VEÐURSTOFA ÍSLANDS

Report
02014

Esther Jensen
Thomas Sönser

Process orientated landslide hazard assessment for Eskifjörður

VÍ-ÚR10
Reykjavík
Apríl 2002

Table of contents

List of figures

List of tables

List of Maps

Abstract
Hillslope processes causing landslides including floods and rockfall where mapped during a trip to Eskifjörður in June 2000. Three river courses were chosen for a detailed study as they were considered the most dangerous sites. The Grjótá and the Lambeyrará rivers are active debris flows areas. Bleiksá river has evidence of debris flows in the past and is considered an active debris flow path. A few cross sections where made in the paths of the torrents to calculate the mass balances for possible floods and debris flows.

1 Introduction

Two catastrophic avalanches in Súðavík and Flateyri in the year 1995, when 34 people were killed led to a complete revision of the laws and regulations concerning hazard mapping for avalanches and landslides (including debris flows) in Iceland. Older hazard maps were made invalid.

Avalanches in Iceland have now been studied for several decades. Monitoring of avalanches was established after an accident in Neskaupstaður in 1974, where 12 persons were killed. Snow observers were hired in the most endangered villages as local contacts for Civil Defence Authorities and to register and analyse snow conditions and avalanches. After the events in 1995, the avalanche department of IMO was extended, additional snow observers were hired and evacuation plans were set up for several villages. Around the same time, a computerised avalanche database was established.

A historical chronicle of landslide events in Iceland was first made by the pioneer Ólafur Jónsson in 1957. This review was based on magazines, newspapers, old annals *etc*. and was updated in 1992 (Jónsson *et al.* 1992). Often only the largest events were recorded or those that caused some damage. This makes it difficult to relate the landslides to a certain trigger, such as a rainstorm or earthquakes because the "non-event storms" for instance are far too many. The landslide database is still only in a text format but a digital database and a GIS database are being developed by the IMO in co-operation with the Icelandic Institute of Natural History.

This study uses a process orientated Austrian method for assessing the landslide hazard in the village Eskifjörður, in eastern Iceland. Landslide hazard assessment has previously been developed for Seyðisfjörður using the same method (Jensen and Sönser 2002). Some sections of the present report are identical to sections in the report about Seyðisfjörður in order to make the report more self-contained.

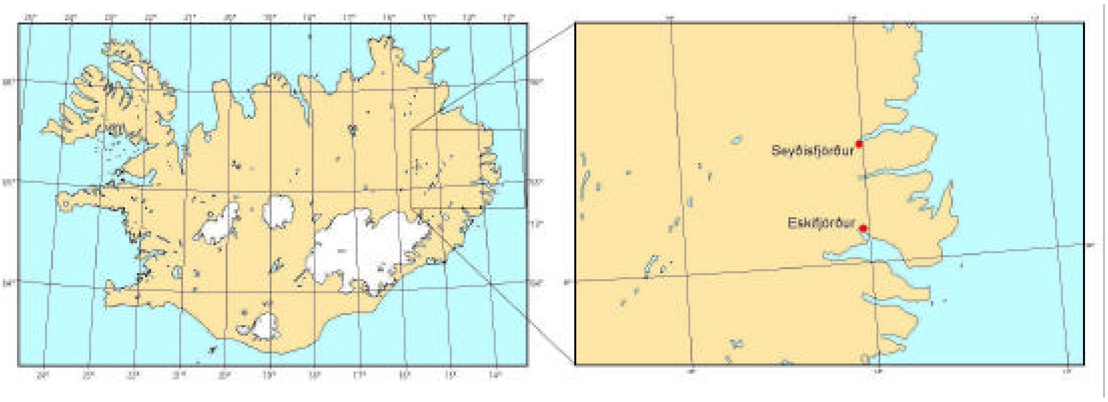
2 General Settings

Iceland is situated in the middle of the Atlantic Ocean on the latitude of 64 to 66 degrees north. The size of the country is 103,000 km^2. The coastline is 4,970 km and the longest distance between north and south is around 300 km and from west to east around 500 km. Glaciers cover about 11.5% of the country. Iceland is sparsely populated, with only about three persons per km^2 living mostly along the coast (Gylfadóttir, 2000). The interior of Iceland consists entirely of mountains and high plateaus. The average height is 500 m above sea level; the highest point is Hvannadalshnúkur in the Öræfajökull glacier in Southeast Iceland, reaching a height of 2.119 m.

2.1 Topographic characteristics and land use

The coastline of Iceland is cut by fjords all around the country except the south coast. The fjords were formed when glaciers reached the sea during ice age. The land rises steep from the sea in these fjords resulting in very little lowlands. Villages are built on the lowlands below the mountains and are often extended into the slopes.

Figure 2.1 Location of the study area



Eskifjörður extends north-west from the fjord Reyðarfjörður in eastern Iceland. The village Eskifjörður is located on the north side of the Eskifjörður fjord. To the south of the fjord and opposite the village rises the mountain Hólamatindur, 1000 m high and very steep. To the north and above the village there are also 1000 m high mountains but not as steep. They are the mountains Harðskafi, Ófeigsfjall and Hólmgerðarfjall, Harðskafi being the innermost and Hólmgerðarfjall the outermost.

Figure 2.2 The names of the main landscape features Eskifjörður

There is a shelf at 4-600m a.s.l. in the mountain that forms a small valley above the village. This shelf narrows towards the bottom of the fjord where it disappears. Above the shelf are two cirque valleys, Ófeigsdalur and Lambeyrardalur. Inside the main valley, the slope is even up to 600 m elevation. Many streams fall down the hillside above the village. Most of them are small but five run in well defined gullies through the village. These rivers are called (the innermost first), Bleiksá, Grjótá, Lambeyrará, Ljósá, and Hlíðarendaá.

Bleiksárhlíð and the innermost part of the village

The slope is even and only cut by shallow channels except for the course of the river Bleiksá. Bleiksá has often flooded and water has spread all over the debris cone at the foot of the slope. In 1940 the river changed its course and is now in a well defined channel where it flows through the settlement. Floods from the small brooks in Bleiksárhlíð have many times caused problems for the settlement.

The central part of the village (Grjótá/Hlíðarendaá)

The settlement between Grjótá and Hlíðarendaá is located below an irregularly shaped hillside with several rivers that flow down well defined gullies. Water floods, slush flows, and debris flows from the gullies Grjótá, Lambeyrará, Ljósá, and Hlíðarendaá pose a hazard to the settlement close by the river courses.

The outer part of the village

Outside Hlíðarendaá, the hillside has a similar shape as in the innermost part of the town. The small brooks have often caused problems during heavy rainstorms.

2.2 Human settlement

The farm Eskifjörður has existed since the first centuries (the 9. and 10. century) of settlement in Iceland. It is a so called “settlement farm”. Through the ages, more farms were established. Around 1800, a village started to grow, with the establishment of trade and fishery. As many other villages on the east and the north coast of Iceland the growth was fastest during the so called “herring years” when Norwegians started fishing herring around Iceland (*anno* 1879). In these years people were already aware of the danger of landslides in the village and there was discussion whether this location was suitable for dense settlement (Ágústsdóttir, 2001).

2.3 Climate

Iceland lies in a border region between two climate types, i.e. the Temperate Zone to the south and the Arctic Zone to the north. The climate of Iceland is a maritime climate with cool summers and mild winters. The Gulf Stream influences the mild climate. The weather is also affected by the East Greenland polar current curving south-eastwards round the north and east coasts. The south and west, as well as the interior of northern and eastern Iceland have an average temperature of the warmest month warmer than 10^{o}C while the coldest month is warmer than –3^{o}C. On the highlands and the northern peninsulas the climate is Arctic where the warmest month is colder than 10°C (Einarsson, 1976). The weather in Iceland depends mostly on the tracks of the low-pressure systems crossing the North Atlantic. Shifts between frost and thaw are very common and storms are frequent.

2.3.1 Thirty years annual means

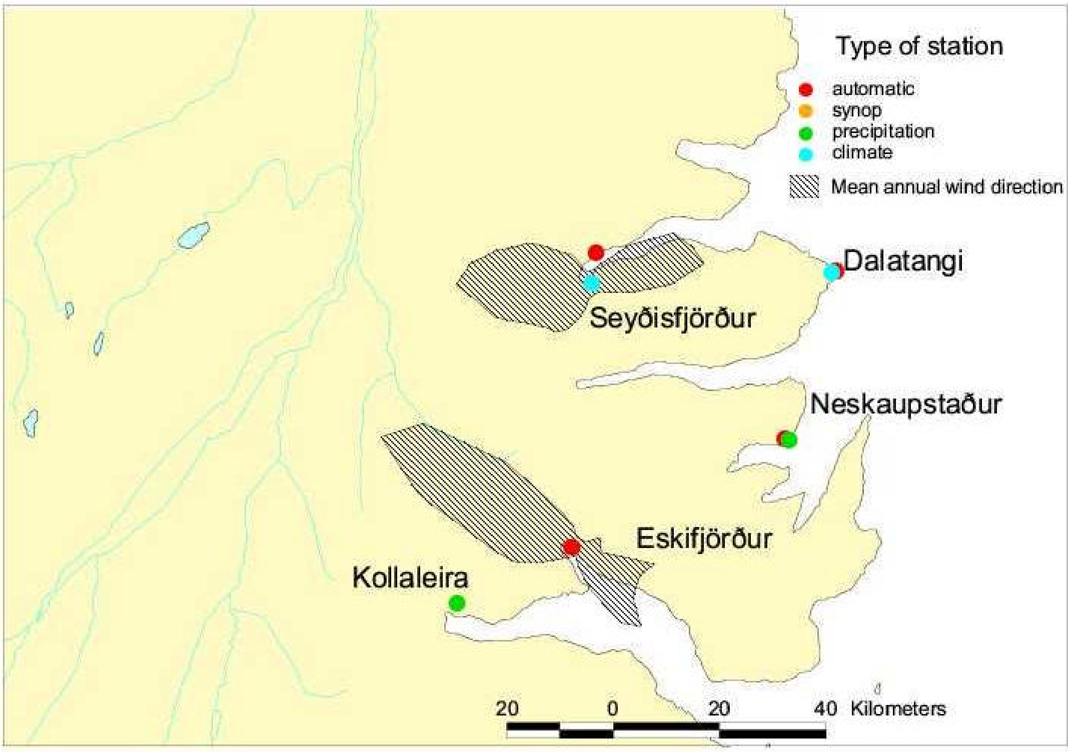
The 30-years (1961–1990) mean values of temperature and precipitation for the meteorological station Dalatangi in eastern Iceland are given in Table 2.1. Stations at Seyðisfjörður, Neskaupstaður and Kollaleira do not have continuous recordings for the same time period but mean values have been calculated for other periods and are also given in the table.

