



Volcanogenic floods at Sólheimajökull. Hazard identification,
monitoring and mitigation of future events

Baldur Bergsson



**Faculty of Life and Environmental
Sciences
University of Iceland
2016**

Volcanogenic floods at Sólheimajökull. Hazard identification, monitoring and mitigation of future events

Baldur Bergsson

90 ECTS thesis submitted in partial fulfillment of a
Magister Scientiarum degree in Geography

Advisors
Melissa Anne Pfeffer
Ingibjörg Jónsdóttir

Faculty of Life and Environmental sciences
School of Engineering and Natural Sciences
University of Iceland
Reykjavik, June 2015

Volcanogenic floods at Sólheimajökull. Hazard identification, monitoring and mitigation of future events

Volcanogenic floods at Sólheimajökull

90 ECTS thesis submitted in partial fulfillment of a *Magister Scientiarum* degree in Geography

Copyright © 2016 Baldur Bergsson
All rights reserved

Faculty of Life and Environmental sciences
School of Engineering and Natural Sciences
University of Iceland
Sturlugata 7,
101
Reykjavík
Iceland

Telephone: 525 4000

Bibliographic information:

Baldur Bergsson, 2015, Volcanogenic floods at Sólheimajökull. Hazard identification, monitoring and mitigation of future events, Master's thesis, Faculty of Life and Environmental sciences, University of Iceland, pp. 97.

Printing: Háskólaprent ehf.
Reykjavík, Iceland, June 2016

Abstract

Volcanogenic floods from underneath glaciers happen almost on a yearly basis in Iceland, mostly due to build-up of water from geothermal melting beneath glaciers or due to sub-glacial eruptions. This work examines the vulnerability of the growing tourist sector in the area of Sólheimajökull to volcanogenic floods of all sizes, but with a special focus on the most frequent minor flood events. Employees from the four largest tour operators in the area, local law enforcement and civil protection officials are interviewed to learn about their perception of risk from volcanogenic floods at Sólheimajökull and their current strategies to minimizing risk. The July 2014 minor flood of geothermal water was closely monitored and observed changes in the hydrological and seismic data from this event is applied to identify past undocumented minor events. The risk associated with these minor floods is assessed in light of their high frequency, with particular emphasis on the until-now under-monitored hazard associated with high concentrations of gas released during minor jökulhlaups. An overview of the current monitoring techniques for monitoring volcanogenic floods in the area is given, putting focus on the real-time systems. Suggestions are made for mitigating the risk associated with the ever greater number of people visiting the area of Sólheimajökull. Atmospheric gas measurements and adequate informative infrastructure are found to be needed in the area, and the tour guides could have better knowledge of the processes that take place before and during a volcanogenic flood.

Útdráttur

Jökulhlaup eru flóð sem koma undan jöklum og eru nánast árlegur viðburður hér á landi. Þau orsakast aðallega vegna uppsöfnunar vatns frá jarðhitakerfum undir jökli eða vegna eldgosa undir jökli. Þetta verkefni metur aukna hættu sem steðjar að vaxandi fjölda ferðamanna við Sólheimajökul vegna flóða af öllum stærðum er verða af völdum jarðhita eða eldvirkni, en með sérstaka áherslu á minniháttar atburði sem hingað til hafa ekki verið talnir til jökulhlaupa. Tekin eru viðtöl við örryfisfulltrúa fjögurra stærstu ferðaþjónustuaðilanna á svæðinu og viðkomandi lögregluþyrirvöld til að meta skilning þeirra á áhættunni vegna jökulhlaupa undan Sólheimajökli og þær viðbragðsáætlanir sem eru til staðar. Lítið hlaup af jarðhita vatni er kom undan Sólheimajökli 2014 var vandlega vaktað vegna mikillar gaslosunar. Vatna og jarðskjálftamæligögn frá atburðinum eru notuð til að bera kennsl á fyrri óskráða atburði og áhættuna af þeim, vegna þess hve algengir þeir eru. Greint er frá þeim aðferðum sem notaðar eru í dag til vöktunar Jökulhlaupa, þar sem áhersla er lögð á rauntímakerfi. Tillögur eru gerðar til að draga úr áhættu vegna síaukins fjölda ferðamanna við Sólheimajökul. Yfirborðs- gasmælingar og fullnægjandi aðgengi að nauðsynlegum upplýsingum þarf að betrumbæta á svæðinu. Fararstjórar gætu haft betri yfirsýn yfir þá ferla sem viðhafðir eru, fyrir og meðan á Jökulhlaupi stendur.

Table of Contents

Abstract	iii
Útdráttur	iv
Table of Contents.....	v
List of Figures	vii
List of Tables.....	x
Abbreviations.....	xi
Acknowledgements	xii
1 Introduction.....	15
1.1 Study area	15
1.1.1 Jökulhlaups and cauldron formation	16
1.1.2 Accessibility.....	18
1.2 Objective of this study.....	19
1.3 Key definitions	19
2 Volcanogenic Jökulhlaups and their hazards: theory and state of knowledge.	21
2.1 What is a Jökulhlaup?.....	21
2.1.1 Volcanogenic floods	22
2.1.2 Hazards accompanying volcanogenic floods.....	25
2.1.3 Monitoring a volcanogenic flood.....	27
2.1.4 Jökulhlaups at Sólheimajökull	28
2.2 Human activity and risk.	31
2.2.1 Hazard, risk and exposure.....	Error! Bookmark not defined.
2.2.2 Locals.....	31
2.2.3 Tourism	35
2.2.4 Changes during the study period.....	31
3 Methods.....	38
3.1 Hazard and risk (stage 1).....	38
3.1.1 Hazard identification and perception of risk.....	38
3.1.2 Interview topics.....	39
3.2 Monitoring/Mitigation (stage 2).....	41
4 Results	44
4.1 Awareness and preparedness for the flood hazard (stage 1)	44
4.1.1 Authorities.....	44

4.1.2	Tour companies (stage 2)	46
4.2	Hazard monitoring.	52
4.2.1	Real-time network	53
4.2.2	Real-time measurements (network not established).	61
4.2.3	Campaign measurements.	64
4.2.4	Techniques not used currently at Sólheimajökull.....	67
5	Discussion and Conclusions	69
5.1	Human activity	69
5.2	Monitoring actions	72
5.3	Conclusions	74
	References	78
	Appendix A	83
	Appendix B.....	85
	Appendix C	86
	Appendix D	91

List of Figures

- Figure 1: Overview map of the study area showing the location of cauldrons, the red dots mark the cauldrons impacting Sólheimajökull. The yellow star marks Sólheimajökull and the location of the tourist area. The Ice divides represent if melt water will flow south, east or west (Björnsson, Pálsson, & Guðmundsson, 2000). 15
- Figure 2: The three main flood routes from Mýrdalsjökull. Map created for the ICP showing evacuation centers and locations of road closures during volcanic eruptions of Katla and Eyjafjallajökull (Ríkislögreglustjórnin, 2016). 16
- Figure 3: Sólheimajökull the glacier front is less than 6km from the ring road of Iceland. The road to the glacier has been paved since late 2014. 17
- Figure 4: Illustration showing the different forms of water accumulation (<http://pubs.usgs.gov/pp/p1386a/gallery2-fig86.html>). 22
- Figure 5: Illustration showing the two main processes causing the formation of cauldrons (Guðmundsson M. T., Högnadóttir, Kristinsson, & Guðbjörnsson, 2007). 22
- Figure 6: Hydrographs showing two typical characteristic time evolutions of different floods (Björnsson H. , 2002). 24
- Figure 7: A schematic timeline of the different hazards to be expected for a minor flood. The timeline includes the real-time data including electrical conductivity, water temperature and cumulative seismic moment released within the catchment area of Sólheimajökull in the 2014 minor flood. The conductivity peak lasted for 9 days from the start of the increase to when the concentration reached background levels again. 24
- Figure 8: Vertical profile of Sólheimajökull, Source taken from Guðmundsson 2015 data from Mackintosh (1999) and Björnsson (2000). 25
- Figure 9: Skeiðarárbrú after the Jökulhlaup in 1996 (Fréttablaðið, 2011). 25
- Figure 10: Subglacial flow paths of water draining from the Skaftár cauldrons in Vatnajökull (Veðurstofan, 2015). 27
- Figure 11: The minor event of July 2014. The darker water close to the ice margin is the geothermal water. Site of gas instrument is marked in red 29
- Figure 12: Flood hazard map by Almannavarnir. Time on map indicates arrival of flood water from initiation of eruption (Almannavarnir, 2016b). 30
- Figure 13: An aerial photograph showing the extent of different flood scenarios down Sólheimajökull. The sides of the glacier are red as it is likely that the flood water may break out from the glacier surface in those areas. (Guðmundsson M. T., 2015). 31

- Figure 14: Flow of information from monitoring official to local residents. 34
- Figure 15: Overview map of the study area showing locations of signs, the two parking areas and two examples of typical routes taken on the glacier by the guided groups. Photos from the locations of the signs are found from Figure 29-33 in Appendix C. (Aerial photograph from loftmyndir ehf, GPS tracks from Matteo Meucci a guide from Icelandic Mountain Guides and the outline of past glacier extent is from Oddur Sigurðsson). 36
- Figure 16: Flow of information from monitoring official to the tourist. 45
- Figure 17: Signs installed after the publishing of the report by Guðmundsson et al. in 2015. 46
- Figure 18: Different hazards present, separating the everyday hazards from the volcanogenic induced hazards. 47
- Figure 19: Health effect of gas exposure. Identification of symptoms caused by exposure to the human body (Bergsson & Pálsson, 2016). 50
- Figure 20: Overview of area of seismic interest in the catchment area of Sólheimajökull showing the location of seismic stations around Katla. 55
- Figure 21: Melissa Anne Pfeffer and Njáll Fannar Reynisson taking a water sample at the outflow location of the flood. 56
- Figure 22: Subset of time series of data used to identify floods. The green points indicate times when the rise in conductivity and drop in water temperature meet the thresholds to distinguish a flood. The yellow points indicate when the increase of seismic moment meets the threshold. 57
- Figure 23: The four floods identified at Sólheimajökull from January 2009 to January 2016. Larger figures of these floods can be seen in Appendix D. 60
- Figure 24: Gas concentrations during the July 2014 flood. 62
- Figure 25: An example of the time period of different monitoring techniques that could be of use to an early warning system. 63
- Figure 26: Flight lines over the cauldrons of Mýrdalsjökull (Guðmundsson M. T., Högnadóttir, Kristinsson, & Guðbjörnsson, 2007). 65
- Figure 27: A plot showing ice subsidence of the eastern Skaftár cauldron in 2015 monitored by a GPS instrument in the cauldron. The event was forecasted by 4 days of warning. 68
- Figure 28: Proposed timelines of stages for flood events of Skaftá and Sólheimajökull. 73
- Figure 29: Sign 1. The only sign mentioning that the area is restricted. 86

Figure 30: Sign 2. Warning sign by the start of the hiking path. 87

Figure 31: Information signs about the geology of the area. One of the signs has a yellow box with the text: "only go on the glacier with a professional guide". 88

Figure 32: Sign 4. Location of closed road segment. No road restriction has been in place since August 2014. 89

Figure 33: Sign 5. In northern parking lot (advises you to seek a glacier guide to go on the glacier). 90

Figure 34: The minor flood of July 2014. 92

Figure 35: The minor flood of June 2012. 93

Figure 36: The minor flood of October 2011. 94

Figure 37: The minor flood of September 2011. 95

List of Tables

Table 1: Table grouping together Jökulhlaups based on peak flowrate to assess their size (Guðmundsson & Larsen, 2013)	21
Table 2: Exposure limits to volcanic gases a set by the AOSH covering maximum 8 hour average exposure and maximum average 15 minute exposure (Vinnueftirlitið, 2016).	26
Table 3: Techniques currently used to monitor volcanogenic floods and their relevance to monitoring Sólheimajökull.....	53
Table 4: Minor volcanogenic floods in the period from 2009-2016 at Jökulsá	58

Abbreviations

- Administration of Occupational Safety and Health (AOSH)
- Multi component gas analyzing system (MultiGAS)
- Icelandic Civil Protection (ICP)
- Icelandic Meteorological Office (IMO)
- Icelandic Coast Guard (ICG)
- Icelandic tourist board (ITB)
- Institute of Earth Sciences (IES, University of Iceland)
- World Meteorological Organization (WMO)
- United Nations international strategy for disaster reduction (UN-ISDR)
- Part per million (ppm)

Acknowledgements

Many people have assisted me during the work of this thesis in one way or another. To begin with I would like to thank my two supervisors for supporting me in this project involving the field work and the writing of this thesis.

I thank Alessandro Aiuppa for getting me involved with gas monitoring and for giving me the opportunity to present the first results of this project in the CCVG workshop held in Chile 2014.

I would like to thank Sara Barsotti and Matthew J. Roberts at the IMO for reading over the thesis and helping with outlining the monitoring techniques.

Oddur Sigurðsson and Snorri Zóphóníasson are thanked for the open discussions we had regarding Sólheimajökull and for sharing their knowledge about the area in many ways.

Martin Hensch is thanked for assisting with the selection of seismic data and for teaching me how to display the data and for offering help with different interpretations and general discussion on the subject.

Njáll Fannar Reynisson and Gunnar Sigurðsson also assisted greatly with selection and data interpretation for the hydrological data to be used and answered frequent questions about the dataset.

The technicians from the IMO including Njáll Fannar Reynisson, Hilmar Björn Hróðmarsson, Þorgils Ingvarsson and Jón Otto Gunnarsson helped make the measurements during the minor flood event of Jökulsá á Sólheimasandi in 2014.

I thank all the people that participated in interviews for this project including:

- From IMO: Matthew J. Roberts, Benedikt Ófeigsson, Kristín Vogfjörð and Melissa Anne Pfeffer
- From IES: Eyjólfur Magnússon, Magnús Tumi Guðmundsson, Finnur Pálsson and Ingibjörg Jónsdóttir
- From Almannavarnir: Björn Oddson

- From Police in Hvalsöllum: Kjartan Þorkellson
- From Arcanum: Benedikt Bragason and Tómas Birgir Magnússon
- From Arctic Adventures: Guðmundur Kjartansson
- From Icelandic Mountain Guides: Ívar Finnbogason and Stefán Páll Magnússon
- From Extreme Iceland: Björn Hróarsson and Sighvatur Blöndahl.

I thank my friends and colleagues for giving me support to finish this thesis.

Finally I thank my father Bergur H. Bergsson for reading over my projects and supporting me throughout my time at the University of Iceland.

Thank you.

1 Introduction

Volcanogenic floods (Jökulhlaups) are a risk to lives and infrastructure in Iceland. They can affect large areas in a single event and may change landscapes in the process. As an example, a flood down Markarfljót in southern Iceland could damage or destroy many man-made structures in an area of 800km² including parts of the ring road of Iceland (Pagneux & Roberts, 2015). These floods are geographically bound and the direct flow of water can only effect certain areas while the gas emission from these floods can spread wider. This thesis will focus on the potential jökulhlaup hazard from Sólheimajökull (Figure 1), which is a popular tourist destination today.

1.1 Study area

Mýrdalsjökull in south Iceland covers the caldera of the active volcano Katla. The glacier is 200-700m thick, has an area of 100km² and reaches an elevation of about 1450m. The volcanic system is not only confined by the caldera but stretches out in a fissure swarm that extends about 80km from underneath the glacier to the northeast while the central volcano is 30km across (Larsen G. , et al., 2015). Katla is one of Iceland's most active volcanoes with 21 recorded eruptions since the settlement of Iceland and is regarded as one of Iceland's most hazardous volcanoes (Guðmundsson

M. T., Högnadóttir, Kristinsson, & Guðbjörnsson, 2007). The threats of the volcano include tephra fall out, lava flow, lightning strikes, high gas emissions and Jökulhlaups (volcanogenic floods) (Larsen, Guðmundsson, & Sigmarsson, 2013).

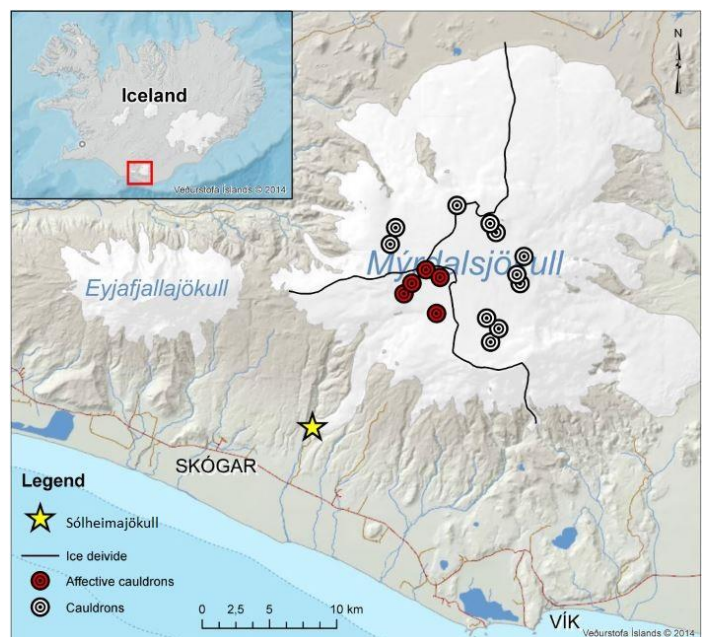


Figure 1: Overview map of the study area showing the location of cauldrons, the red dots mark the cauldrons impacting Sólheimajökull. The yellow star marks Sólheimajökull and the location of the tourist area. The Ice divides represent if melt water will flow south, east or west (Björnsson, Pálsson, & Guðmundsson, 2000).

1.1.1 Jökulhlaups and cauldron formation

The caldera of Katla has three main drainage paths that are valleys cut through the ice covered caldera rim. The water divide shown in Figure 1 is very simplistic showing only if the water beneath the glacier will flow South, East or West but cannot anticipate through which outlet glacier the water will flow. These divides have been identified by the work of the glacier group at the Institute of Earth sciences (IES) (Björnsson, Pálsson, & Guðmundsson, 2000). A more detailed map by the glacier group exists, showing the watershed for each underlying river system, but for this work the simplistic watershed is sufficient. The water flow under a glacier will not in every case follow gravity as the pressure above from the glacier may divert the flow. Thus when the glacier thickens or gets thinner the flow channels may change over time. The main flood pathways of volcanogenic floods are to the east down Kötlujökull to the river Múlakvísl, to the west down Entujökull to the river Markarfljót and to the southwest down Sólheimajökull to the river Jökulsá á Sólheimasandi (referred to as Jökulsá hereafter) as can be seen in Figure 2.



Figure 2: The three main flood routes from Mýrdalsjökull. Map created for the ICP showing evacuation centers and locations of road closures during volcanic eruptions of Katla and Eyjafjallajökull (Ríkislögreglustjórnin, 2016).

All known subglacial eruptions from Katla have produced volcanogenic floods as the lava/ice interaction rapidly melts large volumes of ice creating a flood. Since the settlement of Iceland 1100 years ago, 18 confirmed eruptions have produced Jökulhlaups from Katla and three smaller events have been related to unconfirmed eruptions that did not break the ice surface. One such flood came down Sólheimajökull in 1999 (Larsen G. , et al., 2015).

The catchment area of Sólheimajökull reaches some 2 km into the caldera of Katla and flows through a breach at an elevation of 1050m down to the glacier tongue close to sea level (Björnsson, Pálsson, & Guðmundsson, 2000). The glacier is a temperate non-surging glacier with the glacier snout being visible from the ring road of Iceland (Björnsson H. , 1991).

The catchment area of Jökulsá is approximately 110km² when the gauging station on the ring road is used as a reference point, with the majority (78km²) of the catchment being covered by glacier (Lawler, Björnsson, & Dolan, 1996).

As the caldera is ice-covered, the bedrock topography cannot be seen at the surface apart from the occasional nunatak. The fact that the glacier is covering an active volcano means that the hydrothermal interaction of water with shallow magma intrusions under the glacier causes depressions in the glaciers called cauldrons (Björnsson H. , 2002). Up to 18 cauldrons have been identified on the glacier, this number changes between years due to the ever changing system and are monitored on an annual basis by the glacier group at the IES at the University of Iceland (Guðmundsson, Högnadóttir, & Oddsson, 2015). As the geothermal systems melt the overlying glacier, geothermal water can be detected in the glacial rivers flowing from the glacier. Geothermal gas can escape easier through the drainage channels than through the glacier above, and the glacial rivers of Katla are known to smell of H₂S that has the distinctive rotten egg smell. The cauldrons all fall within the basic watersheds. Each cauldrons can be linked to a river system, the catchment area of Jökulsá hosts at least 5 geothermal sites (five red cauldrons seen in Figure 1) and in the past the river has been known to emit gas and has the nickname Fúlilækur or “Stinky creak” by the locals (Ragnarsson, 2016). This distinctive smell of H₂S has in the last 10-15 years not been as frequent as the years before and there are speculations

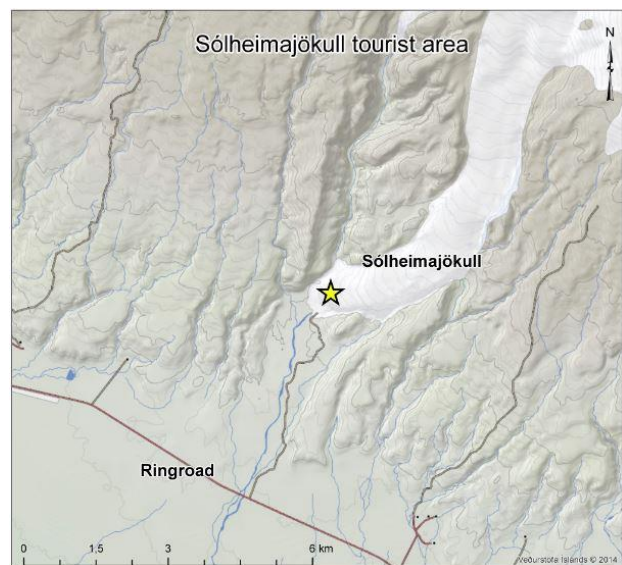


Figure 3: Sólheimajökull the glacier front is less than 6km from the ring road of Iceland. The road to the glacier has been paved since late 2014.

about the cause of this. Locals say the river stopped emitting gas on a regular basis, and now only occasionally the smell of gas is noticed by the people living in the area (Bragason, 2016; Ragnarsson, 2016).

