I. VOLCANOGENIC FLOODS IN ICELAND: AN EXPLORATION OF HAZARDS AND RISKS

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1. Introduction

This publication presents the results from an exploratory project on the risk assessment of glacial outburst floods (jökulhlaups) caused by volcanic eruptions in Iceland. Such floods result from the interaction of hot freshly erupted lava, tephra or hot gases with glacier ice and snow on the slopes of volcanoes.

Jökulhlaups related to volcanic activity, caused both directly by volcanic eruptions and indirectly through geothermal activity, are one of the main volcanogenic hazards in Iceland (Gudmundsson *et al.*, 2008). Over half of all Icelandic eruptions occur in ice covered volcanoes, resulting either directly or indirectly in jökulhlaups (Larsen *et al.*, 1998; Larsen, 2002). The magnitude and frequency of these events is variable. During the 19th and first half of the 20th century, major jökulhlaups were frequent, not least due to conditions at Grímsvötn, the most active volcano. In Grímsvötn, a large, geothermally sustained subglacial lake issued periodic floods with peak discharges of tens of thousands of cubic meters per second about once every 10 years, with some of these events being directly caused by eruptions (e.g. Björnsson, 2003). A source of truly catastrophic jökulhlaups throughout settlement history has been the Katla volcano, where the recurrence time of eruptions is about 50 years. The largest of these eruptions have caused rapidly rising floods with a maximum discharge 100–300,000 m^3/s (e.g. Tómasson, 1996; Larsen, 2000; Elíasson *et al.*, 2006).

The largest hazard and risk to life in volcanogenic floods occurs on populated slopes of large, steep-sided ice-clad volcanoes. This particular environment is found in Iceland on the foothills of Eyjafjallajökull, Snæfellsjökull and Öræfajökull volcanoes. The most severe events have occurred at Öræfajökull, which erupted in 1362 and 1727. On both occasions the eruptions and the associated floods lead to destruction, devastation and loss of life (Thorarinsson, 1958). In the last 20 years, volcanic unrest has resulted in several jökulhlaups that have caused significant damage, including Vatnajökull in 1996 (Haraldsson, 1997; Björnsson, 2003) and Eyjafjallajökull in 2010 (Þorkelsson, 2012; Magnússon *et al.*, 2012; Snorrason *et al.*, 2012). As half of the Icelandic volcanic systems considered active in the Holocene period are covered by ice (Figure I-1), and despite an expected reduction in ice cover due to climate change (Jóhannesson *et al.*, 2012), the threat posed by volcanogenic floods will persist for at least one or two centuries.

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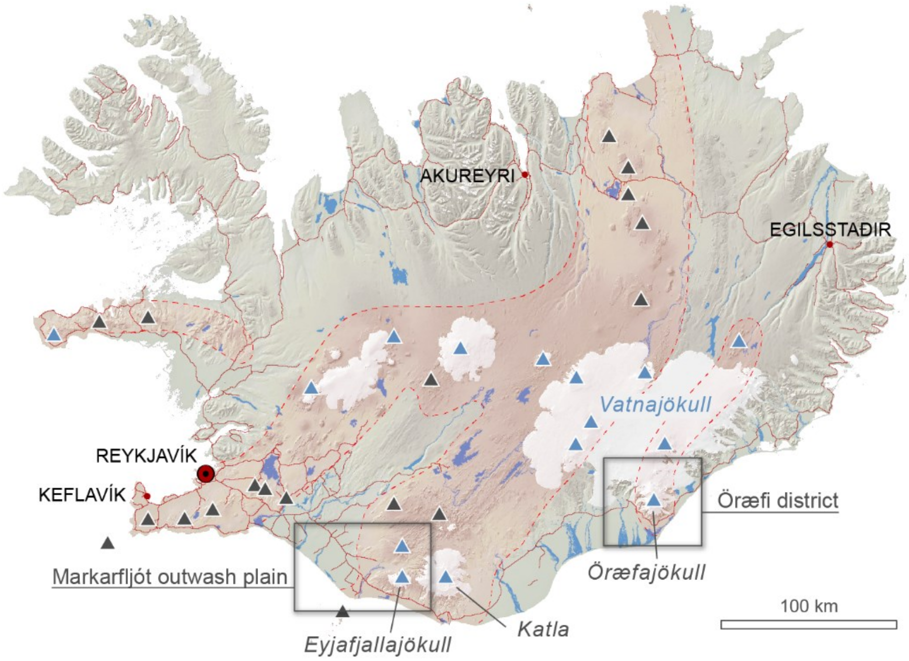

