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Linking debris-flow hazard assessments with geomorphology

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Abstract

Debris-flow hazard assessment schemes are commonly based on empirical, physical, or numerical methods and techniques. Inherent in all methods is generally the assumption of unlimited sediment supply. This study compares model inputs of sediment requirements for debris flows with estimated sediment reproduction from both solifluction and rockwall retreat. The analysis is carried out in Bíldudalur, a community in the Westfjords of Iceland. Geomorphic techniques are applied to determine the set of natural processes acting in this landscape to estimate spatial distribution of relevant processes, to approximate level of processes activity, and to provide information for scenario modeling. Debris-flow volumes are determined by coupling rainfall magnitudes and catchment sizes with average sediment contents. Rockwall retreat and solifluction rates are based on literature reviews.

For a rainstorm with a 10-year return period, debris-flow volumes are calculated for 12 different creeks. Rates are assumed for solifluction with a velocity of 0.25 m/yr at an average depth of 0.5 m and for rockwall retreat with 2 mm/yr. Comparing sediment requirements with estimated sediment reproduction leads to a factor of deficit ranging between 6.2 and 8.5. Thus, the sediment storage is not refilled as fast as the next potential triggering rainfall occurs. Consequently, if a debris flow has occurred in the past, all sediment is removed, and the following rainstorm event is 'just' causing a flood, which is by far less destructive than a debris-flow event. The challenge of future debris-flow hazard-assessment schemes is to include geomorphic analysis to be able to obtain more sustainable results.

Keywords: Debris-flow hazard assessment; Sediment budget; Iceland

1. Introduction

Debris flows occur in various environments. In particular, in arctic and alpine regions, steep slope gradients and the availability of loose debris precondition these areas for landslides. Triggers are commonly prolonged or heavy rainfall often accompanied by snow melt. These natural processes are an important factor for landscape evolution. However, if humans are exposed either deliberately or unintentionally to these processes, natural events turn to natural hazards with the potential to cause disasters. Therefore, solutions which offer a reduction of hazard

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and in particular risk to the exposed population are demanded. These preventive solutions can be either direct countermeasures mostly based on geotechnical engineering such as deflecting dams, stop bars, and reinforcement of endangered structures or indirect procedures such as raising awareness of potentially affected people and land use planning.

To avoid the confusion resulting from the wide range of definitions, the term debris flow used within this study refers to the internationally accepted definitions given by Cruden and Varnes (1996) and Dikau et al. (1996). Debris-flow hazard analysis is generally carried out either by applying numerical and physically based models or using empirical approaches. While advanced numerical models are able to calculate debris-flow characteristics in detail, they have their limitations in application due to detailed requirements of input data. Rheological and physical–mathematical based modeling of debris flows needs detailed information on rheologic, hydrologic, and hydraulic properties. Numerous authors are working with such physical models (e.g., Costa and Wieczorek, 1987; Iverson, 1997a,b; Major and Iverson, 1999). A recent review on different approaches is given by Hutter et al. (1996) and Jan and Shen (1997). Most recent research on debris-flow modeling is summarized in Chen (1997), Wieczorek and Naeser (2000), and within the proceedings of the International Symposium Interpraevent (2000a,b,c). In contrast, empirical models are based on few parameters and consequently allow generalized conclusions only. However, they generally offer an easily applicable and verifiable approach. Various authors have developed empirical relationships between debris-flow characteristics and conditioning parameters. A sound review of worldwide study has been published by Rickenmann (1999). Numerous other authors have developed site-specific relationships (e.g., Evans and Hungr, 1993; Hungr, 1995; Corominas, 1996; Bathurst et al., 1997; Wieczorek et al., 2000).

The need to carry out debris-flow hazard assessments in Iceland became evident as a result of a series of catastrophic snow avalanche and debris-flow events. Snow avalanches in Iceland have been studied for several decades. Monitoring of snow avalanches was established after an accident occurred in Neskaupstaður in 1974 with 12 casualties. Snow observers were hired in the most endangered villages as a local contact for Civil Defence Authorities. Responsibilities include the registration and analysis of snow conditions as well as specific snow avalanche events. Despite these efforts, two snow avalanches in Súðavík and Flateyri in 1995 caused 34 fatalities. As a consequence, the snow avalanche department of the Icelandic Meteorological Office (IMO) was extended, and the laws and regulations concerning hazard mapping for snow avalanches and landslides (including debris flows) in Iceland were revised. Landslides were included because of numerous failures also posing a serious threat to communities. Along with these revisions, older hazard maps became invalid. According to this new regulation (The Ministry of the Environment, 2000), risk zones for snow avalanches, debris flows, and rock fall have to be prepared for and applied to the endangered communities on request. The Icelandic Meteorological Office (IMO) is responsible for carrying out the avalanche and landslide hazard assessments.

Landslides, and in particular debris flows, occur regularly and cause considerable damage in Iceland (Jóhannesson, 2001). A historical review of landslide events was first undertaken by Ólafur Jónsson in 1957. This review is based on magazines, newspapers, old annals, etc. and demonstrates a nationwide landslide occurrence throughout Iceland. Often, only the largest events or those causing server damage were noticed and/or recorded, which is indeed a problem common to historical reports on landslides (Glade, 1998). Consequently, a direct comparison of triggering events is rather difficult because the consequences of a 'nontriggering event' might just have not been recorded. Thus, the derived frequency is a minimum information on landslide occurrence only, real frequency might be higher. The current landslide database is still in paper format only, but a digital inventory and a GIS database are being developed by IMO in cooperation with the Icelandic Institute of Natural History (IINA). If such a database becomes available, further analysis of landslide-triggering conditions might be possible despite the limitations given by the recording procedure (e.g., Glade, 2000).

Based on this history and legislative demand, landslide hazard assessments have been developed for Seyðisfjörður and Eskifjörður, east Iceland and for Bíldudalur, Bolungarvík, and Patreksfjörður in the Westfjords. In eastern Iceland, an Austrian method was applied, which is based on semiphysical models. The description of the method and the calculated landslide hazard zones are given in Jensen and Sönser (2002a,b). For the Westfjord communities Bolungarvík, Bíldudalur, and Patreksfjörður, Glade and Jensen (2004) developed a landslide hazard assessment scheme based on empirical models. Both approaches are applicable to other Icelandic villages.

An assumption inherent to most debris-flow assessments is unlimited sediment supply. Although already conceptually addressed by various authors (e.g., Zimmermann and Haeberli, 1992; Haeberli, 1996; Zimmermann et al., 1997; Bovis and Jakob, 1999), this underlying assumption will be investigated in more detail for the Bíldudalur study area. The availability of sediments in different types of sediment storages (Moore et al., 2002; Schrott et al., 2002) has important consequences for any hazard analysis. Clearly, rheology and mechanics of debris flows are an important considerations in many situations, however, if the sediment has been removed in the source areas, further hazard in the near future can be ranked as low. A different hazard ranking might be derived from physical or empirical models based on past events because they assume unlimited sediment availability. Therefore, not only the debris-flow process itself has to be determined, but also sediment sources, sinks within catchments, and rates of refill of sediment storages after removal (i.e., after a debris flow has occurred) have to be evaluated (Bovis and Jakob, 1999). This refill of different sediment storages is termed *sediment reproduction* in the current study.

This study aims to evaluate the Icelandic Westfjord debris-flow hazard assessment with respect to the assumption of unlimited sediment availability. The overall aim is thus to assess debris-flow hazard by taking into account geomorphic preconditions, processes, and sediment supply. This includes approximation of sediment reproduction rates and delivery of sediment from other sources which is finally available for debris flows. To determine the potential of these processes correctly, it is necessary to assess the availability of sediment to be mobilized by the debris flow (e.g., Keaton and Lowe, 1997; Bovis and Jakob, 1999). Only the high content of sediment, and in particular the content of large clasts, changes a large flood into a disastrous event. Investigations of sediment reproduction and sediment movement are common procedures in geomorphic analysis and are highly applicable to debris-flow hazard assessments. Specific goals of this study include

- identification of geomorphic processes within the study area;
- determination of spatial distribution and level of activity of geomorphic processes;
- detailed characterisation and categorisation of debris-flow incidences;
- definitions of areas most susceptible to debris flows based on field evidence;
- assessment of sediment available for debris-flow occurrence;
- reconstruction and scenario modeling of debris-flow movement to define potential run-out zones and depositional areas;
- comparison of modeled sediment requirements with current estimated sediment reproduction rates; and
- approximation of over- or underestimation of debris-flow hazard schemes.

