VEÐURSTOFA ÍSLANDS

Report
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Process Orientated Landslide Hazard Assessment for the South Side of Seyðisfjörður

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Abstract

Hillslope processes causing landslides, including floods and rockfall, on the south part of the village Seyðisfjörður were mapped during a field trip in June 2000. Several places where chosen to represent the different types of active geomorphological processes on the hillside. In the Þófi area both active debris flows originating from the uppermost part of the mountain and creep in the lower part can be observed. Búðará has mainly water flooding problems due to the size of the watershed and in the Botnabrún area problems with rockfall processes occur. A few cross sections were made in the torrent paths to interpret events that happened in the past. Active processes were mapped and in combination with the results, design debris torrents were established for different system conditions by calculating the mass balances for the respective watersheds. A rockfall simulation was made using three representative cross-sections for the Botnabrún area to estimate rockfall danger in the settlement. Runout zones were delineated and by including the calculation from mass balances, the hazard was estimated.

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 dangerous villages to be a local contact 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.

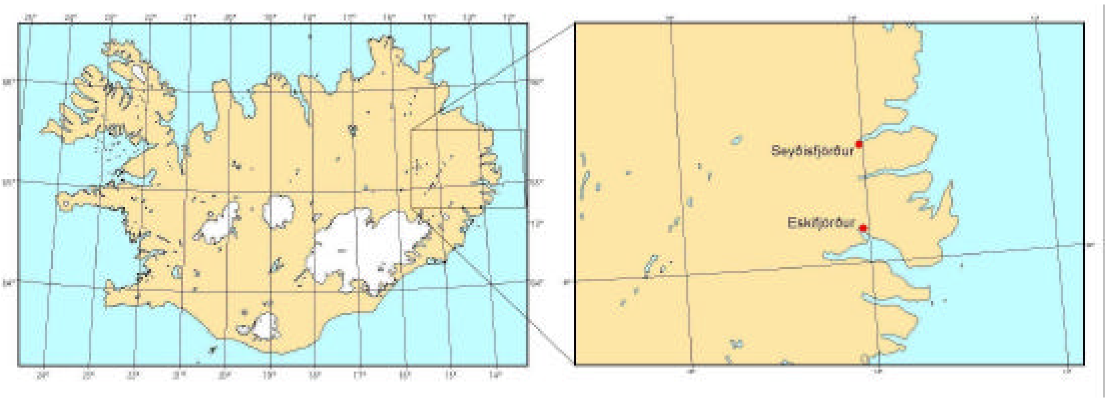
A historical chronicle of landslide events in Iceland was first made by the pioneer Ólafur Jónsson in 1957. This review was based on magazines, newspapers, old annals *etc*. and was updated in 1992 (Jónsson *et al.* 1992) Often only the largest events were recorded or those that caused some damage. This 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.

Landslide hazard assessment has not been developed specifically for Icelandic conditions before, and landslide hazard zones have not been defined before. This study uses a process orientated Austrian method for assessing the hazard in the south part of the village Seyðisfjörður, in eastern Iceland.

2 General Settings

Iceland is situated in the middle of the Atlantic Ocean on the latitude 63° to 66° N and longitude 13°to 24° W. 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 2119 m.

Figure 2.1 Location of the study area



2.1 Topographic characteristics and land use

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

The village Seyðisfjörður is located in the bottom of the fjord Seyðisfjörður. The direction of the fjord is mainly ENE–WSW but the innermost part has a NNE–SSW direction. The mountains Strandartindur, Miðtindur (the middle peak) and Innri-Strandartindur (the inner Strandartindur) are on the southeast coast and the mountain Bjólfur is located on the northwest Coast. The mountains are about 1000 m high (See Map 1, Location Map, Appendix C).

Figure 2.2 The names of the main landscape features at the slopes of Strandartindur

(photo Þ. Sæmundsson)

The hillside above the south part of the village is analysed in this report. The Bjólfur area is not a part of the study but a short description of the area follows together with other parts of the village for completeness.

Bjólfur
The Bjólfur mountain is located to the west of the town of Seyðisfjörður. A large east facing bowl shaped snow accumulation area is located above a shelf at 650m a.s.l. Several deep gullies are located in the lower part of the slope. The width of the area is about 1200m. Buildings are located close to the foot of the slope and the runout zone above the uppermost buildings is essentially non-existent. There are many residential and other buildings in the area.

Strandartindur
Strandartindur is located to the east of the town of Seyðisfjörður. It has a high west and north-westerly facing mountainside with many deep undulating gullies in the lower part. The mountainside of Strandartindur is steep and cut by gullies. The outermost area analysed in this report in the mountain Strandartindur is called Þófi. It is a shelf in the mountain at 70–80m a.s.l. The surface of Þófi is mostly covered with till. To the east of Þófi is the gully Imslandsgil and to the west is the gully Hæðarlækur. In the Þófi area there are five gullies, the two biggest ones are Þófalækur and Hæðarlækur. The width of the Strandartindur area is about 1300m. Buildings are located close to the foot of the slope and the run-out zone above the uppermost buildings is essentially non-existent. There are many industrial buildings in the area, but few residential buildings.

Botnar
The Botnar area lies to the south and east of the innermost part of the fjord. The hillside above the area faces west and has a complicated shape with large cirques in the upper part and deep gullies in the lower part. Below the cirques is a shelf in the mountain at 500–600 m a.s.l. called Efri-Botnar. Another shelf is at 100–130 m a.s.l. called Neðri-Botnar. It is about 400–500m wide. The river Búðará is situated in the middle of that shelf and to the south is the river Dagmálalækur. The width of the inhabited area is about 1300m. Buildings are located close to the foot of the slope and the run-out zone above the uppermost buildings is essentially non-existent. There are many residential and other buildings in the area.

2.2 Human settlement
The Seyðisfjörður area was fully settled by the year 1000. The first settlers where farmers living on 10–20 farms through the centuries until the 19th century when trading in Seyðisfjörður started. The trading increased slowly, but around 1870 a densely populated area had formed at the bottom of the fjord. These where the first years of the so called “herring years”. During the first herring years the population increased from 200 up to 1000 inhabitants. The densely populated area was split into four loosely defined villages, Fjarðaralda and Vestdalseyri on the north side of the river Seyðisfjarðará, and Búðareyri and Eyrar on the south side. The villages Vestdalseyri and Eyrar have now been deserted but the other two form the current town of Seyðisfjörður. Further information on human settlement and the age of houses in Seyðis-

fjörður is described in Guðmundsdóttir (1985) and age of houses concerning avalanches by Grímsdóttir (1997).

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 southeastwards 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 >10°C while the coldest month is warmer than –3°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