Figure I-1: Extent of the Icelandic volcanically active zones (semi-transparent red area bordered by a dashed line). The centres of the active volcanic systems are shown as triangles, coloured either in blue (ice-covered volcanoes) or black (ice-free). Location of the Markarfljót outwash plain and Öræfi district, the two areas studied in the project, is also shown.

2. Project description

2.1. The Icelandic volcanic risk assessment programme

The present project belongs to *Gosvá*, a national collaborative research programme on the assessment of volcanic hazard risks in Iceland led by the Icelandic Meteorological Office (IMO). The programme's steering committee is composed of representatives from IMO, the Institute of Earth Sciences (IES, University of Iceland), the Department of Civil Protection and Emergency Management of the National Commissioner of the Icelandic Police (NCIP-DCPEM), the Soil Conservation Service of Iceland (SCSI), and the Icelandic Road and Coastal Administration (IRCA).

Three additional projects have been conducted as part of the first phase of the programme: (i) An appraisal of the current knowledge of eruptive activity and potential volcanic hazards; (ii) an initial risk assessment of large explosive eruptions; and (iii) an initial risk assessment of volcanic eruptions that may cause extensive damage to property (i.e. eruptions in the vicinity of urban areas and international airports).

2.2. Financial support

This assessment project was funded mainly by the National Avalanche and Landslide Fund, with additional financial contributions from IRCA and the National Power Company.

2.3. Areas studied

The study was undertaken on the Markarfljót outwash plain and in the Öræfi district (Figure I-1), two regions of Iceland that have been subjected to volcanogenic floods in the last millennium. In the Markarfljót outwash plain (Figure I-2), the present project can be seen as a continuation of the extensive effort dedicated to the assessment of floods caused by eruptions of Katla (the volcano underlying Mýrdalsjökull) and Eyjafjallajökull performed in the years 2002–2005 (Guðmundsson and Gylfason, 2005). In the Öræfi district, this project is the first attempt to assess together the magnitude and impact of jökulhlaups on the inhabited slopes of Öræfajökull Volcano, situated west and south from the caldera (Figure I-3).

2.4. An exploration of both flood hazards and flood risks

Both the magnitude of volcanogenic floods and their impact were investigated in the project. Potential adverse consequences received particular attention, with the present project being the first attempt in Iceland to systematically map flood-damage potential as well as spatio-temporal patterns in population exposure. As regards the magnitude of floods, flood timings and routing, the methodologies set out in previous Katla and Eyjafjallajökull hazard assessments were applied (Guðmundsson and Gylfason, 2005; Guðmundsson and Högnadóttir, 2005).

Investigation of other direct volcanic hazards such as ash fall, lava flow, and gas emission are not part of the study presented here. Similar assessment of such hazards, which could have acute, far-reaching effects, is expected to be carried out in other phases of *Gosvá*. These hazards could also influence decisions about when and where to evacuate people at risk.

Exploring both flood hazards and flood risks is in line with the goals of the Icelandic authorities, which are committed to a comprehensive, self-standing regulation on the assessment and management of flood risks, comparable in its scope to the Icelandic regulation on avalanche risks (Arnalds *et al.*, 2004).

2.4.1. The International Strategy for Disaster Risk Reduction

Iceland is signatory to the Hyogo Framework for Action 2005-2015 (United Nations, 2005) and Sendai Framework for Disaster Risk Reduction 2015–2030 (United Nations, 2015). The International Strategy for Disaster Risk Reduction of the United Nations (UNISDR), to which the two above-mentioned frameworks apply, is the base for all the risk assessment projects that have been conducted by the Icelandic Meteorological Office on behalf of the Icelandic government.

