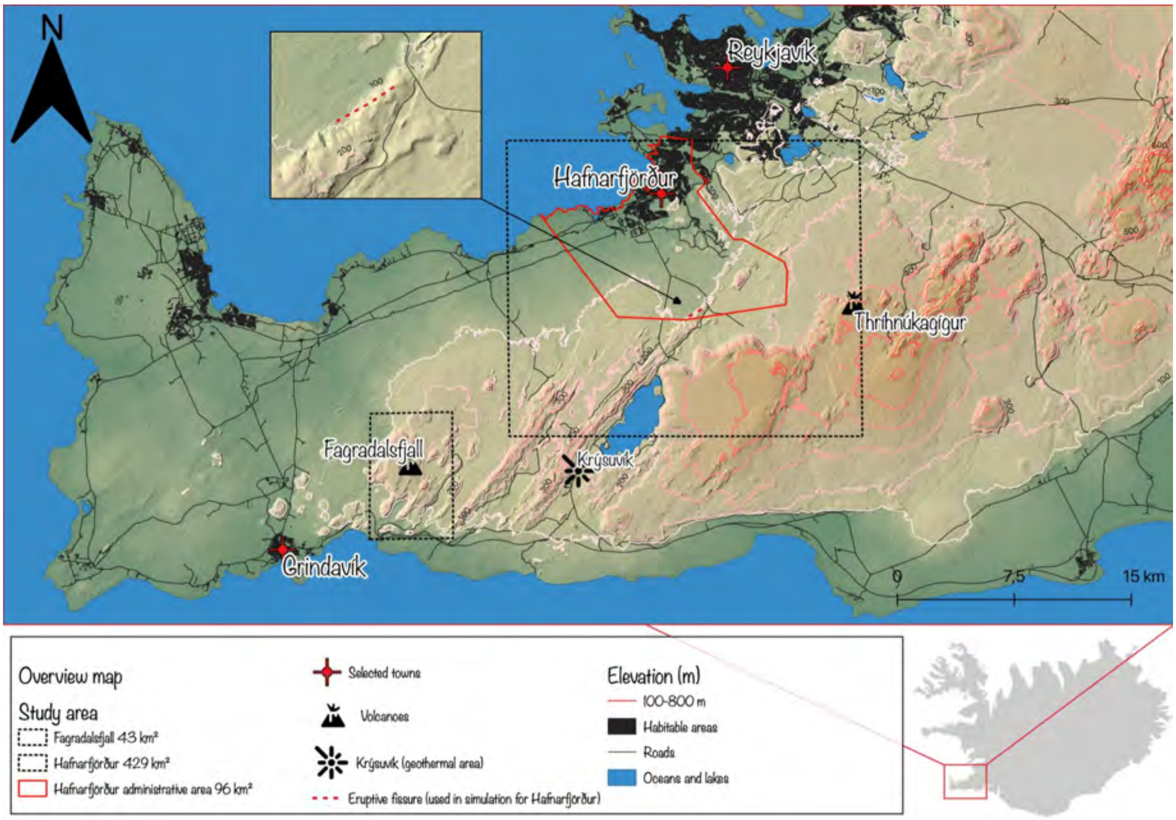


Figure 2*. Area of study, three nearest towns (Reykjavík, Hafnarfjörður, Grindavík), volcanoes (Thrihnukagigur, Fagradalsfjall) and the geothermal area Krýsuvík. Created 2022-04-22 with the projection ISN2016/Lambert 2016 EPSG:8088 (National Land Survey of Iceland, n.d.a; National Land Survey of Iceland, n.d.b; QuickMapServices, n.d).*

Figur 2*. Studieområdet, tre närmaste städerna (Reykjavík, Hafnarfjörður, Grindavík), vulkaner (Thrihnukagigur, Fagradalsfjall) och det geotermiska området Krýsuvík. Skapad 2022-04-22 med projektionen ISN2016/Lambert 2016 EPSG:8088 (National Land Survey of Iceland, n.d.a; National Land Survey of Iceland, n.d.b; QuickMapServices, n.d).*

Hafnarfjörður is the third largest town in Iceland, located 10 km from the capital Reykjavík with a population of approximately 26 000 people. The town is placed mostly on top of 7300 year old postglacial lavas, but also on historic basaltic lavas and plio-pleistocene bedrock (as seen in figure 1), which has various lava flow formations surrounding them. Historically, the town Hafnarfjörður has shifted from a fishing village where trading occurred, making the harbor an important part of its identity, into a tourist spot (see appendix 3 & 4). Due to myth, folklore and legend beliefs connected to Hafnarfjörður, it creates a mythical culture alluring more people there (Adventures.com, n.d; ZhujiWorld.com, n.d) (see appendix 5 & 6). In general, the data collected from OpenStreetMap (2022) figure 3 shows the current number of buildings in Hafnarfjörður are about 4520. The majority of the area contains living areas mainly apartments but also houses, followed by industries, workplaces, constructions and what is categorized as “other” which in this case is garages, roofs and retail. In this area there are also schools, kindergartens and churches (OpenStreetMap, 2022).

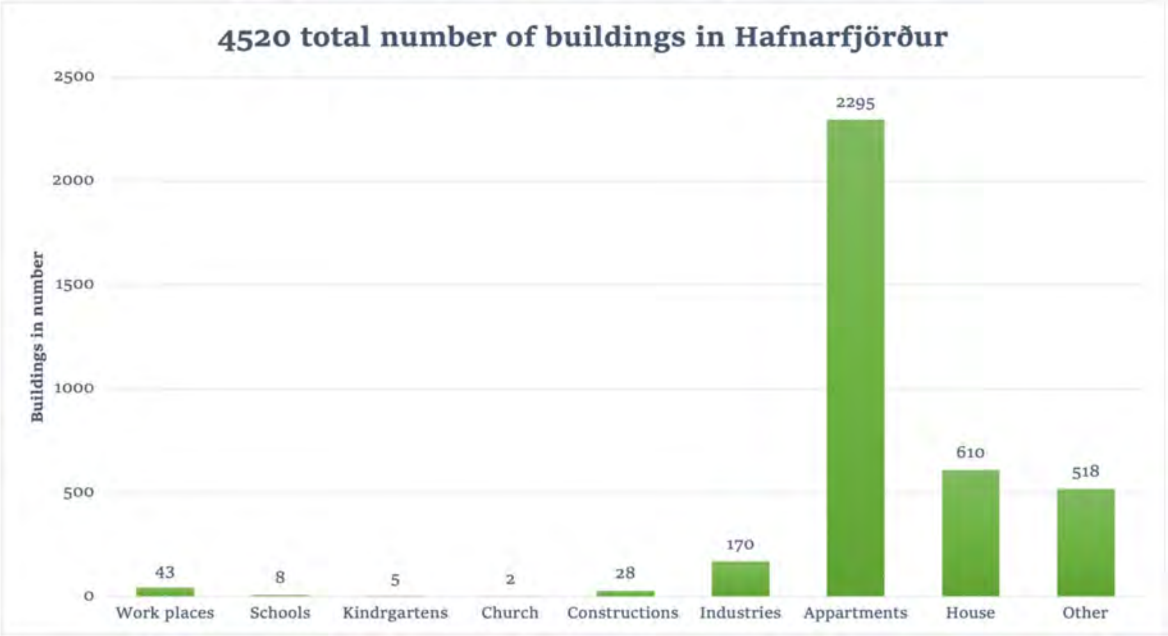


Figure 3. *Total number of buildings in Hafnarfjörður (OpenStreetMap, 2022).*
Figur 3. *Den totala andelen av byggnader i Hafnarfjörður (OpenStreetMap, 2022).*

The Reykjanes Ridge is the longest (approximately 900 km) and most hotspot influenced ridge in the world and is said to mark the maximum range for hotspot influence in Iceland, figure 4 (with the Ridge visualized at approximately 110 km). There are four volcanic systems on the peninsula, named *Reykjanes, Krýsuvík, Brennisteinsfjöll* and *Hengill*. The geothermal area *Krýsuvík-Trölladyngja* is centered in the peninsula and part of the Krýsuvík volcanic system, taking the biggest role in the area of study, as shown earlier in figure 1, while the geothermal area Krýsuvík is visible in figure 2. The seismic activity that occurs in the peninsula happens mostly in the Krýsuvík area, which is a high temperature location characterized by postglacial lava fields, steep mountains and fault swarms at an angle of 30-40 degrees (which is causing a lot of the activity) (Khubaeva, 2007; Palgan, Devey & Yeo, 2017). The system experiences high seismic activity and micro-earthquakes on the regular and has a frequent gas emission. It is also dominated by rifts instead of any central volcano, and therefore has no central magma chamber. The reason for the system's heat is said to be because of dyke intrusions. Gudjónsdóttir et al. (2018) points to a 1000 year interval between eruptions, with episodes lasting for almost 400-500 years.

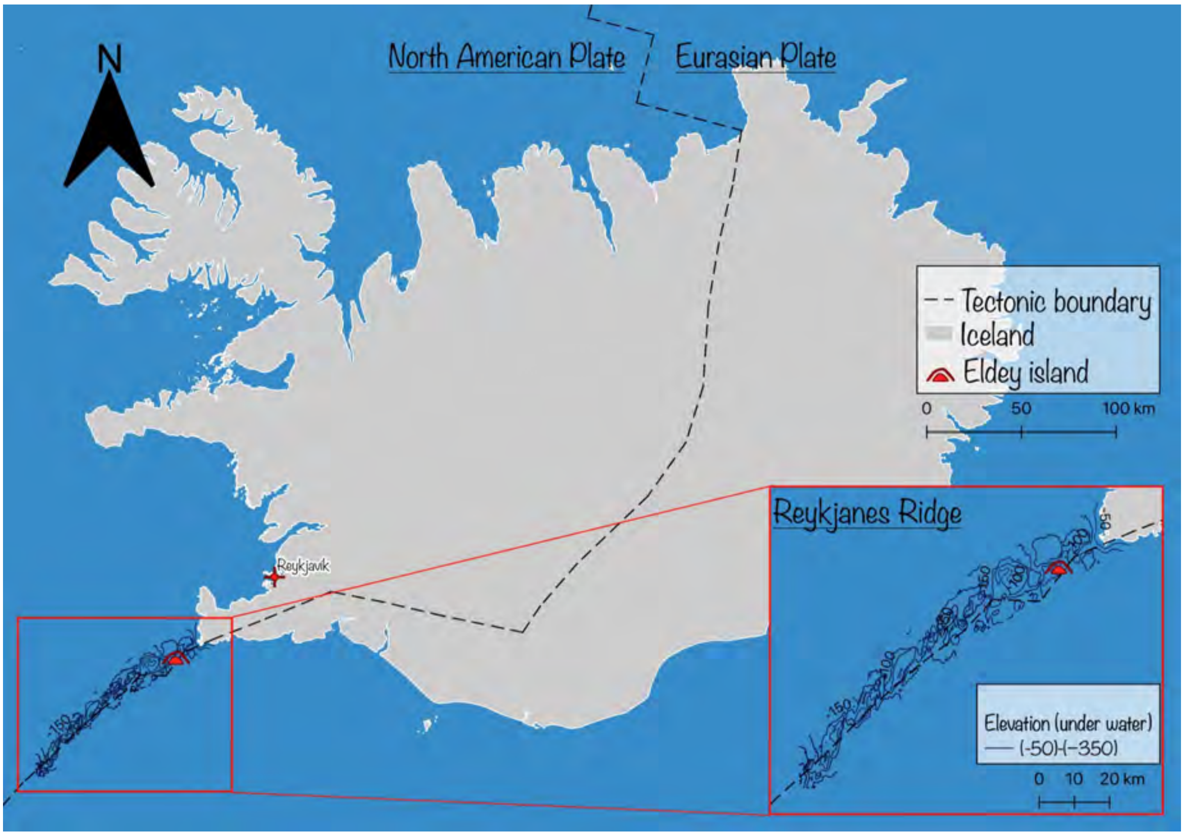


Figure 4. *The tectonic plates in Iceland are split into two parts by the Mid-Atlantic Ridge. The Reykjanes Ridge follows the tectonic boundary and in reality reaches 900 km; here it is visualized at approximately 110 km. Created 2022-04-22. Projection ISN2016/Lambert 2016 EPSG:8088 (DIVA-GIS, n.d; GitHub, Ahlenius, Nordpil & Bird, 2014; Bathymetry Viewing and Download service, n.d).*

Figur 3. *De tektoniska plattorna på Island, dras isär i två delar av den Mittatlantiska ryggen. Reykjanes ryggen följer den tektoniska gränsen och är i verkligheten 900 km; här är den visualiserad till närmare 110 km. Skapad 2022-04-22 med projektionen ISN2016/Lambert 2016 EPSG:8088 (DIVA-GIS, n.d; GitHub, Ahlenius, Nordpil & Bird, 2014; Bathymetry Viewing and Download service, n.d).*

Figure 4 shows how the *North American plate* boundary and *Eurasian plate* boundary splits Iceland into two parts. Iceland is placed on top of the *Mid-Atlantic Ridge*, both boundaries drifting to different locations. The North American plate is drifting west while the Eurasian plate is drifting east. *The Icelandic National Land Survey Iceland* has measured an expansion of 2-2.5 cm per year, due to magma swelling the ground under the earth's crust. On the tip of the Reykjanes peninsula lies the only location in the world where one can see the Mid-Atlantic Ridge above water (appendix 7). The movement of these tectonic plates are one reason behind the mass of earthquakes that Iceland experiences, along with volcanic earthquakes and geothermal activity. As mentioned in the introduction, Eldey island (figure 4) by the Reykjanes peninsula is part of the system that experiences the most earthquakes, along with other parts of Iceland (i.e the Katla volcano, Mount Hekla, etc.). *The South Iceland Seismic zone (SISZ)* also lies on the peninsula reaching through the *Reykjanes Volcanic Belt (RVB)* (figure 1), where earthquakes are frequent even though there are no central volcanoes. The seismic zone lies between the North American and Eurasian plates, and between the RVB and the *Eastern Volcanic Zone (EVZ)*, causing it to continuously be pulled apart. Because of *SISZ*, the south part of Iceland is known to experience earthquakes as high as magnitude 7.1 (in the year 1784), and magnitude 7 (1912), and are calculated to hit at least every 100-150 years causing damage to infrastructure and awakening volcanic activity with it (Iceland Magazine, 2017; Iceland Magazine,2018).

2 Theory

2.1 Fissure, crater and vent

Fissures, craters and vents are normal morphological components of different rift zones. A vent is where the lava fountain (the mixture of lava and gasses) erupts. The difference between a crater and a vent, is that a crater can host several vents in one specific crater. A fissure is the area of the eruption which forms cones for craters and vents to take place (Witt et al., 2018) (see Fagradalsfjall´s crater in appendix 8).

2.2 Earthquake

Earthquakes occur when large processes in the earth's inner parts are in motion, resulting in energy being released from the crust, which causes the ground to shake or move as there is a sudden shift. The earth's structure contains concentric layers: the inner part is the core surrounded by a mantle, and the outer layer is known as the earth's *crust*. The lithospheric plates are divided parts of the crust and the upper part of the mantle. These plates are in constant motion: toward, along or away from each other. Parallel to the crust movement along with faults, earthquakes can then occur. The energy known as *magnitude* is compared to the ground's motion effect on people and architecture, also known as *intensity.* Magnitude is measured from a *Magnitude scale*, which is a logarithm. For example, an earthquake with a magnitude of 6 is around ten times greater than an earthquake with a magnitude of 5. An earthquake can be devastating and cause a large amount of disruption and destroy cities, leading to thousands of deaths in a timespan of seconds (Swedish Geological Survey [SGU], 2020; Keller & DeVecchio, 2012, p.51-53, 533).

2.3 Volcanic eruption

Volcanoes are created by the solidification of magma when it penetrates the surface from the interior of a sturdy celestial body. The creation of volcanoes takes up to over 10 000-500 000 years through occurrence of repeated eruptions, when every new lava flow covers the previous one. Volcanism is often connected to tectonic plates and is the process when magma and gasses from within the earth releases into the atmosphere. When lithospheric plates sink or spread, they interact with other materials on earth resulting in the creation of molten rocks and volcanic activities. Within the earth it is known as magma, but during a volcanic eruption when it connects with the earth's surface it is called lava (Keller & DeVecchio, 2012, p.125; Nationalencyklopedin [NE], n.d.b; Woods Hole Oceanographic Institution, n.d).