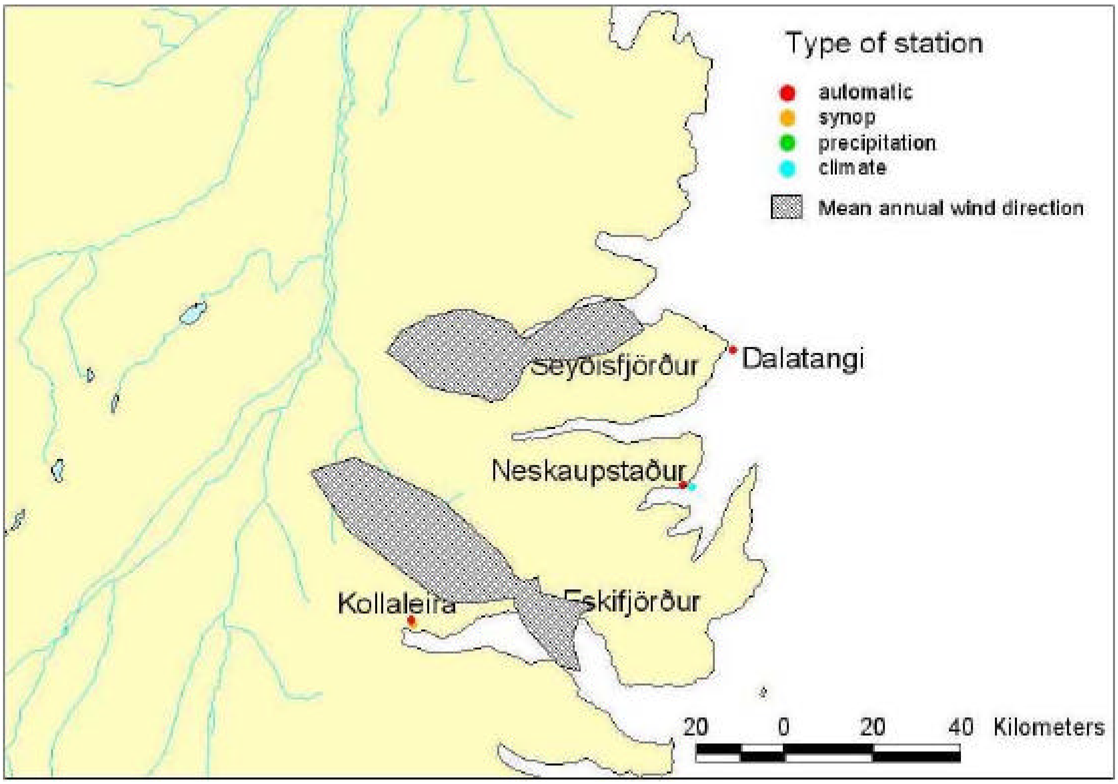
The 30-years (1961–1990) mean values of temperature and precipitation for the meteorological station Dalatangi, in eastern Iceland are given in Table 2.1. Stations at Seyðisfjörður, Neskaupstaður and Kollaleyra do not have continuous data for the same time period but mean values have been calculated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

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

	Dalatangi 1961–1990	Kollaleyra 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

The distribution of wind directions was calculated based on measurements from an automatic weather station in Seyðisfjörður operating since 1995. The most common wind directions are westerly winds and then easterly winds with a slightly higher wind speed. 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 Seyðisfjörður and Eskifjörður.

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



According to Sæmundsson and Pétursson (1999) rainstorms accompanied by north-easterly wind directions have caused most of the recorded landslide events in Seyðisfjörður.

2.3.2 Extreme Precipitation

The extreme cumulative 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 cumulative precipitation over 1, 2, 3, and 5 day periods.

Table 2.2 Cumulative precipitation of a 1 to 5 day rainfall event within a 1 to 50 year return period for the locations (a) Seyðisfjörður, (b) Kollaleyra, (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) Kollaleyra 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

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.

Extreme precipitation events with a shorter duration than one day are needed for the flood and debris flow calculations. These events are estimated based on the estimated extreme daily precipitation that is tabulated above. The maximum intensity for a shorter time 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, and for evenly distributed accumulated precipitation over 1, 2 and 5 days (block rain) with a 100 year return period. Distributing the accumulated precipitation evenly over such long time periods is clearly not realistic with regard to short term extreme water discharge from the watersheds, but 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 mass movements

Intensive rainfall and high discharge is a major cause of debris flows. Debris flows in Seyðisfjörður have mostly been recorded in connection with intensive rainstorms. Such an event was analysed by Pétursson and Sæmundsson (2000). From September, 8th until noon of September, 9th 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 and therefore shows well the intensity of the storm. The most intensive rain was in the evening of the 8th when 30 mm were recorded in one hour. Debris flows occurred the same evening just before midnight. In Seyðisfjörður a rainstorm of 100 mm in one day has a return period of about 5 years (Table 2–2a, Jóhannesson, 2000). This storm can be assumed to have somewhat longer return period since the 100 mm fell in only 16 hours. Smaller storms have triggered landslides in Seyðisfjörður but 10 min rainfall data is only available for two additional events and they have not been analysed further. These return periods seem, however, to be shorter than those of the debris flows in Seyðisfjörður. Lack of recorded debris flows events could be a possible explanation. Other explanations are that the recorded rainfall is not reflecting the situation on the hillside, snowmelt is affecting the system and/or antecedent rainfall.

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 there 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.

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 flake by frost weathering (Einarsson, 1968).

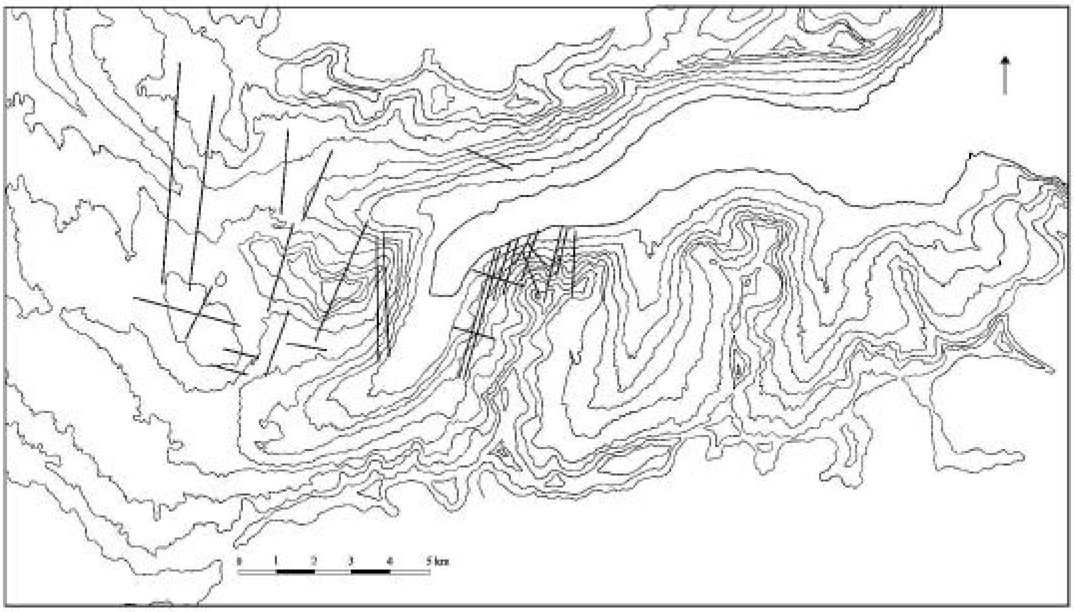
2.4.1 Bedrock of Seyðisfjörður

The bedrock in the Seyðisfjörður area is about 12 million years old. It is mostly basaltic lava layers, slightly metamorphosed, with sediment in-between. The area is on the outskirt of old central volcanoes and therefore the bedrock is less metamorphosed than in many other areas in the eastern fjords. The dip of the strata is SW or even W. It differs from 4–6° on the outside of the fjord to about 2–3°on the inside where the village is located. The description of the stratigraphy by Guðmundsson (1992) shows that the first 650 m of the exposed bedrock are mainly tholeiitic basalts. The next 70 metres are predominated by sediments and rhyolitic tuff. The uppermost part of the mountain is mostly olivine basalt layers. The sediments are less than 8% of the stratum.

2.4.2 Tectonics

Numerous faults, fissures and dikes break the bedrock near Seyðisfjörður. The main directions of the fracture system is N-S to NNE-SSW but there are also fractures with WNW-ESE to NNW-SSE directions (Guðmundsson, 1992). The shelves in the mountain Strandartindur have developed on intersections where fractures with WNW-ESE and NNE-SSW directions intersect (Sæmundsson and Pétursson, 1999). In the Neðri-Botnar area, in the gully of Búðará, the bedrock is metamorphosed probably as the result of heating around a fault. This material is highly weathered resulting in large quantities of loose material.

Figure 2.4 Fracture system in Seyðisfjörður (Sæmundsson and Pétursson, 1999)



2.5 Hydrology

The bedrock in the Eastfjords is mostly 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 produce geothermal water.

2.6 Geomorphological Processes

Glaciers have eroded the area. After the main glacier of the Ice Age left, 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 environments 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).

"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.*, 2000).

"Andosols in Iceland cover all together about 80.000 km^2 and therefore make up a substantial proportion of the Andosols in the world." (Arnalds, *et al.*, 2000)

The soils in the neighbourhood of Seyðisfjörður are mainly classified as Andosol and Leptosol (Arnalds and Grétarsson, 1998).

