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Regional Scale Assessment of the Natural Hazard Potential for Road No 76 from Siglufjörður to Straumnes

Report

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Regional Scale Assessment of the Natural Hazard Potential for Road No 76 from Siglufjörður to Straumnes

Report

1 Objectives

A substantial part of the Icelandic road network lies in areas which are affected by natural hazard processes. Though the resulting road maintenance costs are considerable there is no general overview of the natural hazard situation up to now.
The total length of the classified highway road network in Iceland today is ca. 8200 km, mostly low-volume roads outside built-up areas. The rural network contains ca. 4300 km highways and ca. 3900 km distributor roads. Collector roads and mountain tracks are not included.

The aim of this investigation is to describe and assess the generalized natural hazard situation on classified rural roads, i.e. following a regional scale approach. The results are maps indicating the natural hazard potential for specific road sections, which can provide a basis for detailed planning.
The main emphasis is on the following natural hazard processes:

- rockfall and sagging
- flooding and debris flows
- avalanches

The regional scale approach is calibrated by a detailed investigation of the section of road no 76 from Siglufjörður to Straumnes.
This comprises the following steps and results/deliverables:

- mapping the natural hazard areas
- evaluation of the specific natural hazard processes
- comparison of the investigated natural hazard processes
- comprehensive assessment for the specific road sections
- recommendations

To guarantee that the developed approach can be applied to all classified roads in Iceland the investigation needs to be mainly based on already existing data most of which is available at the offices of Vegagerðin and Veðurstofa Íslands.

The investigation was made by an interdisciplinary team consisting of

- Mag. Stephan Jenewein (alpS Centre of Natural Hazard Management and GRID-IT GmbH)
- Mag. Klaus Kleebinder (GRID-IT GmbH)
- Dr. Hannes Kleindienst (GRID-IT GmbH)
- Dipl.-Geogr. Jörn Lippert (alpS Centre of Natural Hazard Management)
- Dipl.-Ing. Alexander Ploner (i.n.n. GmbH & Co KG)
- Prof. Dr. Friedrich Schöberl (Institute of Geography, University of Innsbruck and alpS Centre of Natural Hazard Management)
- Dr. Haraldur Sigþórsson (Línuhönnun verkfræðistofa)
- Mag. Thomas Sönser (i.n.n. GmbH & Co KG)
- Prof. Dr. Johann Stötter (Institute of Geography, University of Innsbruck and alpS Centre of Natural Hazard Management)
- Dr. Maria Wastl (Institute of Geography, University of Innsbruck)

Members of this team were significantly involved in the development of the approaches and models used in this investigation. Thus Alexander Ploner and Thomas Sönser as well as the Institute of Geography, University of Innsbruck contributed substantially to the development of the EGAR approach (see 4). PROMAB-GIS (see 4.2) was developed in collaboration by Stephan Jenewein, Hannes Kleindienst, Alexander Ploner, Friedrich Schöberl, Thomas Sönser and Johann Stötter. Klaus Klebinder and Hannes Kleindienst produced the models GRID-rock and GRID-aval (see 4.1 and 4.3).

2 Investigated Part of Road No 76

The investigated part of road no 76 reaches from Siglufjörður to Straumnes (see Fig. 1) and has a length of 38.7 km.