Table 2.1 Mean annual values for a several meteorological stations close to Eskifjörður (Data from the Icelandic Meteorological Office)

	Dalatangi 1961–1990	Kollaleira 1976–1995	Seyðisfjörður 1966–1995	Neskaupstaður 1975–1995
Mean annual temp. [°C]	3.5	3.6	3.7	4.0
Mean max temp. [°C]	6.0	6.7	6.7	6.7
Mean min temp. [°C]	1.4	0.7	0.6	1.1
Mean annual precipitation [mm]	1410	1306	1623	1764
Max. daily precipitation [mm]	200	115	141	186

Figure 2.3 shows the location of the meteorological stations on the east coast given in Table 2.1 and Table 2.2 and the mean annual wind-directions for Eskifjörður and Seyðisfjörður. The wind directions are affected by the shape of the fjord with westerly winds being the most common wind directions.

Figure 2.3 Meteorological stations on the East coast discussed in the report



Wind and stability observations have been made at Sómastaðagerði since May 1998 in connection with plans for a proposed aluminium plant. The wind observations show that the autumn and winter period October 1999 to March 2000 have the highest frequency of westerly winds (12.5%), and the highest average wind velocity was in westerly and easterly directions. The spring and summer period May to September 1999 has the highest frequency of easterly winds (9.8%) and the highest average wind velocity in easterly directions.

2.3.2 Extreme Precipitation

The extreme precipitation with return periods 1, 2, 5, 10, 20, and 50 years was calculated for selected weather stations in Iceland (Jóhannesson, 2000). The calculations were based on a Gumbel distribution, which is fitted to 1, 2, 3, and 5 day precipitation.

The values in the table for Seyðisfjörður (with an extrapolation to a return period of 100 years) were used for calculating a mass balance described in chapter 4. It was decided to use the Seyðisfjörður values since the two adjacent stations, that is Kollaleira and Neskaupstaður do not have recordings covering a 30 year period (1961-1990). Also because Kollaleira has considerably lower precipitation values than Neskaupstaður.

Table 2.2 Precipitation during 1 to 5 day rainfall event within a 1 to 50 year return period for the locations (a) Seyðisfjörður, (b) Kollaleira, (c) Dalatangi and (d) Neskaupstaður (based on data from Jóhannesson (2000)).

Location	T/P	1d	2d	3d	5d
(a) Seyðisfjörður 1961–1996	1	72	103	122	150
	2	87	124	146	177
	5	106	151	177	213
	10	120	171	201	240
	20	134	191	224	267
	50	153	218	255	302
(b) Kollaleira 1976–1996	1	60	87	102	124
	2	72	105	123	146
	5	87	129	151	176
	10	98	146	172	198
	20	110	164	192	220
	50	124	187	220	249
(c) Dalatangi 1949–1996	1	62	86	99	121
	2	75	104	120	145
	5	91	127	147	176
	10	104	145	167	199
	20	116	162	187	221
	50	132	185	214	252
(d) Neskaupstaður 1975–1996	1	78	109	129	162
	2	92	131	156	193
	5	110	160	190	235
	10	124	181	217	266
	20	138	203	243	297
	50	156	231	277	338

Extreme precipitation events with a shorter duration than one day are needed for the flood and debris flow calculations. The estimated events are based on the estimated extreme daily precipitation that is tabulated above. The maximum intensity for a shorter period than one day is calculated with Wussow equation in combination with the Kirpich equation (Bergþórsson, 1968, 1977, see Chapter 4). Flood and debris flow computations were also carried out for a 5 hour accumulated precipitation with an unspecified return period based on a recorded event in Seyðisfjörður in 1999. Calculations were also made for evenly distributed precipitation over 1, 2 and 5 days (block rain) with a 100 year return period. Distributing the precipitation evenly over such long periods is clearly not realistic with regard to short-term extreme water discharge from the watersheds. However, it serves to roughly estimate the response of the source areas for loose materials to prolonged periods of rain.

2.3.3 Weather conditions connected to landslides

Intensive rainfall and high discharge is a major cause of debris flows. Debris flows in Seyðisfjörður (neighbouring community of Eskifjörður) have mostly been recorded in connection with intensive rainstorms. Such an event was analysed by Pétursson and

Sæmundsson (2000). From September, 8. until noon September, 9. 1999, 100 mm of rain were recorded by an automatic station in 16 hours, most of it fell in 6–7 hours. The station has been operating since 1995, recording 10 minutes values, which show well the intensity of the storm. The most intensive rain was in the evening of the 8. when 30 mm were recorded in one hour. Debris flows occurred the same evening just before midnight. The 16.-17. September 1999 debris flows were recorded in Eskifjörður, in the mountain Hólmatindur, opposite the village. In 23 hours about 110 mm of rain were recorded by an automatic station. Again in 2001 debris flows fell in the same area. On the 21.-22. August about 90 mm of rain were recorded in 15 hours. Other events have not been recorded in Eskifjörður since the automatic station started operating.

2.4 Geology

Geologically Iceland is a very young country, and the process of its formation is still active. Iceland is situated on a spreading ridge on the boundaries of the N-American and the Eurasian plates. The Reykjanes Peninsula to Langjökull is a direct continuation of the Reykjanes ridge, part of the mid-Atlantic ridge. A more active zone lies from the Westman Islands trending north-east and north across Iceland to the north about 50–70 km wide. Because of the spreading effect, the northwest and the east coast of the country have the oldest bedrock and the surface bedrock is more metamorphosed in those areas than in the centre of Iceland.

The erosion differs with the type of the bedrock. Dikes are often harder than the neighbouring rock and in that case, they stand out of the bedrock. If the dikes are softer they are more easily eroded and gullies appear at the location of the dikes. Gullies are also often formed on the sides of dikes because there is usually a film of metamorphism on the neighbouring rock. This film makes the rock close to the dike softer than the rock further away and therefore more easily erodible. Old faults and slips are also easy paths for flowing water.

The main bedrock units are widespread tholeiitic layers, olivine tholeiitic, porphyritic basalts, and intrusions and lavas of rhyolitic basalts. Interbeds consist of red baked soil, basaltic tuff and ash layers. The tholeiitic layers are usually hard and dense. They brake up into large columns during solidification and the separation of the columns is later widened by frost action. The olivine basalts are softer and therefore more easily eroded and they often form thick layers of talus (Sæmundsson and Pétursson, 1999). Rhyolit layers are usually flaky with gas holes and therefore they brake easily up into flakes by frost weathering (Einarsson, 1968).

2.4.1 Bedrock of Eskifjörður

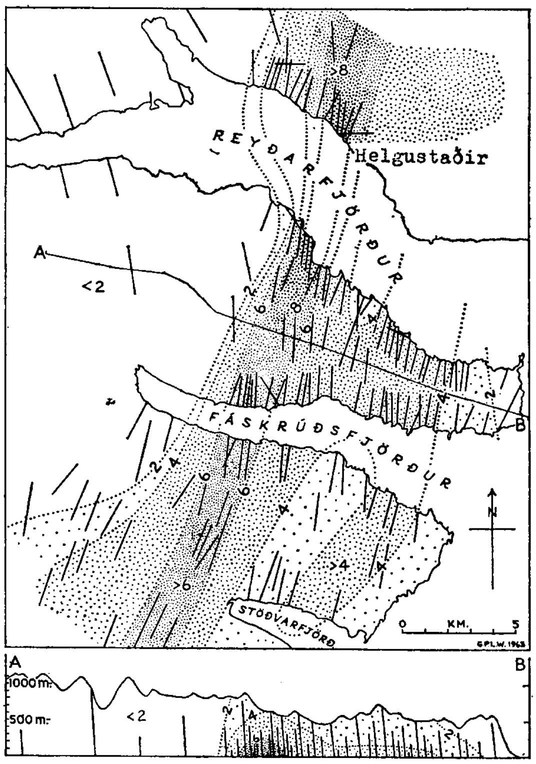
The bedrock in the Eskifjörður area is about 10-15 million years old. It is mostly basaltic layers with sediments in-between. The strata tilt to the west about 7-10° by see level but higher up about 2-4°. The Reyðarfjörður old central volcano was described by Walker (1959, 1963). Around the volcano (see Figure 2.4), there are some rhyolitic layers and the strata tilt locally towards the centre of the old volcano. Dikes are more frequent close to the central volcano. The bedrock is slightly metamorphosed with many zeolits. The youngest formation of the volcano is a basaltic lava shield pile, which can be found by the road in Oddskarð (Hönnun *et al.* 1999).

In the beginning of the ice age and even earlier, glaciers must have covered the volcanoes and started eroding their hillsides. In the inner part of Eskifjörður valley there is clear evidence of the glaciers, i.e. glacial stria, terraces and roche. However, where the rhyolitic layers are situated the evidence about the glacier is lost due to rapid erosion of the rock (Hönnun *et al.* 1999).

2.4.2 Tectonics

There are two main fracture systems in Eskifjörður the main system has the direction NNW-SSE, and a less clear fracture system with NE-SW direction. The frequency of dykes is not high (2-3%) especially if kept in mind how close the area is to the Reyðarfjörður central volcano (Guðmundsson, 1992). Earthquakes are considered to have very low impact in the area. The closest seismically active area is more than 100 km away (Hönnun *et. al,* 1999).

Figure 2.4 Reyðarfjörður central volcano by Walker (1963)



2.5 Hydrology

The bedrock in the east fjords is impermeable due to metamorphism. Therefore, water flows on the surface where the bedrock is exposed. However, cracks and dikes are passageways for surface water into the ground and therefore groundwater can travel long distances and sometimes deep enough to heat up and become geothermal water. If geothermal heating has not affected the water, the mean temperature of spring water is between 2-4°C.

The river Bleiksá has the biggest watershed of the rivers that fall through the village. It drains the valley Ófeigsdalur and is about 4.3 km^2. The other main rivers, Grjótá, Lambeyrará, Ljósá and Hlíðarendaá all drain the valley Lambeyrardalur. Grjótá has the biggest catchment of the four, of about 2.3 km^2.