2.4.2. The EU Floods Directive

The European Directive on the Assessment and Management of Flood Risks (European Parliament and Council, 2007) has at present not been implemented in Iceland. However, the comprehensive nature of the directive made it a framework well suited to structure the project as a coherent workflow of investigations, manifest in this book as a suite of thematic chapters (Table I-1; Figure I-4).

2.4.3. Acceptable risk

It is expected that recommendations on a legally binding acceptable risk will be formulated during the second phase of the volcanic risk programme, to be started in 2016. A new step towards a normalised, comprehensive risk assessment of volcanogenic floods in Iceland would be reached should the Icelandic Parliament validate such an approach.

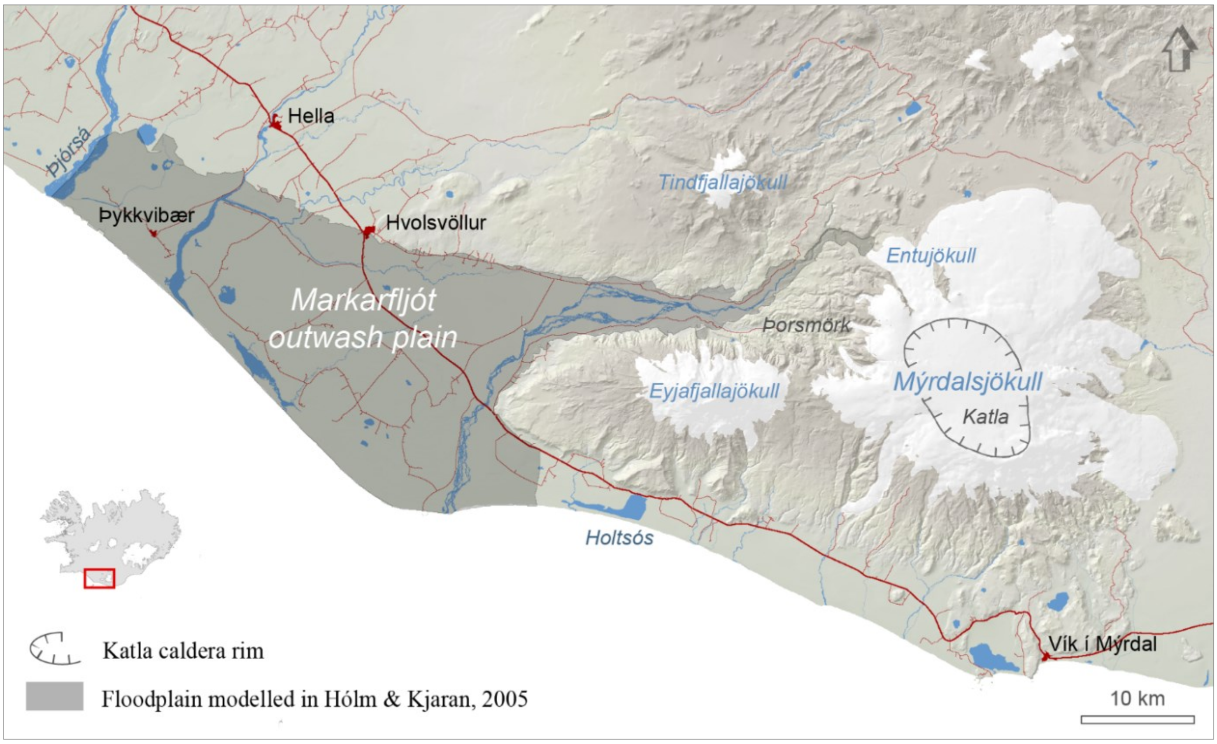

Figure I-2: Markarfljót outwash plain. The grey area shows the extent of a hypothetical 300,000m³/s flood originating from the caldera of Katla Volcano (Hólm and Kjaran, 2005).