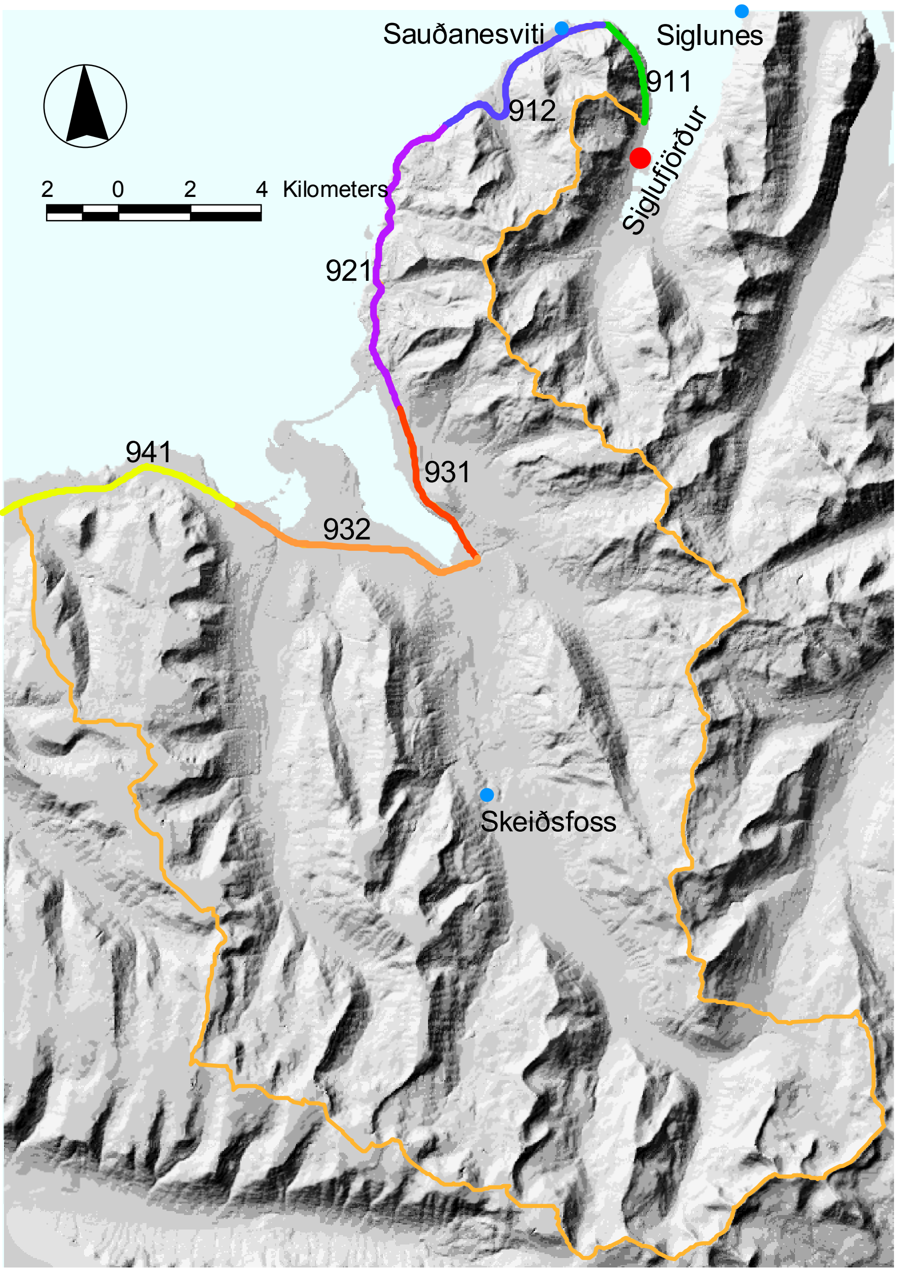

Fig. 1: Overview of the investigated section of road no 76 from Siglufjörður to Straumnes

For this assessment it has been divided into six sections:

- Section 911: km 0-3.2 – Siglufjörður to the northernmost point of road no 76

Description:
This section reaches from the town of Siglufjörður to the northernmost point of road no 76. The road rises slowly from Siglufjörður to the southern exit of the tunnel with steep slopes

getting increasingly close to the road on its western side. Both at the southern and the northern exit of the tunnel these slopes are very steep and unstable.

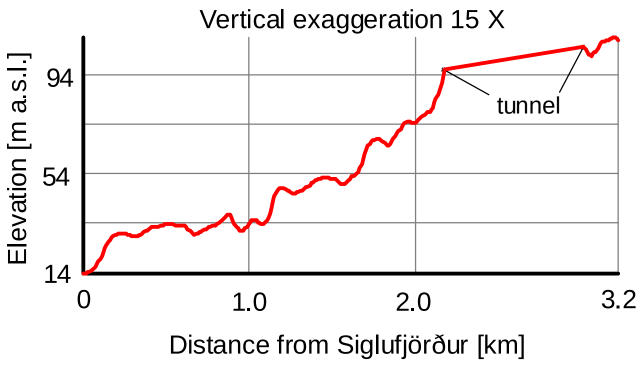

Fig. 2: Vertical section of road section 911: km 0-3.2 – Siglufjörður to the northernmost point of road no 76

- Section 912: km 3.2-9.5 – northernmost point of road no 76 to Skriðnavík

Description:
This section reaches from the northernmost point of road no 76 to Skriðnavík. Steep slopes rise immediately from the road in most stretches of this section. The road crosses piped streams from Engidalur and Úlfsdalir.