2.7.1 Tephra layers

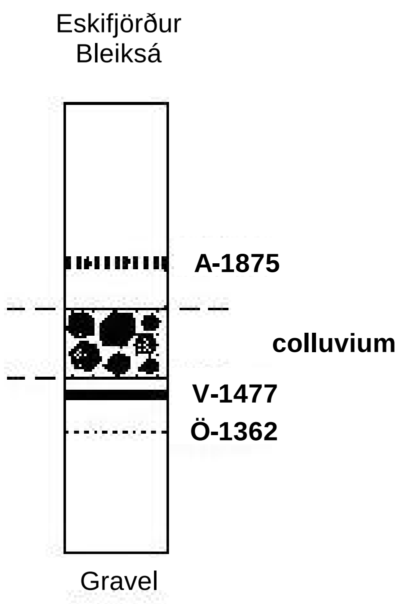
Tephrochronology has not been used much for dating landslides or avalanches in Iceland but there is a good possibility to do that. Sigurgeirsson (2000a) has summarised information about tephra layers in the eastern fjords. There are eight main tephra layers and these are often seen in undisturbed profiles.

- 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 (a neighbouring community of Seyðisfjörður) 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.

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 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.

Figure 2.5 Soil profile from Bleiksá (from Sigurgeirsson (2000b))



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 to 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. These studies do, however, show that this period has been an active erosion period in the whole area.

2.7.2 Physical properties of Icelandic soil

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

Table 2.4 Drainage 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).

Soils in Seyðisfjörður were analysed by Skúlason (1998) concerning planning of mitigation structures. Based on these analyses the values for drainage were selected from Table 2.6.

2.8 Vegetation

More than 37 000 km^2 of Iceland are barren deserts with an additional area of 10–15 000 km^2 of limited plant production, some of which is caused by volcanic activity (Arnalds *et al.*, 2000).

A national soil erosion assessment was made by Arnalds *et al.* (2001). The following Table 2.7 gives the percentage of surface area affected by erosion and vegetation coverage in the Seyðisfjörður area and a neighbouring community. The total size of the whole area is 676 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.

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

County	Size	Erosion map					Vegetation			
		%					%			
	Size (km^2)	0+1+2	3	4+5	Erosion in Veget. land	Deserts Mountains	Deserts	Scarce	Rather Scarce	Good
Borgarfjarðarhr. Seyðisfj.	676	48	38	14	36	54	45	10	14	31

3 Study Aim

Based on a request from the Seyðisfjörður community 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

An avalanche chronology was made by Ágústsson (1988). Partially based on Ágústsson's report a landslide chronology was written by Pétursson and Sæmundsson (1998). The table in Appendix A lists the events and their dates, and Map 4 in Appendix C, shows the events with a known location. Both are based on Pétursson and Sæmundsson (1998) but the table has also information about the most recent events based on Pétursson and Jónsdóttir (2000). Sæmundsson and Pétursson (1999) wrote a report on the danger of landslides including debris flows. Flow paths were analysed and identified by numbers, which are also used in the table in Appendix A. An overview report stating the need for avalanche protection measure around the country was written by Jóhannesson *et al.* (1996). Skúlason (1998) made a geotechnical investigation in connection with plans for protection measures. A report on avalanche hazard and suggested protection measures was made for Seyðisfjörður in 1998 (Verkfræðistofa Austurlands and NGI, 1998). The avalanche hazard was assessed, and the debris flow and rockfall activity in the northern part of Seyðisfjörður was also briefly discussed. The avalanche hazard was considered being much higher than the danger of debris flows and rockfall.

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 more complex catchments 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

Different time series of air photos and different flight heights are interpreted. 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 visit.

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):

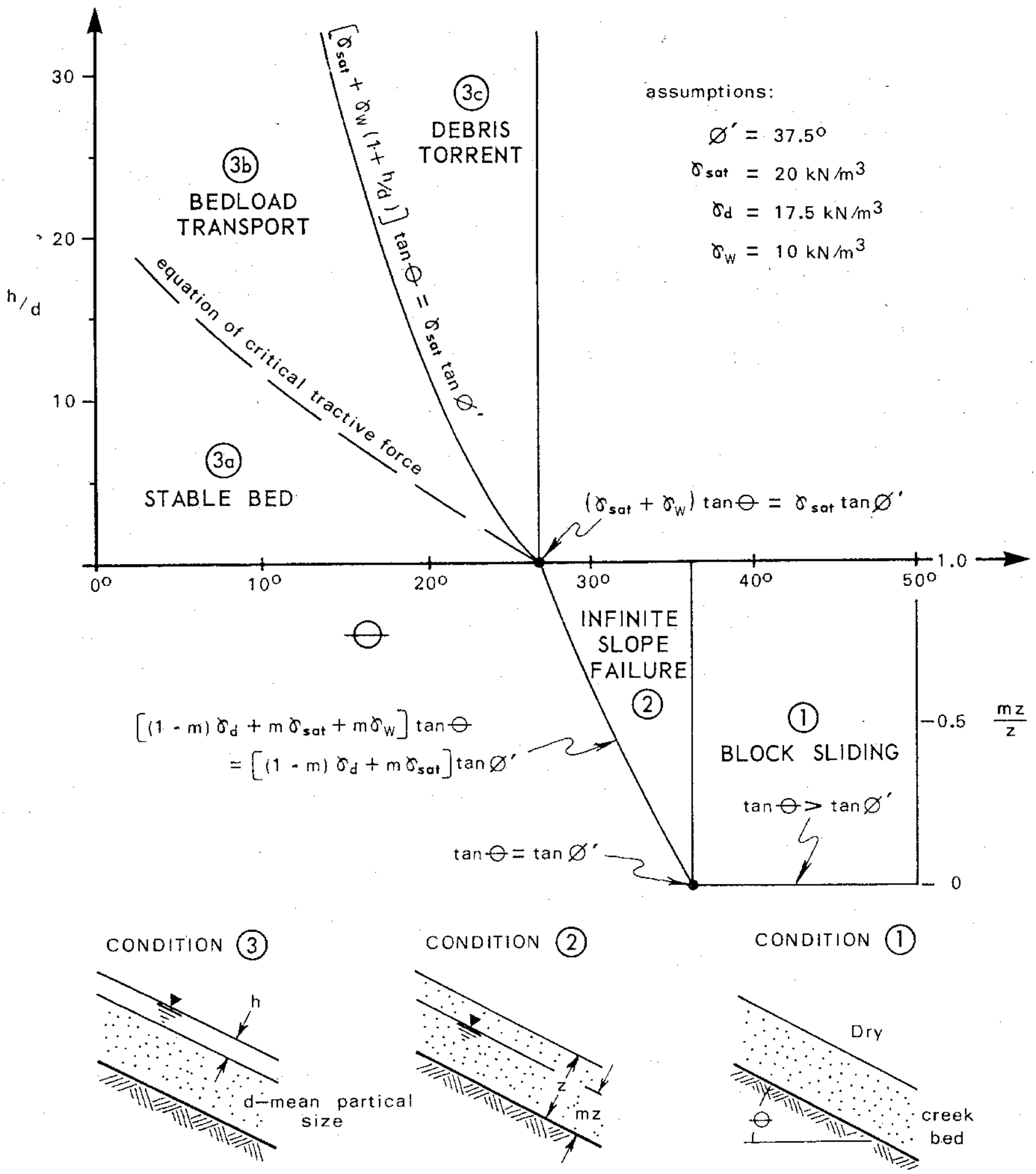
   Kirpich equation: $T = 0.0195 * L^{1.155} / H^{0.385}$

   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 streem (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 Wussows' 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 time period in question. The time period *T* for the high intensity event was chosen in the range 10-15 minutes for the watersheds that were considered in Seyðisfjörður.

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.

