THE INFLUENCE OF THE EYJAFJALLAJÖKULL HAZARDOUS VOLCANIC ERUPTION IN APRIL 2010 ON ROADS AND AIR TRAVEL

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ABSTRACT

In April 2010 an eruption started under the glacier Eyjafjallajökull in southern Iceland. A few hours later, the meltwater emerged from the northern side of the glacier and flowed down to the glacial river Markarfljót, heading towards roads and bridges crossing the riverbed farther away. The road authorities had 2-3 hours warning time to close the roads to traffic, and make arrangements to try to minimize the foreseen infrastructure damage, especially on the important ring road, Route 1. The bridges were saved by excavating through the road embankments, directing much of the flood through those openings. However, the road washed away for about 400 meters.

This volcanic eruption with the subsequent ash cloud caused enormous disruption to air travel across western and northern Europe over an initial period of six days in April 2010, and additional localised disruption continued into May 2010, creating the highest level of air travel disruption since the Second World War.

The great hazards posed by a number of volcanoes covered with glaciers has led to special monitoring with seismometers, continuously recording GPS, radio-linked river gauges, regular airborne radar profiling and inspection flights over the ice caps. Most of these data can be viewed in real time on the internet.

1. VOLCANIC HAZARDS

1.1. Introduction

During the eleven centuries of settlement in Iceland volcanic activity has repeatedly affected the population, directly and indirectly, and sometimes with extreme severity. Eruptions and events directly related to volcanic and geothermal activity commonly occur and their consequences range from direct impact of ash and pumice ejection columns or flowing lava to water outburst floods (jökulhlaups) and contamination of air, water and crops. For the most part Iceland is sparsely populated with no permanent settlements in the interior highlands. Population clusters mainly occur along the coast, with about 70% of the 320 thousand inhabitants living in the greater Reykjavík area and along the southern shore of Faxaflói Bay in southwest Iceland. The Reykjavík metropolitan area is located just outside the margins of the active volcanic zone and the occurrence of volcanic eruptions inside the Reykjavík area is therefore considered remote although its southern and easternmost parts are susceptible to lava flows from future eruptions.

Moderately populated areas are located close to very active volcanic centres in south, southeast and northeast Iceland. Major eruptions occur every few hundred years and have major regional effects which in some cases in the past, as in Laki 1783–84, caused famine in Iceland and had a marked temporal effect on climate in the northern hemisphere. In recent decades, explosive eruptions have posed a threat to aviation traffic in the busy routes between Europe and North America and East Asia.

The aim of this paper is to present a brief overview of the principal types of volcanic hazards in Iceland with special emphasis on the time since the settlement (last 1130 years), the widely known Eyjafjallajökull eruption in the year 2010 and the risk management system used for natural disasters in Iceland.

1.2. Volcanic activity in Iceland

Volcanic activity in Iceland is confined to the active volcanic zones (Figure 1). These are composed of volcanic systems which usually consist of a central volcano and a fissure swarm that may extend tens of kilometres in both directions away from the central volcano. Out of the 30 identified volcanic systems, 16 have been active after 870 AD. Most eruptions occur within central volcanoes, with Grímsvötn, Hekla and Katla having the highest eruption frequencies and, together with their associated fissure systems, have the highest volcanic productivity. The central volcanoes have often developed calderas that frequently host active geothermal systems, and erupt a range of magma compositions. In many central volcanoes typical eruptions are small, although in historical times eruptions in both Hekla and Katla have frequently been considerably larger. Eruptions on the fissure swarms produce basalts. They are less frequent but tend to be larger than eruptions confined to the central volcanoes, with volcanic fissures extending up to several tens of kilometres. Some of the largest known eruptions in Iceland are of this type.

Eruptions have occurred in Iceland on average once every 3–4 years over the last four centuries. Explosive eruptions and explosive phases of mixed eruptions are basically of two categories, magmatic eruptions, where the explosive fragmentation is primarily caused by the expansion of magmatic gases, and phreatomagmatic eruptions, where fragmentation results from magma-water interaction. In Iceland, by far the greatest majority of explosive events are phreatomagmatic explosive basaltic eruptions. These occur in volcanic systems that are partly covered by ice caps such as the Grímsvötn and Katla volcanoes, have high groundwater level (e.g. the Veiðivötn fissure swarm), or are situated on the continental shelf (like Vestmannaeyjar).

Short-term warning of an impeding eruption is at present based on short-term seismic precursors. These are usually intense swarms of earthquakes in the hours before the onset of an eruption. The start of an eruption often distinguishes itself on seismic records as a sudden drop in the frequency and magnitude of earthquakes and the onset of continuous seismic tremor. All confirmed eruptions since 1996 have been predicted on the basis of such seismic activity.