1.1.2 Accessibility

Due to its easy access (Figure 3), popularity and its proximity to Reykjavík (160km), the area is accessible year round. Sólheimajökull is one of the main glaciers visited in Iceland with mountain guide companies offering guided hikes on the glacier year round. The number of people exposed to hazards in an area that is prone to volcanogenic floods and has experienced many in its geological history is ever greater. Prior to 2005, with the latest substantially large event happening in 1999, very few people were directly exposed to the hazard of a flood coming from Sólheimajökull as the flood plain only intersects the ring road in one location and the floodplain is uninhabited by humans (Bragason, 2016). However a substantial flood would have had impact on the local community as power lines, road and the bridge over Jökulsá could have been damaged. As the bridge is one of two evacuation routes during eruptions, the destruction of it would leave evacuations only possible to the East. Today, the situation is very different and has been the cause of great worry for experts as now the flood plain is visited daily by a great number of people (Sigurðsson, 2016; Ólafsson & Þórhallsdóttir, 2016).

1.1.3 Icelandic civil protection (ICP)

“Civil protection” refers to the system for coordinating all the actions that will be made during an emergency that may arise within a community or on the national level. The management of the system is in the hands of the government while the local municipalities control the civil protection in their area. In collaboration with the Icelandic National Police Commissioner Department of Civil Protection (Almannavarnir), the police commissioner of each of the nine police districts is in charge of the operations within their district. The system may be activated at different levels, ranging from small assistance provided by organizations such as the police, fire brigade, ambulance, the road authority, the Red Cross, or the local rescue team, while national emergencies will need greater coordinated response actions. Three different stages: uncertainty, alert, and emergency phases are utilized to guide the actions of the different parties who will follow contingency plans that may be general reaction plans or specialized plans that focus on specific emergencies such as the contingency plans for volcanic eruptions. The initiation of the system can start from any phase as some hazards may come without an uncertainty or alert phase (Almannavarnir, 2016a).

1.2 Objective of this study

The objectives of this study will be to identify 1) the potential hazards that people could face during volcanogenic flood events at Sólheimajökull, 2) the methods currently used to monitor the hazards and 3) what could be done in the future to minimize the risk of these hazards. To do this, a study of the area will be made to identify the frequency, size and the characteristics of floods at Sólheimajökull and to assess the impact such floods could have on the local population and the tourists in the area. The work will be split in two main sections. 1) A study of the general awareness and preparedness of the legislative officials and the tourism industry towards the hazard of a volcanogenic flood and 2) an analysis of the current monitoring networks and the precursory signals that can give a warning for future events as well as identify past events. Additionally a discussion on further mitigation actions will be made and the efforts that could improve the monitoring and management of the area, if deemed necessary. The results may be of use to other locations, where similar problems are faced.

1.3 Key definitions

In 2011 a risk assessment project of volcanic risk in Iceland was started where all the active volcanoes in Iceland were to be studied and documented into an interactive online catalogue for future reference during crisis situations or for further research purposes. This ongoing project follows the hazard framework of the World Meteorological organization (WMO) and the United Nations international strategy for disaster reduction (UN-ISDR) where the UNISDR terminology is used. For clarification this project will follow the same definitions as given by the UNISDR (United-Nations, 2009).

Key definitions followed:

Acceptable risk: The level of potential losses that a society or community considers acceptable given existing social, economic, political, cultural, technical and environmental conditions.

Awareness: (public awareness) The extent of common knowledge about disaster risks, the factors that lead to disasters and the actions that can be taken individually and collectively to reduce exposure and vulnerability to hazards.

Capacity: The combination of all the strengths, attributes and resources available within a community, society or organization that can be used to achieve agreed goals.

Contingency planning: A management process that analyses specific potential events or emerging situations that might threaten society or the environment and establishes arrangements in advance to enable timely, effective and appropriate responses to such events and situations.

Disaster: A serious disruption of the functioning of a community or a society involving widespread human, material, economic or environmental losses and impacts, which exceeds the ability of the affected community or society to cope using its own resources.

Exposure: People, property, systems, or other elements present in hazard zones that are thereby subject to potential losses.

Geological hazard: A geological process or phenomenon that may cause loss of life, injury or other health impacts, property damage, loss of livelihoods and services, social and economic disruption, or environmental damage.

Hazard: A dangerous phenomenon, substance, human activity or condition that may cause loss of life, injury or other health impacts, property damage, loss of livelihoods and services, social and economic disruption, or environmental damage.

Mitigation: The lessening or limitation of the adverse impacts of hazards and related disasters.

Preparedness: The knowledge and capacities developed by governments, professional response and recovery organizations, communities and individuals to effectively anticipate, respond to, and recover from, the impacts of likely, imminent or current hazard events or conditions.

Prevention: The outright avoidance of adverse impacts of hazards and related disasters.

Risk: The combination of the probability of an event and its negative consequences.

Risk assessment: A methodology to determine the nature and extent of risk by analyzing potential hazards and evaluating existing conditions of vulnerability that together could potentially harm exposed people, property, services, livelihoods and the environment on which they depend.

Risk perception:

Vulnerability: The characteristics and circumstances of a community, system or asset that make it susceptible to the damaging effects of a hazard.

As the framework followed did not have a precise definition of a flood, the Oxford Dictionary definition will be used:

Flood: An overflow of a large amount of water beyond its normal limits, especially over what is normally dry land (Dictionary, 2016).

2 Volcanogenic Jökulhlaups and their hazards: theory and state of knowledge.

As many of Iceland's volcanoes and geothermal systems are covered by glaciers, Jökulhlaups are practically a yearly event in the country. Three main glaciers cover active volcanoes that regularly produce such floods: Vatnajökull, Eyjafjallajökull and Mýrdalsjökull. Vatnajökull and Mýrdalsjökull cause the most frequent floods with events happening annually. Other glaciers, such as Hofsjökull, produce floods less frequently (Guðmundsson & Larsen, 2013). This study will focus on Mýrdalsjökull and particularly the outlet glacier Sólheimajökull.

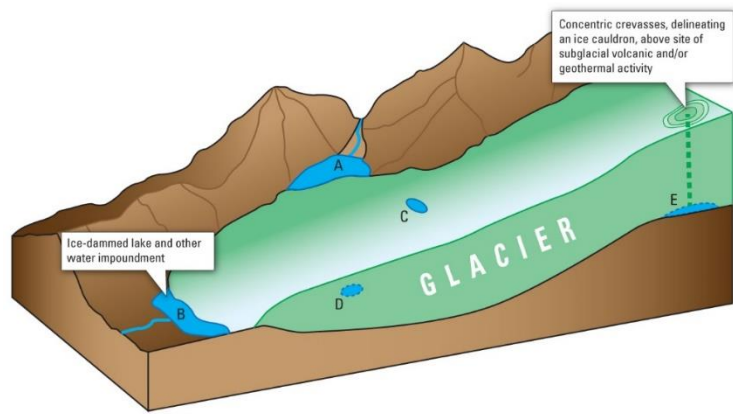
2.1 What is a Jökulhlaup?

A Jökulhlaup is a geological phenomenon consisting of a flood of accumulated glacial meltwater that drains in an event taking a number of hours to a few weeks to evolve. Jökulhlaups can be categorized using different scales, the glacier group at the IES uses an intensity scale of 0-6 as seen in Table 1, while other classification systems are also in use. The intensity in scale in Table 1 is only representative of its peak volume but not its destructive potential, which may be linked to the peak flow volume. The impact of a flood will largely depend on the human exposure in the area referring to people, property, systems, or other elements present in the hazard zones that are subject to potential losses (United-Nations, 2009). The flood water can originate from different sources and based on that, five categories are usually considered: The first two are formed by the accumulation of meltwater either englacial, supraglacial or in glacially-dammed lakes at the glacier margin as can be seen as lagoons A, B, C and D in Figure 4 (Guðmundsson & Larsen, 2013).

Table 1: Table grouping together Jökulhlaups based on peak flowrate to assess their size (Guðmundsson & Larsen, 2013)

size	Peak flow rate
0	< 1.000
1	1.000-3.000
2	3.000-10.000
3	10.000-30.000
4	30.000-100.000
5	100.000-300.000
6	>300.000

These types of floods have happened at Sólheimajökull in the past when the glacier tongue blocked off the valley Jökulsárgil allowing water to accumulate in the blocked valley, periodically flushing the underlying river (Roberts,



Tweed, Russell, Knudsen, & Harris, 2003). These types of

Figure 4: Illustration showing the different forms of water accumulation (<http://pubs.usgs.gov/pp/p1386a/gallery2-fig86.html>).

floods have however not happened since the glacier retreated further up the valley and are no longer considered the same threat as before. These floods will not be discussed further in detail as they are not of direct relevance to the current conditions at Sólheimajökull. The later three mechanisms are all related to volcanic activity (volcanogenic) and are thus of direct relevance to this study. For this reason these three categories are outlined in more detail in the next section. The term Jökulhlaup will hereafter be used as a general term for a glacial flood where a flood is not necessarily of volcanic origin.

2.1.1 Volcanogenic floods

A volcanogenic flood is generated by volcanic activity, and it is classified in three categories:

1. Floods caused by subglacial geothermal systems. These floods happen as geothermal systems melt the bottom surface of the glacier forming either a reservoir of water that drains in a flood event once the water volume is great enough to lift the glacier or where continuous drainage is allowed as shown in Figure 5. Typically water seepage events

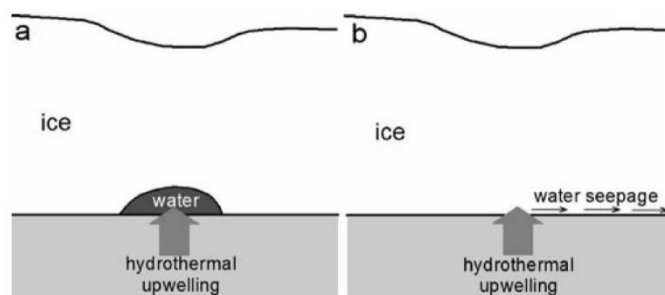


Figure 5: Illustration showing the two main processes causing the formation of cauldrons (Guðmundsson M. T., Högnadóttir, Kristinsson, & Guðbjörnsson, 2007).

will only cause minor events that can be compared in volume to high precipitation events or spring floods. Substantial flooding may however happen if the subglacial melt rate increases significantly or if the topography of the glacier bed allows for the accumulation

of water. The drainage of accumulated water in cauldrons may result in larger floods with examples including the Skaftár cauldrons and Grímsvötn that regularly produce substantial floods (Guðmundsson & Larsen, 2013).

2. Floods caused by volcanic eruptions. Eruptions within glaciers melt water rapidly and usually the water drains straight away rather than accumulating (Guðmundsson & Larsen, 2013). These eruptions can produce some of the largest flood events presently known on earth with peak discharge reaching maximum flow rates of 300,000-1,000,000m³/s. These events generally carry large loads of sediment (Tómasson, 1996; Larsen, Guðmundsson, & Sigmarsson, 2013).
3. Floods during phreatic eruptions. When pyroclastic flows melt the glacier surface or lava flows over snow and ice on the slopes of volcanoes, floods (also referred to as lahars) may occur. This happens during eruptions on the edge of glaciers or on volcanoes that have small icecaps. An example of an Icelandic volcano prone to these floods would be Hekla (Guðmundsson & Larsen, 2013).

Grouping floods to assess their impact can be a troublesome task as when one groups them according to the water volume a skewed picture may form. The duration and size of the flood and topography of the area flooded will have great effect on its impact. Typical flood characteristics vary between different locations and the flow behavior of a volcanogenic flood can be very different from place to place. Some floods have a gradual buildup of flow rate until a peak is reached and then a suddenly stop, whereas other have a fast buildup and slow finish. Figure 6 shows two hydrographs illustrating this difference. There are many factors that control the shape of the hydrograph and the same flood area can see floods that behave differently depending on the size of the flood and how fast they are generated (volcanic eruption or not). The general idea is that the larger the flood the faster an established subglacial flow channel can form resulting in a high peak right at the start and a slow finish (Björnsson H. , 2002). For this reason it can be useful to create timelines of the events.

While a large volcanically induced flood is obviously hazardous, seepage type cauldrons may also release minor events that are characterized by increased conductivity and gas emission.

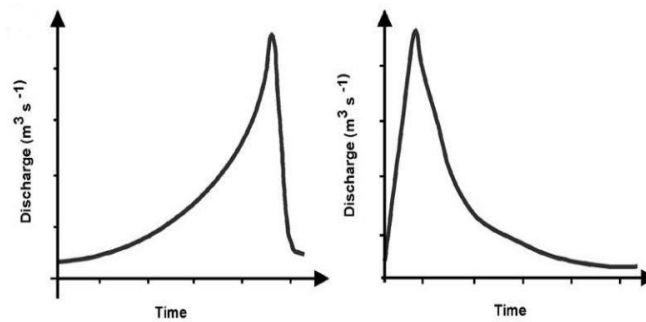


Figure 6: Hydrographs showing two typical characteristic time evolutions of different floods (Björnsson H. , 2002).

These events are not necessarily considered floods based on water volume and can go undetected by hydrological networks but are definitely characterized by increased flow of water and often increased gas emissions. These small events, although far less serious than the large events, can be dangerous on a local scale with a small impact zone. For this reason it is important to identify the difference between large ($> 30.000 \text{ m}^3/\text{s}$), medium ($3.000\text{-}30.000 \text{ m}^3/\text{s}$), small ($1.000\text{-}3.000 \text{ m}^3/\text{s}$), and minor events ($<1.000 \text{ m}^3/\text{s}$) so that they can be monitored in an appropriate fashion. Hereafter floods will be grouped in to these four categories for simplicity rather than using the same scale as the glacier group at the IES uses, as this scale is particularly suited to considering the impacts of the most frequent floods, as opposed to the other system, which is particularly suited to characterizing the largest flood events.

Timelines can be created to show the approximate sequence of the hazards associated with the different size-groups of floods as shown in Figure 7 for minor floods. The key monitoring networks and the timescale they work in can also be included in such schematics.

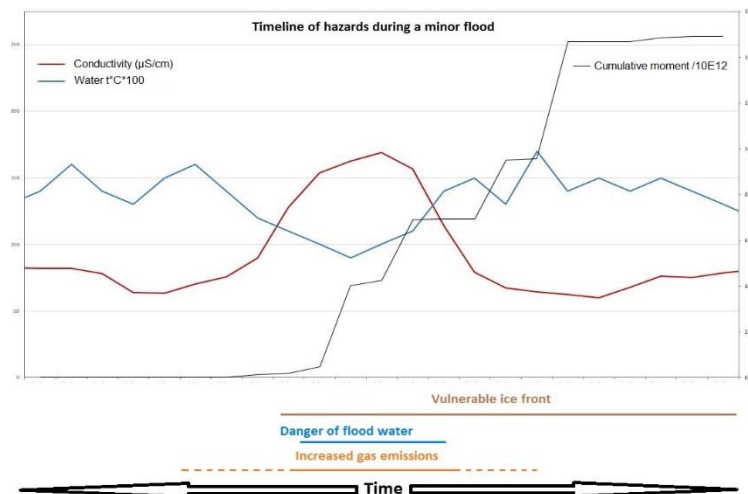


Figure 7: A schematic timeline of the different hazards to be expected for a minor flood. The timeline includes the real-time data including electrical conductivity, water temperature and cumulative seismic moment released within the catchment area of Sólheimajökull in the 2014 minor flood. The conductivity peak lasted for 9 days from the start of the increase to when the concentration reached background levels again.

Skeiðará has for example been known to emit H_2S and this has usually been noticed prior to

the increase in flowrate. The color of glacial rivers also changes in advance of events as they start to transport greater volumes of sediment. Precursors have also been seen at Sólheimajökull that resemble other glacial rivers (Guðmundsson & Larsen, 2013). These precursors can be observed as the fingerprints of a system

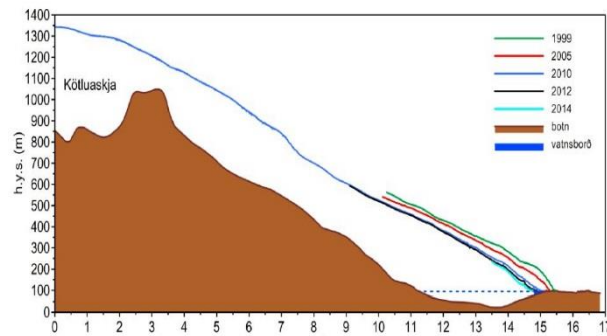


Figure 8: Vertical profile of Sólheimajökull, Source taken from Guðmundsson 2015 data from Mackintosh (1999) and Björnsson (2000).

and by studying them one can start to attempt forecasting events with advanced warning, thus allowing for increased mitigation efforts to take place. Identifying these precursory signals is particularly important at Sólheimajökull as the subglacial flow channel from the cauldrons is very short (10-15km) with a high gradient (Figure 8) which results in short potential warning-time (Björnsson, Pálsson, & Guðmundsson, 2000).

2.1.2 Risks accompanying volcanogenic floods.

The hazard of a jökulhlaup is due to two main immediate components: the flood itself and the release of toxic gases. The direct flow of sediment and ice laden meltwater can have huge impacts as it destroys most things in its path. The water can threaten life due to drowning as people become instable in the flowing water and due to the low or high temperature of the



Figure 9: Skeiðarárbrú after the Jökulhlaup in 1996 (Fréttablaðið, 2011).

water. Injury or death may also occur through direct contact of large objects carried by the flood (Pagneux & Roberts, 2015). Flood water can also damage infrastructure like roads, bridges (Figure 9), power lines and houses. They can also wash away farmland leaving a slushy layer of rock, ice and clay once the flood has

passed. Secondly a Jökulhlaup is dangerous due the transportation of toxic volcanic/geothermal gases. Volcanoes emit great amounts of gas, both through the degassing

of geothermal fields and during volcanic eruptions. Gases cannot escape easily through a glacier while the surface is intact. This means that the gas from geothermal fields and small eruptions that remain subglacial can escape most easily through the same channels the melt water flows. During a Jökulhlaup the gas can escape from the water and become volatile in turbulent flow. This threat can be very substantial. The main volcanic gasses associated with human health include H₂S, SO₂, CO, CO₂, HCl and HF, they can cause a range of different health problems ranging from respiratory problems to death. CO₂ and CO are odorless and thus particularly difficult to identify by an untrained person and high concentrations of H₂S and SO₂ will numb the sense of smell (Hansell & Oppenheimer, 2004; Vinnueftirlitið, 2016). The public health limit for H₂S set by the Administration of Occupational Safety and Health (AOSH) in Iceland is 5 parts per million (ppm) for every 8 hour period and 10ppm for a 15 minute period as can be seen in Table 2 (Vinnueftirlitið, 2016).

Table 2: Exposure limits to volcanic gases as set by the AOSH covering maximum average 8 hour and 15 minute exposure (Vinnueftirlitið, 2016).

Gas species	8 hour exposure limit (ppm)	15 minute exposure limit (ppm)
H ₂ S	5	10
SO ₂	0,5	1
CO	25	50
CO ₂	5000	10.000
HCL	NA	5
HF	0,7	3

Although the gas hazard is most associated with volcanic eruptions, volcanogenic floods of geothermal origin can transport high concentrations of gas. Numerous reports of dead birds and fish during Jökulhlaups exists and many scientists have reported being sick due to the gas poisoning (Guðmundsson & Larsen, 2013). Although this danger of gas has been present during most if not all volcanogenic floods, it only recently has become a major topic as the number of people in the potentially hazardous areas is ever growing with the rapid increase in tourism.

Additionally a further hazard can be associated with calving glacier fronts as Jökulhlaups may rapidly melt /break ice and make previously relatively stable ice become unstable. This can result in large blocks of ice breaking and floating away from the glacier edge (Sigurðsson, 2016).

2.1.3 Monitoring a volcanogenic flood

Volcanogenic floods are considered to be a substantial hazard and as a result the monitoring of these events and the identification of precursory signals has received considerable attention. Many different techniques have been used in the past ranging from visual observation of cauldron formation from aircrafts to monitoring electrical conductivity of river water. Lately the addition of atmospheric gas measurements has proven to be a very useful tool. The main goal in these efforts has been to gain better understanding of the driving processes behind the phenomenon and how the occurrence of a flood can be anticipated in the future. As these floods happen in different glaciers under different circumstances it is important to define factors that identify the typical behavior of these events.

As an example the recent Skaftárhlaup event in Iceland in September/October 2015 was forecasted by 3-4 days giving the local community and the responsible authorities good time to react and take the appropriate precautionary actions. This could be done as the Skaftár cauldrons in western Vatnajökull have released volcanogenic floods periodically for a



Figure 10: Subglacial flow paths of water draining from the Skaftár cauldrons in Vatnajökull (Veðurstofan, 2015).

long time giving a flood every two years from each cauldron (Roberts & Zóphoniásson, 2013). As a result of these frequent events, known “fingerprints” for floods from these cauldrons have been established. The subglacial flow path of water from the Skaftár cauldrons is shown in Figure 10. This event demonstrated the potential of the monitoring techniques currently available for these cauldrons using a GPS instrument.

Not all cauldron systems can be monitored in the same fashion as many have short subglacial flow routes and some never accumulate any substantial amount of water to monitor. For this reason it is important to identify what techniques can be used for each system. In recent years better monitoring techniques have been established and a continuing effort is being made to give longer pre-flood reaction times. As the monitoring potential widens, early warning systems can be modified further, enhancing the capability of individuals, communities and private companies to react, that could otherwise come to harm (United-Nations, 2009).

2.1.4 Jökulhlaups at Sólheimajökull

The river Jökulsá á Sólheimasandi drains from Sólheimajökull and has been subjected to numerous floods in its geological history as demonstrated by Maizels (1991). The recurrence time of large volcanic eruption-induced floods has been shown to be 500-1500 years in the last 6000 years (Guðmundsson, et al., 2005; Larsen G. , et al., 2015). However research indicates that up to 10 large-scale floods capable of drastically changing the underlying flood plain have happened in the last 4000 years. (Björnsson H. , 2009). As this frequency of large-scale floods is greater than the frequency of large volcanic eruption-induced floods, it shows that some of the large-scale floods are of geothermal or meteoric origin. The flood plain of Sólheimasandur (the floodplain of Sólheimajökull) is built up by Jökulhlaup deposits rather than the steady buildup of sediment one would expect at a glacial front (Maizels, 1991). From settlement (873 AD) it is not clear how many Jökulhlaup events have happened in this area and if they were volcanogenic or caused by the accumulation of water in surface manifestations. The earliest indication of floods are in 934 and 1357 during Katla eruptions, and then in 1860 (Einarsson, Larsen, & Thorarinsson, 1980). The most recent medium/small event happened on the 18th of July 1999 shortly before 02:00 (local time). Discharge estimates suggest a peak discharge of 1700m³/s at the bridge 4 km from the glacier edge with a peak estimate of 5000m³/s at the glacier edge with the flood lasting only a few hours.

