Lava Flow Modelling In Iceland

Gestur Leó Gíslason
Aalborg University
Department of Development and Planning
Msc Geoinformatics
Final Thesis
13. June 2013

Title: Lava Flow Modelling In Iceland

Theme: Final Thesis

Project period: 3.9.2012 – 13.6.2013

Author:

Gestur Leó Gíslason 20082650

Supervisor:

Professor Henning Sten Hansen

Copies: 3

No. Of pages: 96

Appendix: 1

Report Finished: 13.06.2013

Abstract

Lava flow is a threat to settlements in many countries where one of them is Iceland. There have been made many plans for how to minimize the damage that an eruption can make but there has not been focus on where the lava is flowing in these plans.

This project handles therefore about how lava flow can be modelled. First, the threat from volcanoes is analysed and then other approaches to model lava are analysed.

On basis of that a new method and then a program to model lava is developed. The program is based on Cellular Automata and is programmed in the programming language Python.

When the program is made there is executed a case study for Grindavík in Southwest Iceland where the program is tested and there is analysed if the town of Grindavík or other build areas within the municipality could be threatened by lava.

Finally, the Spatial plans for Grindavík are analysed to see if there are needs of modification of the Master plan for the municipality.

Preface

This project is final thesis on the MSc program in *Surveying, Planning and Land Management* with specialization in *Geoinformatics* at *Aalborg University*. This report focuses on development of a method that models lava flow from volcanoes during an eruption. This project is made in the period from 3. September 2012 to 13. June 2013.

I would like to thank the National Survey of Iceland and the Icelandic Institute Of Natural History for access to data regarding topography and volcanoes. I will also thank photograph Mats Wibe Lund and Ulrich Latzenhofer for allowing usage of their photos in the project. Finally, I will thank my supervisor, Professor Henning Sten Hansen for guidance throughout this project.

Table of Contents

List of Figures

List of Tables

1 Introduction

Volcanic activities are a big threat in many countries which one of is Iceland. The close distance from build areas to the volcanoes makes it dangerous to live in some areas of the country. There are couple of factors that are dangerous about volcanoes and one of them is the lava that flows from them during an eruption. When lava flow over buildings they get destroyed and even if the people staying there cannot run away the can lose their life. Lava flow might not be the most deadly danger that volcanic eruption can cause as there is in most cases enough time to evacuate the area, but it can lay big areas in ruins.

One of the towns that might be in danger is the Suðurnes Region in southwest Iceland. In analyses conducted by the Civil Protection and Security Council it is described that two towns in the area might be in danger together with important connection to other areas including the International Airport in Keflavík, furthermore important power lines could be in danger together with two steam power plants. (Ríkislögreglustjórinn Almannavarnadeild (A) 2011) Although these areas probably would be evacuated in good time, the houses and infrastructure will be damaged and big amount of people could end without a home.

There is nothing to do with the areas where there already have been built, other than create good evacuation plans combined with methods to divert the lava from there. Nevertheless, there is still ongoing need to consider new areas for planning new parts of town or separate structures outside the towns. Therefore, lava flow is an important factor that needs to be considered while planning new neighbourhoods.

The two biggest factors in a lava flow is the topography in the area and the thickness of the magma coming from the underground. Therefore, such a lava flow model has to be calculated mainly by using a Digital elevation model. (Jensen 2010)

Taking the topography of areas like the Suðurnes Region in Iceland there is more than one volcano that can cause lava covering a given area. Therefore, it is necessary to identify all the volcanoes that can possible send lava to the area and then make a model of the lava flow. To do so it is necessary to develop a program that calculates the flow of lava using a Digital Elevation Model

(DEM) and eventually other necessary data. This can be either a separate program or a model within GIS software.

1.1 Problem statement

On background of the introduction the following problem statement is formulated

How is it possible to calculate using GIS the risk of an area being covered by lava during a volcanic eruption? In addition, how can it be applied to spatial planning?

To help getting to the results the following research questions are formulated

1. Is it possible to model lava flow using GIS?
2. How can lava flow be modelled in a simple way?
3. How can it be secured that all possible volcanoes are taken into consideration?
4. How can lava flow modelling be used in spatial planning?

1.2 Project overview

The purpose of this chapter is to give an overview of how this report is build up. It outlines how the process from problem statement to the conclusion is described. Below the different chapters of the report are described

Theory

This chapter start by describing the theory of lava and volcanoes with focus on Iceland. Then there is described several different approaches that have been done to model lava flow. At last, the theory of GIS systems and programming in Python are described followed by a description of the Agile development method.

Method

In the method chapter, the method of the program developed in this project to model lava flow is described.

Data

The data Chapter describes the spatial data infrastructure in Iceland together with the data used in the process to calculate lava flow and to analyse the results.

Implementation

The chapter implementation describes the script that is developed to calculate lava flow in this project. This is followed by a description of the challenges that were important in the development phase of the script.

Case study

The Case study chapter describes an execution of the developed tool to find out if there is any threat of Grindavík in southwest Iceland might be covered in lava following an eruption.

Spatial Planning in Iceland

This chapter describes spatial planning in Iceland together with the procedures that are used to plan according to threats from volcanoes. Furthermore, there is a description of how lava flow modelling could be implemented into the spatial planning process.

Discussion

This chapter discuss the methods and results of the project

Conclusion

The conclusion chapter concludes if the Problem statement and research questions have been solved throughout the project.

Perspectives

The Perspective chapter describes the possible future improvements to the lava flow modelling program.

2 Theory

This chapter handles about the theory that is needed for modelling lava flow. First volcanoes and lava are described with focus on the threat they cause in Iceland and especially the Suðurnes region. Then different methods and solutions to model lava flow are described. After that, the GIS and Python theory important for the project is described, followed by program development theory.

2.1 Volcanic threats

There are several different threats from volcanic eruptions in Iceland. The first one is lava flow, which can make huge damages on buildings and other structures but are rarely live threatening. Ash fall have many different threats, when it fall on buildings it can destroy the roofs and if falling on farming areas these might be damaged due to the ash, furthermore the ash can cause breathing problems in people and animals. If an eruption happens under a glazier there is danger of water flowing in big amount from the glazier, which causes flooding of big areas, and destroys houses and roads and that can even happen so quickly that the area cannot be evacuated although it is rare. Other dangers are fault movements where the land close to a volcano rises, falls, or goes from sides to side resulting in earthquakes that might destroy buildings and other structures.

2.1.1 Lava

To be able to model lava it is necessary to know the dynamics of lava and how it behaves. In general, it can be said that lava flow is *'partially molten rock that cool as they flow, in some cases melting the surface over which they flow but in all cases gradually solidifying until they come to rest.'* (Griffiths 2000, 477) Lava flow has a behaviour that is instable and depends *'on the properties of the erupted magma, the effusion rate, the ground topography over which the lava flows, and it new environment (which primarily determines the rate of heat loss).'* (Griffiths 2000, 477) This might eventually lead to a halt of the flow front, sometimes even before the eruption stops. (Griffiths 2000)

There are several different types of lava. Generally, they are divided into three classes: The first one is basalt or basaltic rock, which is the most, frequent type covering around 70% of the earth's

surface. The second one is intermediate rocks that cover around 20% of the earth's surface and the last one is acid rocks covering around 10% of the earth. These are categorised according to the amount of silicon dioxide in the lava. Lava with low percentage of silicon dioxide tend to be very hot when reaching the earth's surface and therefore it is very thin floating and spreads over big area. The opposite is acid lava, which contains big amount of silicon dioxide, is generally very thick, and make a thick layer of lava that hopes op around the eruption vents and only flows very short distance. (Sólnes, et al. 2013)

Researches show that the distance lava flows is mainly based on the size of the eruption and not the thickness of the lava although thin lava tend to distribute more to all sides while thicker lava follows one or more smaller paths. How long the lava flows is also dependant on if it flows in open or closed streams where the closed streams forms as the lava on top cools down and make a roof that isolates the flowing lava, which makes it able to flow longer. The thickness of lava is very different but for pahoehoe lava that is the most common type of lava from eruption happening on land in Iceland the thickness is in most cases between 5 and 15 meters. For a'a lava, which is the most common for intermediate rock the thickness is on average somewhere between 4 and 20 meters. (Sólnes, et al. 2013)

2.1.2 Volcanoes in Iceland

Iceland is located on the edge of the North American and Eurasian tectonic plates. The edge between these plates is named The Mid-Atlantic Ridge. As the two tectonic plates are drifting apart with a speed of around 2 cm a year there is need for material to fill op that crack which result in magma flowing from deep in the earth to the surface to fill in the cracks. In most cases, the magma stops before it reaches the earth's surface but in some cases, it enters the surface resulting in an eruption. (Guðmundsson 2007) It is not only the Mid-Atlantic Ridge that is the reason for the volcanic activity in Iceland as there is under the middle of Iceland a so-called hotspot which is a stream of very hot magma from deep in the earth which slowly flows towards the surface. (Sólnes, et al. 2013)

There are eight volcanic zones in Iceland with five of them located at the divergent plate boundaries where the two plates are on the way away from each other. The three remaining are

so-called edge volcano zones located away from the divergent plate boundaries. These volcanic zones are visualised in Figure 1.
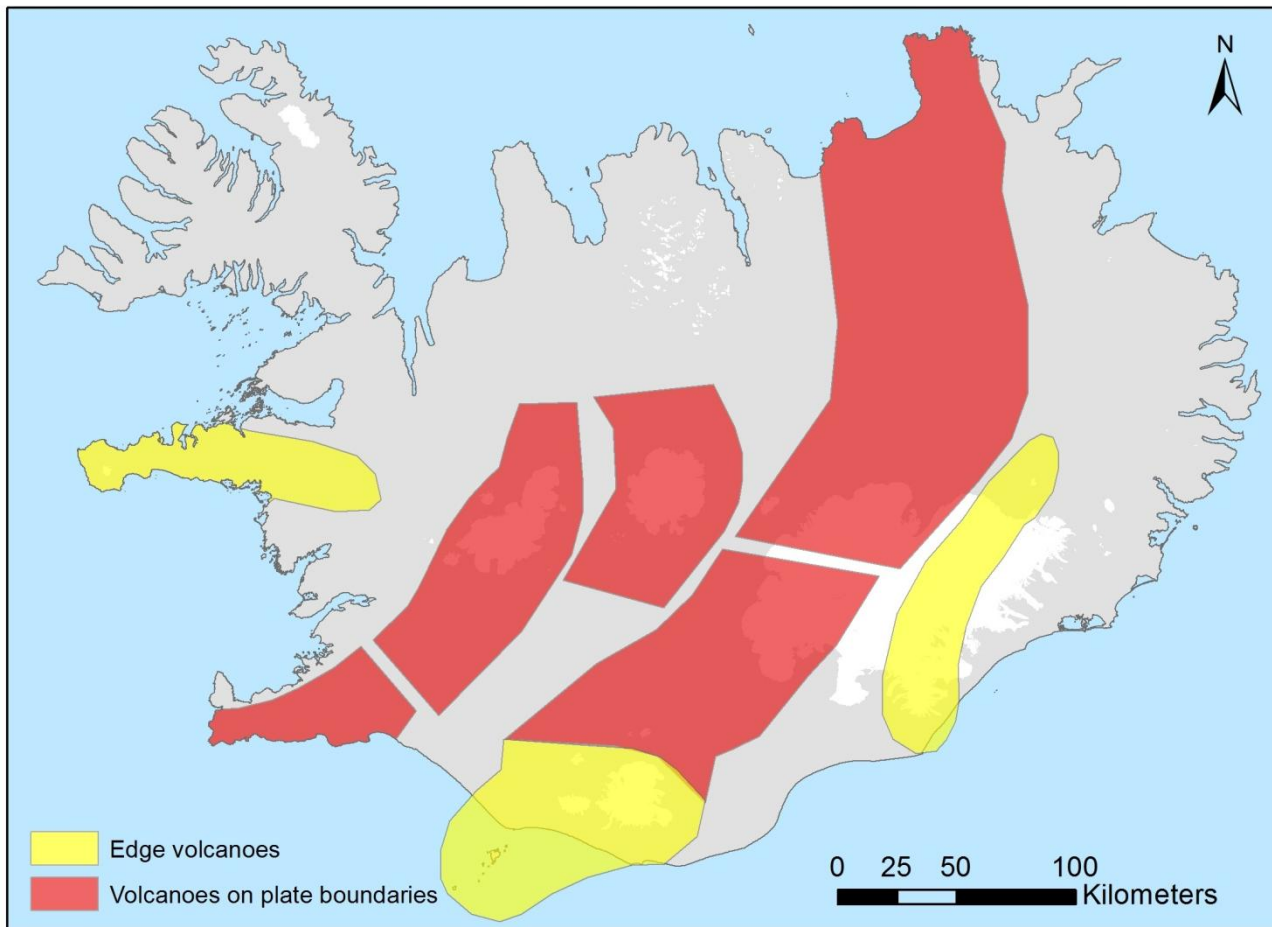
Figure 1 - Volcanic zones in Iceland. Made on background of (Sólnes, et al. 2013) © Landmælingar Íslands

It´s hard to define how many volcanoes are in Iceland as a definition of a volcano is very unclear and the volcanoes might even cross so magma from one reaches the earth's surface within another's volcano boundaries. Although there is estimated that there are over 30 main volcanoes in Iceland where there are more activities than in the surrounding areas. Out from the main volcanoes there are volcanic fissure swarms that can be op to 70 kilometres long. (Sólnes, et al. 2013)

2.1.2.1   Volcanoes in Suðurnes area

The Suðurnes region is located on the southwest coast of Iceland. Within that region there are located three volcanoes where of them are two that are interesting for threat to build areas in the area. These are Reykjanes volcano and Trölladyngja volcano as shown on the map in Figure 2. In

analyses made by the Department of Civil Protection it is estimated that volcanoes together with earthquakes are the only disasters that falls into the category tremendous danger and it should be analysed further. It is stated in the analyses that it is expected that an eruption occur every 700 – 1000 years. It is furthermore estimated that the main threat is on disturbance of transport, ash fall and lava flow. An eruption can have serious consequences. (Ríkislögreglustjórinn Almannavarnadeild (B) 2011)
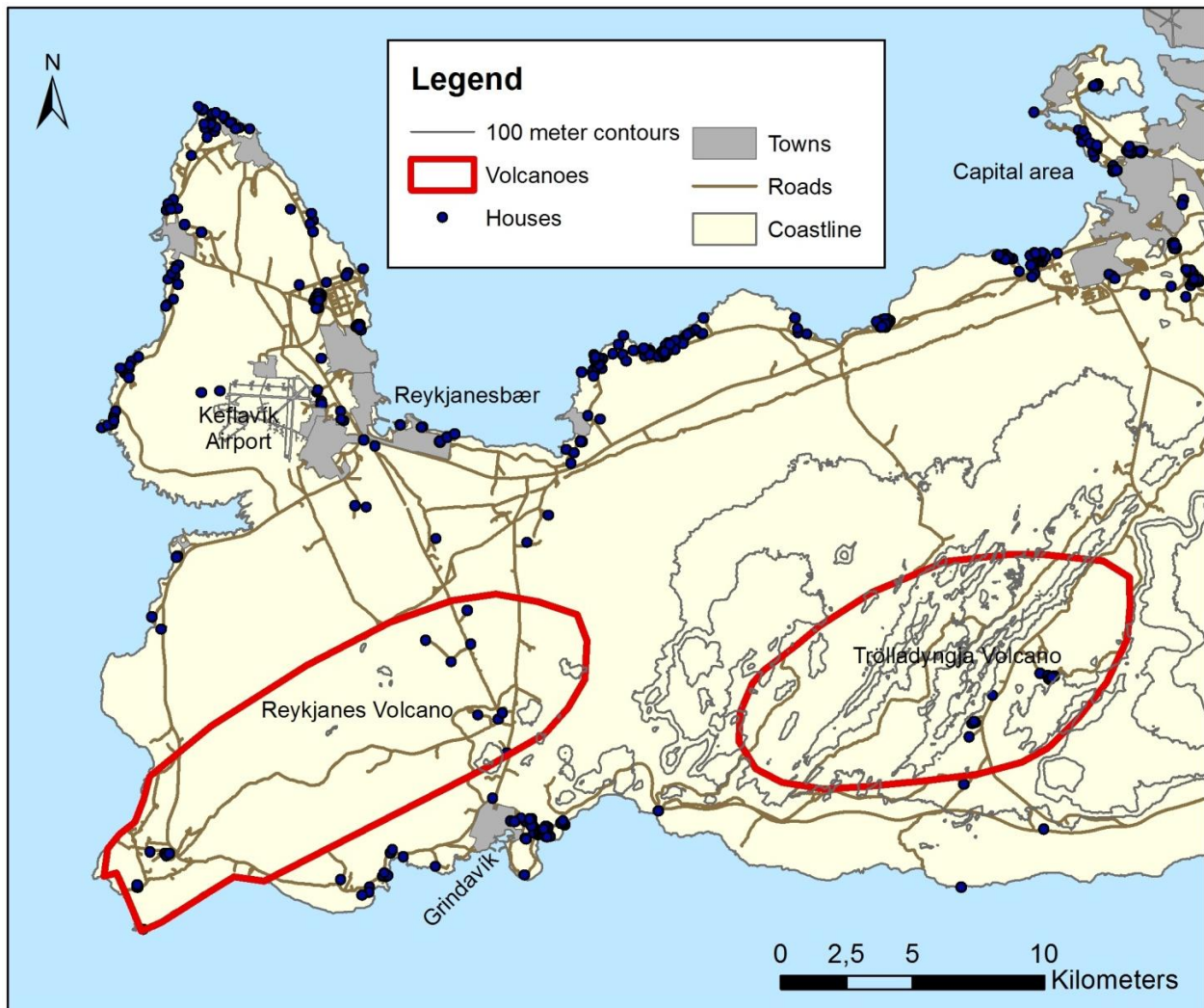
Figure 2 - Overview of the Suðurnes area ©Landmælingar Íslands ©Náttúrufræðistofnun Íslands

Reykjanes

The Reykjanes volcanic zone consists of around 50 eruptive vents from several volcanic and rifting episodes and 14 shield volcanoes, which are volcanoes that are made from a longstanding eruption from one-eruption vent. The last eruptions in this system are the Reykjanes fires that

occurred from 1211 – 1240. This eruption occurred on both land and sea from several cracks. The lava in this system is generally of the basaltic type tholeiit. (Guðmundsson 2007)

Trölladyngja

The Trölladyngja volcano system consists of around 40 – 50 eruption vents from several volcanic episodes and eruption and rifting zones, together with three shield volcanoes. The last eruption in the area occurred in 1050 – 1180. The lava in the area consists of the basaltic lava type tholeiit. There are examples that lava from eruption in this area has reached the outskirt of the Capital area. (Guðmundsson 2007)

The elevation of these volcanoes and the surrounding areas is shown in the elevation model in Figure 3 below.
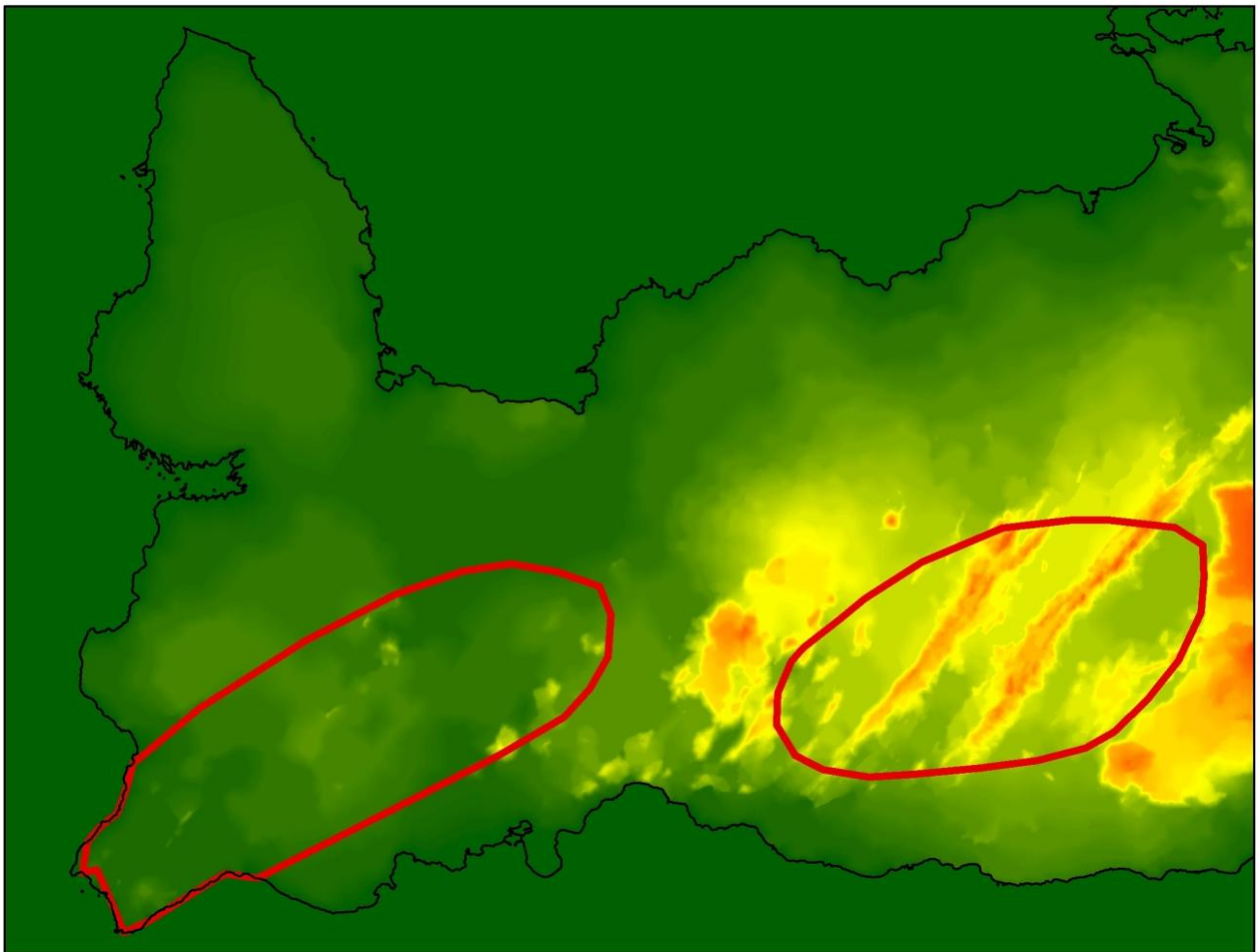
Figure 3 - Elevation model of Suðurnes region