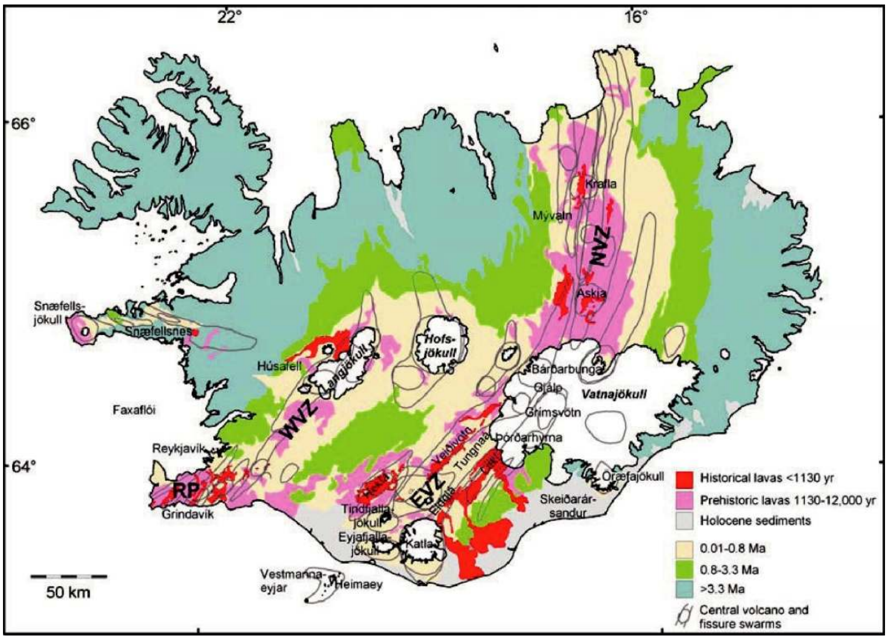

Figure 1 – Simplified geological map of Iceland

Figure 2 – Volcanic eruption in Eyjafjallajökull April 2010

1.3. Main types of volcanic hazards

1.3.1. Volcanic tephra (ash) fallout

Plinian eruptions are marked by columns of gas and volcanic ash extending high into the atmosphere. The key characteristics are the ejection of a large amount of pumice and very powerful continuous blast eruptions.

The factors influencing tephra (volcanic airborne particles) dispersal can broadly be divided into those governed by the type, intensity and magnitude of the eruption, including the height of the eruption column and the duration of the eruption, and those governed by external factors such as wind strength, wind direction and changes in wind direction during an eruption. The location of a volcano relative to inhabited areas is also important with respect to potential hazards from tephra fallout. Tephra fallout from eruption columns, normally lasting an hour to several hours, is most often confined to relatively narrow sectors but tephra thickness within these sectors can reach tens of cm in proximal areas (figure 3).

Hekla volcano, the most famous in Iceland, is characterised by eruptions having a plinian opening phase. The largest of the 18 Hekla eruptions of the last millennium, in 1104, deposited a 20 cm thick tephra layer 30 km from Hekla and devastated farms up to 70 km from the volcano.

The largest plinian eruption of the last millennium, which produced about 10 km^3 of uncompacted tephra, occurred in 1362 at the ice-capped Öræfajökull volcano located in the middle of the Öræfi district in south-east Iceland. The inhabited area at the foot of the volcano and stretching eastward along the coast to Hornafjörður was devastated by tephra fallout. The tephra reached a thickness of 1 m some 15 km from the source. The plinian eruption of Askja in 1875, which produced 2 km^3 bulk volume, caused abandonment of farms in the highlands 60–70 km away from the volcano.

The moderate-sized explosive eruptions that have occurred in recent decades have produced eruption plumes rising to 8–15 km. As a result, eruption plumes have repeatedly caused temporal disruption to air traffic within Iceland and in parts of the North Atlantic. The most recent one is the Eyjafjallajökull eruption presented in chapter 3.