After the Jökulhlaup in 1999, cauldron 7 was identified for the first time with a volume of 0.02km³ (Sigurðsson, Zóphóníasson, & Ísleifsson, Jökulhlaup úr Sólheimajökli 18.Júlí 1999, 2000; Roberts, Tweed, Russell, Knudsen, & Harris, 2003). The cause of this Jökulhlaup is thought to be a small subglacial eruption or a shallow magma intrusion that caused a rapid increase in the glacier bed melt rate, however other causes for the flood cannot be ruled out

(Guðmundsson M. T., Högnadóttir, Kristinsson, & Guðbjörnsson, 2007; Roberts, Tweed, Russell, Knudsen, & Harris, 2003). The five known cauldrons in the catchment area of Sólheimajökull are all believed to be seepage type cauldrons, although it is possible that the highest elevation cauldron in the catchment area may accumulate some water. Further research is needed to confirm this. This means that any larger flood will be directly related to increased glacier bed activity as no substantial water should build up (Björnsson H. , 2002). The distance the water travels under the glacier is rather short having a subglacial path of less than 15 km with a high vertical profile (Figure 8). This in turn means that the time the water takes to reach the glacier edge can be short, giving less than one hour during eruptions (Guðmundsson, Högnadóttir, & Oddsson, 2015). This short subglacial flow channel makes monitoring the event much more demanding as monitoring systems need to have high temporal resolution to be useful to early warning systems.



Figure 11: The minor event of July 2014. The darker water close to the ice margin is the geothermal water. Site of gas instrument is marked in red

While large to medium sized volcanogenic floods have shown to be historically infrequent, smaller events are known to happen more frequently. The smaller events have however not been documented well due to their small volume. A minor flood happened between 6 - 12 July 2014, which can be seen in Figure 11 as the darker colored water patch flowing from the red star. An increase in the flow rate

of the river was not detected at the nearest hydrological station but a clear spike in the electrical conductivity was observed and gas concentrations locally reached hazardous levels for human health.

Currently very little work has been put into assessing the potential hazard associated with these minor events and the main focus has been put on the larger events with detectable changes in water volume.

Two different reports have been published on this matter. The earlier work was done by Almannavarnir in 2006 focusing on large eruption induced events (Almannavarnir, 2016b). This work produced a map showing the possible flood arrival times for Sólheimajökull after an



Figure 12: Flood hazard map by Almannavarnir. Time on map indicates arrival of flood water from initiation of eruption (Almannavarnir, 2016b).

eruption has started (Figure 12). The fact that the flood may reach the ring road in less than 50 minutes from the onset of an eruption gives very little time for people to evacuate.

Work focusing on small to medium sized floods between 1.000 -10.000 m³/s started in 2014 (Guðmundsson, Högnadóttir, & Oddsson, 2015). This work attempted to answer six main questions (found in Appendix A in Icelandic). The questions focused on determining the spread, size, impact, warning time and frequency of smaller and medium sized floods (2000-10.000m³/s) similar to that of 1999 and how the area will likely change over the coming years as the glacier melts further in land. No attempt was made to evaluate the hazard associated with geothermal gas release as the experts determined that not enough data was available (Guðmundsson, Högnadóttir, & Oddsson, 2015). The results of this work were presented at a public meeting held in Vík í Mýrdal on the 23rd of July 2014. An aerial photograph from this work is shown in Figure 13.

They concluded that the northern parking area seen in Figure 15 is unsafe and would likely be submerged in a flood of medium size (5000 m³/s) and that the road from the ring road to the glacier will be submerged in some locations, meaning that the road would not be safe to pass once a flood has commenced. The results were presented in an open public meeting to the locals of the area as well as the representatives of the tourist companies.

Since the publication of the work done by Almannavarnir in 2006 many things have changed. The glacier has retreated further up the valley and is now thinner than it was before.

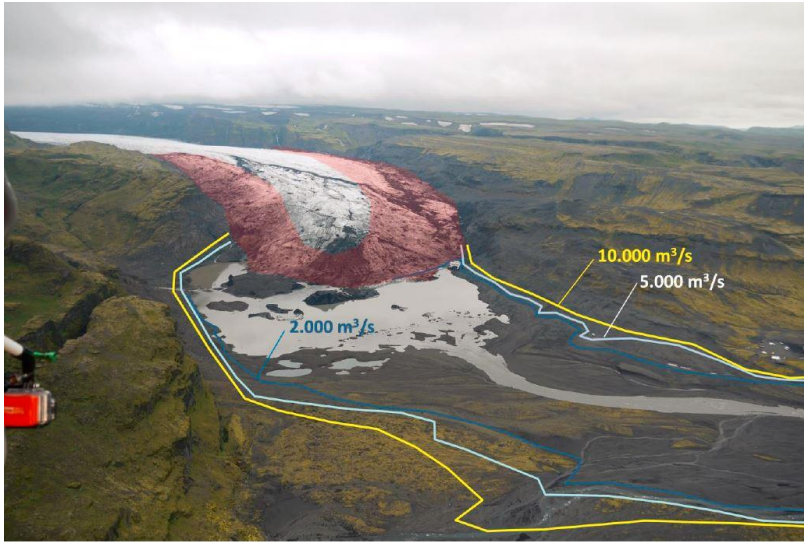


Figure 13: An aerial photograph showing the extent of different flood scenarios down Sólheimajökull. The sides of the glacier are red as it is likely that the flood water may break out from the glacier surface in those areas. (Guðmundsson M. T., 2015).

Both the work of Almannavarnir and Guðmundsson et al. 2015 did not evaluate the hazard accompanied by minor events such as that of July 2014, as they have very little water volume. These events can however pose a threat to people and an attempt to identify the frequency of these floods is made in this study.

2.2 Human activity and risk.

2.2.1 Changes during the study period.

During the course of this study (July 2014 - April 2016) the area of Sólheimajökull has seen drastic change in the number of tourists visiting. The road to the lower parking area has been improved, a café is now operating on a year-round basis and plans for a landowners union to manage the area have started to form (Bragason, 2016). This improved accessibility has opened the area to a great number of independent travelers that are not relying on guides to visit the area. The glacier has retreated substantially over the past two years and completely changed shape. The routes used to hike the glacier have changed and different routes are used depending on condition. Three information signs on the geology of Sólheimajökull and the volcanoes around it are present giving useful information to visitors. Additionally three warning signs informing about a natural hazard site at the ice margin are present and can be seen in the appendix C in Figure 29, Figure 30 and Figure 33.

2.2.1 Hazard, risk and exposure

Assessing the risk of a natural hazard involves evaluating what potentially can happen. The hazard present at Sólheimajökull with regards to volcanogenic floods can be viewed as a constant, while the risk of it can be subject to change. As an example, the risk towards loss of life at Sólheimajökull was far lower 20 years ago than it is today while the hazard is the same now as it was then, given that the likelihood of a flood is calculated to be the same now as it was then. The risk is directly related to the probability of a hazardous event having a negative outcome (United-Nations, 2009). As the hazardous area around Sólheimajökull now has a far greater human exposure with a growing number of visitors from year to year the probability of a hazardous event having a negative outcome is higher than 20 years ago (Smith, 2013). This assumption of risk being higher today at Sólheimajökull is however only based on the increased exposure in the area, not taking into account any changes in the management of the area. The risk of an event can be viewed as:

$$\text{Risk} = \text{Hazard} \times \text{Elements at Risk} \times \text{Vulnerability} \text{ (Smith, 2013)}$$

Assessing the risk can be viewed as a three step process following this equation: 1) Identifying the hazard, 2) Estimating the likelihood of an event (probability) and 3) Evaluation of the potential social conciseness (losses).

For assessing vulnerability, risk takers can be split in to two main groups: Voluntary and involuntary (Smith, 2013). Involuntary risk takers can be subject to increased vulnerability as they may lack awareness and become exposed to a hazard without knowing what they could face. The exposed people in an area can be viewed as two main groups: Local residents and the transient people (the tourists). Estimating the number of resident people in a confined area of Iceland is a straight forward task as residency records exists for the entire population of Iceland (Þjóðskrá, 2016). Estimating the number of transient people is far more challenging as the temporal distribution of the transient population is subject to change between months as well as during different times of the day (Pagneux, 2015). The diurnal fluctuation in population size will additionally be significant at a tourist site that offers no accommodation facility on-site such as at Sólheimajökull. As the transient population may span different groups of people ranging from foreign tourist to nationals traveling in small to large groups the awareness and preparedness, and thereby the vulnerability of the group as a whole varies.

This approach assesses the risk in an objective way as if focuses on looking at statistical data on the risk of the hazard in order to put a certain class to it. The perception of risk can be viewed for the same three steps, however assessing the perception relies on subjective personal factors including opinion, intuition, awareness and experience (Smith, 2013). The perceived risk of the local population that are both aware and possibly have experience of the risks they could face will thus differ from the transient population. This perception of risk has to be taken into account during risk assessment as it can influence the outcome greatly. For example if people in an area are very aware of the likelihood of a hazard and have gone through efforts to minimize the consequences potentially faced, the risk assessment may show an area to be highly resilient having low vulnerability, while an unaware community may be far more vulnerable. This example may be the case for the area of Sólheimajökull as the locals are perceived to be more aware and better prepared than the tourists.

In Iceland, risk assessments for natural hazards including avalanches, debris flows and floods are to be carried out and lead by the Icelandic Meteorological Office (IMO) by the request of the local authority of an area or by the national planning agency. In order to do a risk assessment for an area certain background information first needs to be gathered. This includes five main factors: 1) mapping of the area, 2) gathering of background information, 3) study of climate, 4) human history in the area and 5) a field assessment should be carried out. This assessment will, for example, ascertain if the risk within the area is acceptable or unacceptable and produce a map of the hazardous areas. After a risk assessment has been introduced for an area and approved by the government minister the area shall be managed accordingly, such as by discouraging or prohibiting building of infrastructure and other activities in the areas of unacceptable risk. Following this risk assessment the Icelandic civil protection develops a contingency plan for the area (Alþingi, 1997). The law regarding avalanches and debris flows does not cover volcanic activity and thus the law is not directly relevant for assessing the risk of volcano related hazards. However in the laws regarding the IMO a segment states that the IMO is to produce a risk assessment for natural disasters in the country by the request of parties within the ICP following the same assessment process (Alþingi, 2011). A framework regarding risk assessment for tourism in Iceland has been presented as a parliamentary resolution but has yet to be agreed-upon (Alþingi, 2015)

Although this thesis will not be a formal risk assessment it will gather much of the background information needed for a risk assessment of the area of interest.

2.2.2 Locals

In 2006 a full-scale evacuation of residents living in the areas that could be affected by a Jökulhlaup from Katla volcano was carried out. During the exercise studies were done of the residents' perception and preparedness towards the hazard (Jóhannesdóttir & Gísladóttir, 2010; Bird, Gísladóttir, & Domeney-Howes, 2009). The studies showed that the general awareness of the residents in the area was good and the perception of risk of a Jökulhlaup was high although many people lacked knowledge of the mitigation, preparedness and preventive measures that need to take place (Jóhannesdóttir & Gísladóttir, 2010). The flow of information from the monitoring official to the locals during this exercise can be illustrated as a simple three step process shown in Figure 14. This view is of course very simplistic but highlights the main steps that information must pass to reach the residents during a future event.

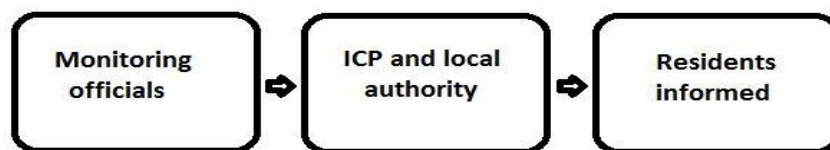


Figure 14: Flow of information from monitoring official to local residents.

The locals can be viewed as taking voluntary risk as they are aware of the risk but choose to stay, thus accepting the risk. The local population has in the past contributed to the monitoring of changes in the environment of Sólheimajökull demonstrating the awareness present. As an example one can look at the flood in 1999 of Jökulsá. It was reported by farmers and the police in the area that Jökulsá had a different color but not increased flow, hours before the flood happened (Sigurðsson, Zóphóníasson, & Ísleifsson, 2000). Additionally one could say that a volcanogenic flood at Sólheimajökull is maybe not an alarming threat to the residents that are closest to Sólheimajökull as the direct flood area is not inhabited. Although the resident population may be seen as being aware and resilient towards the risk of a volcanogenic flood the growing tourist industry has received less attention than it perhaps should.

2.2.3 Tourism

Studies on the risk perception and awareness of tourists and the tourism industry in the area surrounding Katla are not many. A study focusing on the tourist sector and employees of tourist companies in the area of Þórsmörk (seen in Figure 2) was done in 2009, showing that the sector was not well informed about the Jökulhlaup risk in the area (Bird, Gísladóttir, & Domeney-Howes, 2010). The study questioned both wardens and tourists in the area of their basic knowledge on the geological background of the area as well as if they were aware of the danger of a Jökulhlaup. A study of this sort has not been done at Sólheimajökull until now.

Tourism is a fast growing industry in Iceland, where the untouched nature is marketed to a great extent with tour-companies offering a wide range of trips to exotic locations. The transient population of areas such as Svínafell and Fljótshlíð (both areas at risk of volcanogenic floods) have been estimated to represent 80% and 40% of the total population in the areas respectively during the peak tourist season (Pagneux, 2015). Glacier trips have recently become very popular as they are known to be extraordinary, offering people the chance to see and experience the wonders of ice. These trips came about very recently and have a very short history in Iceland. Around 2005 the first scheduled tours were offered at Sólheimajökull by the tour operator Icelandic Mountain Guides, while only a few guided tours had been specially offered before then upon request. Since then the area has seen rapid growth in tourism with multiple tour operators offering trips to the area (Bragason, 2016). The popularity of these trips is ever growing with them being offered at a number of different glaciers in Iceland in a number of different setups. Some trips are set to go to the top of the glaciers in converted jeeps or snowmobiles, while others are hiking trips on the lower parts of the glaciers as is the case at Sólheimajökull (see hiking routes on Sólheimajökull in Figure 15). In the hiking trips people get the chance to walk in crampons with a helmet and ice-axe on the crevassed ice.

Sólheimajökull offers the location closest to Reykjavík where people can walk on a highly crevassed glacier. The area is not in a national park and is not currently controlled by any estate manager/warden making the area very open for tour companies and solo travelers. Four main companies take the majority of tourists on prescheduled hikes. As this work field is rather new and located in a rather dangerous environment the safety guidelines from the companies are also new and maybe don't cover all aspects needed. These guidelines are usually based on documents from experts in North America or the European Alps. The main focus on safety is usually put on people not falling into moulins, crevasses or bogs, how people are to walk when wearing crampons and generally how first aid is to be given in these extreme circumstances (Finnbogason & Magnússon, 2015). As stated above volcanic activity can create many different hazardous scenarios to the people on and near the glacier and while the number of tourists grows the risk associated to such a hazard increases unless mitigation efforts are made. This study aims to make suggestions on how this may be improved. As no studies

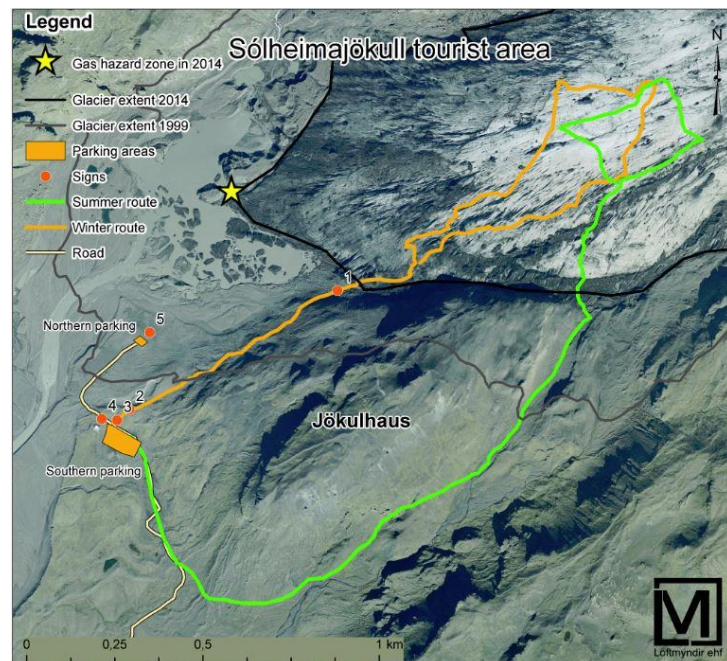


Figure 15: Overview map of the study area showing locations of signs, the two parking areas and two examples of typical routes taken on the glacier by the guided groups. Photos from the locations of the signs are found from Figure 29-33 in Appendix C. (Aerial photograph from loftmyndir ehf, GPS tracks from Matteo Meucci a guide from Icelandic Mountain Guides and the outline of past glacier extent is from Oddur Sigurðsson).

on the awareness of tourists and the employees going to Sólheimajökull are available, it is important to look at the results of the study done by Bird, et al. in 2010 and the studies on the resident population Jóhannesdóttir & Gísladóttir in 2010 (Jóhannesdóttir & Gísladóttir, 2010; Bird, Gísladóttir, & Domeney-Howes, 2010). As Bird, et al. demonstrated that the tourist awareness was low it could be argued that tourist may be subject to involuntary risk towards the hazards associated with volcanogenic floods (Bird, Gísladóttir, & Domeney-Howes, 2010; Smith, 2013)

Regulation and organization in the tourism sector is often thought of as a problematic field in Iceland. The adequate infrastructure and solutions to basic problems are frequently not present and the ever-growing number of tourists coming to Iceland seems to enlarge the situation. Since 2003 the total number of tourists visiting Iceland has gone from around 300.000 people to 1.2 million and is projected to increase further (Ferðamálastofa, 2016). The southern part of Iceland from Reykjavík to Vík í Mýrdal is seeing ever-growing tourist numbers and the infrastructure is lacking. Accidents are becoming more frequent and more serious as accessibility is improving while the safety measures, like sanding icy walking paths or controlling the access to hazardous areas, is not seeing the same improvements (Tryggvason, 2016b; Tryggvason, 2016a). This topic has recently gained a lot of attention in the country and little is being done other than fixing temporary problems especially in areas that have reached their current carrying capacity (Tryggvason, 2016b; Sæþórsdóttir, 2015). This problem can be viewed as a result of different factors such as too few regulatory employees in the area compared to the drastically increasing number of tourists and that this new field lacks adequate structure around it. This is changing in some tourist locations with the introduction of a new proposition by the Ministry of Industries and Innovation initiated on March 23rd 2016 where popular tourist locations are to be built up in a sustainable way (Atvinnuvegaraduneytið, 2016).

3 Methods

In this section the methodology used in this study will be introduced and explained in two main parts. The first part will focus on the human involvement in the area, utilizing predefined questions asked in personal interviews to assess the risk perception and awareness of the leading tourist industry officials and the legislative authority in the area. The second part will focus on the current monitoring status in the area and the ways an event could be forecasted and what could be improved. The research behind the two parts was conducted in sequence of each other. This was done so that any specific questions brought up by the people in the human involvement part could be addressed to the monitoring representatives in the second part. Additionally the area was visited four times during the study to evaluate the information given and the general organization of the area.

3.1 Awareness and preparedness (stage 1)

3.1.1 Risk identification and perception of risk

The risks at Sólheimajökull range from the risk of falling into moulins and crevasses to the risks associated with large scale volcanogenic floods. The risk of people falling in crevasses or moulins will not be discussed further as this is considered a more constant hazard that tour guides are trained to avoid or face. However this risk will not be neglected as the everyday hazards may enhance the impact of volcanogenic floods. The main focus will be on the awareness and preparedness that tour guides have of the risk of a volcanogenic flood at Sólheimajökull thus assessing their perception of risk in a subjective way (Smith, 2013).

Two main questions need to be answered. First an estimate of the number of people visiting the area per day /year needed to be found in order to assess the exposed population. Second how aware/prepared the different groups working in the area are if a flood were to happen and how capable they would be to mitigate the risk of the hazard to the greatest extent possible. To answer these questions interviews were taken with six different people who will play key roles in future events. They are: the police commissioner in the area, a representative of Almannavarnir and the safety officials of the four largest tour companies that take tourists on the glacier. These six people do not represent all the different parties

that would be involved in the response actions of a volcanogenic flood at Sólheimajökull, but through this questioning quantitative conclusions can be drawn of the perception of risk.

As the police commissioner in collaboration with Almannavarnir control operations during events and know how things *should be* according to the contingency plan, they were questioned before the safety officials of the tour companies who know how things *presently are* in the area. This was done to evaluate the flow of information from the police and Almannavarnir to the tour-companies and how this is maintained.

Although asking the safety officials of the tour companies may give a skewed picture of the awareness of the guides that go to the glacier, it should at least show the state of information available within each company. By assuming that the information passes on to the tour guides in the field from the safety officials, one can assess the awareness of the guides that regularly visit the area rather than focusing directly on the tourists. Of course replicating a study such as that done by Bird et al. in 2010 would be of great value here but is outside of the scope of this project. The tour companies have no legal obligation towards the tourist regarding their safety other than their moral obligation. The questions were not designed for any statistical analysis but were rather aimed to get an open discussion that would reflect the feeling of the people regarding the matter of safety and organization at Sólheimajökull getting their perception of the risk. The interviews were not recorded, instead notes were taken during the interviews and a summary of each interview was made immediately after to ensure that no details would have been left out. As the questions differ for the tour companies and the other two groups they will be explained separately. The two lists of questions were not necessarily asked in order and are thus not numbered. The lists of questions (in Icelandic) can be seen in Appendix B.

3.1.2 Interview topics

a) ICP

Almannavarnir and the police commissioner work together as Almannavarnir directs information to the police from monitoring institutes like the IMO and IES. Thus both were asked the same questions. The people questioned were Björn Oddson at Almannavarnir (co-author on the report on small Jökulhlaups down Sólheimajökull (Guðmundsson, Högnadóttir, & Oddsson, 2015)), and the chief police commissioner in south Iceland, Kjartan Þorkelsson. Kjartan shares a closer link with both the local population and is the

official responsible for the area. He also frequently communicates with the population on police matters. The questions addressed what is presently being done and how effective an evacuation would be today. The different questions asked can be grouped under two key terms that are being assessed: awareness and preparedness. The questions focused on the recent event of July 2014 and what has changed since that event. Additionally a question was asked on what has been improved since the 2014 event and what the legal requirement of the tourist agencies is to the tourist.