2.3.1 Lava Shield

One of the volcanic activities that occurs on the Reykjanes peninsula is what is known as *lava shields*, which in itself have one large eruption. During an eruption the lava does not violently explode, instead it flows down slowly on the side from a crater. As a result of a lava shield eruption, it can be active for several years leading to the lava flowing for several kilometers as the basaltic magma flows relatively easily. Because of these properties it can create a mountain with relatively flat sides (Keller & DeVecchio, 2012, p.130; Sturkell & Stockmann, 2021, p.9-11).

2.3.2 Lava flow

Lava is the magma that penetrates the surface and continues to flow from a volcanic eruption. Its temperature is connected to its chemical composition. Non silicon rich lavas such as the basaltic ones can have a temperature between 1,150 °C to 1,225 °C, while the lavas that contain high levels of silica, for example rhyolite, have a temperature around 735 °C. Because of the high temperature it continues to flow across the ground and remains molten, as it slowly cools off and starts to harden (NE, n.d.a; Woods Hole Oceanographic Institution, n.d), changing topography.

Lava flows have a volume that corresponds to approximately less than 1 km^3. The lava flows that have the highest volume and largest spread on the surface come from fractured volcanoes, as a “pool” of lava forms and have a basaltic composition. While lava with the chemical composition of rich silica, which is more acidic, rarely has resulted in flowing longer than 1 km from the source of eruption (NE, n.d.a) (see appendix 9 & 10).

2.3.3 Geothermal area

In Iceland, geothermal areas are divided into high and low temperature locations. Krýsuvík is one of Iceland’s high temperature geothermal areas, which are areas that are only found where there is volcanic activity and active fissure swarms. At 1 km depth in the rift zones, the ground can reach temperatures up to 200°C (Khubaeva, 2007).

2.4 Barriers as risk management measure

As a part of the risk management measure in Iceland, barriers are an option. To protect the sites near Fagradalsfjall, three work site protection barriers were created on the places where dams and dikes were supposed to be built which are other measurements to affect the lava flow. The first barrier was at a height of 1,5-2 m, which resulted in delaying the lava and creating a higher lava front as it rises 2-4 m above the barriers, but as soon the lava developed to pahoehoe (a lava form of basaltic rock that is dark and often a rope shape) it overtopped the barrier as more fluid lava progressed (Gudmundsson et al., 2021) (appendix 11 & 12).

3 Methods

3.1 Q-LavHA (Quantum-Lava Hazard Assessment) plugin

Simulation of lava flow has been made by using the Q-LavHA free plugin for QGIS following their manual. The main goal of the plugin is to simulate the most accurate lava flow for basaltic volcanoes, thereby hopefully aiding scientists and groups of interest through trying this method and potentially showing areas that might be at risk. This could help with land use planning and evacuation strategies before a crisis occurs, both for long-term and short-term forecasting. The plugin uses a DEM and one or more vents to simulate a potential flow with the longest spatial distribution and terminal longevity. The length of the lava flow will be determined by where the vent is projected on the DEM and the volume of lava (including cooling effects), therefore forecasting its probability for a specific longevity. The vent projected can be either a point, line or a polygon. Since lava has a high viscosity it differs from flows of water bodies, and can continue over topographical interferences, fill sinks and maneuver laterally which means that the lava does not always follow the path that is steepest, even though it is more likely. The plugin uses the pixels of a DEM starting from the source pixel to the eight surrounding pixels, after which a flow probability is calculated for every surrounding pixel. In a case where the pixel is elevated, the flow stops since lava cannot ascend in an uphill slope. To overcome small interferences such as small ascendants or sinks, the plugin includes smaller corrections to simulate the flow past such obstacles, using factor H_c (a float number that is enabled to represent the lava thickness, and is always added to the elevation) and H_p (a higher topographical correction of H_c added when H_c is not enough and should always be higher value than H_c). When using a higher H_p factor, it simulates the lava flow´s ability to fill sinks and makes it possible for a higher terminal longevity. H_{16} will consider the next 16 surrounding pixels if the lava reaches a depression (and overcomes H_c and H_p) and will be activated for the purpose of study. To be able to terminate a flow line, the user has to have all the parameters needed to determine the extent and therefore be able to account for the uncertainties that might occur. Since this project is a testing of the method of simulating a lava flow pathway, it is recommended by the Q-LavHA to maximize the length when there is little data or knowledge of the eruption. The FLOWGO parameter is recommended for more expert users that have more data on the eruption. When using FLOWGO, the slope of the DEM will determine the velocity and cooling rate of the lava flow. The DEM resolution will have a say in the result simulation, as a lower resolution can make the pixels flow a different path, while a higher resolution might not have the same extent as a low resolution since every pixel is calculated for the distance. On a gentler slope, it is better to use a lower resolution, while a higher resolution is better for more steep slopes. The lava flow pathways made with the plugin should be interpreted with care (Mossoux et al., 2016).

3.1.1 Validation of the lava flow model

To validate the Q-LavHa plugin, the latest eruption of Fagradalsfjall and its real lava flow was used as a reference. By applying the same method on an older DEM model of the area (before the eruption) the possible lava flow pathway could be simulated to see if it matches with the actual lava flow pathway. Important to notice is that the 2x2 m DEM needed to be reverted to 25x25 m, to lower the resolution of the DEM layer. This helped get a longer extent but also made the simulation faster. Even though the manual might want to have a different resolution for each steep and gentle slope, for this exercise they will be used equally to see what the result might give. The lava flow reference was based on a map created by Benjamin Hennig (Hennig, 2021) showing the lava flow on 2021-10-28. To be able to apply Hennig's (2021) map it needed to be georeferenced to the existing map, so it lined up to the DEM layer. Hennig's (2021) map was easily georeferenced because of the DEM layer having the same topography; slopes, mountains, roads, etc. After georeferencing it in place, a polygon was created to mimic the flow's longevity as of 2021-10-28 (figure 5). Since this is only used as a reference flow, the accuracy of the polygon was not so important as it was only needed to help see where the flow originated and its extent. Hennig's (2021) map also provided the six craters of which the eruption started and has been used in the simulation according to his numeration (1-6). The craters were easily spotted in the DEM after the eruption (figure 5) and were digitized into six polygon craters. The source of eruption in Q-LavHA can be either a point, line or a polygon, and in this case, polygons were used as craters. This is to mimic the similarity to craters in Fagradalsfjall, since polygons were created there on top of the existing craters.

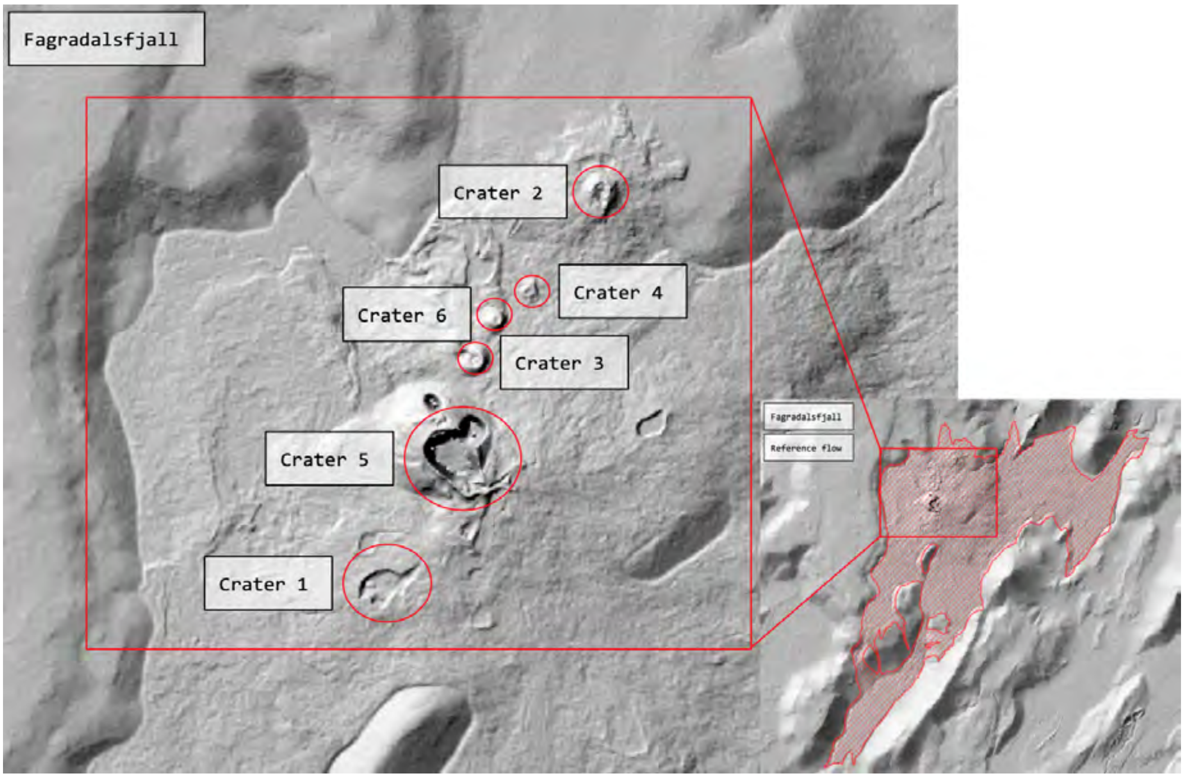


***Figure 5**. DEM after the eruption. The craters from the Fagradalsfjall eruption by which the simulation was based to validate the Q-LavHA plugin. The polygon reference flow extent as of 2021-10-28.*

***Figur 5**. DEM efter utbrottet. Kratrarna från utbrottet i Fagradalsfjall som simulationen var baserad på för att validera Q-LavHA pluginet. Referensflödet som polygon med utbredning från 2021-10-28.*

Figure 6 shows the Q-LavHA's three (out of four; four is FLOWGO, used later for worst-case scenario) ways to simulate lava flow from "Crater 1". Manhattan Length simulates a flow from the travel distance between two points, while *Euclidean Length* simulates a flow from the crow fly distance. *Decreasing Probability* needs parameters for *mean* and *standard deviation* from previous lava flow to work accordingly. The Manhattan Length feature simulates the lava flow pathway most accurately according to the reference flow. Decreasing Probability and Euclidean Length were at this time too extended and had overridden the reference flow. Manhattan Length in this case the original meter 10 000 m was used. The length parameters 15 000 m, 20 000 m & 30 000 m were tested for Manhattan Length, but it did not change the lava flow pathway extent and was therefore not changed. There were also no changes to H_c and H_p for this reference and simulation. H_{16} and *Probability to the square* (which increases the probability for the flow to take the steepest path) were also not changed. The reference flow polygon reached approximately 4.9 km^2 while the lava flow pathway from Manhattan Length reached 3.3 km^2, coming closer than the other simulations where Decreasing Probability reached 15.3 km^2 and Euclidean Length reached 14.9 km^2 (figure 6). This was the reason for using Manhattan Length in the result for the lava flow pathway near Hafnarfjörður. New simulations are executed under the result chapter and will not have the exact same extent.

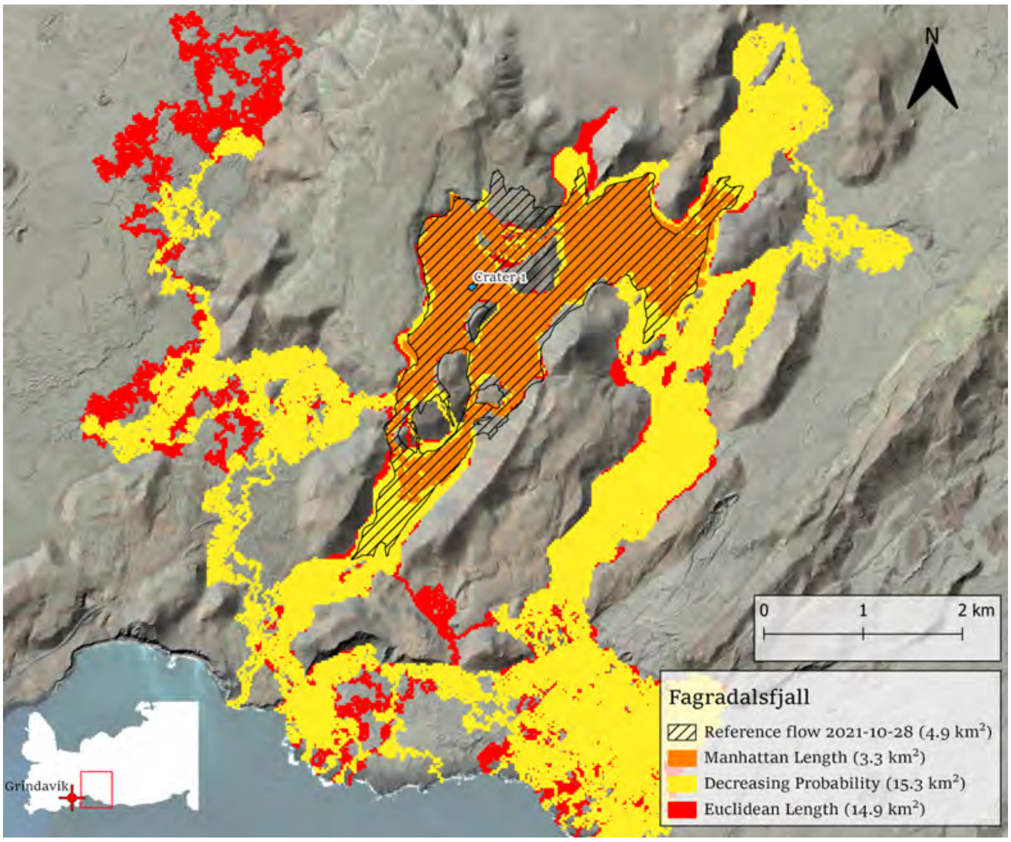


Figure 6*. The flow simulated from Q-LavHA features; Manhattan Length, Decreasing Probability and Euclidean Length. WGS 84 / UTM zone 27N EPSG:32627.*

Figur 6*. Flödet simulerat från Q-LavHA: Manhattan Length, Decreasing Probability and Euclidean Length. WGS 84 / UTM zone 27N EPSG:32627.*

To work with the reference flow, it helped to know where the lava was the thickest and to see where the lava flow had reached at different dates. *The National Land Survey of Iceland* (n.d.c) has a map feature showing where the lava's extent was at a certain date from 2021-03-20 to 2021-09-30. The terminal extent (2021-09-30) and craters line up to Hennig's (2021) map almost identically, making it easy to adjust, for example, a flow on the 2021-04-06 to the terminal flow (figure 7 & 8). This helped to validate the Q-LavHA probability outcome, showing in figure 7 & 8 that the flow from 2021-04-06 lines up to the high probability outcome from Q-LavHA. "Crater 1" and "Crater 2" were used because they were the first two active craters, most visible in The National Land Survey of Iceland (n.d.c) map feature. Pedersen et al. (2021) provides a map showing lava thickness, which also helped validate the method. It shows where the lava was the thickest (highest probability for this simulation), therefore where it accumulated the most. Comparing the reference flow with Pedersen et al. (2021)'s lava thickness, there are some similarities between the probability from the simulation and their accumulation of lava. They refer to *phase 1* as the flow from "Crater 1", and *phase 2* as "Crater 1" and "Crater 2" activate craters 3-6, *phase 3* resembles the reference flow on 2021-10-28 with "Crater 5" the only one still active. To draw a conclusion from this, there might be a chance to see after validating the method where the flow on the study area of Hafnarfjörður will accumulate the most and possibly build up lava lakes (which can help the lava overcome higher topography, leading to longer longevity). This also concludes that the Manhattan Length with high probability mimics the actual flow pathway the lava took in Fagradalsfjall, and therefore can be used in the result for Hafnarfjörður with minor errors in mind.