2.1.2.2   The eruption in Heimaey1973

Heimaey is an island in the Vestmannaeyjar island class at southern Iceland as shown in Figure 4. The Vestmannaeyjar class is a volcano but until 1973, it was believed that the volcano on the island of Heimaey was inactive. In 1963, an eruption happened southwest of Heimaey that created the Island Surtsey. On 23 of January 1973 in the middle of the night, the inhabitants on the island woke up to a nightmare. There were started an eruption just east of the town where there at that time lived over 5000 people. The eruption groove very fast, and soon the crack were around 1600 meters long. This eruption came to surprise as people had seen no sign of what were going to happening although there had been measured few earthquakes but they were wrongly possession due to fact that they were only measured by two earthquake meters while three are needed to possession an earthquake. (Vestmanneyjabær n.d.)
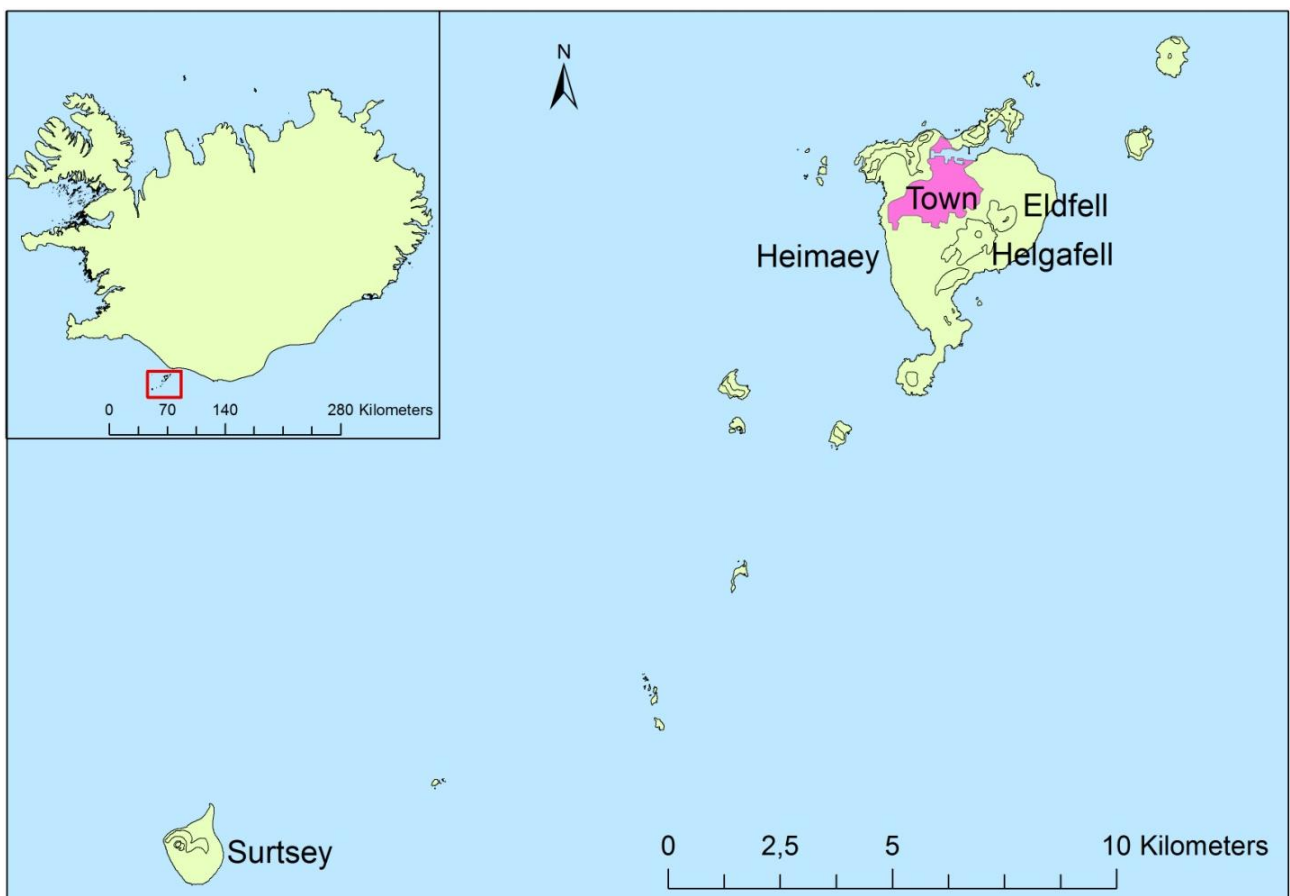
Figure 4 – Vestmannaeyjar ©Landmælingar Íslands

Immediately the island was evacuated, people run from house to house to wake people up, the police drove around with sirens on and the fire alarms were started. The most of the evacuation

were done with boats with the first one leaving only 35 minutes after the eruption started. It was a great luck for the inhabitants that the day before there had been a big storm so all the fishing vessels were in the islands harbour. People were also evacuated with airplanes but that were mainly elderly and sick people that were evacuated using the airport. In the morning most inhabitants had been evacuated and there were only around 200-300 people left that stayed there to do whatever that had to be done such as trying to save houses and peoples furniture's and cars. (Vestmanneyjabær n.d.)

The first months the lava from the eruption flooded towards the sea, which was good for the town. Nevertheless, in the end of February the lava started to flow towards the town and harbour. At first, a soil-based wall that were made kept the lava from flowing over the houses but on 18 of marts the wall failed and the lava started to flow over houses. To keep the lava from destroying the town and the harbour a system of water-cooling were established, see Figure 5. This water cooling system saved lots of houses and probably also the harbour, which was close to be filled with lava as Figure 6 and Figure 7 shows. In May and June, the eruption got smaller and on third of July the eruption was officially declared finished. (Vestmanneyjabær n.d.)

Figure 5 - Lava threatening the power plant on Heimaey, fire fighters getting ready to cool the lava © Sigurgeir Jonasson / Mats Wibe Lund

Figure 6 - Heimaey after the eruption, the new lava is the dark are in the bottom left of the photo ©Mats Wibe Lund

Soon a cleaning of the town were started where op to many meters thick layer of ash were cleared from the streets and houses. Before the eruption, there were around 1350 houses in the town, 417 ended under lava and other 400 were badly damaged. People started soon to move back and

in November, around 2000 people lived on the island. (Vestmanneyjabær n.d.) The changes the eruption made are visible on Figure 7.

Figure 7 - Vestmanneyjar Before the eruption to left and after the eruption to the right. ©Mats Wibe Lund

This eruption is the only example of lava destroying a town in Iceland and the first eruption to start so close to a town. This eruption proves that there is need to think about where an eruption happens and how to minimize the damage due to lava flow.

2.1.3   Monitoring of Volcanoes

This chapter describes the methods used to monitor volcanoes to analyse if they are going to erupt. There are mainly three methods used for monitoring of volcanoes; the first one is to monitor seismic activity, the second one is to use GPS surveys to monitor how the land moves and the last one is to use strain measurements to monitor pressure changes in the underground. In the following, these three methods are described.

2.1.3.1   *Seismic activity*

When magma is moving under the earth's surface, it causes earthquakes than can be measured using seismograph, which registers the earthquake. By comparing measurements from three or more seismographs, the exact location of that earthquake can be found in three dimensions. Another use of seismographs' is to measure the average vertical movement registered by the seismograph over a period of one minute on three different frequencies, this is called measure of turmoil. The measuring of earthquakes shows if the magma is just moving little bit or if it is on the

way towards the earth's surface. When an eruption is happening the first earthquakes are often located deep in the underground but slowly the earthquakes gets closer and closer to the surface until an eruption starts. The measurement of turmoil gives a great picture of the general activity in the area. (Sólnes, et al. 2013)

Earthquake measurements in Iceland are done in a system of digital seismographs called the SIL system. There are located seismographs on strategic places around the country that send data every 5 minutes to computer located in Reykjavik, which then automatically process the data. If something abnormal happens, a warning will be automatically sent immediately to the personal at the Icelandic Met Office. (Sólnes, et al. 2013)

2.1.3.2   GPS surveys

When a volcano is getting close to an eruption there is pressure build up within it, which sometimes causes the earth's surface to changes. By monitoring the location of a given point using GPS surveys it can be seen if this point is moving in an abnormal way. A normal movement of a point is that it is moving at a speed of about 2 centimetres to either east or west based on if they are on the Eurasian tectonic plate or the North American tectonic plate. A movement of a point that differs from that that can be described as abnormal and there is either building op tension on the tectonic plates that could cause earthquakes or there is magma close to the earth's surface. The best way to see if it is magma is by comparing the movements of two or more points on different locations around a volcano and if they are going upwards or away from each other there is probably magma streaming to an area close to the earth's surface. These movements are often seen many years before an eruption happens. (Sólnes, et al. 2013)

2.1.3.3   Strain measures

Be monitoring the strain in the underground there is possibility to see signs of eruptions. The strain measurement stations are cemented in holes in the underground and measure changes in pressure. This technique is still under development as they show changes during eruptions and earthquakes but the geologists have not cracked the code completely yet and therefore it is mainly used to collect information during eruptions and earthquakes although for the volcano Hekla these results have been used as described below. (Sólnes, et al. 2013)

2.1.3.4   *Monitoring in practise*

There are several examples of these methods making it able for the geologists to tell that an eruption is going to happen soon. In some cases, it is estimated that a volcano is getting ready for an eruption few years in advance and in other cases, it has been declared that an eruption is going to happen within short time. (Sólnes, et al. 2013)

Following the eruption in Hekla in 1980, the geologists found out that the eruption could have been seen 25 – 30 minutes before it started as the strain measurements showed quite big changes. There were also spotted earthquakes but they started only 20 minutes before the eruption and the seismic data took too long time to analyse. During an eruption in Hekla in 1991 turmoil were spotted on seismic meters but as the data had been analysed the eruption had already started and reported by people living close to the volcano before the geologists could do anything. These eruptions gave valuable data and in an eruption in Hekla in 2000 the geologists were able to send out a precise warning that an eruption were going to happen 15 minutes later and were right as around 20 minutes later the first eye witnesses reported an eruption. This is the first time in Iceland that a warning has been sent out before an eruption happens in Iceland. (Sólnes, et al. 2013)

There are also examples of volcanoes that are monitored extra well as they are showing signs that they might erupt in the near future. One of these volcanoes is Trölladyngja in the Suðurnes region. Another example is the eruption in Eyjafjallajökull in 2010 where signs of eruption had been spotted throughout many years. These signs lead to creation of evacuation plans, which came in good use when the eruption finally occurred. In that eruption, the precise earthquake locations lead to a precise location of the eruption from the start of the eruption although the area was not visible due to the weather conditions. (Sólnes, et al. 2013)

2.2   **Lava flow modelling**

As described before lava has a very complex structure that can be affected by many things. Therefore, lava flow is complex to model and requires good mathematical models to give the right result. There have been made many approaches to model lava flow and this chapter describes three different approaches. At the end, these methods are analysed to find the positive and

negative elements of them and if they could be used as inspiration for modelling lava flow in Iceland.

2.2.1   Assessment and Modelling of Lava Flow Hazard on Lanzarote (Canary Islands)

Felpeto, et al. (2001) created a lava flow model for Lanzarote, which is one of the Canary Islands, which evaluate the lava flow hazard on the island. As the physical properties of the lava are hard to determine, the parameters that should be used in a more complex models are hard to define. Therefore they *'used a probabilistic approach that does not describe the evolution of the lava flow, but gives the probability of each point to be invaded by lava: a probabilistic maximum slope model.'* (Felpeto, et al. 2001)

In this model, it is assumed that the topography of the area is the major factor on the path the lava flow will follow. There are several random paths calculated by using Monte Carlo algorithm to determine the probability of each cell being invaded by lava.

The topography is represented as a DEM model where the lava is located in cell (i =0). Then the probability of the lava flow entering one of eight neighbourhood's cells is calculated using the following expression:

$$P_i = \frac{\Delta h_i}{\sum_{j=1}^{8} \Delta h_j}, \quad i = 1, 2, \dots 8, \quad \text{(Felpeto, et al. 2001)}$$

Where Δh_i is the height difference between the cell with lava and each of its respective neighbours. As Lava is very thick, it flows through the landscape in thick layer, to take this into consideration, *'a corrective factor (h_c) is added to the height of the cell where the flow is currently located'* (Felpeto, et al. 2001). By adding this parameter, the height of the lava flow is simulated which makes it possible to pass small topographic barriers. If the height of the neighbourhood cell is higher than the correlated height of the cell, containing lava the lava cannot flow into that cell. If all neighbour cells are higher than the original one, the 16 cells surrounding them should be taken into calculation to avoid the flow stopping in a small sinkhole that in reality would be filed very fast so the lava would keep on going. Taken more cells into consideration combined with relatively big cell size would mean that the flow calculation becomes more realistic.

When the probability for all the neighbourhood cells has been calculated, the cell the lava will flow into is selected using a Monte Carlo algorithm. Then this calculation is repeated until the lava flow reach a max distance defined at the start that is used to stop the calculation when it reaches expected distance.

Then the probability of each cell being invaded is calculated by dividing the number of paths crossing a cell with the total number of paths and the probability of an eruption starting at the respective eruption site.

This calculation is done for all possible eruption centres, first with equal impedance of all eruption centres. Then by defining a main axis from where it is expected that it is higher possibility of an eruption to happen closest to this axis than away from it.

The DEM model used has a cell size of 25*25 meters, but in the first calculation, it was used with a cell size of 50*50 meters.

 (Felpeto, et al. 2001)

2.2.1.1   VORIS

The Spanish National Council for Scientific Research (CSIC) has developed a GIS system that can be used for volcanic hazard assessment. This program is Called VORIS (**VO**lcanic **R**isk **I**nformation **S**ystem), is currently in version 2.0.1, and requires *ArcGIS* to be able to run. (A. Felpeto 2009)

This system can calculate the risk of three different volcanic activities; Lava flow, ash fallout and pyroclastic density. (Felpeto, Marti and Ortiz 2007)

The part of the program that handles about lava flow uses the same model as Felpeto, et al. (2001). That model was described before and therefore it does not need to be described in more details.

In all, this program seems to be a good automated tool to calculate risks of an area being affected by an eruption, not only if it will be covered in lava but also Ash and pyroclastic density. (Felpeto, Marti and Ortiz 2007)

The tools simplicity is positive in terms of computational techniques as it minimizes the need of computer power to make the calculation that makes it easy to use, both during eruption and to calculate big areas prior to an eruption.

Another interesting thing about this program is that it has actually been used during one eruption in Iceland. This eruption is the eruption on Fimmvörðuháls in southern Iceland that started on 20. Mars 2010. The Icelandic Meteorological Office used the tool to simulate both the lava flowing from the eruption and the ash fallout. The results seem to be similar to what happened during the eruption. (Jensen 2010)

2.2.2　Probabilistic approach to modelling lava flow inundation: a lava flow hazard assessment for a nuclear facility in Armenia

This model developed by Connor, et al. (2012) handles about nuclear facility in Armenia that is located close to couple of volcanoes. This method focuses on site-specific calculation of lava flow. The main reason for this lava flow modelling is that it cannot be secured that there is enough time to shut down the power plant safely if an eruption occur that can send lava to the plant.

The developed methodology can be divided into two parts; the first on is Spatial density estimation that calculates distribution of possible eruption vents and the amount of lava that might flow from them based on analyses of previous eruptions. This is done by using known eruption vents location and amount of lava flowing from them by *calculating 'a two dimensional radically-symmetric Gaussian kernel for estimating spatial density'* (Connor, et al. 2012).

On basis of the results from the spatial density estimation, the lava flow is calculated using numerical simulation. The parameters used in the calculation are parameters that are easily available from previous eruption such as thickness, length area and volume. The main parameter is the volume of lava that is expected to flow from that specified eruption vent.

The lava flow is calculated from the source cell where 10.000 m^3 of lava is added at the start of the calculation. Then to distribute that amount of lava to the other cells max three neighbourhood cells are chosen as receiving cells and a predefined amount of lava is added to these cells and what is left is used in the further distribution. The distribution of lava to these cells can be summarized as following: The thickness of lava received by a neighbour is equal to the excess lava thickness an

active cell has to give away multiplied with the elevation difference between the active cell and the receiving cell. This is then divided by the total elevation difference between an active cell and all of its 8 neighbours. Then the receiving cells become active cells and distribute the lava further to their receiving cells using the same method. When the lava is distributed, a new iteration is made by adding another 10000 m3 of lava to the source cell. This is done until the predefined total value of lava is reached. Then the lava flows for the remaining eruption vents are calculated.

Totally 10.000 simulations were executed and 24,9 % of them entered the site of the power plant. These results showed that there was mainly one volcano that caused lava to flow to the site and from that they can learn when to shut the plant down under an eruption. In all this method to model lava flow is effective, especially if there are many known eruption in the neighbourhood that can be used to get the start volume and possible start ventures.

(Connor, et al. 2012)

2.2.3   Lava Flow Simulation With Cellular Automata: Applications for Civil Defence and Land Use Planning

The most active volcano in Europe is Mt. Etna in South Italy. In the surrounding of the volcano there are lot of towns and farms, and by looking at eruption history for the last four centuries the majority of eruption in the volcano affected these human properties in many of these towns and farms. As Mt. Etna is very active there has been made several approaches to model the lava flow from the volcano and for example in 2001 when the path of lava flow from an ongoing eruption was estimated, which was a great help for the local Civil Defence authorities. Although it was a great help more could have been done to save the town if this simulation had been done prior to the eruption instead of when it was going on. (W. Spataro, et al. 2011)

To try to improve this, a new program called SCIARA were invented. This program is based on Cellular Automata and is effective in demonstrating how the lava can flow. The main criteria's the program should fulfil are following: It should be calibrated and validated against other known eruptions to assess its reliability. The model efficiency should also considered due to the extent of the area an eruption can occur from which requires multiply simulations to be done. The

calculation of the lava flow is made according to many factors that are determined by analysing the three newest eruptions on the volcano. (W. Spataro, et al. 2011)

The process of calculation can be divided into two parts; the first one is the actual lava flow calculation from a central cell and into its neighbouring cells and the second, one is the temperature variation and solicitation of the lava.

To calculate the first step they use a Minimisation Algorithm of the Differences (MAD) combined with a Bingham like rheology that describes lava as fluid that is solid under low stress. One of the important factors used to calculate the lava flow is the temperature of the lava, which is the main factor determining how solid it is, and therefore when there have been added new lava to a cell its thickness and heat has to be calculated to be used during next iteration. This is done by using the heat from the lava already in the cell and the heat of the inflowing lava combined with factors that are important in the cooling of lava. (W. Spataro, et al. 2012)

In total, there are 13 parameters that were used in the calculation and they are all shown in Table 1 below.

Parameter	Meaning	Unit	Best value
w	Cell size	m	10
t	CA clock	s	120
T_{Sol}	Temperature of solidification	K	1143
T_{Vent}	Temperature of extrusion	K	1360
r_{Tsol}	Relaxation rate at the temperature of solidification	-	0.5
r_{Tvent}	Relaxation rate at the temperature of extrusion	-	0.95
hc_{Tsol}	Critical height at temperature of solidification	m	40
hc_{Tvent}	Critical height at temperature of extrusion	m	1.5
δ	Cooling parameter	-	2.8
p	Lava density	$Kg\ m^{-3}$	2600
σ	Stephan-Boltzmann constant	$J\ m^{-2}s^{-1}K^{-4}$	$5.68 * 10^{-8}$
c_v	Specific heat	$J\ Kg^{-1}K^{1}$	1150

Table 1 - parameters used by the SCARIA model with the values used to simulate the flow from eruption in 2006 (W. Spataro, et al. 2012)

To evaluate the hazard, a grid consisting of 4290 craters with 500-meter space in between them was defined. Then there were for each of these craters calculated six different lava flows based on

different effusion parameters. In total, this resulted in 25740 different simulations and the calculation took 10 days to be executed. Then the lava flow hazard for each cell was evaluated according to all of the simulations that can affect the respective cell.

There are more possibilities on how the results can be used. By adding it into a GIS system it is possible to trace back the flow and show for instance all the craters that can affect a town which could be useful during an eruption to decide if the town have to be evacuated or not. Furthermore, it is also possible to build a virtual barrier into the DEM model to see if a town could be saved by building an earth barrier or digging a channel.

2.2.4 Resume

All four represented methods are useful for modelling lava flow and will therefore be discussed below.

The example from Lancarote is a very simple model that is easy to use and do not need lot of adjustments to make it able to be implemented into a new area with a different volcano as it focuses on the slope as the main parameter of lava flow. The simplicity also affects the speed positively of the calculation, which is important as such a model can take very long time to run due to many possible eruption vents.

The Voris system that is build on the same method as the system for Lanzarote is available for free to everyone and can therefore be used to test a new system to see the similarities in the lava flow.

The system from Armenia is very effective in areas where there is a big knowledge of the volcanoes in the area. In the example for the nuclear plant, most known eruption sites had similar thickness length and other factors and therefore it is very accurate for a well-known area. This precision is though something that is not good for an area with only few known eruptions as this system is build up on amount of lava flowing from a volcano. Their method of defining eruption sites is interesting as it means that the eruption vents close to the volcano automatically is weighted higher than further away and as it requires fewer simulations than if every cell within a volcano was used as an eruption site.

The SCIARA system from Italy is a very detailed system based on many years experience and three known eruption and should be very accurate for the area around Mt Etna but to use it in other areas there is need of known eruption that can be used to define the input parameters to keep the simulation effective and accurate. The way the eruption sites are created by having 500 meters between them which seem to be a good distance as it covers the area quite well but at the same time there isn't too long distance between them.

Looking at the three presented methods all of them are able to fill the requirements of the Problem Statement (page 12) while only the first example from Lanzarote answer Research question 2 " How can lava flow be modelled in a simple way" as the two others are very complex.

Therefore the method used in this project is going to be build on the general theory of the example from Lanzarote that the topography has most effect on the lava flow. Although some good elements from the two other methods might be used such as using Cellular Automata to create the model and choosing expected eruption sites. The method of the project is described in Chapter 4, Method.