All questions were asked within the time period November 2015 to December 2015. The interviews were held in Icelandic with the questions translated to English here:

Awareness:

What is of concern regarding natural hazards at Sólheimajökull?

What if no warning is given?

Who is responsible for the tourists?

Preparedness:

Is there a contingency plan for a Jökulhlaup event?

How do channels of information flow and what are the roles of the different partners?

What are the different orders of operations?

How do you deal with stages of uncertainty?

Do you have evacuation plans?

What communication links are present?

What actions have been taken since July 2014?

b) Tour-companies

Representatives from four companies were interviewed: Arcanum, Arctic adventures, Extreme Iceland and Icelandic mountain guides. All four companies offer daytrips departing every day of the year depending on the weather. Confining the questions to the four largest companies will of course mean that smaller companies and those that don't have a fixed schedule will be left out of this study. The effects of integrating this contribution on the study will be discussed further in the discussion section and a re-evaluation of the strategies used will be made. At this point it is not believed to influence the study to a great extent.

The tour guides were asked to estimate the number of tourists they bring annually to the glacier and to give an estimate of the peak number per day. To get an idea of the size of the exposed population, estimation of tourist numbers in the area will be based on the number of tourists brought in by the four companies and hence is a minimum estimate and not a firm number. This estimate can then be used to evaluate the vulnerability of the population the guides take on the glacier, as the awareness and preparedness level of the guides can be viewed as a factor affecting the direct vulnerability of the tourist.

All questions were asked within the time period December 2015 to January 2016. The interviews were held in Icelandic with the questions translated to English here:

Awareness:

What responsibility do you have for the tourists and employees?

What is the greatest hazard in your opinion at Sólheimajökull?

Are you aware that the northern car park is closed and will remain closed and that unaccompanied tourists are not allowed to go on the glacier?

(Although the last question may be regarded as leading the safety officials towards an answer, it is an important question to ask as it shows the extent of communication between the local authority and the tour guides.)

Preparedness:

Do you have a contingency plan if something hazardous occurs?

What communication links will be used?

Are your clients informed of the different hazards at the glacier including the volcanic hazard?

Exposure:

How many people do you take to the glacier per year/day and at what time of day do you go?

3.2 Monitoring (stage 2).

During the interviews with the tour-guides, a frequent question asked to me was how often volcanogenic flood events happen at Sólheimajökull as the tourism industry in the area is very young. A flood in a remote area will have little effect whereas one in an accessible location would have greater impact. For this reason it is important to reevaluate the area of

Sólheimajökull as it can no longer be considered a “remote area”. If a flood similar to the 1999 event would happen today the event would likely have far greater consequences than the flood 17 years ago.

The ultimate goal of monitoring is to mitigate and prevent a hazard from turning into a disaster. To do this many organizations around the world have complex monitoring systems that monitor different aspects of the earth. To monitor ice-capped volcanoes in Iceland a number of instruments and techniques are used both by the IMO and the IES. The IMO has the legal obligation to monitor and to inform Almannavarnir of any unrest or present activity of the volcanic systems in Iceland (Alþingi, 2011). The IES supports this effort to a large extent collaborating with the monitoring and participating in the expert group of Almannavarnir. It is important to distinguish which monitoring tools can be directly relevant to an early warning system to monitor volcanogenic floods at Sólheimajökull. This means that monitoring techniques that maybe cannot be utilized directly to give timely warning at Sólheimajökull may however contribute to the early warning system through increased understanding of the system as a whole.

To get a scope of the different techniques and how they complement each other, interviews were taken with the specialists at the IMO and IES. The structure of the interviews varied greatly as the goal was to get a clear answer of how each technique works in order to create an objective evaluation of the techniques that will be most relevant to an early warning system. Rather than having a predefined question list each person questioned was asked to give a thorough introduction to their monitoring field. The experts were asked to give an explanation of how relevant their field is for Sólheimajökull and to give examples of early detection when possible and what needs to be improved in the future. The supervisors of this thesis are included as specialists in this study as they both specialize in monitoring fields relevant to this study. The results to these questions aim to give an overview of the techniques but not a detailed scientific explanation of how each technique works. This is done as one of the aims of the project is to gather information that can be used to improve the present situation for Sólheimajökull. The topics discussed with the specialists at the IMO and IES include:

1. *How early can a flood be forecasted?*
2. *How do different techniques complement each other?*

3. *How can one distinguish between floods of different sizes?*
4. *Does seismicity precede or follow floods?*
5. *How frequent are volcanogenic floods at Sólheimajökull?*

Once an assessment of the monitoring techniques had given an overview of what techniques would add to the real-time warning for the area, a data analysis was done to evaluate the frequency of hazardous events in the area and their how they are monitored.

4 Results

4.1 Awareness and preparedness towards the risk of floods (stage 1)

4.1.1 Authorities

Contingency plan:

A special contingency plan for the flood hazard of Sólheimajökull does not exist today, rather the contingency plan for Katla eruptions will be operative during volcanogenic flood events at Sólheimajökull.

When a phase is activated by the appropriate official, a message will be sent out by the emergency line 112 by SMS and/or by a prerecorded voice messages to all phones in the area. The roles of the different parties located in the area are defined for each phase in the contingency plan. The tour operators in the area are to follow set instructions depending on the phase and are responsible for canceling trips and calling back all departed trips during the alert phase (Appendix A). The police commissioner in the area is responsible for closing the area and is in charge of the coordinated response. There is no direct mention of Sólheimajökull in the Katla eruption contingency plan. The company Arcanum is indirectly identified, and said to run a strong tourist business offering snowmobile trips to Mýrdalsjökull, with no mention made of their glacier walks (Almannavarnir, 2013).

In August 2014 the uncertainty phase of this plan was activated. Almannavarnir issued the temporary closure of the northern parking as the event posed the threat of the glacier front breaking, potentially sending a wave of flood water in the process as the ice overturns in the water (Almannavarnir, 2014).

Awareness:

The local police and Almannavarnir are well aware of the potential geological hazard present. This was expected since they had recently been involved with making a new threat analysis of the area (Guðmundsson, Högnadóttir, & Oddsson, 2015) and developed the contingency plan for the area. They are worried about the location due to the number of people present on a daily basis. When asked what would happen if no or little warning would be given, the police said that the response would depend on the size of the event. If an event is small in water volume but gas rich then evacuation is simple as the area is

already confined and the road is in good paved condition. The tourist agency has responsibility for the tourist as stated in the contingency plan during guided trips but the tourist is always responsible for his/her own actions. This makes the tour guide the official responsible on the glacier if an event would happen although they are not legally bound.

Legally the area is closed and people that are not on guided tours are at their own risk. This ultimately means that the flow of information from the monitoring officials to the tourist (Figure 16) can have an additional step compared to that of the local residents seen in Figure 14. Of courses the tourist may receive the message through the SMS system directly, but not all tourist will have their phones on during their visit. Additionally a person that is unaware of the hazards present could react to a warning in a wrong way.

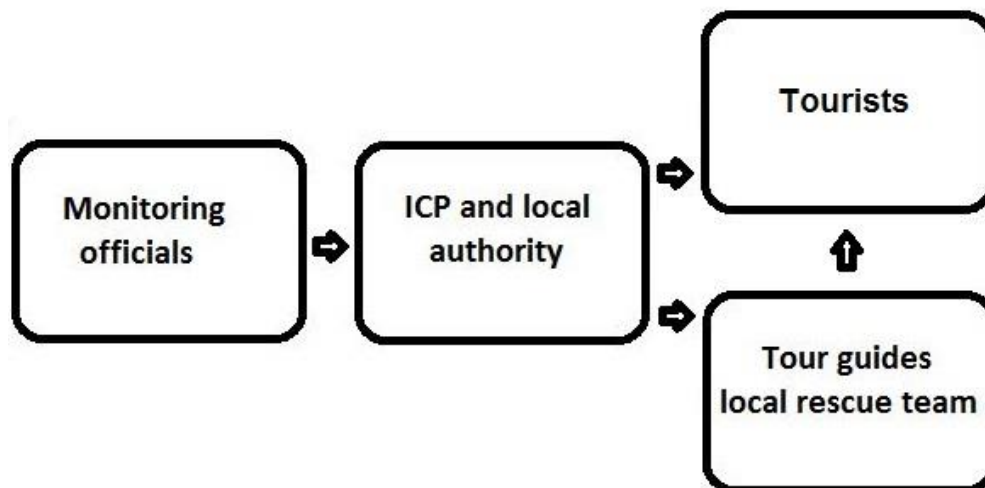


Figure 16: Flow of information from monitoring official to the tourist.

Preparedness:

The tour guides will get everyone, including any solo travelers or uninformed guides, off the glacier (although this is not their mandated duty) and will gather them to the southern carpark. People will then leave in cars and buses to Ytri Sólheimar 2 if this is advised to be safe. The police is ready to respond and manage mitigation efforts during such events by closing and evacuating unsafe areas and providing emergency aid to those who may need it. There is ongoing work integrating the municipality into the police's plan and the first stages are ready. The next time a warning will be given, Almannavarnir and the police



Figure 17: Signs installed after the publishing of the report by Guðmundsson et al. in 2015.

commissioner in the area will act according to the phase of the warning. The communication links present are GSM (SMS system), Tetra and VHF. These links provide total coverage on the glacier meaning that people on the glacier that are carrying one of the three communication devices should be contactable during a crisis event. These links were improved after the publishing of the report by Guðmundsson et al. in 2015. Additional improvements have been made in the area including the paving of the road to the area by the Icelandic road authority making potential evacuation faster and smoother than before (Guðmundsson, Högnadóttir, & Oddsson, 2015). The northern car park closest to the river has been closed officially and the glacier is now listed as “off limits” to people that are not on guided tours and two signs prohibiting access have been installed (Figure 17). The area is still regarded as dangerous but people are expected to make informed decisions. The police adds that no complaints have been received after the closure of the northern parking area.

A full scale evacuation has never been attempted at the glacier and the police commissioner says that this is not planned as of now.

4.1.2 Tour companies (stage 2)

The area around Sólheimajökull covers 9 different private properties with an equal number of owners. Currently a landowner association is being formed to unify the efforts that need to be made at Sólheimajökull to make the area a sustainable and safe tourist site for the future. The association is planning for improvements that involve building and fixing infrastructure, to meet this growing field (Bragason, 2016). These improvements are likely to improve the conditions at Sólheimajökull, but have not been carried out yet. The following results reflect the current situation in the area for the time period July 2014 to May 2016.

Awareness:

The safety officials were aware of the hazard associated with volcanogenic floods and conversations were started by the questioned, where they expressed concern about such events. All guides stated that they assume full responsibility for the tourists even though they were aware that they are not mandated bound to do so. Each safety official had a different thought on what was the greatest risk at Sólheimajökull. The hazards identified ranged from ice covered moulins in winter to gas accumulation in ice caves. Stories of what guides had seen and reported were often shared, including stories of locations on the glacier which had fountains of water shooting up in to the sky from the glacier and small crevasses that you could smell gases from. No guide considered volcanogenic floods to be the greatest danger as they did not consider them frequent while the other everyday hazards present a constant risk (Figure 18).

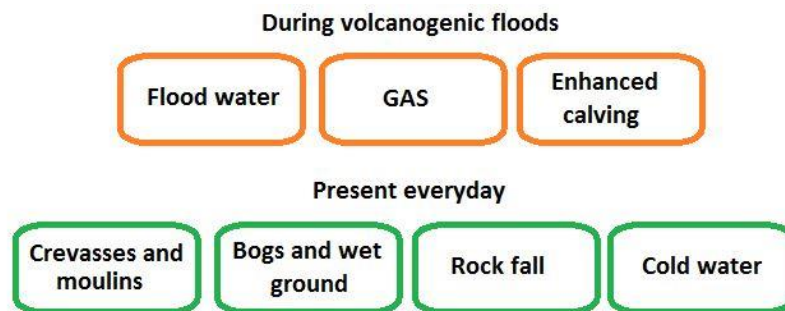


Figure 18: Different hazards present, separating the everyday hazards from the volcanogenic induced hazards.

It was evident that not all safety officials knew much about the processes that take place during the event of a volcanogenic flood other than that the flood water can destroy the area and that there will be the danger of gas. Secondly the safety officials were not aware of the different sizes of events especially when it comes to minor events. It was evident that further work may be needed in better informing the guides this hazard.

All guides were aware of what routes would be safest to use in the case of an event and stated that their operating people mostly use the safe trail to the east of Jökulhaus (Figure 15) as the western trail underlies an unstable glacier scree slope where small rock falls are frequent. Additionally they reported that many close calls had happened with the freelance guides, other tour operators and independent travelers who are often ill-equipped and lacking knowledge of the area. They stated that many groups will walk next to the river and lagoon towards the glacier instead of staying at higher ground on their way to the glacier. Although this criticism could be considered to be subject to bias due to conflicting interest, where the

established companies want to rule the market in the area, the field visits confirmed this statement. During the field visits numerous groups of people were seen wandering around the area both close to the glacier and on the glacier without any equipment. Additionally news reports of similar events exist where people have come to danger (Tryggvason, 2016a).

When asked about the closure of the northern parking area and the restricted access to the glacier, only two of the questioned were aware of the closure of the parking area and no one knew that the glacier was off limits to the general public. It was added that the police put up a blockade in July 2014 closing the access to the northern parking but that had been broken and put aside within a month after its installation. Currently the “closed” parking area is extensively used by smaller companies as it shortens the hike to the glacier, spreads the number of people over a larger area, and offers a better view for people who don’t want to hike to the glacier front. This may be regarded as a reason why no one has complained about the closure of the area. However after being informed of this closure during the interviews, the guides say that since the southern parking area has been improved the majority of people use the southern parking area. All the safety officials apart from those of Arcanum state that they have used the northern parking recently. Improvements to this area are to come as plans exist to further improve the infrastructure in the area and the landowners plan to remove the entrance to the northern parking area (Bragason, 2016). When asked if a representative of their company had attended the public meeting held in Vík in July 2014, two of the officials stated that no one had attended the meeting on their behalf to their knowledge and added that they did not know much about the meeting. This may reflect an imperfect connection between the responsible authority and the tour operators that take a large part of the tourist to the glacier.

Preparedness:

It was clear that the questioned had thought about risk of volcanogenic floods, however only one company (Arcanum) had made work plans that included identifying potential precursory signals such as being aware of flood water on the surface of the glacier and smelling sulfurous gasses is enhanced. Arcanum is the only company founded and run by local people so the awareness of these events does not come as a surprise. Additionally, Benedikt Bragason, the owner of Arcanum, has assisted scientists from the IMO and the IES with monitoring and research campaigns and is very knowledgeable about the area.

The other companies relied on expert provided warnings for volcanogenic floods but had extensive safety procedures for all kinds of accidents that may happen during trips. All companies however added that their guides were instructed to leave the glacier by their own initiative if they found something unsafe or unusual. The guides of all four companies have work rules that limit 8-12 people per guide depending on the length of the trip and everyone is equipped with a helmet, crampons and an ice axe. All companies state that in the case of emergency they could be off the glacier in less than 30 minutes after being informed of a potential event, but none of the questioned had tested this. This could mean that they would take the shortest safe route off the glacier to the nearest high point and need more time to get to the parking area. Every guide must have attended a safety course given by each company, where skills such as first aid, navigation and communication in emergencies are taught and practiced. The contingency plans of the companies all focused on the everyday hazards including moulins, crevasses, rock fall, cold water and variable weather conditions (outlined in Figure 18). A large emphasis was also put on making sure to be in connection with one of the communication networks. While all of the companies covered this aspect of everyday hazards well, only Arcanum had a prepared contingency plan for volcanic events, with a section on volcanogenic floods. A copy of the contingency plan was received to examine for this study. The contingency plan from Arcanum has a chapter focused on the volcanic hazard of Katla, with potential scenarios and what should be done in each event. The contingency plan covers the main hazards associated with volcanogenic floods including the gas hazard of sulfur species during floods. The work outlines the history of events at Sólheimajökull and where the water broke out from during the 1999 flood and requires its guides to have attended a course on the geology and history of the area. Two areas on the glacier are define including the routes that should be used to exit the glacier during emergency. An example from the Arcanum document is found below. Where the main risks during floods are listed, the cause and consequence explained and ways to mitigate the risk of the hazard are put forward.

Risks that may arise due to floods from Sólheimajökull:

Flood water can break the ice of the glacier margin

Flood water can flow on the glacier

Flood water can strike people and vehicles that are located in front of the glacier

Sulphur gas can cause serious illness

What can cause this to happen:

Warnings of the danger of volcanic eruptions are not heeded
Sudden and unpredictable natural disasters

Crises that can arise:

The flood could strike people causing drowning, hypothermia or other physical trauma

Measures to reduce the risk of floods before Sólheimajökull:

Track earthquakes in and around Katla

Be in good telecommunications contact within and outside the region

Comply with the response and evacuation plans in cooperation with the emergency authorities (Arcanum, 2014)

This list covers the main hazards that guides could face. Improvements to this document could be made such as conductivity measurements as a precursor are not mentioned. Information about minor flood events is not included and further detail could be given. This is likely due to the fact that no documentation is available on these events as they have not been studied before. Additionally the document could give more information on the gas species and what their typical symptoms are, an example of such information is shown in Figure 19

Exposure limits of H ₂ S (ppm)	H ₂ S	Health effects
0.008 - 0.2		Olfactory threshold (rotten egg smell)
1.0 - 20		Concentration tolerated for some time without harm
20.0 - 50.0		Eye irritation, Sense of smell to gas lost.
50		Prolonged exposure may cause bronchitis
60		Prolonged exposure may cause conjunctivitis and eye pain
60.0 - 100.0		Irritation of upper respiratory tract. Sense of smell lost. (maximum of GasPro instrument 100ppm)
100+		Pulmonary oedema with risk of death

Exposure limits of SO ₂ (ppm)	SO ₂	Health effects
0.0 - 1.0		Threshold for respiratory response in healthy individuals upon exercise or deep breathing
1.0 - 5.0		Gas is easily noticeable. Fall in lung function at rest and increased airway resistance
5		Increased Airway resistance in healthy individuals
6		Immediate irritation of eyes, nose and throat
10		Worsening irritation of eyes, nose and throat
10.0 - 20.0		Threshold of toxicity for prolonged exposure
20+		Paralysis or death occurs after extended exposure (maximum of GasPro instrument is 45ppm)

Figure 19: Health effect of gas exposure. Identification of symptoms caused by exposure to the human body (Bergsson & Pálsson, 2016).

The present communication links on the glacier with the guides are GSM, VHF radio, tetra radio and satellite phones. Not all tour companies use all of the above mentioned communication links. Satellite phones and tetra radios are costly and some companies state that the tetra system is not good enough in the area and thus don't want to use it. Two of the

companies, Arctic Adventures and Icelandic Mountain Guides share a channel on the VHF to be able to work together but they generally stay on their private channels. A general concern was raised regarding the SMS system run by Almannavarnir as the guides say that they do not like to check their phones during a guided tour as it looks unprofessional.

The tourists are informed about Katla by all the tour companies and are always informed that a huge flood could happen in the area. This is however said in a humoristic and simple way to not scare the customer, often referring to the glacier as having the potential to become the world's biggest surf board. This is routine for all the companies as it generates interest and discussion on the dynamic area.

Vulnerability:

The number of tourists on the glacier varies with weather conditions from day to day. The combined estimated number from the four companies is 38000-52000 people per year. The safety officials were not asked to give a firm number of tourists but rather an estimate of the number. The distribution is not even throughout the year as there are times of increased traffic in early summer and autumn when school groups, mainly from the UK, visit the glacier. The guides estimate that on a good day the number of tourists going on the glacier can easily reach over 400 with most trips taking place between 09:00 and 18:00 with a typical length of 1-3 hours. During all the field visits the parking area was crowded and at one instance over 180 people were counted standing on the glacier with lines of people walking towards the glacier.

After the interview stage was finished, a report on the number of tourists at popular tourist locations in Iceland was published by the Icelandic Tourist Board (ITB). The work included a count of tourist in the area of Sólheimajökull for 4 months in 2014 and during January-October 2015. This work revealed that in 2015 up to 160.000 people may have visited the area with August being the peak month with 30.000 people based on a car counter on the road to the area (Ólafsson & Þórhallsdóttir, 2016). Although the count by Ólafsson and Þórhallsdóttir contains uncertainty due to average passenger numbers in cars counted to achieve their number, this order of magnitude is believed to represent a more accurate number than the estimate made by the tour operators for this thesis. The trend they observe of the monthly variance resembles that found by Pagneux in 2015 for the Markárfjót area when observing overnight stays in the area using road traffic as a weighting factor (Pagneux,

2015). The four biggest tour operators thus only bring in a third of the transient population, and we conclude that the people accompanied by a licensed and trained guide resemble that proportion. The remaining 110.000 people that visit the area are thus either traveling on their own or with a different tour operator that may have a different awareness level. From this study and the one conducted for the ITB it is not possible to say how many people go on the glacier, however it would be fair to assume that the majority of the people will hike towards the glacier in the time period from 07:00 to around 22:00 in the summer and 09:00 to 17:00 in the winter with peak activity around 13:00-14:00 as demonstrated by the results of Ólafsson & Þórhallsdóttir (Ólafsson & Þórhallsdóttir, 2016).

4.2 Hazard monitoring.

Monitoring a volcanogenic flood is done in different ways depending on the volcanic system and river being monitored. The main techniques used to monitor the evolution of these events include seismicity, hydrology, GPS, radio echo sounding, radar altimetry of the surface of the glacier, gas measurements, satellite remote sensing and visual over flights. These techniques can be grouped in two categories: real time and campaign measurements, as shown in

Table 3. Currently the focus of the real-time monitoring at Sólheimajökull is on hydrological measurements and seismic monitoring done by the IMO. Campaign-based monitoring by the IES in conjunction with the ICG reveals snapshots of the state of the cauldrons twice a year and in 2014 atmospheric gas measurement were attempted for the first time. This section will be divided into four categories, 1) the real-time system, followed by an example of the monitoring of the 2014 event and how this event can be used to identify similar events, 2) the real-time measurements that are not part of an established network 3) the campaign measurements and 4) the techniques that are currently not in use at Sólheimajökull as they are not adequate to use for early warning for the area studied while they may be useful for other systems. The following techniques are introduced as they are presently operated and may be subject to change in the future.