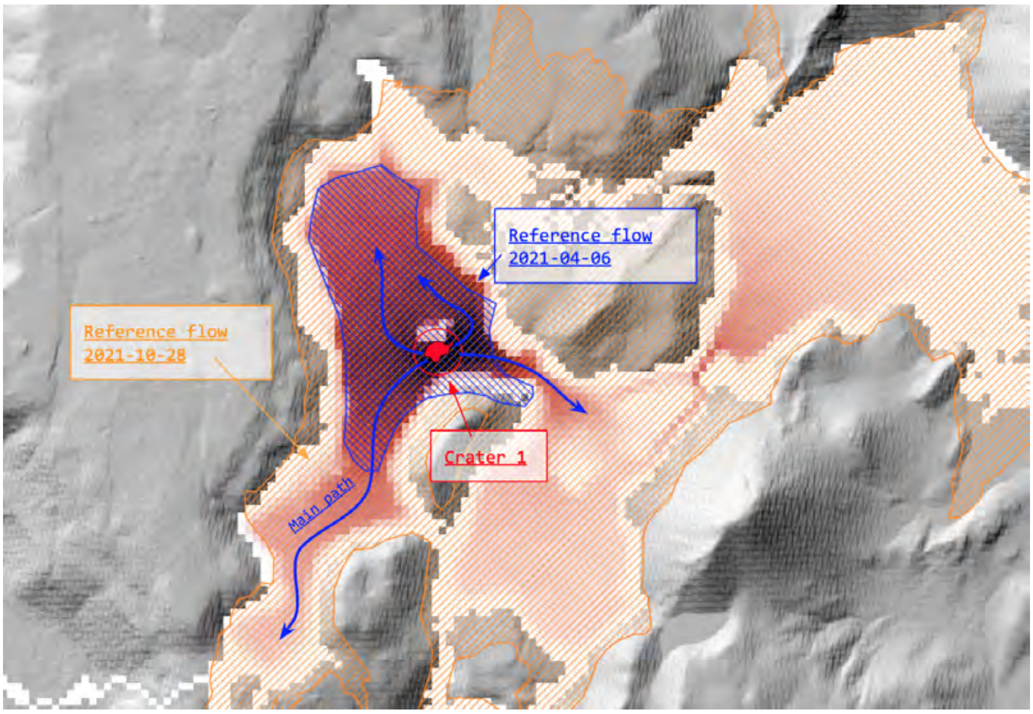


***Figure** 7. The eruption from Q-LavHA (Manhattan Length) starting from "Crater 1" in Fagradalsfjall. The reference flow at 2021-04-06 almost lines up to the outcome from Q-LavHA (probability: high (darker) to low).*

***Figur** 7. Utbrottet från Q-LavHA (Manhattan Length) med start från "Crater 1" i Fagradalsfjall. Referensflödet från 2021-04-06 ligger nästan i linje till flödet från Q-LavHA (sannolikhet: hög (mörkare) till låg).*

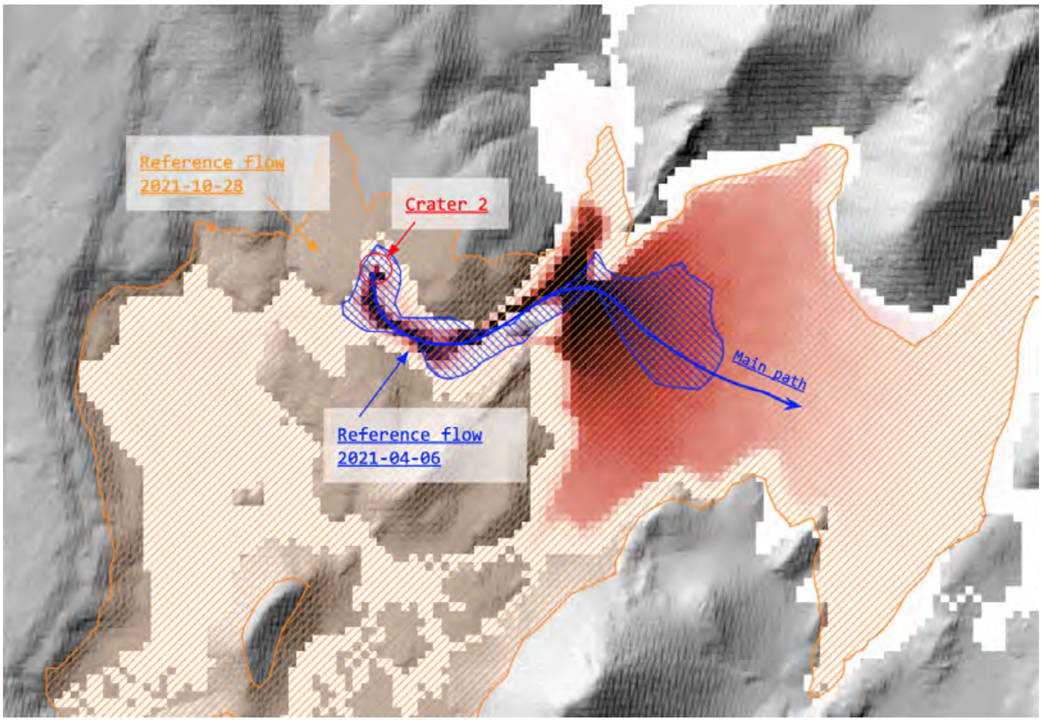
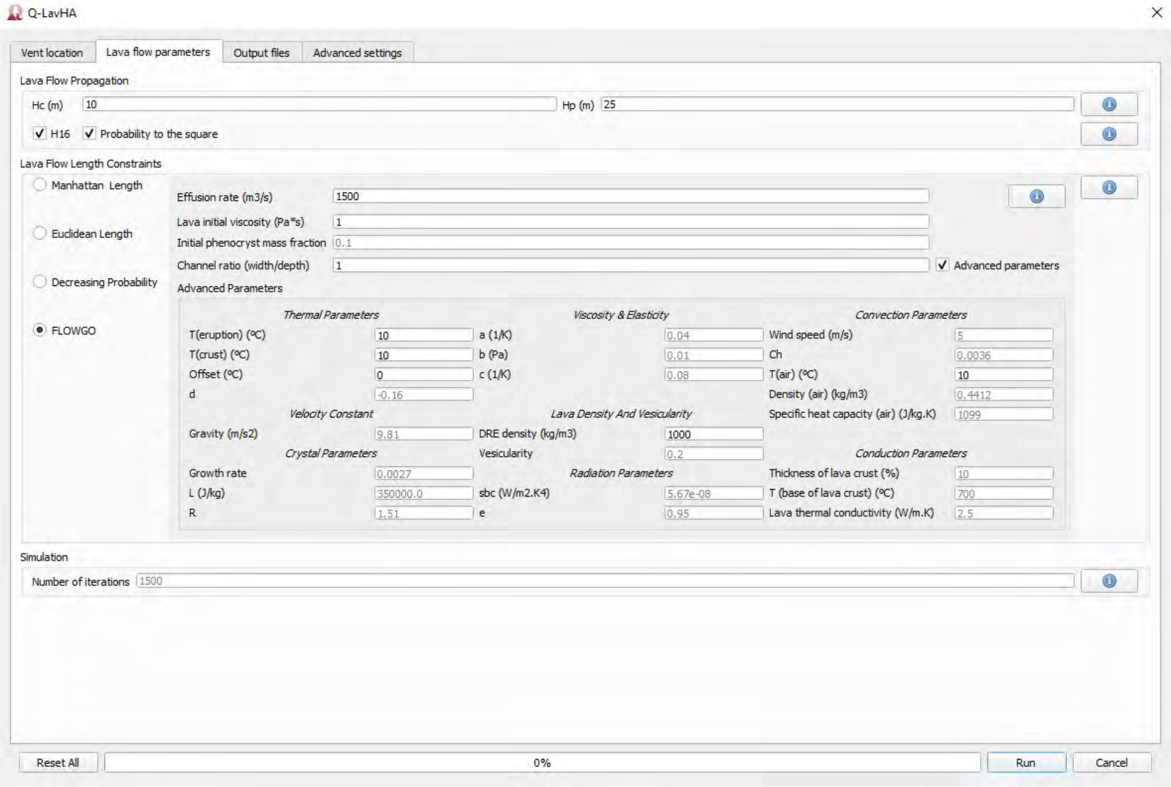


Figure 8*. The eruption from Q-LavHA (Manhattan Length) starting from "Crater 2" in Fagradalsfjall. The reference flow at 2021-04-06 almost lines up to the outcome from Q-LavHA (probability: high (darker) to low).*
Figur 8*. Utbrottet från Q-LavHA (Manhattan Length) med start från "Crater 2" i Fagradalsfjall. Referensflödet från 2021-04-06 ligger nästan i linje till flödet från Q-LavHA (sannolikhet: hög (mörkare) till låg).*

A recurring problem with the Q-LavHA plugin is that the longevity of the lava flow pathway is too short. To aid to the problem, the parameters used in the FLOWGO lava flow parameter can simulate the flow of water since this is the only length option in the plugin that can manually change the parameters. This will give the result of a longer possible extent in which a water body might have taken because it can be similar to choosing the same pathway in a slope, due to the surrounding topography. To visualize this through the plugin, water parameters were used. This is to show a potential longer longevity, since a basaltic lava can reach a much longer extent (Einarsson, 2019), than the one made with Manhattan Length. The parameters used for the simulation is shown in figure 9 using FLOWGO and is not an accurate flow of normal lava, but more the flow of water. It can, however, follow the same path and therefore it is relevant to show. This result will depend mostly on the place of where the polygon craters are placed and the topography. The parameters that are changed for this simulation are H_c ($3m \rightarrow 10m$), H_p ($10m \rightarrow 25m$), effusion rate ($100m^3/s \rightarrow 1500m^3/s$), lava initial viscosity ($1000Pa*s \rightarrow 1Pa*s$), T(eruption) ($1140^oC \rightarrow 10^oC$), T(crust) ($500^oC \rightarrow 10^oC$), DRE density ($2600kg/m^3 \rightarrow 1000kg/m^3$) and T(air) ($20^oC \rightarrow 10^oC$). H_c and H_p needed to be changed to a higher number, otherwise the simulation would stop with the original number 3 m and 10 m.

Effusion rate is increased to be able to flow at a higher rate. Viscosity is decreased, as well as temperature of air, eruption and crust. Density is decreased to mimic water.



Lava Flow Propagation
Hc (m) 10
Hp (m) 25
☑ H16 ☑ Probability to the square

Lava Flow Length Constraints
○ Manhattan Length
○ Euclidean Length
○ Decreasing Probability
● FLOWGO

Effusion rate (m3/s) 1500
Lava initial viscosity (Pa*s) 1
Initial phenocryst mass fraction 0.1
Channel ratio (width/depth) 1
☑ Advanced parameters

Advanced Parameters

Thermal Parameters		Viscosity & Elasticity		Convection Parameters	
T(eruption) (ºC)	10	a (1/K)	0.04	Wind speed (m/s)	5
T(crust) (ºC)	10	b (Pa)	0.01	Ch	0.0036
Offset (ºC)	0	c (1/K)	0.08	T(air) (ºC)	10
d	-0.16			Density (air) (kg/m3)	0.4412
Velocity Constant		*Lava Density And Vesicularity*		Specific heat capacity (air) (J/kg.K)	1099
Gravity (m/s2)	9.81	DRE density (kg/m3)	1000		
Crystal Parameters		Vesicularity	0.2	*Conduction Parameters*	
Growth rate	0.0027	*Radiation Parameters*		Thickness of lava crust (%)	10
L (J/kg)	350000.0	sbc (W/m2.K4)	5.67e-08	T (base of lava crust) (ºC)	700
R	1.51	e	0.95	Lava thermal conductivity (W/m.K)	2.5

Simulation
Number of iterations 1500

***Figure 9**. The parameters that are used to simulate a worst-case scenario in FLOWGO (Q-LavHA), to enhance the longevity.*

***Figur 9**. Parameter som används för att simulera ett värstafallsscenario i FLOWGO (Q-LavHA), för att kunna förlänga utbredningen.*

3.1.2 Simulating the lava flow

After validating the plugin, it was applied to the study area of Hafnarfjörður to simulate a potential lava flow and to showcase a possible outcome scenario. By following the Q-LavHA manual, preparation was started with reprojecting the DEM model to WGS84/UTM projection, since the plugin would not work in a different projection. The raster analysis *Fill NoData*" was applied as this is suitable to fill small holes and cracks in images that are irregular. This is followed by the tool terrain analysis-hydrology *Fill sinks* to be able to stimulate a continuous lava flow, if this is not applied it could result in a discontinuous flow. To conclude the first part of the manual, the layer was exported into a geotiff (Esri, n.d; VUB, n.d; QGIS documentations, n.d). To represent the craters, several polygons were created along an existing eruptive fissure (see figure 2) as a new shapefile which then was digitized onto the map by following a shape similar to the craters from Fagradalsfjall. This was added into Q-LavHA by using the finished prepared DEM geotiff to add coordination through the vent type, converting it into an *asc file*.

Then, Manhattan Length, with the standard parameters for H_c (3 m) and H_p (10 m) was used with an output path leading to a simulated lava flow pathway.

To showcase the worst-case scenario in Hafnarfjörður, the same parameters as shown earlier in figure 9 in FLOWGO made for a longer extent and made it possible to simulate a flow that reached the town. The polygon with "Crater 13" was used in this simulation, as it only needed one crater for the flow to reach the town in the plugin.

3.1.3 Simulating changed topography and barriers

The last part of the method included a changed topography simulation using the existing DEM and adding the simulated lava flow as a height parameter to add to the DEM. This was done to see if a changed topography would change the lava flow pathway, in case a new eruption on top of an old one occurs. Inspiration was taken from Fagradalsfjall as there is speculation around more possible eruptions (Sturkell & Stockmann, 2021; Ravilious, 2021). To be able to apply the simulated lava flow, it needed to be multiplied in the raster calculator to get a higher m (meter) value. To compare, the simulation was made for Fagradalsfjall as well, since the new DEM provided a new topography already with the added cooled lava. Figure 10 shows the old DEM (black line) and the new DEM (purple line) across a projected line in the valley. The new DEM was then used to see if the Q-LavHA plugin showed a different result when projecting the same parameters (Manhattan Length & FLOWGO) on a different elevation (see result).