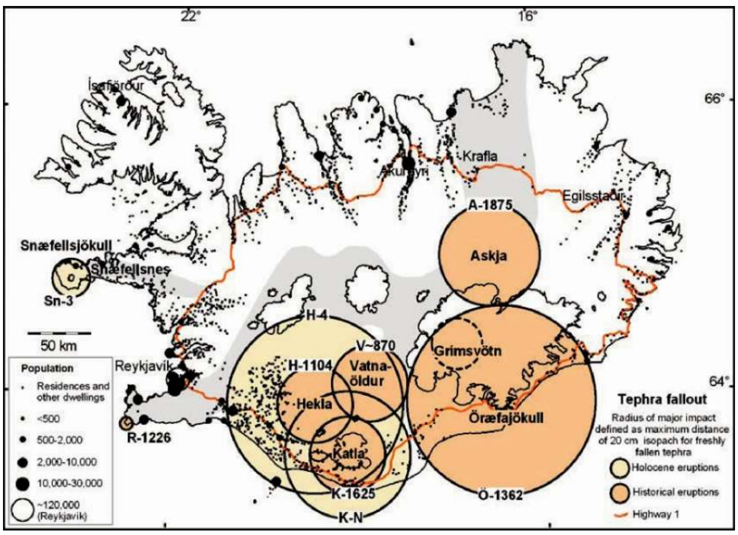

Figure 3 – Areas with over 20 cm of tephra fall in major explosive eruptions

1.3.2. Lava flows

Postglacial lava flows cover large parts of the volcanic zones. Many of these are 8000–10000 years old, formed in a surge of activity following the deglaciation at the end of the Ice Age. This includes the large lava shields which have volumes ranging from 1 to 20 km^3. Lava flows formed in historical times (figure 6) cover 3300 km^2. Small volume lavas are confined to the volcanic systems and central volcanoes, while the larger volume lavas can flow for tens of kilometres away from the source into areas outside the active volcanic zones. The rate of advance of lava is relatively slow except close to vents or for lava formed at a very high eruption rate. The risk of fatalities in effusive eruptions is therefore low. Property loss has been frequent in Icelandic effusive eruptions, especially when eruption occurs close to inhabited areas. Examples of loss of property are the Eldgjá eruption in 934, the Hekla eruptions, in particular the eruption of 1389, the Laki eruption in 1783, the Mývatn fires in 1724–29 and the eruption of Heimaey (Vestmannaeyjar) in 1973. The hazard of future effusive eruptions flowing into populated areas in Iceland is relatively high and increasing considering the growing population of the island; of special concern are the southern suburbs of the capital Reykjavík, Grindavík on the Reykjanes peninsula, the town of Heimaey, the Mývatn district and the populated lowlands around Snæfellsjökull.

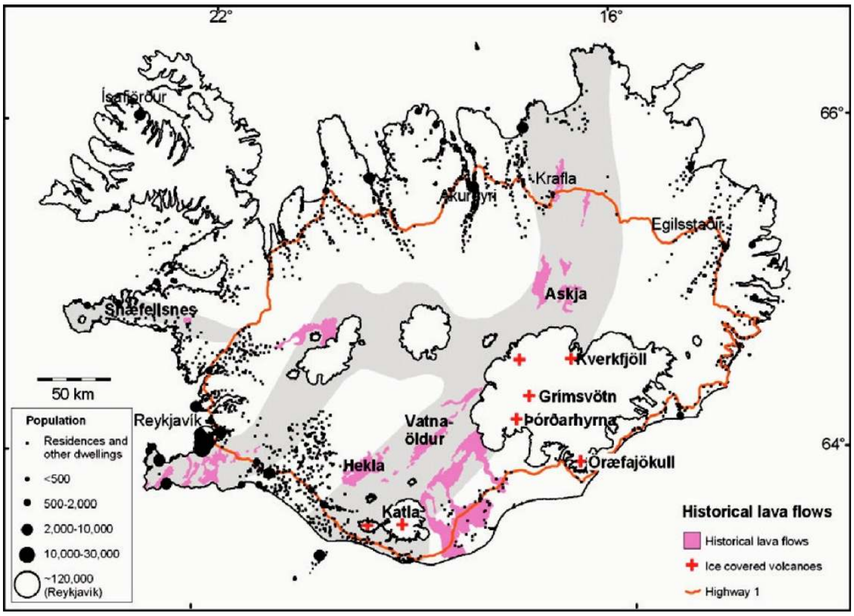

Figure 4 – Historical lava flows in Iceland (less than 1140 years old)

1.3.3. Jökulhlaups (glacier water outburst floods)

A jökulhlaup (or glacier burst) is an internationally adopted Icelandic term for a glacial outburst flood, mainly triggered by geothermal heating and occasionally by a volcanic subglacial eruption.

The most common hazards related to volcanic and geothermal activity in Iceland are frequent jökulhlaups, the majority coming from the glaciers of Vatnajökull and Mýrdalsjökull (Katla) (Figures 2 and 7). Most of these events are water flows although they may often carry a heavy load of sediments and sometimes ice blocks. Two main types of volcano-related jökulhlaups occur. Firstly, where the meltwater is produced in volcanic eruptions by release of thermal energy from rapidly cooling volcanic material. Secondly, where subglacial geothermal areas continuously melt the ice, the meltwater accumulates in a subglacial lake and is then drained at semi-regular intervals when the lake level exceeds some critical value. This latter type tends to be smaller and is much more common. Jökulhlaups also occur from ice-dammed lakes without any volcanic involvement. These are usually much smaller than jökulhlaups due to subglacial volcanic eruptions.