Table 3: Techniques currently used to monitor volcanogenic floods and their relevance to monitoring Sólheimajökull.

Group	Relevant techniques to Sólheimajökull	Potential Techniques not in use at Sólheimajökull
Real-time	Hydrology, Seismic monitoring (gas monitoring)	GPS monitoring of cauldron depth and satellite detection of crevasse formation
Campaign measurements	Radar altimetry, echo sounding, visual observation, and gas monitoring in atmosphere and in water	

4.2.1 Real-time network

Hydrological stations

The hydrological network in Iceland consists of many different river gauging stations that are river specific. They focus on different events ranging from floods due to heavy rainfall, snow melt in spring or jökulhlaups. In rivers that regularly experience volcanogenic floods the electrical conductivity of the water is measured and a web-camera is active to observe the water color and sediment load during day time hours (Roberts, 2015).

Gauging station V263 at the ring road bridge of Jökulsá was installed shortly after the 1999 flood and has sent data since. Electrical conductivity (measured in $\mu\text{s}/\text{cm}^3$) has shown to be an important parameter to monitor (Kristmannsdóttir, et al., 2002). Generally geothermal water tends to have high conductivity (while precipitation, surface meltwater and pure glacier melt water are poor electrical conductors. Conductivity is generally higher during periods of low surface runoff and lower during high runoff. This natural variance of conductivity means normal background levels are not simply defined. The threshold for detecting a volcanogenic flood will depend on the surface runoff. If it happens during a meteorological peak, it may go un-noticed. This problem may be solved in the future by setting basic rules depending on water volume measured. In general the conductivity may fluctuate gently without there being a flood, as soon as there is a big increase in the conductivity (on the order of 10s of $\mu\text{s}/\text{cm}^3$), during a short period (day or less) a rush of geothermal/volcanic water is expected to be in the river. While slow changes in gradually

rising conductivity (a few $\mu\text{s}/\text{cm}^3$ per week/month) may rather reflect changes in other factors such as the input of meteoric water.

Presently the monitoring of the hydrological measurements are done in a semi-automatic way with alarm thresholds that are changed depending on the state of the river, following predefined instructions. The general rule is that if conductivity rises sharply, it is likely that a small flood is happening, this can be seen in Figure 23. A decrease in the water temperature during minor events is also characteristic as more subglacial water flows during these events. This change is however very small compared to the increase in conductivity as can be seen in Figure 23.

The gauging station at Jökulsá has gone through many different sensors since 1999 because monitoring a glacial river full of sediment is a very difficult task. In addition to destroying sensors, the river changes its flow channel from time to time meaning that the instrumentation of the gauging station needs to move with it. This factor of high maintenance needed, shows the weakness in the system. If the station is not maintained and sending reliable measurements then there are no other hydrological measurements available (Roberts, 2015). This leaves the natural hazards specialist blind in monitoring this field and puts their focus solely on the seismic network.

Seismic network

The seismic network of Iceland is spread over the tectonically active areas focusing on its main volcanic systems. The network consists of over 70 near real-time stations. The seismicity in Iceland is monitored on a 24 hour basis at the IMO by the same natural hazards specialists who monitor the hydrological data. As these two monitoring techniques complement each other the specialist on duty will follow changes in both conductivity and seismic activity. This is currently done manually to a great extent.

Around Katla there are 11 seismic stations within a 40km radius of the central volcano. The tight network around Katla and Eyjafjallajökull has detected many different events, ranging from ice quakes to the volcanic tremor of Eyjafjallajökull in 2010. The network around Katla has improved significantly in the last years with the addition of new stations making the detection potential greater. In general, seismic signals look different depending on the event that caused them. Deep events may be characteristic of movements within a

magma chamber while shallow events may be related to smaller systems such as the geothermal systems. Thus the source of the seismic signals can give warning of what is happening. Deep events moving towards shallow depths could for example be indicative of an eruption while shallow events could be typical for enhanced activity in geothermal fields. Katla is a large central volcano and is seismically very active.

Volcanogenic floods are usually preceded or accompanied by an increase in seismic activity, regardless of the category the flood originates from. Earthquakes and tremor can be caused by volcanic activity or increased geothermal activity before an event as was likely in 1999. Or due to the lowering of pressure above a geothermal field as gases and fluids leave the area. These events can be located using the seismic network and can give valuable information on what cauldron system is being affected. Additionally when the flood water starts to flow beneath the glacier a flood tremor signal can often be tracked giving the approximate location of the flood water. The July event of 2011 in Múlakvísl was preceded by seismic activity both in the form of earthquakes and tremor. The rise in conductivity of Múlakvísl only started as the tremor was peaking (IMO, 2011). The seismic network has played a key role in forecasting events in the past and will do so in the future as well. For this reason it is important to maintain this network to a high standard and develop it further to increase its detection potential.

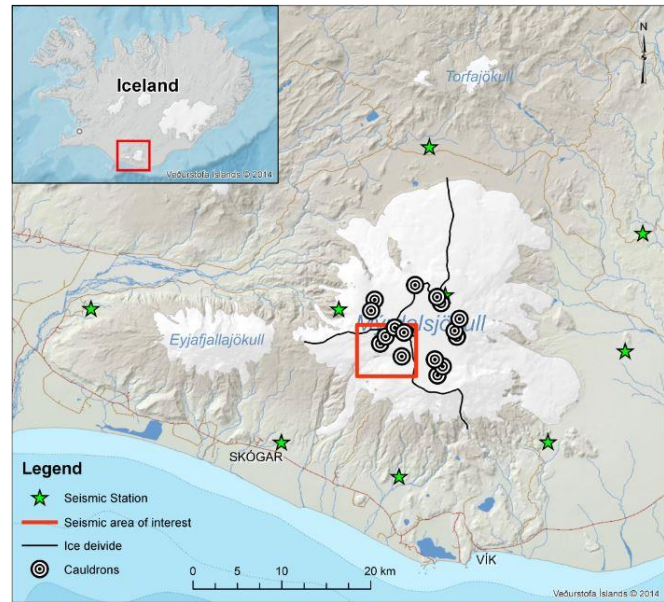


Figure 20: Overview of area of seismic interest in the catchment area of Sólheimajökull showing the location of seismic stations around Katla.

The minor flood of July 2014

The event of July 2014 started on 4th July and ended on the 12th. The event was minor and no significant changes could be seen in the stage height of Jökulsá nor could any change in the river color be identified at the bridge. The event was first noticed as the conductivity of the river increased rapidly while the water temperature decreased (Figure 23). Soon after the conductivity increased, reports from tour guides in the area came of unusual amounts of water flowing from beneath the glacier (Figure 21) and a strong smell of gas was reported. On the 8th the conductivity peaked (Figure 23) and that same day seismic activity in the catchment area of Sólheimajökull started and continued until the 15th. In the evening of the 9th a Multi component Gas Analyzing System (MultiGAS) was installed by Melissa Anne Pfeffer and myself with the help of two technicians in the hydrology department of the IMO. The instrument was installed near to the outflow of the flood water (Figure 11) and collected and transmitted the concentrations of CO₂, H₂S, SO₂ and H₂ for 30 minutes every 3 hours until the 15th. These gas measurement revealed high pulsating concentrations of H₂S with a maximum value of 140ppm right by the outflow. This concentration is well above the public health exposure limit set by the AOSH and can have serious effects on eyes, lungs and nose during prolonged exposure (Vinnueftirlitið, 2016). At this concentration of H₂S the smell of the gas cannot be detected by humans as the gas paralyses the noses sense of smell and long exposure can lead to permanent loss of smell (Vinnueftirlitið, 2016). Although the flood was



Figure 21: Melissa Anne Pfeffer and Njáll Fannar Reynisson taking a water sample at the outflow location of the flood.

minor, the threat of the high concentration of H₂S was substantial in the confined area around the outflow location and was perceived as the greatest threat to human health during the event. Consequently a confined area was closed spanning the northwest region of the glacier snout, the tour guides were asked to use the eastern route seen in Figure 15 to get to the glacier and we told to be cautious.

Identifying past events similar to the 2014 event

To identify the frequency of minor events, similar to the 2014 event, characteristics of the flood were identified and basic rules set to identify past events. The trends observed were that the conductivity rises while the water temperature falls and the seismicity increases. The past hydrological data was analyzed by applying filters to the data. This analysis of a long time series of data utilized 24 hour averages of the data while 5 minute resolution is available. 24 hour averages were used as the data analyzed spanned over 8 years making the data set very large to work with. As the 24hour average of the data showed the 2014 event very clearly it was deemed appropriate. The 9 day running means of the conductivity and the water temperature were inversely correlated with a coefficient of determination (r^2) greater than 0.7. The second threshold applied was that the conductivity must have increased by at least 25 $\mu\text{s}/\text{cm}^3$ from the previous day. The green marks in Figure 22 show when both these thresholds were met for a subset of the data. A third threshold needed to be reached, that the daily sum of the relative seismic moment from the catchment area of Sólheimajökull

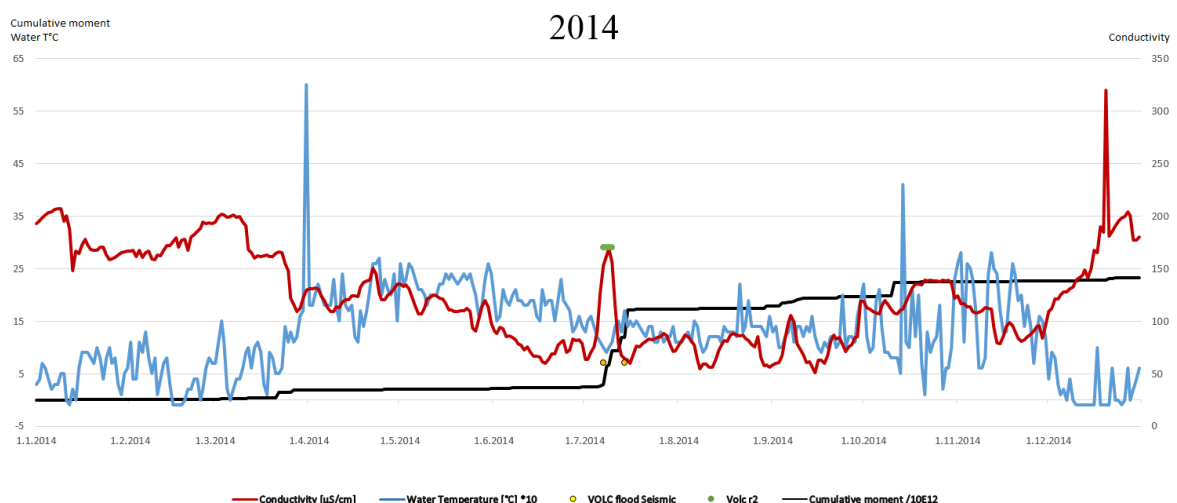


Figure 22: Subset of time series of data used to identify floods. The green points indicate times when the rise in conductivity and drop in water temperature meet the thresholds to distinguish a flood. The yellow points indicate when the increase of seismic moment meets the threshold.

(red square in Figure 20) exceeded $3.0 \cdot 10^{13}$. This means that the data was only analyzed for earthquakes but not for tremor events. As tremor is more difficult to identify and requires filtering of data from many stations it cannot easily be displayed. Tremor data has only recently started to be stored in a proper manner and the events were not analyzed with regards to tremor as this would have been troublesome. But would have added to the detection of the past flood events to a great extent. However analysis of the two more recent floods identified events could be done to see if the events were accompanied by flood tremor. This was however not done in this analysis as the main goal was to identify the frequency of past events. The yellow marks in Figure 22 indicate when the seismic moment threshold was met.

All three criteria being fulfilled indicates a minor flood. Four events meeting this criteria were identified from January 1. 2009 - January 1. 2016 (Table 4 and Figure 23). As the time series of hydrological measurements prior to 2009 is rather broken, only data from 2009 to 2016 was used, although the station was installed in July 1999. There may have been higher gas emissions like measured in 2014 during the other three floods but unfortunately no gas records were found for these events although locals state that the river has occasionally emitted gas in the last 10-15 years (Bragason, 2016; Ragnarsson, 2016). For future events of similar size it would be safest to assume that the direct zone of the outflow of the water be regarded as a gas hazard zone until proven otherwise.

Table 4: Minor volcanogenic floods in the period from 2009-2016 at Jökulsá

Flood	Change in Conductivity ($\mu\text{s}/\text{cm}^3$)	Change in Relative MO (N m)	Change in water Temp ($^{\circ}\text{C}$)
7/6/2014	98	$1.4\text{E}+14$	0.5
6/6/2012	86	$3.6\text{E}+13$	0.4
10/5/2011	79	$8.5\text{E}+13$	0.2
9/5/2011	88	$5.9\text{E}+13$	0.4

The methods used here to identify past minor events could be modified to provide early warning of future minor events by changing a few factors. Firstly, high-resolution real-time data would need to be used instead of daily averages. Secondly, the changes in the three parameters: conductivity, water temperature and seismicity, including the tremor data as well would need to be operative. A system of this sort is active at the IMO but focus has not been put on the detection of these minor events. Through the setup of a system of this sort the

detection potential could be improved for larger floods as well, but primarily this system would be optimized to identify these higher frequency small events where the primary risk is due to gas emissions.

In the subset of data seen in Figure 22 it can be seen that the change in conductivity during a minor flood event is less than the variance in conductivity for the year of 2014. What is however important is that the rate of change during the flood event is greater, with the pulse lasting a few days. The increase in the seismic moment is also conclusive as the energy release throughout the year is relatively low but during the flood it is elevated. Furthermore the water temperature falls at the same time as the conductivity increases. All of these three factors can fluctuate on their own, as can be seen in Figure 22 with high spikes of both conductivity and water temperature, but when they all happen at the same time it indicates that a flood happened.

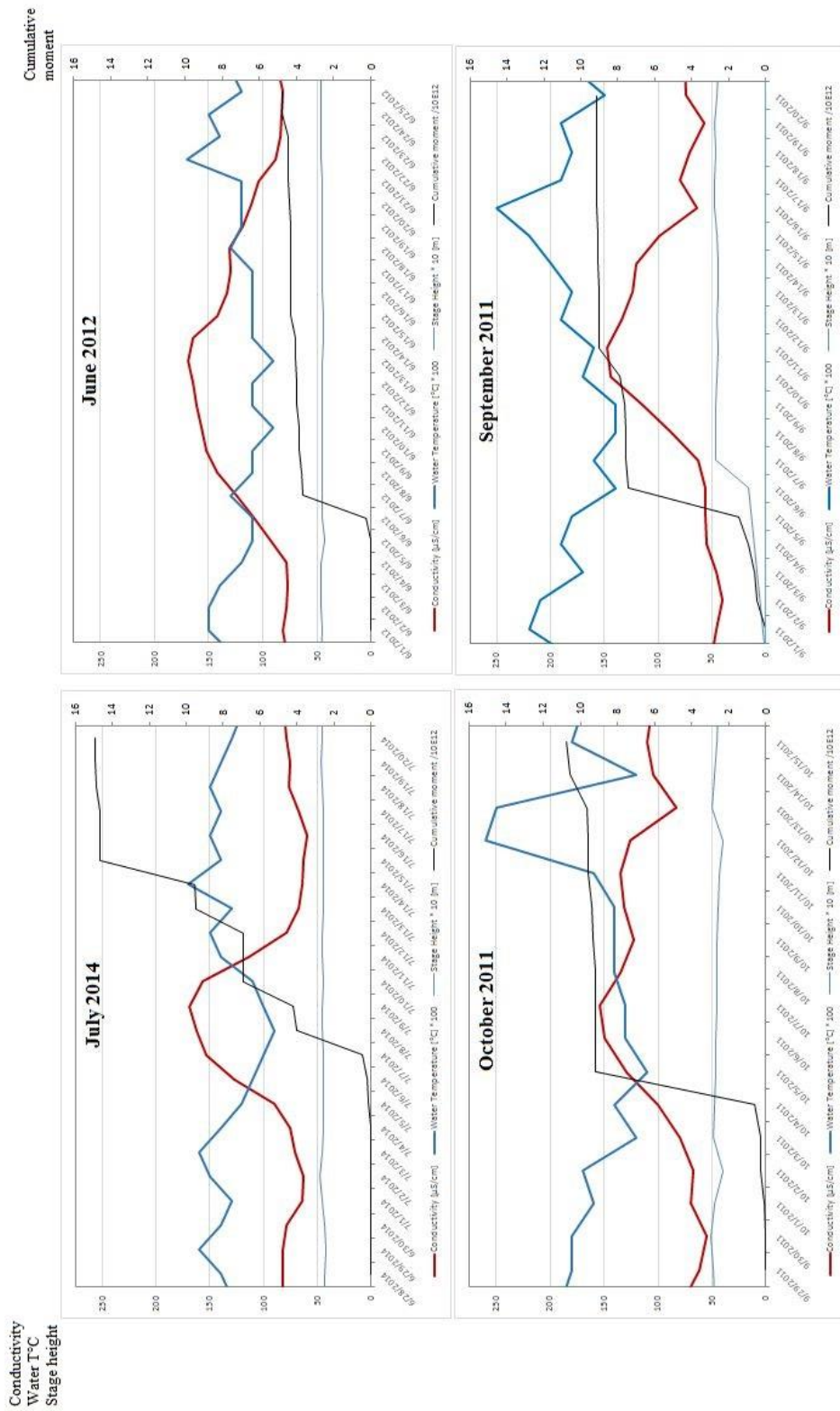


Figure 23: The four floods identified at Sólheimajökull from January 2009 to January 2016. Larger figures of these floods can be seen in Appendix D.

4.2.2 Real-time measurements (network not established).

Gas measurements

During volcanogenic floods of all sizes, local gas concentrations are known to far exceed the worker and general public health limit standards and have had serious effects on workers (Zófoníasson, 2016; Vinnueftirlitið, 2016). One such example happened during the July 2002 Skaftárhlaup when two technicians from the hydrological department (then a part of the national energy authority, now part of the IMO) were rescued by a helicopter from the ICG after having been exposed to high concentrations of gas. Both were hospitalized for some time after the event (Zófoníasson, 2016).

Real-time measurements of volcanic gas are a relatively new field in the natural hazard monitoring network used in Iceland. The first automatic station was installed on the summit of Hekla in July 2012 (Ilyinskaya, et al., 2015). In 2014 the first attempt to measure the gas concentration in real-time was made at Jökulsá. Unfortunately the measurements only started after the flood had started and a gas sensor was only installed after the peak of the flood as shown in Figure 24.

The gas monitoring of volcanogenic floods operated by IMO has until now only been campaign fashioned, meaning that as soon as an event is noticed by one of the other networks, gas measurements will be made. Two flood events have been monitored in such fashion: Jökulsá á Sólheimasandi in 2014 and Skaftárhlaup 2015. During both these event a MultiGAS was installed as close to the glacier's edge as possible. In the case of the flood at Jökulsá á Sólheimasandi the data was sent automatically to the IMO for remote monitoring of the situation in the area and Almannavarnir was updated regularly on the ongoing situation. Measurements during a non-flooding period were made in the summer of 2015 at Sólheimajökull to measure normal background concentrations (both H₂S and SO₂ were zero).

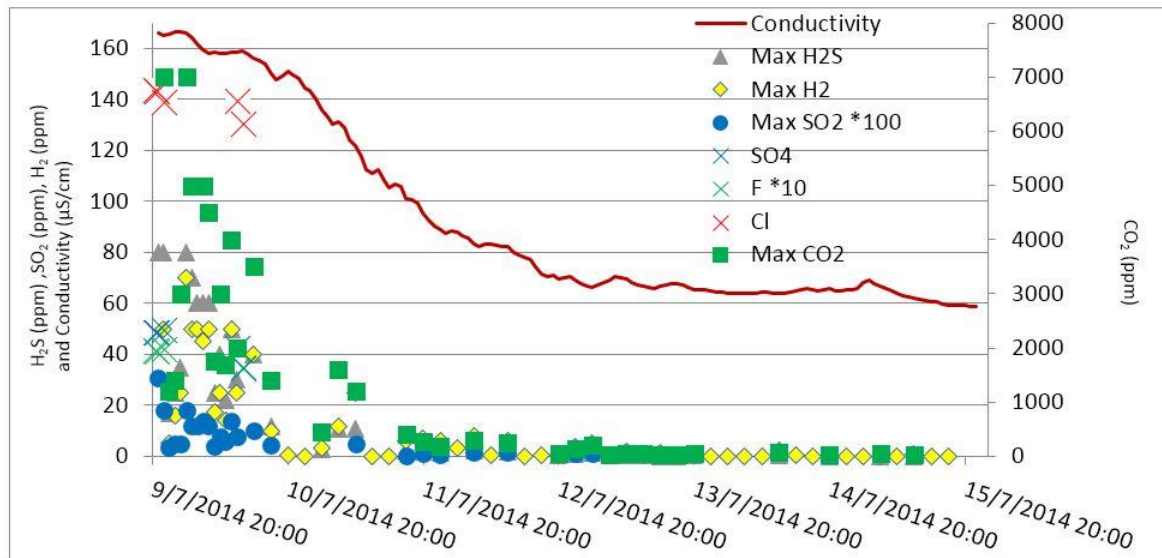


Figure 24: Gas concentrations during the July 2014 flood.

As the field of atmospheric real-time gas measurements is relatively new in Iceland the infrastructure and experience in measuring gas signals from glacial rivers needs to be improved. This field has potential to grow as new instrumentation has developed in recent years that can measure gas in real-time and with the use of numerical models one could attempt to investigate atmospheric transport of pollutants for simulating the dispersal of gases in the affected area. Models such as the CALPUFF code were used during the Holuhraun eruption (2014-2015) to forecast hourly concentration of SO_2 originating from the eruptive fissure (Gislason, et al., 2015). The accuracy of these models is of course dependent on the quality of the meteorological input data. Within Iceland, the HARMONIE meteorological prediction model continues to be improved, producing higher resolution, more accurate wind fields than have been available before (Narwi, 2014). The model results for the Holuhraun eruption were accessible through IMO's web-site and the general public was able to visualize the maps and identify events of high SO_2 concentrations in areas close to their lives/activities. This information could be implemented at Sólheimajökull in the future and could define the hazardous/restricted areas like was done in Holuhraun during periods of higher gas emission.

Potential monitoring techniques.