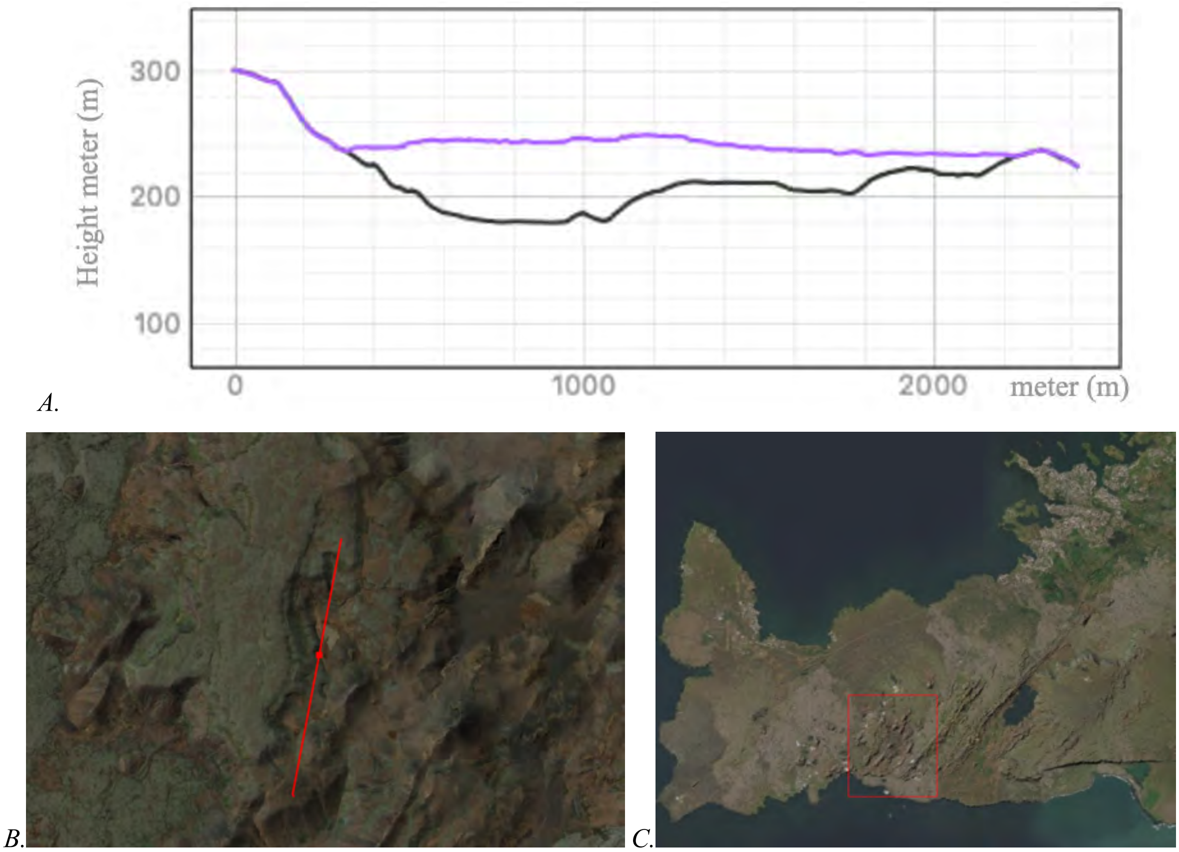


__Figure 10__. (A) The difference in height of the old DEM (black line) and the new DEM (purple line). (B) The projected line in which the difference in height was taken in Fagradalsfjall. (C) Area where the line was taken.
__Figur 10__ (A) Skillnaden i höjd på det gamla DEM (svart linje) och det nya DEM (lila linje). (B) Den projicerade linjen där skillnaden i höjd togs i Fagradalsfjall. (C) Vart linjen är tagen ifrån.

The simulated most probable flow from Hafnarfjörður resulted in a probability value (the probability for a lava flow) between 1.4-0.0007, which was then multiplied by 100 in the raster calculator to be used as a height parameter added to the DEM. This resulted in a height difference of approximately 30-35 m in the highest area, which is close to Fagradalsfjalls 40 m. This method was recommended to be able to use the lava flow as a height parameter. The same was done for the worst-case scenario; outcome probability value 0.5-0.0007 only multiplied with 500 to get a more extreme result and is more randomized, resulting in a height difference of almost 100 m in the highest area. Not that this layer had to be multiplied with a higher value (500) because its probability value was the highest at 0.5, compared to multiplying 100 with 1.4. This resulted in a changed elevation as shown in figure 11, with the projected line in figure 12. The original DEM (gray line), the added times 100 (orange line) and the added times 500 (red line) show the elevation changes used for the simulation, as it is only tested to see how accurately it can be simulated.

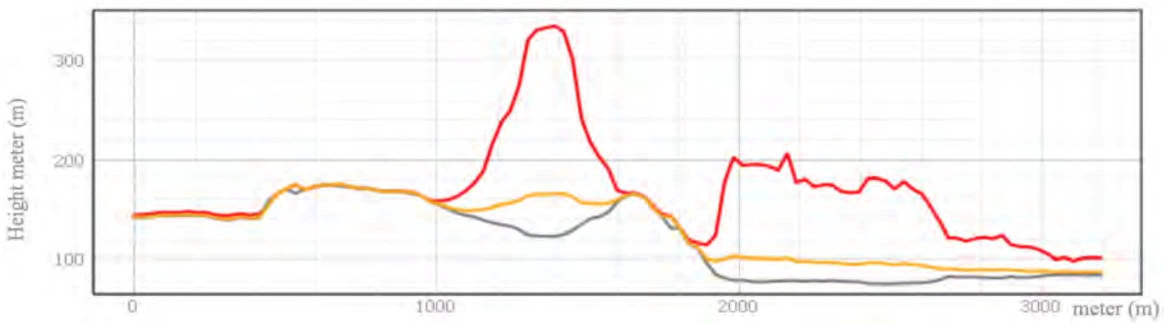
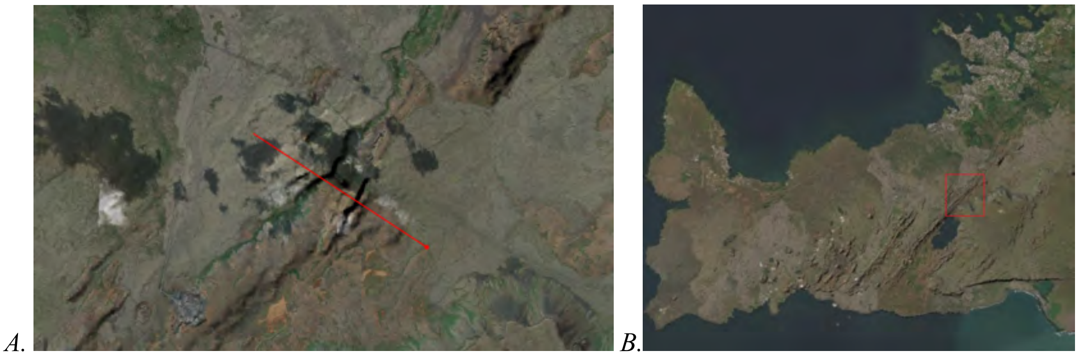


Figure 11. *The difference in height between the old DEM (gray line), DEM times 100 (orange line) and DEM times 500 (red line).*

Figur 11. *Skillnaden i höjd mellan det gamla DEM (grå linje), DEM gånger 100 (orange linje) och DEM gånger 500 (röd linje).*



A. *B.*

Figure 12. *(A) The projected line in which the difference in height was taken in Hafnarfjörður (B) Area of which the line was projected.*

Figur 12. *(A) Den projicerade linjen där skillnaden i höjd togs i Hafnarfjörður (B) Platsen vart linjen är projicerad.*

Adding a barrier was the last step for the method, to see if it was possible to stop a lava flow pathway using QGIS and the Q-LavHA plugin. This was done by creating a barrier shaped polygon with height parameters and rasterized (with values; Height: 25 m, Width: 25 m, no data value: 99 and fixed values to burn: the height parameters 30-40 m) and then adding it to the existing DEM through raster calculator. The lava simulation was then run again to see how high and broad the barriers needed to be to be able to stop the simulated flow to a certain extent. Figure 13 shows a test by creating a polygon line with added height parameters and adding it to the DEM (see figure 14 to see the overview of the method´s steps that was followed).

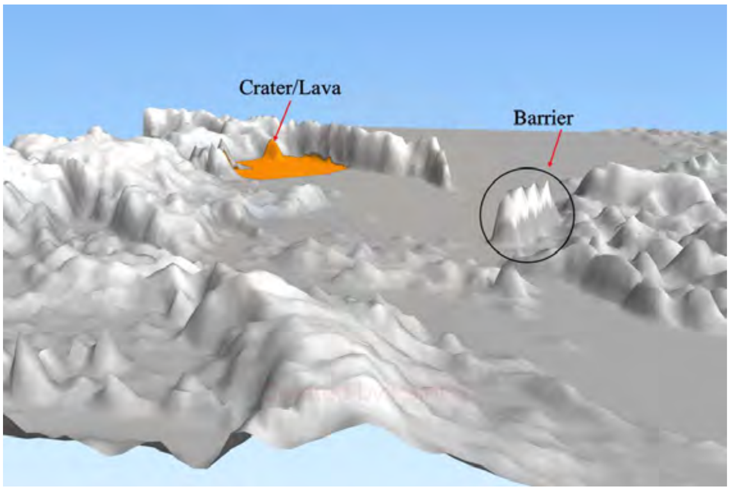


Figure 13. *A barrier was added and built into the original DEM layer to see how the lava flow pathway will change.*

Figur 13. *En barriär som är tillagd till det originella DEM lagret för att se hur lavaflödet ändrar väg.*

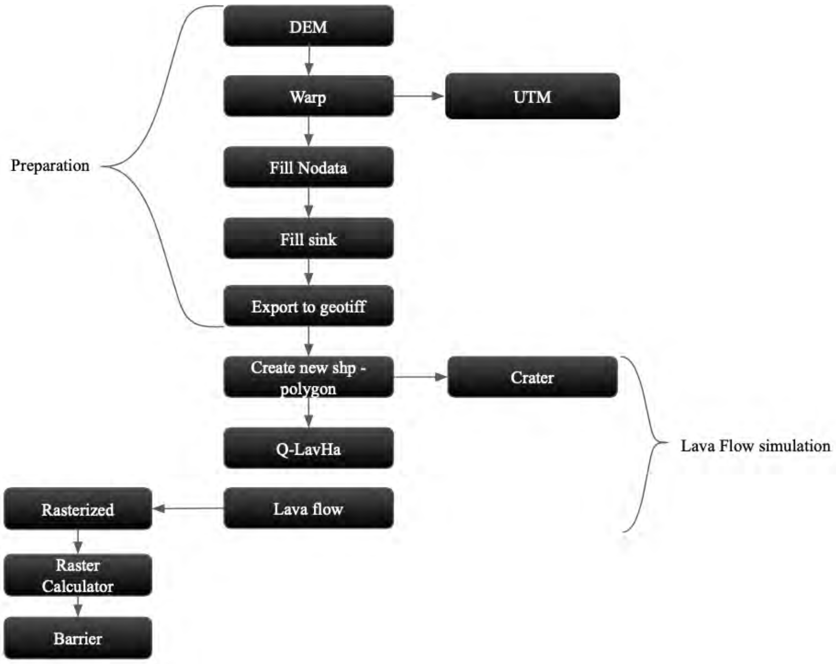


Figure 14. *Flowchart for the method used to simulate the possible lava flow pathway.*

Figur 14. *Flödesschemat för metoden som användes vid simulationen av en möjlig lavaflödesriktning.*

3.2 Data

To get the result all data that have been used are summarized in Table 1, with its ID, area of use, what type, source and date of download.

Table 1. The information of all the data that was used in QGIS.

Tabell 1. Information för all data som använts i QGIS.

ID	**Area of use**	**Type**	**Source**	**Date**
[IslandsDEMv1.0_2x2m] (Grid number: 56, 57, 67, 68)	Iceland elevation after Fagradalsfjall eruption, Iceland elevation for Hafnarfjörður	raster	National Land Survey of Iceland (n.d.a)	Downloaded: 2022-03-25
[islandsdemv1_rkns_preeruption_zmasl]	Iceland elevation before Fagradalsfjall eruption	raster	National Land Survey of Iceland (n.d.d)	Downloaded: 2022-04-08
[“Area of interest”]	Reykjanes Ridge	raster	Bathymetry Viewing and Download service (n.d)	Downloaded: 2022-04-20
[PB2002_steps]	Tectonic plates	vector	GitHub, Ahlenius, Nordpil & Bird (2014)	Downloaded: 2022-04-20
[ISL_adm0]	Administrative areas Iceland	vector	DIVA-GIS (n.d)	Downloaded: 2022-04-20
[building]	Habitable areas	vector	QuickMapServices (n.d)	Downloaded: 2022-04-10
[is_tn_ro_lmi_wgs_84]	Roads	vector	National Land Survey of Iceland (n.d.b)	Downloaded: 2022-04-10
[FLOKKUR]	Geology of Iceland	vector	Icelandic Institute of Natural History (n.d)	Downloaded: 2022-03-28
[j600v_gosspr_1utg_li]	Eruptive fissures	vector	Icelandic Institute of Natural History (n.d)	Downloaded: 2022-03-28
[j600v_gigar_1utg_p]	Craters	vector	Icelandic Institute of Natural History (n.d)	Downloaded: 2022-03-28
[j600v_brotalina_1utg_li]	Faults	vector	Icelandic Institute of Natural History (n.d)	Downloaded: 2022-03-28

3.3 Probability discussion

Errors occur when trying to visualize the flow and add them to one layer. In the result (later in figure 15, 16, 22 & 24) it is shown that adding several flows to one layer will disturb the probability value and give it a value above 1. These values are between 2.7-0.0007, which is not a probability value (these are usually 1-0). It is used anyway to visualize the flow in one layer, and still gives a good representation of all the flows together but is not easy to interpret by itself. The method for this does not go well with the model, and for this report there was not another way used for them all to be added together. Further studies would be to find a better way to visualize the flow into one layer without disturbing the probability value.

Another important consideration is that when there is a low probability value in the outlines of the worst-case scenarios, the simulation randomizes the lava flow. This is due to the fact that the plugin is based on the topography surrounding the crater, as the topography helps to direct the lava flow. With the added water parameters giving the lava a higher volatility, it is not clear for the plugin´s calculation of the outlines, making it harder for it to give an exact simulation if topography is not there to support the outlines. Resulting in giving different possible scenarios.

4 Results

4.1 Validating the lava flow model

The Q-LavHA plugin has shown the highest accuracy when using Manhattan Length as a lava flow parameter, with no change to the parameters H_c (3 m) and H_p (10 m). Figure 15 shows the result from all six existing craters using the Manhattan Length parameter after combining them into one raster layer, together with the reference flow that took place in Fagradalsfjall. The reference flow has an area of 4.9 km^2 while the new flow has an area of 4.2 km^2, showing a 0.7 km^2 difference. The higher the value, the higher probability for a lava flow according to the plugin. This validates the method and its accuracy to simulate a real lava flow pathway, since it is taking a similar path to the reference flow and has a similar km^2. The value 2.7-0.0007 is the probability of the lava flow combined from all six craters since their values are merged into one value, created by the plugin. Value 2.7 is the value for the highest probability outcome, as it goes down to 0.0007 the probability decreases. This value can be used to add to the DEM as a height parameter, to simulate a potential eruption on top of this flow (i.e., cooled lava, this can be done for Hafnarfjörður). Since the new DEM already has changed height parameters in Fagradalsfjall (since the lava that has cooled has been added to the height of the ground), these new values will only be used in simulating a new flow in Hafnarfjörður with parameters from the lava flow result in that area as discussed earlier in the method.