The Katla jökulhlaups have been preceded by earthquakes 2–10 hours before the floodwater emerges from the glacier. A large Katla jökulhlaup as in 1918 may reach a peak discharge of 300,000 m^3/s and flow over an area of 600–800 km^2 to the east of the volcano. The short warning time puts severe strain on civil defence authorities as only about 1–1.5 hours are available to close roads and evacuate areas potentially at risk. Recent studies show that during the last 10.000 years, large Katla jökulhlaups have on average flowed towards the west once every 500–800 years. Simulations indicate that a westward flowing jökulhlaup of the same magnitude as the 1918 jökulhlaup would flow over an area of 600 km^2 with a population close to 600. Water depths exceeding 1 m and flow velocities >1 m/s are predicted over most of the populated part of the overflowed area. The onset of a Katla eruption calls for evacuation of a large area on both the west and east side of the volcano, and over a limited area on its south side. Figure 8 shows the results of simulations of propagation times and inundation areas for jökulhlaups towards the west, south and east. The great hazard posed by Katla has led to special monitoring with seismometers, continuously recording GPS, radio-linked river gauges, regular airborne radar profiling and inspection flights over the ice cap. Most of these data can be viewed in real time on the internet. The monitoring of this mountain complex waiting for an eruption in the Katla volcano was crucial for the timely warning of the Eyjafjallajökull eruption in 2010.

Jökuhlaups from Grímsvötn are either geothermal or eruption-induced, with the latter type usually being much larger but less frequent. A frequent size of geothermal jökulhlaups in the latter half of the 20th century was 1,000–10,000 m^3/s while the jökulhlaup caused by the Gjálp eruption in 1996 reached 45,000 m^3/s. The high frequency of Grímsvötn jökulhlaups has made Skeiðarársandur, the pathway of the jökulhlaups, uninhabitable. Volcanic jökulhlaups may, however, overflow and damage Route 1 and in that way block the main transportation route in southeast Iceland. Smaller jökulhlaups caused by geothermal activity can issue from various places in the western part of Vatnajökull and Mýrdalsjökull (Katla) but these are usually relatively minor.

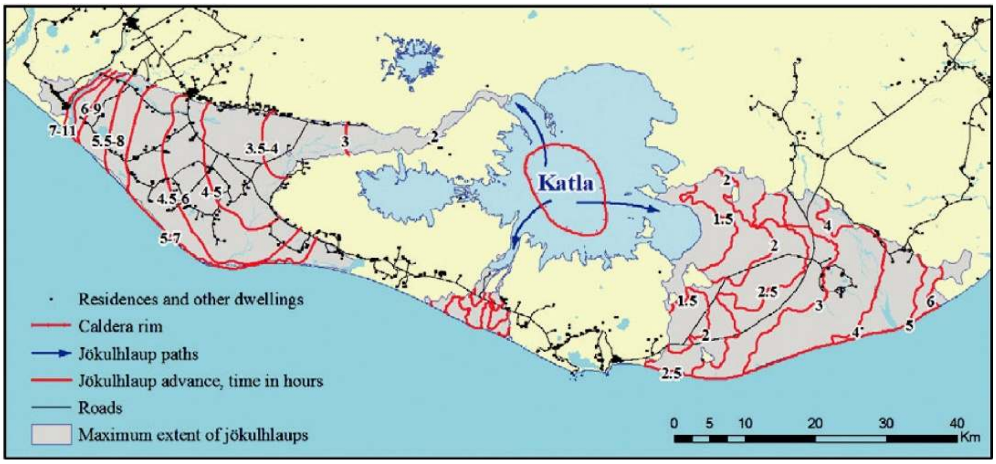

Figure 5 – The overflowed area and predicted propagation times in hours for jökulhlaups of peak discharge 250.000-300.000 m^3/s from eruptions within the ice-covered Katla volcano