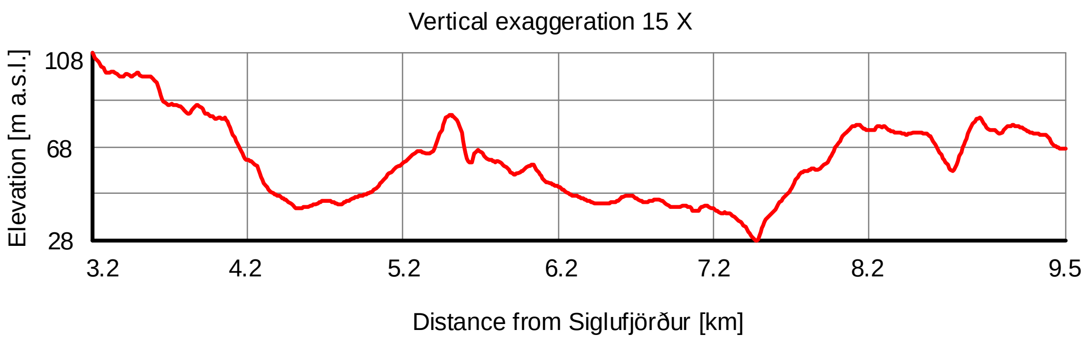

Fig. 3: Vertical section of road section 912: km 3.2-9.5 – northernmost point of road no 76 to Skriðnavík

- Section 921: km 9.5-18.7 – Skriðnavík to south of Hraun

Description:
This area is characterized by gravitational mass movements of varying age, velocity and size, from landslides to small-scale sagging. Some of these processes are still active. (See also the detailed report on the section of Siglufjarðarvegur around Almenninga by Sæmundsson et al. 2004.) The vertical section of the road shows frequent inclines as it passes many small catchments.

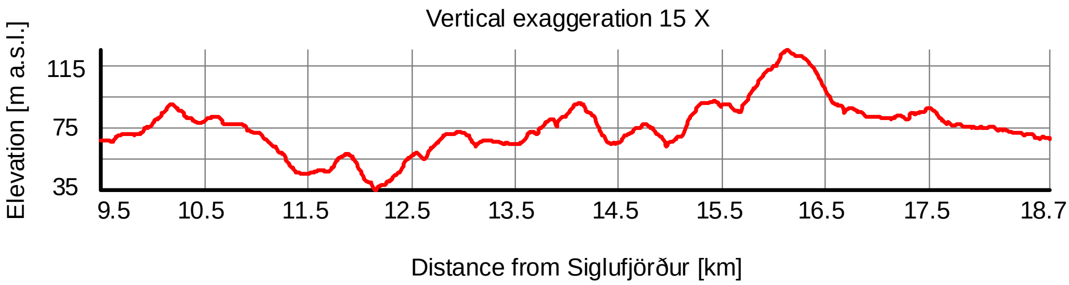

Fig. 4: Vertical section of road section 921: km 9.5-18.7 – Skriðnavík to south of Hraun

- Section 931: km 18.7-23.6 – south of Hraun to Ketilás

Description:
The area surrounding road no 76 is less steep in this section. The road itself however shows an incline at Lambanesás. The road crosses two medium-sized streams, there is a pipe under the road for Reykjaá and a bridge over Brúnastaðaá.