While the first five goals require a detailed field investigation, the last three goals are most crucial and important. For example, if a debris-flow has occurred and removed all the material from the stores, and if these stores will not be refilled, or if the rate of storage refill is very low (e.g., 500 years), there will be no apparent danger for the near future from that particular site. Therefore, under these conditions, even rainstorm events with a 10-year return period do not initiate debris flows. They trigger only floods with reduced damaging potential. But if the store is filled within the next 2 years, the return period of the debris flow is equivalent to the return period of the triggering climatic event. Therefore, it is critical to investigate different sediment sources, mobilization, and reproduction in more detail in a specific study area.

2. Bíldudalur, northwest Iceland

This study is carried out for Bíldudalur, one of the three previously mentioned communities in the Westfjords. Bíldudalur is located in Bíldudalsvogur in the Arnarfjörður fjord in the southern part of the Westfjords in Iceland (Fig. 1). Legally, it is part of the

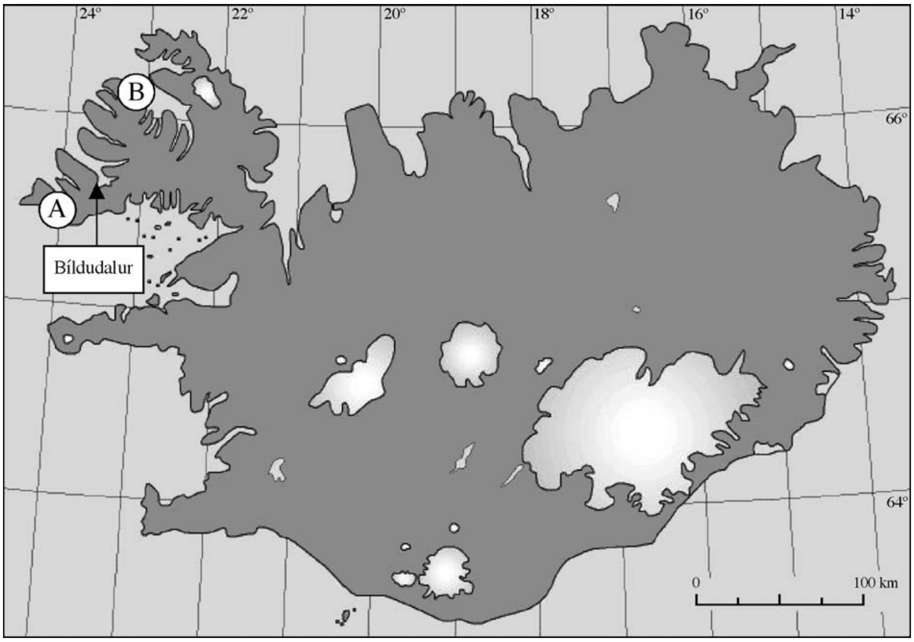

Fig. 1. Location of Bíldudalur in the Westfjords of Iceland. Climatic stations are included as circled letters and refer to (a) Kvígindisdalur and (b) Bolungarvík.

Patreksfjörður community. This community is exposed to various natural processes such as snow avalanches, slush flows, rock falls, debris flows, and flooding.

The top of Bíldudalsfjall mountain above the village is 460 m a.s.l. Two large gullies *Búðargil* and *Gilsbakkagil* have steeply dissected the slope, formed large gully heads, and developed significant debris cones. The settlement of Bíldudalur is partially located on these large cones (Fig. 2). The approximate 400- to 500-m wide SE facing *Búðargil* gully is located above the eastern part of Bíldudalur. The *Gilsbakkagil* gully is above western Bíldudalur with a size similar to *Búðargil*. The smaller gullies in the southeast facing slope between *Búðargil* and *Gilsbakkagil* are called *Milligil*. Several debris flows have been recorded from all gullies and slopes.

2.1. Environmental setting

Geologic strata are composed of lignite deposits slightly dipping at 2–3° to SSE (Kristjánsson et al., 1975). The soils in the Bíldudalur area are commonly andosols and vitrisol and are classified as BA-WA and cambic vitrisols on the Soil Map of Iceland (Arnalds and Gretrasson, 2001; refer to http://www.rala.is/desert/ for detailed description). Forests are almost nonexistent in Iceland. Trees, mostly birch, grow in some places along with some willows. Absence of forests in Bíldudalur does not allow information about the age distribution of tree species which could be used for evaluating landslide hazard. This relates also to information on spatial and temporal landslide occurrence based on damage to vegetation, a factor which has often been used elsewhere for evaluation of landslide hazard schemes. Various geomorphic processes are acting. Glacial, periglacial, aeolian, limnic, marine, fluvial, and soil erosion processes—and in particular gravitational processes driven by tectonic and climate forces—can be observed. These processes act on different temporal and spatial scales ranging from glacier movements over long periods in glacial–interglacial cycles to a singular rock fall lasting seconds or minutes. All these processes act continuously on the Icelandic land surface and depend on the predominance of one or a set of these processes, which define a typical arctic process system with its characteristic forms. Large polygonal stone-ring patterns on the plateaus as well as stone stripes on

Fig. 2. Bíldudalur from opposite fjord side (view north) (a) and from the plateau at an approximate height of 410 m a.s.l. downwards towards south (b).

slopes steeper than 2° were observed and indicate highly active periglacial processes (Fig. 3a). These processes are also driven by weathering, which form deeply weathered horizons on plateaus and thus prepare sediment ready to be transported to the slopes. This sediment is pushed into adjacent slopes and small first-order catchments by periglacial processes (e.g., solifluction) acting on the plateaus (Fig. 3b). Consequently, empty sediment storages on slopes and gullies are refilled continuously and become sources for debris flows ready to be triggered by external forces. This process contributes to debris flows originating both on slopes and in drainage lines. The second sediment source is the

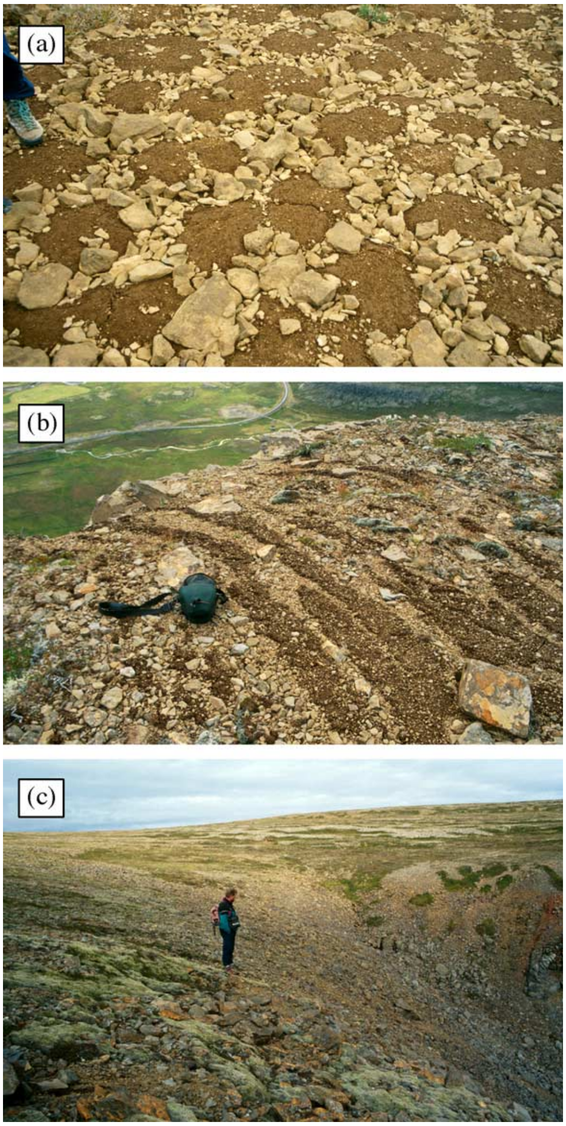

Fig. 3. Stone ring pattern on the plateau (a) and creep into the slopes (b) and gully heads (c).

supply by rock weathering. However, the sediment supply by plateaus should not be underestimated.

The slope profile can be divided into a flat upper slope (supply of sediment to the slopes), steep upper slope (bedrock), and steep to moderate midslope (bedrock with some sediment deposits) followed by moderate well-developed talus slopes which are interfingering with adjacent alluvial plains and fluvial terraces (Fig. 4).