2.3   GIS

Now lava flow modelling theory has been described and now the GIS theory that is necessary to model lava flow will be described. GIS or Geographic Information Systems *'is concerned with the description, explanation, and prediction of patterns and processes at geographic scales'* (Longley, et al. 2011, xii). GIS is very important in the modern world as '*almost everything that happen, happens somewhere*' (Longley, et al. 2011, 4). Therefore, it can be very important to know where something happens to make the correct decision to solve the problem. In the following chapter, the theory of GIS will be described.

2.3.1   Representing geography

A complex element within GIS is how to represent the geography. The complexity of the geographic world is extreme as there is always possible to get more details the closer to the element in question you get. Therefore, the geographic information has to be generalized in such a way that it can be used in Geographic Information Systems. In general, generalization can be divided into two parts; the first one is how much data there is added to the system, for instance if

a small cliff on a beach should be used or not. The second one is how detailed the element should be described which could be the coastline that contains infinite amount of data.

To represent geographic data digitally there are two methods there are used in this project to represent the geographic phenomena's into a digital database. These methods are Raster and Vector based data models and will be described below.

2.3.1.1   Raster

Raster representation means that the space is divided into rectangular cells in an array. Then there is assigned an attribute to each cell that represents a geographic variation. (Longley, et al. 2011)

When representing Geographic data in Raster format the information about the variation within each cell is lost and the cell only contains the attribute that has the highest importance. There are couple of methods to assign an attribute to a cell. Creating a typical map there are two methods used, the first one is the largest share method that assign the attribute that is must off within the cell and the other is the central point method that select the attribute that is in the middle of the cell. Creating maps, the largest share method is in most cases preferred. There are also other methods to assign the attribute to a cell like average, max, min and count. These are used when doing analyses of for instance the soil where we have results in points in vector format but visualization might be better using raster. (Longley, et al. 2011)

2.3.1.2   Vector

Data represented in vector format is based on points that can be connected by lines. One point represent a single element that is on a map while points connected by line represent also a single element that is represented by a line like a road or a river, at last an area is represented by a polygon that is defined by series of points where a polyline has the same start and end point. (Longley, et al. 2011)

2.3.2   Spatial Analysis

Spatial analyses are the analyses that are done using spatial data. The spatial analyses are often the biggest and most challenging part of a GIS project although some researches show that most time is spent on preparation of data and analysing the results. Some of the analyses are simple but

often there is need to combine one or more methods. (Balstrøm, Jacobi and Bodum 2006) Below, the methods and tools needed to perform spatial analysis in the project are described.

2.3.2.1 Cellular Automata

Cellular Automata (CA) is a method used to automatically calculate phenomena using a cellular network, which in case of GIS analyses are raster layers. Each cell have a given status to start with, the simplest version is that a cell is either alive or dead. Then there is given a transition rule that is used to determine if a dead cell becomes alive or if a live cell becomes dead. This transition rule is based on a defined neighbourhood, which can have many different forms and sizes. Cellular Automata is done for all cells at the same time and then replied as many times as the user define where one iteration is normally equal to a given amount of time. Theoretically, Cellular Automata can be done on a piece of paper but a computer is much more effective to do such a calculation as it can do a high amount of calculation over a very short time period. (Shalizi 2012) Below in Figure 8 an example of Cellular Automata is shown where a dead cell becomes alive if there are three or more cells alive within its eight neighbourhood cells.
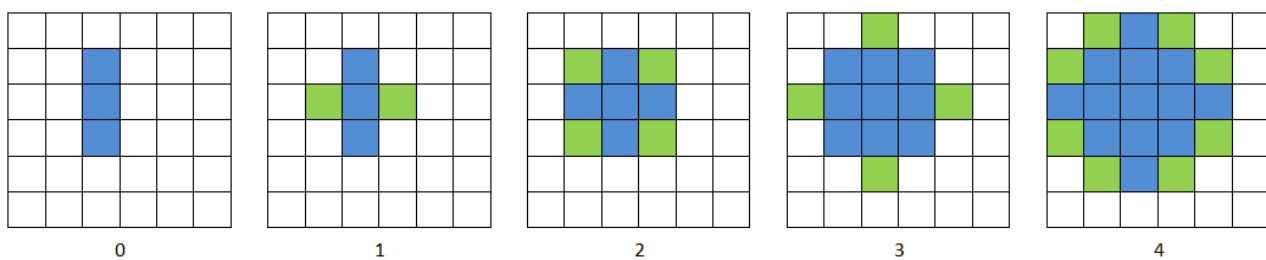
Figure 8 - Example of Cellular Automata, A cell becomes active if there are three active cells in the eight surrounding neighbourhood cells. Blue shows active cells at start if each iteration and green shows the cells that become active during that iteration.

2.3.2.2 Focal Statistics

Focal Statistics is a tool, based on a method with the same name, within *ArcGIS* and *ArcPy* that creates an output raster by calculating a value for each input cell based on the values of a specified neighbourhood surrounding the cell. The value assigned to the cell in the new raster layer is therefore a statistic of a defined neighbourhood of the original raster layer. There are six methods for defining the neighbourhood in this method which are listed below: (Esri (C) 2012)

- Annulus, which is a donut shaped neighbourhood created by defining inner and outer radius.

- Circle, which as the name says is circular neighbourhood defined by a specified radius

- Rectangle, which is a rectangular neighbourhood defined by width and height

- Wedge, which is a pie-shaped neighbourhood defined by starting angle, ending angle and radius

- Irregular, which is an irregular neighbourhood defined by a kernel file.

- Weight, similar to Irregular but allows adding weight to the input layers.

In the first four cases, the distance can be defined by both numbers of cells and in map units. Ten statistics types can be used to calculate the value of the output cell. These methods are Majority, Maximum, Mean, Median, Minimum, Minority, Range, STD, Sum and Variety. In this actual project, the Maximum statistic type, which assigns the highest value of the neighbourhood to the output cell, is used. (Esri (C) 2012)

The last option of the tool is how to treat NoData values, which are values, that means the cell is empty. If there is NoData Value within the neighbourhood it can either be ignored in the calculation or the output value is NoData depending on how this parameter is set. (Esri (C) 2012)

When the tool is executed, an algorithm calculates for each cell the specified statistic within the specified neighbourhood. Figure 9 below shows an example of a calculation for a rectangular neighbourhood of 3x3 cells, with the Maximum value statistics that finds the highest value within a neighbourhood, and with NoData values ignored.

1	0	3	5
	1	2	4
4	7	0	3
3	3	2	2

InRas

=

1	3	5	5
7	7	7	5
7	7	7	4
7	7	7	3

OutRas

Figure 9 - Focal statistics using Maximum value of a 3X3 neighbourhood

2.3.2.3   Conversion between Raster and Vector

There is often need to convert data from raster format to vector format and the other way around. In this project, there are both needs to convert points in vector format to raster and to convert raster layer to points.

To convert raster layers to points the *Raster To Point* conversion tool in *ArcGIS* is able to do that. That tool makes a point for each cell in the raster layer, which gets the value of the cell.

To convert points in vector format into raster the *Feature To Raster* conversion tool from *ArcGIS* does what is needed. The *Feature To Raster* conversion tool can convert any feature class supported by *ArcGIS* containing polygons, lines or lines into a raster dataset. When executing the tool a field in the attribute table of the feature class is selected as the value that the exact cell should get in the new raster dataset. (Esri (B) 2012)

2.3.2.4 Split Layers

To split layers according to attribute there is no available tool from *ArcGIS* to do that. Therefore instead there is used a tool developed by *Dan Patterson* from Dept *of Geography and Environmental Studies* at *Carleton University* in Canada. He has developed a script called *Split layer by attribute* and made it available for everybody to use through Esri's *Geoprocessing Model and Script Tool Gallery*. This Tool uses a unique ID field in the attribute table of an input feature class and creates separate shapefiles for every value of the ID field. The program is distributed as a Python script and a corresponding *ArcGIS* Toolbox. (Patterson 2011)

2.3.2.5 Condition

An important tool to execute the Cellular Automata is the Con tool that '*performs a conditional if/else evaluation on each of the input cells of an input raster*' (Esri (A) 2012). An example of a condition could be that if a value of an input cell is higher than or equal to two then the value of that cell in the output layer is 40 else the value of that cell in the output layer is 30. That condition would be written in the following way: OutRas = Con(InRas >= 2, 40, 30). In Figure 10 below this condition is visualized.
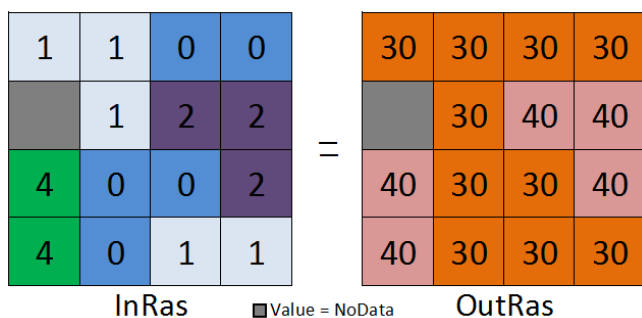
Figure 10 - Example of a Condition Calculation (Esri (A) 2012)

2.3.2.6 Slope

To calculate the slope of an area a calculation is done on each cell in a DEM using box of 3x3 cells that the slop is calculated for and then the slop value and for each cell in degrees or percents is added into a new layer. (Balstrøm, Jacobi and Bodum 2006) In this project, the slope tool from *ArcGIS* is used to calculate the slope of the area.

2.3.2.7 Clip

A clip analyses is a method that is used to cut a piece of a feature class according to another feature class. The clip analyses can be executed on both point's lines and polygons. To clip an input polygon the clip feature class has to be a polygon. To clip input points the clip feature class have to be point's lines or polygons. To clip input lines the clip feature class have to consist of lines or polygons. Figure 11 below illustrates a clip analysis of a map. (Balstrøm, Jacobi and Bodum 2006)
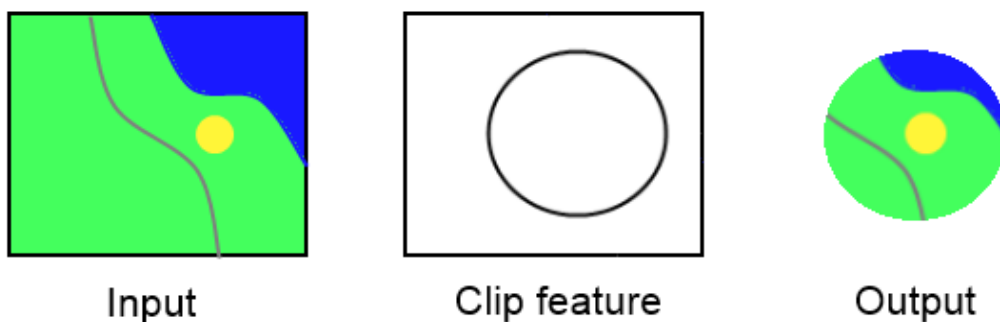
Figure 11 - Illustration of clip analysis

2.3.3 GIS modelling

To make a GIS model using the tools from *ArcGIS* there are two effective possibilities: The first one is to use ModelBuilder, which is a graphical interface to *ArcGIS* and makes it simple to combine geoprocessing tools into a model that then can be executed as one tool. The second one is an extension to Python called *ArcPy*, which makes it able to use the tools from *ArcGIS* in Python scripting. (Jennings 2011)

For this project, Python is chosen and therefore ModelBuilder will not be described furthermore.

For making GIS models, Python has quickly become the programming language that GIS professionals and students need and want to become skilled at working with. The possibility to use the geoprocessing tools from *ArcGIS* gives Python a big advantage for developing a GIS program. In next chapter, Python programming will be described. (Jennings 2011)

2.4   Programming in python

The Python Software Foundation describes the Python programming language as following:

'Python is a programming language that lets you work more quickly and integrate your systems more effectively. You can learn to use Python and see almost immediate gains in productivity and lower maintenance costs.' (Python Software Foundation (B) n.d.)

The way Python is build using well-designed syntax and dynamic typing combined with its interpreted character makes it easy to use and learn even for beginners in programming. Both the python interpreter and a big standard library are freely available for all key operating system platforms. Furthermore, there is possibility for extern libraries to be added to it. (Python Software Fundation (C) n.d.)

The history of Python can be traced back to 1989 when the author were working with operating systems and needed a better method for the system administration than using the existing programming languages. In 1991 the languages first version were made official and has been updated every 6 – 18 months since then. Currently there are two general versions of stable releases, version 2.x and 3.x. The reason for two general versions of releases is that version 3.x is so different from 2.x that not all third party software is available for Python 3.x but only Python 2.x. (Python Software fundation (A) n.d.) This project uses version 2.7 of python as that is the version that is supported by ArcPy.

2.4.1   Important elements of python used in the project

Below the important elements of python used in this project are described.

Datetime

Datetime is a module in Python that makes it able to use and manipulate date and time in Python. There are several different classes within the module where the class used in this project is the

datetime class which is can reply both date and time with the following attributes: hour, minute, second, microsecond and tzinfo. There are several different constructors within this moduleclass but the only important for this project is the .now constructor, which replies the variables for the current time and date. These variables can then be used in either the following process or where for instance the date and time is printed to the screen or a log file. (Rossum and Drake 2013)

Os

The os module within Python is a portable way of using functions dependant on the operative system. I this project the module am used to create a new folder on the hard drive using the makedirs under module. (Rossum and Drake 2013)

Print

The Print function in python makes it able to print outputs, variables and other information to the screen. (Rossum and Drake 2013)

Calculator

Python can be used as calculator with both numbers and strings. To do a calculation in a script the formula or numbers are written just as they would be written on a normal calculator (Rossum and Drake 2013)

Compound statements

Compound statements are statements that contain other statements and controls or execute these. In the project, there are two types of clauses used, *while* and *for*, which both apply conventional control flow constructs.

The *while* statement is used to repeat an execution as long as the while statement is true. This is done by calculating if the expression is true and if so then the connected expression is executed. If the result of the *while* statement is false then either an else statement is executed or the loop is terminated.

The *for* statement iterates over specified elements of a sequence that can be iterated through such as string, tuple or list. The *for* expression is evaluated once and results in a new iterator

containing the necessary items. Then the following statement is executed for every item in the iterator. (Rossum and Drake 2013)

2.4.2 ArcPy

As said before, *ArcPy* is an extension to Python from Esri, which makes it available to use the tools from *ArcGIS* in Python. The access to the tools together with additional functions, modules and classes makes it able to create complex workflows or programs easily in Python. Before a tool from *ArcPy* is used in Python, the *ArcPy* module has to be imported into the python script. (Jennings 2011)

2.5 Agile Development

Agile software development is a group of software development methods based on incremental and iterative development, where requirements and solutions evolve through teamwork between self-organizing, multi-functional teams. The Agile Alliance has described the values of Agile as following:

- *'Individuals and interactions over processes and tools*
- *Working software over comprehensive documentation*
- *Costumer collaboration over contract negotiation*
- *Responding to change over following a plan'* (Agile Alliance (B) n.d.)

In Agile development the highest priority is to have valuable software delivered early and continuous to keep the customers satisfied, as the best measurement of process is working software. There have to be constant conversations within the development team as face-to-face conversation is the most efficient way to convey information. (Agile Alliance (A) n.d.)

The development can be build up as a circle with five steps that are repeated until the final product is finished and approved by the costumer. The circle starts at design where the product is designed, and then the software is build followed by configuration ending with test and release of the program. This circle is then repeated multiply times until the final version of the program are released. This circle is illustrated in Figure 12. (New Horizons 2012)
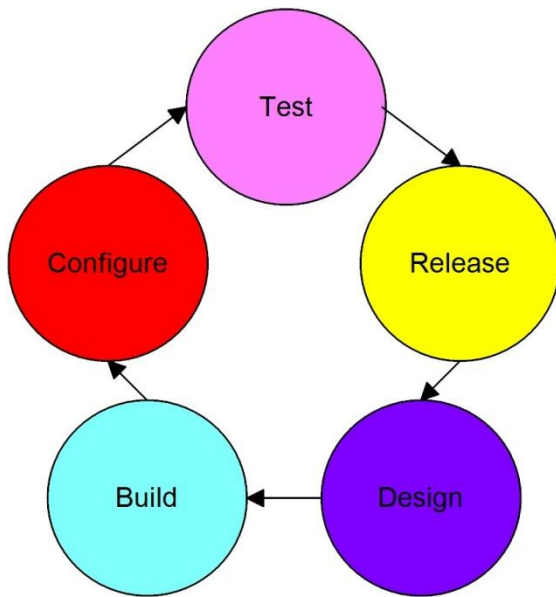
Figure 12 - Agile Development Process (New Horizons 2012)

The main advantages of Agile development are that the client is involved actively and early in the process which secure that there are less defects and fewer surprises in the final product as the client is able to make changes in requirements during the development process. There is also always a product on ready release stage, which makes the process more transparent for the costumer.

Looking at the biggest disadvantages or threats to software development using Agile is that the transparency and frequent feedback actually can be harmful to the project as the customer requirements are not clear, too many changes can delay the project, and the cost could become high. The frequent delivery of product can also be harmful as the developers are pressed to have always the program ready and often the costumer does not have enough time for testing the program. Finally, there is not much documentation related to the development, which can cause problems on later stages and makes it hard for other developers to put hands on the project.

From it can be concluded that the Agile method is a good method to use for software development although there has to be kept an extra eye on things like the economy and documentation. The Agile method is very good for software development where the requirements are not always clear while for project where the requirements are clear there might be an idea to think about other development methods.

3   Method

This chapter describes the method used in this project to model lava flow.

In chapter 1.1 Problem statement the following problem statement were formulated.

How is it possible calculating the risk of an area being covered in lava during a volcanic eruption, using GIS?

Throughout chapter 2.2 Lava flow modelling, three different methods are described to solve this problem statement. These methods are using different solutions to come to a usable result. Therefore, to see what can be used in this project it is necessary to look into the four research questions:

1.   Is it possible to model lava flow using GIS?

This research question is the most basic and has already been answered through these three described examples from before, which show that it is possible to model lava flow although it is complicated.

2.   How can lava flow be modelled in a simple way?

There is only one of these methods that can be considered as simple and that is the VORIS system. The two other are very complicated and require detailed data that might need to be collected throughout many years and multiply eruptions. Although the Mt Etna example is complicated, the idea of using Cellular Automata could be used with much simpler calculation that is similar to the method from the VORIS system.

3.   How can it be secured that all possible volcanoes are taken into consideration?

None of the presented examples presents a solution to this problem. Therefore, the best solution is to find the theoretic maximum distance the lava will flow and then use all the volcanoes that are within this distance of the area under consideration.

4. How can lava flow modelling be used in spatial planning?

The lava flow can be used in spatial planning by making a layer that counts how many of different lava flows can reach a given cell in a raster layer. From that, it can be evaluated if an area is suitable for building, eventually in comparison with other layers in for example a Multi criteria Analysis. As the files made during the calculation are stored, it is also possible for a GIS specialist working for the municipality or a company to analyse the layers in any way he wants to do.

3.1 Lava flow modelling

On background of that that the Lava flow modelling program can be developed. The program can be divided into three parts:

1. Lava flow modelling
2. Data preparation
3. Analysing results

Although the program is developed in three steps this is not visible in the program as the program starts by calculating the data preparation, then calculates the lava flow to end by analysing the results.

3.1.1 Lava flow modelling

The first and main part is the lava flow modelling itself. As lava can have different lava thickness, the calculation has to be done according to an estimated thickness. Therefore, this program focuses on basalt, which is not very thick and floats very easily. Basalt is also the type that can make biggest damages long distance from a volcano while thicker lava only distributes close to the volcano and the respective eruption vent and in such cases, there is more important to avoid building close to the volcano than avoiding possible lava. To model lava flow the Cellular Automata method is used. To do a Cellular Automata the first step is to analyse the neighbourhood of each cell and assign the maximum value of a cell containing lava in the neighbourhood to it. This is called Focal statistics and is done by using a tool from *ArcPy* with the same name. The focal statistics tool has to be executed twice for each iteration; once for the four closest cells and once for the eight closest cells. Then the second step which is the actual Cellular Automata process

where a condition is made to compare the result from step 1 to the Digital Elevation Model (DEM). The condition in this actual program is based on the five following variables:

- The elevation of the cell (DEM)
- The maximum elevation plus lava thickness in the neighbouring cell (Focal1 and Focal2)
- The elevation of the cell plus lava (LavaDEM)
- Maximum lava thickness (X)
- Lava thickness lowering factor on a flat area (Y)

The lava thickness lowering factor is calculated for every cell on basis of defined lowering factor for flat area, the slope and maximum lava thickness according to the following formula where Y_1 represents the lava thickness lowering factor for a flat area. The value of the lowering factor is calculated using fuzzy logic, which means that the value is assigned precisely according to the slope. There are defined upper and lower boundaries for the calculation, which are 75 for the upper and 5 for the lower. The used formula is as following:

$$Low = con(slope \leq 5, Y, \frac{(slope - 5)}{75 - 5} * (X - Y) + Y$$

All of these layers are used both in the conditions and to calculate the output value that then is written to the output layer which is the LavaDEM layer.

As the cells are rectangular, the distance between cells is not the same if going from cells that share a border and cells that only share a corner. Therefore, that has to be taken into calculation.