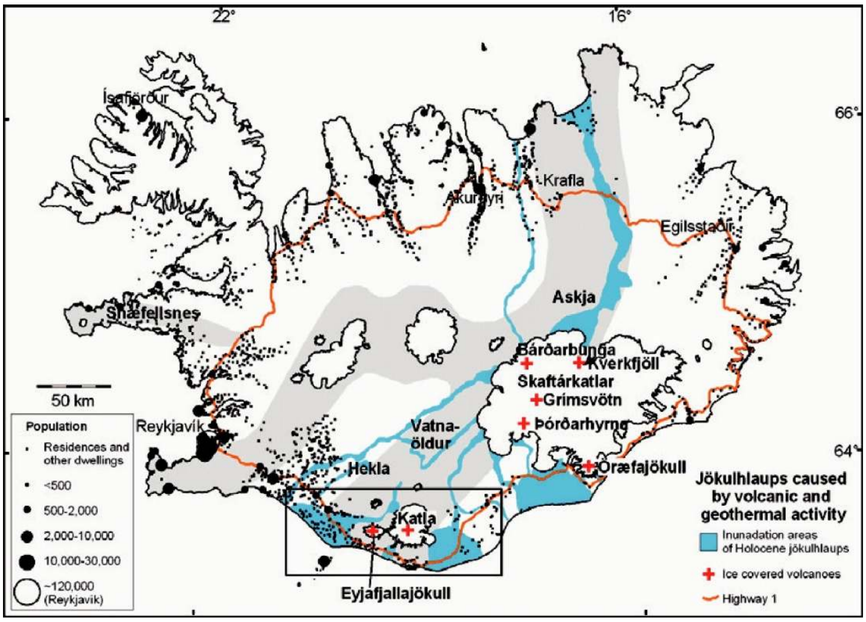

Figure 6 – Areas affected by jökulhlaups (outburst floods) attributed to volcanic activity

1.3.4. Damage due to volcanic hazards

Damage to infrastructure and the economical consequences of eruptions can be severe for a nation of only 320,000 people. Roads, communication and power lines cross known flood paths of major jökulhlaups from Grímsvötn and Katla and geothermal power plants can by necessity be located on or immediately adjacent to central volcanoes. Some losses are therefore inevitable in the future as in the past. During medieval times and the Little Ice Age, the community in Iceland was poor and relied mostly on subsistence farming. Hence, loss of life due to famine as a result of volcanic eruptions could be very severe. Considering the technological and economical advancement over the last 100 years, such fatalities are extremely unlikely in present-day Iceland. Moreover, the increasingly sophisticated warning systems, notably the real-time seismic network, hold great prospects of advance warning for most volcanic eruptions. Infrequent high-magnitude events, such as the Öræfajökull eruption of 1362 could today, as in 1362, nevertheless cause major damage and loss of life if affected areas could not be evacuated in time. The economic impact of volcanic events can be considerable and some towns in Iceland are vulnerable to lava flows. For instance a large part of the town of Heimaey (part of Vestmannaeyjar) was buried by lava and tephra in a moderate-sized eruption in the year 1973.

2. THE EYJAFJALLAJÖKULL ERUPTION

Eyjafjallajökull is one of Iceland's smaller ice caps located in the far south of the island. The ice cap covers the caldera of a volcano 1,666 metres in height that has erupted relatively frequently since the last ice age. The most recent major eruption occurred from 1821 to 1823. Previous eruptions of Eyjafjallajökull have in some cases been followed by eruptions in its larger neighbour, Katla volcano.

The 2010 eruptions of Eyjafjallajökull are a series of volcanic events at the Eyjafjöll mountain range in Iceland which, although relatively small for volcanic eruptions, caused enormous disruption to air travel across western and northern Europe over an initial period of six days in April 2010. Additional localised disruption continued into May 2010. The eruption was declared officially over in October 2010, when snow on the glacier did not melt.

The eruption in Eyjafjallajökull was the largest natural hazard event in Iceland for decades. It began with a small flank eruption in March, but the main event was the explosive summit eruption in April. The volcanic events are considered to be a single eruption divided into different phases.The flooding that resulted from melting of ice at the eruption site posed considerable danger for the local population and to road infrastructure, fallout of ash made conditions south of the volcano difficult for several weeks, threatening the future of farming in this rural area, and lead to unprecedented disruption to air traffic in Europe and the North Atlantic. Explosive activity was continuous for 39 days with repeated fallout of ash in many areas and continued disruption on busy flight routes over the North Atlantic. About 800 people were evacuated in a hurry three times during these events because of imminent flood hazard, but fortunately no dwellings were damaged and people could usually return the same day.

2.1. Initial phase – first eruption in the mountainside

Seismic activity started at the end of 2009 and gradually increased in intensity until on 20 March 2010, when a small eruption started in the mountainside, which lasted until 12 April. The 2010 eruptions are the culmination of 18 years of intermittent volcanic unrest but without any eruptions. Before the eruption, a ~0.05 km^3 magmatic intrusion under the volcano grew over a period of three months, in a complex manner, as revealed by GPS (Global Positioning System) geodetic measurements and analysis of satellite radar images. In early January 2010, the rate of deformation and the number of earthquakes began to increase. As the deformation and seismic unrest continued, the researchers installed more GPS stations near the mountain. Just a few weeks later, the instruments detected more rapid inflation, indicating that magma was moving upwards through the "plumbing" inside the volcano. This rapid deformation stopped as soon as the eruption in the summit began.