2.6 Geomorphic Processes

During the ice age the fjord and the valley was filled with a glacier. Simultaneously and some time after the ice age small valley glaciers were located above the main glacier. After the main glacier of the Ice Age melted, glacial erosion remained high in the small valleys up in the mountains. There is also evidence of more rapid processes, such as large mass movements related to bedrock failure, but this was not investigated in the present study.

The main geomorphologic processes occurring on the hillside were mapped in the field and results are presented on maps that were made in a digital-mapping program.

Four main processes of mass movement were detected:

- **Debris flows** usually take place on slopes covered by unconsolidated rock and soil debris. Three elements of the path are distinguishable: source area, main track, and depositional cone (Hübl, 1995).
- **Rock fall** has been regarded as the predominant process controlling talus formation (Kirkby and Statham, 1975). Active rockfall areas are frequent below steep rock faces and sometimes in combination with toppling rocks.
- **Slides** or landslides may be discrete and catastrophic events or slow episodically moving (Selby, 1993). The size of the slides can vary greatly. Small slides can have great impacts by blocking channels during storms resulting in large debris flows.
- **Creep** is a time-dependant behaviour of unconsolidated material or bedrock usually promoted by factors like temperature and temperature variations, water content, pore water pressure and ambient stress such as loads of overburden (Selby, 1993; Bunza, 1982). Creep can be deeply seated if large masses are involved. When a creeping mass reaches the edge of a cut slope it often results in slides. The size of the slides depends on how deep the creep is.

A channel that is subjected to debris flows can be divided into three zones, where the operating processes require different gradients (VanDine, 1985).

Initiation zone >25° but can be as low as 15°

Transportation and erosion zone >10°

Deposition of leveés may begin at 15°/deposition on the fan or cone <10°

The source of debris can be estimated by grouping important characteristics, such as: slope, type and distribution of bedrock and overburden, vegetation and land use adjacent to the creek as well as in the drainage basin. The potential contribution of the creek to debris "is depended upon the character of the creek banks and adjacent valley walls" and can be classified as (VanDine, 1985):

Table 2.3 Classification of potential creek contribution to debris (VanDine, 1985)

Contribution to debris	Incisement of channel, cohesiveless soil	Incisement of channel, cohesive soil	Creek banks
Low	0	<5 m	<15°
Moderate	>5 m	<5 m	15–35°
High	–	>5m	>35°

There are three main causes for the largest floods, debris flows and slush flows from the gullies. The first possibility is an intensive rainstorm and/or rapid melting of snow. Erosive processes start and the channels may then not be large enough to carry the flow and the streams and the rivers overflow their course. The second possibility is bursting of a dam created by snow blocking the channel. The third possibility is that debris blocks the channel, leading to a debris flow or a flood when it bursts.

2.7 Soil

Soils formed in volcanic active environment have special characteristics and are classified as Andosols or Andisols. Icelandic soils can be classified into three groups based on characteristics of the site (Strachan, *et.al* 1998).

These are:

- Soils of poorly drained sites (including Histosols and Andisols)
- Typical Andisols of freely drained sites
- Soils of barren areas, about 40% of Icelandic soils (Arenosols, Leptosols, Regosols, Gleysols, usually exhibiting andic soil properties).

A substantial proportion of the Andosols in the world is found in Iceland, covering about 80.000 km^2 (Arnalds, et.al, 2000).

"Soils that form in materials that are rich in volcanic ash are called Andisols (US) or Andosols (FAO), see also www.rala.is/andosol. Andosols have unique properties, some of which are responsible for their erosion susceptibility. The soils have low cohesion but can absorb large quantities of water (>100% on dry weight basis). This high water holding capacity intensifies freezing effects that result in solifluction, landslides, needle ice formation, and the formation of hummocks ("thufur"). The lack of cohesion make the soils extremely vulnerable to rain-splash and running water, especially when the soils are water saturated. The soils tend to be super-saturated in winter and spring when a frozen layer prevents drainage. Wind erosion is further intensified by lack of cohesion, stable silt-sized aggregates, and often low density of soil grains, especially coarse tephra grains (often about 1 g/cm^3)." (Arnalds, et. al, 2001).

According to The Soil Map of Iceland (Arnalds and Grétarsson 2001 and http://www.rala.is/desert/) the soil in Eskifjörður can be classified as the following:

Histic Andosols (HA)

Found in poorly drained areas with relatively small eolian additions on an Icelandic scale, but enough to reduce the organic content below the 20% C limit for Histosols.

Hydric Andosols (WA)

Andic soil materials carry a distinct set of attribute soil properties that separate Andosols from other soils. Hydric Andosols include a variety of wetland soils that have lower organic content than 12% in surface horizons. This soil type is dominant in wetland areas in the central highlands where eolian deposition is relatively rapid.

Brown Andosols (BA)

They are the classical freely drained Andosols in Iceland, and perhaps the most studied to date. They are often 0.5–2 m thick and have considerable allophane content.

Leptosols (L)

Icelandic Leptosols have not been studied to date, but they include lava surfaces with shallow eolian-andic mantle and scree slopes.

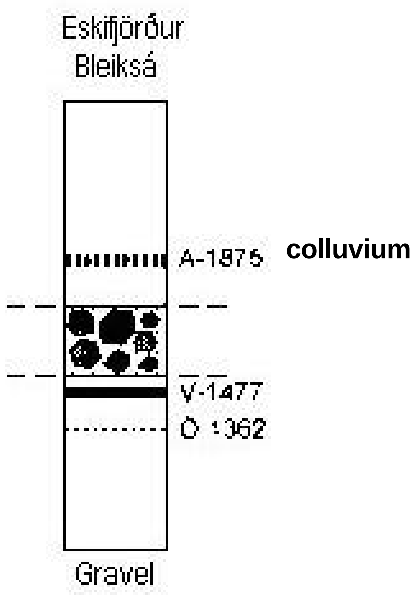
2.7.1 Tephra layers

Tephrochronology has not been used much for dating landslides or avalanches in Iceland but there is a good possibility to do that. Sigurgeirsson (2000a) has summarised information about tephra layers in the eastern fjords. There are eight main tephra layers and these are often seen in undisturbed profiles.

- A-1875, Askja (1875 AD)
- Vv-1477, Veiðivötn (a-layer) (1477 AD)
- Ö-1362, Öræfajökull (1362 AD)
- LNL, the settlement layer, change of colour in the soil (~900 AD)
- Hekla-3 (2900 BP)
- Hekla-4 (4500 BP)
- Hekla-5 (6600 BP)
- Saksund Lake's tephra, Vatnajökull (9000 BP)

Tephra layers in a few profiles near Eskifjörður were analysed (Sigurgeirsson, 2000b). This preliminary study showed that tephra layers could be used to date landslides in Iceland and possibly the distribution of certain events. The limiting factor is of course the number of tephra layers in each area and the length of intervals between them. The fact that landslides erode the surface also limits the accuracy of the method. The method is most useful to distinguish between periods with and without landslides.

Figure 2.5 Profile from Sigurgeirrson (2000b)



A profile in the path of Bleiksá river in the inner part of the village Eskifjörður showed a layer of debris below an *in situ* tephra from Askja-1875 and above the *in situ* Vv-1477 tephra (Figure 2.3). This debris can possibly be linked to an event 1849 in Grjótá where three persons where killed in a slush flow. The records do not mention slush- or debris flows in other paths during that event but it is possible that the event was not a single flow but more distributed event including debris flows in other paths.

The structure of loose material that has been accumulated on the foot slope of the mountain above Neskaupstaður (a neighbour community of Eskifjörður) was analysed by Hjartarson (2000) in connection with the construction of protecting measures above the settlement. The loose material in Neskaupstaður also has a thick debris layer between A-1875 and Vv-1477. Nevertheless, these events cannot be linked without further investigation. However, these studies do show that this period has been an active erosion period in the whole area.

2.7.2 Physical properties of Icelandic soil

Permeability values for Icelandic loose material are tabulated in the ÍST 15:1990 standard (Table 2.5).

Table 2.4 Permeability in Icelandic sediments (ÍST, 1990)

Material	Permeability k [m/s]
Gravel	10^{0}–10^{-2}
Course sand	10^{-1}–10^{-4}
Fine sand	10^{-3}–10^{-6}
Silt	10^{-5}–10^{-8}
Till	10^{-2}–10^{-8}

Table 2.5 Shear strength (φ) in Icelandic sediments (ÍST, 1990)

Material	c [MPa]	φ [°]	Attn.
Sand	0	35–43	3)
Silt	0	40	1) 3)
Silt*	0.35*σ	0	2) 4)
Till	0	40	3)

1) the material is resistive
2) the material is cohesive (c > 0)
3) water pressure caused by stress should be estimated according to runoff coefficient
4) σ is active vertical strain before added stress

The standard also includes a table for the shear strength of different materials. The standard is intended in use in building construction and the material analysed is not typical for material found on a hillside. From the shear-strength table the sand, silt and the moraine can be used for calculations of design debris torrents (see below).

The soils in the Eskifjörður area have not been analysed specifically but an investigation on loose material was made for Neskaupstaður in combination with construction of snow avalanche protecting measures (VST, 1998). The material was classified according to the U.S.C.S. standards for grain size. The samples analysed were mostly either medium to coarse grained sand (SM and SM-SC) or gravel (GW, GW-GC, GP-GM, GM).

2.8 Vegetation

More than 37 000 km^2 of Iceland are barren deserts some of which is caused by volcanic activity. In addition is an area of 10–15.000 km^2 of limited plant production (Arnalds *et al.*, 2000).

A national soil-erosion assessment was made by Arnalds *et al*. (2001). The following Table 2.6 gives the percentage of surface area affected by erosion and vegetation coverage in the Reyðarfjörður and Eskifjörður area. The total size of the whole area is 405 km^2. The soil erosion assessment uses classes of erosion forms that can be identified in the field. An area can have several active erosion processes. The following classes were used:

- *Rofabards* (erosion escarpments)
- Encroaching sand
- Erosion spots
- Erosion spots on slopes / solifluction
- Gullies
- Landslides
- Deserts

The severity of erosion in each class is recorded with an erosion scale of 0–5 (0 = no erosion, 5 = very severe erosion). Deserts were classified further into eight classes including mountains, but mountains were not mapped further. Vegetation coverage was classified as: deserts, scarce, rather scarce and good. The basis for this mapping is satellite images in the scale 1:100.000. The table shows that 35% of the area has good vegetation cover but 62% of the vegetated land suffers from erosion, and 12% of the whole area is severely eroded.