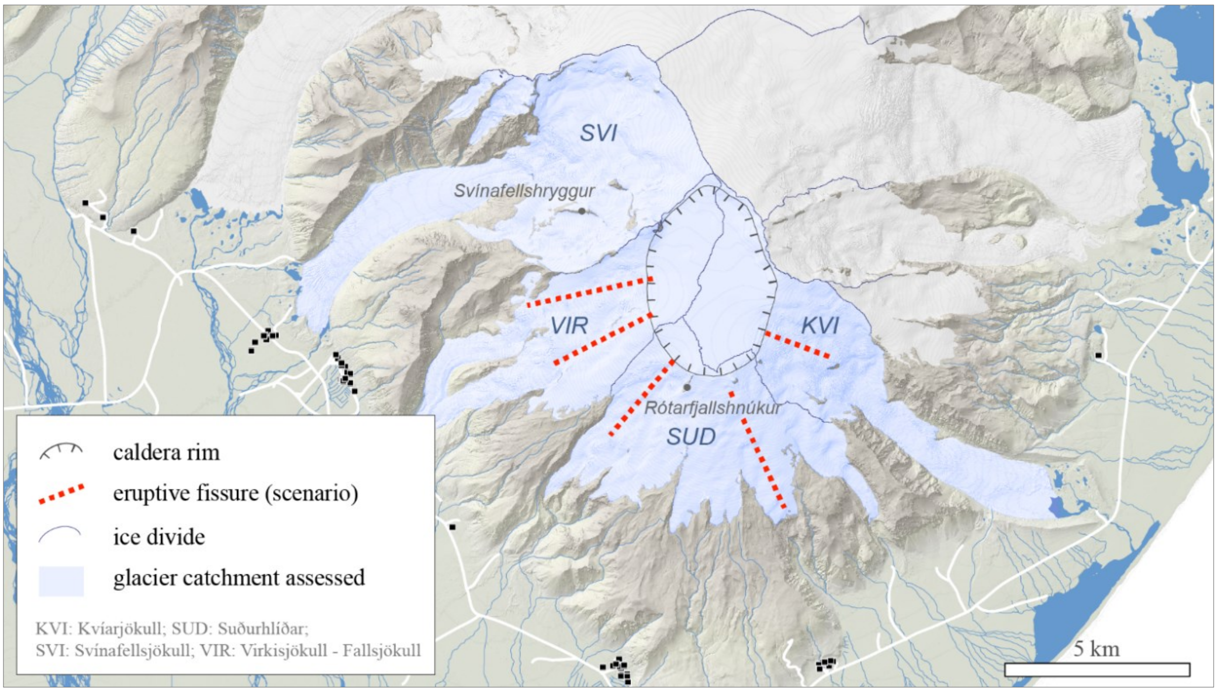

Figure I-3: Öræfajökull volcano (See Figure I-1 for general location). The glacier catchments examined in the project are shown in light blue, settlements as black dots. From chapter IV (Helgadóttir et al., 2015).

Table I-1: Correspondence between (i) the chapters featured in the book and (ii) the EU Floods Directive (2007/60/EC) phases.

Book		2007/60/EC Directive		
Chapters	*Subject(s) covered*	*Phase*	*Article (Alineas)*	*Key topic(s)*
II	Geology and historical floods	Preliminary flood risk assessment	4.2 (b)	Past floods and known impacts
III	Melting scenarios	Flood hazard maps and flood risk maps	6.3 (a,b)	Medium and low probability event scenarios
IV	Hydraulic simulations		6.4 (a,b,c)	Flood extent, water depths, flow velocities
V	Damage potential		6.4 (d)	Other useful information
VI	Population exposure		6.5 (a)	Indicative number of inhabitants potentially affected
VII	Evacuation time modelling	Flood risk management plans	7	Reduction of potential adverse consequences