Figure 7 – First eruption, March 2010

2.2. The summit eruption

After a two-day pause, the volcano began to erupt again on 14 April. This time, the lava broke out through a new vent under the ice-capped summit of the mountain. Shortly after, the eruption entered an explosive phase and ejected fine, glass-rich ash to over 8 kilometres into the atmosphere.

What made this volcanic activity so disruptive to air travel was the combination of the following four factors:

1. The volcano is located directly under a jet stream (jet streams are fast-flowing, narrow air currents found in the atmosphere at around 7–12 km above sea level, the strongest being the polar jets).

2. The direction of the jet stream was unusually stable at the time of the eruption, maintaining a continuous south-easterly heading.

3. The eruption took place under 200 m (660 ft) of glacial ice. The resulting meltwater flowed back into the erupting volcano which created two specific phenomena:

    1. The rapidly vaporising water significantly increased the explosive power of the eruption.

    2. The erupting lava cooled very rapidly, which created a cloud of highly abrasive, glass-rich ash.

4. The volcano's explosive power was sufficient to inject ash directly into the jet stream.

Without the specific combination of the above factors, the eruption of Eyjafjallajökull would have been a medium-sized, somewhat nondescript eruption that would have been of little interest to those outside the scientific community or those living in the immediate vicinity. However, the above factors were precisely those required for the jet stream to carry the ash directly over northern Europe into some of the busiest airspace in the world.

Figure 8 – Volcanic ash covered the roads in vicinity of Eyjafjallajökull eruption

2.3. Ice melting and floods

The explosive eruption lasted for 39 days but extensive melting in the vent area mostly occurred in the first two days, leading to repeated jökulhlaups towards the north into the river Markarfljót. Melting continued after that, but drainage was continuous and the rate was not sufficient to cause jökulhlaups.

The eruption under the centre of the glacier, below the initial ice thickness of 200 m, almost immediately released meltwater which caused flooding in nearby rivers by the morning of 14 April as it travelled in two flows down either side of the volcano, forcing the evacuation of around 800 people. The main flood entered the glacial river Markarfjót on the northern side of the volcano and at its maximum around noon the discharge reached 2700 m^3/sec, where the usual discharge is 100 m^3/sec. A second somewhat smaller jökulhlaup travelled down the Markarfljót valley in the evening of 15 April.

Figure 9 – Eyjafjallajökull eruption in April 2010 and the Markarfljót glacial river

2.3.1. Roads and bridges

A flood control embankment system of armourstone protecting dams in the Markarfljót valley diverts the river under the bridges and protects vegetated land from river over flooding and erosion. The 250 m long bridge across Markarfljót river on the important Route 1 was designed to withstand a flood of around 2500 m^3/s, but scientists estimated in the beginning of the eruption that the flood could exceed 10000 m^3/s at its culmination. When the meltwater started to run along its path in the morning, the Icelandic Road Administration closed roads to all traffic and started to prepare to save the highway infrastructure, knowing that there were some 2-3 hours before the flood entered the location of the bridge. Channels were excavated through the armourstoned river embankments and the roads on both sides of the main bridge, to try to divert the flood away from the much more valuable concrete structure.

The maximum discharge of 2700 m^3/s might have been carried by the bridge opening, but specialists belive that it probably would have suffered some damage. The decision to cut through the road and divert the flood away from the bridge therefore proved right.

On 17 April the road cuttings had been filled up and emergency drive through was allowed. Provisional reparations went on day and night and as early as 18 April the road was opened for all public traffic, even though the volcano was still very active and there was always the risk of yet another flood. Warning systems with water level and water conductivity gauges were set up, together with emergency plans, in close co-operation with the police and local authorities. Fortunately, no larger floods followed, as the volcanic eruption had already melted most of the ice in the vicinity of the crater. Final reparations and paving of the the damaged sections of Route 1 were completed in early summer 2010.

Figure 10 – The flood at maximum discharge at Route 1. Roads and dams were damaged.

Figure 11 – Rebuilding of roads started already the day after the catastrophic flood.