Table 2.6 Erosion and vegetation in Eskifjörður and surrounding area (from Arnalds *et al.* (2001))

County	Size (km^2)	Erosion map %					Vegetation %			
		0+1+2	3	4+5	Erosion in Veget. land	Deserts Mountains	Deserts	Scarce	Rather Scarce	Good
Reyðarfjörður, Eskifjörður	405	18	70	12	62	35	36	11	18	35

3 Study Aim

Based on a request from the Eskifjörður community (Fjarðabyggð) the aim of this study is to make a mass movement hazard assessment for this area. As stated in the legislation (The Ministry of the Environment, 2000) the communities should request IMO to make a hazard assessment were avalanches or mass movement processes have occurred or are likely to occur. According to the legislation, the hazard assessment should include:

1. A summary of historical events and a map with recorded events
2. Frequency map, at least 100, 300, 1000 and 3000 year events. Alternatively, if that is not possible an estimate of return periods for each area (written text).
3. A description of the method, what data was available and used, assumptions that were made and results from calculations. If results are not gained with calculations, they have to be explained by supporting arguments.

4 Methodology

Two field trips were made during the summer of 2000. The first trip was made to the Eastfjords where landslides in Eskifjörður and the south part of Seyðisfjörður were investigated. The other trip was to the Westfjords Patreksfjörður, Bíldudalur and Bolungarvík. Two different teams made the trips. On both trips, there was a specialist from IMO, accompanied by a foreign consultant on each trip, an Austrian consultant on the first trip and a German consultant on the second. The aim was to get two different opinions on how to investigate landslide hazard in Iceland. The landslide hazard assessment for Seyðisfjörður is based on the Austrian method. The other method that was used in the Westfjords is described in Glade and Jensen (in prep.).

Literature search

Egilsson (1990) made an avalanche- and landslide chronology for Eskifjörður. It included three known avalanches but several flood and debris flow events. One event, a slush flow that occurred in 1849 killed three persons. Partially based on this report and a landslide chronology written by Pétursson and Jónsdóttir (2000) for the whole country, an extended avalanche- and landslide chronology was compiled by Ágústsdóttir (2002). Events with known locations were mapped. The map is also included in this report, in Appendix C. Potential slushflow hazard was analysed by Hestnes (2002). An overview report stating the need for avalanche protection measures around the country written by Jóhannesson *et al.* (1996).

The Austrian method

Hazard mapping in Austria was developed in the late 1960´s and was based mainly on an interpretation of chronicle data and accumulation cones. About 10 years ago a process orientated method, suitable for catchments that are more complex was developed. It is a procedure of different investigation tools to estimate geo, hydro and bio parameters of the catchment areas. It ends up with the elaboration of process orientated mass balances for different scenarios (Angerer 1998; Mölk *et al.*, 2000; Ploner and Sönser, 1997, 1998, 1999a,b, 2000) used to delineate hazard zones for a recurrent design event of about 150 years.

Literature analysis

The work starts with the interpretation of pre-existing reports, maps *etc.* of the site for topics of the geo-inventory (geological & geomorphologic basement), bio-inventory (soil & vegetation) and hydro-inventory (precipitation, runoff, system conditions, different scenarios).

Air photo interpretation

Interpretation of different time series of air photos and air photos taken at different flight heights. After a review of the literature data, the first “real” connection to the site is achieved by analysing air photos. From the aerial photos, it is possible to identify main erosion areas, on one hand, and on the other, the photographs are essential to get an overview to plan the field investigations. The relevant areas are then mapped in a scale of 1:2000 – 1:5000 showing special features that have been identified from the aerial photographs.

Overview-field trip
After the first two steps, a map with a scale of 1:10,000 – 1:20,000 (regional planing) with a draft of the location of relevant "process-areas" is made and verified and adjusted in the first field trip.

Detailed field investigations for slope processes
After the pre-selection of main process-areas, processes that endanger the settlement areas are mapped in detail, based on a special sign-catalogue (Sönser and Wanker, 1998; Mölk, 1998; Wanker, 2001). The processes are split up into two parts:

A. Outside the channel (rockfall, slides, creeps)
B. In the channel (debris flows, floods)

A process-orientated map is made of the catchment areas describing various types of endangering processes and system conditions. The characteristic parts of the catchment area are judged for their critical runoff coefficients for different system conditions:

- dry
- wet
- saturated
- dense (*e.g.* frozen)

In addition, the map also includes main sources of loose material, *e.g.* moraine, talus and colluvium.

Channel Investigation
During the detailed field investigations, the characteristic channel processes are registered for each homogenous part of the channel. To get a reasonable upper limit of the volume of a possible event, cross sections of the channel bed and specific material parameters are mapped. In relation to the characteristic runoff in each part of the channel the volume of different design events is estimated (VanDine, 1985). The following information are collected:

1. The channel inclination and the transverse slopes are measured.
2. The visible height of old channel events is measured to calculate the hydraulic radius.
3. The composition of the channel bed is an important part, and is described with the following parameters:

    - Mineralogical quality of sediment
    - Composition of sediment (porosity, friction angle, specific weight)
    - Fabric and structure of the sediment

Calculation and assumptions for process orientated mass balances
When calculating a process orientated mass balance, the following steps are taken:
1. The calculation of water runoff in a channel is based on dividing the area into subcatchments with reference to the relevant channel processes. During this grouping the following is considered:
    - Precipitation intensities for different return periods
    - Runoff coefficients for different system conditions

2. The flood peaks for the characterised parts of the catchment area are calculated, based on the calculated runoff.
3. Hydrographs for the different parts of the catchment area are developed using the following procedure:
   Time till flood peak is reached is computed from Kirpich equation (Bergthaler, 1991):

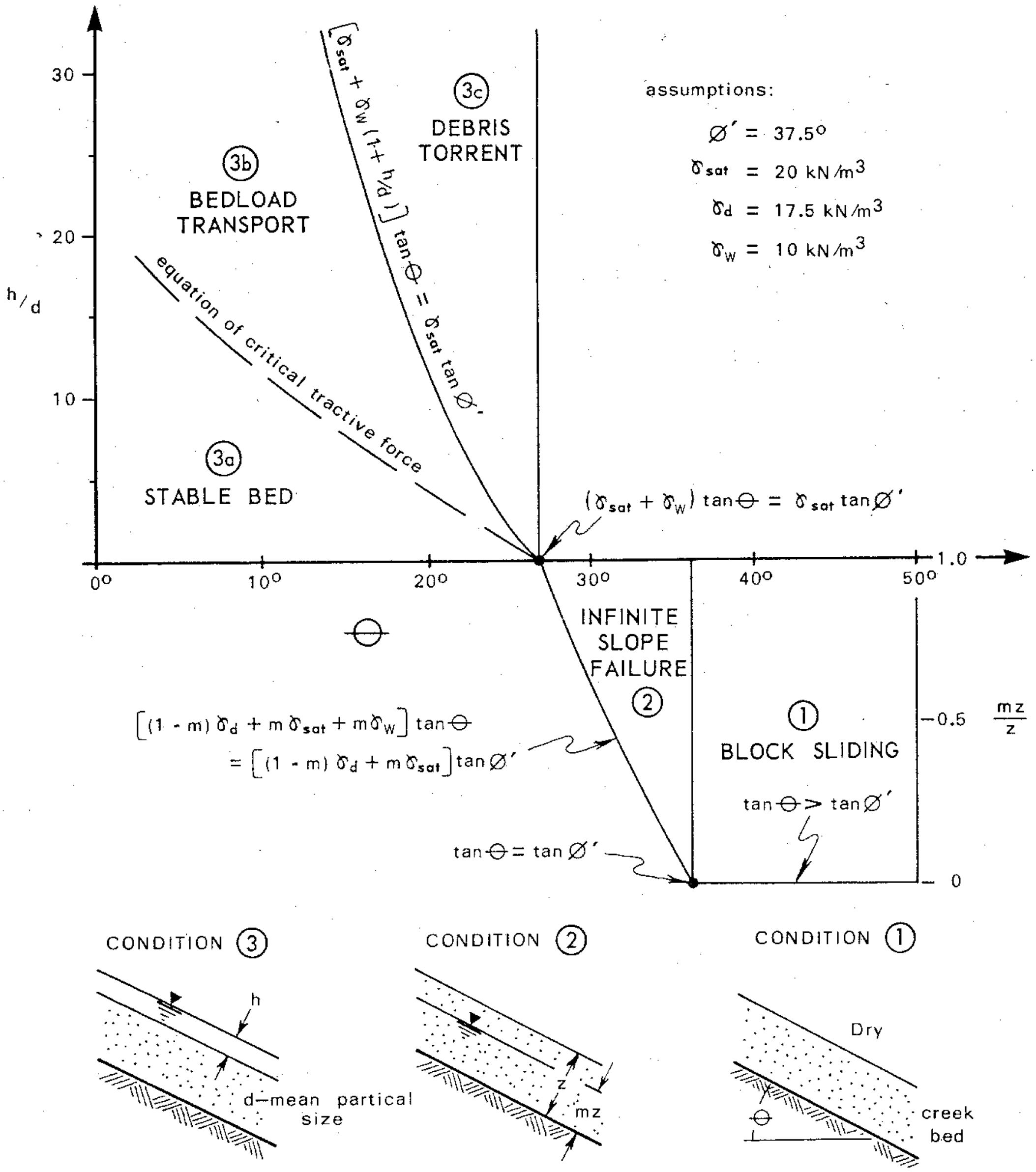
   Kirpich equation: $T = 0.0195 * L^{1.155} / H^{0.385}$

   T = The time till flood peak is reached [min]
   L = Maximum length of travel of water [m]
   H = The difference in elevation between the most remote point on the basin and the outlet [m]

   Approximated time of the whole runoff event is an interactive response corresponding to the intensity of the critical precipitation event.
4. The integrated event runoff is calculated based on a unit hydrograph.
5. The amount of available sediment for the event is estimated.
   - A potential of available sediment in the channel was estimated based on field investigation.