Rockfall simulation

The rockfall simulation was carried out with the software „Rockfall 5.0" (Spang, 1988; Spang and Sönser, 1995). The following input parameter are used:

- Starting points
- Design block size and block form (bowl or cylinder)
    - Specific weight of bedrock
    - block size – radius
    - block form – height of cylinder
- geometric characteristics of the slope
- starting type of movement
- relevant parameters for energy
    - tangential damping
    - normal damping (restitution coefficient)
    - rolling resistance
    - friction angle
    - roughness of the slope surface

The setting of the parameters is done by field investigation and by a variety study in the beginning. The plausibility is checked by judging, if the resulting path are realistic compared to the results of the field investigations. Since the effects of the different parameters differ with blocks, the block have different slope contacts while bouncing (*e.g.* once with the flat side, once with an edge) a specific variability of the parameters is then fixed. Within this variation, the program calculates the exact value at each contact randomly. On the base of that pre-selection procedure a number of rockfall paths are calculated. There is a possibility to define points to analyse on the path, where the velocity and type of movement (bouncing, rolling, sliding) of all passing blocks are checked. These analyses can be used to establish mitigation structures based on a risk analysis.

The geometric characteristics of the slope are derived from a contour map adapted by field investigations with regard to roughness and material properties of the slope surface. The runout distance estimated by the model computations in the selected paths was extrapolated to other locations along the slope and adapted by field investigations. The estimated runout distance for rockfall derived in this way is indicated with a brown line on Map C, Appendix A.

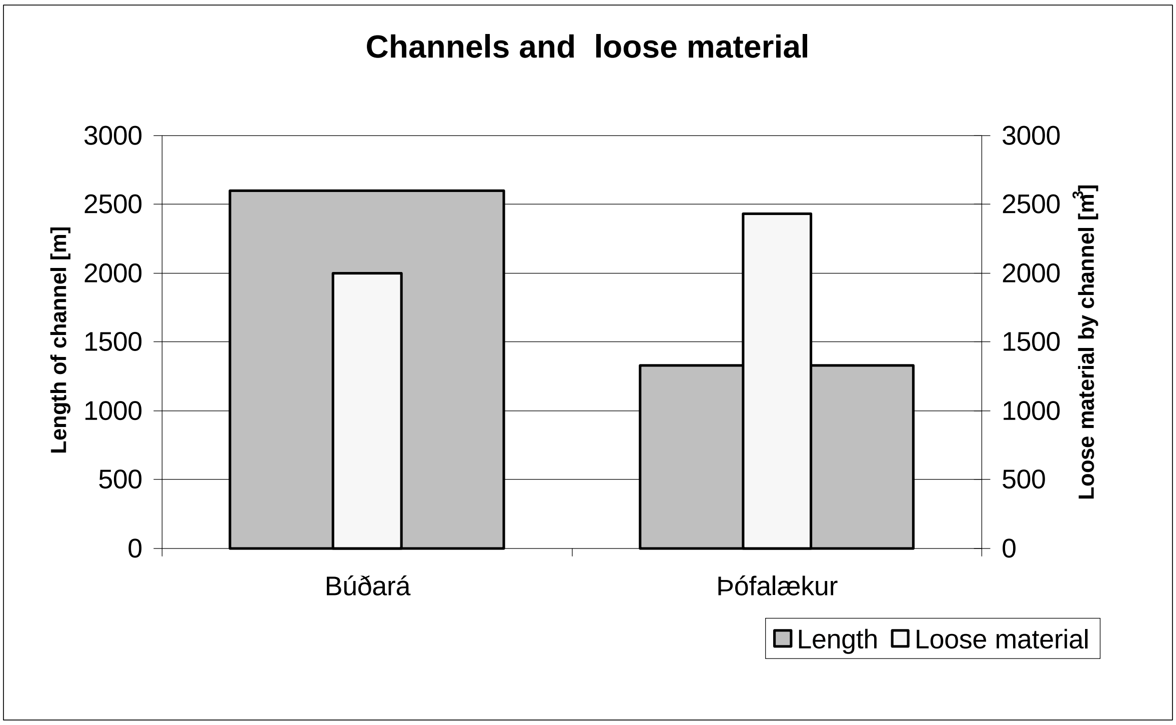
Creep profiles

Profiles of the hillside where evidence of creep was detected in the field were drawn. The profiles help to show the situation and to find which areas have to be further analysed.

5 Field investigations

The investigation area was too large to analyse all the channels in a consistent manner within the time limit of the project. It was, therefore, decided to find two 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 serve as examples of different types of hazard processes. The main difference between the selected catchments can be seen in Figure 5.1.

Figure 5.1 Channels and available loose material



The main parameters of the dominant processes along the channel are very important when judging the accumulation areas of the debris flows. 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 Búðará, Þófalækur and Hæðarlækur. 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 [°]	
Hæðarlækur	180	1	2	36	36	34	23	0.3
Hæðarlækur	420	1	1.5	41	36	18	18	0.15
Þófalækur right	500	1	1	36	36	31	31	0.1
Þófalækur left	480	1	1.5	36	36	31	31	0.15
Þófalækur	100	2	1	41	41	14	11	0.15
Búðará	190	1.5	1.5	45	32	11	9	0.1

With these parameters (Table 5.1), it is possible to calculate the main process type in this part of the channel based on the approach of creek-bed instability from VanDine (1985). This 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.

5.1 Erosion area, origin of the landslides

Almost every type of mass movements and mass transport can be found in the two investigated areas. From rockfall and sliding to mass creep, debris flows and water floods. The most important ones are those that endanger the settlement areas. They are:

- Debris flows
- Floods
- Rockfall, in certain parts

The field investigations and the calculations for water runoff and sediment masses give a quite interesting overview of the situation in the area:

- Large catchments with high peaks of water runoff. These channels are mostly in bedrock, but there is a possibility of small debris flows from the lateral slopes into the channel, which can easily be transported during bigger events.
- Slides in small channels with small catchments, but enough sediment to be transported.
- Rockfall events endanger some parts of the settlement area starting in the lowest basaltic layers, which build up low wall faces.
- Evidence of a huge landslide was found in the background of the processes mentioned above.

All these processes are visible in different stages of current activity.

5.2 Paths

In the same way that there are different types of processes there are also different types of paths (see Geomorphology map in envelope). The most obvious difference is between debris flow (small, long catchments) and the flooding areas (bigger catchments) (see Figure 5.1). By mapping the characteristics of the paths it is possible to draw conclusions about channel-events in the past, 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.

5.3 Depositional area

Two main types of catchments are relevant for the development of the depositional areas. On one hand, there are catchments with a quite steep area in the upper part and only one depositional area almost down by the sea level. On the other hand, there are catchment areas, which have more than one accumulation zone, with several embankments along the path. These embankments are mostly generated by glacial erosion in combination with structural geological conditions that have subdivided the slope. In those areas, the change of the slope inclination and the width of the channel are extremely important for the predominant processes during channel events.

5.4 Selected sites

Site 1 Búðará

Erosion areas

Búðará has a big catchment area starting at the top of Strandartindur in the east and Miðtindur in the west. The main part of the upper catchment area in Efri-Botnar is a wide glacial cirque with characteristic glacial deposits on its lower part. The uppermost part consists of bedrock wall faces, which are starting zones for rockfall processes. Large talus areas have formed below the cliffs.

Paths

Below and under the talus in the erosion area, there is a large area of old talus, which is rather thin. In the lower parts of the area, the channel is wide and is eroded down to bedrock.

Depositional areas

There are three different depositional areas in the catchment, which can be seen on the map (Map 2, Process Map). The debris cone on the fjord level is the most important for the settlement.

Site 2 Þófi/Þófalækur

Erosion areas

Indications of mass movements in the area of Þófi were found in the overview based on the air-photo interpretation and in the investigation by Sæmundsson and Pétursson (1999). The field investigations showed evidence of shallow landslides in the glacial deposits without bedrock being involved in the movement. A mass creep and shallow slides were detected in till on the steep slope above the fish factory (see location of houses in Map 1, Appendix C). This movement is considered active because of fresh open gaps and obvious vertical displacements at the surface (see Figure 5.2).

Figure 5.2 Evidence of creep in Þófi

After acquiring an overview of the area, a closer inspection was made at Þófalækur in order to check how events from the gully endanger the settlement area. One reason for taking a closer look at this area was evidence of an event in the past, that migrated sideways over the creeping area and into the path of Hæðarlækur. Consequently, the event was able to pick up more sediment than available in its usual path and bring it down to the settlement area. In contrast to Búðará, Þófalækur has a very small catchment area (see Figure 5.1).