Due to Sólheimajökull's short subglacial flow distance (Figure 8) and the fact that all its cauldrons are seepage type cauldrons, there are currently two operating monitoring systems available. These are the two established networks of the IMO (hydrological and seismic). The airborne gas measurements that have until now been at a development state can in the future become a real-time monitoring tool. The gas measurements share most logistical needs with the other systems allowing for remote setup of instrumentation that can gather data in real-time. These techniques can be displayed on a timeline to illustrate their affective timely detection as seen in Figure 25. As gas has not been measured prior to volcanogenic floods the timeline illustration in Figure 25 displays a dotted line before the flood starts even though reports of people smelling gas preceding volcanogenic floods exist.

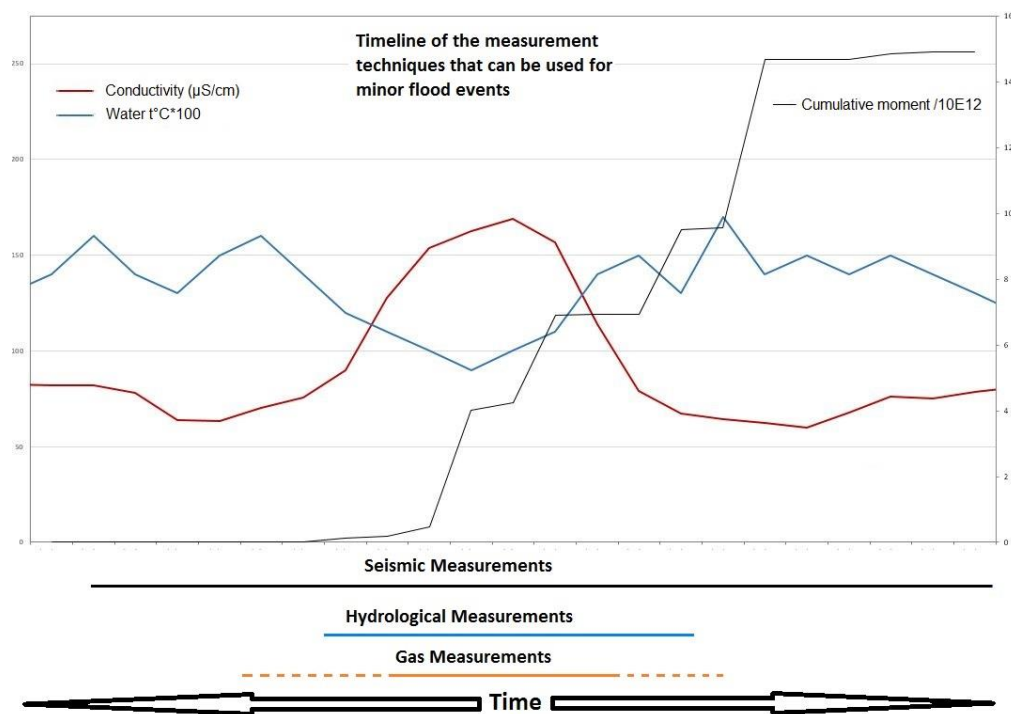


Figure 25: An example of the time period of different monitoring techniques that could be of use to an early warning system.

4.2.3 Campaign measurements.

Chemical analysis of river water

River water composition can be used to indicate the origin of the flood water to distinguish if it is from a subglacial eruption or from hydrothermal buildup of water underneath the ice. This involves identifying trace elements of the water that are only be present if there is an eruption (Galeczka, Oelkersa, & Gislason, 2014; Kristmannsdóttir, et al., 2002). Measurements of the trace elements F, Cl and SO₄ during the 2014 event are shown in Figure 24. This technique is useful for defining the chemical fingerprint of the flood but it currently takes time to analyze these samples so they do not give real-time warning for these events. Instrumentation that analyses these trace elements in real-time exists but have until now not been used to monitor volcanic/geothermal signatures in glacial rivers (AIS , 2016).

Altimetry

The size and depth of ice-surface depressions (cauldrons) can be monitored to assess meltwater accumulation in locations where geothermal activity causes melting at the base of an ice-cap. This is currently done at Mýrdalsjökull utilizing two methods, the first method having the longer time series uses airborne observations with radar-altimetry. This technique measures predefined flight profiles over each cauldron in Mýrdalsjökull giving a depth profile with a relatively small error (Figure 26). A time series from 1999 (just after the Jökulhlaup in July) is available so any change in the cauldron activity can be observed from these flights. The general idea behind these measurements is that the cauldron ice surface will swell up or rise when water starts to accumulate under the cauldron and will then rapidly lower once the flood starts to flow from the cauldron. This technique allows one to track this swelling and thus give a rough time frame for when it is likely that the cauldron will be ready to empty. This technique has some limitations as it measures the surface of the glacier rather than the bottom so any substantial drift snow events or a decrease in bottom melting can look like swelling of a cauldron (Guðmundsson M. T., Högnadóttir, Kristinsson, & Guðbjörnsson, 2007). Another technique focusing on the same theory of cauldron swelling

exists that monitors the bottom of the glacier rather than the surface, this is the technique of radio echo sounding.

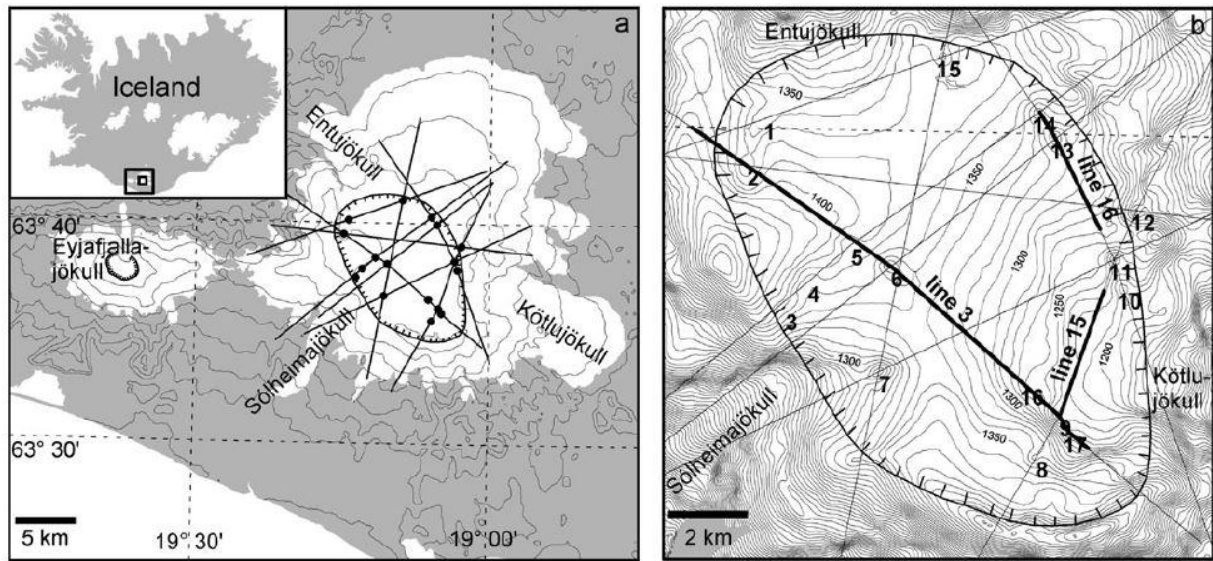


Figure 26: Flight lines over the cauldrons of Mýrdalsjökull (Guðmundsson M. T., Högnadóttir, Kristinsson, & Guðbjörnsson, 2007).

Radio echo-sounding

Radio echo sounding eliminates the uncertainty of accumulating snow in cauldrons as it scans the bottom of the glacier with radio waves and receives back scattering echo with a microphone. Different materials back scatter different intensities of the radio waves, showing a big difference in the received signal of ice, rock and liquid water. The measurements are taken on the surface of the glacier and by taking sections across the glacier a picture of the glacier bottom and any liquid water can be created. Measurements of this sort have been carried out twice a year since 2012 (Magnússon, 2014). These measurements are very time consuming and dangerous as a trip has to be made across the cauldrons with either a snow mobile or a jeep dragging the radio echo sounding instrument behind it. The process involves repeating the same cross section as frequently as possible to try and see if there is any water buildup. This can of course be dangerous as crossing the cauldrons repetitively can put the field scientist at risk. For example in 2011 a field scientist from the IES passed one of the cauldrons three days before it emptied. Both the techniques of radar altimetry and radio echo sounding require people to take measurements and process the results manually. This effectively means that the time lag will in most cases be substantial and the results of these measurements cannot give an accurate timing of future events especially when the subglacial flow channel is as short as that of the catchment area of Sólheimajökull. Additionally the techniques require substantial water accumulation for it to

be detectable and, as Sólheimajökull's cauldrons are all seepage cauldrons, it is unlikely that the technique will contribute for a timely early warning of a volcanogenic flood at Sólheimajökull.

Visual observation

Reynir Ragnarsson, a local of the area and former policeman in Vík, has for many years assisted scientists from the IMO and IES in monitoring Katla and Eyjafjallajökull. Reynir has monitored the conductivity of the glacial rivers in the area using hand held instruments, giving valuable spot measurements, as well as flying over the glaciers and the surrounding areas photographing the cauldrons, rivers and any areas that may be of interest to scientists. His spot measurements of conductivity have been used to supplement and compare with the data of the real-time sensors. Reynir regularly sends photos from his overflights where he identifies the cauldrons he has observed and how the flow channels of rivers change. Reynir's work and knowledge of the area is very valuable and his work has greatly added to the monitoring of the region.

Another perhaps under used monitoring tool is the presence of tour-guides in the area on a daily bases. Many guides go to the area 15-20 times per month and have reported changes in the past, including the reporting of the 2014 July event. Having people on site that are capable on reporting changes as they happen may be very valuable and should be used to a greater extent.

4.2.4 Techniques not used currently at Sólheimajökull

GPS network

The GPS network is spread over the same area as the seismic network with a total number of over 100 stations. These permanent stations do however not directly increase the monitoring potential of volcanogenic floods. A different technique exists using GPS instruments to monitor the surface elevation of ice-cauldrons. This technique relies on the same theory as the previous methods do, i.e. that a cauldron will swell up prior to draining. This has been implemented in one of Katla cauldrons in the past, namely after the 2011 volcanogenic flood at Múlakvísl. As the 2011 flood washed away the ring road bridge at Múlakvísl a new bridge had to be constructed. Due to the fear of a second flood the Icelandic road authority asked that the newly drained cauldron were monitored during the construction of the new bridge to protect its workers. After the construction was finished the equipment was taken down, as it is almost impossible to maintain a GPS station on the ice-shelf of Mýrdalsjökull for the glacier gets up to a 10m snow accumulation each year in some locations.

Monitoring the elevation of cauldrons has been attempted before and after this effort with different success levels. The river Skaftá has been known for its regular volcanogenic floods, resulting from the drainage of the two cauldrons in its drainage area. The 2015 Skaftárhlaup was successfully monitored giving a four day warning as the ice shelf above the cauldron started to descend four days before the floodwater reached inhabited areas. This descent of the ice shelf can be seen in Figure 27, as the shelf dropped by 82 meters. This technique is has not been used for monitoring Sólheimajökull as all its cauldrons are located in areas where water continually leaks and the drainage path is short. A long warning time such as given for the Skaftár cauldrons will however not be achieved at Sólheimajökull even if water accumulation would happen, due to the short subglacial flow path. For scientific proposes there are plans of installing a GPS instrument in one of Sólheimajökulls cauldrons for the summer of 2016 with a logging instrument that will not transmit data in real-time this will show if the technique is useful.

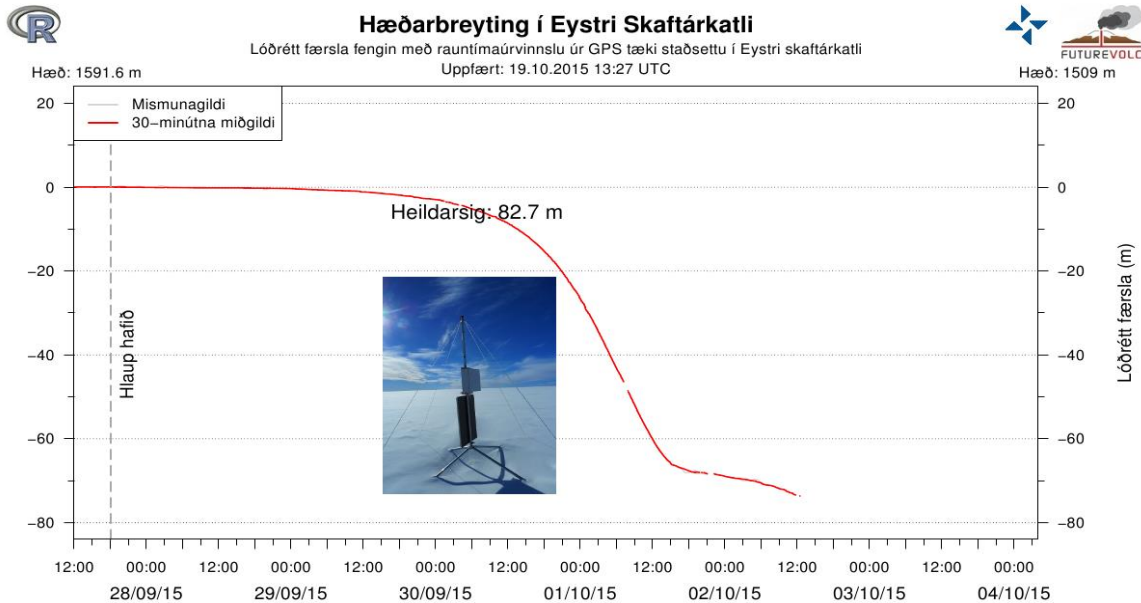


Figure 27: A plot showing ice subsidence of the eastern Skaftár cauldron in 2015 monitored by a GPS instrument in the cauldron. The event was forecasted by 4 days of warning.

Satellite monitoring.

The fact that the surface of a cauldron that has emptied breaks and forms crevasses, means that they can be observed from satellites as these crevasses are large and may be detected both by radar scans and on photographs. Although this technique relies on satellites that pass at certain times of the day, it can provide useful information of the state of the cauldrons and may provide supportive information to other systems confirming for instance what cauldron has emptied. Additionally it has the potential to assess the size of cauldrons similar to the altimetry measurements with a higher temporal resolution. Work on utilizing satellites however needs further attention and the technique may be very useful in the future if linked with the altimetry measurements. Currently sufficient time resolution and automatic processing is not available so the technique is not considered to be suitable for monitoring Sólheimajökull in real-time today.

5 Discussion and Conclusions

5.1 Human activity

All tour guides questioned were aware of the potential risk of a volcanogenic flood and of what locations/routes were the safest to use during events, although all companies apart from Arcanum admitted to using trails that would be unsafe during flood events. Little was known of the different scenarios that could happen and not much was known about the difference in size of floods. This was especially apparent for the two companies that had not attended the public meeting held in Vík in July 2014 where the results of the study of small to medium sized floods was presented (Guðmundsson, Högnadóttir, & Oddsson, 2015). The safety officials trusted that they would be informed by the authorities about any danger in time to safely leave the area and act according to the contingency plan set by the ICP. This leaves us with the question if a special risk assessment needs to be done for the area followed by a more detailed contingency plan focusing on the tourism sector to a greater extent.

Although it cannot be demanded that the glacier guides are experts in identifying precursory flood warnings, it would be good if their knowledge of this hazard would be higher such as that of Arcanum so that mitigation efforts could run smoother in the case of an event. The local tour operator Arcanum should in this case be made as an example as their risk assessment document proved to be very informative giving the guides clear information on what can happen, going into detail about past events and the different hazards associated with volcanogenic floods and how they are monitored. The information about the gas hazard during minor floods demonstrated in this study should be added to this document and the high temporal occurrence of them should be highlighted.

An example of the improved document could then be something in the lines of this:

Hazards that may arise due to floods from Sólheimajökull:

- Flood water can break the ice of the glacier margin
- Flood water can flow on the glacier
- Flood water can strike people and vehicles that are located in front of the glacier
- Gas can cause serious illness or death even during minor events

What can cause this to happen:

- Warnings of the danger of volcanic eruptions are not heeded

- Sudden and unpredictable natural disasters
- Precursors to events are not detected by monitoring officials

Crises that can arise:

- The flood could strike people causing drowning, hypothermia or other physical trauma.
- Gas poisoning can damage organs and may lead to death particularly concerning people with respiratory conditions.

Measures to reduce the risk of floods at Sólheimajökull:

- Track earthquakes in and around Katla
- Track conductivity in Jökulsá
- Be aware of gas as this may be a precursor and poses threat to human health
- Be aware of sudden changes in river color
- Inform monitoring officials if something unusual is happening that may indicate flood water
- Be in good telecommunications contact within and outside the region
- Comply with the response and evacuation plans in cooperation with the emergency authorities

The fact that no evacuation exercises have been carried out on the glacier means that even if the tour guides estimate that they can have all their people off the glacier in 30 minutes, this should be viewed as the minimum time needed and should be put to test with a mixed group of clients as people react to stressful situations differently. The fact is that a far greater number of people are in the area and no test has been made of how fast the information will reach people from first detection to the completion of the evacuation for the area.

Currently the responsibility of the tour operators according to the contingency plan is that the tour operators order their staff in the area at risk to come back and stop any further trips from entering the area. There is however not a law that makes them responsible for the tourist even if the safety officials and police commissioner state that the guides would bring every one of the glacier. This makes the situation unclear as the tour guides have now legal obligation but are given a moral obligation to act accordingly. The question should be raised if this level of trust in the moral responsibility of the tour guides is too high, and if this inconsistency should be dealt with.

Another important point as what raised the most concern during the interviews and the field visits, was the lack of informative infrastructure or material for people visiting the area who are not accompanied by guides. Informative infrastructure in the area has not increased at

the same rate as the flow of tourist. After the 2014 flood two signs were installed as seen in Figure 17. These signs do not deliver a clear message about the risk of the hazards in the area: in my opinion they only convey that the area is hazardous. A clear sign informing the traveler about the state of the glacier from a hazard and legal perspective is not existent. Finding information regarding the closure of both the glacier and the northern parking lot is very difficult as no documentation regarding this is available to the public. Apart from the temporary closure of the area during an uncertainty phase in August 2014 the only information on the closure was received straight from the police commissioner, this means that the public will perceive the area as being open. This lack of information leads to people entering the risk area involuntary, and leaves them far more vulnerable to the hazard than they need to be. It would not come as a surprise if a study as the one conducted by Bird et al. in Þórsmörk would likely show similar results at Sólheimajökull as it is up to the travelers and guides to get information regarding the hazards at Sólheimajökull.

Indications of this lack of awareness were clear during the field visits to the area as on two occasions, groups of foreign students (13-15 year olds) were seen wandering around the area, relying on the supervision of two teachers. One of the groups came by a bus that was parked in the northern parking area and the teenagers all entered the glacier without equipment. There are other examples of independent people wandering around the glacier without equipment and getting into trouble, this has been quite prominent in Icelandic news for the last years (Tryggvason, 2016a). Although this problem of unaccompanied, under-qualified visitors is very apparent, the majority of the people seen during the field visits were traveling in a group apparently led by a person who is familiar with the area.

As the numbers of people visiting the area of Sólheimajökull has been shown to be far greater than this study indicated, it is fair to say that the techniques adopted to assess the population in the area gave a drastic underestimation (Ólafsson & Þórhallsdóttir, 2016). However since the information on the size of the population visiting the area has been published, it can be said that only a third of the people visiting the area are certainly accompanied by a licensed guide. Although it is unlikely that the remaining people all visit the glacier on their own it would be important to study this as two thirds of the people visiting the area are entering an area of risk that they may be unaware of thus being subject to involuntary risk making them more vulnerable. This was very evident in the interviews with the safety officials who discussed different problems often relating to the under-management of the area and this

matches well with the field observations made during the study. Additionally the fact that half of the tour guides did not know about the “closure” of the northern parking lot and none of them knowing that the glacier is off limits to the general public raised considerable concern regarding the flow of information from the local authority to the tour operators. The fact that the area is regarded as being closed without any one knowing about it cannot be acceptable. This field needs to be managed better and signs or information about the hazards in the area needs to be available if the glacier is to be off limits to people who are not on guided tours. This is crucial for any evacuation of the area as the general lack of knowledge of the solo travelers present will increase the number of potentially vulnerable people in the area.

As the four tour operators only cover a third of the population visiting the area, it would be a valuable study to try to question all the different tour operators in the area about their knowledge of jökulhlaups and what they plan on doing if such an event happens.

5.2 Monitoring actions

Although the present state of the real-time network and measurements can be very informative, improvements need to be made because as the number of visitors grows so does the vulnerable population. Currently there are only two real-time networks that are relied on to give an immediate warning of any unusual activity in the area consisting of the hydrological gauging station and the seismic network. Other techniques, such as the altimetry measurements and the radio echo sounding of the cauldrons, are very valuable for the monitoring of the cauldrons but as these techniques cannot provide real-time information at their current level they are not reliable for an early warning for the area today. Additionally these techniques may not indicate an incipient minor event such as that of 2014 as no substantial water buildup is associated with them. Being able to give an as timely warning as possible is always be the goal so that warnings and mitigation actions can take place. The example of the Skaftárhlaup in 2015 demonstrates how this was done successfully. A timeline of events may be created for this event as seen in Figure 28. For Sólheimajökull a timeline of this sort would be very different as the subglacial flow channel is far shorter and putting higher stress on real-time aspect of the monitoring techniques, an example of a

timeline for this was created in Figure 28 to illustrate that the detection of an event could so late that the event may already have started before a warning is given.