Here below the used Condition statement is shown, first as it is written in the condition tool from *ArcPy* in Python, then in diagram in Figure 13 - A diagram visualising the condition for calculating if lava enters a cell. To left the inputs are listed, the conditions are in the white boxes and the outputs in the green ellipsoids.and at last in text format.

$$Con((LavaDEM > Focal1 - Low * 1.414 \; Or \; LavaDEM > Focal2 - low) \& LavaDEM$$
$$> 0, LavaDEM, Con(Focal1 - Low * 1.414 > Focal2 - low,$$
$$Con(DEM + Low * 1.41 \geq Focal1, 0, Con(Focal1 - DEM$$
$$\geq X + Low * 1.414, DEM + X, Focal1 - Low * 1.414), Con(DEM + Low$$
$$\geq Focal2, 0, Con(Focal2 - DEM \geq X + Low, DEM + X, Focal2 - Low)))$$
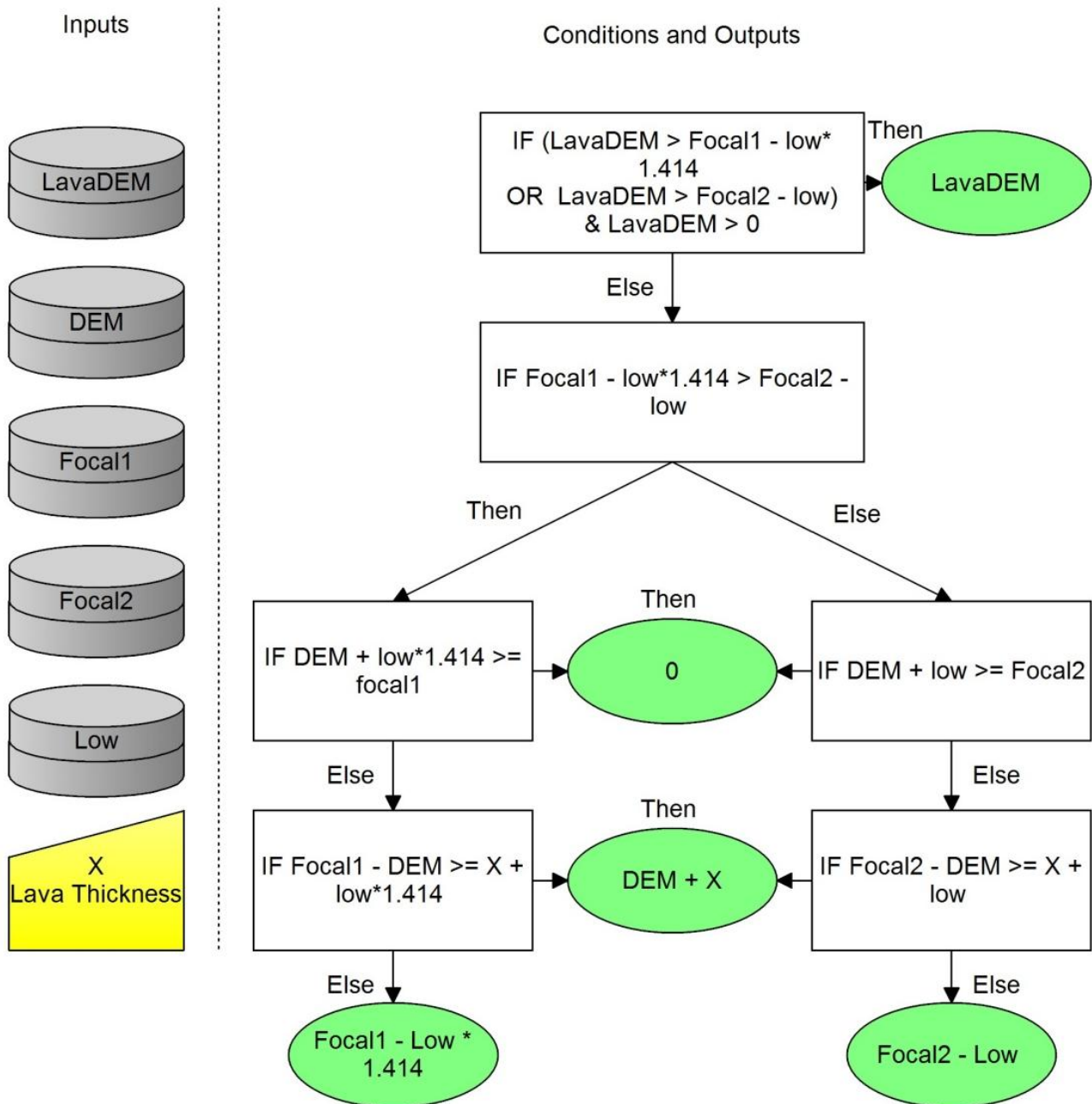
Figure 13 - A diagram visualising the condition for calculating if lava enters a cell. To left the inputs are listed, the conditions are in the white boxes and the outputs in the green ellipsoids.

The first condition determines if there is lava in the cell and if so then it analyse if there can be added more lava to it than there is now. If there is lava in the cell and there cannot be added more lava to the cell then the output value is the same as before else there is added a new condition. If the first condition is false then Condition number two is used. There it is investigated if the lava is flowing from a cell that share side with that cell or if it only shares a corner. This is done because the distance is different dependant of which cell the lava is flowing from as shown in Figure 6.

There have been done two calculations of focal statistics at this time; Focal1 that calculates using the cell being calculated and it eight surrounding cells and Focal2 that only uses the four cells that share side with the cell being calculated. This has to be done as the lowering factor is calculated according to distance of 20 meters and has to be multiplied with 1.414 for the cells that only share corner with the centre cell, these cells marked with green in Figure 14. Therefore we know that if Focal1 minus the lowering factor multiplied with 1.414

is bigger than Focal 2 minus the lowering factor then the cell the lava has biggest change of flowing from is one of the green cells in Figure 14 and if not, the cell the lava flows from is one of the four closest cells marked with pink in Figure 14.

As the output from Condition two is two different conditions the process split here according to from where the lava is flowing. In basic the two new conditions, 3a and 3b do the same thing the only difference is that in 3a, the condition is DEM plus the lowering factor multiplied with 1.414 is bigger than
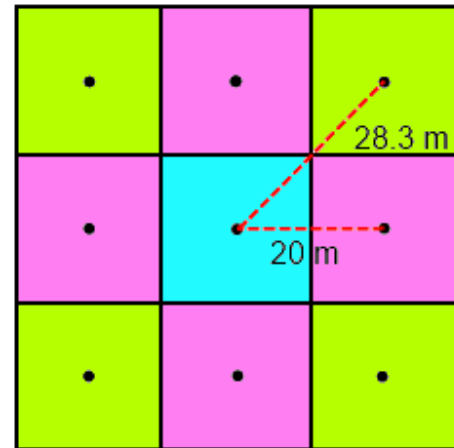
Figure 14 - blue cell is the cell being calculated, green are them that uses Focal1 and pink are them that uses Focal2

Focal1, and in 3b the condition is Dem plus the lowering factor is bigger than Focal2. If these conditions are true then the output is zero, as there cannot flow lava into the cell. If the conditions are false then conditions 4a and 4b are used to determine how much lava flow into a cell.

Condition 4a is for lava flowing from cells that only share a centre with the middle cell. The conditions is that if Focal1 – DEM is bigger than max lava thickness plus the lowering factor multiplied with 1.414 then the output is DEM plus max lava thickness else the output is Focal1 – the lowering factor multiplied with 1.414.

Condition 4b is similar to 4a but calculates the lava flow from cells that share side with the centre cell. The condition here is that if Focal2 – DEM is bigger than the max lava thickness plus the lowering factor then the output is Dem plus max lava thickness else the output is Focal2 minus the lowering factor.

This condition is then replied together with the Focal statistics tool using a while statement until a predefined number of iterations is reached.

The lava flow modelling part of the program is the part that has been modified and developed most from version 1 of the program to the final version described in this chapter. In first version the lowering factor were the same for all cells that resulted in lava flowing sideways on a steep hill where it only should flow downwards. This was fixed by calculating the lava flow according to the slope of each cell. To calculate the lowering factor for each cell then caused another problem as lava could flow on quite flat area towards a step downward facing hill and stop there. That was caused, as the slope of the receiving cell was quite high while the slope between giving cell and receiving cell were very low. This makes the lava flow stops as the lowering factor is calculated from the receiving cell. This was solved by fine-tuning the upper boundary of the lowering factor so it could treat such cases.

As the Lava flow, calculation requires input raster layers that represent one eruption vents each layer there need to be done some preparation of data. Furthermore, every input layer has to be build op in a way that at start the cell representing eruption vents contains the elevation of it plus the lava thickness in it. On the other hand all other cells contain the value zero and then as the lava flow is calculated the cells that receive lava gets the calculated value and are therefore in next iteration taken into consideration as an active cell. Next chapter describe how the data should be prepared.

3.1.2 Data preparation

The input data representing volcanoes is in a polygon format and needs to be converted into multiple raster layers representing one eruption vents each. There are few possibilities to make these eruption vents:

The first one is to say that every cell within the polygons is an eruption vent. This method gives the best possible result but at a very high cost in term of time as if a volcano is 1x1 km in size with a cell size of 20 meters the number of cells taken into calculation is 2500. The second one is to randomly distribute points within the polygon with a given number of points for each square kilometre. This could reduce number of eruption vents calculated but it could also

result in big areas without eruption vents within a volcano as shown in Figure 15 below. The third method is to equally create points with a certain distance in between them. This method is quite good as the number of eruption vents is reduced and the representation of the possible eruption vents is still usable when the distance is set properly.

In Figure 15 below the points from the three methods are illustrated. The number of points developed using the Random points method is the same as creating points with 200 meters in-between them to make compares of method 2 and 3 easier.
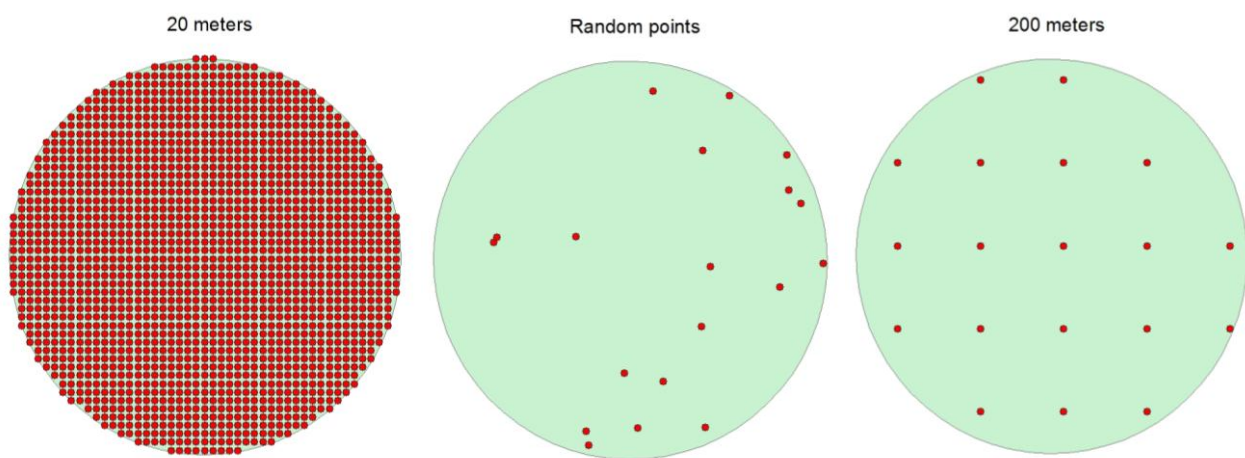
Figure 15 - The three methods to develop eruption vents, the circle represent a volcano

As Figure 15 shows, method one where all cells within a defined volcano are used to represent eruption vents is the most detailed but it could result in big performance issues. The method two with using random points leaves significant amount of areas without eruption vents, which could cause big errors in the calculation. Method three which distributes points over the area with a chosen distance in-between them is equally distributed but have some minor areas close to the edges not covered but they are acceptable, especially if the distance is set little bit smaller than needed.

In the program going to be developed, method three is used as evaluation of the methods shows that it gives the best compromise between time and quality. To develop the eruption vents at first a raster layer is made with a cell size that is the same as the decided distance between the eruption vents. Then this raster layer is converted into a point layer where there is made a point representing the middle of each cell. This point layer could also contain points that are outside the

polygon representing volcanoes and therefore the layer has to be cut according to the polygon. As there need to be made separate raster layer for each eruption vent the next step is to split the points op into separate files containing one point each file. After the points representing eruption vents have been divided the next step is to convert them into raster layer where the cell that contain the point representing eruption vents gets the value of the elevation of it plus the value representing lava thickness while the rest of them gets the value 0. These raster layers are then going to be used to model lava flow as described before using Cellular Automata

There is also use for a Digital Elevation Model (DEM) in the calculation. The program uses a DEM in a raster format and if the used DEM is in other format it has to be converted to raster. The DEM used in this project is in raster format and will be described in chapter 4 Data.

In the lava flow modelling part of the program there is also need for information about the lowering factor. The lowering factor is calculated using a slope model developed from a DEM. The lowering factor is then stored in a new raster layer.

3.1.3   Analysing results

The analysing of results part handles about taking care of the raster layers outputted for each of the eruption vents. To analyse the results there is made a layer that count how many different eruption vents can cause lava to flow into a given cell. To do so all the layers have to be reclassified in a way that if there is lava in a cell it gets the value 1 otherwise it gets the value 0. Then by using map algebra to sum all of the layers together there is count of how many eruption vents affect a given cell. By comparing this number of each cell with the total number of eruption vents, the probability of the cell being covered in lava can be calculated. As in this case, there is undefined number of raster layers there have to be done some loop that sums the layers one by one until all layers have been summed.

The output layer from that calculation is in raster format and can therefore be used in for instance a multicriteria analysis combined with other layers important for spatial planning.

3.2   **Development method**

The program is developed according to the Agile development method that is described in chapter 2.5 Agile Development. The program development phase is divided into five main steps that then can then be divided into more steps. The five main steps are:

1. Lava flow modelling
2. Data preparation
3. Analysing results
4. Combining step 1-3 in one program
5. improvements

Where step 1 – 3 are different parts of the program described before while step 4 just handles about combining the first three steps into one program and then step 5 is to improve the program.

If we look how this fits into the Agile development method, step one of the program is also the first development circle of the program. Then actually next circle is steps 2 and 3 as they are developed at same time although they are not connected directly. Then in circle 3, the different parts of the script are combined. When the third circle is finished, there is time to make further development and improve the program, which then is fourth development circle and so on.

4 Data

To be able to perform the analysis described in Chapter 0

Method there is mainly to kind of data needed to do lava flow analyses, that is a Digital Elevation Model (DEM) and polygons representing volcanoes. Furthermore, there is need for data over towns, buildings, infrastructure together with other topographic data to visualize and analyse the results. In this chapter, the data available and the Spatial Data Infrastructure in Iceland will be described.

4.1 Spatial Data Infrastructure in Iceland

The National Survey of Iceland (LMÍ) is the responsible authority for Spatial Data Infrastructure (SDI) in Iceland. LMÍ has a leading role in cooperation with other to secure access to geographic data of good quality and to promote the use of it, especially according to environmental matters. SDI is administrated according to the Inspire directive, which is being implemented. (Landmælingar Íslands (B) 2012)

LMI belongs to the Environmental Ministry and works according to law about surveying and mapping and law about spatial data infrastructure. The main things LMI works with is collection of spatial data, mapping, maintenance of the reference systems used in Iceland and administration of SDI in Iceland according to the Inspire directive. (Landmælingar Íslands (B) 2012)

4.1.1 Reference systems

In 1993 a new reference net for Iceland were surveyed using GPS technology on 120 points distributed around Iceland with an average of 40 kilometres in-between them. This reference net that got the name ISNET93 replaced an older reference net surveyed with triangular network in 1955 called Hjörsey55. In 1991 the process towards the new reference were started due to bad stand of the old Hjörsey55 reference as the distance between surveyed points were too long and in an active country like Iceland the landscape is in constant reshape and earthquakes and volcanic eruptions can cause changes that can results in major errors on the reference network. The official coordinates of the ISN93 net is in geocentric coordinates in system ITRF93.6 and geographic coordinates according to the GRS80 ellipsoid. Together with the reference net there were also published a Lambert's conformal conical projection with a central meridian at 19°W and 65°N,

standard parallels at 65°45′ and 64°15´ with false easting and northing at 500.000. This Lambert projection is not official but has become a standard in Iceland from that time. (Valsson, et al. 2007)

As Iceland is a very active country in term of geology, the reference network has to be resurveyed approximately every 10 years. The most of the changes is due to that Iceland is located at the border between the Eurasian and North American tectonic plates which results in the country slowly being towed apart. At the northwest and east coast this changes are quite regular which make it simple simple to calculate the changes but in areas with big geological activity these changes are very irregular and therefore regular surveys are needed. (Valsson, et al. 2007)

Therefore, in 2004 a new reference network was surveyed based on 154 points. The geocentric coordinates of the system is calculated according to the IGb2004.6 system. There was also calculated Lambert projection as in ISN93 but with different false Easting and Northing with the values of 700000E, 300000N at the centre. The new values of false easting and northing is made for two things; the first one is to avoid interference with the ISN93 coordinates and the second is that in ISN93 there were complains that it were possible to switch Northing and Easting coordinates very easily as they had almost the same numbers. (Valsson, et al. 2007)

4.2   Data from National Survey of Iceland

Since January 2013, all data from The National Survey of Iceland (LMI) are free to use. This includes the two vector based datasets IS50V and IS500. Other data that are also available for free are Landsat satellite photos with a pixel size of 30 meters, old topographic maps and other materials important for surveying. In the following, the IS 50V dataset will be described.

4.2.1   IS50V

The IS50V database is a digital geographic database from the National Survey of Iceland developed to be used in the scale 1:50000. This database is free to use and consists of following eight categories. (Landmælingar Íslands (A) 2013)

Elevation

The elevation data consists of elevation contours, elevation points and a digital elevation model. The contours are made with 20 meters interval although in some places there are 10 meters

contours. The contours are made on basis of data from 12 different actors and productions methods. Originally, the contours come from old map sheets printing films but they have slowly been exchanged with newer data collected using aerial photographs, satellite photos and Laser scanning. There has also been added data collected due to construction works of big power plants. The Digital Elevation Model (DEM) consists of cells with the size of 20x20 meters and is developed on background of the contours. (Landmælingar Íslands (A) 2013) The fact that the DEM is made of the contours makes the model quite good in step areas, but there is danger for lack of details in flat areas as there can be very long distance between contours.

Facilities

The facilities layer is made of four different layers: The first one is a polygon layer that shows the boundaries of towns and contains some information about the town. The next layer is a line that represents all power lines. Then at last there are two point layers, one that contains all important buildings outside towns and another that contains information about communication towers. (Landmælingar Íslands (A) 2013)

Boundaries

The boundaries layer contains information about administrative and political boundaries such as municipalities, postal code and similar subjects. (Landmælingar Íslands (A) 2013)

Transport

The transport layer consists of two elements: roads and airports. The road layer contains information such as surface, road class, road number and usage. The road layer is surveyed either using GPS surveys or plotted from aerial photographs. There is around 27.000 km of roads in the newest version. The roads in the countryside are mainly from LMI or The Icelandic Road Administration while roads within towns are in most cases from the private company Samsýn. (Landmælingar Íslands (A) 2013)

Hydrological data

The hydrological data is divided into three layers: lines, points and polygons. In the polygon layer all glaziers, rivers and lakes are represented. The line layer contains rivers and canals. The point

layer contains location of significant waterfalls, geysers and rapids. This data originates mainly from old map sheets printing films, but has lately been updated for part of the country using Spot satellite photos. (Landmælingar Íslands (A) 2013)

Common Place name

Place names comes in three layers; polygon, lines and points. In addition, there are also annotations to add the names to maps in ten different scales. (Landmælingar Íslands (A) 2013)

Coastline

The coastline is available as both lines and polygon layers. It is divided in two layers; one for the mainland of Iceland and its bigger islands and one for smaller islands and cliffs. The coastline is mainly drawn on basis of Spot satellite photos. (Landmælingar Íslands (A) 2013)

Surface

The surface layer is a polygon layer that is a simplified layer showing vegetated and unvegateted areas together with planned areas and water. This layer is created by simplifying CORINE land use data. (Landmælingar Íslands (A) 2013)

4.3   Volcano Layers

The layers about volcanoes are collected from a geological map over Iceland developed by Haukur Jóhannesson and Kristján Sæmundsson in 1998. This map is in the scale 1:500000 and need to be georeferenced before it can be used as this is developed as a paper map although a PDF version were used in this case.

5 Implementation

The implementation or programming of the program used to calculate the lava flow could be divided into few steps. The first one is the most important part of the program that is the actual part that calculates the lava flow using *Cellular Automata*. The second step is the preparation of data, the third step is the analysing of results and the final step is to connect all of the first three steps together. The order of these steps might seem strange, as it is not the order the program is executed in but it makes good sense if we look at how important these steps are. As the *Cellular Automata* is the most difficult and important of these steps it should therefore be developed first as it would be bad having to remake the data preparation part due to changes in the input of the *Cellular Automata* part.

5.1 The script

In this chapter, the script will be described. The description of the script will start in the first line of it and end in the last line of code. Therefore, we start by describing step 2 before we go describing step 1 of the development process.

The script is shown in figures that show one-step each figure. There are several colours used to make it easier to read the script and they mean as follows:

- **Navy-blue** means a reserved word which calls a function from Python
- **Green** shows comments that are added to the script to describe the different functions of it. Comments are furthermore identified with # in front of the sentence.
- **Olive** shows strings, which means that it is text.
- **Teal** shows numbers.

The script can furthermore been seen in one piece in Appendix 1.