In addition to slope profiles and fluvial terraces, swampy areas have been observed within the alluvial plains. Coastal beach lines indicate sea-level change due to isostatic uplift following glacier retreat. The latter geomorphic processes and related forms have not been investigated further within this study. However, this local example demonstrates nicely the general need for comprehensive geomorphic assessment of the landscape to be able to determine the interaction between different processes and forms. This assessment is the basis for modeling singular processes for hazard assessments. For Bíldudalur, snow avalanches, rock falls, and debris flows constitute in particular a continuous hazard to some parts of the municipality.

The weather in Iceland depends mostly on the pathways of low pressure systems crossing the North Atlantic (Einarsson, 1991). Changes between frost and thaw are very common, and rainstorms are frequent. The mean annual precipitation for the period 1961–1990 was calculated for all stations in Iceland that have continuous data (a selection is given in Table 1). In Kvígindisdalur, on the south side of the Westfjords, where measurements have been made since 1927, the annual mean is 1380 mm.

Extreme cumulative precipitation with return periods of 1, 2, 5, 10, 20, and 50 years has been calculated for a few weather stations in Iceland by Jóhannesson (2000). The calculations are based on a Gumbel distribution which is fitted to cumulative precipitation over 1-, 2-, 3-, and 5-day periods (Table 2).

2.2. Human history and current land use

Population in the Westfjords grew considerably after 1860. Employment has been in particular related to the construction and building of boats (deck boats) and fishing. In 1910, approximately 16% of the Icelandic population lived in the Wesfjords. By the year 1960, the Westfjords were heavily depopulated mainly due to poor transportation and communication facilities (Einarsson, 1985).

In the 18th century, trading started in Bíldudalur. By the end of the 19th century, the population had grown to 317 inhabitants, and Bíldudalur was one of the biggest towns in the Westfjords. But the growth did not continue, and, by the end of the 20th century,

Fig. 4. Schematic profile of west fjord slopes near settlements. Please refer to the text for circled numbers. The bold line at the top gully head refers to the slope/plateau crest, also shown in Fig. 6. Dashed line indicates unknown bedrock–sediment contact. Jagged line in unit 5 symbolizes the interfingering of talus and fluvial sediments.

the population had decreased to 291 inhabitants in 1999 (Geirsdóttir, 2000; Glade and Jensen, 2004). Currently, the town extends over 1400 m along the fjord. While residential buildings and industry are located near the sea front, the power house is situated high up on the *Búðargil* cone and is, despite artificial barriers above the building, exposed to slush flows, snow avalanches, and debris flows.

Table 1
Mean annual temperature and precipitation for selected stations on the northwest coast (based on the period 1961–1990) (Glade and Jensen, 2004)

	Kvígindisdalur[a] 65°33.372′N, 24°00.704′E (49 m a.s.l.)	Lambavtn 65°30′N, 24°06′E (5 m a.s.l.)
Mean annual temperature (°C)	3.2	3.7
Mean maximum temperature (°C)	5.6	6.0
Mean minimum temperature (°C)	0.9	–
Mean annual precipitation (mm)	1379.5	942.9
Maximum daily precipitation (mm)	102.4[b]	106.4

Refer to Fig. 1 for location of stations.
[a] 28 years within this period are used in the calculations.
[b] The maximum recorded precipitation was 131.6 mm in March 2000.

2.3. Debris-flow types

Debris material originates either from slope or upstream sediment deposits of a gully drainage.

Table 2
Cumulative precipitation of a 1- to 5-day rainfall event within a 1- to 50-year return period for the locations (a) Kvígindisdalur and (b) Bolungarvík (based on data from Jóhannesson (2000), locations are marked in Fig. 1)

Location	T/P	1d	2d	3d	5d
(a) Kvígindisdalur	1	57	78	92	114
	2	68	93	109	134
	5	82	113	131	162
	10	92	127	148	182
	20	103	142	164	202
	50	117	161	186	229
(b) Bolungarvík 1949-1953 & 1994-1997	1	31	43	49	59
	2	37	50	56	68
	5	43	59	65	78
	10	48	66	73	86
	20	53	72	80	94
	50	59	81	89	104

T/P refers to return period/probability of occurrence. Bold values have been applied in debris-flow scenarios. Grey tones give similar rainfall magnitudes of different rainstorm types and return periods.

Therefore, two main debris-flow types must be distinguished: debris flows originated on slopes (often termed slope or hillslope debris flows) and those occurring in large gullies (gully or valley-confined debris flows). These types can be subdivided as given in Table 3. In the Westfjords, in particular debris flows of types 1a and 2 to 4 occur.

Upslope rock walls are the water catchments and sediment sources for slope debris flows (Fig. 5). Water and sediment channelized in small steep drainage lines flow onto the rock fall talus, possibly eroding material from the top and transporting it downslope, but the flows stop rather quickly before they reach the valley bottom. The coarse sediment of the talus with a large porosity and consequently high infiltration capacity quickly drains the debris flow during movement. This results in a short run-out. Therefore, antecedent climate conditions seem to be of minor importance due to low water storage capacity in the water source area (mostly bedrock, including fresh weathered rock fragments) and on talus slopes.

In contrast, sediment mobilized by gully debris flows originates either from deposits on slopes of the valley walls or on valley floors and is transported in incised river channels. Therefore, these gully debris flows have long run-out distances and accumulate the sediment on large debris cones. Large cones are an indication of high activity. If vegetation is absent, these formative processes are currently active and not just the product of past processes. This can be clearly related to larger upstream catchments providing more sediment and water from these basins than from slopes. It can be assumed that antecedent climatic conditions are more important for initiation of valley-confined debris flows. This differentiation of debris flows has also implications for the respective calculations and models, which vary significantly. Empirical models validated for gully debris flows cannot easily be transferred to slope debris flows.

In Bíldudalur, debris flows are regularly triggered by heavy rainfall and have caused considerable damage (Jóhannesson, 2001; Jónsson, 1957). For example, Gunnlaugsson (1972) describes catastrophic debris flows from 1887 in detail. However, records are available for damaging events only (Glade and

Table 3
Generalized debris flow classification according to material origin (extended from Haeberli et al. (1991) and Zimmermann (1990))

Slope debris flows		Gully debris flows	
Type 1a	Source in a steep less consolidated talus slope; regularly influenced by backwards erosion	Type 3	Source is sediment deposited in drainage lines
Type 1b	Sediment source is a mostly shallow translational earth or debris slide on a slope, which changes into a debris flow when reaching the channel	Type 4	Source is remobilized sediment of previously deposited material
Type 2	Source on the border between rock wall and talus slope. Water is channelled in the rock wall and drains fast into the high permeable talus slope		

Fig. 5. Rockwall sources for backward weathering in a height of approximately 400 m a.s.l, view towards northeast.

Jensen, 2004). Before 1900, the landslide chronology in Bíldudalur did not include details of recorded events, but historical archives do mention damages to hayfields caused by debris flows in earlier times. Since 1902, 18 debris flows have been recorded (Glade and Jensen, 2004). Most of these events have originated in the *Milligil* gullies. Smaller events did occur in the two gullies *Búðargil* and *Gilsbakkagil.* Some of those events have caused considerable damage, fortunately there were no casualties. This relates to both gullies *Búðargil* with permanent settlement on the cone starting before 1700 and to *Gilsbakkagil* inasmuch as the house *Gilsbakki* was constructed on the cone in 1890 (Sæmundsson and Pétursson, 1999). Despite the fortunate situation of no loss of life within historic times, there still is an apparent hazard to the current settlement.

Therefore, Stuðull (1990) proposed deflecting dams near the main slush and debris-flow paths in the gullies *Búðargil* and *Gilsbakkagil* and below the slope between the two gullies. Jóhannesson et al. (1996) suggested also a deflecting dam for the *Búðargil* gully. It is proposed to divert snow avalanches and slush and debris flows to the north, where 10 residential houses would have to be purchased and removed by the government (Jóhannesson et al., 1996). Below *Milligil* and *Gilsbakkagil*, the inhabited area extends over 800 m. It has been pointed out that it is difficult to construct defence structures in this area that are in a reasonable cost/benefit relation, in particular, considering the value of the buildings along the shore. These reports provided the basis for developing the standardized methodology for the hazard assessment scheme, which has been set-up to investigate processes and in particular run-outs for different sized events in this area (Glade and Jensen, 2004).