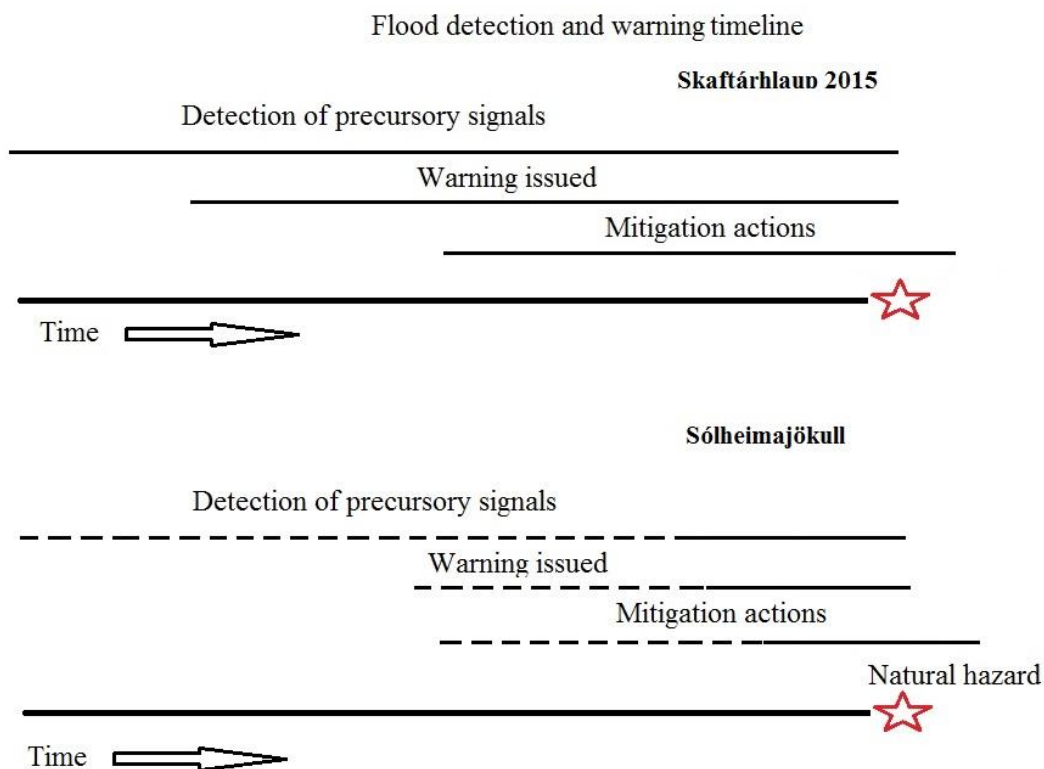


Figure 28: Proposed timelines of stages for flood events of Skaftá and Sólheimajökull.

As minor events have been shown to be a frequent event having had 4 events in the last 8 years a greater focus needs to be set on detecting them reliably as they start to happen, so that mitigating actions can be made in a smooth fashion. The identification rules set in this study could be modified to assess in real-time if a minor flood has started or not. This effort would add to the monitoring potential of larger events to as they share the same precursors just at greater magnitude. If minor events are supposed to be monitored reliably, both the hydrological station and seismic network need to run reliably, in particular the gauging station is very important and resembles a weak link as only one station is installed in the river, it would be valuable to have an additional system in the river at a different location to have some backup for these important measurements. This would also give reference measurements to cross check the system as a faulty sensor may go unnoticed if it is giving values within the fluctuating range of the river. Making sure that these networks are maintained and constantly refined is of great value, although maintaining and adding stations

to the network is arguably costly due to installation and equipment cost, the benefits of evacuating the area prior to an event would be prevention of any unnecessary risk. To maintain an active monitoring system means that a continuous effort needs to be made to adopt new techniques and the techniques that are currently only used in campaign fashion may get a higher temporal factor in the future as technology improves.

Gas measurements currently have the potential to be a useful technique to monitor the area as it is very likely that an increase in the atmospheric gas concentration could be detected as the conductivity rises. This technique could add substantially to the present monitoring and give supportive data if changes are detected. Additionally, gas monitoring could be used to define hazardous areas during smaller events similar to what was done by the IMO during the Holuhraun eruption of 2014 (Gislason, et al., 2015). And systems to inform the guides in real-time in the area could be made. In the future systems that measure the dissolved concentration of gas in water could be utilized such as those developed by AIS (AIS, 2016).

Larger events at Sólheimajökull will likely be preceded by seismicity in the area and volcanic unrest would most probably lead to the closing of the area prior to any flood. No hydrological record for Jökulsá exists flood larger than the minor events identified in this project as the hydrological station was installed after the most recent event in 1999.

Another perhaps under-utilized resource in the monitoring of the river is the expertise of guides who visit the area many times a month. As the water color of the river has been observed to change prior to eruptions, it would be valuable to inform tour guides who regularly visit the area of what is expected. Including precursory signals such as unusually high flow of water and smell of gas. (Sigurðsson, Zóphóníasson, & Ísleifsson, 2000).

5.3 Conclusions

As the number of people visiting the area of Sólheimajökull has increased greatly over the past 10-15 years without the adequate buildup of informative infrastructure, the vulnerability of people in the area to volcanogenic floods has increased. Since 2009, at least four minor flood events have happened. These floods were all likely accompanied by a gas phase that could have been harmful to people in the area. Floods of this sort will likely happen in the future and they need to be monitored more closely with the increasing number of vulnerable

people. Following are six main points that would be valuable to consider to increase the capacity to deal with the hazards associated with volcanogenic floods at Sólheimajökull.

- 1) The knowledge of the tour guides about safety procedures is good regarding the everyday hazards, but improvements can be made in their knowledge regarding volcanogenic floods. This could be achieved through an improved version of a document like that presented by Arcanum. This way guides could be educated to identify early signals, like gas emission, color of the river and other changes in the area and could inform the monitoring agencies possibly resulting in earlier warning of an event. This would improve the capacity of the guide to act correctly during a hazardous event and decrease the vulnerability of the tourists accompanied by the guide. Implementation of this could be through material offered to the safety official of each company to be added to their already established safety training program. As a result from this, a link could be established with the monitoring institutions, where the guides could simply report any unusual activity in the area. This link is of course present today, but is very rarely used and could be optimized further to the benefit of both the people in the area and those monitoring.
- 2) The information infrastructure in the area needs considerable improvement as currently the glacier is supposed to be closed to the general public (people not on guided tours) and the northern parking area is “closed” but it appears to be open to unaccompanied visitors and too many of those on guided tours.
- 3) An evaluation of the awareness and preparedness of guides of other companies would be provide useful information as the guides will in most cases know more about the area than the tourists.
- 4) Studies on the awareness of the tourist sector (employees and tourists) in the area similar to the study conducted by Bird et al. would give needed information about vulnerable people in the area. This would provide information about the tourist awareness rather than focusing on the awareness of the guide. Additionally through a study like this the proportion of solo travelers could be assessed.
- 5) Some improvements to the reliability of monitoring could be achieved. Suggestions include 1) having an additional hydrological station installed at Jökulsá to ensure that the river is always monitored in real-time and 2) installing gas monitoring instrumentation close to the outlet of the glacier. The addition of gas monitoring

could support any detections made by other networks. These instruments could further be utilized to inform people in the area of the present danger associated with gas. Steps such as those taken during the Holuhraun eruption by the IMO could be taken such as the production of maps of the most likely regions to have dangerous concentration of gas. This would also allow the guides to see if the area is safe to work in during small events and where they should lead their people.

- 6) Work on applying the algorithm used to identify the past minor events at Sólheimajökull should be made to identify the early signals of future floods in the real-time data streams. This work would also increase the detection potential of larger floods.

References

- AIS . (2016, May 02). Retrieved from AIS Analytical Instruments Systems: <http://www.aishome.com/>
- Almannavarnir . (2013). *Viðbragðsáætlun vegna eldgoss undir Mýrdalsjökli*. Almannavarnir Ríkislögreglustjóra.
- Almannavarnir. (2014, August 3). *Óvissustig við Sólheimajökul 3. ágúst 2014*. Retrieved from Ríkislögreglustjórinn Almannavarnadeild: http://www.almannavarnir.is/displayer.asp?cat_id=8&module_id=220&element_id=3147
- Almannavarnir. (2016a, May 15). *Almannavarnastig*. Retrieved from Ríkislögreglustjórinn almannavarnadeild: http://www.almannavarnir.is/displayer.asp?cat_id=306
- Almannavarnir. (2016b, April 15). *Viðbrögð íbúa vegna eldgoss í Mýrdalsjökli og jökulhlaups nður Mýrdalssand og Sólheimasand*. Retrieved from Ríkislögreglustjórinn Almannavarnadeild: http://www.almannavarnir.is/displayer.asp?cat_id=193
- Alþingi. (1996, July 1). *Lögreglulög*. Retrieved from Alþingi: <http://www.althingi.is/lagas/145a/1996090.html>
- Alþingi. (1997, May 23). *Lög um varnir gegn snjóflóðum og skriðuföllum*. Retrieved from Alþingi: <http://www.althingi.is/lagas/145a/1997049.html>
- Alþingi. (2008, June 1). *Lög um Almannavarnir*. Retrieved from Alþingi: <http://www.althingi.is/lagas/145a/2008082.html>
- Alþingi. (2011, September 30). *Lög um Veðurstofu Íslands*. Retrieved from Alþingi: <http://www.althingi.is/lagas/145a/2008070.html>
- Alþingi. (2015, November 6). *Tillaga til þingsályktunar um áhættumat vegna ferðamennsku*. Retrieved from alþingi: <http://www.althingi.is/altext/145/s/0383.html>
- Arcanum. (2014). *RISK ASSESSMENT FOR GLACIER WALKS: SÓLHEIMAJÖKULL GLACIER, SOUTH ICELAND*. Vík: Arcanum glacier tours.
- Atvinnuvegaraduneytið. (2016, March 25). *Atvinnuvegaraduneytið*. Retrieved from atvinnuvegaraduneyti/útgáfur: <https://www.atvinnuvegaraduneyti.is/idnadar-og-vidskiptamal/frettir/baett-oryggi-a-ferdamannastodum-tillogum-stjornstodvar-ferdamala-hrint-i-framkvaemd>
- Bergsson, B., & Pálsson, S. (2016). *Vinna þar sem hættu er á gasmengun*. Reykjavík: IMO.
- Bird, D. K., Gísladóttir, G., & Domenech-Howes, D. (2009). Resident preception of volcanic hazards and evacuation procedures. *Natural Hazards and the Earth System Sciences*, 251-266.

- Bird, D. K., Gísladóttir, G., & Domenech-Howes, D. (2010). Volcanic risk and tourism in southern Iceland. Implications for hazard, risk and emergency response education and training. *Journal of Volcanology and geothermal research*, 33-48.
- Björnsson, H. (1991). Jökulhlaups in Iceland: prediction, characteristics and simulation. *Annals of glaciology*, 95-106.
- Björnsson, H. (2002). Subglacial lakes and jökulhlaups in Iceland. *Global and Planetary Change*, 35, 255-271.
- Björnsson, H. (2009). Jöklar á suðurlandi. In H. Björnsson, *jöklar á Íslandi*. Reykjavík: Bókaútgáfan Opna.
- Björnsson, H., Pálsson, F., & Guðmundsson, M. T. (2000). Surface and bedrock topography of the Mýrdalsjökull ice cap Iceland: The Katla caldera, eruption sites and routes of Jökulhlaups. *Jökull*, 49, 29-46.
- Bragason, B. (2016, April 20). Present state at Sólheimajökull and future plans. (B. Bergsson, Interviewer)
- Dictionary, O. (2016, February 17). *definition/english/flood*. Retrieved from oxford dictionaries Language matters: <http://www.oxforddictionaries.com/definition/english/flood>
- Einarsson, E. H., Larsen, G., & Thorarinsson, S. (1980). The Sólheimar tephra layer and the Katla eruption 1357. *Acta Naturalia Islandica*, 28.
- Ferðamálastofa. (2016, April 13). *HEILDARFJÖLDI ERLENDRA FERÐAMANNA 1949-2015*. Retrieved from Ferðamálastofa: <http://www.ferdamalastofa.is/is/tolur-og-utgafur/fjoldi-ferdamanna/heildarfjoldi-erlendra-ferdamanna-1949-2015>
- Finnbogason, Í., & Magnússon, S. p. (2015, December 17). Öryggismál á Sólheimajökli. (B. Bergsson, Interviewer)
- Fréttablaðið. (2011, May 23). *Fjórða eldgosíð síðan hléinu lauk*. Retrieved from Visir.is: <http://www.visir.is/fjorda-eldgosid-sidan-hleinu-lauk/article/2011705239941>
- Galeczka, I., Oelkers, E. H., & Gislason, S. R. (2014). The chemistry and element fluxes of the July 2011 Múlakvísl and Kaldakvísl glacial floods, Iceland. *Journal of Volcanology and Geochemical Research*, 273, 41-57.
- Gislason, S. R., Stefánsdóttir, G., Pfeffer, M., Barsotti, S., Jóhannsson, T., Galeczka, I., . . . Guðmundsson, M. T. (2015). Environmental pressures from the 20014-15 eruption of Bárðarbunga volcano, Iceland. *Geochemical Perspectives Letters*, 84-93.
- Guðmundsson, M. T., & Larsen, G. (2013). Eldfjallavá: Jökulhlaup. In F. Sigmundsson, & B. Bessason, *Náttúruvá á Íslandi Eldgos og jarðskjálftar* (pp. 156-164). Reykjavík: Viðlagatrygging Íslands/Háskólaútgáfan.
- Guðmundsson, M. T., Högnadóttir, Þ., & Oddsson, B. (2015). *Sólheimajökull: Hættumat vegna lítilla og meðalstórra Jökulhlaupa*. Reykjavík: Jarðvísindastofnun Háskólans.

- Guðmundsson, M. T., Högnadóttir, Þ., Kristinsson, A. B., & Guðbjörnsson, S. (2007). Geothermal activity in the subglacial Katla caldera, Iceland, 1999-2005, Studied with radar altimetry. *Annals of Glaciology*, 45, 66-72.
- Guðmundsson, M., Elíasson, J., Larsen, G., Gylfason, Á. G., Einarsson, P., Jóhannesson, T., . . . Torfason, H. (2005). *Yfirlit um hættu vegna eldgosa og hlaupa frá vesturhluta mýrdalsjökuls og Eyjafjallajökli*. Reykjavík: Almannafræðistofa Ríkislögreglustjóra.
- Hansell, A., & Oppenheimer, C. (2004). health hazards from volcanic gases: A systematic literature review. *Archives of environmental health*(12), 628-639. doi:10.1080/00039890409602946
- Ilyinskaya, E., Aiuppa, A., Bergsson, B., Di Napoli, R., Fridriksson, Þ., Óladóttir, A. A., . . . Giudice, G. (2015). Degassing regime of Hekla volcano 2012-2013. *Geochem. Cosmochim. Acta*, 159, 80-99.
- IMO. (2011, July 11). *Icelandic met Office*. Retrieved from Glacier-outburst flood from Mýrdalsjökull: <http://en.vedur.is/about-imo/news/nr/2236>
- Jóhannesdóttir, G., & Gísladóttir, G. (2010). People living under threat of volcanic hazard in southern Iceland: vulnerability and risk perception. *Natural Hazards and Earth System Sciences*, 407-420.
- Kristmannsdóttir, H., Snorrasson, Á., Gíslason, S. R., Haraldsson, H., Gunnarsson, Á., Hauksdóttir, S., & Elefsen, S. Ó. (2002). Geochemical warning for subglacial eruptions- background and history. *The Extremes of the Extremes: Extraordinary Floods*, (pp. 231-236). Reykjavík.
- Larsen, G., Guðmundsson, M. T., & Sigmarsson, O. (2013). Katla. In J. Sólnes, F. Sigmundsson, & B. Bessason, *Náttúruvá á Íslandi* (pp. 211-233). Reykjavík: Viðlagatrygging Íslands/Háskóla útgáfan.
- Larsen, G., Guðmundsson, M. T., Vogfjörð, K., Ilyinskaya, E., Oddson, B., & Pagneux, E. (2015, April 12). *The Katla volcanic system*. Retrieved from Catalogue of Icelandic Volcanoes: <http://futurevolc.vedur.is/?volcano=KAT#>
- Lawler, D. M., Björnsson, H., & Dolan, M. (1996). Impact of subglacial geothermal activity on meltwater quality in the Jökulsá á Sólheimasandi system, southern Iceland. *Hydrological Processes*, 557-578.
- Magnússon, E. G. (2014). *Niðurstöður íssjármælinga á Mýrdalsjökli frá maí 2012 til febrúar 2014*. Reykjavík: Vegagerðin. Retrieved from Vegagerdin.is.
- Maizels, J. K. (1991). The origins and evolution of Holocene sandur deposits in areas of Jökulhlaup drainage, Iceland. In J. Maizels, & C. Caseldine, *Environmental Change in Iceland: Past and Present* (pp. 267-302).
- Narwi, N. (2014). *Evaluation of HARMONIE reanalyses of surface air temperature and wind speed over Iceland*. Reykjavík: Veðurstofa Íslands. Retrieved from http://www.vedur.is/media/vedurstofan/utgafa/skyrslur/2014/VI_2014_005.pdf

- Ólafsson, R., & Þórhallsdóttir, G. (2016). *Fjöldi ferðamanna á átta áfangastöðum á suður og vesturlandi 2014-2015*. Reykjavík: Ferðamálastofa.
- Pagneux, E. (2015). VI. Öräfi district and Markárfljót outwash plain: Spatio-temporal patterns in population exposure to volcanogenic floods. In E. Pagneux, M. T. Guðmundsson, S. Karlsdóttir, & M. J. & Roberts, *Volcanogenic floods in Iceland: An assessment of the hazard and risk at Öräfajökull and on the Markarfljót outwash plain*. (pp. 123-140). Reykjavík: IMO, ESI-UI, NCIP-DCPEM.
- Pagneux, E., & Roberts, M. J. (2015). Chapter V. Öräfi district and Markárfljót outwash plain: rating of flood hazards. In E. Pagneux, M. T. Guðmundsson, S. Karlsdóttir, & M. J. & Roberts, *Volcanogenic floods in Iceland: An assessment of the hazard and risk at Öräfajökull and on the Markarfljót outwash plain*. (pp. 101-122). Reykjavík: IMO, ESI-UI, NCIP-DCPEM.
- Ragnarsson, R. (2016, April 20). General discussion about Sólheimajökull . (B. Bergsson, Interviewer)
- Ríkislögreglustjórnin. (2016, April 15). *Volcanic eruption*. Retrieved from Ríkislögreglustjórnin
Almannavarnadeild:
http://www.almannavarnir.is/upload/files/almv_baekl_EN_vef.pdf
- Roberts, M. J. (2015, December 26). The hydrological network. (B. Bergsson, Interviewer)
- Roberts, M. J., & Zóphóníasson, S. (2013, August 14). *Yfirvofandi Skaftárhlaup og möguleikar á hlaupi í Hverfisfljóti*. Retrieved from Vefurstofa Íslands:
<http://www.vedur.is/um-vi/frettir/nr/2721>
- Roberts, M. J., Tweed, F. S., Russell, A. J., Knudsen, Ó., & Harris, T. D. (2003). Hydrological and geomorphic effects of temporary ice-dammed lake formation during jökulhlaups. *Earth surface processes and Landforms*, 723-737.
- Sæþórsdóttir, A. D. (2015). *Polmörk ferðamanna á átta vinsælum ferðamannastöðum á Suður og Vesturlandi sumarið 2014*. Reykjavík: Ferðamálastofa.
- Sigurðsson, O. (2016, April 26). Sólheimajökull. (B. Bergsson, Interviewer)
- Sigurðsson, O., Zóphóníasson, S., & Ísleifsson, E. (2000). Jökulhlaup úr Sólheimajökli 18.Júlí 1999. *Jökull*, 49, 75-80.
- Smith, K. (2013). *Environmental Hazards assessing risk and reducing disaster*. Abingdon: Routledge.
- Þjóðskrá. (2016, April 15). *Þjóðskrá*. Retrieved from Þjóðskrá Íslands: <https://www.skra.is/>
- Tómasson, H. (1996). The Jökulhlaup from Katla in 1918. *Annals of Glaciology* , 22, 249-254.
- Tryggvason, T. P. (2016a, February 11). *Ferðamaður hætt kominn í sprungu á Sólheimajökli*. Retrieved from Visir: <http://www.visir.is/ferdamadur-haett-kominn-i-sprungu-a-solheimajokli/article/2016160219649>

- Tryggvason, T. P. (2016b, March 6). *Leiðsögumaður við Gullfoss: „Vantar stórkostlega upp á alla gæslu“*. Retrieved from Visir.is: <http://www.visir.is/leidsogumadur-vid-gullfoss--%EF%BF%BD-vantar-storkostlega-upp-a-alla-gaeslu-/article/2016160309141>
- United-Nations. (2009). *2009 UNISDR Terminology on disaster risk reduction*. Geneva, Switzerland,: United Nations International Strategy for Disaster Reduction.
- Veðurstofan. (2015). *Vedur.is*. Retrieved from http://en.vedur.is/media/http://en.vedur.is/media/vatnafar/flod/full/skafta_kort_1-heilt.png
- Vinnueftirlitið. (2016, March 16). *Áhættumat í tengslum við eldgos* . Retrieved from Vinnueftirlitið.is: <http://www.vinnueftirlit.is/um-vinnueftirlitid/frettir/nr/1170>
- Zófoníasson, S. (2016, April 26). (B. Bergsson, Interviewer)

Appendix A

Questions Asked to (Guðmundsson, Högnadóttir, & Oddsson, 2015)

1. Hverjar eru stærðir og útbreiðsla smærri hlaupa sem koma niður Sólheimajökul? Mat af þessu tagi var gert 2005 fyrir stærri hlaupin en það vantar fyrir smærri hlaup.
2. Hver er tíðni smærri hlaupa?
3. Hver yrðu áhrif minni og meðalstórra hlaupa nú? Átt er við hlaup af svipaðri stærð og kom sumarið 1999. Hvar myndu flóðmörkin liggja og eru vegir eða mannvirki ofan við brúna á þjóðvegi 1 í hættu?
4. Hver er viðvörunartími vegna hlaupa af mismunandi stærðum og gerðum, m.a. af þeirri stærð sem komið hefur endutekið úr Kötluöskjunni (1955, 1999, 2011)?
5. Við hvaða breytingum má búast í stærð (þykkt og lengd) Sólheimajökuls á næstu árum. Má reikna með að hop hans haldi áfram á næstu árum og hvaða áhrif mun það hafa á hættu af hlaupum?
6. Hversu mikil hætta getur stafað af útstreymi H₂S og annarra gasa við hlaup og rennsli jarðhitavatns?

Obligations of the tour operators and the police at Hvolsvöllur in the area surrounding Katla Volcano according to the contingency plan set by the ICP

Ferðapjónustuaðilar í Rangárvalla- og V-Skaftafellsýslum

ÓVISSUSTIG Fara yfir þau verkefni sem þeim eru ætluð á hættu og neyðarstigi og tryggja að lágmarks viðbúnaður sé fyrir hendi til að sinna þeim.