5.1.1 Preparation

The first six lines of the script as shown in Figure 16 handle about importing the necessary extensions that will be used in the rest of the script. To start with, in line 2 the *ArcPy* package from Esri is loaded. This package makes all of the tools from *ArcGIS* available to be executed within Python. Next step is to load two extensions to *ArcPy*, the first one is the spatial analyst in line 3

which contains a variety of different geoprocessing tools and the second one is the *env* class in line 4 which contains the geoprocessing environments tools. Then in line 5, the *datetime* module from Python, which gets the exact date and time, is imported. The last thing to be imported is the *os* module in line 6, which later will be used to create new folders.

```
1 # Import arcpy and other nessecary extensions
2 import arcpy
3 from arcpy.sa import *
4 from arcpy import env
5 import datetime
6 import os
```

Figure 16 – Import of needed modules

When all modules and extensions are imported, the next step in line 8 and 9 in Figure 17 is to print the date and time to screen. This is not necessary to do for the functionality of the script but can give a good overview of how long time it is taking to run the script. The time is printed in the following format: "Year – month – day Hour: minute". Then in line 11, it is allowed to overwrite existing files by setting the *overwriteOutpu*t to 1, if existing files should not be deleted either this value could be set to 0 or the line deleted permanently. Then this part is finished in line 13 by checking if the *spatial analyst* extension is licensed, as it is an extension, which runs on a separate license from ArcGIS. Again, line 13 is not necessary as there would just occur an error later in the script but the message from this method is much easier to understand than if an error occurred when tools from the extension should be executed.

```
 7 # define and print the current date and time
 8 now = datetime.datetime.now()
 9 print now.strftime("%Y-%m-%d %H:%M")
10 #Allow excisting outputs to be owerwritten
11 arcpy.gp.overwriteOutput = 1
12 # Check out any necessary licenses
13 arcpy.CheckOutExtension("spatial")
```

Figure 17 – Preparation of the program

Then the next step in lines 14 to 21 is to define paths and variables as shown in Figure 18. This is done by using the *raw_input* function in python that lets the user to write the necessary info into a field. These values are then use later in the script. First, the path to the workspace for the output files is defined in line 15 and then the location of the layers defining volcanoes and the Digital

elevation model in lines 16 and 17. Then in lines 18 to 21 the different variables are defined, first the lava thickness, then the lowering factor of the lava in a flat area followed by the number of iterations and at last the raster size of the raster layer used to create the eruption vents. As the output from *raw_input* is a text it is formatted as a *string* and therefore it need to be converted into either *integer* or a *float value*. The *integer* is chosen for three of the variable as the only need to be a whole number while the lowering factor called *alfa* need to be a *float* value as it might be defined as a decimal number.

```
14 #Define paths and variables
15 path = raw_input("write the path to the workspace")
16 vulcanoes = raw_input("link to the polygons representing volcanoes")
17 dem = raw_input("write the path to the Digital elevation model")
18 lava = int(raw_input("write lava thickness"))
19 alfa = float(raw_input("write the lowering factor for a flat area"))
20 maxit = int(raw_input("write the number ot iterations to be done for each venture opening"))
21 rastersize = int(raw input("Write the distance beetween eruption centers"))
```

Figure 18 – Defining variables and paths to folders and files

When the parameters are ready, the next step is to create geodatabases and folders to store the different output files. To create the three geodatabases needed the *CreateFileGDB* management tool is used as shown in lines 23 to 25, see Figure 19. Then the *makedirs* tool from python is used in line 26 - 27 to create new folders. The reason for creating a folder is that one of the tools used later cannot output files into a geodatabase and in some cases, it is faster to write and read raster layers to a folder than geodatabases.

```
22 # create geodatabases and folders
23 arcpy.CreateFileGDB_management(path, "trash.gdb")
24 arcpy.CreateFileGDB_management(path, "inputpoints.gdb")
25 arcpy.CreateFileGDB_management(path, "finaloutput.gdb")
26 os.makedirs(path + "\\lavaraster")
27 os.makedirs(path + "\\lavapoints")
```

Figure 19 - Creation of geodatabases and folders

5.1.2 Preparation of input data

As the preparation of modules, inputs and output locations is done, the next step is to prepare the data used as input. The volcanoes are defined at the start as polygons but need to be as raster layers representing possible eruption vents to make them usable in lava flow modelling.

To create the points representing eruption vents the first step is to make a raster layer covering the *extent* of the polygons with a cell size that is the same as the distance between the eruptions vents should be. To create the raster the *Create Constant Raster* tool is used as shown in line30, see Figure 20. In line 31 there is added a *print* statement, which print to screen that the raster have been made.

```
28 # Process: Create Constant Raster
29 CreateConsta2 = path + "\\trash.gdb\\raster"
30 arcpy.gp.CreateConstantRaster_sa(CreateConsta2, 15, "INTEGER", rastersize, vulcanoes)
31 print "Raster createt"
```

Figure 20 - Create Constant raster to develop eruption vents from

As the raster have been created, the next step is to convert them into points representing eruption vents as shown in Figure 21. Lines 33 to 35 represent the input raster layer, the output point layer and the field variable, which is used to define that the value of the cell should be written to the table in the output point layer. Then in line 36 the *Raster to point Conversion* tool is executed using the parameters defined in lines 33 to 35. The tool creates a point, in the middle of every cell, containing a field that gets the same value as the cell has, in this case the lava thickness. As the points are created from raster that are made according to the extent of the volcano polygons there might be points that are outside the polygons and therefore the points layer need to be cut according to the polygons. This is done in line 39 where the *Clip Analysis* tool is used to clip the points according to the polygons representing volcanoes. Then to avoid problems with point ID later in the script the point ID is recalculated by adding 10000 to the ID so point ID 1 becomes 10001 and so forth. The tool used to do this is the *Calculate Field Management* tool which calculates a value in a given field of the *attribute table* and is executed in line 41.

```
32 # Convert raster to point
33 inRaster = path + "\\trash.gdb\\raster"
34 outPoint = path + "\\inputpoints.gdb\\pointsuncut"
35 field = "Value"
36 arcpy.RasterToPoint_conversion(inRaster, outPoint, field)
37 #clip the points according to the polygons defining the volcanoes
38 pointscut = path + "\\inputpoints.gdb\\pointscut"
39 arcpy.Clip_analysis(outPoint, vulcanoes, pointscut, "")
40 # Calculate new Field "pointid"
41 arcpy.CalculateField_management(pointscut, "pointid", "[OBJECTID]"
```

Figure 21 - Convert raster to points

When the points have been made, they have to be divided into one file for each point, see Figure 22. To do so the *Split Layer By Attributes* tool is used. This tool is from an extern developer and is used in this program as Esri does not have a tool that can divide points into multiply layers. In line 43, the toolbox containing the tool is imported followed by defining the output location in line 45 and the input file in line 46. Then in line 48, the tool is loaded and finally executed in line 49 where the points are divided according to point ID. Then in line 50 there is added a line to print to the screen that the points are developed to make it easier for the user to see how the process is going on.

```
42 # Load required toolboxes for the Split layer by attributes tool
43 arcpy.ImportToolbox("C:/lava/SplitLayerByAttributes.tbx")
44 # Local variables:
45 lavapoints = path + "\\lavapoints"
46 pointscut = path + "\\inputpoints.gdb\\pointscut"
47 # Process: Split Layer By Attributes
48 arcpy.gp.toolbox = "C:/lava/SplitLayerByAttributes.tbx";
49 arcpy.gp.SplitLayerByAttributes(pointscut, "pointid", "lavaflow", lavapoints)
50 print "points developed"
```

Figure 22 - Split points into separate layers

5.1.3   Creating raster and calculate lava flow

After the points representing eruption vents have been split into separate files they have to be converted to raster layers but first one new layer is made which is the layer containing the lowering factor as described in chapter 0

Method. The lowering factor is calculated in line 51 – 56 of the script as shown in Figure 23. First, the *slope* layer defined in line 51 is created in line 52 by using the *Slope_3D tool* from *ArcPy* that uses the *DEM* to calculate the slope of each cell in percents. The 1 at the end of line 52 is a Z factor, which in this case is set to one as all measurements are in meters, if the x,y values and z values were in different units of measure this value would be different. Then a new layer is opened and defined as raster in line 53 to 54. Then the next step in line 55 is to calculate the lowering factor for each cell using the *Con* expression shown in chapter 0

Method. Finally, in line 56 the new lowering layer is saved

```
51 slope = path + "\\trash.gdb\\slope"
52 arcpy.Slope_3d(dem, slope, "PERCENT_RISE", 1)
53 slope = path + "\\trash.gdb\\slope"
54 slope1 = Raster(slope)
55 lowering = Con(slope1 <= 5,0.6,(slope1 - 5)/75*(15 - 0.6) + 0.6)
56 lowering.save(path + "\\trash.gdb\\lowering")
```

Figure 23 – Calculating lowering factor

The next step is to convert the layers representing eruption vents to raster layers as shown in Figure 24. There the first step is to define *variables*, *extend* and *workspace*. In line 58, the extent of the new raster layers is defined as the same as the *DEM* layer to make sure that the cells from the new raster layers cover the same area as the *DEM* layer. Then in line 60, the *workspace* is set to the folder containing the shapefiles representing the eruption vents. Now in line 61 the variable *num* is created with the value of 10000. Then there is made a new variable *dem1* which is the *DEM* defined as raster. Next in line 63 and 64 the layer containing the lowering factor is opened and defined as raster in a variable named *low*. Then in line 65 there is created a *list* of all shapefiles within the *workspace* defined in line 60. To create the list the *ListFiles* tool from *ArcPy* is used. Finally, the variable *valField* define in which field of the table of each shapefile representing eruption vents the lava thickness is located.

```
57 # Set the extent of the raster layers
58 arcpy.env.extent = dem
59 # Set the workspace.
60 arcpy.env.workspace = path + "\\lavapoints"
61 num = 10000
62 dem1 = Raster(dem)
63 lowering = path + "\\trash.gdb\\lowering"
64 low = Raster(lowering)
65 shp_List = arcpy.ListFiles("*.shp")
66 valField = "grid_code" # the field containing the lava thickness
```

Figure 24 – Defining variables, extent and workspace

Now there is time to convert the listed files from last step into raster layers as shown in Figure 25. As there are now multiply files that have to be converted there has to be created a *for* loop as shown in line 67 to loop through every file in the *sph_List* created in line 65. First, the *num* variable is changed to one higher than before as shown in line 68 to change to the next file in the list, and then in line 69 this number is converted to a *string*, called *s*, which means that it is formatted as text to be used in the path for the input and output. Then in line 70, the link to the input layer

called *inFeatures* is defined and in line 71, the link to the output layer called *outRaster* is defined. Then in line 72, the cell size is set to 20 meters. When the input parameters have been defined the *Feature To Raster conversion* tool that convert a feature into raster layer is executed as shown in line   74. As the output layer has to contain the eruption vents with a value of the lava thickness plus the elevation at the given eruption centres there has to be done one more calculation until the lava flow calculation can begin. To do this there is defined a new layer in line 77 called *LavaDEM*. The new layer is calculated by adding the layer containing the respective eruption vent to the *DEM*. By doing so there is made a new layer that contains the height of the eruption vent plus the lava thickness in the respective cell. All other cells get a *NoData* value. Then at last, in line 77 the new *LavaDEM* layer is saved.

```
67 for layer in shp_List:
68     num = num + 1
69     s = str(num) # the number has to be string in next step
70     inFeatures = path + "\\lavapoints\\lavaflow" + s + ".shp"
71     outRaster = path + "\\trash.gdb\\lava" + s #the raster layer made
72     cellSize = 20 # define the cellsize of the new layer
73     # Execute FeatureToRaster
74     arcpy.FeatureToRaster_conversion(inFeatures, valField, outRaster, cellSize)
75     # add DEM to lavaflow layers
76     lavaDem = dem1 + Raster(outRaster)
77     lavaDem.save(path + "\\lavaraster\\lavadem" + s)
```

Figure 25 – Convert eruption vents from points to raster

As the *LavaDEM* layer has been made, it is time to calculate the lava flow. The lava flow is calculated within the *for* loop from before and starts as shown in Figure 26 line 78 to 80 by printing which layer is under processing and the date and time. Then in line 81, a new variable is created called *numit*, which has the value of zero and is used to count the number of iterations done in the lava flow calculation.

Now a *while* loop is created which is looped while the *numit* value defined in line 81 and later changed in line 104 is lower than the *maxit* value which is defined in line 20 and represents the number of iterations to be done for each layer. The first step within the loop happens in line 83 where the *LavaDEM* layer is recalculated to remove all *NoData* values and replace them with zero using the *Con* and *IsNull* tools. The layer is then saved in line 85 under the name *lavacal*. The

change of name of the file is done because the original file can´t be overwritten using map algebra and the *Con* tool. Then the original raster layer is deleted.

```
78    print layer + "is being calculated"
79    now = datetime.datetime.now()
80    print now.strftime("%Y-%m-%d %H:%M")
81    numit = 0
82    while numit < maxit:
83        rastercalc = Raster(path + "\\lavaraster\\lavadem" + s)
84        rastercalc2 = Con(IsNull(rastercalc), 0, rastercalc)
85        rastercalc2.save (path + "\\lavacal" +s)
86        del rastercalc
```

Figure 26 – Preparing for lava flow calculation

The next step is to run the two *focal statistics* calculations to find the neighbourhood cell with the highest value as shown in Figure 27. In lines 88 – 89 there is made two new variables that represents the path to the two *focal statistics* layers. Then in line 91, the *focal statistics* tool is executed for a rectangle of 3*3 cells, which represent the centre cell and its eight neighbouring cells. In line 92, the *focal statistics* tool is then executed for a circle with a radius of one cell, which represents the centre cell and its four closest cells. Then at last, the two new layers are opened and defined as raster to use in the further process.

```
88    focal1 = path + "\\focal1"
89    focal2 = path + "\\focal2"
90    # Process: Focal Statistics
91    arcpy.gp.FocalStatistics_sa(rastercalc3, focal1, "Rectangle 3 3 CELL", "MAXIMUM", "DATA")
92    arcpy.gp.FocalStatistics_sa(rastercalc3, focal2, "Circle 1 CELL", "MAXIMUM", "DATA")
93    focal1 = Raster(path + "\\focal1")
94    focal2 = Raster(path + "\\focal2")
```

Figure 27 - Focal statistics

When the *focal statistics* tools have been executed, the next step is to run the lava flow calculation using the *Con* tool in line 95 – 99 (See Figure 28) using the statement presented in chapter 0

Method. The reason for creating new file in line 100 instead of updating the old one is that while using the *Con* tool the output cannot be the same as the input. By creating that file the output from lines 95 - 99 can be saved with the same name as the original file which secures that the new file is then used in line 83 during next iteration. Then all of the intermediate files are deleted in

lines 101-103. Then at last, the value of *numit* is changed to *numit* plus one for the next iteration through the loop. When the value of *numit* reaches the value of *maxit* the loop stops running and the next step is to *print* the number of the created lava flow layer and the time, which is done in line 105 to 107.

```
 95      outcon = Con(((((rastercalc3 > focal1 - low*1.414) | (rastercalc3 > focal2 - low)) & \
 96          (rastercalc3 > 0)), rastercalc3, Con(focal1 - low*1.414 > focal2 - low,\
 97          (Con(dem1 + (low*1.414)>= focal1, 0, Con(focal1 - dem1 >= lava + (low*1.414),\
 98          dem1 + lava, focal1 - (low*1.414)))),\
 99          (Con(dem1 + low >= focal2, 0,Con(focal2 - dem1 >= lava + low, dem1 + lava, focal2 -low)))))
100      outcon.save (path + "\\lavaraster\\lavadem" +s)
101      del focal1
102      del focal2
103      del rastercalc3
104      numit = numit + 1
105   print "Lawaflow from eruption vent nr." + s + "is ready"
106   now = datetime.datetime.now()
107   print now.strftime("%Y-%m-%d %H:%M")
```

Figure 28 – Lava flow modelling

Now the *for* loop that started in line 67 is finished for one layer and the process replies while there are layers in the list of shapefiles. When all layers have been calculated the loop stops and the next step is the calculation of the probability of a cell being covered in lava.

5.1.4 Probability calculation

The probability calculation is done by using a *for* loop. Before the loop is executed, there are couple of variables that need to be defined first as Figure 29 shows. It starts by defining the used *workspace* which is the folder containing the lava flow layers in line 108. Then in line 110 there is created *list* of all of the raster layers that are located within the defined *workspace* using the *List Rasters* tool from *ArcPy*. Then there are developed two variables in lines 111 and 112: the first one is *i* and gets the value 0 and the second is called *iname* and is *i* converted to string to use in file names.

Next step is to make a new constant raster layer called sumras0 by using the *Create Constant Raster* tool from *Spatial Analyst* in *ArcPy* as shown in line 115 with a cell size of 20 and the *extend* defined as the same as the *DEM*.

```
108 arcpy.env.workspace = path + "\\lavaraster"
109 #create a List of rasters in the workspace
110 rasters = arcpy.ListRasters("*", "All")
111 i = 0
112 iname = str(i)
113 #Create raster with value 0 to base the calculation of the number of lava flows on
114 conras = path + "\\finaloutput.gdb\\sumras0"
115 arcpy.gp.CreateConstantRaster_sa(conras, "0", "INTEGER", "20", dem)
116 #loop through rasters in List
```

Figure 29 – Preparations for probability calculation

As this is done the next step is as shown in Figure 30 to create the *for* loop that starts in line 117 and loops through all the raster layers in the *list* created in line 110. The first step within the loop in line 118 is to *print* which raster is under processing. Then in line 119 there is added a double condition to convert first all *NoData* values to zero and then all values that are not zero to 1 to make it able to sum the layers together later. That new layer is then saved in line 120 under the name *out*. The next step is to sum the *out* layer to the *sumras* layer opened in line 122 and defined as raster variable with the name *outSUM*. The sum calculation is done in line 124 and saved in line 127 after *i* and *iname* have been made 1 higher in lines 125 and 126.

The loop is then executed until all raster layers in the folder have been looped through.

```
  116 #loop through rasters in List
• 117 for raster in rasters:
• 118     print raster + "is under processing"
• 119     out = Con(IsNull(raster), 0, Con(Raster(raster) == 0, 0, 1))
• 120     out.save(path + "\\trash.gdb\\out")
• 121     out = Raster(path +"\\trash.gdb\\out")
• 122     outSUM = Raster(path + "\\finaloutput.gdb\\sumras" + iname)
  123     #sum rasters together
• 124     outSUM2 = outSUM + out
• 125     i = i + 1
• 126     iname = str(i)
• 127     outSUM2.save(path + "\\finaloutput.gdb\\sumras"+iname)
```

Figure 30 - Summing lava flow layers

Now the end of the program is reached with three lines that prints that the processing is finished and what time it is as shown in Figure 31.

```
·128 print "end of processing"
·129 now = datetime.datetime.now()
·130 print now.strftime("%Y-%m-%d %H:%M")
```

Figure 31 – Print date and time

5.1.5 Challenges

There were several challenges spotted during tests of the script. In the following chapter, the most significant of these will be described.

5.1.5.1 *Point numbers*

One of them is the problem described before with the naming of files where the "Split Layer By Attribute" tool added zero in front of the numbers used to name each file. This problem was solved by starting the naming at number 10.001 instead of 1. The number 10.000 is chosen because there we enough of possibilities as there would first be problem if 90.000 points are going to be reached which will not happen in the scale of this project. If more than 90.000 points are sometime in the future to be used it is easy to change the start number to 100.001 which give in total possibility for 900.000 points.

5.1.5.2 *Projection errors*

Another problem and perhaps the biggest were spotted during tests in the development phase. The problem was that the raster layers that were converted from the points did only contained NoData values and not the lava thickness value for the active cell. By analysing the layers in *ArcGIS,* it soon became clear that there was a projection error. The input polygon were in the coordinate system ISN2004 together with the point layer developed from that polygon but while dividing the points into separate layers the notation got lost and only the coordinates were left in the separate files. Then the elevation model used to define the extend of the new raster layer were in ISN93 which has other false Easting and Northing than ISN2004. Therefore the points were far out of the extend of the elevation model which caused the error. By converting the elevation model into ISN2004 this problem were solved. This problem shows the importance of having similar coordinate system with different false values as this error might not have been spotted if the coordinates were similar.

5.1.5.3   Cellular Automata

The first tests and development of the cellular automata calculation were done using model builder in *ArcGIS* as that environment uses the same tools as the *ArcPy* extension in python but have easier interface for testing the different tools. There the Raster Calculator tool was used for the calculation of the statement used to model the lava flow with a setup as shown in Figure 32. The colours on the figure mean the following; yellow boxes are tools, blue ellipsoids mean input and green ellipsoids means output, if a layer is used both as input and output it is green.
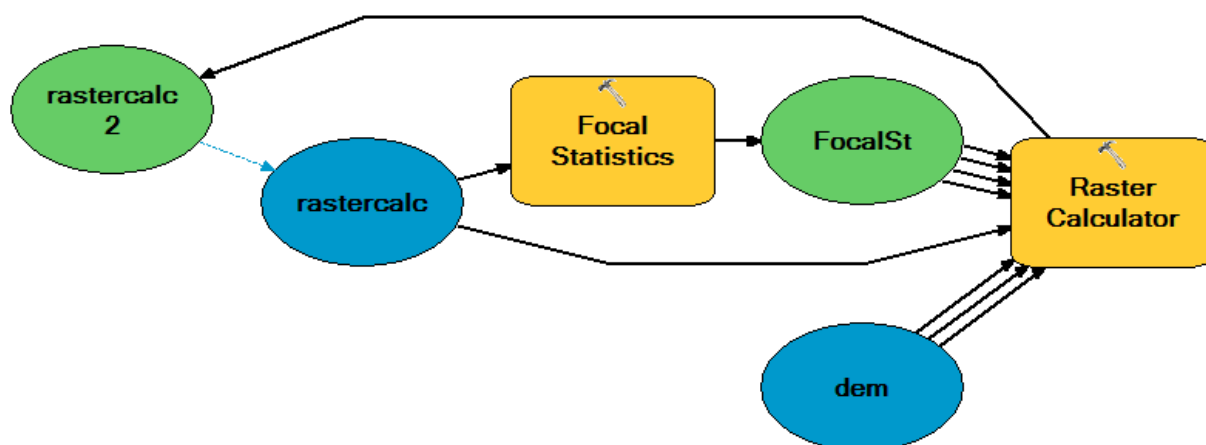

Figure 32 - The Cellular Automata part of the program during the development phase

This setup were working fine in Model Builder but as soon as it were exported to Python it didn´t work properly. Several tests were made to fix the problem but none of them worked. Then a further research were done on Map Algebra in Python using *ArcPy* revealed that Raster Calculator is not supported in Python even though *ArcGIS* and *ModelBuilder* makes it able to convert the model containing Raster Calculator to Python. The solution was quite simple, as the Con tool that actually was used within Raster Calculator in the first tests should be used on itself without any use of Raster Calculator. The reason for why the Raster Calculator were converted to Python although it is not supported is probably due to the fact that the earlier versions of ArcGIS supported it in ArcPy.

5.1.5.4   Stability of geodatabases

While running the Case study described in next chapter there were spotted stability problems using geodatabases to store the output of the lava flow modelling which resulted in the program stopping running. This is due to that something unknown makes the file that need to be overwritten broken which results in that the save tool can´t save the output over the old file. This problem was solved by taking the layers *Lavacal*, *LavaDEM*, *focal1* and *focal2* out of geodatabases and instead save them as raster Grid in a folder. Furthermore, there was added delete tool, which delete the original file before the new calculation is saved. These changes made the program more stable and actually increased the performance of the program significantly although numbers cannot be set to the speed due to that the speed did were not measured before the modification.