3. Methods

3.1. Field mapping and aerial photography

To determine overall dynamics of the general geosystem, the geomorphic situation has been mapped. This includes all major past and recent processes and forms in the landscape. Focus was given to the specific features of the particularly important landslide processes. The applied geomorphic mapping legend is based on the Geomorphological Legend Key, developed within a large German scientific project on standardising geomorphologic mapping (Leser and Stäblein, 1975). This legend key has been adapted to mountain areas by Leser and Schaub (1987) and Kneisel et al. (1998). Within the Icelandic project, specific attributes for landslides have been additionally adopted from the UN working group on the World Landslide Inventory (WLI) and specifically for debris-flow mapping from Gärtner (1996) and Holl (1996). To display the maps in GIS software, some symbols had to be newly designed. To apply and integrate these new symbols, existing symbol sets from the National Energy Authority (Iceland) had to be extended.

Mapping of debris flows was focused on detailed analysis of source areas, investigations of travel paths, levees and characteristic cross-sections, and delineation of debris deposits, where possible. Length and height of total longitudinal profiles as well as paths between nick points in the travel pathways have been determined in the field using Leica binocular. Topographic parameters such as water catchment area, length of run-out, and height difference between source and deposit, including respective slope angle, have been delineated from available contour maps and digital terrain models. The resulting debris-flow map summarizes debris-flow source areas, including potential catchment sizes for rainfall events, travel paths with debris-flow levees, and—if identifiable—the deposition area. In addition, characteristic cross-profiles have been recorded (Fig. 6).

Basic assumptions inherent in these maps include the following:

- all major debris flows, which have been initiated in historic times, have been mapped;
- grade of activity could be determined using indirect indicators such as vegetation cover or weathering condition of exposed bedrock surfaces;
- any debris-flow feature is still in its deposited location and has not been disturbed, and, if so, it has been noticed;
- any debris-flow dimension examined in the area is characteristic and thus representative for this region;

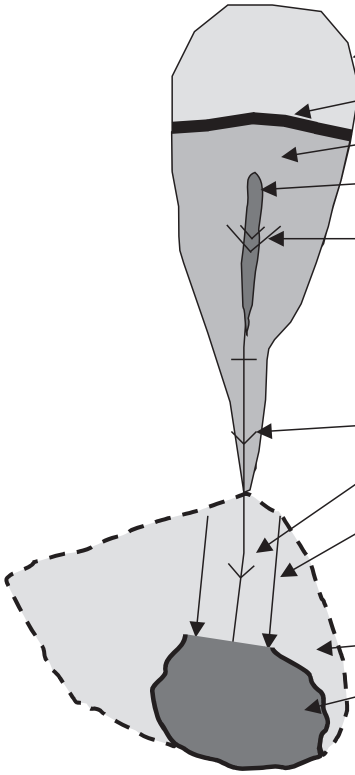

Fig. 6. Schematic sketch of mapped gully debris flows. Slope debris flows are characterized by water catchments and originate most of the transported material from the top of the talus slope.

- largest and disrupting debris flows which had considerable impact to the affected municipality and were quickly removed by remedial works, thus dimensions can only be estimated; and
- current debris-flow paths are the most probable ones for the future; however, debris flows are able to leave their channel and to affect the total area within their reach.

3.2. Historical records and literature review

Historical data and eyewitness accounts have been used to approximate maximum run-out length of historical debris flows. A major problem in historical records is that the records did not distinguish between debris flows events and hyperconcentrated flows, which are generally not as destructive as debris flows. Thus, information had to be treated with care.

To examine the sediment reproduction, it was not possible within this study to carry out field measurements of weathering depth on the plateau, creep rates, and rockwall retreat. Therefore, a literature review of rock wall retreat rates through weathering was carried out. Solifluction rates have been approximated from literature to estimate sediment creep from the plateau into the slope.

3.3. Climate data analysis and debris-flow observations

Climate data have been analysed, and calculations have been allowed to establish recurrence intervals of storms (Jóhannesson, 2000). Typical rainfall events have been applied to each catchment size, resulting in a water total available for debris flows. The water storage capacity of each catchment above the talus slope has been assumed as 0 (no water storage on slopes and channels due to coarse material and large bedrock areas). The time lag between maximum rainfall and peak discharge has been limited to 0 because no measurement are available, and very steep catchments suggest an immediate discharge in the gullies. This was also observed by eyewitnesses. Based on investigations in the European Alps (EASF, 1974), it is assumed that 85% of the precipitation reaches the outlet, the rest 15% evaporates.

3.4. Scenario modeling

Detailed information necessary to apply numerical- and process-based models were not available within this study. Herein, the focus is on empirical and semiempirical methods using different sized rainstorm events to model scenarios for debris flows, in particular, with respect to run-out distances (e.g., Wieczorek et al., 2000). These are highly important for most governmental or private agencies dealing with debris-flow hazards.

The method of calculating debris-flow run-out distances is not explained here. Refer to Glade and Jensen (2004) for a detailed description. The focus of this study is on sediment availability and reproduction. Therefore, the whole area has been classified into units characterized by similar response of debris flows to a given triggering event. Two main debris-flow sources and thus response areas could be identified: channelized debris flows in gully basins and slope debris flows on concave profiles. Within each unit, single creeks have been mapped. The scenario modeling of debris-flow events is based on catchment size and consequent water availability. The volume of water V_w (m^3) has been calculated using the following equation:

$$V_w = aPA$$

where a is the constant of water loss, here 0.85, P is the precipitation (mm), and A is the catchment area (m^2).

A water/sediment volume ratio of 30:70 for total debris-flow volume has been assumed in the Bíldudalur region. The formula for total debris-flow volume writes

$$V_{wd} = V_w + V_d$$

where V_{wd} is the volume of debris flow (m^3), and V_d is the volume of sediment, thus V_w*2.3 (m^3).

Consequently, the debris-flow volume is directly dependent on the rainfall magnitude and catchment size. Three different rainstorm magnitudes have been applied. These design events refer to return periods as given in Table 4. Total debris-flow volume has been calculated and used for further sediment analysis.

It has to be noted explicitly that any currently installed protection measures have not been considered within the scenario modeling. This has a twofold advantage. First, the scenarios give the potentially endangered areas without any landscape modification. Consequently, any subsequent demands on installing or continuing the maintenance of already existing structures has a sound basis. Second, consequences of a potential failure of already existing protection measures can be estimated.

3.5. Sediment calculations

For each creek, the rock wall source area and the length of the escarpment (linear border from plateau to slope) has been determined and attributed to each catchment. Due to missing observations, solifluction rates and rockwall retreat rates are based on simplified assumptions (Fig. 7).

Rockwall retreat S_r (m^3/yr) is based on the following equation:

$$S_r = dA$$

where d is the rockwall retreat rate (m/yr).

The sediment delivery from the plateau S_p is calculated by applying

$$S_p = efD$$

where e is the creep rate (m/yr), f is the depth of moving material (m), and D is the plateau length within each creek (m).

These simplified equations are used to calculate for each creek the sediment supply for rockwall retreat and solifluction creep from the plateau into the slopes. The assumptions of constant rockwall retreat in the whole area and of steady creep in the total depth show

Table 4
Applied design rainstorm events with respective event duration and return period

Design event	Event duration/return period	Rainfall magnitude (mm)
1	1 d/2 yr	68
2	1 d/10 yr ≈ 2 d/2 yr ≈ 3 d/1 yr	92
3	1 d/50 yr ≈ 2 d/5 yr ≈ 3 d/2 yr ≈ 5 d/1 yr	117

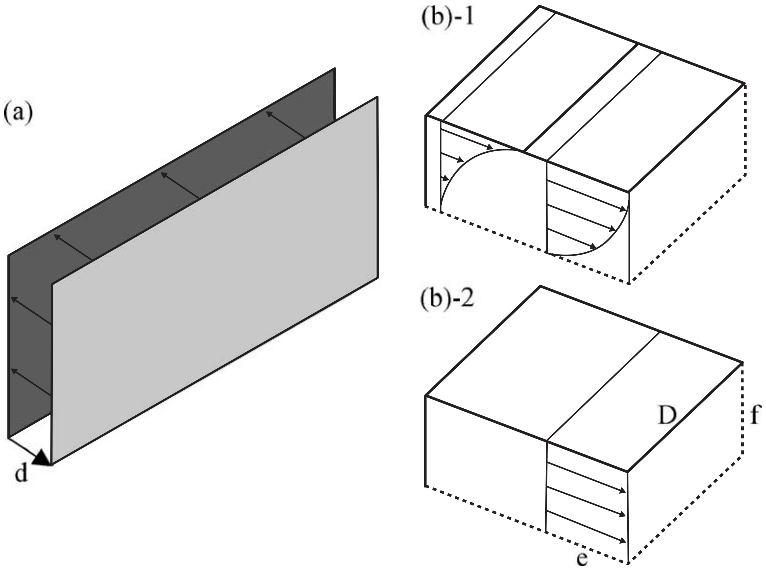

Fig. 7. Schematic diagrams of rockwall retreat (a) and sediment delivery from the plateau to the slope (b). Two different solifluction velocity profiles are given in panel (b)-1 and panel (b)-2. The applied model is seen in panel (b)-2. Characters refer to Table 8 (*d*—average rockwall retreat; *D*—plateau length; e—creep rate; *f*—creep depth).

that the calculated values give a 'worst case,' therefore values in nature might be significantly smaller. These calculations are compared with sediments required from analysis of climatic data to get an approximate information of surplus or deficit of sediment production for each creek.