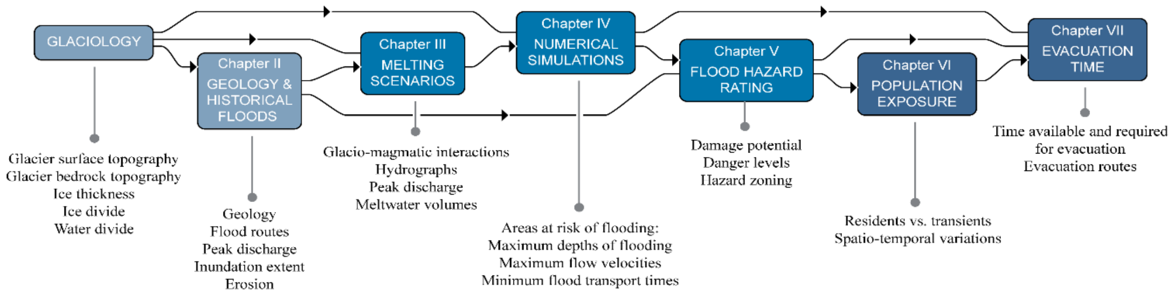

Figure I-4: Project workflow. Each chapter of the book covers a specific domain of investigation and links to the other chapters as a predecessor or as a follower.

3. Chapter overviews

Brief summaries of the subjects covered in the chapters are given below. Main findings are outlined in a separate section.

Chapter II. Öræfajökull Volcano: Geology and historical floods

A description of the geology of the Öræfajökull region and of the geomorphic impacts of volcanogenic floods caused by Öræfajökull eruptions in 1362 and 1727 CE is given in Chapter II (Roberts and Gudmundsson, 2015). Of the two known historical floods, the 1727 jökulhlaup is better documented, allowing estimates of the timing, size, and extent of the flood. These inferences are applied to the 1362 jökulhlaup, for which contemporary documentation is lacking. Using available descriptions, field observations, aerial photographs, and modern-day analogues, the duration, extent, composition, and maximum discharge of the jökulhlaups during these two events is approximated. The insight gained on the routing and maximum discharge of volcanogenic floods from Öræfajökull, is applied in Chapters III and IV.

Chapter III. Öræfajökull Volcano: Eruption melting scenarios

Chapter III (Gudmundsson *et al.*, 2015) assesses the ice melting to be expected during eruptions in Öræfajökull central volcano. Three main types of melting scenarios are considered: (i) Caldera eruptions (ice thickness up to 500 m), (ii) flank eruptions (ice thickness <100 m), and (iii) surface melting by pyroclastic density currents in Plinian eruptions. Models of melting for thick ice (>200 m) and thin ice (<200 m) are presented based on empirical evidence and thermo-dynamic considerations. These models are applied to the slopes of Öræfajökull and serve as a basis in hazard assessment for events with peak discharges ranging from 10^4 m^3/s (flank eruptions) to 10^5 m^3/s (large caldera eruptions).

Chapter IV. Öræfajökull Volcano: Numerical simulations of eruption-induced jökulhlaups using the SAMOS flow model

Chapter IV (Helgadóttir *et al.*, 2015) identifies regions around Öræfajökull Volcano that would be liable to flooding during a subglacial eruption. Jökulhlaups are simulated as viscous fluids using the SAMOS 2D avalanche model (Zwinger *et al.*, 2003). Simulations are made for jökulhlaups caused by a caldera eruption, flank eruptions, and pyroclastic density currents using the melting scenarios developed in Chapter III. Information produced on inundation extent, maximum depths of flooding, maximum flow speeds and minimum surface transport times is used in the of rating flood hazards (Chapter V), assessment of the populations exposed to floods (Chapter VI), and modelling of evacuation time (Chapter VII).

Chapter V. Öræfi district and Markarfljót outwash plain: Rating of flood hazards

In Chapter V (Pagneux and Roberts, 2015), a provisional method for rating of flood hazards is proposed, followed by the designation of flood hazard zones in the Markarfljót outwash plain and the Öræfi district. The presence of life-threatening debris and the temperature of floodwater are considered, along with information on depths of flooding and/or flow velocities given in Chapter IV and Holm and Kjaran (2005). The aim of the study is to provide authorities with spatial information on flood danger levels and flood damage potential in the two study areas.