   The dominating channel process is estimated according to the detailed field investigations, and by using a model from VanDine (1985) (split up into water runoff/bedload transport/hyper concentrated flow/mass movements, see Figure 4.1). When major channel processes have been determined, the possible transport capacity within each process group is estimated using:
   - An integration of channel geometry resulting from the field investigations.
   - The channel bed composition also from field investigations.

Figure 4.1 Creek bed instability for wide stream (From VanDine (1985))



The result is a process orientated mass balance for a special channel event. Different scenarios for different types of precipitation events and system conditions were set up to check the possible variety of channel processes for different starting conditions. The precipitation scenarios were:

An intensive short term event corresponding to the watershed in question
A 5 hour event based on precipitation measurements in Seyðisfjörður
1 day rain with 1 year return period
1 day rain with 100 year return period
2 days rain with 100 year return period
5 days rain with 100 year return period

The input into the mass balance calculations are minute values of precipitation related to the calculated concentration time (by the Kirpich equation, see above). Since long term automatic records from precipitation stations do not exist in Iceland, the Wussow's equation (Bergþórsson, 1968, 1977) was used to calculate a short time high-intensity rainfall event. Accumulated precipitation (*I*) over a time interval (*T*, in minutes) on the same order as given by the Kirpich equation (*T*) for the watershed in question was estimated by Wussow's formula from the one day precipitation (*I24h*) with a 100 year return period:

$$I = I24h * (1/1440) * \sqrt{(T * (2880 - T))}$$

The one minute values were computed by distributing the precipitation evenly (block rain) over the period in question. The time *T* for the high intensity event was chosen in the range 10-30 minutes for the watersheds that were considered in Eskifjörður.

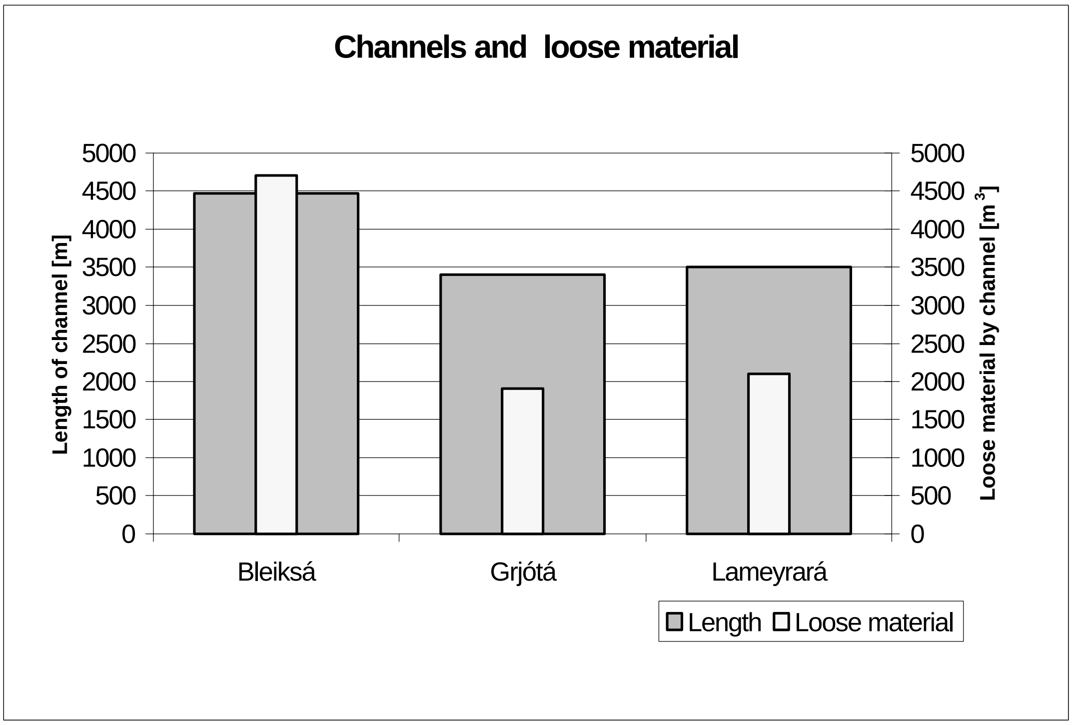
Three different system conditions were considered. For the high intensity event, unsaturated and partly saturated surface conditions were considered (runoff coefficients of 0.4 away from the channel and 0.6 near the channel for the unsaturated conditions, and 0.5 and 0.8, respectively, for the partly saturated conditions). The potential for the saturated conditions may be expected to increase with the length of the precipitation event. Therefore, saturated surface conditions were assumed for the 5 hour and the long term events (runoff coefficients of 0.7 away from the channel and 0.8 near the channel). A surface runoff coefficient on the order of 0.4 is often used for determining design floods in engineering applications for similar watersheds in Iceland.

Using the above approach one can also assess mitigation structures – either those that exist or structures planned in the future.

5 Field investigations

The area for the investigations was too large to analyse each channel in the same way within the time frame of the project. It was therefore decided to select three typical catchment areas for the dominant types of watersheds. This fact has to be considered when judging the results. Consequently, the investigated catchments are not the only ones that endanger the settlement area. The catchment areas chosen for the most detailed study were considered most dangerous. These are Bleiksá, Grjótá and Lambeyrará, but that does not rule out the potential danger from other catchments although it is expected to be less.

Figure 5.1 Channels and available loose material



The main parameters of the dominant processes along the channel are very important when estimating the potential hazard on the accumulation cone. The most important parameters are:

- The average size of boulders
- The general composition of the regolith
- The geometric characteristics of the channel including the inclination in flow-direction

Table 5.1 Measurements of cross sections and other important parameters of the channel characteristics of Bleiksá, Grjótá and Lambeyrará. The locations of the cross sections are in the geomorphology map in the envelope.

Channel	Sea-level [m]	Base-width [m]	Height [m]	Side slope inclination		Channel inclination		Average grain size estimation [m]
				left [°]	right [°]	upwards [°]	downwards [°]	
Bleiksá-contrib.	260	0.8	0.4	38	38	32	25	0
Bleiksá-cone	20	5	0.7	90	90	5	5	0
Lambe.-brigde main road	5	2	1	80	80	5	2	0
Lambe.-brigde upper road	10	1.7	1.2	40	40	10	5	0.3
Lambe.- upper cone	20	4	1.5	41	40	15	10	0.3
Grjótá bridge main road	5	4.5	3	90	90	5	5	0
Grjótá bridge upper road	20	3	3	70	70	10	5	0
Grjótá upper cone	35	4	3.5	45	40	20	10	0.3

With these parameters (Table 5.1), it is possible to calculate the main process type in each part of the channel based on the approach of creek-bed instability from VanDine (1985). The calculation, which is done in a separate step, becomes the base input for evaluating the transport capacity in the mass balance model. This procedure is most important in catchments where the possibility of debris flow reaching the endangered (settlement) area is high.

Erosion area, origin of the landslides

The catchments are characterised by steep edges that are starting zones of rockfall with the talus areas below. Large bowls carved by local glaciers (cirques) are below the steep walls. Then comes the inclined slope of the main valley, which is formed by the main valley glacier. Accumulation cones of different sizes reach the sea.

Evidence of many types of mass movements and mass transport were found in the three investigated areas. These are rockfall, slides and mass creep, as well as debris flows and water floods. The most important ones are those that endanger the settlement areas. They are:

- Debris Flows
- Floods

The field investigations and the calculations of water runoff and estimate of sediment masses give an interesting overview of the situation in the area:

- Large catchment with high flood peaks. The channels are mostly eroded to bedrock. There is a possibility of small debris flows caused by slides from the lateral slopes falling into the channel that can easily be transported during large flood events.
- Medium catchments with high flood peaks. The lower part of the channels are eroded to bedrock. Where the bedrock is exposed, there is a possibility of small

debris flows caused by slides from the lateral slopes falling into the channel. This debris can easily be transported during large flood events. In the higher part of the catchments, the channel bed consists of local glacial deposits and from there it is possible to transport debris from the channel bed under extreme conditions.

Paths

There is some difference in the characteristics of the paths (see Geomorphology map, Map 4 in envelope). By mapping these characteristics, it is possible to draw conclusions about past channel-events. Which, in a further step allows, in combination with the geo- and hydro-inventory, to evaluate future events. The possible scenarios are valued by interpreting cross sections measured in different parts of the catchments. One of the main aims of a process-orientated work, when working with natural hazards is to assess the potential of the path and to derive ideas about the type of process that caused large events in the nearest past.

Depositional area

The difference in the inventories of the chosen catchments and therefore in the possible channel events can be seen in how differently the accumulation cones have developed. The size of the Bleiksá watershed (4.3 km²) may be compared with the Grjótá (2.3 km²) and Lambeyrará watersheds (1.8 km²). The Grjótá cone is almost double the size of the other cones, even though it does not have the largest watershed.

5.1 Selected sites

Bleiksá

The size of the watershed is about 4.3 km².

Erosion areas

Bleiksá has the largest catchment area of the five rivers, starting at almost 1000 m a.s.l. in the north. The main part of the upper catchment area is a wide cirque with characteristic deposits of a local glacier in its lower part. The uppermost part consists of peaks with bedrock wall faces that are starting zones for rockfall with talus areas below. Below the cirque, the catchment slopes into the main valley over a protruding band of rock. Large talus areas have accumulated on top of the deposits of the local glacier, which still cover the bedrock on the lower areas.

Paths

The lower part of the watershed is characterised by deposits from the local glacier. The creek is eroded into till, and the channel is wide and is eroded down to bedrock. There are many indications of small slides that have started in the assumed 20 m thick glacial deposits.

Depositional areas

The accumulation cone is the depositional area of the watershed, and can be seen on the map (see Geomorphology map, Map 4 in envelope). Terraces of fluvial sediments from the river of the main valley characterise the change of the slope to the main valley bottom. There is a recently constructed church situated in the middle of the debris cone.

Grjótá
The size of the watershed is about 2.3 km².

Erosion areas
Grjótá has a smaller watershed than Bleiksá. It runs through the western part of the wide cirque of Lambeyrardalur, starting at almost 1000 m a.s.l. in the north. The lower part of the upper catchment area is covered with thick glacial deposits. The uppermost part consists of bedrock wall faces, which are starting zones for rockfall. Large talus areas have formed below the cliffs.