Paths

The upper part of the channel is steep. The first noticeable change is the transition to the flat area of Þófi. The inclination decreases suddenly at this location in the path and there are no deep gullies beyond this point. Debris cones are below each gully in the upper part of Þófi resulting from the loss of potential energy in the channels.

There are no obvious signs of debris flows in the deep gullies above Þófi except the typical U-shape form of the dominant debris flow erosive process (Hübl, 1995). However, on the flat area of Þófi, there are very clear forms of leveés and other typical accumulation forms.

Depositional areas

The active mass creep in the moraine on the surface of Þófi leads to a high debris flow danger in the populated area. It was assumed that the movement is confined to the sediment and the bedrock is stable. This was based on the following field investigations:

- There are clear fresh gaps on top of the moving mass.
- There are no fresh slides on the border of the unmoving area.
- Therefore, it can be stated that there is an increasing inclination at the front of the body.

There is also evidence of openings of the front slope in some parts near the middle of the slope that suggest an active creeping process (see Figure 5.2). During a heavy rainstorm in October 2001, when 153 mm of rain fell in one day, a 100 m long crack opened in the surface of the front slope of Þófi immediately north of Hæðarlækur. The movement did stop before a catastrophic failure of this part of the slope was initiated but small slides were released from the front slope further to the north. Fixed points were installed after the storm to detect future movement of the surface masses. Insignificant movement has been recorded since then and therefore the movement seems to be caused by increased pore pressures related to heavy precipitation (Jensen, 2001).

In general, the areas that are fed with coarse material build up channel systems with steep slopes, whereas the flatter parts are filled up with soil and regolith that have higher clay and silt content.

Site 3 Botnabrún

Erosion areas

In the overview based on the air-photo interpretation and the existing investigation, there were also suggested large mass movements in the area of Neðri-Botnar. The first impression was comparable to Þófi plateau. That is, again evidence of shallow landslide in the glacial deposits without bedrock involved in the movements. The field investigations showed deep mass creep in moraines and shallow slides on the front of the mass down to the settlement area. This creeping is judged as being potentially active because of quite young slides on the front but there were no fresh gaps or sliding planes on top of that area. During the previously mentioned rain storm in October 2001, a 30 m long crack was detected in the surface of the front slope in Nautaklauf but this movement stopped before it lead to a slide or a debris flow.

Slides on the front of this creeping mass might endanger the settlement to some extent. Under this creeping sediment body, a horizon of thick basaltic layers form a long 20–40 m high rock wall in this area. In combination with the main fault systems, cleavage builds the detachment planes for rockfall. The loose rocks are mainly eroded basalt columns. Sediment layers that are in-between the basalt layers erode more easily. The columns loose their support and fall down. This results in step-like landscape. In some places toppling of rock from the surface of the creeping glacial deposit causes the “rockfall danger”.

Paths

Below the rock walls the rockfall processes generated talus. Depending on the intensity of faults and cleavage in different parts of the walls there has been more rockfall activity in some places than in others and therefore, the talus in these more active places reaches higher. That also means that the wall is higher in these areas since the bedrock dips towards the edge and the area below is filled up with scree. Since this process occurs over a quite long distance along the rock walls the rockfall danger is continuos along the slope.

Depositional areas

There are only relict detachment planes in the uppermost part of Neðri-Botnar. On the border to the firm bedrock area, there are only relict slides except for some shallow creep in association with local springs. The rock wall crops out at the base of the creeping mass. The boulders that fall from the rock face accumulate on the talus. The lowest part of the talus is used for settlement, which is therefore endangered by rock-fall.

6 Hazard

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

The fundamental question is how to specify the “delineation” of the 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 scenarios 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 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 event, are in a yellow zone. Within the red and yellow zones, constructions are restricted, reps. 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 Búðará and Þófalækur based on an event with a return period of 100 years. Calculations were made for intense short term precipitation events with duration on the order of 10 minutes and also 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 time-frame 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. In Þófalækur, another fact is also important. The soils in the investigated areas, which are classified as Andosols, can store more than 100% of its dry weight as water. This makes the cohesion of the loose material extremely low.

Other soils that are more typical for the steep parts of the slopes are classified as Leptosols. These soils can have water contents of up to 55% of their dry weight (Skúlason, 1998). That means that up to 35–40% of the bulk volume of the soil can store water. This was considered in the calculations (in Appendix B), since it can be expected that a part of this water would be released when movement starts.

6.1 Preliminary hazard assessment

The basic input data for calculating mass balances for debris flows/floods comes from the map of the geo- and hydro-inventory. This part can be called basic disposition. System conditions and specific precipitation events of the area give the varying disposition.

Site 1 Búðará

There were some indirect hints about the characteristics of possible hazards in the catchment of Búðará, which were verified by calculating the mass balances and their possible effects on the settlement areas. The fact that the catchment area is relatively large and the sediment in the direct slopes to the channel is already eroded (see Figure 5.1) results in a high flood discharge. The main part of the channel is quite wide and the bedrock is exposed. The possibility for lateral erosion in the middle part is low, even though the surrounding bedrock is fractured and metamorphosed as described in chapter 2.4.2.

Long and intensive rainstorms can cause over-saturated conditions and thus mass movement processes from the lateral slopes during high runoff in the channel. This debris can be transported instantly down the channel and, depending on the volume, accumulate in three different steps in the catchment, as mentioned in chapter 5.

- In the worst case the debris flows accumulate on the debris cone on the fjord level.
- Under "normal" circumstances the debris does not reach the fjord level cone, because of high discharge of water indicated by the mass balance.
- Floods cause less damage per event, but occur comparatively more often because of the special conditions indicated by the geo-, hydro- and bio-inventory in this catchment.

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

Since the upper parts of the cone are not settled it can be expected that the debris will in most cases accumulate before it reaches the area with houses. The debris flows have of course the most destroying effects if they can get to the populated 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. Debris flows are, thus, mainly to be expected under "unusual" conditions, but the debris flow chronicle (see Appendix A) shows that such conditions can arise. A flooding problem arises more frequently. During water-flood events bedload material is transported to the settlement area and is able to endanger it.

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

Table 6.1 Design events of Búðará

Rainfall periods	Rain [mm]	Discharge in lowest point [m^3/s]	Water volume [m^3]	Debris volume [m^3]
12min* u.sat	22	11.8	15000	2100
12 min* p.sat	22	14.9	19000	2100
5 hours***	100	3.7	67000	1100
1 day**	72	0.6	47000	300
1 day*	172	1.3	114000	500
2 days*	230	0.9	151000	400
5 days*	360	0.6	236000	300

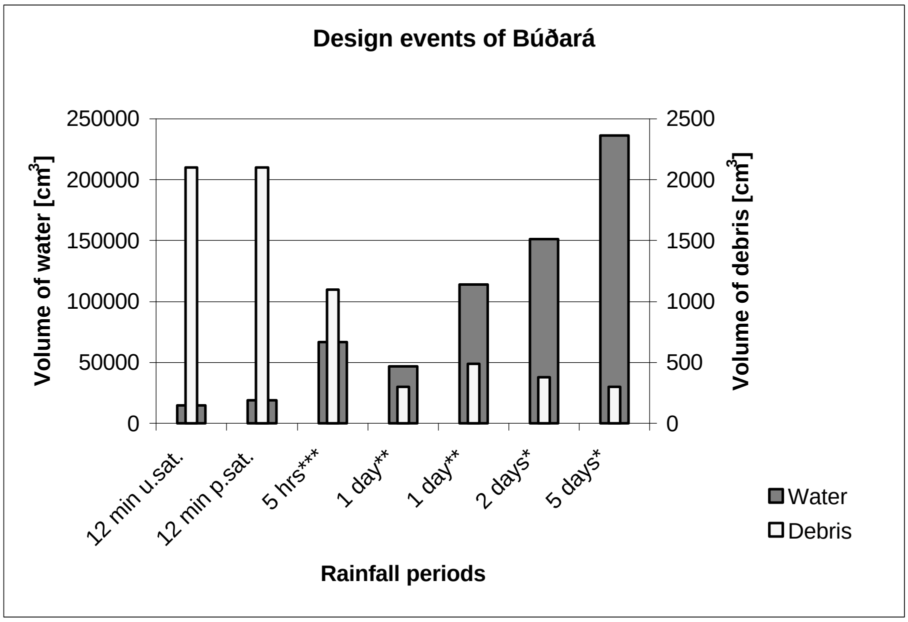
*A 100 years return period **A 1 year return period
*** selected event from IMO database
u.sat. = unsaturated conditions, p.sat = partly saturated conditions

It turned out in most situations when using “extreme precipitation” data (Jóhannesson, 2000), the longer a precipitation event lasts (1–5 days) the danger for debris flows increases, due to increased instability of the slope. But the short term precipitation events result in a higher possibility of flooding because the maximum runoff peak is high, due to high precipitation intensity. Assuming that the same source of debris is available in the cannel bed in both cases, the short term event could result in larger 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, but such an event may be expected to have a substantially longer return period than 100 years.