It has to be pointed out, however, that the scenario modeling aims to give a regional distribution of the respective process. It is not intended to analyze a local problem, e.g., to actually design the technical protection measures for a single house. If someone is interested in dimensioning local structures, site-

FIELD WORK:	• Mapping of geomorphic forms and processes • Identification of debris flow type • Mapping sediment sources, travel paths and deposits • Measuring cross-sectional profiles of debris flow paths
↓	
SCENARIO MODELING:	• Calculation of cross-sectional areas • Determination of morphometric parameters • Calculation of return periods of different precipitation events • Analysis of debris flow volumes for respective rainstorm sizes
↓	
SEDIMENT CALCULATIONS:	• Approximation of weathering depth and creep rates on the plateau • Approximation of average rockwall retreat • Definition of average sediment reproduction • Calculation of sediment requirements based on hazard modelling • Determination of sediment deficit / surplus

Fig. 8. Flow chart of debris-flow investigation, modeling, and sediment calculations.

specific analysis has to be undertaken to guarantee an appropriate design. Rather, the study is aimed to provide a regional overview of the process. Thus, interpretation of results has to consider an inherent uncertainty. Fig. 8 gives a summary of the methodology used within this study. A more detailed description of the method embedded in the general debris-flow hazard assessment scheme is given by Glade and Jensen (2004).

4. Analysis and results

4.1. Geomorphic map

The geomorphic map shows that, in particular, periglacial, gravitational, and fluvial processes and forms dominate the glacial-shaped landscape (Fig. 9). Periglacial processes on the plateau of *Bíldudalsfjall* include stone sorting, solifluction, and gelifluction, as well as a high activity of bedrock weathering. Stone sorting features on plateaus change with increased slope angle towards the slope from rings (flat area) to stripes (creeping area), indicating a slow but continuous material supply from the plateaus into the slopes and gullies (Fig. 3). Similar findings have been presented by Rubensdotter (2002) for the Abisko region in Northern Swedish Lapland. This argument is strengthened by the observation of fresh sediment surface at the break from gently dipping plateau surfaces to steep upper slopes. Although this investigation could not prove the existence of permafrost, it might be possible to find sporadic permafrost on the plateaus similar in height of Bíldudalsfjall (Humlum, O., Ballantyne, C., personal communication). If the existing of permafrost is assumed, sediment weathering and thus sediment production would be larger than approximated in this analysis, and consequently, more material would be available for debris flows.

Upper and middle slopes are dominated by gravitational processes. Bedrock is barely covered with vegetation and is freshly weathered, indicating a high supply of sediment, which is available to rock falls and debris flows, as well as for snow avalanches. In addition, material supply from the plateau might even increase the volume of removable sediment. Talus slopes formed below the bedrock exposures have the characteristic distribution of small rock sizes on the top and increasing rock diameter associated with further distance to talus top. Therefore, also porosity and infiltration capacity increase. While the top of talus slopes is free of vegetation, middle and lower parts are covered by grass and moss, which is interrupted by active debris flows. Debris-flow channels and levees have been identified on the talus slope and the large debris cones.

Valley bottoms are flat and have been aggraded by fluvial processes. Rivers are not considered to endanger the community of Bíldudalur and are not included in further analysis.

4.2. Debris-flow map

As detected in the geomorphic map, debris flows occurred throughout the whole region. Mapped debris-flow paths, debris levees, potential water and sediment delivery catchments, and actual and potential debris-flow deposits have been classified in active (red colour) and currently inactive zones (green colour in Fig. 10).

Near the locality of Bíldudalur on the slope of *Milligil*, talus sediments interfinger with small slope debris-flow deposits from small gullies. Within a distance of 1.4 km, 7 out of 13 debris flows have been classified in the field as active. Although these are numerous and active, they seem not to endanger the village. In contrast, two large cones below the gullies *Gilsbakkagil* and *Búðargil* reach the ocean. Sediment of both cones is unsorted and, as small exposures show, randomly embedded in a fine matrix, which is evidence for debris-flow deposits. Both debris-flow paths have distinct channels in the gullies but also on the cones. This might suggest that potential impacts are limited to the near surroundings of these channels. Inherent to the debris-flow kinematic is, however, that they are able to leave previously used channels easily and to endanger other parts of the debris cone. This general behaviour is also supported by the regularity of both cone shapes, suggesting a deposition of sediment over the whole area by previous events. Thus, both gullies have been mapped as active. This high grade of activity is also documented in reports.

In addition, the steep most northern slope adjacent to the large gully is also a potential source area for large debris flows. Despite the fact that no recent debris-flow deposits have been investigated, former

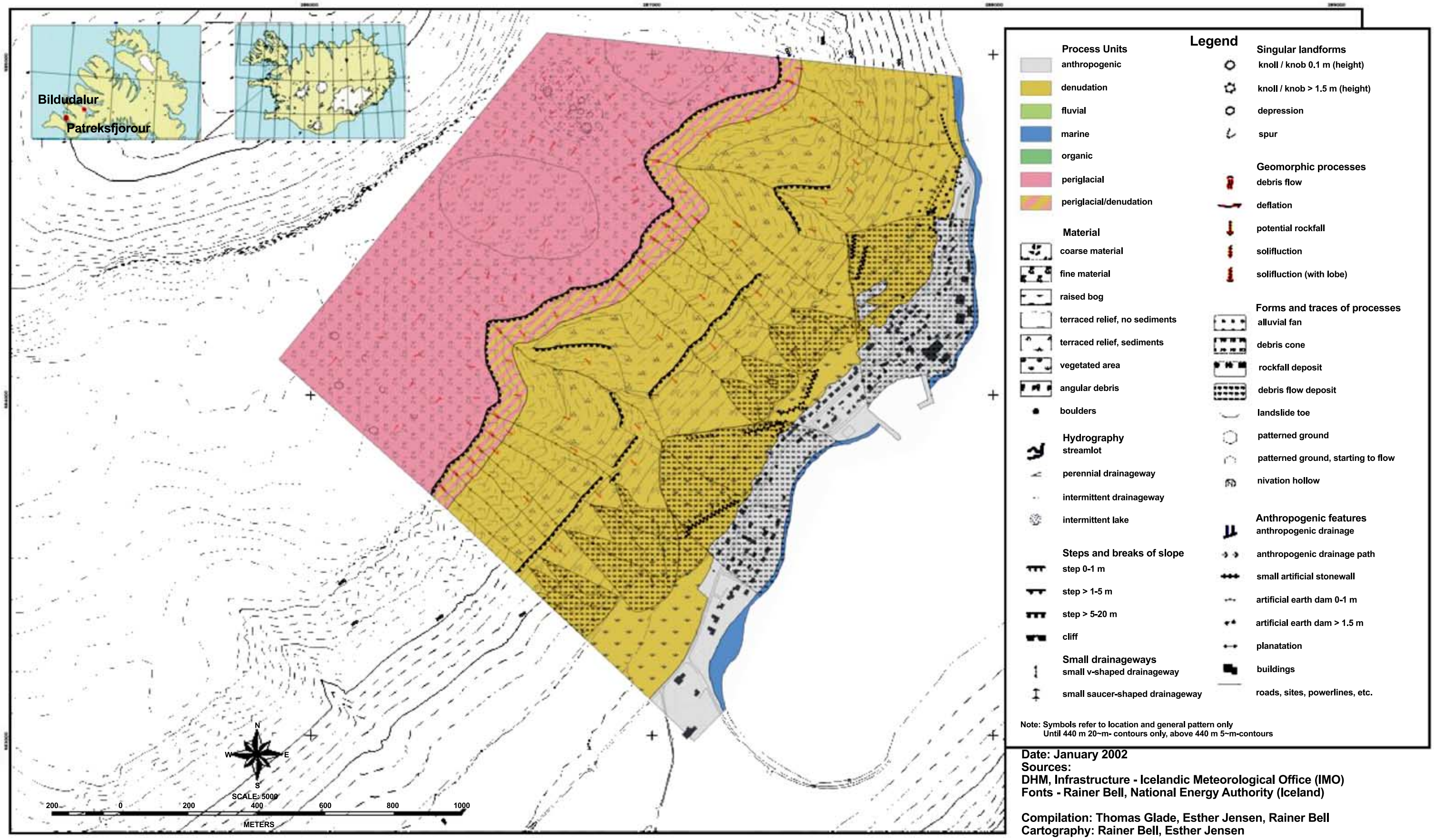

Fig. 9. Geomorphological map of Bíldudalur (Glade and Jensen, 2004).