Paths
The lower part of the watershed is characterised by glacial deposits. Compared to the Bleiksá channel, the creek is not yet eroded through the till and therefore the bedrock is only exposed in the lower part of the catchment. The channel is wide in this part of the catchment. There are many indications of small slides that have started in the assumed 30 m thick glacial deposits.

Depositional areas
The main settlement of Eskifjörður is located on the Grjótá accumulation cone. The area of the cone, above sea level is much larger than the area of the Bleiksá cone, as can be seen on the map (see Geomorphology map, Map 4 in envelope).

Lambeyrará
The size of the watershed is about 1.8 km².

Erosion areas
Lambeyrará has the smallest catchment area of the investigated watersheds, starting in the middle of the wide cirque of Lambeyrardalur at almost 1000 m a.s.l. in the north. The characteristics are similar to Grjótá.

Paths
The lower part of the watershed is characterised by glacial deposits and is similar to the lower part of the Grjótá watershed.

Depositional areas
A part of the main settlement of Eskifjörður is also located on the Lambeyrará accumulation cone, which is larger than the Bleiksá cone but smaller than the Grjótá cone.

6 Hazard
Debris flows and flood processes are the focus of this investigation. Rockfall, slides and creeps were also investigated, but not in the same detail.

The fundamental question is how to delineate hazard zones, i.e. which criteria should be set. During the fieldwork an estimation of zones was done, as they would be delineated using the criteria of the Austrian regulations (Sauermoser, 1997). This is a subjective method based on the knowledge of field investigation including the results of an empirical mass balance model of different relevant events and the experiences of process documentation. Therefore, it is estimated, how the relevant events could behave when reaching the settlement area, how much water and debris will be accumulated or transported further on.

In Austria, hazard zones are delineated without actual risk assessment. A red zone is for example, an area where a damaging debris flow event has an occurrence probability of 1-10 years, debris flow deposits thicker than 70 cm have been observed or flood waters higher than 150 cm have occurred. All other areas, which are affected by that critical events, are in a yellow zone. Within the red and yellow zones, constructions are restricted, and have to fulfil special construction requirements.

In the present study, runout-zones were delineated based on designed events within selected areas. Design events were calculated for Bleiksá, Grjótá and Lambeyrará based on an event with a return period of 100 years. Calculations were made for intense short-term precipitation events with duration approximately 10-20 minutes and for longer events with duration of a 1 day, 2 days and 5 days. Based on measurements a single day event with a return period of 1 year was also calculated as well as an event of 100 mm in 5 hours. The next step should be a verification and discussion of the zones in the field based on the assessed data and the results of the calculations, but the timeframe of the project did not make that possible.

The duration of the relevant damaging events is selected related to the duration of the precipitation event and the runoff coefficient. Long precipitation and snowmelt events are able to fill the pores in the sediments. In combination with high pore-pressures, surface runoff caused by long lasting rainfall, can be enough to start small slides from the lateral slopes.

Formal hazard zoning for Eskifjörður according to Icelandic hazard zoning regulations (The Ministry of the Environment 2000, Jóhannesson and Ágústsson, 2002) is described by Arnalds *et al.*(2002). The landslide hazard zones described there are partly based on the geological investigations and hazard assessment described here.

6.1 Hazard assessment

The basic input data for calculating mass balances for debris flows/floods come from the map of geo- and hydro- inventory. This part can be called basic disposition. The varying disposition is shown in system conditions and the different specified precipitation events for this area.

Site 1 Bleiksá

The characteristics of the catchment of Bleiksá indicated possible hazards. The calculated mass balances supported these indications. The catchment area is large and there is sediment in the lateral slopes of the channel. In the steep slope of the main valley the channel is eroded to bedrock. The main part of the channel is wide. There is possibility for lateral erosion of glacial deposits in the middle part of the channel.

Long and intensive rainstorms can cause over-saturated conditions and thus mass movement processes from the lateral slopes. This debris can be transported instantly down the channel and, depending on the volume, accumulate mainly in 2 ways:

- Deposition of small debris flows and parts of the bedload immediately at the neck of the cone.
- Large debris flows that reach further out because of higher velocity and more persistent flow direction.

Most of the time there is more or less only water runoff with bedload transport in Bleiksá. However, the flow in the channel can reactivate the accumulated debris and transport it as bedload to the fjord level.

The following table (Table 6.1) summarises the results of the calculations based on the process orientated field investigation for Bleiksá; details are listed in the table in Appendix B.

Table 6.1 Design events of Bleiksá

Rainfall periods	**Rain [mm]**	**HQ (m^3/s)**	**Waterload (m^3)**	**Debris volume [m^3]**	**Debris volume [m^3] with slides**
23 min* u.sat	30	40	109,000	Debris flow 4,600	low chance
5 hours***	100	15.0	292,000	Debris flow 5,100	5,600
1 day**	72	2.5	220,000	Suspension	2,300
1 day*	172	6.0	528,000	Bed load 4,600	4,200
2 days*	230	4.5	785,000	Suspension	3,400
5 days*	360	2.5	1,090,000	Suspension	2,300

*A 100 years return period **A 1 year return period *** selected event from IMO database
u.sat. = unsaturated conditions

It is expected that most of the debris will stop before it reaches critical sites (the church, roads) since they are situated on the lower part of the cone. There is also a camping place located on the outermost part of the accumulation cone. The chance for a debris flow to reach the campground is extremely slim because of the volume of possible debris flows and the location below old river terraces of the main valley. There is a chance that debris flows can hit the church and the same can be said for the road. Unless a large amount of debris is catastrophically released from the sideslopes, the water runoff in the channel is expected to be high enough to constantly transport the debris as bedload or hyperconcentrated flow. Therefore, debris flows are mainly expected under “unusual” conditions. A flooding problem arises more frequently.

The maximum runoff peak of the short time events is high, due to high precipitation intensity. Therefore, the short term precipitation events result in the highest possibility of flooding in the settlement areas. If the same source of debris is available in the channel bed in both cases, the 5 hours short term event results in the largest debris flow events. The danger of such a large debris flow event would be much higher if the 100 year high precipitation intensity event occurred as a part of a prolonged precipitation period, for example, 2 days into the 5 days event in table 6.1. Such an event may, however be expected to have a substantially longer return period than 100 years.

Site 2 Grjótá

The main erosion area in Grjótá is the steep slope of the main valley. The fact that the catchment area is relatively large and the sediment in the direct slopes to the channel is not completely eroded leads to a slightly different results than for Bleiksá but still shows a high flood discharge. The main part of the channel is narrow and the bedrock is only exposed in the lower part. There is a possibility for deep erosion in the higher parts of the steep slope of the main valley and lateral erosion in the middle part. These are the areas where the deposits of the local glacier are still available.

The conditions of transport and accumulation of debris are similar as described above for Bleiksá. Most of the time there is more or less only water runoff with bedload transport in Grjótá. However, the flow in the channel can start deep erosion processes in the upper part of the steep slope within the glacial deposits. It can reactivate the accumulated debris in the lower part of the steep slope and transport the debris as bedload to the fjord level.

The following table (Table 6.2) summarises the results of the calculations based on the process orientated field investigation for Grjótá; details are listed in the table in Appendix B.

Table 6.2 Design events of Grjótá

Rainfall periods	Rain [mm]	HQ (m^3/s)	Waterload (m^3)	Debris volume [m^3]	Debris volume [m^3] with slides
18 min* u.sat	27	24	52,000	Debris flow 2,600	low chance
5 hours***	100	8.4	160,000	Debris flow 4,400	1,900
1 day**	72	1.4	123,000	Suspension	1,000
1 day*	172	3.4	294,000	Suspension	1,700
2 days*	230	2.5	438,000	Suspension	1,600
5 days*	360	1.4	606,000	Suspension	1,000

*A 100 years return period **A 1 year return period *** selected event from IMO database
u.sat. = unsaturated conditions

Since there are many houses located on the cone there is a high probability of damage if debris flows and floods reach this area. Unless a large amount of debris is catastrophically released from the sideslopes, water runoff in the channel may be expected to be sufficiently high to constantly transport the debris as bedload or hyperconcentrated flows. Therefore, debris flows are mainly expected under conditions, when the flood peak is high enough to start deep erosion in the glacial deposits. A flooding problem arises more frequently.

As for Bleiksá the maximum runoff peak of the short time events is high, due to high precipitation intensity. Therefore, the short-term precipitation events result in the highest possibility of flooding in the settlement. There is a chance to start larger debris flows for the 5 hours and the 18 minutes events. Then glacial sediment from the riverbed is activated. If the same source of debris is available in the channel bed in both cases, the 5 hours short term event can result in the largest debris flow events. On the neck of the accumulation cone the greatest chance for a debris flow to overflow the channel is to the right side, since there is a deflection dam on the left side. However, on the right side, there is a small deflection dam closing an old channel. It is possible that the debris overflows the channel just above that small dam. The next critical place is the first bridge (cross section 4, see Map 4 in envelope) in case the debris flow has enough fine particles to transport large blocks. Hyperconcentrated flows resulting from slides falling into the channel can block the channel at the next bridge (cross section 3). Due to a decreasing energy of the flowing mass, because of lower inclination and increasing width of the channel, the debris can overflow the channel above the main road. The danger of such a large debris flow event would be much higher if the 100 year high precipitation intensity event occurred as a part of a prolonged precipitation period.

Site 3 Lambeyrará

The watershed of Lambeyrará is comparable to Grjótá and the hazard situation is almost the same. The main erosion may be expected in the steep slope of the main valley.

The conditions of transport and accumulation of debris are similar as described above for Bleiksá.

The following table (Table 6.3) summarises the results of the calculations based on the process orientated field investigation for Lambeyrará; details are listed in the table in Appendix B.

Table 6.3 Design events of Lambeyrará

Rainfall periods	Rain [mm]	HQ (m^3/s)	Waterload (m^3)	Debris volume [m^3]	Debris volume [m^3] with slides
18 min* u.sat	27	17.5	14,000	Debris flow 2,900	low chance
5 hours***	100	5.9	55,000	Debris flow 4,200	1,800
1 day**	72	1.0	43,000	Suspension	700
1 day*	172	2.4	103,00	Suspension	1,200
2 days*	230	1.8	154,000	Suspension	800
5 days*	360	1.0	214,000	Suspension	700

*A 100 years return period **A 1 year return period *** selected event from IMO database
u.sat. = unsaturated conditions

Since there are many houses located on the cone there is a high probability of damage if debris flows and floods reach this area. As for Grjótá, debris flows are mainly expected under conditions, when the flood peak is high enough to start deep erosion in the part of the channel, where the bed is in the glacial deposits. A flooding problem arises more frequently.