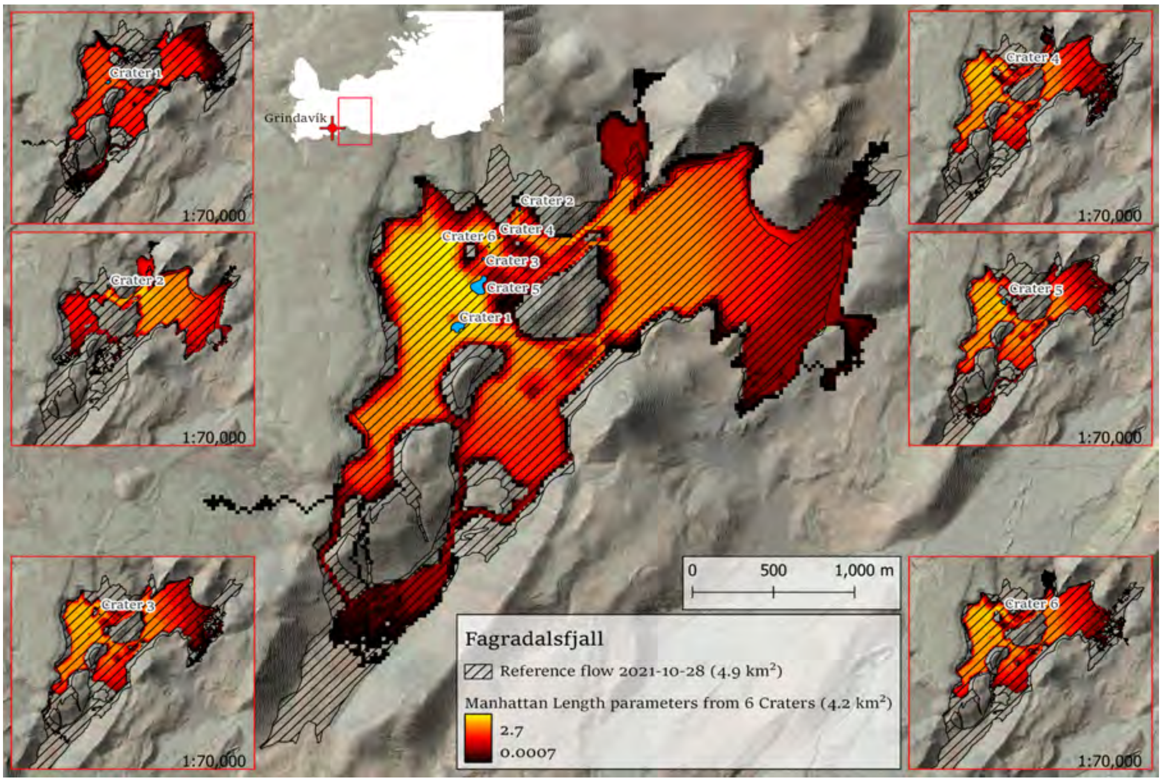


Figure 15*. The flow generated from Q-LavHA with the Manhattan Length parameter combined from all six craters, and then each individual crater together with the reference flow. Created 2022-04-28 with the projection WGS 84 / UTM zone 27N EPSG:32627 (National Land Survey of Iceland, n.d.d; Background map: QuickMapServices, n.d).*

Figur 15*. Flödet som genererat från Q-LavHA med Manhattan Length parametrar tillagt från alla sex kratrar, och sedan varje individuell krater tillsammans med referensflödet. Skapad 2022-04-28 med projektionen WGS 84 / UTM zone 27N EPSG:32627 (National Land Survey of Iceland, n.d.d; Background map: QuickMapServices, n.d).*

4.2 Lava flow simulation in the Hafnarfjörður area

Figure 16 shows seven possible craters and their lava flow pathway when simulated. As a result, Q-LavHA simulated possible future scenarios through using the Manhattan Length parameter with the standard H_c (3 m) and H_p (10 m) values. Seven craters were created near an existing eruptive fissure (see figure 2) where there might be a high probability for a future eruption. All seven craters and their lava flow are shown separately, as it connects to the middle flow which illustrates the total value. The probability values 1.4-0.0007 will be used as a height reference when adding cooled lava to the DEM. This result is based upon validating the method with Fagradalsfjall and shows the most probable simulation from a near eruptive fissure according to the Q-LavHA plugin.

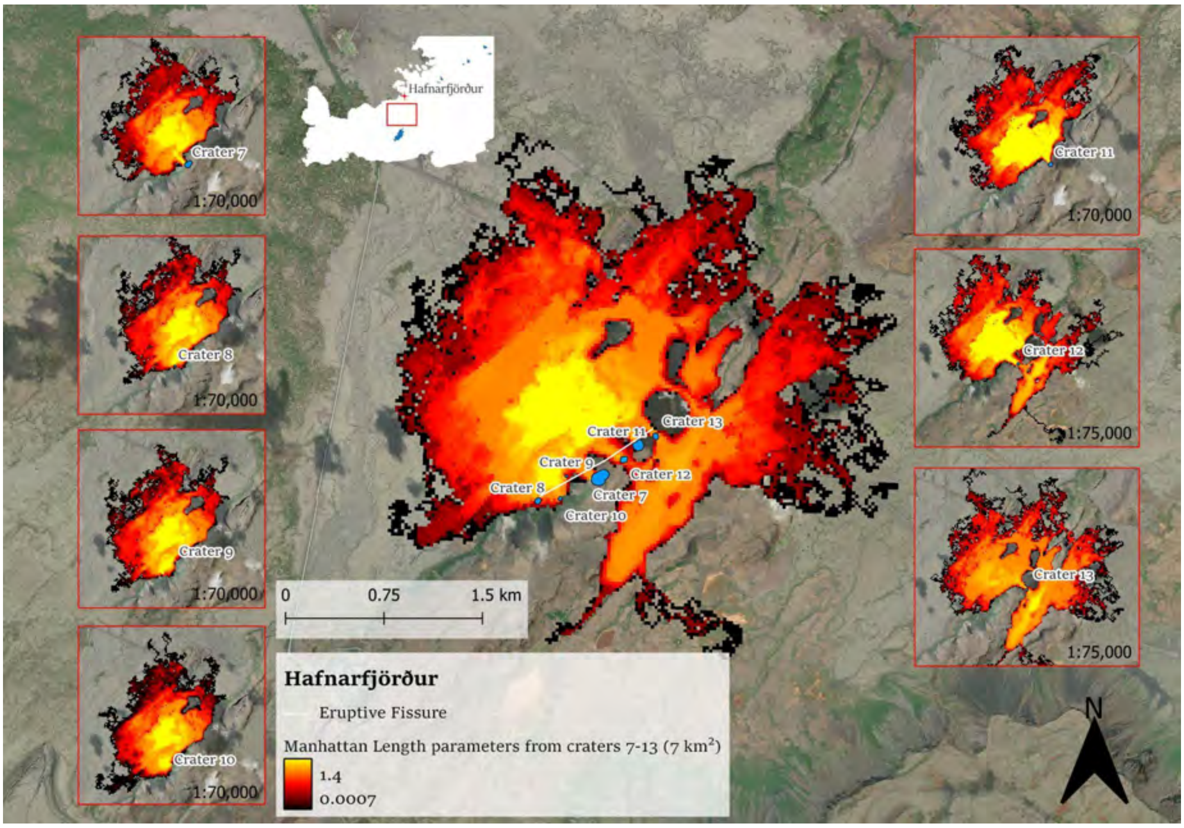


Figure 16*. The total lava flow from all the seven craters along an existing eruptive fissure and simulation of each individual crate. Created 2022-05-04 with the projection WGS 84 / UTM zone 27N EPSG:32627 (National Land Survey of Iceland, n.d.a; QuickMapServices, n.d).*

Figur 16*. Det totala lavaflödet från alla sju kratrar längst en existerande spricka och simulation av varje individuell krater. Skapad 2022-05-04 med projektionen WGS 84 / UTM zone 27N EPSG:32627 (National Land Survey of Iceland, n.d.a; QuickMapServices, n.d).*

4.3 A worst-case scenario with FLOWGO

Fagradalsfjall is used as a reference here, together with the illustration of the worst-case scenario to visualize how extreme this scenario is (figure 17). This is because the reference flow exists (the real lava flow), so the lava outside the reference flow is only a scenario that could/could not happen. According to Q-LavHA, even though the probability is lower the further the lava flow pathway is, basaltic lava can still reach longer. These results show an approximate longevity of 8.5 km, 6.5 km and 6.4 km. The longevity will depend on the amount of craters and the intensity of a real outbreak, as well as the time of eruption, which are parameters that cannot be configured in the plugin. This result shows where the lava could flow if it were to do so, reaching the ocean as well as getting closer to the town Grindavik. "Crater 5" is used for reference, since it is the crater with the longest activity to date. The simulated worst-case scenario reaches an area of 25.6 km^2 as compared to the real lava flow of 4.9 km^2, with a difference of 20.7 km^2. Value 1-0.0007 is the probability value configured by the plugin.

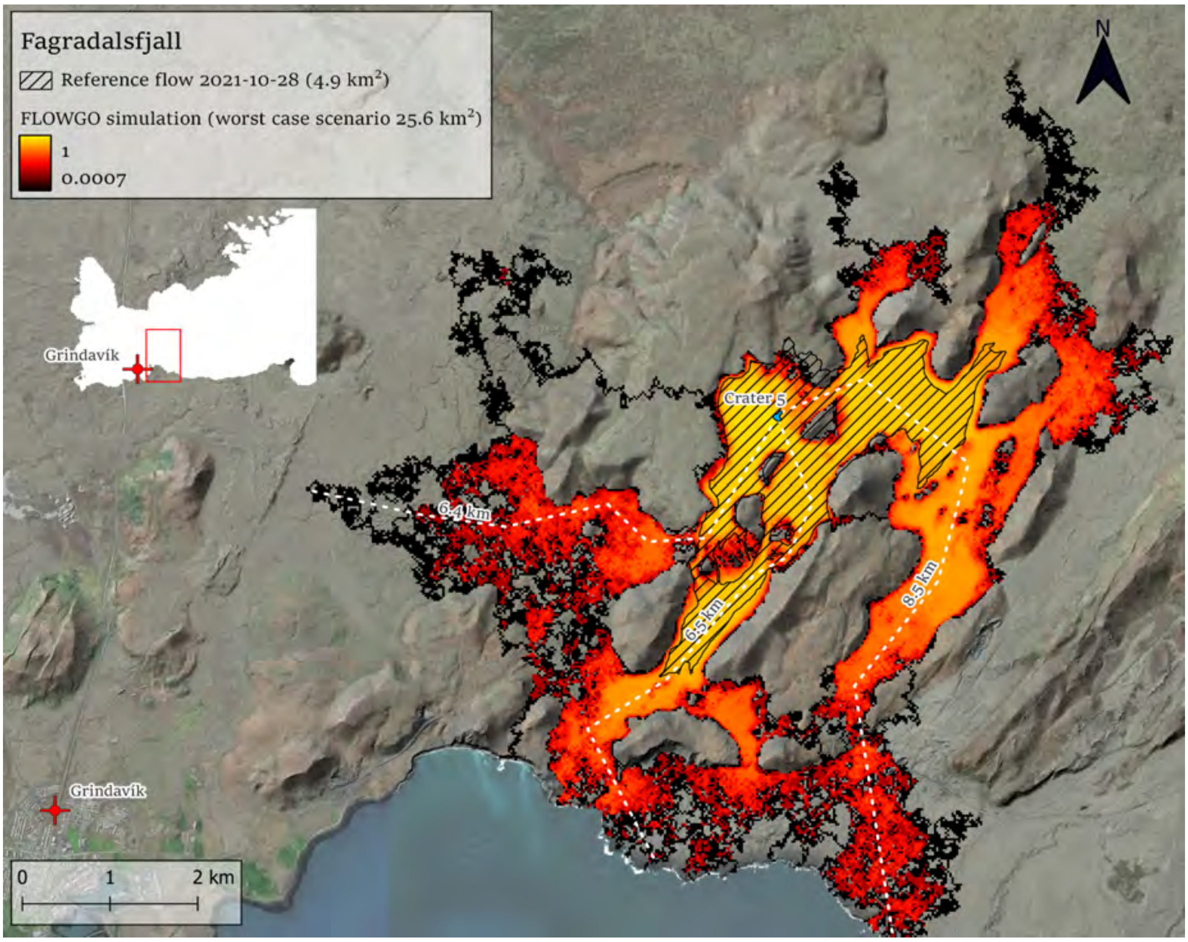


***Figure 17**. The result when using FLOWGO with changed parameters on Fagradalsfjall, along with the length of the lava flow pathway. Created 2022-05-04 with the projection WGS 84 / UTM zone 27N EPSG:32627 (National Land Survey of Iceland, n.d.d; QuickMapServices, n.d).*

***Figur 17**. Resultatet vid användandet av FLOWGO med förändrade parametrar på Fagradalsfjall, tillsammans med längden av lavaflödets väg. Skapad 2022-05-04 med projektionen WGS 84 / UTM zone 27N EPSG:32627 (National Land Survey of Iceland, n.d.d; QuickMapServices, n.d).*

Figure 18 shows the worst-case scenario in Hafnarfjörður with water parameters in FLOWGO according to Q-LavHA. This is simulated from “Crater 13” to give an example of how much the town of Hafnarfjörður might be affected by a simulation in the plugin. The lava stretches to the coastline with a pathway towards the northwest and a measurement between 9.6 km to 10.5 km. While it also stretches south of the crater between 2.9 km to 4.3 km. The most accurate lava flow illustrates the flow from figure 16 with an area of 7 km^2, compared to the worst-case scenario with an area of 70 km^2. The lava flow from the simulation affects the southest parts of the town continuing to the coastline. This result has a probability value of 0.5-0.0007.

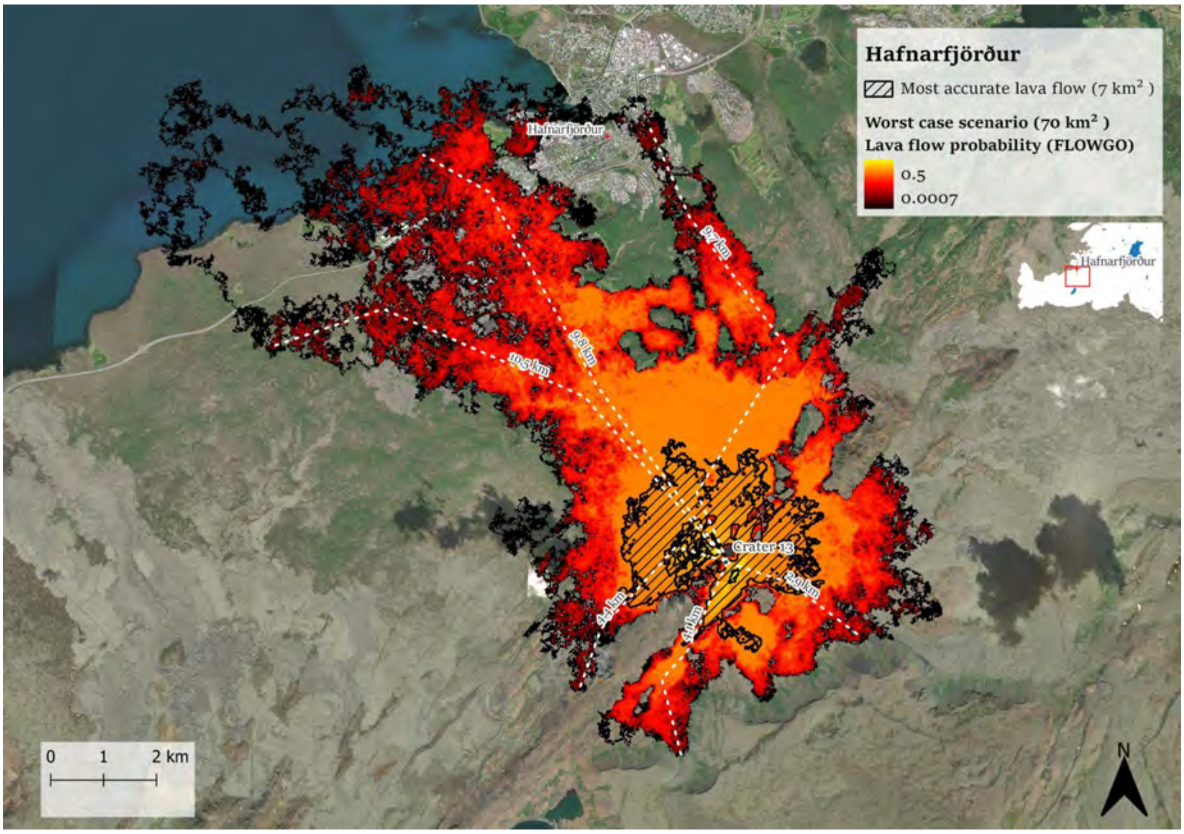


Figure 18. *The worst-case scenario, if it is simulated through the digitized "Crater 13" near an eruptive fissure. Created 2022-05-04 with the projection WGS 84 / UTM zone 27N EPSG:32627 (National Land Survey of Iceland, n.d.a; QuickMapServices, n.d).*

Figur 18. *Ett värstafallsscenario om det är simulerat genom digitaliserade "Crater 13" nära en spricka. Skapad 2022-05-04 med projektionen WGS 84 / UTM zone 27N EPSG:32627 (National Land Survey of Iceland, n.d.a; QuickMapServices, n.d).*

Figure 19 is based on the worst-case scenariosimulation of a FLOWGO lava flow pathway probability to see what buildings could be at risk according to Q-LavHA. The lava flow has an area of approximately 70 km^2, with a low probability as mentioned in figure 18. This shows the result of a worst-case scenario in FLOWGO, intersected with the buildings in the area that might be affected according to the simulation. As the buildings colored with red are intersected with the lava, while the white buildings are not.