The calculations show, considering the land use on the debris cone of Búðará that the main problem lies in the high amount of water, especially when the possibility of slides is high. Without slides from the lateral slopes the mix of water and debris can pass the channel easily. If slides occur, most of the debris accumulates on the top of the cone, they could block the channel and the cone become flooded. The timing of such slides is important, i.e. whether they occur early or at the end of the storm. This affects the possibility of flood in the settlement area.

Estimated flood discharge for the high intensity events is on the order 10-20 m^3/s. It is clear that the current river channel is unable to transport this discharge and it may thus be expected that extreme floods will spread out of the channel and enter the populated area. The channel above the settlement is also much too small for the estimated debris volume (on the order 1000-2000 m^3) in case debris flows released from the sideslopes reaches the lowest part of the channel.

Figure 6.1 Design events of Búðará



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

Site 2 Þófi/Þófalækur

As described before, there are clear hints from field investigations of active creep and therefore progressively increasing inclination on the front of the creeping mass in the area of Þófi. Recent openings of cracks and slides falling from the front slope in October 2001 have confirmed the conclusions of the earlier investigation. A slip/debris flow of approximately 400 m^3 at the source and another one of 48 m^3 were released. The new cracks and seeping water coming out of the front slope about 15 m below the edge were interpreted such that movement of an area of about 4000 m^2 was possible. The mass was estimated as being on the order of 20000 m^3 ± 10000 m^3 (Jensen, 2001).

The Seyðisfjörður community asked a group of engineers, and specialists from IMO to analyse the situation. The result was that immediate actions were needed. It was decided to make draining ditches in order to reduce the water pressure in the creeping mass and keep a close look on the area and evacuate buildings below the slope during heavy rainstorms.

The field investigations indicate that most of the slides from the sideslopes have a volume of approximately 100 m^3. The existing channels would not transport debris flows larger than 100 m^3 but build up new paths on their way to the accumulation areas. Only large debris flows and debris flows originating in the uppermost parts of the catchments have a chance to pass the Þófi area. Once a debris flow has passed the flat area of Þófi it will continue down the steep area just above the settlement, as there is no natural feature that may stop it.

The main results of the mass-balance calculations, when the area is assumed to be saturated and therefore, extremely high runoff coefficients are used, is that a 5 hour intensive rainfall event causes the largest debris flows in the catchment of Þófalækur. These circumstances might not be realistic and therefore partly saturated and unsaturated conditions were set up for calculations of the intensive 10 min. event (see Table 6.2). This type of event would lead to a worst case discharge, even though the area was not assumed to be saturated. Since the time period of such precipitation event is extremely short, the maximum possible debris flow is smaller than the one from the maximum 5 hours event. The results from these calculations are summarised in Table 6.2, details are shown in the tables in the Appendix B.

Table 6.2 Short term design events of Þófalækur

Rainfall for special periods	Rain [mm]	Discharge in lowest point [m^3/s]	Water – whole event [m^3]	Debris [m^3]	
				Side-slope slides	Bed
10 min*. max. u.sat.	22.6	3.01	2900		2000
10 min*. max. p.sat.	22.6	3.35	3100		2100
5 hrs.**max. sat.	100	0.71	13200		4700
5 hrs.** sat.	100	0.71	13200	2200	

* intensive rainfall (Wussow) calculated from 100 year event
** selected event from IMO database
max. = relates to maximum possible event defined by VanDine model
u.sat. = unsaturated conditions, p.sat = partly saturated conditions

Assuming the area is partly or completely saturated, debris flows starting in the uppermost part of the channel or from the lateral slopes, do not need high runoff in the channel to transport the debris because of the water held within the regolith itself. Time windows derived from the concentration time (from Kirpich equation, see Chapter 4) are used to evaluate the size of the debris flows for the long term events. This was done because only the peak flow is considered to cause enough water height in the channel to transport debris. The transport capacity is not expected to increase even though the peak lasts for several hours, since the peak discharge does not change. The results are in the Table 6.3; details are shown in the tables in Appendix B.

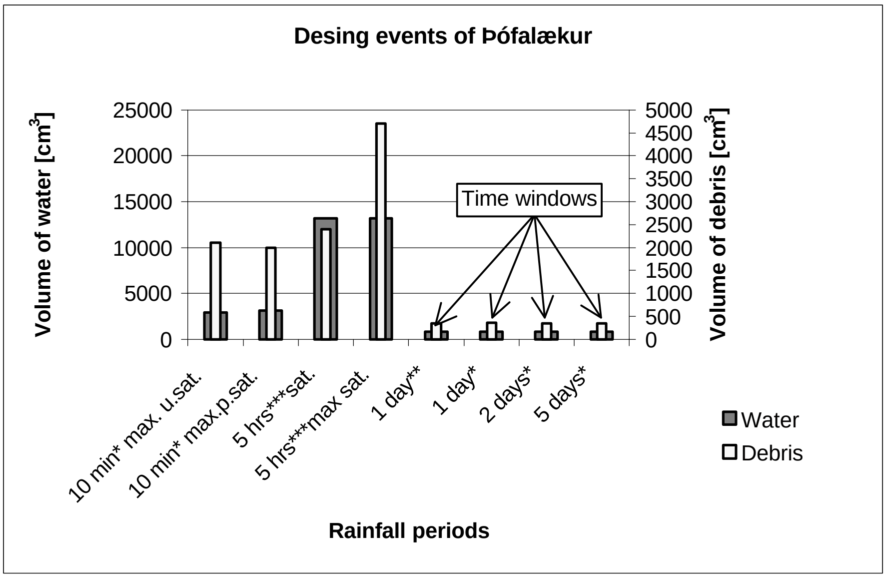
The discharge for the long term events is low in Þófalækur, but still some debris might be transported. The debris volume is similar to what could happen in the long term events in Búðará, even though the discharge is much lower. The short intensive events (10 min or 5 hrs) however, still having lower discharge than Búðará, can produce much larger debris flows. This is because the channel contribution to debris is high, whereas in the Búðará catchment the source is limited. There are other channels in the area with similar characteristics as Þófalækur but Þófalækur is the largest one of that kind, with the largest source of loose material.

Table 6.3 Long term design events of Þófalækur

Rainfall for special periods	Rain [mm]	Discharge in lowest point [m^3/s]	Water – Time window [m^3]	Debris [m^3]
				Side-slope slides
1 day** sat.	72	0.11	790	340
1 day*sat.	172	0.26	840	360
2 days*sat.	182	0.17	810	350
5 days*sat.	360	0.11	790	340

*A 100 years return period **A 1 year return period, sat = saturated conditions

Figure 6.2 Design events of Þófalækur



*A 100 years return period **A 1 year return period *** from IMO database
max. = relates to maximum possible event defined by VanDine model
u.sat. = unsaturated conditions, p.sat = partly saturated conditions

The channel of Þófalækur is far to small to transport the largest design debris flow. This could cause the debris to change its course and flow into the residential area (as discussed in Chapter 5). The speed of such a large debris flow in a steep and narrow channel like Þófalækur is expected to be high.