6 Case study

The Case study used in the project is the town and municipality of Grindavík on the southwest coast of Iceland. Grindavík is located on the Suðurnes region, which has multiply volcanoes. There are mainly two volcanic systems that might threat the town of Grindavík. These two are the Reykjanes system and the Trölladyngju system and are shown on the map in Figure 33.
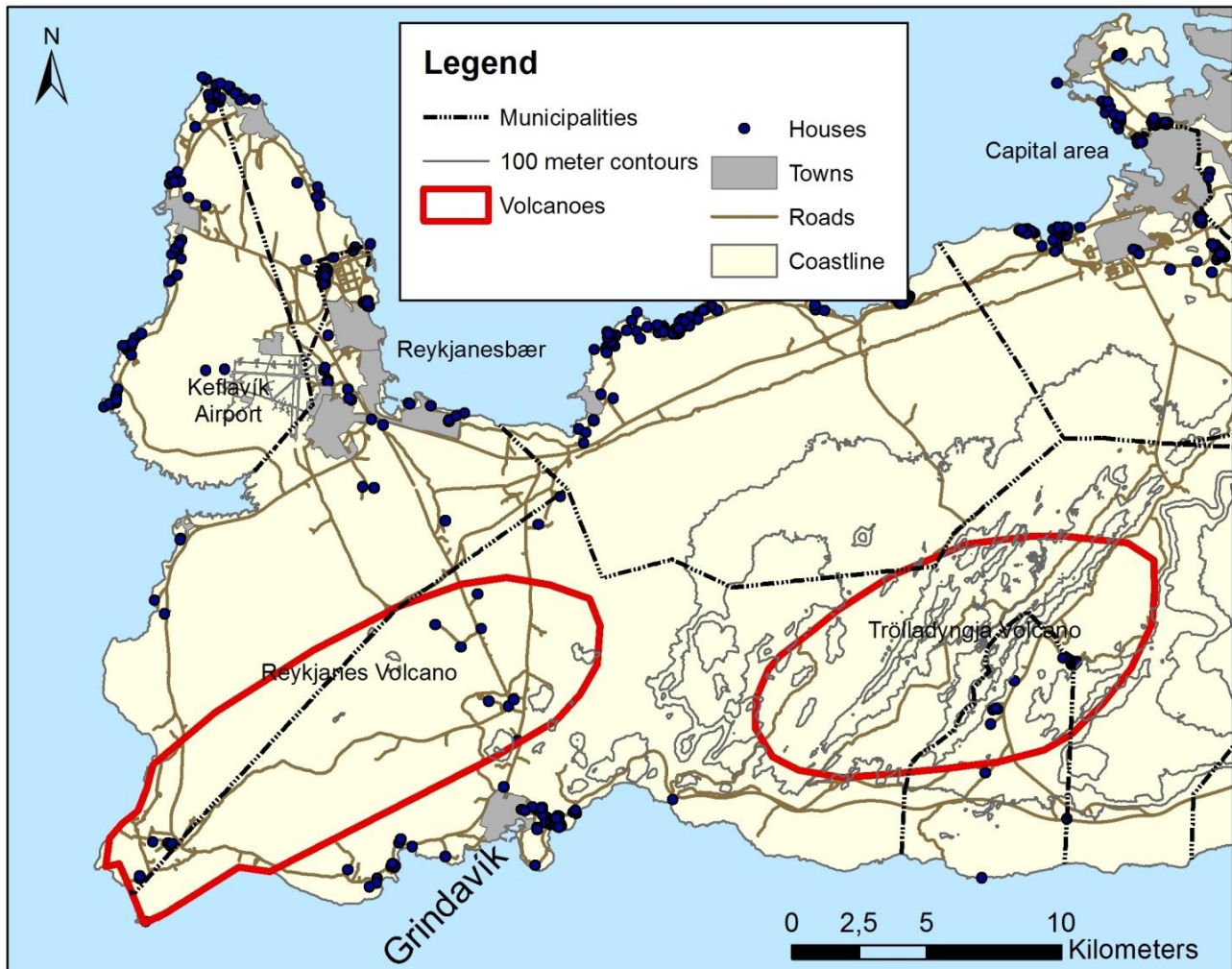
The elevation of the area is varying, quite flat around Reykjanes volcano and mountainous around Trölladyngja as Figure 34 shows.
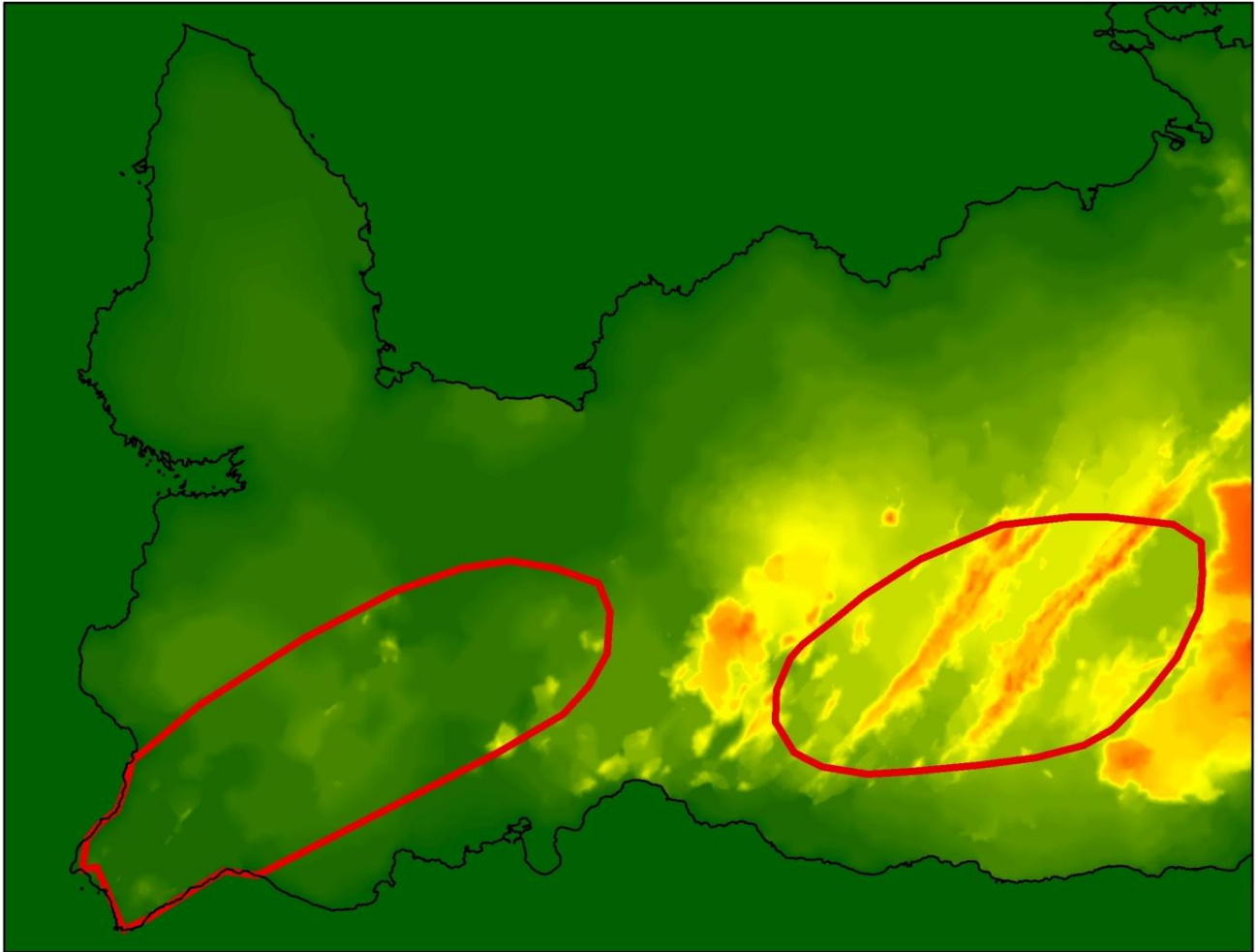
Figure 34 - DEM of Suðurnes region ©Landmælingar Íslands ©Náttúrufræðistofnun Íslands

The map in Figure 35 shows that there are three locations within the municipality of Grindavík containing buildings. The first one is the town of Grindavík and its surrounding areas. The second one is Svartsengi where there is located a power plant and The Blue Lagoon which is one of the biggest tourist attractions in the area. The third and last one is Staðarhverfi where there are summerhouses and a fish farm. The points north of Svartsengi are holes where there is pumped hot water from the underground to use in the power plant in Svartsengi.

Figure 35 - Build areas in Grindavík municipality, Grindavík municipality is on the right site of the block dotted line. ©Landmælingar Íslands ©Náttúrufræðistofnun Íslands

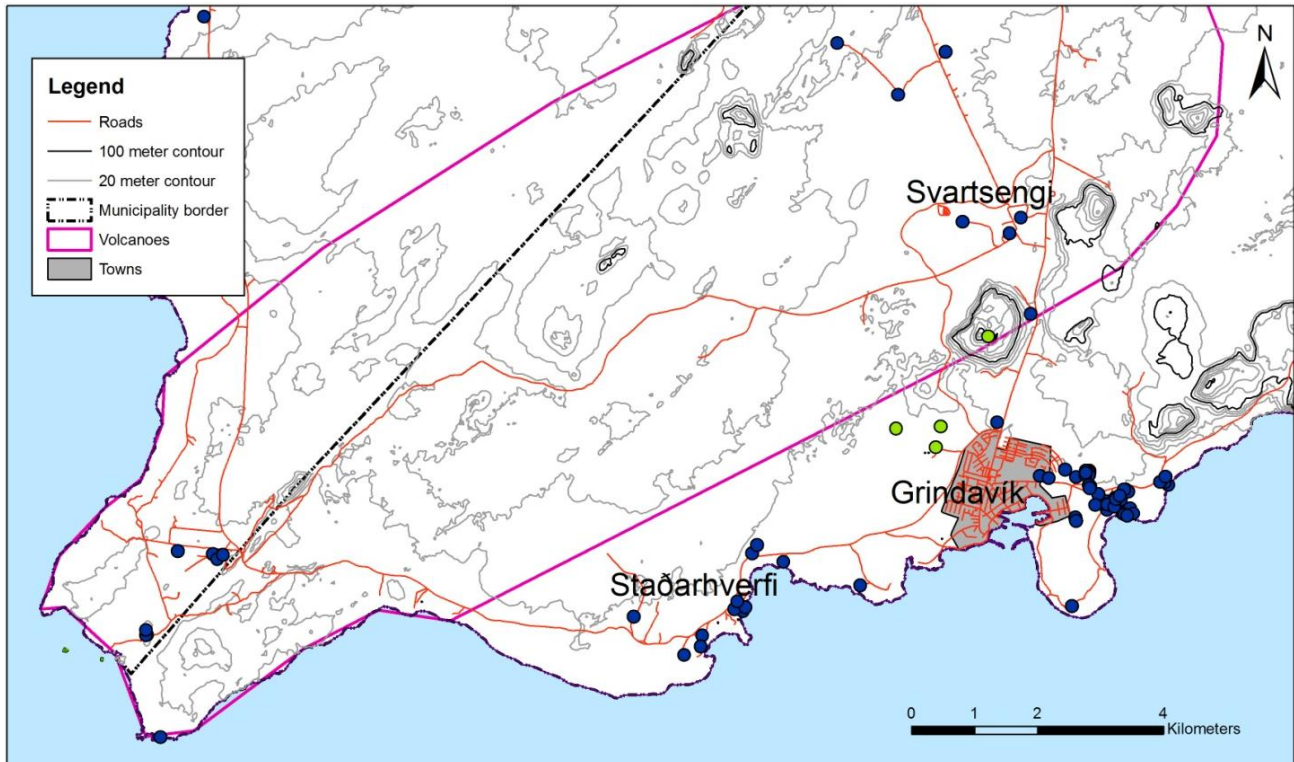As the definitions of the volcanoes are not clear, the definition used to calculate the lava flow is the main volcano as described in the geology map from The Icelandic Institute Of Natural History released in 1998. There could also be used the outer boundaries of the volcanoes but in this case the town is actually within that boundary as the map show and as there is bigger probability for an eruption to happen within the definition of main volcano that definition is selected.

The parameters for lava thickness is set to 10 meters, as this is the average of basalt as described in chapter 3 Theory. Then the lowering factor for flat area is sat to 0.3 meters, which allows the lava to flow long way without flowing too much sideways. The number of iterations for each eruption vent is sat to 1000, which gives a theoretical length of lava flow between 20 and 30 km, which should be enough for this area as even though the lava might flow longer it would be towards north and away from Grindavík. The distance between eruption vents are then sat to 1500 meters in favour of performance.

Using these parameters there were calculated lava flow for 84 eruption vents. The results of these analyses are illustrated in Figure 36.
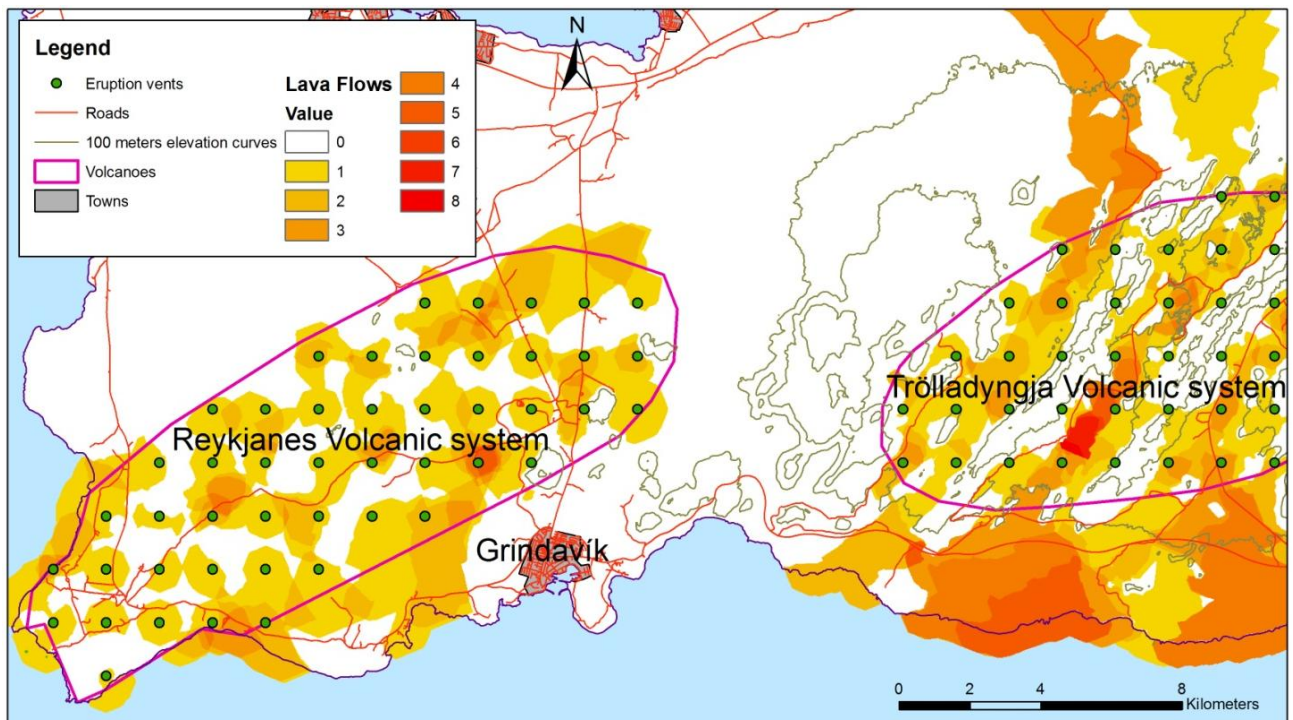
Figure 36 - Calculated lava flow ©Landmælingar Íslands ©Náttúrufræðistofnun Íslands

The result of the calculation of the lava flow for this area shows that Grindavík seems to be quite well located according to the danger of lava flow. The lava flow calculation shows quite clear picture of where the lava could flow if an eruption happens in the Trölladyngja volcanic system while the results for Reykjanes volcano system contains more uncertainty due to the fact how flat the area of it is. This difference in the landscape can be seen both on the Landsat satellite photo in Figure 37 and on the DEM in Figure 34 that shows clearly that there is much more contrast in the landscape of Trölladyngja than Reykjanes.

Figure 37 - Landsat Satellite photo of the volcano systems ©Landmælingar Íslands ©Náttúrufræðistofnun Íslands

The mountains surrounding Grindavík also seem to have effect on this as the make a kind of shield for the town making the lava to flow away from it. Although there is the possibility that an eruption could star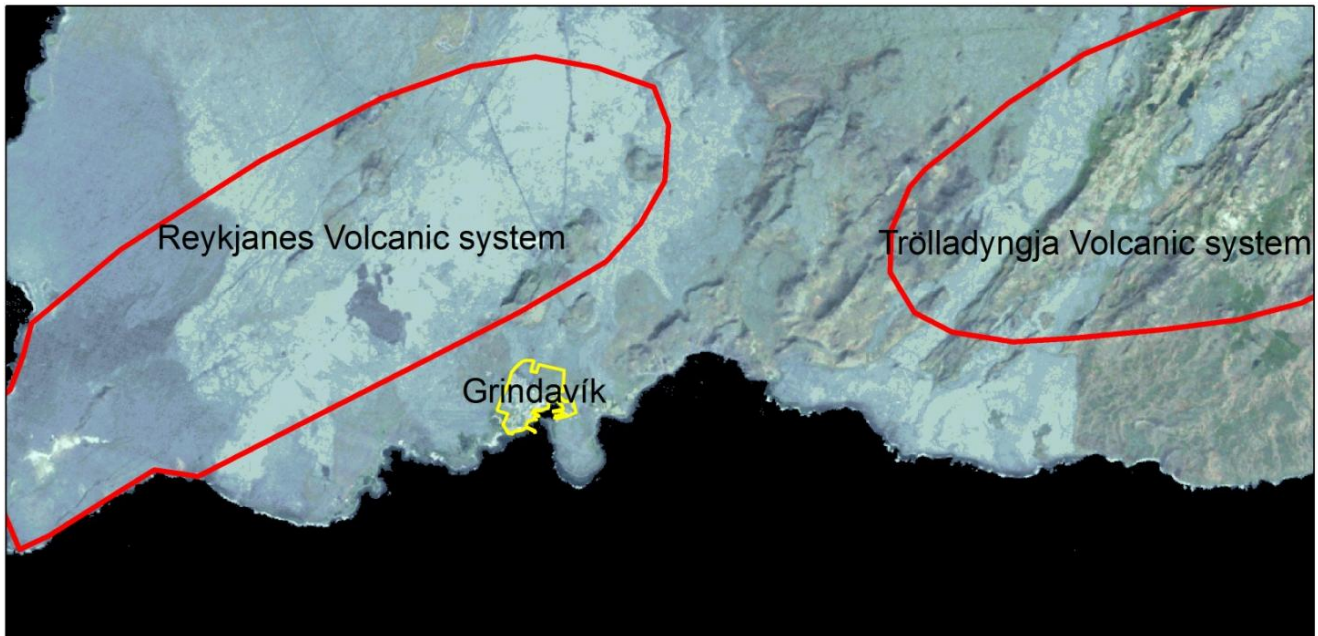t at the top of some of these mountains, which could result in that the town would be threatened with lava, but the probability of that is low.

As the results for the Reykjanes volcano are not very clear there is need to do another calculation with smaller distance between eruption vents. The results from Trölladyngja make it quite clear that the municipality of Grindavík do not need to think about eruption from there and therefore the second calculation only need to be done for the Reykjanes volcano. As the area is quite flat, the lava thickness is sat to 15 meters, which is just about as thick as basalt can become. The distance between eruption vents is sat down to 500 meters, which should increase the quality of the results. At last, to increase the performance the DEM is modified to a cell size of 40 meters, which should not affect the results as the flatness of the area means that the quality of the DEM is not god. By doing this the amount of cells that have to be used in every iteration is four time lower and the number of iterations to be done is reduced by half as the lava flows longer following each iteration. To adjust the lowering factor to the new cell size it is sat to 0.6 meters which makes the lava flow just the same way as before.