Chapter VI. Öræfi district and Markarfljót outwash plain: Spatio-temporal patterns in population exposure to volcanogenic floods

In Chapter VI (Pagneux, 2015a), a spatio-temporal exploration of population exposure is performed in the Markarfljót outwash plain and in the Öræfi district. Inventory of the populations exposed to floods is performed for night time, using daily overnights estimates weighted with road traffic data as an indicator. The main objective of the assessment is to provide authorities with a realistic estimate, at different periods of the year and at particular locations within the two studied areas, of the likely number of residents and guests potentially in the path of a flood or those that would be stranded due to flooding. Results of the assessment in the Öræfi district are used in Chapter VII to estimate the time required for a full evacuation of the areas liable to be flooded.

Chapter VII. Öræfajökull: Evacuation time modelling of areas prone to volcanogenic floods

An evacuation time model and evacuation routes for areas exposed to floods due to eruptive activity of Öræfajökull Volcano are presented in Chapter VII (Pagneux, 2015b). The aim of the study is to provide the authorities in charge of the emergency response with critical baseline estimates for the development of an effective flood evacuation plan.

4. Main findings

4.1. Öræfajökull

Öræfajökull is an ice-covered stratovolcano that has been and will remain a source of hazardous jökulhlaups in the event of an eruption:

1) The recurrence time of eruptions in the last several thousand years is in the range 500–1000 years.

2) The two known eruptions since settlement, in 1362 CE and 1727 CE caused major jökulhlaups that had a large impact on the lowlands through flooding, formation of sandur plains (outwash deltas) and large quantities of ice blocks that took years or decades to melt. The magnitude of the 1362 jökulhlaup was of order 100,000 m^3/s, whereas the 1727 flood was about half that size.

3) Volcanogenic jökulhlaups can be of three types, depending on source:

- Floods resulting from eruption in the caldera, where the ice is up to 500 m thick. Large eruptions can melt of order 100,000 m^3/s. Jökulhlaups can be expected from Virkisjökull-Falljökull or Kvíárjökull.
- Floods resulting from fissure eruptions on the upper flanks where the ice is 50–100 m thick. Expected melting in eruptions is in the range 1,000–10,000 m^3/s. Jökulhlaups of this type can happen anywhere on the slopes from Virkisjökull in the west to Hrútárjökull in the east.
- Floods resulting from hot (300–600°C) pyroclastic density currents in large explosive eruptions (as occurred in 1362 CE). The discharge may be in the range 1,000–20,000 m^3/s. Such jökulhlaups can occur anywhere on the slopes from Svínafellsjökull in the west to Hrútárjökull in the east.

4) Jökulhlaups caused by volcanic activity can be hyperconcentrated, carrying large quantities of sediment and ice down to the lowlands.

5) Jökulhlaups can be very swift, reaching the lowlands in as little as 20–30 minutes from the onset of an eruption.

6) A large part of the lowland between the rivers Skaftafellsá and Breiðá (340 km^2) is susceptible to flooding because of volcanogenic jökulhlaups descending the western and southern slopes of Öræfajökull.

7) Jökulhlaups from Öræfajökull can cause complete destruction or unrepairable damage to dwellings and outbuildings almost anywhere in sectors at risk of flooding. The potential impact of major floods on the local economy is therefore high.

8) If the largest of the potential floods assessed in this study where to happen **without warning and evacuation**, it is estimated that up to 130 people could be in severe danger and potentially lose their lives, with a further 240–250 people isolated due to destruction of sections of the road network. Proper monitoring and early warning systems with regularly updated response plans are therefore essential for the area around Öræfajökull.

9) During summer time, tourists represent the vast majority (up to 90 %) of the population staying overnight in areas susceptible to flooding or at risk of isolation.

10) Full evacuation of the populated areas cannot be achieved in less than 30–35 minutes.