Estimated flood discharge for the high intensity events is on the order 3 m^3/s. Although this is much smaller than for Búðará it can cause problems were the river goes through the culvert in the road. As for Búðará the channel above the settlement is much too small for the estimated debris volume (on the order 2000-5000 m^3) in case the debris flows reach the lower part of the cone.

Site 3 Botnabrún

The area of the Neðri-Botnar is characterised by evidence of an old, large mass creep. A part of the creep is still active, on the front of the mass associated local springs can be found. The general field investigations do not indicate that this area is in a reactivation phase.

To get more information about the rockfall hazard and the possible damage to houses, it was decided to look at this problem in more detail. Input data was collected for rockfall simulations. Three cross sections were selected to get an overview of:

- How far blocks could reach?
- At what surface conditions?
- Which degree of energy can be expected in the settlement area?

As a result of the field work, the size of the blocks in the simulation was always 1 m^3. The locations of the profiles can be seen on the Hazard map (Appendix C). The input values are different depending on the surface material with small variations (Table 6.4):

Table 6.4 Values for damping and roll resistance in rockfall simulation

Ground surface	normal damping	tang. damping	roll resistance
Bedrock	0.06	0.9	0.02
Till	0.05	0.8	0.08
Scree, Talus	0.02	0.7	0.16
Outrunning scree, talus	0.06	0.68	0.18

The aim of the rockfall simulations in this case was to get a better idea about the runout distance of rockfall since the lower parts of the talus are already used as settlement area. As houses are not included as retaining structures in the model the uppermost row of houses has no protective effect for the houses below. The simulation profiles are in Appendix D, profile 1 has a runout distance 200 m, profile 2 has a runout distance 221 m and profile 3 has a runout distance 233 m. Simulations were also made for winter conditions (rock falling on frosen ground), which resulted in longer runout distances below Botnabrún. The rockfall line (see Hazard Map, Appendix C) represents mainly the results of field investigations using the simulations as background information.

6.2 Discussion and 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 6.5 Overview of Main Results

Process		**Búðará**	**Þófi-Þófalækur**	**Botnabrún**
Debris flows/floods	Short intensive rain	High possibility of floods with short enclosed time windows with small debris flows	Large debris flows possible	Not analysed
	Long term rain (1–5days)	Danger of small floods with small debris flows	Danger of small debris flows	Not analysed
Creep/small slides		–	Active/Active	Potential/Active
Rockfall		Active	–	Active

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:
Búðará:

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

Þófi:

There is almost no space between the road and the mountainside and therefore protection measures for the industrial area along the coast are difficult to implement. There is typically no space for catching- or deflecting dams above the buildings. Some limited actions to protect individual buildings are, however, possible. The most important actions are:

- Monitoring of the landslide areas
- Point protection measures for important buildings were people are working
- A debris retaining basin in the uppermost part of the debris cone
- Improvements on the hydraulic characteristics of the channel

It is recommended to perform a detailed field investigation specially focused on the creeping phenomena to define the rate of movement and determine the mechanism of the mass movement. If necessary the subsurface structure should be investigated by use of geophysical methods. Different scenarios for possible events should be modelled. Finally, a monitoring system should be established to see how this area develops in the future.

For future plans, move the present activity to a safer area.

Botnabrún: Evidence of old creep suggests that the next step should be to have a close look at how this area develops. This could be done by mapping the changes on a regular long-term basis. At the same time the variations of available water in the slopes should be checked. As solution to rockfall problems rockfall retaining structures (dams, netting systems) are suggested.

7 Summary

In this study, different precipitation events during different system conditions were used as inputs into a physical model. Extreme rainfall calculations extrapolated to a return period of one hundred years (data from IMO, Jóhannesson 2000) were used in the first calculations. Then short rainfall events with higher intensity based on information in the IMO database were used as inputs to the model. An empirical formula was used to calculate the peak flow for extreme short time rainfall intensity. Definition of a design event is made according to a well defined 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.

In the Þófi area both active debris flows originating from the uppermost part of the mountain and creep in the lower part can be found. Problems in the Búðará area arise mainly from water flooding due to the size of the watershed, while in the Botnabrún area rockfall is the predominant problem.

The investigations of the geo-, hydro- and bio-inventory as carried out in this study, simplifies the design of mitigation structures in following steps of a risk orientated way of land use since all the basic information on processes and their characteristics has already been 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. 1998. *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

Ágústsson, K. 1988. *Könnun snjóflóðahættu á Seyðisfirði.* Icelandic Meteorological Office.

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.

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 an english version.

Glade et al 2001. *Recommendations for landslide hazard assessment for Bolungarvík and Vesturbyggð, NW-Iceland.* Icelandic Meteorological Office, in prep.

Grímsdóttir, H. 1997. *Byggingarár húsa á Seyðisfirði*. The Icelandic Meteorological Office, VÍ-G97016-ÚR12.

Guðmundsdóttir, Þ. 1985. *Húsasaga Seyðisfjarðarkaupstaðar.* Safnastofnun Austurlands og Seyðisfjarðarkaupstaður, Seyðisfjörður.

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.

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

Jensen, E. H., 2001. Hætta á skyndilegu jarðskriði úr brún Þófans á Seyðisfirði. A memo, ÚR-EHJ-2001-01.

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.

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

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

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

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.G. and Sæmundsson, Þ., 1998. Saga skriðufalla á Seyðisfirði 1882–1997. Icelandic Meteorological Office, rep. VÍ-G98024-ÚR19.

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.

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.

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.

Skúlason, J. 1998. *Snjóflóðavarnir á Seyðisfirði, Bjólfur frumathugun. Athugun á lausum jarðlögum.* Almenna verkfræðistofan h.f.

Spang R.M. (1988): Empirical and mathmatical approaches to rockfall protection and their practical applications. – Proc. 5th. Int. Symp. Landslides, Lausanne

Spang, R.M. and Sönser Th. 1995. *Optimized Rockfall Protection by „Rockfall“. Proc.* 8th Int. Rock Mech., Tokyo.

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.

Verkfræðistofa Austurlands and NGI, 1998. *Assessment of snow avalanche hazard and defence structures in Bjólfur area.* Seyðisfjörður city council, rep. VA-9807, NGI-974079-1.

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

D Rockfall profiles

Appendix A. Landslide chronicles for Seyðisfjörður.

Date		Path	Path name	Type of landslide	Cause	Description
20.10.1882	Bjólfur	B6?	Uppgöngur	Debris flow?	Rain storm	Landslide fell on the house Liverpool, not much damages.
03.07.1892	Strandartindur	S13	Skuldarlækur	Debris flow	?	Landslide fell on the retail company and did a great damage.
15.08.1897	Bjólfur	B8?		Debris flow	Rain storm	No damage but many smaller debris flows fell that same day all around Seyðisfjörður.
15.08.1897	Strandartindur	S8, S9 (1st) and S13? (2nd)	Þófalækur and Skuldarlækur?	Debris flows	Rain storm	A great damage. Two large debris flows fell on Búðareyri. The first one fell outside the settlement but the second one fell inside it and damaged two houses (the retail company and Steinholt).
14.01.1903	Strandartindur	S11?	Hörmungar-lækur	Debris flow	Rain storm	A debris flow fell on Búðareyri a little bit outside where the large flow went 1897.
August 1905	Strandartindur	S6?	Imslandsgil	Debris flow	Rain storm	One large and a few smaller debris flows. The large one damaged the herring factory not far from the last two events on Búðareyri.
Winter 1925	Botnabrún	?	Neðri-Botnar	Creep?	?	Cracks were found in the soil in Botnabrún above Búðareyri. When better surveyed it was obvious that the soil had moved.
14.09.1935	Strandartindur	S11	Hörmungar-lækur	Debris flow	Rain storm	Many debris flows fell on this day. One house was damaged and the port of the oil station. Some oil went into the sea.
14.09.1935	Strandartindur	S13	Skuldarlækur	Debris flows	Rain storm	The flow fell on the house Pöntun but did not do a lot of damage.
15.09.1935	Strandartindur	(S8 or	Þófalækur	Debris	Rain storm	A flow fell on the fishery in Fjarðarströnd and