Below in Figure 38 the result from the second lava flow modelling is illustrated.
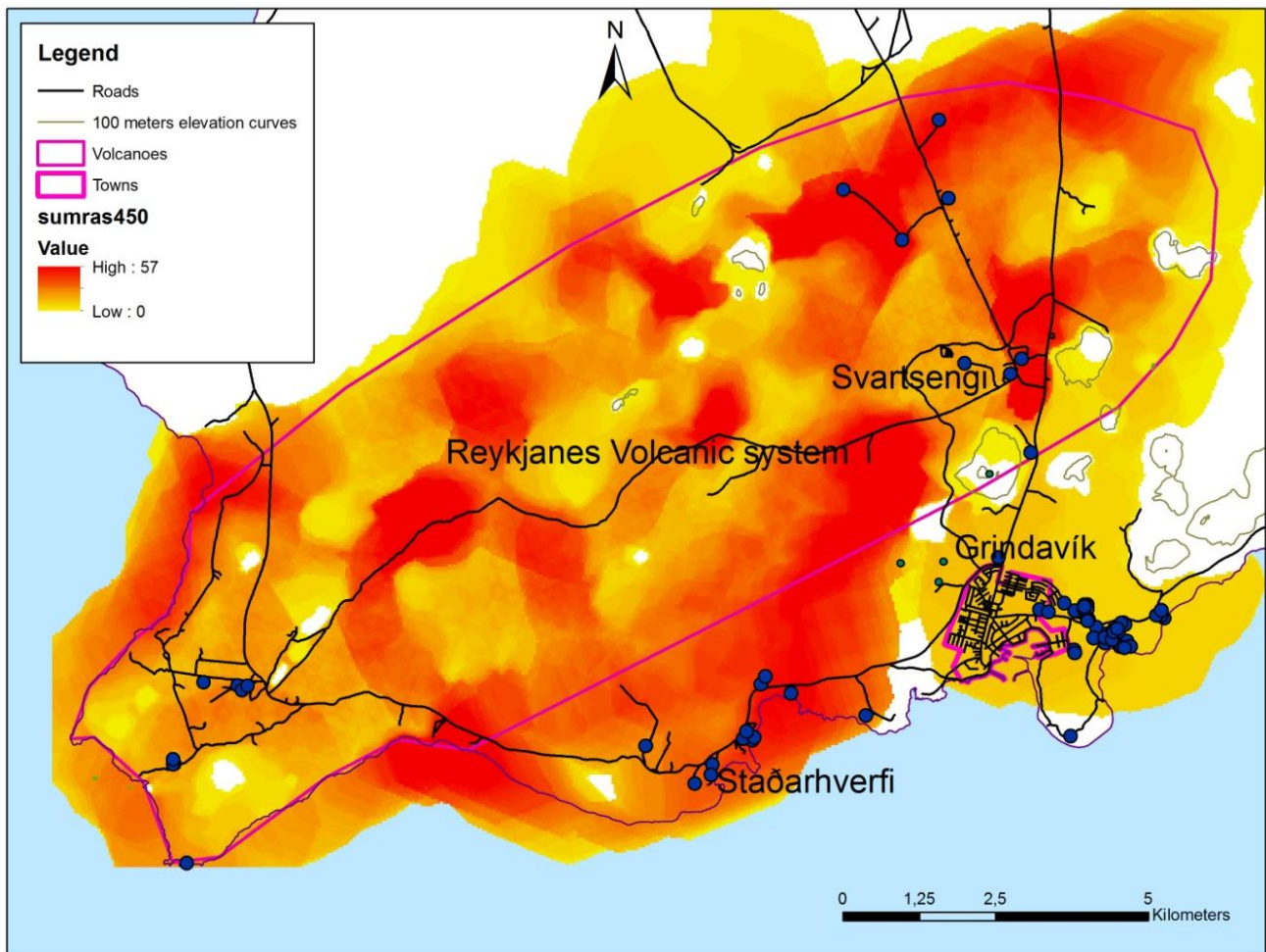
Figure 38 - Map over the lava flow for Reykjanes volcano ©Landmælingar Íslands ©Náttúrufræðistofnun Íslands

As Figure 38 shows the result from the second lava flow calculation gives much clearer view of where the lava might flow if an eruption happens. All three build areas within Grindavík municipality are at threat of being covered in lava during an eruption in Reykjanes volcano. If we look at the town of Grindavík it is similar amount of threat all over the town and it nearest neighbourhoods. There is although a small area towards southwest that is without lava covering it and therefore it might become a future part of the town. For Grindavík town it might be need to analyse how the lava could be diverted away from the town.

The area Staðarhverfi is in quite a big danger of being covered by lava but as there is enough space there now, the lava might be easily diverted using different methods. If there is build more in this area such a diversion might become harder to do and even become impossible.

If we look at Svartsengi, it is clear that there is great threat of lava flow in that area which threatens the power plant and the Blue lagoon. There the threat is most east, north and southeast of the power plant while the threat is less south, west and northwest of the Blue Lagoon as Figure 39 shows.
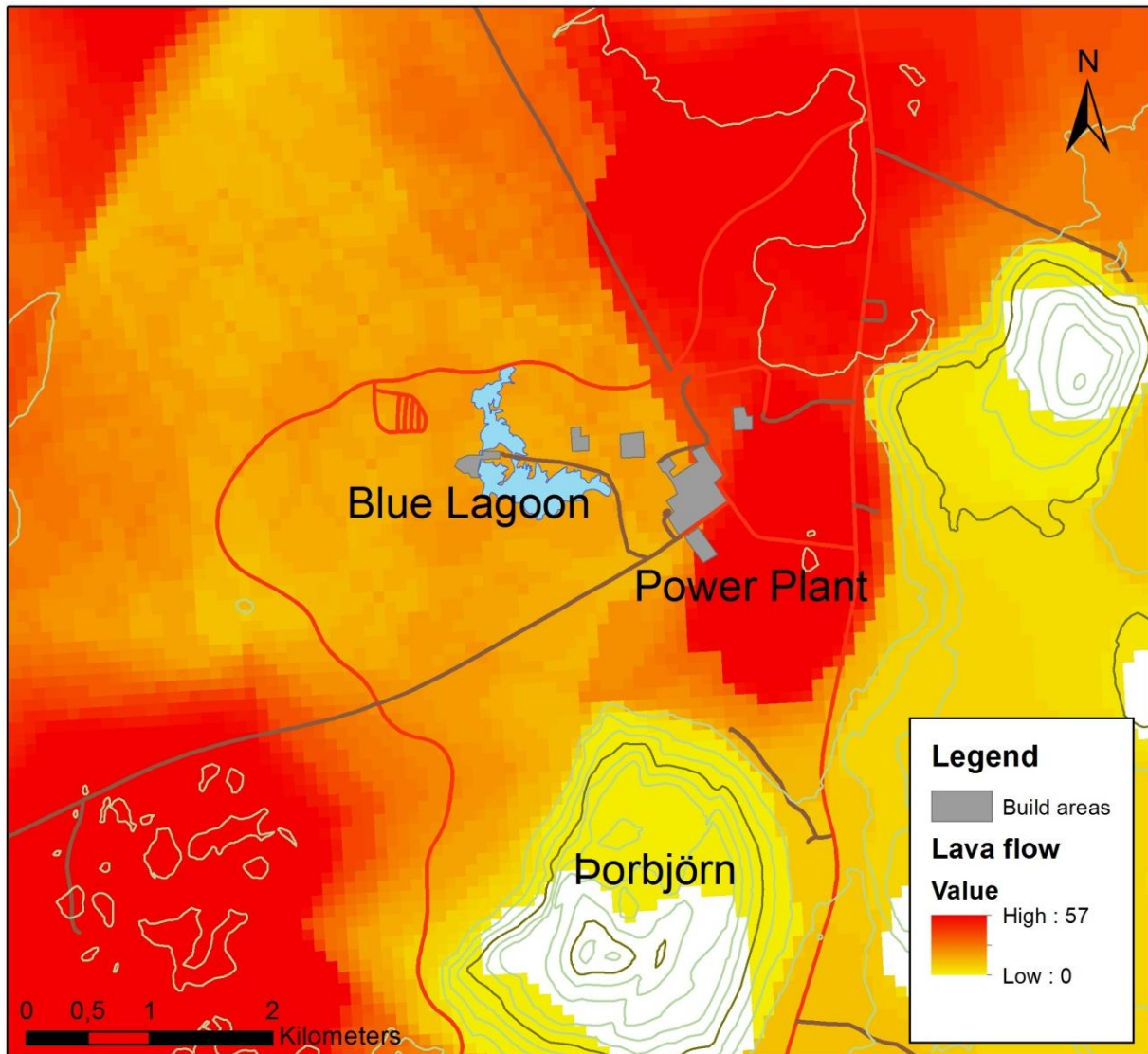
Figure 39 - Lava flow calculation around Svartsengi ©Landmælingar Íslands

Therefore, if there is need for building anything in Svartsengi this should be done west or south of the Blue Lagoon. Of course this area is not very suitable but there are buildings that require being in an area such as Svartsengi where there is very hot water in the underground.

In General new buildings and structures in the Reykjanes area should either be located on top of hills or in middle of flat areas to avoid possible damages due to lava flow.

7   Spatial planning in Iceland

7.1   Spatial planning system

Spatial planning in Iceland is done according to the Planning Act No. 123/2010 and The Strategic Environmental Assessment Act No. 105/2006. The environmental minister is the administrator of spatial planning with The National Planning Agency as the executive authority. The spatial planning is divided into 4 different levels of plans as shown below. (Skipulagsstofnun (A) n.d.)

1. National Planning Strategy (Landsskipulagsstefna)
2. Regional Planning (Svæðisskipulag)
3. Master Plan (Aðalskipulag)
4. Local Plan (Deiluskipulag)

The first one, the National Planning Strategy describes the general strategies that the government and authorities have about transport, nature protection, energy usage, regional policy and other important areas of concern for land use. The strategy is made for 12 years at a time and is developed according to land use planning and with focus on sustainability. (Skipulagsstofnun (A) n.d.)

The Second one Regional Planning is a Plan strategy for two or more municipalities where their common strategy for regional policy and common interests are submitted. The geographical area a regional plan covers is has to be selected according to common geography, economy or social elements. The strategy should tell which strategy the municipalities board have for at least the next 12 years and should be created on basis of the Planning Act and the National Planning Strategy. The municipalities are responsible for these plans and should have a committee that controls the work of it. After municipalities election the committee should look into the strategy to see if there is something that has to be changed. Every municipality is free to define if there is need for a Regional planning strategy and there is only the Capital area of Iceland that has to be covered of a Regional plan according to the Planning Act. The regional plans have to be accepted by the National Planning Agency. (Skipulagsstofnun (B) n.d.)

The third one, Master Plan is development plan that covers a municipality and describes the local government's strategy on land usage, environment and the development of built areas for at least

next 12 years. The municipality plan has to be accepted by the National Planning Agency or in some cases The Environmental Minister. The Master plan has to be made according to the objectives of the Planning Act, The National Planning Strategy and the Regional plan. Following municipal election, it has to be discussed if the Master plan should be revised. (Skipulagsstofnun (D) n.d.)

The forth one, The Local Plan is a more detailed version of the Master Plan for a limited, coherent area that. The local plan administrates the settlement patterns, landscaping, type of houses, cadastral boundaries, land usage and other similar elements on a detailed level. (Skipulagsstofnun (C) n.d.)

7.2 Handling volcanic hazards

According to the Planning act there have to be described the strategy for natural catastrophes in the plan strategies. In the Planning directive it is described that in the master plan for the municipalities there should be discussed the danger of Natural catastrophes and other danger that could compromise the safety and health of the inhabitants. Examples of Catastrophes mentioned there is earthquakes and volcanic activity. On the planning sketch, these areas should be marked with a polygon with red edge. (Umhverfis og Auðlindaráðherra 2013)

In the local plans the areas that are noted as areas for natural catastrophes in the master plan have to be marked on map and the limits of building construction in the area described. It is illegal to build or plan buildings on known flooding areas, where there is danger of avalanches and if there is known cracks, fault or hot springs. (Umhverfis og Auðlindaráðherra 2013)

7.3 Example from Grindavík

As the area of interest in the case study is Grindavík municipality it is optimal to use that municipality as example of what there is written in the master and local plans about the threats of nature catastrophes and especially the lava flow hazard

Looking at the planning sketch of the Master plan of Grindavík there are no areas marked as in danger of natural disasters. In the Master plan strategy description there is described that the town is build on lava that flowed for around 2500 years and that in the neighbourhood there is

newer lava where the youngest is from around 1300. There is also described that there are 2 known cracks that goes through the town but as they are not known exactly there has to be taken care of them prior to construction work. Prior to building a new school in 2008 there were spotted three cracks on the ground that had to be taken care of when locating buildings on the parcel. In the part that handles about natural disasters there is mentioned the threats of earthquakes and volcanic eruptions but only the examples from before about the cracks is described further and it seems that flooding areas near sea gets much bigger focus than volcanoes. (Grindavíkurbær 2011)

Based on that it seems that in the municipality of Grindavík the local council knows about the threat of Lava flowing from volcanic eruption but do not analyse where the threat is biggest and where there eventually could be safe areas.

7.4   Possible use of lava flow modelling in Spatial Planning

The program and method developed in this project can be used to give the threat from lava flow more importance in the planning products, especially on the municipality level.

Lava flow modelling can be used in several ways for planning according to lava flow. The method and program developed and presented in this project has it strongpoint in finding the areas that are most suitable for new neighbourhoods as it models how the lava flows without any influences from future manmade changes in topography.

The output from the program has to be analysed to find the most suitable areas. Of course, the most suitable areas are these that will not be covered in lava but in some cases, it cannot be avoided to build new neighbourhoods on areas that might be covered in it.

Another use of lava flow modelling could be to add defensive structures to the DEM to analyse if there might be done anything to divert the lava from already build areas. Knowing in advance where there could be possible to divert lava is a clear advantage to build these structures as there we might know the right place for them. If the structures are placed in wrong places they might not divert the lava but just stopping it at a place so it hopes up and end by putting such a big pressure on the defensive structure that it breaks and the lava flows at very high speeds over the area that should be defended. Another advantage if knowing where these structures should be created is to avoid that there will be build new buildings in the zone the lava should be diverted to.

To use the data in more automated process there might be a good idea to use them in a Multi Criteria analyses. There the output layer could be used combined with other layers combined with other layers to find the best suitable areas to build new neighbourhoods. There it has to be defined what acceptable threat to an area is if an eruption occurs. If we say that there is acceptable that the threat of a build area being covered in lava if an eruption happens is 5% then it could be found out how many lava flows there can be in a cell to fulfil this criteria. This number of lava flows then defines the upper boundary of the analyses and all cells with fewer flows gets a value based on number of lava flows, the less threat the more valuable thee cell will get.

7.4.1   Possible improvements for Grindavík

Figure 40 - The master plan for Svartsengi in Grindavík municipalitybelow shows part of the plans around the Blue lagoon and the power plant in Svartsengi. The black polygons represents existing building, the dark grey polygons illustrates planned industry zones and the light grey polygon shows areas to be used for activities connected to the other areas. The green areas are open areas, the yellow are planned shopping and service zones and finally the orange colour represents areas for service institutions
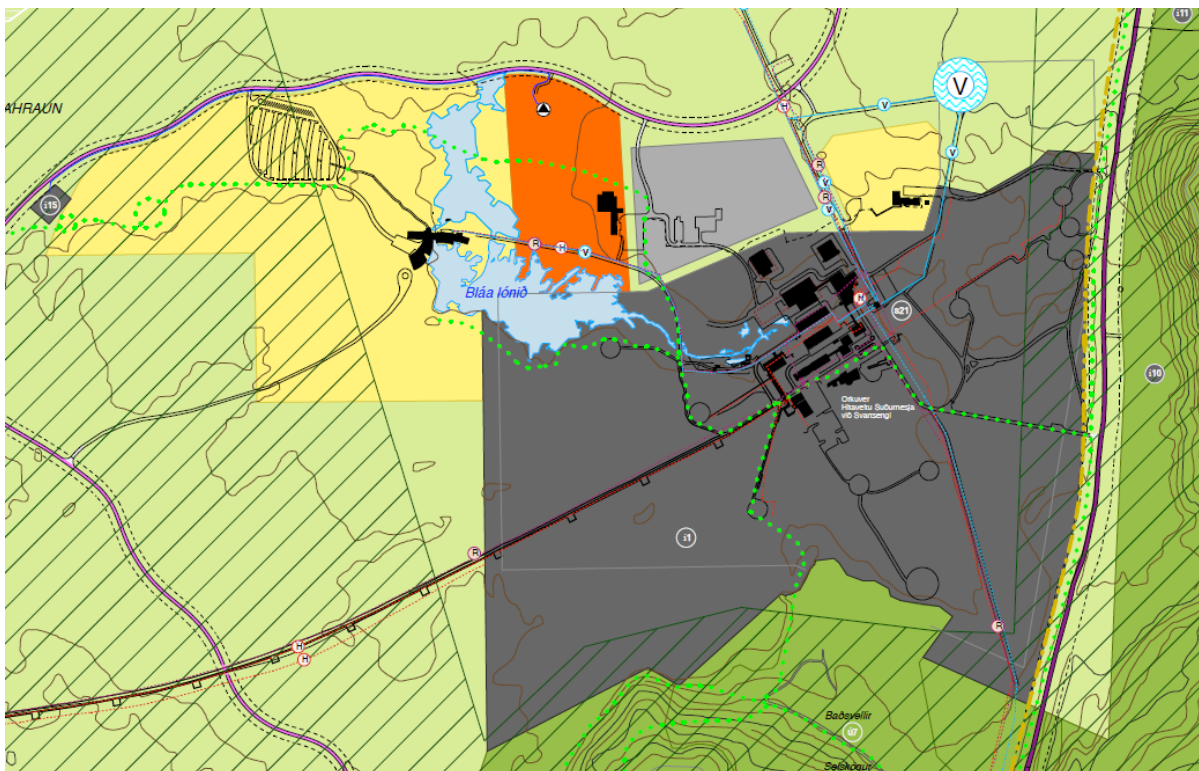
Figure 40 - The master plan for Svartsengi in Grindavík municipality

To see if this plan is good according to the threat from lava flow it is necessary to combine this plan to the results from the lava flow modelling as shown in Figure 41.
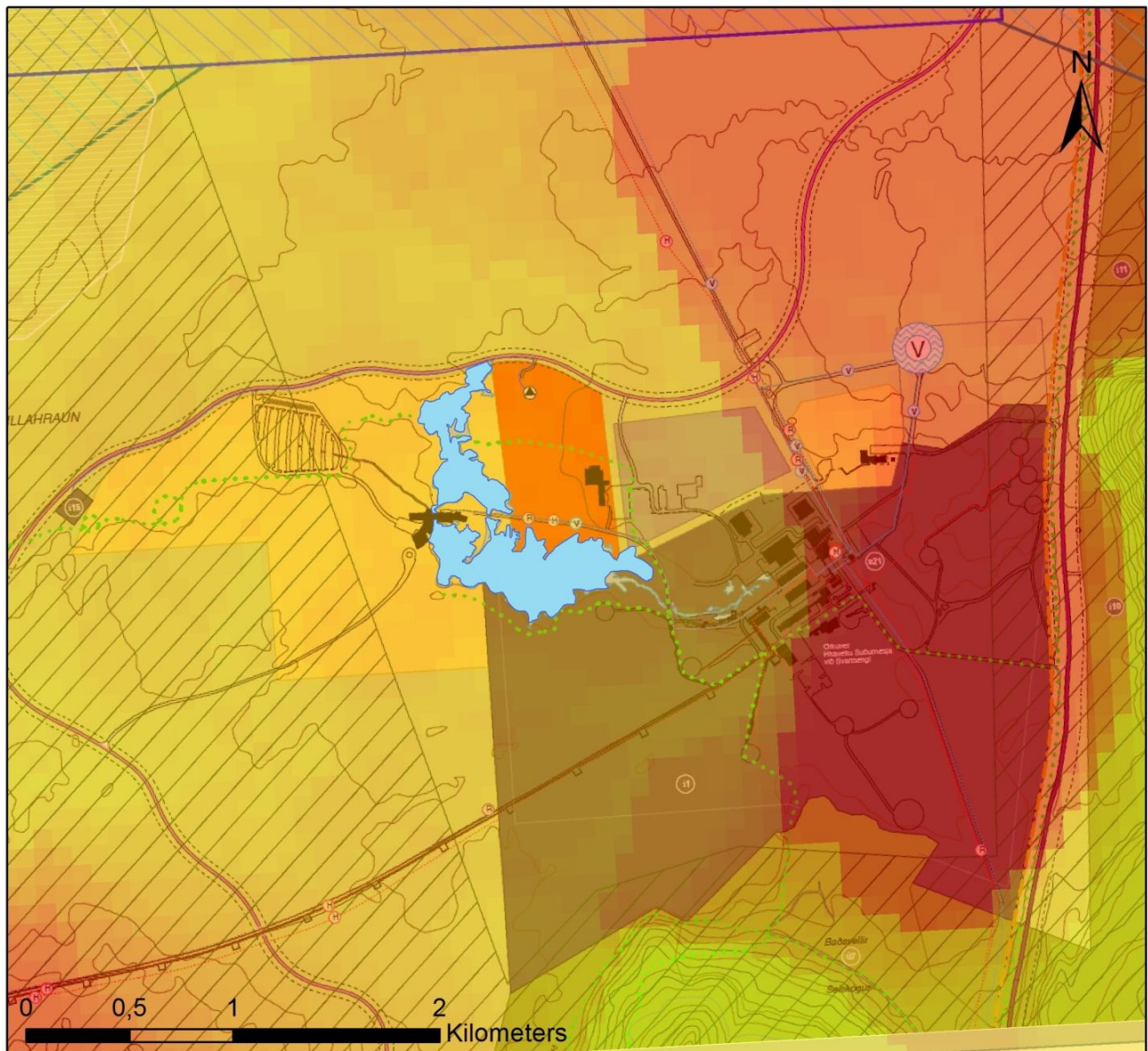
Figure 41 - Combination of the master plan for Svartsengi and the results from the lava flow modelling

Looking at the map shows that there is need for modifications of the master plan based on lava flow modelling. The area east of the power plant that is according to the master plan going to be used as industry zone is badly located and should be moved to an area for instance northwest of the Blue lagoon.

8 Discussion

In the following chapter, the theory methods and results of the project will be discussed.

The idea behind the project was to find out if there was possibility to develop a system that could model lava flow from a volcano. Analyses of scientific articles showed that there have been made several approaches to model lava flow based on different technologies. These methods were very different and with different level of details. On background of these analyses of these methods, it were decided to make a simple model that had it focus on the effect the topography of the area has on how the lava flow as that is one of the biggest factors in how the lava flows. This method does not give the most detailed results of the methods analysed but it also requires less detailed input data and is not as sensitive for wrong input. This is important in case of the Suðurnes area where we do not know the volcanoes and the lava they could distribute very well.

The developed program bases its lava flow calculation on Cellular Automata method that proves to be a good method for the lava flow calculation, as it is effective and offer many possibilities in term of complex analysis.

The software is developed in the programming language Python that is simple to develop using and offer third party extensions. To help an extension called *ArcPy* from ESRI is used as it adds geospatial capabilities to Python. Using the *ArcPy* extension makes the development process faster than if the tools were created in Python but it also has limited abilities and in some cases, it can affect the performance. The development method used was Agile that proved to work well in the development process as it supports very well the amount of unknown elements that were in the development of the program. Especially with focus on the conditions to analyse if lava could flow from one cell to another were modified during the development process.

In general, the developed program is working well. The case study although proved that there is need to be critical to the results and select the input parameters very carefully as otherwise the result might be wrong. It is not possible to say exactly how good the model is, as there is no previous eruption where we know how the topography of the landscape was before the eruption occurred to be able to compare it precisely. In the book 'Natural Disasters' (Sólnes, et al. 2013) there is map of all known lava flows in the area and by comparing that map to the results from the

lava flow modelling show some of the same tendencies in how the lava flow. From that, we can estimate that even though there has not been possibility to test the method properly the results are at least giving good estimate of which areas could be threatened of lava flow if an eruption would occur.