On the neck of the accumulation cone the greatest chance is that the river overflows the channel to the left side. The right bank is higher and deflects the river. On the right side is the road to Neskaupstaður just beside the riverbed. Houses are also on the right side below the road and the channel is reinforced (lined) with a stone wall. A few small bridges cross the channel on the cone and increase the possibility of a blocked channel. The bridges are much smaller than those crossing Grjótá are and therefore the chance is higher that the channel could be blocked during a debris flow event.

Similar to Grjótá the next critical place is the first bridge (cross section 7), *i.e.* if the debris flow has enough fine particles, and is therefore able to transport large blocks. Hyperconcentrated flows resulting from slides falling into the channel can also block the next bridge (cross section 6). This could result in the debris overflowing the channel above the main road, because of less energy of the flow mass, due to lower inclination and a widening channel. The danger of such a large debris flow event would be much higher if the 100 year high precipitation intensity event occurred as a part of a prolonged precipitation period.

6.2 Discussion & Recommendation

The best way to assess natural hazard is to investigate the natural environment as it is today. An important fact is that using this kind of mapping procedure makes it possible to improve the database by considering changes and developments in the catchment areas. Evidences of former events give important information about the capacity of the catchment and can be used to set up different scenarios for the present and the future.

Table 6.4 Overview of main results

Process		**Bleiksá**	**Grjótá**	**Lambeyrará**
Debris flows/floods	Short intensive rain	High possibility of floods and large debris flows	High possibility of floods and large debris flows	High possibility of floods and large debris flows
	Long term rain (1–5 days)	Danger of small floods with large debris flows	Danger of small floods with small debris flows	Danger of small floods with small debris flows

Protecting measures for debris flows either aim at decreasing the energy of the flow mass and encourage it to deposit or to maintain the energy, and deflect the flow-mass away from settlement.

The following measures are suggested in the three study areas:

- A debris retaining basin in the uppermost part of the debris cone
- Improvements on the hydraulic characteristics of the channels

7 Summary

In this case study, different precipitation-events during different system conditions were calculated. The first approach was a rainfall with a return period of one hundred years (data from IMO, Jóhannesson 2000). Then short time rainfalls with higher intensity based on information in the IMO database. An empirical formula was used to calculate the peak flow for extremely short and intensive storms. All inputs come from field investigations and obtaining the results is an easy-to-follow procedure. The main input is the precipitation, geo-, hydro- and bio inventory and interpreted runoff coefficients, identified processes (that influence the channel process) and finally an assessment of transport capacities of the channel itself. Another important issue is the evolution (stage/phase) of the catchment. After obtaining information about possible triggering factors, hazards can be assessed. All three areas are dominated by flood problems, and a probability of debris flows up to almost 6.000 m^3 exists. The main problems are the floods and debris flows. Parts of the infrastructure, especially the small bridges, increase the danger of a blocked channel even during small events.

Investigations of geo-, hydro- and bio inventory in the present study, simplifies the design of mitigation structures since all the basic information on processes and their characteristics are already collected. This is one of the main positive by-products of the chosen methodology.

8 References

Angerer H. 1998. Geology – *The foundation of debris-flow area mapping*. – Presentation in Taiwan, unpublished.

Arnalds Ó. and Grétarsson, E. 2001. *Soil Map of Iceland.* Agricultural Research Institute, unpublished map.

Arnalds, Ó. *et al*., 2000 http://www.rala.is/desert.

Arnalds, Ó. *et al*., 2001. *Soil Erosion in Iceland*. Soil Conservation Service, Agricultural Research Institute, Iceland.

Arnalds, Þ., Sauermoser, S., Jóhannesson, T. and Jensen, E.H. 2002. *Hazard zoning for Eskifjörður*. Rep. 02015 (ÚR11), Icelandic Meteorological Office.

Ágústsdóttir, K., 2001. *Byggingarár húsa á Eskifirði*. [e. Construction year of houses in Eskifjörður]. Náttúrustofa Austurlands.

Ágústsdóttir, K., 2002. *Ofanflóðaannáll Eskifjarðar*. [e. Snow- and Landslide chronicle of Eskifjörður]. Rep. 02012. VÍ-ÚR08, Veðurstofa Íslands.

Bergthaler, J. 1991. *Anwendungsbereiche von Hochwasserformeln. Wildbach- und Lawinenverbau*, Heft 116, Jg. 55, 47–73.

Bergþórsson, P., 1968. Veðrið, 13, 2, 52-58. IMO.

Bergþórsson, P., 1977. Veðrið, 20, 2, 43-51. IMO.

Bunza, G. 1982. *Systematik und Analyse alpiner Massenbewegungen*. [In:] BUNZA G., KARL J., MANGELSDORF J. & SIMMERSBACH P.: Geologisch - morphologische Grundlagen der Wildbachkunde. - *Schriftenreihe d.Bayer. Landesamt f. Wasserwirtschaft*, Heft 17, S.1–84, München.

Egilsson, J.G., 1990. *Snjóflóð á Eskifirði. Skriðuannáll.* [e. Snow avalanches in Eskifjörður. Landslide chronology]. Veðurstofa Íslands, snjóflóðavarnir.

Einarsson, M. 1984. *Climate of Iceland.* [in] Van Loon, H. : Climates of the Oceans. *World Survey of Climatology*, vol. 15, 637–697. Elsevier Science Publishers, The Netherlands.

Einarsson, Þ. 1968. *Saga bergs og lands.* Mál og menning, Reykjavík. – also available in an english version.

Glade et al 2002. *Recommendations for landslide hazard assessment for Bolungarvík and Vesturbyggð, NW-Iceland.* Icelandic Meteorological Office, in prep.

Guðmundsson, Á. 1992. *Jarðgangnagerð til samgöngubóta á Austfjörðum*. OS-92006/VOD-01 Orkustofnun, Vatnsorkudeild fyrir Vegagerð ríkisins.

Gylfadóttir, Þ. 2000. *Ísland í tölum*. Hagstofa Íslands, Steindórsprent-Gutenberg ehf.

Hjartarson, Á. 2000. *Neskaupstaður, skriðu- og snjóflóðaset við Kvíabólslæk.* OS-2000/007 Orkustofnun, rannsóknasvið fyrir Veðurstofu Íslands.

Hübl, H. 1995 *Muren: Prozesse und Ablagerungsformen*. Bedeutung für die Gefahrenzonenplanung. - unveröff. Diss. 211 S., BoKu Wien.

Hönnun hf, Verkfræðistofa Sigurðar Thoroddsen, Hönnun og ráðgjöf verkfræðistofa, 1999. *Álver í Reyðarfirði: Mat á umhverfisáhrifum 480.000 t álvers: frummatsskýrsla.* Reykjavík STAR.

ÍST. 1990. Grundun, ÍST 15:1990, Foundation Engineering. Staðlaráð Íslands, Iðntæknistofnun Íslands.

Jensen, E.H. and Sönser, T., 2002. *Process orinentation landslide hazard assessment for the south side of Seyðisfjörður.* Rep. 02003, VÍ-ÚR02, Icelandic Meteorological Office.

Jóhannesson, T. 2000. *Return period of cumulative 1, 2, 3 and 5 day precipitation for several weather stations in Iceland.* Icelandic Meteorological Office, TóJ-2000/03.

Jóhannesson, T, Lied, T. K. , Margreth, S. and Sandersen, F. 1996. *An overview of the need for avalanche protection measures in Iceland.* Icelandic Meteorological Office, rep.VÍ-R96003-ÚR02.

Jóhannesson, T. and Ágústsson, K., 2001. *Hættumat vegna aurskriðna, grjóthruns, krapaflóða og aurblandaðra vatns- og krapaflóða í bröttum farvegur.* Memo, ÚR-TóJ/Kri-2001-09, Veðurstofa Íslands.

Jónsson, Ó., 1957. *Skriðuföll og snjóflóð.* Bókaútgáfan Norðri, Akureyri.

Jónsson, Ó., Sigvaldason, J., Pétursson, H.G. and Rist, S., 1992. *Skriðuföll og snjóflóð.* I-III. Bókaútgáfan Skjaldborg hf., Reykjavík.

Kirkby, M. J. and Statham, I. 1975. *Surface stone movement and scree formation. Journal of Geology*, 83: 349–362.

The Ministry of the Environment, 2000. *Reglugerð nr. 505/2000 um hættumat vegna ofanflóða, flokkun og nýtingu hættusvæða og gerð bráðabirgðahættumats.* [Regulation on hazard zoning for avalanches, debris flows and rockfall, the usage of hazard zones, and the making of preliminary hazard zoning]. July 2000.

Mölk, M. 1998. *Naturraumerfassung und Prozeßanalyse - Teil II.* – [in:] Erdwissenschaftliche Aspekte des Umweltschutzes, *Geographische Informationssysteme als neues Werkzeug zur Problemlösung von Umweltfragen*, Tagungsband S.169–174, Österr. Forschungs- u. Prüfzentrum Arsenal, Wien.

Mölk, M., Stepanek, L., Ploner, A. and Sönser, Th. 2000. *Process-Oriented basic Data Assessment and Mass Balance as a Reproducible Approach to design Torrential Mitigation Measures.* – Proceedings to International Workshop after Debris flow events 1999, Merida, Venezuela.

Pétursson, H.G and Jónsdóttir H.E. 2000. *Skriðuannáll 1995-1999.* Icelandic Institute of Natural History, NÍ-00019.

Pétursson, H. and Sæmundsson, Þ. 2000. *The connection between rapid mass-movement and extreme precipitation, examples from Eastern Iceland.* Editors Russel, A.J. and Marren, P.M.. Modern Processes and Past Environments. Keele University, Dep. Geogr. Occasional Papers Series No. 21.

Ploner, A. and Sönser, Th. 1997. *Dynamische Gefahrenzonenplanung - ein Teil des Naturgefahrenmanagements, dargestellt an Beispielen.* - Symp. Risikobewertung und Naturraumprävention von Wildbächen und Lawineneinzugsgebieten, Kurzfassung zum Vortrag, Tagungsband S.48, Wien.