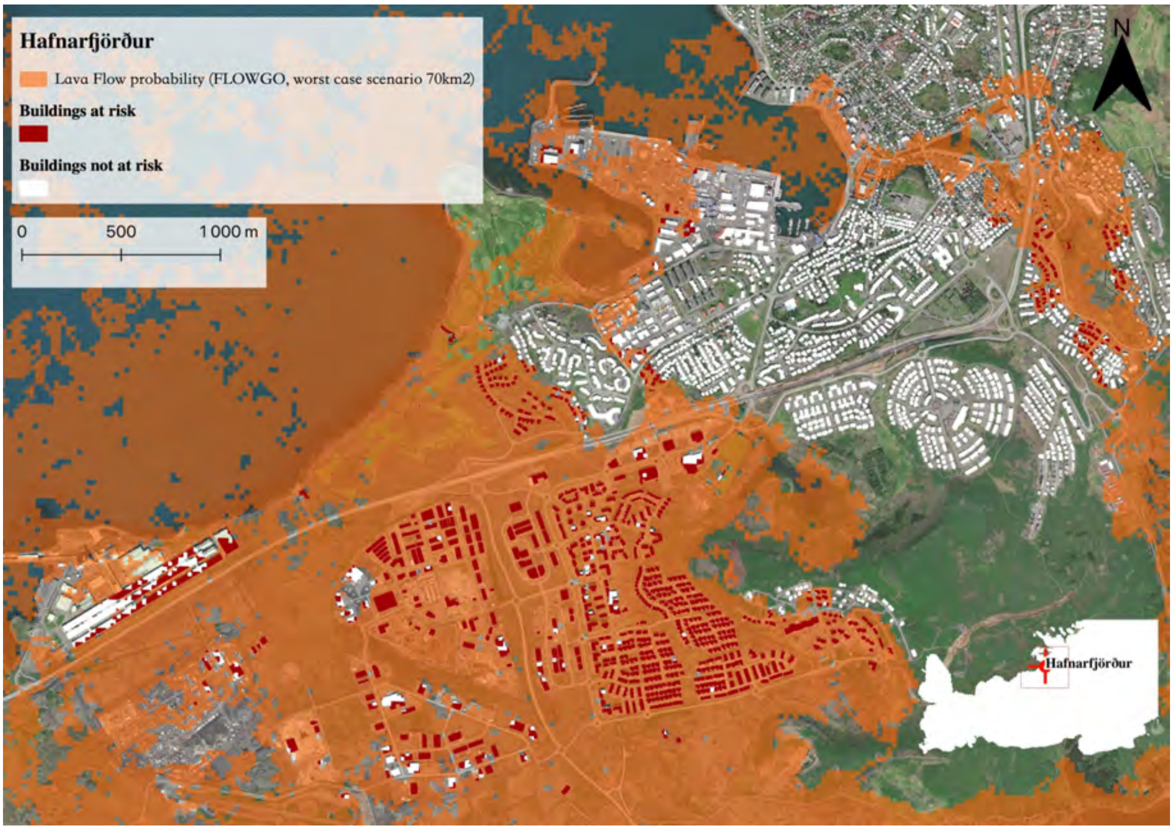


***Figure 19**. Buildings that might be affected in Q-LavHA´s worst-case scenario from the simulation. Created 2022-05-07 with the projection WGS 84 / UTM zone 27N EPSG:32627 (National Land Survey of Iceland, n.d.a; OpenStreetMap, 2022).*

***Figur 19**. Byggnader som kan påverkas av Q-LavHAs värstafallsscenario från simulationen. Skapad 2022-05-07 med projektionen WGS 84 / UTM zone 27N EPSG:32627 (National Land Survey of Iceland, n.d.a; OpenStreetMap,2022).*

Figure 20 shows the number of buildings that might possibly be affected during a potential worst-case scenario in the simulation along the fissure according to Q-LavHA. Overall and in total there are 4520 buildings in the area, where 2295 buildings might be affected. Mostly the living areas might have the biggest impact as there could be 593 houses and 571 apartments being damaged. This is followed by what is categorized as “others” which is a number of 175 buildings and then 162 industries. Moreover, 37 workplaces, 20 construction sites, 2 schools and 2 kindergartens, including 1 church might be affected by lava according to Q-LavHA´s simulation.

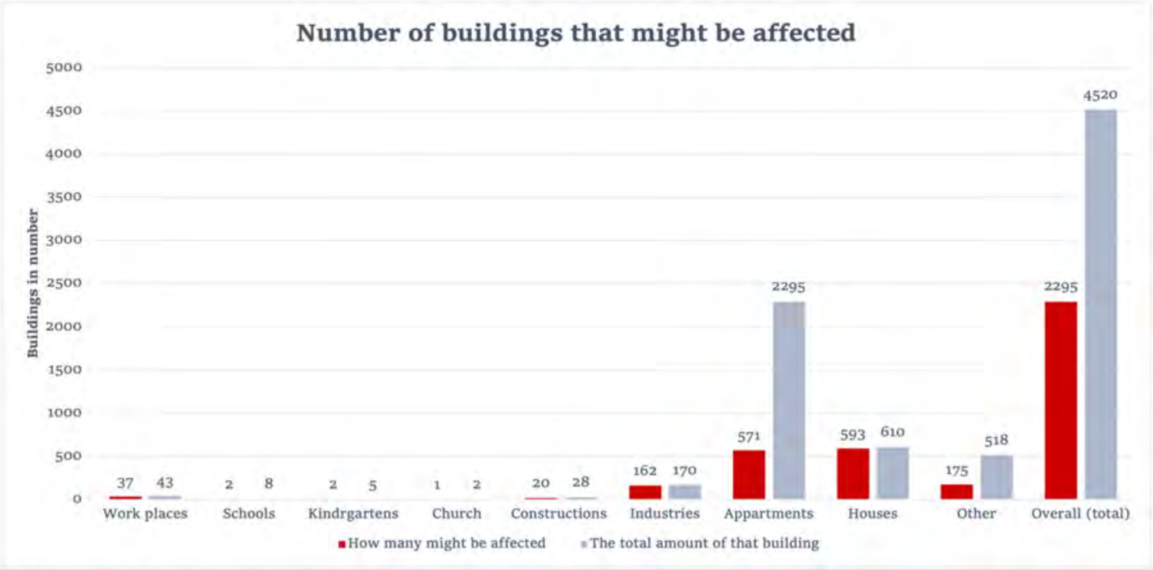


Figure 20. *Detailed information as a supplement for figure 20 (OpenStreetMap, 2022).*
Figur 20. *Detaljerad information till figur 20 (OpenStreetMap, 2022).*

Figure 21 illustrates the population status in the area with an outline of Q-LavHA´s worst-case scenario lava flow. The darker the color is the larger number of people lives in the area where the scale stretches from 0 to 200 people. It illustrates the possible number of people affected by the simulation, which is around 1700, as a detailed intersection has been executed to get this calculation.

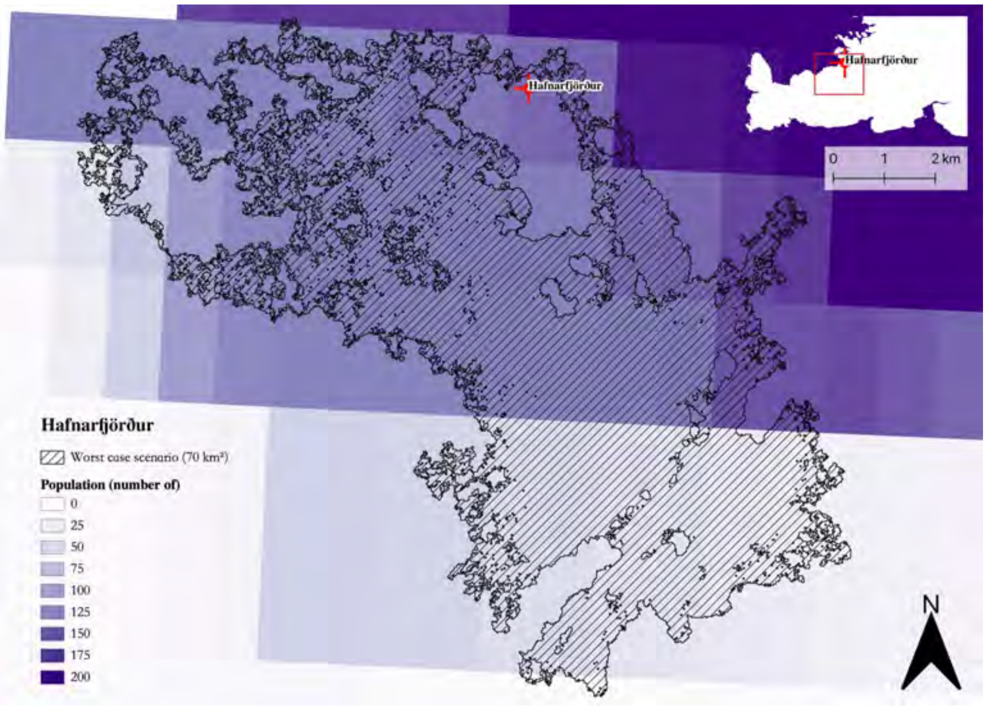


Figure 21. *Population in Hafnarfjörður and the simulated worst-case scenario flow.*
Figur 21. *Populationen i Hafnarfjörður och det simulerade värstafallsscenario flödet.*

4.4 Simulation with changed topography

A DEM layer from Fagradalsfjall is already updated with the new topography and lava on top of the layer, showing that the DEM is 40 m higher in the middle of the area. This means that a flow from the same craters used in figure 15, but with a different DEM with added cooled lava takes another pathway (shown below in figure 22). This result is simulated with the same six craters with the newer DEM, showing the lava flow taking a slightly different path in the same simulation. This is used as a reference for simulating new lava flow with changed height parameters in Hafnarfjörður. The values from all six craters are merged into one, giving the value 2.4-0.0007, where 2.4 is the value for the highest probability for a lava flow. The new lava flow reaches an area of 6.7 km^2 compared to the old flow with an area of 4.2 km^2. This means that the new lava flow reaches a bigger area of 2.5 km^2 more than before, which could prove that a changed topography could accumulate a higher flow when placed on top of an old flow.

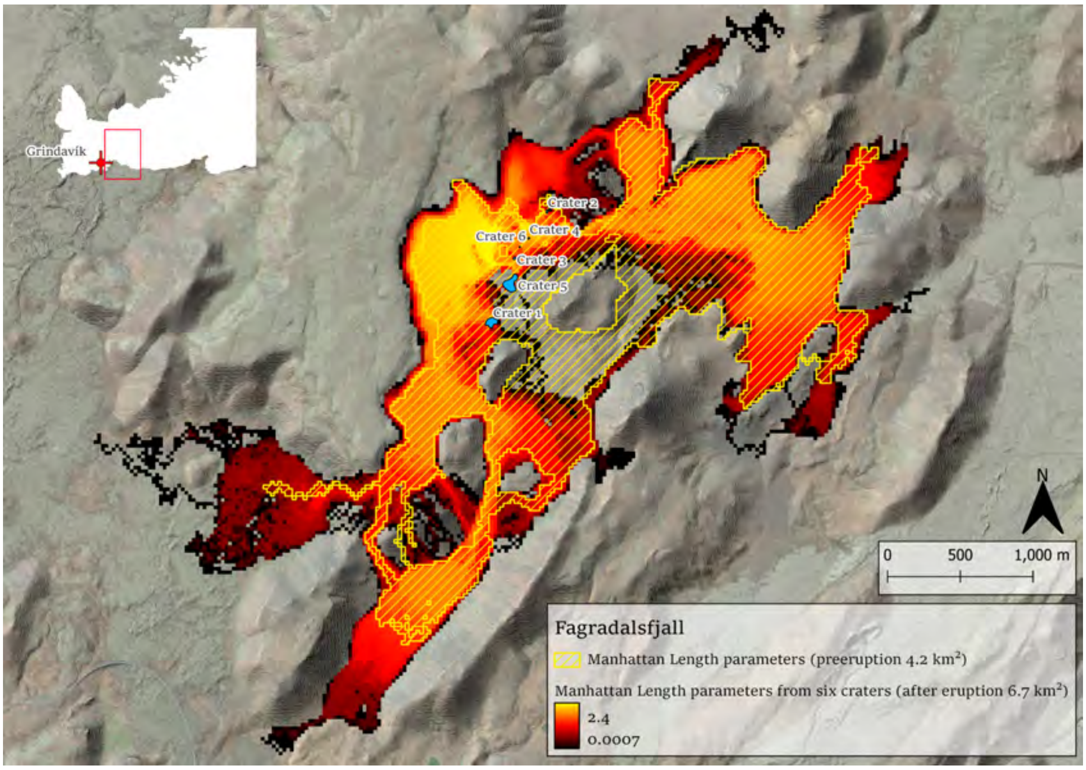


Figure 22. *The lava flow pathway changes with the same craters with a different DEM. Created 2022-05-07 with the projection WGS 84 / UTM zone 27N EPSG:32627 (National Land Survey of Iceland, n.d.a; QuickMapServices, n.d).*

Figur 22. *Lavaflödets väg ändras med samma kratrar men med ett annat DEM. Skapad 2022-05-07 med projektionen WGS 84 / UTM zone 27N EPSG:32627 (National Land Survey of Iceland, n.d.a; QuickMapServices, n.d).*

Figure 23 shows the new DEM for the worst-case scenario with FLOWGO parameters, according to Q-LavHA. It overcomes more topography but there is no change to the lava flow pathway direction. It still reaches the ocean to a great extent, but does however come closer to the town of Grindavik, by 1 km, than the previous flow with the old DEM. Once again, showing that a new eruption on top of an old one could reach a longer extent and higher accumulation. The new flow reaches an area of 44.5 km^2, compared to the old flow of 25.6 km^2. Comparing the two, they have a difference of 18.9 km^2.

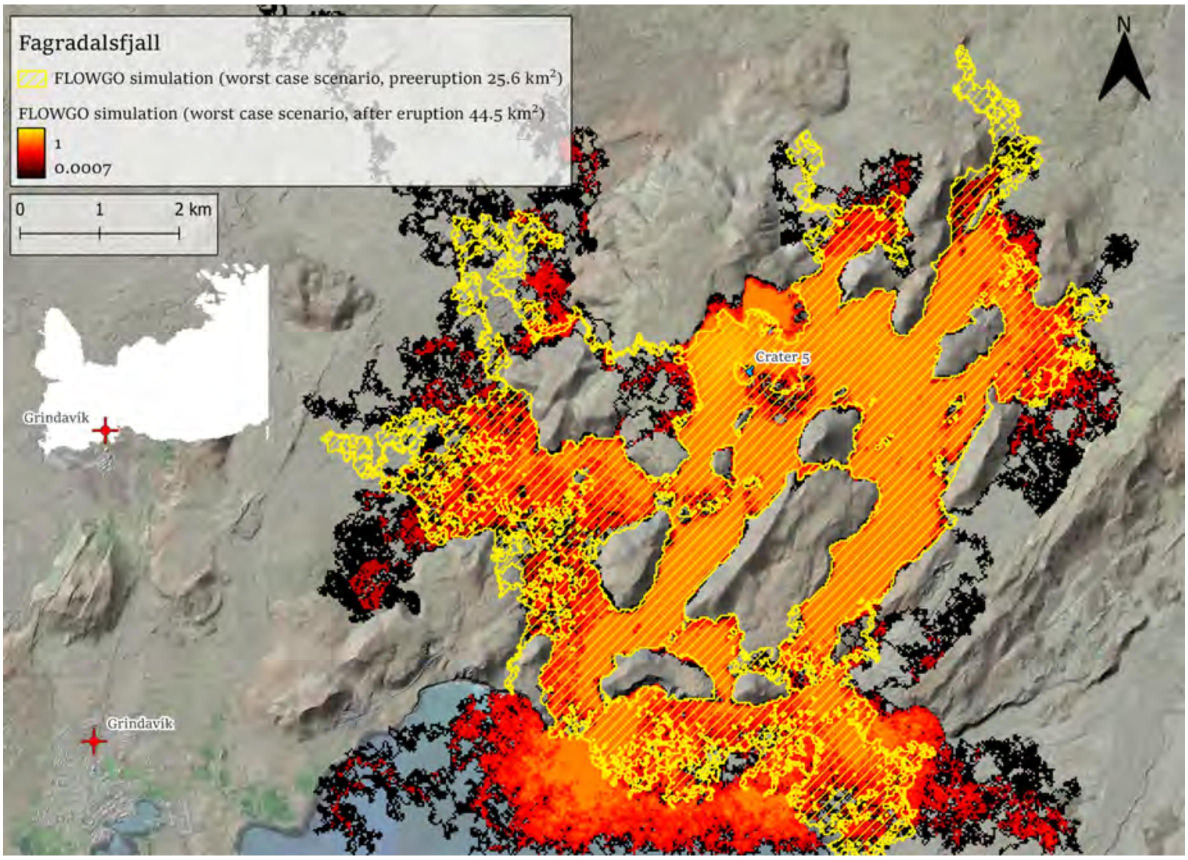


***Figure 23**. The lava flows from "Crater 5" with the DEM after the eruption in a worst-case scenario, compared to the worst-case scenario with a DEM preeruption. Created 2022-05-07 with the projection WGS 84 / UTM zone 27N EPSG:32627 (National Land Survey of Iceland, n.d.a; QuickMapServices, n.d).*

***Figur 23**. Lavan flödar från "Crater 5" med DEM efter utbrottet i ett värstafallsscenario, jämfört med ett värstafallsscenario med ett DEM före utbrottet. Skapad 2022-05-07 med projektionen WGS 84 / UTM zone 27N EPSG:32627 (National Land Survey of Iceland, n.d.a; QuickMapServices, n.d).*

Figure 24 is the newly added DEM height (times 100, as described in the method) with Manhattan length, which shows the most accurate simulation of the lava flow in Hafnarfjörður, according to Q-LavHA. The lava flow pathway changes, as it accumulates around the previous lava in the middle rather than covering it as a whole. Moreover, it flows more towards the southwest and northeast in comparison to the previous lava flow marked as yellow. The area changes and increases from 7 km^2 to 9.7 km^2, a difference of 2.7 km^2.