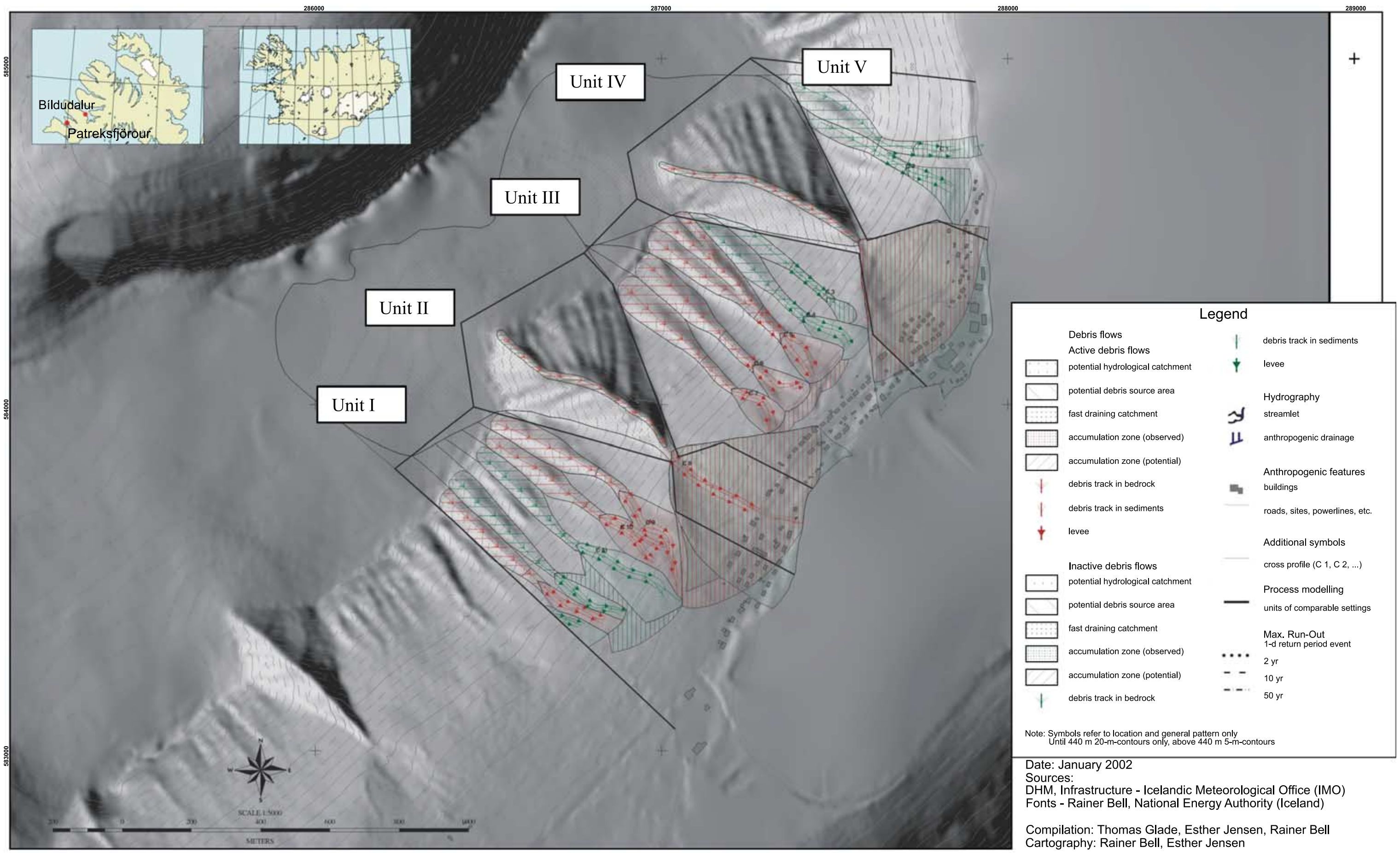

Fig. 10. Debris-flow run-out map, including slope units and debris-flow channels in Bíldudalur. Note: red colour refers to historically active catchments, and green has been inactive (Glade and Jensen, 2004). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

old levees indicate high magnitude events, which might have the potential to affect the most northern part of the settlement.

A general consideration of the classification active versus inactive is that this grade of activity displays the historical occurrence of debris flows only. It might well be possible that the former inactive catchments may be the basins for future debris flows. However, the debris-flow map shows that slope debris flows constitute a threat to the community. Furthermore, the gully debris flows with large catchments for water supply and sediment production have to be regarded as a significant process with high potential to cause damage in Bíldudalur.

Although debris-flow channels, levees, and largest cross-sections within the travel path have been identified and mapped in the field, large distinct debris-flow deposits could not be determined. Various reasons might explain this observation:

- Water content of former debris flows has been very high, thus deposits were widely spread and now difficult to determine. This problem of field recognition is in particular true for older debris-flow deposits, which are now vegetated. Major (1997) determined similar results of widespread and thin deposits accompanied with saturated flows in debris-flow experiments.
- High friction of the sediment leads to a fast loss of kinetic energy, and thus, the debris flow slows down quickly and deposits the mass while reducing velocity. Therefore, no distinct debris-flow deposit can be observed besides the well-developed levees.
- Debris-flow deposits have been removed naturally or artificially. Natural erosion of deposits might be due to floodwaters which might follow the major debris flow. Artificial removal is in particular true for deposits of past debris flows causing impacts on the community. In addition, channels with deposited material have been partially cleared to keep future debris flows in the channel.
- The main debris-flow front reached the ocean. Sediment deposited in the near-shore environment has been reworked through wave action. Of course, this is only a possibility for the channels, which reach the ocean. However, this has been observed in the past.

Despite these limitations, the geomorphological map together with the debris-flow map could be used to determine the potentially hazardous areas for Bíldudalur. However, a more detailed analysis has to be performed to delineate different sized events and to relate sediment requirements to actual sediment availability.

4.3. Scenario modeling

Debris-flow volumes of different sized rainstorms (Table 2) have been assigned to different design events (Table 4). Based on morphometric data for each creek within each unit, magnitudes of water, debris, and debris flows have been estimated for different sized triggering events (Table 5).

4.4. Sediment calculations

Sediment is derived mainly from bedrock weathering and solifluction from the plateau onto the slopes. Present-day rock-wall retreat rates have been calculated with basaltic lithology as 0.07 mm/yr (Hinchliffe and Ballantyne, 1998) and on sandstone and metamorphic rocks as 1 to 3 mm/yr (Barsch and King, 1981) in Svalbard and the Canadian Arctic, respectively. Other examples from a metamorphic region in northern Finland give rates of 0.04 to 0.94 mm/yr in the Holocene and, recently, 0.07 to 0.18 mm/yr (Södermann, 1980) or, for basaltic breccia in west Greenland, 0.05 to 2.4 mm/yr (Frich and Brandt, 1985).

The total literature review of rockwall retreat is summarized in Table 6. The range of values displays different environments but also yearly and decade oscillations of bedrock weathering. Based on comparable other catchments (Table 6), a rockwall retreat rate of 2 mm/yr was assumed within this study.