The eruptions in Reykjanes volcano often tends to be short with small amount of lava but often with many eruptions in different vents over a long period of time. In such cases, the lava streams are short but there is also the risk of a long eruption with much lava, which then streams long distance from the eruption vents. On basis of that in the further development there might be good idea to compute the distance the lava flows and then weight the results before the layers are summed together. This would lead to that the lava close to an eruption vent has higher importance in the analyses of the results than lava far away from the eruption vent.

On background of that, we can estimate that although the model is not accurate due to lack of better input parameters it gives very useful results that shows which areas are in most danger if an eruption happens. In general design of the program is working although there is need for improvements in some materials. These are described shortly below.

8.1 Input Parameters

There are few input parameters that are required for the program to run. The first input is the lava thickness which has to be defined and then the lowering factor which both makes shore that the lava stops if it reach flat area and that it don't flow sideways on a steep hill. These factors are only estimated on the tests made in the Case Study, as they require an analysis of an existing lava flow from a defined eruption vent to be set precisely. Really the only way to define these factors is to analyse lava from one eruption and then try to get the results of the lava flow modelling as close to reality as possible. To do so there is need for a good DEM that is created before an eruption occurs and a précis definition of where the lava did flow. Such a data is not available in the Suðurnes area as there are hundreds of years since last eruption occurred in the area and therefore a DEM created before an eruption does not exist.

Instead of comparing to existing lava flow, the parameters were defined by making test runs and visually analyse the patterns the lava flowed. On background of these analyses, the parameters used in the case study were set to 10 meters lava thickness and a lowering factor of 0.3 meters. This seemed to work well in the test area, which is located inside Trölladyngja volcano, but when executed on Reykjanes volcano the lava did not flow very long is it was quite flat so the lava flow stopped too early. To fix this problem in the second calculation the lava thickness were changed to 15 meters, which is at the upper boundary of how thick basaltic lava can be. This proved to be much more effective and gave better results. This proves although that the input parameters have to be better defined.

8.1.1 DEM

The quality of the DEM used also proves to be bad, especially in flat areas where often the DEM makes the area even flatter. This makes the result questionable, as the DEM is an input parameter. The reason for how bad the DEM is the production method as it is made from elevation contours with 20 meters elevation difference in-between them. This makes lot of information get lost as every small element in the landscape that falls in-between the contours is not in the model. This method is probably used, as the elevation data used to make version 1 of the DEM only were old print plates with contours that were digitalized. Today big parts of the contours are made of never data collected by other methods and according to the metadata of the curves the data for the Suðurnes area and the rest of south west Iceland comes from the private company Samsýn. As Samsýn is the distributor, the data are probably made from aerial photos and on background of that, the model would be much better if created from the original data instead of the contours, as lot of data gets lost in the processing process.

Looking at the DEM there are improvements on the way as in the start of 2014 there will be a new DEM developed using CARTOSAT satellite photos combined with COSMO-SkyMed radar data from satellites. This DEM will have a cell size of 10 meters and precision of around 5 meters. (Landmælingar Íslands (C) 2013)

Another possibility for a better DEM is the private distributor Loftmyndir ehf, which makes a DEM with a cell size of 20 meters, developed from aerial photographs. (Loftmyndir ehf 2012)

8.2   **Performance**

The performance of the program is important, as there is big amount of iterations that have to be done. The calculation of the developed is quite slow due to the number of iterations that have to be calculated. In the second execution of the case study there were for instance done 225000 iterations through the while loop that calculates the lava flow. This second execution also took around 15 minutes for each eruption vent and in total, the program took almost 5 days to execute on a computer with a 3 GHz dual core processor and 4 GB of RAM.

 One of the most important elements spotted during the test is that the program only uses one of the cores of the computers processor even though there are two cores available. This is because for a program to be executed on two or more cores of a processor it has to be doing two processes at the same time, which is very complicate to program for.

Another element which is important for the performance is the fact that the program is build up on tools from *ArcPy* which in some cases can slow the calculation down. A third element is number of iterations as that is preset how many time the while loop containing the Cellular Automata lava flow calculation should run and therefore if it had nowhere to go the lava might have stopped flowing early in the process but the program tries again and again until the defined number of iterations is reached.

9 Conclusion

In this project, the focus was on how and if lava could be modelled. In this chapter, it will be concluded if the result is successful. It came clear early in the process that it was possible to model lava flow although it is a complicated calculation. The selection of method to model the lava flow was based on the fact that the model had to be simple and therefore it was chosen to base the calculation mainly on the topography of the landscape. The model is then developed in Python using extension from ArcPy which proves to be very good choose for the development process but ArcPy also put some limitation on especially further development. To analyse if the Problem statement has been solved the research questions will be answered below and then it will be concluded if the project has been successful.

In chapter 1.1 Problem statement the following problem statement were formulated.

> **How is it possible calculating the risk of an area being covered in lava during a volcanic eruption, using GIS?**

To help finding out if the problem statement has been solved probably we start by see if all of the research questions have been answered.

1. **Is it possible to model lava flow using GIS?**

Analyses of different approaches to model lava flow showed that there is possible to model lava flow using GIS although lava is complicated to simulate and therefore analyses of lava flow is associated with a certain amount of inaccuracy.

2. **How can lava flow be modelled in a simple way?**

As the Theory chapter revealed there are several different methods to analyse lava flow. This project uses a method that focus on the topography of the landscape as the most important element in lava flow calculation and uses Cellular Automata to make a simple calculation of the lava flow.

3. How can it be secured that all possible volcanoes are taken into consideration?

Here there has to be made an evaluation if the lava theoretically can reach the given area from a given volcano. In this project there were only worked with distance but if the landscape shows clearly that lava cant flow from a volcano to the defined area that volcano don't need to be taken into further analyses.

4. How can lava flow modelling be used in spatial planning

This question is described theoretically in the project and the output layer of the developed program can be used to analyse where there is best to plan a new neighbourhood.

On bases of the answers to the research question and the Discussion, it can be concluded that the problem statement has been solved during the project. The developed program is effective and can be used to model lava flow. There is although need for further improvements, mainly in terms of the input parameters, including the DEM. The program itself can also be improved, mainly with focus on performance as if the DEM gets better the programs performance soon can become a problem.

10 Perspectives

This chapter describes the future perspectives of the lava flow modelling program. In the Discussion there were pointed out several elements that could be used to make the program better.

One of the issues described is the performance of the program, which can be serious especially if we look at for instance the Capital area of Iceland where there is much more volcanoes that have to be taken into consideration and therefore execution could take many weeks to do. To improve the performance there are many things to do. The first one is simply to go through the script and see if there are any parts of it that can be simplified.

Another improvement could be to rewrite the script so it does not need to use the extensions from *ArcPy* to run. These both might increase the speed and make the program independent of platform other than Python.

A third way is to develop the program so it can run two or more processes at a time to make it able to fully utilize the computers power in term of using multiply cores of the processor.

To improve the lava flow calculations there is a need to analyse how the program might be improved in terms of almost flat areas where the flow is controlled by the pressure from behind rather than of gravity. This might although not be as big problem with a better DEM as the used DEM does have big areas that are represented as flat but are in fact with a slight slope in some direction.

There might also be done improvements of how points are distributed as there are often mountains that do not contain points close to the top using the current method. To improve that there might be an idea to for instance please the eruption on the highest point within a given area or make all cells within that area to one eruption vent. This would keep the number of eruption vents the same but might make the results better. This although need to be analysed further before a decision is made.

11 References

Agile Alliance (A). "Agile Allience." *The Twelve Principles of Agile Software.*
http://www.agilealliance.org/the-alliance/the-agile-manifesto/the-twelve-principles-of-agile-
software/ (accessed 04 30, 2013).

Agile Alliance (B). "The Agile Manifesto." *Agile Allience.* http://www.agilealliance.org/the-
alliance/the-agile-manifesto/ (accessed 04 30, 2013).

Balstrøm, Thomas, Ole Jacobi, and Lars Bodum. *Bogen om Gis og Geodata.* København: Forlaget
GIS og Geodata, 2006.

Connor, Laura J, Charles B Connor, Khachatur Meliksetian, and Ivan Savov. "Probabilistic approach
to modelling lava flow inundation: a lava flow hazard assessment for a nuclear facility in Armenia."
Journal of Applied Vulcanology, 2012.

Esri (A). *ArcGIS Help 10.1 - Con (Spatial Analyst(.* 08 11 2012.
http://resources.arcgis.com/en/help/main/10.1/index.html#/Con/009z00000005000000/
(accessed 04 18, 2013).

Esri (B). *ArcGIS Help 10.1 - Feature To Raster (conversion).* 24 10 2012.
http://resources.arcgis.com/en/help/main/10.1/index.html#//00120000002v000000 (accessed 04
20, 2013).

Esri (C). *ArcGIS HELP 10.1 - Focal Statistics (Spatial Analyst).* 08 11 2012.
http://resources.arcgis.com/en/help/main/10.1/index.html#//009z000000qs000000 (accessed 04
18, 2013).

Felpeto, A., V. Arana, R. Ortiz, M. Astiz, and A. Garcia. "Assessment of Lawa Flow Hazard on
Lanzarote (Canary Islands)." *Natural Hazards*, 2001: 247 - 257.

Felpeto, Alecia. "Voris User's guide." Vers. 2.0.1. february 2009. http://www.gvb-
csic.es/GVB/VORIS/VORIS_2_0_1_guide.pdf.

Felpeto, Alicia, Joan Marti, and Ramon Ortiz. "Automatic GIS-based system for volcanic hazard
assessment." *Journal of vulcanology and geothermal Research*, 2007: 106 - 116.

Griffiths, R. W. *The dynamics of Lava Flows.* Research School of Earth Scienses, The Australin National University, Canberra, Australia: Annual Reviews, 2000.

Grindavíkurbær. "Grindavík aðalskipulag 2012-2030." 30 11 2011. http://grindavik.is/gogn/2012/adalskipulag/2012_04_03_Greinarger_ASK_Grindavik_2010-2030_minnkad.pdf.

Guðmundsson, Ari Trausti. *Living Earth, Outline of the Geology of Iceland.* Reykjavík: Mál og Menning, 2007.

Jennings, Nathan. *A Python Primer for ArcGIS.* 2011.

Jensen, Esther Hlíðar. *Hraunflæðilíkan|Fróðleikur|Jarðhræringar|Veðurstofa Íslands.* 26 3 2010. http://www.vedur.is/skjalftar-og-eldgos/frodleikur/greinar/nr/1857.

Landmælingar Íslands (A). "IS50V Version 4.0." Akranes, 2013.

Landmælingar Íslands (B). "Nákvæmni - Notagildi - Nýsköpun." *Landmælingar Íslands.* Akranes: Landmælingar Íslands, 02 2012.

Landmælingar Íslands (C). *Stórt skref í Kortagerð á Íslandi.* 12 04 2013. http://www.lmi.is/stort-skref-i-kortagerd-a-islandi/.

Loftmyndir ehf. *TK-50 Stafrænn kortagrunnur í viðmiðunarkvarða 1:50.000.* Data description, Reykjavík: Loftmyndir ehf, 2012.

Longley, Paul A., Michael F. Goodchild, David J. Maquire, and David W. Rhind. *Geographic Information Systems & Sciense.* Hoboken: John Wiley & Sons, Inc, 2011.

New Horizons. *Agile Project Management Meets Custumer Needs.* 12 11 2012. http://computertrainingcenters.com/agile-development-meets-customer-needs/ (accessed 05 02, 2013).

Patterson, Dan. *Split Layer By attributes | ArcGIS Resource Center.* 17 03 2011. http://resources.arcgis.com/gallery/file/geoprocessing/details?entryID=37AEB018-1422-2418-A036-CA6D9920F808 (accessed 04 17, 2013).

Python Software Foundation (B). *Python Programming Language – Official Website.* http://www.python.org/ (accessed 03 20, 2013).

Python Software fundation (A). *General Python FAQ.* http://docs.python.org/3/faq/general.html (accessed 04 25, 2013).

Python Software Fundation (C). *The Python Tutorial.* http://docs.python.org/2/tutorial/ (accessed 04 25, 2013).

Ríkislögreglustjórinn Almannavarnadeild (A). „Áhættuskoðun almannavarna - Helstu niðurstöður." 2011.

Ríkislögreglustjórinn Almannavarnadeild (B). "Áhættuskoðun Almannavarna, Lögreglustjórinn á Suðurnesjum." 2011.

Rossum, Guido van, and Fred L. Drake. *The Python Library Reference - Release 2.7.4.* Python Software fondation, 2013.

Shalizi, Cosma Rohilla. *Cosmas notebook - Cellular Automata.* 29 12 2012. http://vserver1.cscs.lsa.umich.edu/~crshalizi/notabene/cellular-automata.html (accessed 04 25, 25).

Skipulagsstofnun (A). *Skipulagsstofnun: Skipulagsmál.* http://www.skipulagsstofnun.is/skipulagsmal/ (accessed 04 09, 2013).

Skipulagsstofnun (B). *Skipulagsstofnun: Svæðisskipulag.* http://www.skipulagsstofnun.is/skipulagsmal/svaedisskipulag/ (accessed 04 09, 2013).

Skipulagsstofnun (C). *Deiliskipulag.* http://www.skipulagsstofnun.is/skipulagsmal/deiliskipulag/ (accessed 04 20, 2013).

Skipulagsstofnun (D). *Aðalskipulag | Skipulags- og byggingarmál.* http://www.skipulagsstofnun.is/skipulagsmal/adalskipulag/ (accessed 04 19, 2013).

Sólnes, Júlíus, Ásgeir Ásgeirsson, Bjarni Bessason, and Freysteinn Sigmundsson. *Náttúruvá Á Íslandi, Eldgos og Jarðskjálftar.* Reykjavík: Viðlagatrygging/ Háskólaútgáfan, 2013.

Spataro, W., M.V. Avalio, D.D'Ambrosio, V. Lupiano, R. Rongo, and G.A. Trunfio. "Lawa flow simulation with cellular Automata: Applications for Civil Defense and Land Use Planning." *Proceedings of the International Conference on Scientific Computing.* Las Vegas, 2011. 205-211.

Spataro, William, Maria V. Avalio, Valeria Lupaino, Giuseppe A. Trunfio, Rocco Rongo, and Donato D' Ambrosio. "The latest release of the lava flows simulation model SCARIA: first application to Mt Etna (Italy) and solution of the anistropic flow direction problem on an ideal surface." *Procedia Computer science*, 2012: 17-26.

Umhverfis og Auðlindaráðherra. "Skipulagsreglugerð." Umhverfis og Auðlindaráðuneytið, 16 01 2013.

Valsson, Guðmundur Þór, Þórarinn Sigurðsson, Christof Völksen, and Markus Rennen. *ISNET2004 - Niðurstöður úr endurmælingum Grunnstöðvanets Íslands.* Landmælingar Íslands, 2007.

Vestmanneyjabær. *Heimaeyjargosið - Heimaslóð.*
http://heimaslod.is/index.php/Heimaeyjargosi%C3%B0# (accessed 05 02, 2013).

Appendix 1 Lava Flow Modelling

```python
 1: # Import arcpy and other nessecary extensions
 2: import arcpy
 3: from arcpy.sa import *
 4: from arcpy import env
 5: import datetime
 6: import os
 7: # define and print the current date and time
 8: now = datetime.datetime.now()
 9: print now.strftime("%Y-%m-%d %H:%M")
10: #Allow excisting outputs to be owerwritten
11: arcpy.gp.overwriteOutput = 1
12: # Check out any necessary licenses
13: arcpy.CheckOutExtension("spatial")
14: #Define paths and variables
15: path = raw_input("write the path to the workspace")
16: vulcanoes = raw_input("link to the polygons representing volcanoes")
17: dem = raw_input("write the path to the Digital elevation model")
18: lava = int(raw_input("write lava thickness"))
19: alfa = float(raw_input("write the lowering factor for a flat area"))
20: maxit = int(raw_input("write the number ot iterations to be done for each venture opening"))
21: rastersize = int(raw_input("Write the distance beetween eruption centers"))
22: # create geodatabases and folders
23: arcpy.CreateFileGDB_management(path, "trash.gdb")
24: arcpy.CreateFileGDB_management(path, "inputpoints.gdb")
25: arcpy.CreateFileGDB_management(path, "finaloutput.gdb")
26: os.makedirs(path + "\\lavaraster")
27: os.makedirs(path + "\\lavapoints")
28: # Process: Create Constant Raster
29: CreateConsta2 = path + "\\trash.gdb\\raster"
30: arcpy.gp.CreateConstantRaster_sa(CreateConsta2, 15, "INTEGER", rastersize, vulcanoes)
31: print "Raster createt"
32: # Convert raster to point
33: inRaster = path + "\\trash.gdb\\raster"
34: outPoint = path + "\\inputpoints.gdb\\pointsuncut"
35: field = "Value"
36: arcpy.RasterToPoint_conversion(inRaster, outPoint, field)
37: #clip the points according to the polygons defining the volcanoes
38: pointscut = path + "\\inputpoints.gdb\\pointscut"
39: arcpy.Clip_analysis(outPoint, vulcanoes, pointscut, "")
40: # Calculate new Field "pointid"
41: arcpy.CalculateField_management(pointscut, "pointid", "[OBJECTID] + 10000", "VB", "")
42: # Load required toolboxes for the Split layer by attributes tool
43: arcpy.ImportToolbox("C:/lava/SplitLayerByAttributes.tbx")
44: # Local variables:
45: lavapoints = path + "\\lavapoints"
46: pointscut = path + "\\inputpoints.gdb\\pointscut"
47: # Process: Split Layer By Attributes
48: arcpy.gp.toolbox = "C:/lava/SplitLayerByAttributes.tbx";
49: arcpy.gp.SplitLayerByAttributes(pointscut, "pointid", "lavaflow", lavapoints)
50: print "points developed"
51: slope = path + "\\trash.gdb\\slope"
52: arcpy.Slope_3d(dem, slope, "PERCENT_RISE", 1)
53: slope = path + "\\trash.gdb\\slope"
54: slope1 = Raster(slope)
55: lowering = Con(slope1 <= 5,0.6,(slope1 - 5)/75*(15 - 0.6) + 0.6)
56: lowering.save(path + "\\trash.gdb\\lowering")
57: # Set the extent of the raster layers
58: arcpy.env.extent = dem
59: # Set the workspace.
60: arcpy.env.workspace = path + "\\lavapoints"
61: num = 10000
62: dem1 = Raster(dem)
63: lowering = path + "\\trash.gdb\\lowering"
64: low = Raster(lowering)
65: shp_List = arcpy.ListFiles("*.shp")
66: valField = "grid_code" # the field containing the Lava thickness i
67: for layer in shp_List:
```

```python
68:     num = num + 1
69:     s = str(num) # the number has to be string in next step
70:     inFeatures = path + "\\lavapoints\\lavaflow" + s + ".shp"
71:     outRaster = path + "\\trash.gdb\\lava" + s #the raster layer made
72:     cellSize = 20 # define the cellsize of the new layer
73:     # Execute FeatureToRaster
74:     arcpy.FeatureToRaster_conversion(inFeatures, valField, outRaster, cellSize)
75:     # add DEM to lavaflow layers
76:     lavaDem = dem1 + Raster(outRaster)
77:     lavaDem.save(path + "\\lavaraster\\lavadem" + s)
78:     print layer + "is being calculated"
79:     now = datetime.datetime.now()
80:     print now.strftime("%Y-%m-%d %H:%M")
81:     numit = 0
82:     while numit < maxit:
83:         rastercalc = Raster(path + "\\lavaraster\\lavadem" + s)
84:         rastercalc2 = Con(IsNull(rastercalc), 0, rastercalc)
85:         rastercalc2.save (path + "\\lavacal" +s)
86:         del rastercalc
87:         rastercalc3 = Raster(path + "\\lavacal" +s)
88:         focal1 = path + "\\focal1"
89:         focal2 = path + "\\focal2"
90:         # Process: Focal Statistics
91:         arcpy.gp.FocalStatistics_sa(rastercalc3, focal1, "Rectangle 3 3 CELL", "MAXIMUM",
    "DATA")
92:         arcpy.gp.FocalStatistics_sa(rastercalc3, focal2, "Circle 1 CELL", "MAXIMUM", "DATA")
93:         focal1 = Raster(path + "\\focal1")
94:         focal2 = Raster(path + "\\focal2")
95:         outcon = Con(((((rastercalc3 > focal1 - low*1.414) | (rastercalc3 > focal2 - low)) &
    \
96:             (rastercalc3 > 0)), rastercalc3, Con(focal1 - low*1.414 > focal2 - low,\
97:             (Con(dem1 + (low*1.414)>= focal1, 0, Con(focal1 - dem1 >= lava + (low*1.414),\
98:             dem1 + lava, focal1 - (low*1.414)))),\
99:             (Con(dem1 + low >= focal2, 0,Con(focal2 - dem1 >= lava + low, dem1 + lava,
    focal2 -low)))))
100:        outcon.save (path + "\\lavaraster\\lavadem" +s)
101:        del focal1
102:        del focal2
103:        del rastercalc3
104:        numit = numit + 1
105:    print "Lawaflow from eruption vent nr." + s + "is ready"
106:    now = datetime.datetime.now()
107:    print now.strftime("%Y-%m-%d %H:%M")
108: arcpy.env.workspace = path + "\\lavaraster"
109: #create a list of rasters in the workspace
110: rasters = arcpy.ListRasters("*", "All")
111: i = 0
112: iname = str(i)
113: #Create raster with value 0 to base the calculation of the number of lava flows on
114: conras = path + "\\finaloutput.gdb\\sumras0"
115: arcpy.gp.CreateConstantRaster_sa(conras, "0", "INTEGER", "20", dem)
116: #loop through rasters in list
117: for raster in rasters:
118:     print raster + "is under processing"
119:     out = Con(IsNull(raster), 0, Con(Raster(raster) == 0, 0, 1))
120:     out.save(path + "\\trash.gdb\\out")
121:     out = Raster(path +"\\trash.gdb\\out")
122:     outSUM = Raster(path + "\\finaloutput.gdb\\sumras" + iname)
123:     #sum rasters together
124:     outSUM2 = outSUM + out
125:     i = i + 1
126:     iname = str(i)
127:     outSUM2.save(path + "\\finaloutput.gdb\\sumras"+iname)
128: print "end of processing"
129: now = datetime.datetime.now()
130: print now.strftime("%Y-%m-%d %H:%M")
```