4.2. Markarfljót outwash plain

Results of investigations into damage potential and population exposure are outlined next. Information on flood history, melting scenarios, propagation times and possible inundation extent can be found in Guðmundsson and Gylfason (2005).

1) Jökulhlaups can cause extensive damage to structures. The potential for complete destruction of inhabited buildings is possible over a very large portion of land (330 km^2), that covers the outwash plain almost from Entujökull Glacier down to road 255 (Akureyjarvegur).

2) More than one thousand people are located in the flood inundation zone and therefore at risk during the summer season when the number of tourists is highest, distributed over some 720 km^2 of land.

3) Partial destruction of the road network could leave about 600 people isolated in Fljótshlíð, Þórsmörk recreational area and in the lowlands flanking Eyjafjallajökull Volcano to the northwest, west and south-west.

4) Tourists and other temporary visitors represent up to 40% of the people in areas susceptible to flooding or at risk of isolation.

5. Recommendations

5.1. Management of flood risks

5.1.1. Monitoring and early warning

Maintaining risk at acceptably low levels during an eruption cannot be achieved without proper long-term monitoring of precursory signs of volcanic activity. An effective system of monitoring, early warning and regularly updated response plans is required for timely evacuation of the inhabited lowlands in the two regions.

Markarfljót: A system of early warning is already in place but it should be considered whether gaps or blind spots still exist.

Öræfajökull: Work on identifying and correcting possible weaknesses in the current monitoring system should be carried out and additions made as needed.

5.1.2. Land use and spatial planning

In order to increase the resilience of a region, actions to minimize the exposure to hazard need to be an integrated part of all land-use planning. It is beyond the scope of this project to address this issue. However, the full benefits of the assessment can only be achieved if it is ensured that the planning legislation and regulation take full account of the volcanic hazard and in particular the hazards from jökulhlaups.

5.1.3. Awareness raising and education

The continued expansion of tourism-related activities in the two volcanic areas is resulting in an increased number of people in close proximity to sites where volcanogenic flooding is possible. Ongoing awareness campaigns, both for residents and tourists, should form part of strategies for reducing volcanic risks.

5.2. Further research

The potential locations for volcanogenic floods in Iceland include many of the larger rivers issuing from glaciers in the volcanic zones. Further work is needed for many of these areas. This should include:

- Geological mapping of deposits and erosion from older floods to establish better magnitudes and recurrence times, and better assess flood damage potential.
- Extension of the existing results on melting potential for ice-covered regions to eruptions in western Vatnajökull, where historical records indicate repeated occurrence of jökulhlaups.
- Exploration of the melting potential for other areas, and on the basis of the volcanic history, assess the recurrence times and probabilities of volcanogenic jökulhlaups for different rivers.
- Further studying of the various scenarios of ice melting in subglacial eruptions, through both experimental and theoretical approaches. Better understanding is needed on e.g. the melting potential of pyroclastic density currents and effusive eruptions under thick ice.

Work, similar to that presented here on spatio-temporal patterns in population exposure and evacuation time modelling needs to be carried out for regions potentially at risk from other ice-covered volcanoes. It is expected that various local and regional factors will play a major role and further research is needed to assess these potential complications.

At Öræfajökull, post- and syn-eruptive floods should be further investigated, including:

- Flooding due to melting of snow and ice by lava or pyroclastic density currents on the eastern flanks of the volcano.
- Lahars caused by intense rainfall over tephra on the flanks of the volcano following an explosive eruption. Such lahars could occur anywhere on the volcano, irrespective of primary jökulhlaup paths.

Concerning jökulhlaup propagation modelling, the following issues should receive attention:

- Ice-block deposition is prevalent during volcanogenic floods. Further studies of the size and spatial distribution of ice-blocks from past eruptions is needed to help identify regions of high damage-potential.
- The sensitivity of propagation times to flow properties such as solid content (tephra, other debris), solid proportion and grain size, should be studied further. Such studies would allow for more accurate flood routing and better assessment of properties of past floods on the basis of their deposits.

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