HÆTTUSTIG Aflýsa öllum ferðum um áhrifasvæði eldsumbrota. Kalla inn hópa sem hugsanlega eru á þessu svæðum. Þeir sem reka gistingu skulu hafa tiltæka lista yfir þá sem dvelja hjá þeim. Viðhalda banni við skipulögðum ferðum inn á áhrifasvæði eldsumbrota og senda aðgerðastjórn skrá yfir þá aðila á þeirra vegum sem hugsanlega eru innan hættusvæðis eða á leið út af því. Fyrirmæli gefin út til skálavarða að skjóta upp ljós- og hljóðmerkjum

NEYÐARSTIG Athugið: Ef eldgos eða jökulhlaup brestur á fyrirvaralaust, þannig að ekki hafi verið mögulegt að rýma viðkomandi svæði er vísað á verkefni á hættustigi. (Almannavarnir, 2013)

Lögreglan á Hvolsvelli

ÓVISSUSTIG Fer yfir þau verkefni sem henni eru ætluð á hættu og neyðarstigi og tryggir að lágmarks viðbúnaður sé fyrir hendi til að sinna þeim.

HÆTTUSTIG Hvolsvöllur: Lokar við Suðurlandsveg/Nýbýlaveg og Sunnuhvol Kirkjubæjarklaustur: Mannar stjórnstöð. Setur upp lokun við eystri Meðallandsafleggjara

vestan Skaftárbrúar. Vík: Leitast við að koma lögreglumanni til Víkur sem fyrst til starfa í vettvangsstjórn

NEYÐARSTIG Athugið: Ef eldgos eða jökulhlaup brestur á fyrirvaralaust, þannig að ekki hafi verið mögulegt að rýma viðkomandi svæði er vísað á verkefni á hættustigi. Viðheldur: Lokunum Rýmingu byggðar Eftirliti með rýmdum svæðum (Almannavarnir , 2013)

Appendix B

To the chief of Police

Samantekt

- Af hverju hafið þið Áhyggjur?
- Hvað hefur gerst frá útgáfu MTG, ÞH og BO? Hefur hún verið kynnt?
- Hvernig voru spurningarnar valdar?
- Hvaða viðbragðs áætlanir eru til staðar? Boðleiðir, hlutverk?
- Hver ber ábyrgð á túristunum?
- Hver er skilda ferðapjónusta aðila til túristana?
- Hvað þarf að upplýsa?
- Viðbragð?
- Verkefnaskipting viðbragðs aðila?
- Rýming?
- Fjarskipti?
- Hvað ef engin viðvörðun kemur?

Questions to tour guides

Spurningar fyrir ferðapjónustu

- Hvað farið þið með marga ferðamenn yfir daginn/árið?
- Hvaða ábyrgð beríð þið á ferðamönnunum þegar farið er í slíkar ferðir?
- Hvað er mesta hættan að ykkar mati á Sólheimajökli? (Jökulhlaup?)
- Er viðbragðsáætlun til staðar ef eitthvað færi að gerast (rýming)?
- Hvaða fjarskipta tæki notið þið?
- Þegar þið farið yfir öryggis mál með ferðamönnunum, snýst það að einhverju leiti um eldvirkni eða Jökulhlaup?
- Vitið þið að efra bílastæðið (nær ánni) er lokað og að almenningur á ekki að fara á jökulinn án leiðsögumanns?

Appendix C

Pictures from Figure 15:

In Figure 15, five points are marked (1-5) with a red dot as signs. Pictures from the locations of the signs can be seen below from figures 26-30.



Figure 29: Sign 1. The only sign mentioning that the area is restricted.



Figure 30: Sign 2. Warning sign by the start of the hiking path.

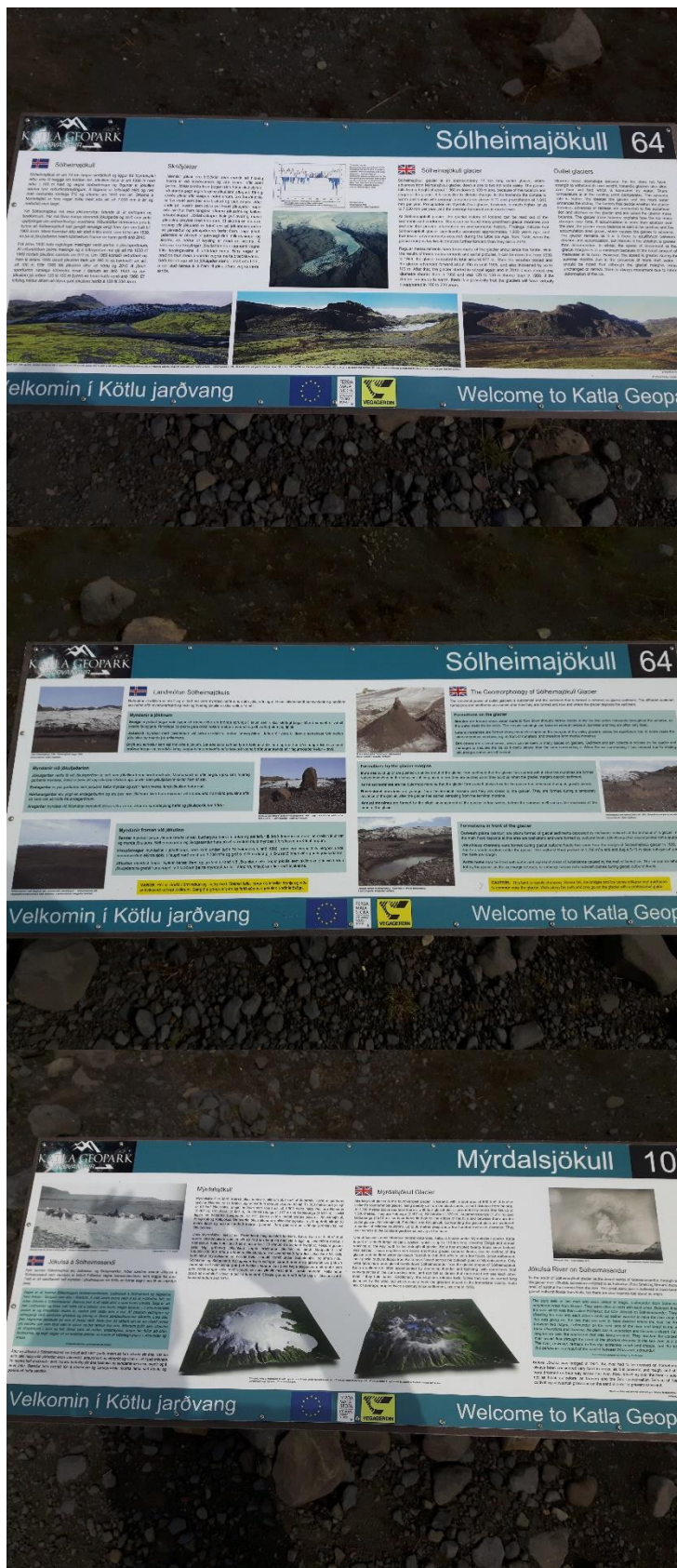


Figure 31: Information signs about the geology of the area. One of the signs has a yellow box with the text: "only go on the glacier with a professional guide".



Figure 32: Sign 4. Location of closed road segment. No road restriction has been in place since August 2014.



Figure 33: Sign 5. In northern parking lot (advises you to seek a glacier guide to go on the glacier).

Appendix D

Following are the enlarged figures of the four minor floods identified.

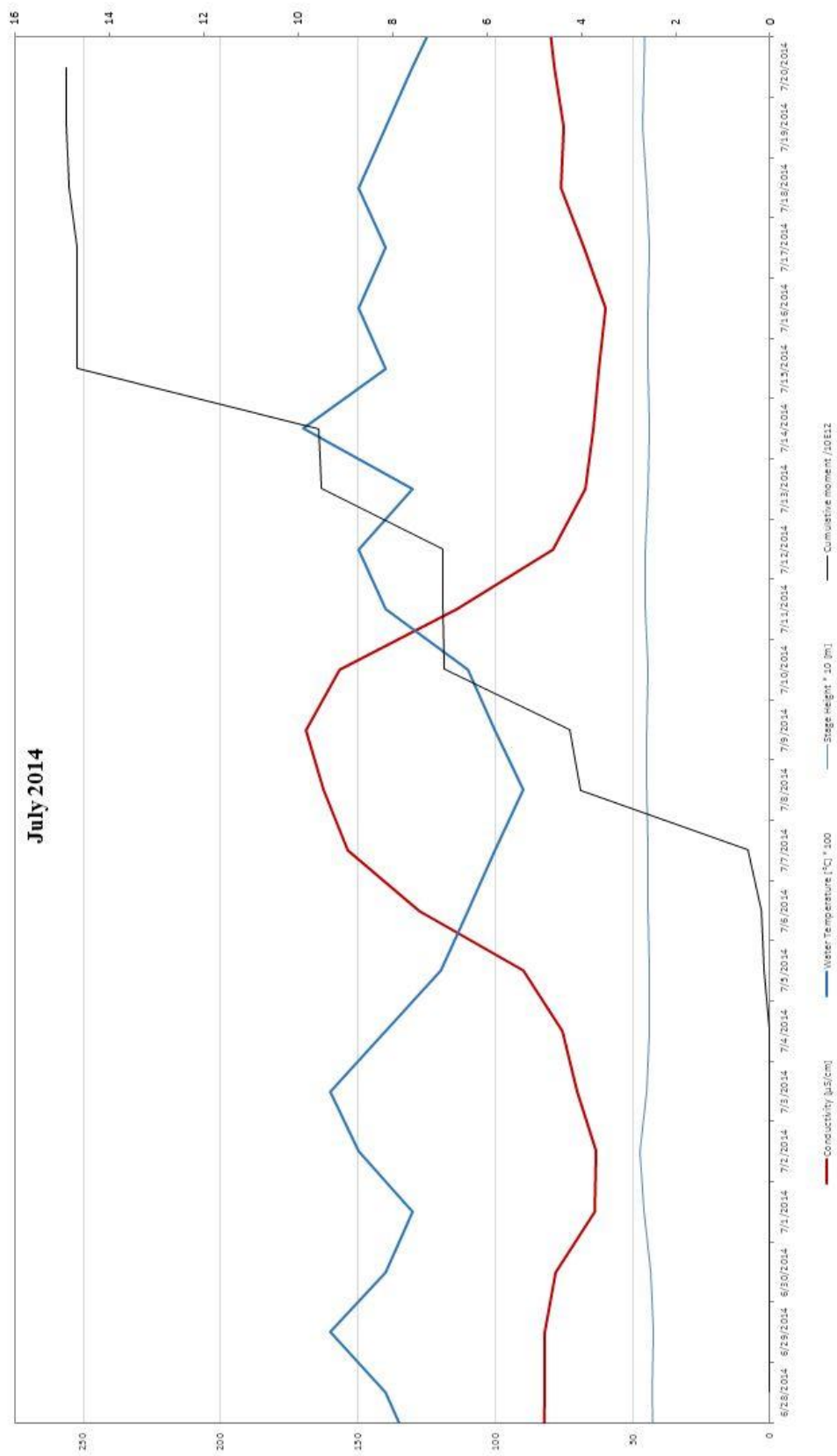


Figure 34: The minor flood of July 2014.

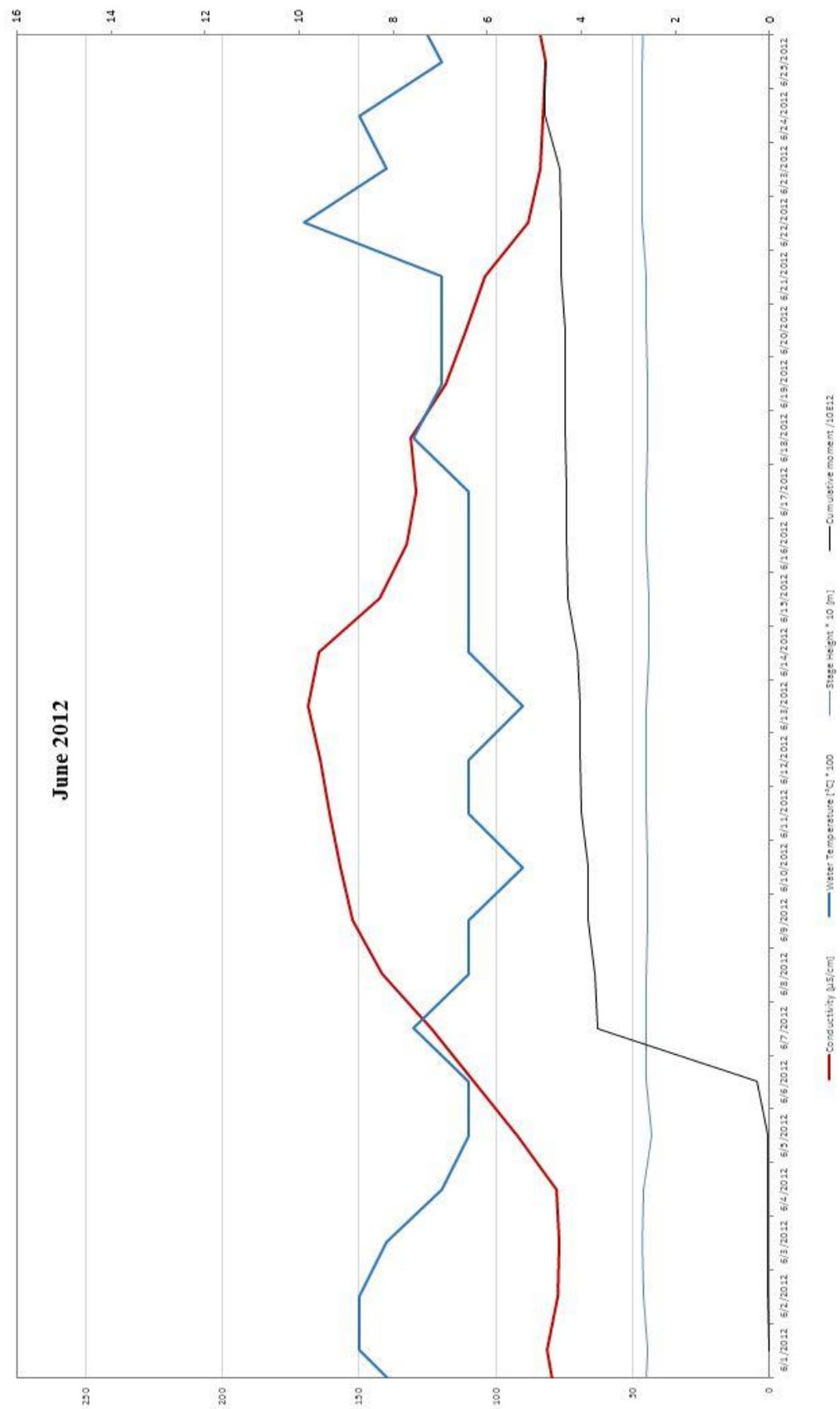


Figure 35: The minor flood of June 2012.

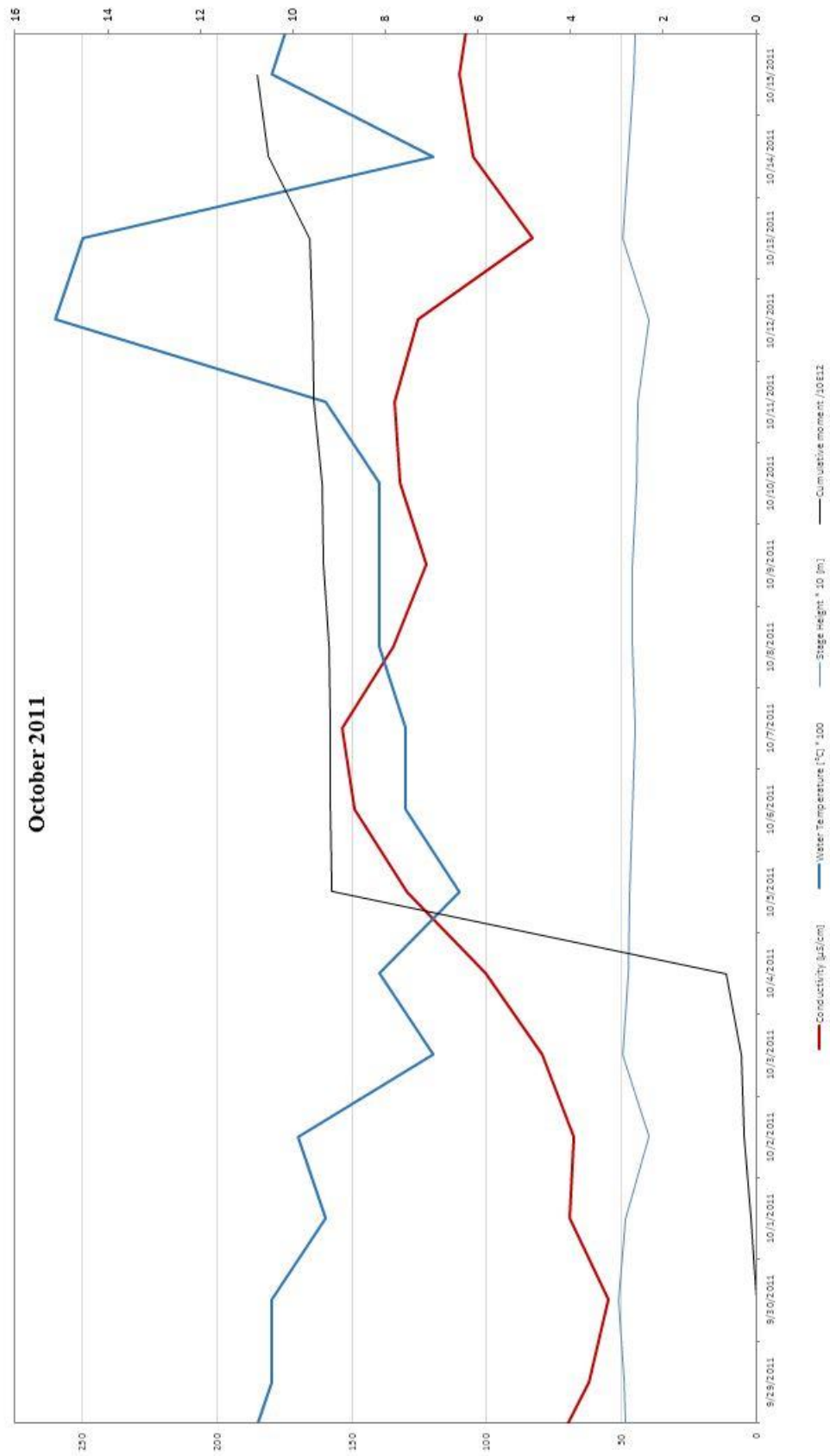


Figure 36: The minor flood of October 2011.

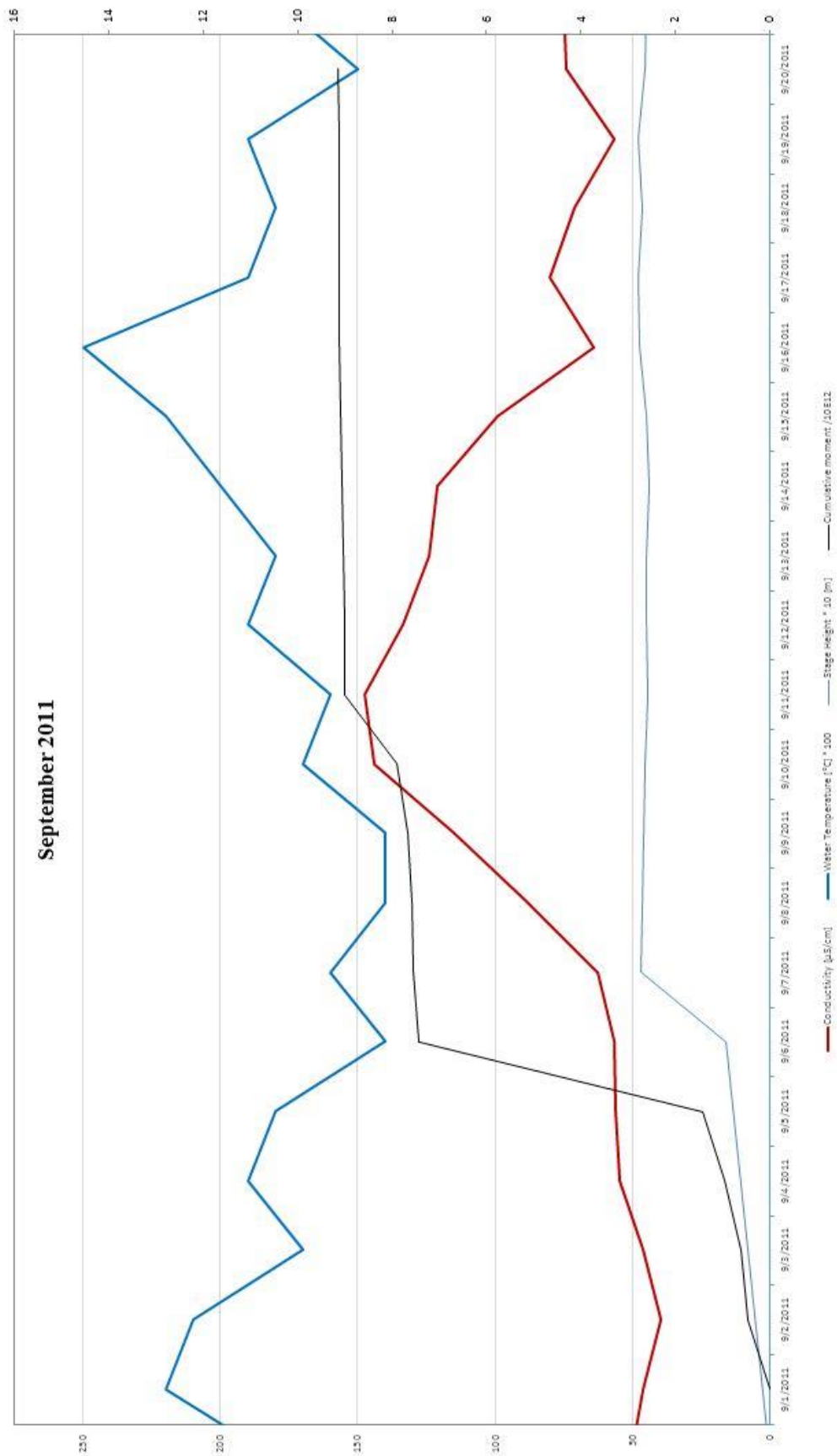


Figure 37: The minor flood of September 2011.