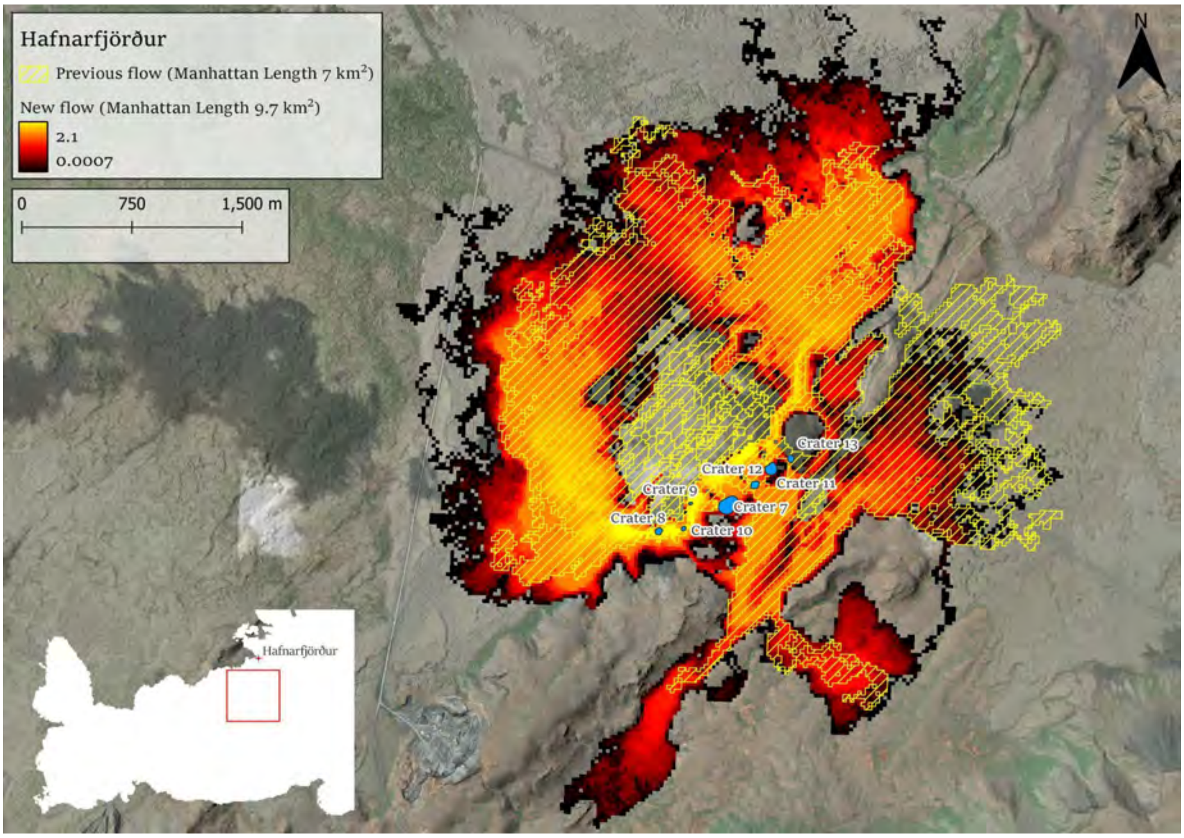


Figure 24. *Manhattan Length parameters are on top of the previous flow (see figure 17) to see the changes in the pathway. Created 2022-05-07 with the projection WGS 84 / UTM zone 27N EPSG:32627 (National Land Survey of Iceland, n.d.a; QuickMapServices, n.d).*

Figur 24. *Manhattan Length parametrar är lagd över det tidigare flödet (se figur 17) för att se skillnader i väg. Skapad 2022-05-07 med projektionen WGS 84 / UTM zone 27N EPSG:32627 (National Land Survey of Iceland, n.d.a; QuickMapServices, n.d).*

Looking at FLOWGO, the worst-case scenario simulated in Q-LavHA in figure 25 shows that the lava´s starting point is further northwest than the previous flow that is cooled (worst-case scenario times 500, as presented earlier in the method). A noticeable change is that the lava flows around and further north past Hafnarfjörður, towards the neighboring cities. The size of the lava expands from 69.6 km^2 to 72.2 km^2, a change of 2.6 km^2, and still flows northwest towards the ocean.

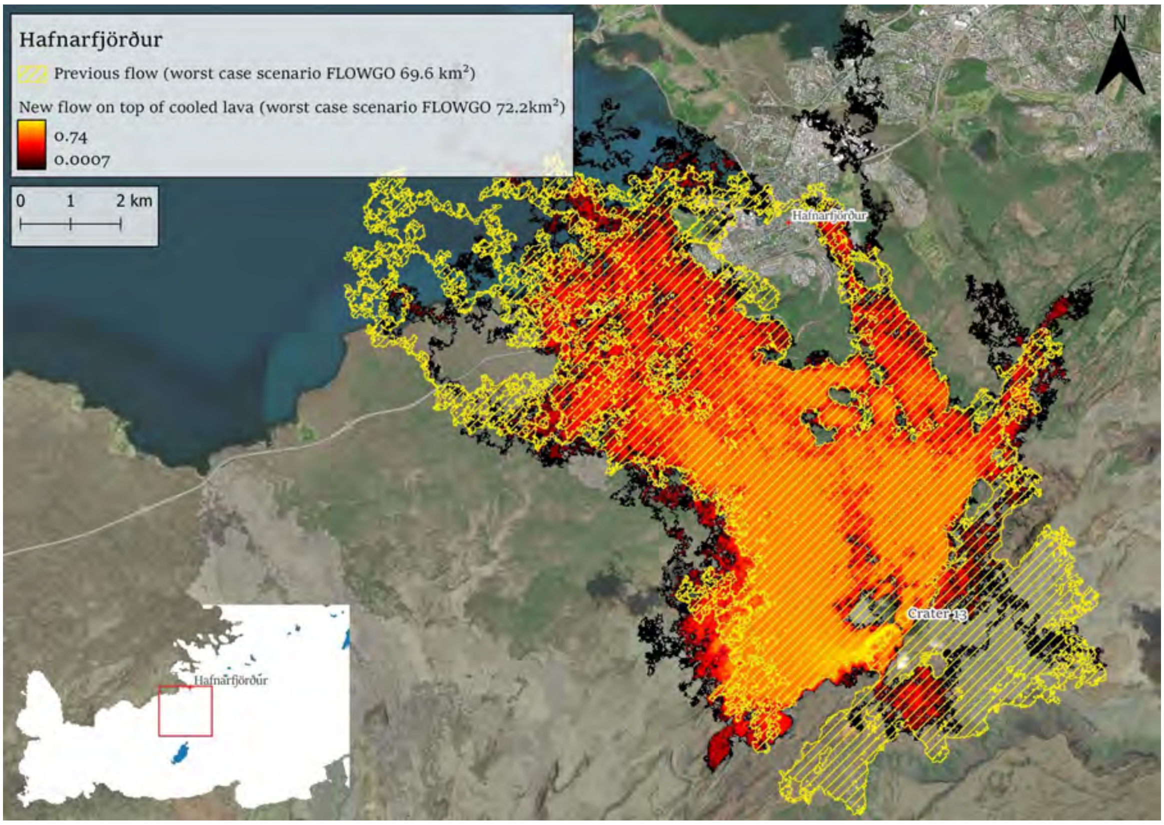


***Figure 25**. The worst-case scenario (see figure 19) added in the DEM with the new lava flow to simulate the possible changes the simulation can make. Created 2022-05-07 with the projection WGS 84 / UTM zone 27N EPSG:32627 (National Land Survey of Iceland, n.d.a; QuickMapServices, n.d).*

***Figur 25**. Värstafallsscenario (se figur 19) adderas i DEM med det nya lavaflödet för att simulera möjliga förändringar simulationen kan göra. Skapad 2022-05-07 med projektionen WGS 84 / UTM zone 27N EPSG:32627 (National Land Survey of Iceland, n.d.a; QuickMapServices, n.d).*

4.4 Barriers

Figure 26 & 27 shows the result of how several barriers in a row can affect the lava flow during Q-LavHA´s simulation of a worst-case scenario when using water parameters in FLOWGO. If two 30 m high barriers and two shorter 40 m high barriers were to be built south of Hafnarfjörður it could stop the lava flow in the simulation from Q-LavHA. The previous flow accumulated an area of 69.6 km^2, while the stopped flow accumulated 51.7 km^2, meaning a difference of 17.9 km^2 when stopping the lava flow pathway in the simulation. The lava does not seem to take another path more than it just stops entirely. Some of the new flow redirects to the ocean, but the simulation does not show if it would take another route. Note that the previous flow and the new simulation on top are not exactly the same, this is due to the flow's randomization which result in similar but different outlines for each simulation.

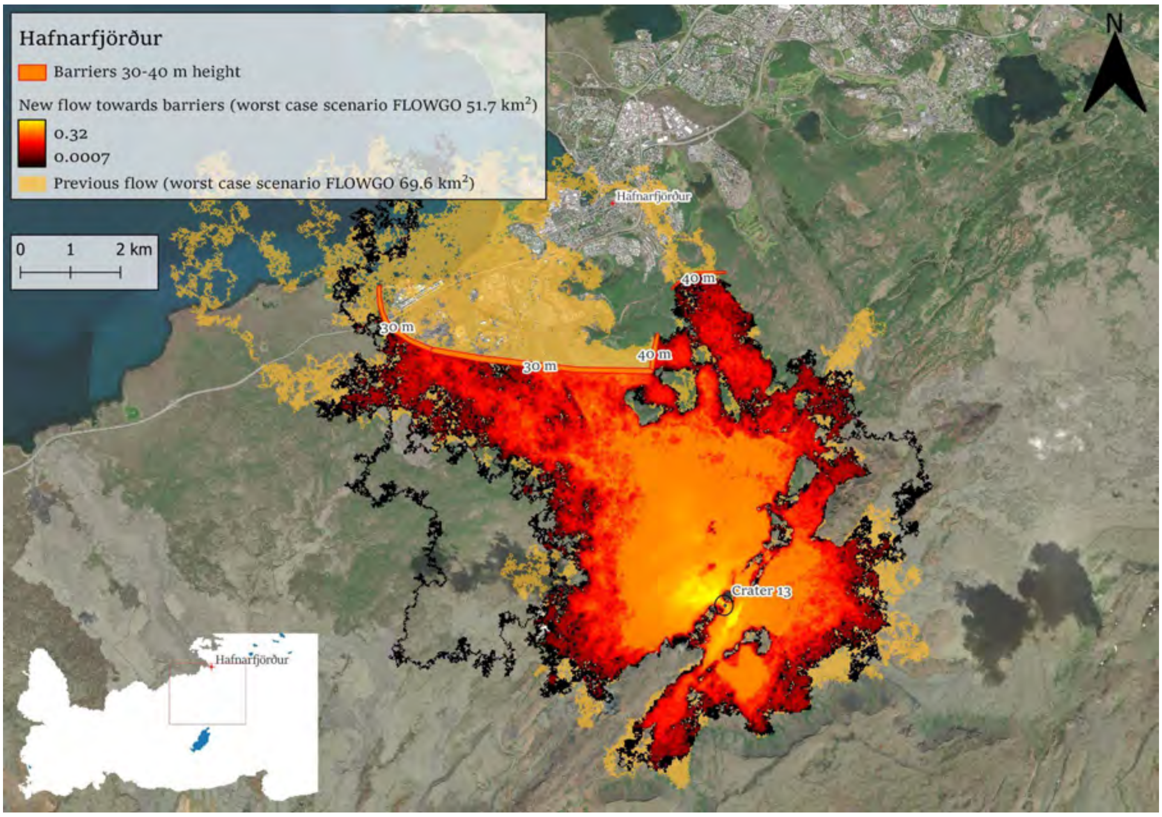


Figure 26. *Several barriers with different heights could affect the worst-case scenario simulation run in Q-LavHA. Created 2022-05-07 with the projection WGS 84 / UTM zone 27N EPSG:32627 (National Land Survey of Iceland, n.d.a; QuickMapServices, n.d).*

Figur 26. *Flera olika barriärer med varierande höjder kan påverka värstafallsscenario skapad i Q-LavHA. Skapad 2022-05-07 med projektionen WGS 84 / UTM zone 27N EPSG:32627 (National Land Survey of Iceland, n.d.a; QuickMapServices, n.d).*

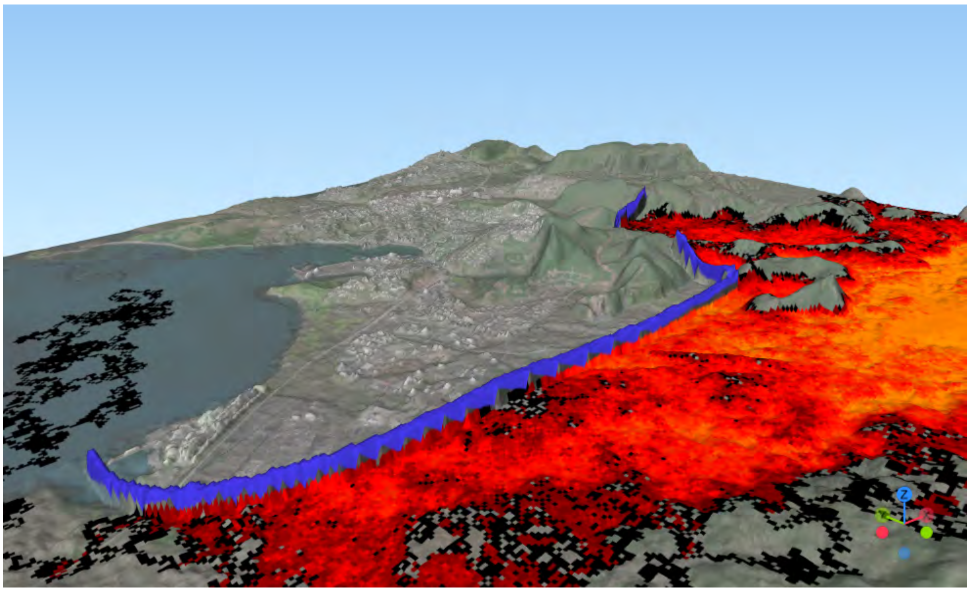


Figure 27. *3D version of the barrier. Supplement for figure 26*

Figur 27. *3D version av barriären. Tillägg för figur 26.*

5 Discussion

5.1 Accuracy of the flow model

Using Q-LavHA´s standard parameters, Manhattan shows the most accurate lava flow as in comparison it is relatively similar to the 2021-10-28 lava flow. However, there are some aspects that need to be considered.