For the Westfjords, the sediment supply from the plateaus through solifluction and creep processes are most important for sediment delivery. For example, Yamada (1999) measured a soil creep rate of maximum 7.6×10^{-4} m^3/m yr in northern Japan. Assuming a weathering depth of 1 m, a 100-m section would supply 0.76 m^3 per year under humid conditions. Matsuoka (1998) observed in Japanese alpine environments surface velocities ranging between 27 and 539 mm per year, while 90% of the annual movement was concentrated on freeze–thaw periods. In addition to creep, downslope

Table 5
Results of debris flow modeling scenarios for Bíldudalur

Debris flow type	Unit	Creek no.	Basin area A (m^2)	Design storm P (mm)	Event magnitude		
					Water (30%) $V_w=aPA$ (m^3)[a]	Debris (70%) V_d (m^3)	Water and debris $V_w+V_d=V_{wd}$(m^3)
Slope	V	1	24,621	68	1,423	3,321	4,744
				92	1,925	4,744	6,418
				117	2,449	5,713	8,162
		2	10,183	68	589	1,373	1,962
				92	796	1,858	2,654
				117	1,013	2,363	3,376
	III	3	3,404	68	197	459	656
				92	266	621	887
				117	339	790	1,128
		4	17,483	68	1,011	2,358	3,368
				92	1,367	3,190	4,557
				117	1,739	4,057	5,796
		5	46,551	68	2,691	6,278	8,969
				92	3,640	8,494	12,134
				117	4,629	10,802	15,432
		6	29,652	68	1,714	3,999	5,713
				92	2,319	5,411	7,729
				117	2,949	6,881	9,830
		7	29,277	68	1,692	3,948	5,641
				92	2,289	5,342	7,632
				117	2,912	6,794	9,705
	I	9	23,633	68	1,366	3,187	4,553
				92	1,848	4,312	6,160
				117	2,350	5,484	7,834
		10	22,198	68	1,283	2,994	4,277
				92	1,736	4,050	5,786
				117	2,208	5,151	7,359
		11	22,550	68	1,303	3,041	4,345
				92	1,763	4,115	5,878
				117	2,243	5,233	7,475
Channel	II	8	573,618	68	33,155	77,362	110,517
				92	44,857	104,666	149,523
				117	57,046	133,108	190,154
	IV	12	390,469	68	22,569	52,661	75,230
				92	30,535	71,248	101,782
				117	38,832	90,608	129,440

[a] a=0.85.

movement of single boulders might be important too. Downslope displacement rates of single boulders in southern Norway range from 5 to 7 mm per year, with maximum rates of 26 mm/yr (Berthling et al., 2001). In the Canadian Arctic, Washburn (1999) has measured over a 10-year period an average displacement of 28 mm/yr on a 7° slope.

Solifluction rates in polar and subpolar regions are summarized in Table 7. Within this study, a solifluction rate of 0.25 m/yr and a creep depth of 0.5 m has been chosen and applied within further analysis. These values seemed appropriate for this study site considering comparable settings given in Table 7.

Both rockwall retreat and solifluction velocity and depth were combined with morphometric catchment parameters to calculate the average annual sediment production for each creek (Table 8). To estimate the sediment 'required' by rainstorm events, the design storm 2 (Table 4) has been chosen for further analysis. The design storm 2 corresponds to

Table 6
Review of rockwall retreat in arctic and alpine environments (extended from Hoffmann and Schrott, 2002 and André, 2003)

Arctic and alpine environments	Rockwall retreat (mm/yr)			Author(s)
	Maximum	Mean	Minimum	
North American environments				
Ellesmere Island, Canada	1.3	n.a.	0.5	Souchez, 1971
Ellesmere Island, Canada	3	n.a.	1	Barsch and King, 1981
Blanca Massif, Southern CO, USA	0.82	0.42	0.05	Olyphant, 1983
Rocky Mountains, USA	4.6	n.a.	0.3	Höllermann, 1983
Tully Valley Area, Finger Lakes Region, NY, USA	n.a.	0.22	n.a.	Jäger, 1997
Front Range, CO, USA	n.a.	0.76	n.a.	Caine, 1974
European environments				
Alpine areas	1.0	n.a.	0	Caine, 1974
Zemmgrund, Alps, Austria	1.0	n.a.	0.7	Poser, 1954
Schobergruppe, Austrian Alps, Austria	5.0	n.a.	n.a.	Buchenauer, 1990
Austrian Alps, Austria	0.1	n.a.	0.01	Becht, 1995b
Northern Finland	0.94	n.a.	0.04	Södermann, 1980
Northern Finland	0.18	n.a.	0.07	Södermann, 1980
Briançonnais, Alps, France	n.a.	3.0	n.a.	Couthard and Francou, 1989
Briançonnais, Alps, France	0.5	n.a.	0.05	Couthard and Francou, 1989
Alps, France	n.a.	1.2	n.a.	Kaiser, 1992
Alps, France	n.a.	1.0	n.a.	Francou, 1988
Alps, France	n.a.	2.5	n.a.	Francou, 1988
Reintal, Bavarian Alps, Germany	1.0	0.5	0.1	Hoffmann and Schrott, 2002
Reintal, Bavarian Alps, Germany	0.17	0.03	0.007	Keller and Moser, 2002
Karwendel, Bavarian Alps, Germany	0.73	0.28	0.06	Sass and Wollny, 2001
Bavarian Alps, Germany	0.1	n.a.	0.06	Becht, 1995a
Zugspitzplatt, Bavarian Alps, Germany	0.4	0.1	0.005	Sass, 1998
Western Dolomites, Alps, Italy	0.1	n.a.	n.a.	Dürr, 1970
Tatra Mountains, Poland	n.a.	0.7	n.a.	Kotarba et al., 1987
Tatra Mountains, Poland	3.0	0.84	0.1	Kotarba, 1971
Mount Tjåmohas, Lapland, Sweden	0.44	n.a.	0.22	Jonasson et al., 1997
Kärkevagge, Lapland, Sweden	0.1	n.a.	0.03	Jonasson et al., 1997
Val d'Hérens, Alps, Switzerland	n.a.	2.16	n.a.	Small, 1987
Swiss Alps, Switzerland	4.5	2.5	05	Barsch, 1977
Swiss Alps, Switzerland	1.5	n.a.	0.8	Barsch, 1996
Swiss Alps, Switzerland	3.4	n.a.	1.5	Barsch, 1996
Alps, Switzerland	0.36	n.a.	0.13	Galibert, 1965
Arctic environments				
Austfirdir, east Iceland	0.2	n.a.	0.03	Beylich, 2000
Wijdefjord, Svalbard	0.004	0.002	0	André, 1997
Wijdefjord, Svalbard	0.11	0.07	0.03	André, 1997
Kongsfjord, Svalbard	0.22	0.16	0.11	André, 1997
Kongsfjord, Svalbard	1.58	0.7	0.1	André, 1997
Central Svalbard	0.5	n.a.	0.34	Rapp, 1960
Northwest Svalbard	0.72	n.a.	0.11	André, 1986
West Greenland	6.0	2.0	n.a.	Humlum, 2000
Igpik, Disko-West Greenland	2.4	n.a.	0.05	Frich and Brandt, 1985
Japanese environment				
Japanese Alps	0.3		0.01	Matsuoka and Sakai, 1999

Table 7
Review of solifluction rates in polar to subpolar environments (modified from Matsuoka, 2001)

Environment	Monitoring period (yr)	Solifluction rate (cm/yr)	Depth of movement (cm)	Author(s)
North American environments				
Ellesmere Island, Canadian Arctic	5	1.7–3.1	60	Lewkowicz, 1988
Southwest Yukon, Canada	16–21	1.3	52	Price, 1973; 1991
Melville Island, Canadian Arctic	2–3	1.6	>65	Bennett and French, 1991
Cornwallis Island, Canadian Arctic	8	2.8	n.a.	Washburn, 1999
Schefferville, Canada	3	9	65	Williams, 1966
Banks Island, Canadian Arctic	11	0.6	n.a.	Egginton and French, 1985
Garry Island, Canadian Arctic	13	0.7	60	Mackay, 1981
Garry Island, Canadian Arctic	11–12	0.5	60	Mackay, 1981
European environments				
NE Greenland	5	0.9–3.7	n.a.	Washburn, 1967
Örafi, southeast Iceland	2	0.9	20	Douglas and Harrison, 1996
Austfirdir, east Iceland	3	2.5	20	Beylich, 2000
Okistindan, north Norway	1	2.1	30	Harris, 1972
Svalbard	6	3.0	51–90	Sawaguchi, 1995
Svalbard	2	2.2	110	Matsuoka and Hirakawa, 2000
Svalbard	2	3–4	n.a.	Jahn, 1985
Svalbard	n.a.	5.1	n.a.	Repelewska–Pekalowa and Pekala, 1993
Svalbard	2	2.5	48	Matsuoka and Hirakawa, 2000
Kap Linné, Svalbard	23	4.4	45	Åkermann, 1996
Kap Linné, Svalbard	23	3.5	30	Åkermann, 1996
Kap Linné, Svalbard	23	2.3	25	Åkermann, 1996
Kap Linné, Svalbard	23	0.9	30	Åkermann, 1996
Kap Linné, Svalbard	23	2.1	15	Åkermann, 1996
Kap Linné, Svalbard	23	1.5	35	Åkermann, 1996
Kap Linné, Svalbard	23	6.8	n.a.	Åkermann, 1996
Kap Linné, Svalbard	23	4.1	35	Åkermann, 1996
Kebnekaise, North Sweden	8	1.9	39	Jahn, 1991
Abisko Mountains, North Sweden	2–3	0.8	n.a.	Rudberg, 1962
Abisko Mountains, North Sweden	1–3	2.4	60	Rudberg, 1962
Abisko Mountains, North Sweden	4	5.2	n.a.	Nyberg, 1993
Abisko Mountains, North Sweden	17	3.1	n.a.	Rapp and Åkermann, 1993
Kärkevagge, Lapland, Sweden	1			Matsumoto and Ishikawa, 2002
Antartic environments				
Sør Rondane Mountains, Antartica	4	1.0	12	Matsuoka and Moriwaki, 1992
South GA, Subantarctic	1	47	25	Smith, 1960
Macquire Island, Subantarctic	5	38–138	n.a.	Selkirk, 1998