		S9) even S7?		flows		caused some damage.
17.06.1944	Bjólfur	B8?		Debris flow	Thaw	A debris flow fell around Bræðraborg, no damage. A few more small flows fell on the 19th if June.
19.08.1950	Strandartindur	S8 and S9	Þófalækur	Debris flow	Rain storm	Great damages occurred and 5 people were killed when a large debris flow hit the house Strönd. Many smaller debris flows fell this day (17 were counted) most of them on Fjarðarströnd.
19.08.1950	Strandartindur	S10	Hæðarlækur?	Debris flow	Rain storm	A debris flow damaged a herring factory but people were saved. In addition, the tubs were damaged. The houses Innri-Hæð and Garðhús and Strandvegur 2 were damaged.
19.08.1950	Bjólfur	B8	All paths in Bjólfur	Debris flows		Debris flows came from every flow path in the mountain but the flow from path 8 damaged the house Bræðraborg. A debris flow from an unknown flow path damaged a fishery located on the northern coast.
30.09.1958	Strandartindur	S-many		Debris flows	Rain storm	Five flows fell within the settlement and at least 16 outside on the south side, and 2 on the north side.
30.09.1958	Strandartindur	S10	Hæðarlækur	Debris flows	Rain storm	A large debris flow, 100 m in width fell around 3 o’clock from Borgartanga. Another flow fell a little later from the same path and they both did some damage on the herring factory.
30.09.1958	Strandartindur	S10	Hörmungar-lækur	Debris flows	Rain storm	A flow fell around 5 o’clock and damaged the house Hörmung and the fish factory Síldarbræðsla.
30.09.1958	Strandartindur	S11	Skuldarlækur	Debris flows	Rain storm	Another flow fell around 10 o’clock on the house Skuld and destroyed it and the rest of the house Hörmung. It also damaged the house of H. Johan-sen’s and a barn and a sheep cot.

30.09.1958	Strandartindur	S14	Stöðvarlækur	Debris flows	Rain storm	A debris flow fell from Strandartindur around 6 o'clock on the street Hafnargata by the telephone service. The road was damaged but not the house.
30.07.1960	Strandartindur	S-many		Debris flows	Rain storm	Many small debris flows fell on this day, but no damage was done.
25.08.1974	Strandartindur	S8 and S9	Þófalækur	Debris flows	Rain storm	A debris flow fell on the same place where the accident occurred in 1950. The road was closed but no other damage occurred.
25.08.1974	Strandartindur	S-many		Disbars flows	Rain storm	Many debris flows fell on this day, most of them outside (to the east) of Strönd.
25.08.1974	Strandartindur	S15	Búðará	Debris flows	Rain storm	Early on Sunday morning the river Búðará flooded. Water and debris was spread over a large area, the flow fell between the houses at Hafnargata 6 and 10. A sheep cot in construction was damaged as well as the premises of the telephone service.
25.09.1981	Bjólfur	B8		Debris flows	Rain storm	Two debris flows fell on this day. One hit an old fisherman's house and damaged some fish that was kept there and closed the road.
25.09.1981	Bjólfur	B9?		Debris flows	Rain storm	Another flow fell about 400 m outside the fisherman's house and closed the road.
25.09.1981	Strandartindur	S6	Imslandsgil	Debris flows	Rain storm	A debris flow fell to the south of the fjord on the infield Neftún.
25.09.1981	Botnahlíð	?		Debris flows	Rain storm	Three debris flows fell close to houses and damaged premises.
25.06.1988	Bjólfur	B1	Jókugil	Debris flows	Thaw	A debris flow started high up in the gully Jókugil in the mountain Bjólfur, fell on an infield and stopped by the old sheep cot below the gully.
03.09.1988	Strandartindur		Borgartangar	Debris flow	Rain storm	The flow fell on the road by Borgartangar.

11.-12.08.1989	Strandartindur	S-many	Fjarðarströnd	Debris flows	Rain storm	Around 13 flows fell this night on Fjarðarströnd, 4 of them where rather big. Houses where evacuated.
11.-12.08.1989	Strandartindur	S8 and S9	Þófalækur	Debris flows	Rain storm	The fishery Norðursíld was hit by a debris flow, which damaged a stock room.
11.-12.08.1989	Strandartindur	S10	Hæðarlækur	Debris flows	Rain storm	A debris flow fell on the herring factory but did not do much damage.
11.-12.08.1989	Strandartindur	S15	Búðará	Debris flows	Rain storm	Water and debris flooded the police station and the post office.
18.-20.10.1996	Seyðisfjörður			Debris flows	Rain storm	Unknown location
28.09.1997	Seyðisfjörður		Múli	Debris flows	Rain storm	A debris flow fell from the highest peak, above the so-called Múli. The stream was coloured all the way down to the power station in Fjarðará.
8.-9.09.1999	Strandartindur		Strandartindur	Debris flows	Rain storm	It was very intensive rain (30 mm/hour), total 100 mm in 16 hours. Small debris flows just above the settlement.
8.-9.09.1999	Bjólfur		Bjólfur	Debris flows	Rain storm	It was very intensive rain (30 mm/hour), total 100 mm in 16 hours. Debris flow from the top of the mountain Bjólfur closed the road.
End of August	Strandartindur		Hánefsstaðir	Debris flows	Rain storm	Debris flow went into the sea.
1.10.2001	Strandartindur	Between S9 and S10	Þófi	Debris flows	Rain storm	A debris flow reached the road above the fish factory around 6 PM. The scar was measured, L = 8 W = 6 m, D = 1 m => $48m^3$
2.10.2001	Strandartindur	Between S9 and S10	Þófi	Debris flows	Rain storm	A debris flow hit a building (the herring factory) at 8:30 am. The road was closed but no other damage. The width of the debris on the road was 40 m 1-2 deep. The scar was measured L = 8 m W = 20 m, D = 2.5 m => $400\ m^3$

2.10.2001?	Strandartindur	S15	Búðará	Slip	Rain storm	A slip fell into the channel of Búðará at 540 m. It was transported down the river channel as a bedload transport. Down by the bridge it went out of the channel where it turned out to be about 50 m^3.
2.10.2001			To the east of Hádegisá	Debris flows	Rain storm	Above the power station
2.10.2001			To the east of Hádegisá	Debris flows	Rain storm	Above the power station
2.10.2001				Debris flows	Rain storm	Above the forestry
2.10.2001	Botnahlíð		Nautaklauf	slip	Rain storm	A tiny slip 20 cm^3 occurred during the storm, the ground was completely saturated. After the 19th of Oct. a 30 m long crack was discovered close by.
2.10.2001?	Strandartindur		Miðtangi	Debris flows	Rain storm	Closed the road and reached the sea
2.10.2001?	Strandartindur		Miðtangi	Debris flows	Rain storm	Closed the road and reached the sea
2.10.2001?	Strandartindur		Borgartangi	Debris flows	Rain storm	Closed the road and reached the sea
2.10.2001?	Bjólfur		Króarhryggur	Debris flows	Rain storm	A debris flow fell at 9 am.
2.10.2001?	Strandartindur		Hánefsstaðir	Debris flows	Rain storm	Reached the sea
2.10.2001?	Strandartindur		Hánefsstaðir	Debris flows	Rain storm	Reached the sea
2.10.2001	Sunnuholt		Sunnuholt	slip	Rain storm	A slip measuerd with a GPS. Length 31 m width 44 m, depth 1.5 m.=> 1980 m^3
2.10.2001	Sunnuholt		Sunnuholt	slip	Rain storm	A slip in 105 m a.s.l. Width 24 m Length 13 m.
3.10.2001	Selstaðir		Selstaðir	slip	Rain storm	Three slips in the lowest sill (220 m a.s.l.) One

						around 5 am the other around 9 am?
7.10.2001	Bjólfur		Fálkagil	Debris flows	Rain storm	A debris flow starting at about 80 m. No denris flows have been recorded in this path before.
7.10.2001	Botnahlíð		Nautaklauf	Cracks	Rain storm	After 19. Oct. crack appeared, 30 m long, exact timing is not known, probably during the storm 7.-8. of October