Ploner, A. and Sönser, Th. 1998. *Prozeßbezogene Erfassung der Geschiebefrachten und Maßnahmenkonzept. – „Prozessorientierte digitale Bearbeitung von Wildbacheinzugsgebieten - Teil III.* [in:] Erdwissenschaftliche Aspekte des Umweltschutzes - *Geographische Informationssysteme als neues Werkzeug zur Problemlösung von Umweltfragen* - Tagungsband S.175–178, Österr. Forschungs- u. Prüfzentrum Arsenal, Wien.

Ploner, A. and Sönser, Th. 1999a. *Natural Hazard Zoning as an important basement of the evaluation of forest protection functions in Austria*. –Proceedings „Risques naturels en montagne" S. 431–436, CEMAGREF, Grenoble.

Ploner, A. and Sönser, Th. 1999b. *Prozessorientierte Massenbilanzen „Griesbach, Gde. Mieders im Stubaital (Tirol, Österreich)" als Basis für ein Schutzprojekt.* – Publikationen Tagung „Erosionsmanagement", Trient.

Ploner, A. and Sönser, Th. 2000. *Naturraumanalyse – neue Strategien für Fliessgewässer*, Beratende Ingenieure, *Zeitschrift des internationalen Consultings*, Springer-VDI-Verlag, Berlin.

Sauermoser, S. 1997. *Elaboration of hazard zone maps in Austria.* Foresttechnical Service in Torrent and Avalanche Control, Innsbruck, Austria.

Selby, M.J. 1993. *Hillslope Materials and Processes, 2nd ed.* Oxford University Press, Oxford.

Sigurgeirsson, M. 2000a. *Gjóskulög á Austfjörðum, samantekt.* Greinargerð 00/04 fyrir Veðurstofu Íslands.

Sigurgeirsson, M. 2000b. *Aldursgreining skriðusets á Eskifirði og Norðfirði með hjálp gjóskulaga.* Greinargerð 00/05 fyrir Veðurstofu Íslands.

Strachan, *et al.* 1998. *Soils of the Gunnarsholt experimental plantation*. *Búvísindi ICE*. AGR. SCI. 12, 1998: 27–38.

Sæmundsson, Þ. and Pétursson, H.G. 1999. *Mat á aurskriðu- og grjóthrunshættu við Seyðisfjarðarkaupstað.* Icelandic Meteorological Office, VÍ-G99003-ÚR02.

Sönser, T. and Wanker, W. 1998. *Integration von Daten des Geoinventars für die räumliche und zeitliche Modellierung bei Wildbachprozessen. – „Prozessorientierte digitale Bearbeitung von Wildbacheinzugsgebieten - Teil I.* – [in:] Erdwissenschaftliche Aspekte des Umweltschutzes - *Geographische Informationssysteme als neues Werkzeug zur Problemlösung von Umweltfragen* - Tagungsband S.163–168, Österr. Forschungs- u. Prüfzentrum Arsenal, Wien.

VanDine, D. F. 1985. *Debris flows and torrents in the Southern Canadian Cordillera. Canadian Geotechnical Journal*, Vol. 22, pp 44–68.

VST and ÁGVST. 1998. *Snjóflóðavarnir í Neskaupstað. Jarðtækni- og jarðfræðiathugun*.

Walker, G.P.I, 1959. *Geology of the Reyðarfjörður area, Eastern Iceland*. Q.J Geol. Soc. London,114:367-393.

Walker, G.P.I, 1963. *The Breiðdalur central volcanoe, eastern Iceland.* Q.J Geol. Soc. London, 119:29-63.

Wanker, W. 2001. *Standardisierte Erfassung und Bearbeitung ausgewählter georelevanter Basisdaten – vom methodischen Ansatz zur interdisziplinären Realität. – Mitt. Für Ingenieurgeologie und Geomechanik*, Bd. 3, Wiener Gespräche Wissenschaft – Wirtschaft, S. 15–30, Wien.

9 Appendices

A Landslide chronicle

B Mass Balance Calculations

C Maps

Appendix A. Landslide chronicles for Eskifjörður.

No	Date	Path name	Description
8502	early 19th century	Between Bleiksá and Grjótá	A water mill a little to the west of Grjótá was destroyed by a torrent shortly after 1805.
8503	21.11.1849	Grjótá	The river Grjótá was blocked at about 100 m a.s.l. A slush flow was released and hit the domestic house Klofi. It killed three persons. The slush stopped at about 25 m a.s.l.
8504	23.2.1904	Lambeyrará	A slush flow hit the domestic house Lambeyri which was the residence of the sheriff Túlinius. It destroyed food and hay. The deposit stopped at about 10 m a.s.l.
8505	1904-1906	West of Bleiksá	A torrent in a brook by the farm Eskifjörður to the west of the current village.
8506	24.6.1906	Hólmaströnd	Large debris flow from Hólmatindur.
8507	1909	Hólmaströnd	A debris flow hit a field at Borgir and caused some damage. No one was living at Borgir at the time.
8509	16.3.1919	Between Bleiksá and Grjótá	A slush flow demolished a barn, fish drying rack and a cow shed in Framkaupstaður. These were the property of the tradesman Friðgeir Hallgrímsson. Two cows, a calf and two sheep were killed but one cow was rescued. The slush flow caused considerable other damages. The houses that were destroyed were located about where Strandgata 33 is presently.
8510	16.3.1919	East of Hlíðarendaá	A slush flow hit a domestic house owned by the tradesman Vilhelm Jensen. It caused considerable damage. The house that the slush flow hit is probably Hlíðarendavegur 1b or possibly Strandgata 92.
8511	16.3.1919	East of Hlíðarendaá	A slush flow caused severe damage at Svínaskálastekkur.
8512	Summer 1930	Grjótá	A torrent in Grjótá damaged fish drying racks and perhaps some fish in Útkaupstaður.
8513	16.9.1935	East of Hlíðarendaá	Debris flows caused severe damage at Svínaskáli.
8514	16.9.1935	Grjótá	A torrent came from Grjótá. The river was diverted back to the river course and little damage was caused.
8515	16.9.1935	East of	Debris flows caused severe damage. A 40–60 m wide debris flow in the easternmost part of

		Hlíðarendaá	the settlement in the vicinity of Hlíðarendi destroyed two valuable fields. The fields are believed to have stood been where there now is Standgata 87A.
8516	1.9.1937	Hólmaströnd	Two debris flows in Hólmaströnd. The third and largest fell near the farm Borgir.
8517	29.6.1940	Many torrents above the settlement	Torrents flowed from all the streams above the settlement. Water filled the basement of Landsbanki. The bridge over Eskifjarðará was taken by a flood in Eskifjarðará and damage was caused to the dam for the Ljósá power station. The torrent caused damage to fields (including Bleiksártún and Lambeyrartún) and some vegetable gardens. Some fish drying racks were damaged. Extensive damage was caused to streets and other infrastructure. Some domestic houses were damaged. The maximum depth of the torrents was about 2 m.
8518	1941	Dalur	
8519	1942	Dalur	Two British soldiers were killed in Háamelur between Stekklækur and Innrilækur in the valley west of Eskifjörður. It is assumed that they were caught by a debris flow.
8520	6/7.8.1946	Many torrents above the settlement, Grjótá	A machine workshop was damage by flooding in Grjótá. The carpenters workshop of Guðni Jónsson at Strandgata 77 was also flooded. Damage was caused to the house as well as to tools and products in the house. Potato and tree plots were covered with mud and rocks. The rivers causing most trouble were Grjótá, Lambeyrará and Ljósá. About sixty people that were living closest to Grjótá fled from their homes.
8521	15.6.1950	Hólmaströnd	Debris flows from Hólmatindur. Both from the north and south sides.
8522	19.8.1950	Grjótá	Many rivers were flooded. People living closest to Grjótá fled from their homes but only one house was flooded. Some damage was caused to roads in the western part of the settlement.
8523	20.9.1953	Hólmaströnd	Debris flow from Hólmatindur.
8524	25/26.9.1959	Bleiksá	Flashflood from the Bleiksá creek damaged the bridge.
8525	12.5.1963	Hólmaströnd	Debris flow fell on the road near Eskifjörður.
8526	27/28.10.1972	Ljósá	Debris flows are recorded in several rivers. A recently built road above the inner part of the settlement was torn apart in several places. Sewers were blocked and as a consequence roads were flooded. A debris flow hit an old warehouse and caused some damage. A lot of mud accumulated at the carpentry shop at Strandgata 77. The torrents also swept the earth away from a recently built house in Bleiksárhlíð.
8527	24/25.8.1974	Hólmaströnd	Debris flows from Hólmatindur.
8528	25.9.1981	Lambeyrará	A debris flow fell in Lambeyrará. It started at about 400 m a.s.l. and blocked the river at about 75 m a.s.l. Considerable damage was caused to gardens and houses. Water and mud

			flooded the basement of Lambeyrarbraut 12 and the basement of the elementary school was flooded by water. The total volume of the deposit in the settlement was estimated at 700–1200 m^3.
8529	apr.88	Bleiksá	Slush flood near the farm Eskifjörður. No damage.
8530	8.8.1988	East of Hlíðarendaá	A debris flow started in a newly built road up to Oddsskarð. It ran about 100 m down the slope and stopped 200–300 m above the houses in Svínaskálahlíð. Mud and water flowed into the house at Hlíðarendavegur 4b.
8531	18.10.1996	Between Bleiksá and Grjótá	A small debris flow fell to the west of Grjótá and stopped several hundreds of meters above the settlement.
8532	7.1.1998	Between Lambeyrará and Ljósá	A debris flow fell between Lambeyrará and Ljósá above the road up to Oddsskarð.
8533	14.4.1999	Harðskafi	A dry slab avalanche fell in Harðskafi.
8535	17.4.1999	Harðskafi	A dry slab avalanche in Harðskafi.
8536	17.4.1999	Harðskafi	A dry slab avalanche in Harðskafi.
8537	17.4.1999	Harðskafi	A dry slab avalanche in Harðskafi.
8538	17.9.1999	Hólmaströnd	Many debris flows hit the road below Hólmaháls in Eskifjörður. The road was torn apart in several places. The width of the largest debris flow was a bit less than half a kilometer.
8534	20-21.8.2001	Hólmaströnd	Debris flows hit the road below Hólmaháls in Eskifjörður.
8568	2-3.2.2002	Harðskafi	A snow avalanche in Harðskafi
8578	13.2.2002	Oddskarð	A snow avalanche started by a man on a snow mobile