Digitizing polygons is a possible source of error as it is based on how accurate one is while drawing it. Especially when digitizing a still active eruption. Reference lava flow polygon is based on Hennig´s (2021) polygon, who mentioned that it is challenging while digitizing the lava flow as it will already be out of date by the time it has been produced. This is due to the activity being both dynamic and still active. Therefore, the lava flow has probably changed since October, which does not give a detailed accurate illustration to base the Q-LavHA stimulated lava flow pathway on. It is also important to have in mind that the digitization was based on the human eye, as it is a question of how detailed it was executed. While this is a problem, the new DEM model shows in detail a similar pattern to the digitized lava flow (see figure 28). The same goes for digitizing craters in Hafnarfjörður, since there are no reference craters to be digitized from. These craters are only hypothetical and will not be accurate, as one cannot predict how or where a crater will look or take place.

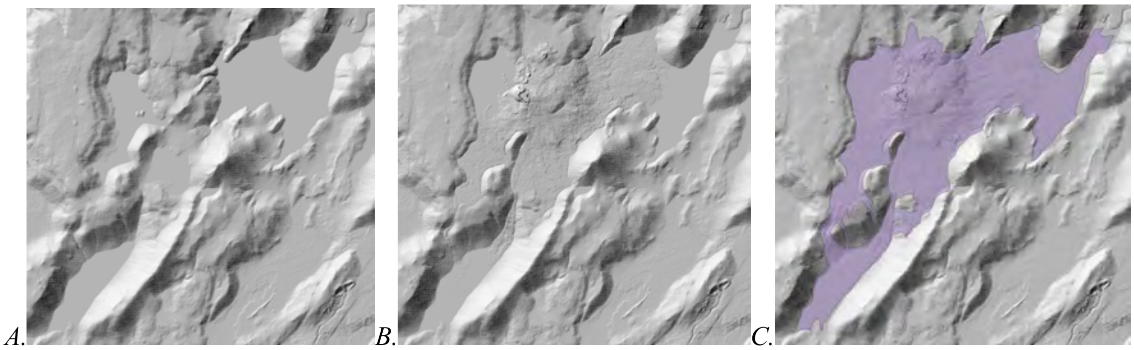


***Figure 28**. (A) Old DEM (B) New DEM with the latest lava flow in Fagradalsfjall. (C) Digitized polygon. It helps to show where the lava flow stopped and is only used to change the parameters in the plugin.*

***Figur 28**. (A) Gamla DEM (B) Nya DEM med det senaste lavaflödet i Fagradalsfjall. (C) Digitaliserad polygon som hjälper till med att visa vart lavaflödet slutar och är endast användbart för att ändra parametrarna i pluginet.*

There are sources of errors with Q-LavHA that need to be considered. The plugin is first and foremost a possible simulation of a non-existing eruption with a reference towards Fagradalsfjall, leading to the result being based on the topography in the area. Therefore, the question to ask is how accurate the method is. When using the 25x25m DEM layer, the simulation worked easier than the original 2x2m DEM layer. This was because the DEM was too detailed, making it hard for Q-LavHA to simulate and resulted in a different lava flow pathway when it was managed. Therefore, the layer was converted to a lower DEM resolution to make the simulation work properly. Another aspect that was mentioned earlier is that the probability parameters are hard to interpret as it does not give a precise result such as 0 to 1. However, it is also detected that the numbers above 1 are due to the layers being added to each other where the probability numbers are calculated together giving the higher value. This is still used to showcase the fact that there is a higher probability if all craters were to erupt.

Furthermore, in this case the Manhattan length shows the most similarities to the real lava flow on Fagradalsfjall. However, the parameters that were used are the standard ones resulting in a general lava flow which might not correspond to the real parameters from Fagradalsfjall. Other factors such as the lava volume, time, temperature, weather conditions, climate change and more have not been considered due to data limitations, including Fagradalsfjall´s eruption that is relatively new. This is also due to volcanic activity being dynamic and hard to predict. By having the right parameters, the plugin could give a completely different scenario than the one suggested in this report. The results also show that the topography is an important factor as the lava flow will be based on it, creating a relatively accurate lava flow. However, the result is not a prediction of the future, but rather a possible scenario based on the standard Manhattan Length parameters from Q-LavHA.

Looking at the worst-case scenario, water parameters were used in FLOWGO. The reason for this was to be able to simulate a scenario where the lava reaches Hafnarfjörður to analyze how much of the town might be affected, but also the possible pathway the lava might flow. Because of using water parameters in FLOWGO it is important to have in mind that the parameters are not based on lava factors, as figure 17 and 18 illustrates a more liquid and flowing lava. Giving a possibly wrong simulation and overly extreme visualization. As mentioned in the method, the plugin randomizes the outlines of the lava flow when simulating the worst-case scenario. Topography has an important role as it can support and direct the outlines of the lava flow. But on flat surfaces such as in Hafnarfjörður, the simulation could result differently than the first simulation because there is not much to base the lava flow on. Especially when the water parameters give the lava a higher volatility which has an easier flow rate than real lava parameters. This is also apparent in figure 26, as the yellow: the previous flow is not exactly the same as the second lava flow which was simulated again to see the barriers affect. Making the result clear that it is a possible scenario and not a prediction. But when analyzed, Fagradalsfjall becomes more accurate due to its variety of topography in the area, creating valleys and obstacles for the lava (see appendix 13). Furthermore, there is a randomization of the outlines of each simulation and the worst-case scenario being an extreme possible scenario that could, or more likely not happen. This is due to the usage of parameters that are not adjusted for lava as there is a higher volatility. However, the necessary information and knowledge taken from this simulation is the possible lava flow pathway. Even if it is an extreme case which has a smaller probability to happen, it still shows the possible direction the lava will flow. Resulting in eventually giving an indication and guidance in future eruptions. So even if a smaller eruption occurs in the area, the direction will possibly be the same as the simulation made by Q-lavHA. Therefore, the worst-case scenario shows the possible pathway that the lava might flow in the future.

There are speculations that Fagradalsfjall might create another eruption through new craters, as earthquakes can lead to new possible eruptions and the lava is coming from a hot source from the deeper mantle. If this happens, the new lava will flow on top of the old one, which contributes to a new or changed topography, forming a possible lava shield volcano due to the lava flowing slow and steady (Ravilious, 2021). Simulations have therefore been executed to see if it affects the new lava flow (figure 22, 23, 24 & 25). When creating figures 24 & 25, the DEM model was added together with the simulated flow times 100 and times 500 to get a height parameter in Hafnarfjörður. These parameters are chosen to mimic the one in Fagradalsfjall and one random, to get a height value close to the one in Fagradalsfjall (x100) and one very exaggerated (x500). This is done to see how well the plugin can simulate a flow on top of a DEM that has been developed or changed by the user. As mentioned before, when multiplying the probability value with 100, it gives a similar height difference (rise of 30-35 m) to the DEM as the one in Fagradalsfjall (had a rise of 40 m). When multiplying the value with 500, it gives an extreme visualization (rise of 100 m) and results compared to multiplying with 100. This will not accurately show a real lava flow pathway scenario if the user does not have the exact parameters for the height. The result did, however, in all cases result in more lava flow area (km^2). The Q-LavHA simulations also indicate in this case that Grindavík will not be affected by this eruption from “Crater 5”, as the lava will flow towards the water and remain in the valley.

5.2 Potential impacts on Hafnarfjörður

Along the eruptive fissure south of Hafnarfjörður (see figure 2), possible craters have been added and simulated through Q-LavHA. When analyzing figure 19, the maps illustrate a very detailed result on exactly which buildings might be affected. This could pose a misunderstanding from the public eye, such as people either getting frightened or too relaxed. People living in the area could either interpret that they are safe due to their houses being in the white zone, or that they need to move immediately because of the red zone. Houses that also are in the white zone but are near the red zone might in this case look like a safe place, but in reality, would not as other natural factors (wind, temperature, etc.) are not calculated. Resulting in people eventually viewing this map literally and therefore wrongly. Also, because the FLOWGO randomizes the outlines of the worst-case scenario it must be considered that this is a general possible scenario that is extreme as the lava is more liquidy and no topography will hinder the lava. On top of that, as part of the method: sinks needed to be filled before simulating Q-LavHA to aid the lava to flow further as sinks will not in this case be an obstacle, resulting in a longer pathway. Furthermore, the numbers of people that might be affected and the large area of buildings that could be covered in lava from the simulation should be interpreted vaguely. With this in mind, figure 20 visualizes what kind of buildings might be affected as it shows how many in numbers according to OpenStreetMap (2022). In this case it is about 2295 buildings that could be affected according to the simulation of Q-LavHA of the total 4520 buildings that exist in the area. Moreover, it also visualizes an example of how many people might be affected in Hafnarfjörður, which is approximately 1700 people according to Q-LavHA´s simulation (see figure 21). In this case, this eventually results in a better understanding of the area and possibly gives aid to creating solutions to how to keep Hafnarfjörður and its local safe with the Q-LavHA simulation (see appendix 14, 15, 16 & 17 to see an example of what area might be affected).

Another aspect to reflect on is the tourism in Hafnarfjörður, as the population increases significantly during different months. Looking at the statistics of international tourism during this year there have so far been around 8000 visitors, and from February 2021 to January 2022 there are on average 3000 people visiting Hafnarfjörður every month (Visit Iceland, n.d). Adding this to the 26 000 people living in the area results in the possibility of an increasing number of people that might be affected. However, this is also very hard to predict as tourism changes every month making it hard to grasp exactly how much could be affected as there is no certain data of this to use in a simulation.

5.3 Measures to protect Hafnarfjörður

As mentioned earlier, three work site protection barriers with the height of 1,5-2 m have been placed near Fagradalsfjall as a measure to delay or stop the lava flow (see appendix 11 & 12). Inspiration was taken from the action and implemented near Hafnarfjörður in the worst-case scenario simulation. Therefore, barriers were added into figure 26 & 27 as an example to show where and how high the barriers must be to be able to completely stop the worst-case scenario lava flow simulation created by Q-LavHA. Several barriers with two different heights: 30 m and 40 m worked in this simulation. Resulting in stopping the flow and changing the pathway slightly due to enclosing the southern part of the town. The barriers by Fagradalsfjall did delay but were later overrun. Therefore, the barrier´s specific height was chosen to see how high it must be to be able to stop or redirect the lava. Heights shorter than 30 m or 40 m in those areas did not work as effectively as the lava still overrun the barriers in the simulation. Again, it is important to understand that the added barriers that are applied onto Q-LavHA´s FLOWGO´s worst-case scenario simulation have some uncertainties with the parameters. However, this is an example and a general idea of how to simulate a lava flow using a barrier. And according to this result the most convenient and efficient barrier to apply is the shorter one standing alone to the left with a height of 40 m (see figure 27). That barrier can possibly result in protecting the central part of Hafnarfjörður. While the longer and bigger barriers of 30 m and 40 m are more complicated and inconvenient as they surround a larger space resulting in closing in the entire area. The smaller one is more durable and can still lead to a great measure of protection for Hafnarfjörður.

5.4 Further studies

Due to data constraints, including the Fagradalsfjall eruption being relatively new, the right parameters for the lava have not been able to be applied. To validate the Q-LavHA method even further, the real parameters from Fagradalsfjall´s eruption should be tested when the data is available as it could give another result than the one given here. Other parameters such as volume, thickness and temperature should be added as well to design a more accurate flow. This could also aid Hafnarfjörður as the result might be more accurate with fewer uncertainties. Therefore, the same method used here should be tested again to support this statement. At the same time, it would be interesting to test Q-LavHA even further with the right parameters and see how an eruption on top of an older one would result in. Especially since there are speculations around more eruptions, and the nearby town of Grindavík might be affected.

Other further studies would be to test the parameters used in FLOWGO, but also in Manhattan Length, Decreasing Probability and Euclidean Length, to be able to see what parameters fit best in a situation. It is also of interest to have in mind how lava lakes are created, as that might fill sinks and overcome certain topography not visualized in the simulation.

6 Conclusions

The question at issue has been answered through testing two different Q-LavHA method simulations: Manhattan Length and FLOWGO. Q-LavHA simulation with the standard Manhattan Length has in this case shown the most similar lava flow pathway as the Fagradalsfjall eruption. Making it relatively accurate when simulating possible lava flow in comparison to the real lava flow in Fagradalsfjall. It was then applied to Hafnarfjörður to see how it would affect the area. Moreover, to see how Hafnarfjörður will be affected by a possible worst-case scenario: FLOWGO with water parameters have shown to be the most relevant as the purpose was to have the lava reach the town. It was understood that topography has an important role as the lava adapted and was designed by it, where in this case Fagradalsfjall has a variety of topography while Hafnarfjörður is relatively flat. This is to analyze the size of the effects and pathways. However, these are extreme visualizations and what is defined as the worst-case scenario, is just one possible simulation scenario created by Q-LavHA. The necessary information taken from this is the possible lava flow pathway that future eruptions can have, if it were to occur in this area. Moreover, it is important to consider that there are some sources of errors, such as the randomization of the lava simulation of the water parameters. Making the result just one specific scenario that might or might not occur. However, it is to give a general understanding of what could happen or what pathway the lava will take. Further, it is also to give a suggestion of what could happen during, for example if a new eruption on top of a cooled one was to occur leading to the topography changing. The real data parameters that have been collected from Fagradalsfjall should be applied in a similar study to validate Q-LavHA one step further. At the same time, it could give more information on the possible lava flow pathways in both areas.

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8 Appendix

Appendix 1 & 2. The fissure south of Hafnarfjörður where the Crater 7, 8, 9, 10, 11, 12 and 13 were created on top.

Appendix 1 & 2. Sprickan/ryggan som befinner sig söder om Hafnarfjörður, där krater 7, 8, 9, 10, 11, 12 och 13 skapades ovanpå.

Appendix 3 & 4. Harbor in Hafnarfjörður.

Appendix 3 & 4. Hamnen i Hafnarfjörður

Appendix 5 & 6. Shops and cafe in Hafnarfjörður.

Appendix 5 & 6. Butiker och kaféer i Hafnarfjörður.

Appendix 7. Mid-Atlantic Ridge.

Appendix 7. Atlantiska centralryggen/Mittatlantiska ryggen.

Appendix 8. Fagradalsfjall´s crater.

Appendix 8. Fagradalsfjalls krater

Appendix 9. The lava created by the Fagradalsfjall eruption.

Appendix 9. Lavan skapad av Fagradalsfjall utbrottet.

Appendix 10. Fagradalsfjall´s crater and lava.

Appendix 10. Fagradalsfjalls krater och dess lava.

Appendix 11 & 12. Barriers at Fagradalsfjall.
Appendix 11 & 12. Barriärer vid Fagradalsfjall.

Appendix 13. Lava flow follows the topography of the valley in Fagradalsfjall. The starting point cannot be seen in this picture (Sturkell, 2021).
Appendix 13. Lavaflödet följer dal-topografin i Fagradalsfjall. Man kan inte se startpunkten i bilden (Sturkell, 2021).

Appendix 14 & 15. Area example in Hafnarfjörður that will be affected during the worst-case scenario according to Q-LavHA.

Appendix 14 & 15. Områden i Hafnarfjörður som kan bli påverkad i värstafallsscenarion enligt Q-LavHA.

Appendix 16 & 17. The Aluminum Industry might be affected in Hafnarfjörður, according to Q-LavHA worst-case scenario simulation.

Appendix 16 & 17. Aluminiumindustrin kan kommas att påverkas i Hafnarfjörður enligt Q-LavHA simulation i värstafallsscenario.