a daily rainfall event with a return period of 10 years, thus represents a common storm event. Consequently, the annual sediment production has been adapted to the 10-year return period. The resulting sediment required by rainstorms is then compared with the sediment total produced by both rockwall retreat and solifluction, and a ratio has been calculated. The ratio is simply the sediment requirements ($S_{(10)}$ in Table 8) divided by the sediment reproduction ($S_{t(10)}$ in Table 8). As the results show, there is always a sediment deficit with a ratio ranging between 6.2 and 8.5. A surplus of sediment has never been observed.

Even if calculated sediment reproduction gives approximations only, these estimates allow some information on sediment refill of storages. The analysis is based on the postulation that rockwall retreat and solifluction are of major importance for sediment delivery to slopes and gullies, and thus for any debris-flow hazard assessment scheme. This is in

Table 8
Factor of sediment deficit as a ratio between calculated sediment based on rainfall calculations and sediment reproduction from rockwell weathering and soil creep from the plateau into the slopes

Debris flow type	Unit	Creek No.	Basin area A (m)^2	Rockwall retreat S_r=dA[a] (m^3/yr)	Plateau length D (m)	Plateau supply S_p=efD[b] (m^3/yr)	Sediment total S_1=S_r+S_p (m^3/yr)	Sediment total[c] V_d=$S_{(10)}$ (m^3/10yr)	Sediment total $S_{1(10)}$=S_1*10 (m^3/10yr)	Factor of deficit $S_{(10)}/S_{(10)}$ (−)
Slope	V	1	24,621	49.2	90	11.3	60	4744	600	7.9
		2	10,183	20.4	25	3.1	23	1858	230	8.1
	III	3	3404	6.8	25	3.1	10	621	100	6.2
		4	17,483	35.0	40	5.0	40	3190	400	8.0
		5	46,551	93.1	165	20.6	114	8494	1140	7.4
		6	29,652	59.3	90	11.3	70	5411	700	7.7
		7	29,277	58.6	105	13.1	72	5342	720	7.4
	I	9	23,633	47.3	75	9.4	56	4312	560	7.7
		10	22,198	44.4	45	5.6	50	4050	500	8.1
		11	22,550	45.1	60	7.5	53	4115	530	7.8
Channel	II	8	573,618	1147.2	650	81.3	1228	104,666	12,280	8.5
	IV	12	390,469	780.9	650	81.3	862	71,248	8620	8.3

[a] d= average rockwall retreat (0.002 m/yr.).
[b] e= creep rate (0.25 m/yr.), f= creep depth (0.5 m).
[c] Refers to design storm 2 (Table 3) and V_d of P=92 mm (Table 5).

particular true for Westfjord conditions because slope angle from the plateau to the slope increases within short distances, leading to an increase of general soil creep and surface displacement rates.

5. Sediment supply considerations

It has to be pointed out that the absolute values of both debris-flow calculations and sediment reproduction rates should be considered as general trend. Despite the limitation of accuracy, however, this analysis demonstrates that there is an inherent danger of overestimating the hazard posed by debris flows when considering rainfall events only. As the conceptual model in Fig. 11 shows, rainstorms with similar totals (circled numbers) do not necessarily always produce similar debris-flow responses.

Each event is changing the catchment conditions. This corresponds to results by Bovis and Jakob (1999). Additionally, the changes relate not only to sediment removal but also to water storage capacity, runoff coefficients, and—in other environments—vegetation covers. Therefore, a detailed geomorphic analysis helps to understand the current catchment condition and is in any case an important addition to debris-flow hazard assessments.

6. Discussion and conclusions

It is evident from local observations that debris flows constitute a potential threat to the communities. The geomorphic map displays the dominant natural processes operating in the study area and

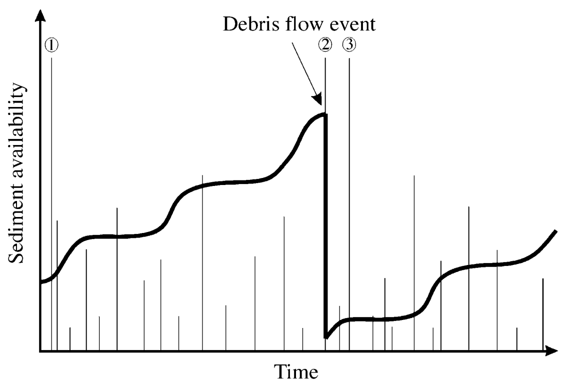

Fig. 11. Conceptual model of sediment change within a given catchment (refer also to Bovis and Jakob, 1999). Small bars refer to precipitation events and fat line gives the status of sediment availability. Circled numbers are rainfall events with a similar magnitude. Only rainfall event 2 is triggering a debris flow because enough sediment is available. Events 1 and 3 do not initiate debris flows but hyperconcentrated flows.

gives some indication of state of activity. It is a first approximation of temporal occurrence and current sediment distribution. The information gained provides the basis for further scenario modeling.

The more detailed debris-flow map indicates the istribution of debris flows and their forms and adds indirect information on the historical activity of debris flows. The analyses of particular debris-flow events are based on empirical relations. A number of assumptions and approximations are required because of the complexity of debris-flow processes and the resulting incomplete state of scientific understanding.

The simplified sediment budget observations show that more debris is required by rainstorm events than actually available. Therefore, there is an inherent danger of overestimating debris-flow occurrence. As the example shows, rainfall will trigger events but not necessarily debris flows. These might only be hyperconcentrated flows which usually are—from an applied point of view—far less destructive. Thus, it is important to be aware of the assumptions on which the debris-flow analysis is based and to investigate the major implications in more detail in any hazard analysis. This result is also supported by similar conclusions of Bovis and Jakob (1999). It can be concluded that geomorphic analysis provides an important and valuable tool, which supports the better understanding of the environment.

These conclusion can be summarized as follows:

- Hazard scenarios are dependent on sediment availability.
- Sediment reproduction might be lower than sediment removal.
- Inherent tendency of overestimation.
- Geomorphic analysis supports any debris-flow hazard assessment.

7. Perspectives

This analysis is based on a number of assumptions and gives approximations only. Numerous issues have been addressed, which should be investigated in more detail in the future. Work might include:

7.1. Sediment budgets

- to determine the depth of the weathered material on the plateau to be able to calculate sediment availability;
- to investigate the velocity of soil creep and solifluction in different depths on the crest between plateau and upper slope to determine the refill potential for debris-flow sources;
- to measure the bedrock weathering on the plateau (e.g., Murton et al., 2000);
- to date exposed rock faces for rock weathering rates and debris-flow deposits to establish a more detailed event frequency;
- to determine the overall sediment production;
- investigation of catchment changes after debris-flow occurrence

7.2. Climatic and hydrologic investigations

- to maintain a climatic station to link observed movement rates to recent climatic conditions, which have to be connected to a regional climatic network;
- to measure pore water pressures and soil temperatures in different depths to be able to quantify subsurface water flow from the plateau to the slopes, thus defining the water catchment for a given gully and the drainage paths and ratesm, which are also important for slush flow events;

7.3. Event data

- to investigate new events immediately after occurrence in detail to allow adoption and verification of chosen parameters and consequently to increase accuracy and reliability of calculations;
- to establish a debris-flow data base, including debris-flow characteristics as well as climate conditions;
- to establish a frequency/magnitude relationship and triggering threshold conditions based on all recent data and on further information, such as data from the early instrumental period EIP (e.g., Jónsson and Gardarsson, 2001) and climate proxy data (e.g., Ogilvie and Jónsson, 2001);

- to run scenarios using GCM downscaling techniques to propose future debris-flow activity (e.g., Schmidt and Glade, 2003).

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