2.4. Ash cloud and air travel

During the ice capped Eyjafjallajökull volcanic eruption in April-May 2010, the volcanic activity was monitored through various geophysical sensors (seismic, strain, GPS), river runoff from the glacier and the behaviour of the volcanic eruption cloud. The main tool for monitoring the volcanic ash cloud was the weather radar located at Keflavik international airport, approximately 150 km west of the volcano. Radar monitoring of the plume height was supported by visual observations, on-site and from a network of web-cameras. Airborne observations allowed for detailed examination of the plume, and pilot reports proved to be an extremely useful aid in verifying the radar data. Furthermore, data from lightning sensors and radiosondes was used to supplement information on plume height. Satellite images, from several frequency bands and both polar as well as geostationary satellites, were used to track the orientation of the eruption cloud, and brightness temperature difference was used to estimate ash dispersal. Ash fall monitoring and meteorological observations supplemented with reanalysis and wind forecasts were used to track local ash dispersal.

The effects of ash on aviation have been known for several decades. Nine Volcanic Ash Advisory Centres (VAAC) around the world are responsible for advising international aviation of the location and movement of clouds of volcanic ash. For better preparedness, regular exercises have taken place through the years, improving the preparative plans. However, a great step forward was taken during the Eyjafjallajökull eruption. For instance, a volcanic ash status report on the plume activity during the eruption was issued every 3 hours, to London VAAC and other sister institutes in Europe and North America.

In response to concerns that volcanic ash ejected during the 2010 eruptions of Eyjafjallajökull in Iceland would damage aircraft engines, the controlled airspace of many countries was closed to instrument flight rules traffic, resulting in the largest air traffic shut-down since World War II. The closures caused millions of passengers to be stranded, not only in Europe but across the world. With large parts of European airspace closed to air traffic, many more countries were affected as flights to and from Europe were cancelled.
After an initial uninterrupted shutdown over much of northern Europe from 15 April to 23 April, airspace was closed intermittently in different parts of Europe in the following weeks, as the path of the ash cloud was tracked.

The International Air Transport Association (IATA) estimated that the airline industry worldwide would lose €148 million each day during the disruption.

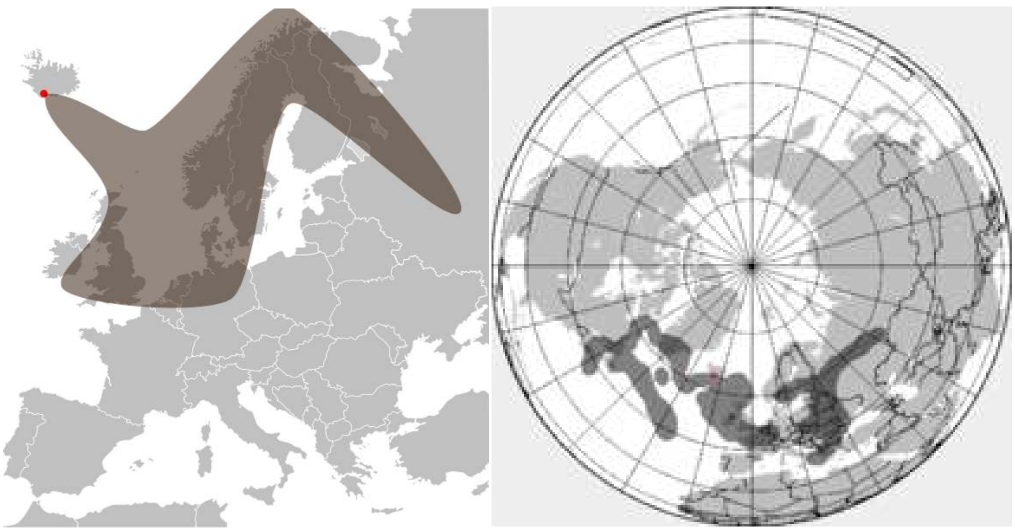

Figure 12 – Approximate depiction of the ash cloud on 15 April and 21 April

Figure 13 – A photograph and a satellite image of the ash plume 17 April 2010

3. RISK MANAGEMENT AND NATURAL DISASTERS

3.1. Monitoring and warning systems

Jökulhlaups (glacier outburst floods) are more common in Iceland than elsewhere in the world because of the interaction of volcanoes with glaciers. The greatest jökulhlaups from the subglacial Katla volcano are among the largest floods that humans have witnessed. At their maximum, the discharge may be larger than the average discharge of the River Amazon. Icelanders have learned to avoid the outwash plains of the most frequent jökulhlaups, Mýrdalssandur and Skeiðarársandur, but the outwash plains of the rivers Markarfljót in southern Iceland, and Jökulsá á Fjöllum in northern Iceland, are potentially dangerous and jökulhlaups will sooner or later flood parts of the current farmlands in those areas.

A warning system is operated by the Icelandic Meteorological Office that informs Civil Protection Authorities and the Icelandic Road Administration of impending floods or jökulhlaups. Unusual increases in water level or electric conductivity at key water level gauges triggers a warning that is subsequently evaluated by scientists. Thus, the Civil Protection Authorities and the Road Authorities may get a few hours' head start in reacting to public hazard.

The monitoring of volcanic activity in Iceland can be devided into two main categories. A geophysical monitoring network includes at present 62 seismic stations, 70 GPS stations and 6 strain meter stations. A hydrological monitoring network includes 160 water level gauges and electrical conductivity meters, which can show early signs of volcanic activity under ice caps.

An important test was put to the system in the advent of the Eyjafjallajökull volcanic eruption on 14 April 2010. Only at this volcano and at Öræfajökull volcano, south-eastern Iceland, are floods expected to reach inhabited areas within an hour from the start of a volcanic eruption. Therefore, quick response to warnings is essential. The gauges and equipment of the Icelandic Meteorological Office as well as the reconnaissance flights of the Icelandic Coast Guard played a key role in the response of Civil Protection Authorities and other official institutions like the Icelandic Road Administration to the hazard caused by jökulhlaups during the first days of the eruption. Particularly in the beginning of the eruption, the jökulhlaups were charged with volcanic debris as well as icebergs and advanced at a very high velocity (up to 20 km/h) and some were dangerously hot.

The warning systems triggered all emergency plans, all people in potential danger were evacuated, roads were closed for traffic and rescue teams entered the area. No person was injured and the most important links of the road system could be saved, as described in chapter 2.3.1.

3.2. Road authorities and future aspects

A close co-operation between the Icelandic Road Administration and the scientific community dealing with natural hazards has existed for decades. Basic and applied research on glaciological phenomena, volcanic activity, jökulhlaups and other natural hazards has been supported through numerous research programs and projects. The administration has also supported and partly financed the creation of the monitoring network. The motive is of course the concern for the safety of traffic as well as the safety of the infrastructure, especially the very important Route 1 along the south coast.

The Director General of Roads is a member of the Civil Protection and Security Council and the organization has permanent seats in the National Crisis Co-ordination Centre during all natural disaster events.

The possibility of natural hazards in connection with volcanic eruptions is something which the people in Iceland must live with and the Icelandic Road Administration cope with. Catastrophic floods caused by eruption in the subglacial volcano Katla were described in chapter 1.3.3. An eruption at this site has been expected for many years, and could start at any time with only a few hours warning. Some scientists belived that the eruption in Eyjafjallajökull 2010 might even trigger an eruption in Katla. The enormous flood caused by an eruption in Katla will certainly destroy roads and bridges and cut off all traffic on Route 1 for weeks or months while the structures are being rebuilt. The crucial factor however is the safety of people which makes the development and continuous operation of warning systems extremely important.

3.3. Road risk management

Road risk management in Iceland is an important element in each management phase, i.e. planning, design, construction and operation. It covers different types of natural hazards, especially flooding, volcanic eruptions, earthquakes, avalanches, rock-falls and windstorms.

The risk management process consists of risk identification, risk evaluation, decision making and execution of measures. At the planning and design stage it includes selection of route alignment, selection of the type of construction, necessary equipment and warning systems applicable to the risk identified (f.ex. bridge bearings are in each case designed according to the seismic risk at the location in question). Maps and other information available showing the type of risk (avalanches, earthquakes etc.) and potential magnitude (regional seismic risk, anticipated maximum river flood discharge, etc.) are used as a base for the planning and design of structures.

For the operational stage the main elements of the risk management system include:

- numerous on-line weather stations for storm warning at selected locations
- installation of seismometers in bridges within the most active earthquake areas – direct connection with The National Earthquake Center
- close co-operation with volcanic scientists and volcanic research centers and a prepared list of measures to be activated in the case of a probable volcanic eruption
- on-line sensors for water discharge, water temperature and water conductivity in glacial rivers running from glaciers covering active volcanoes
- rock-fall identification seismometers at selected locations
- avalanche- warning systems – detailed registration of avalanches entering roads – avalanche hazard zoning - close contacts with the Avalanche Center of The Meteorological Office
- supplies of material for the construction of temporary bridges with a length of up to 400 meters, kept at The Icelandic Road Administration center closest to the most probable floodings
- two teams of bridge construction specialists, on call at short notice for reparation work or erection of temporary bridges in the case of flood or earthquake destruction

In general, the most serious consequences for the road network in the case of natural hazards in Iceland, and also the most probable events, are the destruction of roads and bridges caused by floods following sub-glacial volcanic eruptions, as described in the main text of this paper. Therefore, road risk management in Iceland is heavily concentrated on these potential happenings.

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