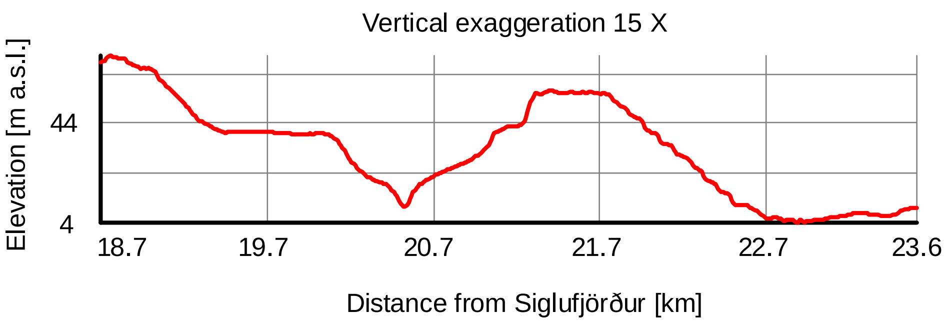

Fig. 5: Vertical section of road section 931: km 18.7-23.6 – south of Hraun to Ketilás

- Section 932: km 23.6-31.1 – Ketilás to pipe 510

Description:
This is the flattest part of the investigated section of road no 76 with bridges over the two biggest rivers (Fljótaá, Flókadalsá).

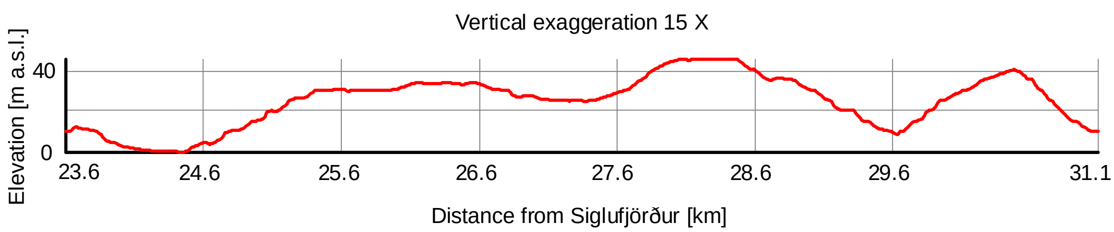

Fig. 6: Vertical section of road section 932: km 23.6-31.1 – Ketilás to pipe 510

- Section 941: km 31.1-38.7 – pipe 510 to crossroads to Straumnes

Description:
In this section steep slopes lie in greater distance from road no 76 than in sections 911 to 921. The road crosses only comparatively small catchments and streams.

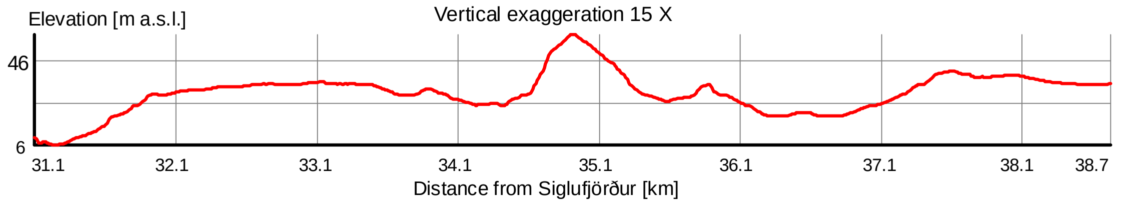

Fig. 7: Vertical section of road section 941: km 31.1-38.7 – pipe 510 to crossroads to Straumnes

3 Data Bases

3.1 Maps

The following sheets of the topographic maps Iceland-Ísland 1:50,000, edition 1-DMA, series C761, prepared and published by the Defense Mapping Agency Hydrographic/Topographic Center, Washington, D.C. and Landmælingar Íslands were used for the investigation area:

- 1816 I Höfðaströnd
- 1817 II Fljótavík
- 1916 IV Svarfaðardalur
- 1917 III Héðinsfjörður

The scanned sheets were georeferenced (UTM grid) by means of ARC-GIS and put together as a background map for the results of the investigation. The margins of the map sheets were fitted manually.

3.2 DTMs

For this investigation three digital terrain models (DTMs) were produced using ARC-GIS:

- DTM1
  based on the digitized contour lines (interval 20 m) and geodetic points of the 1:50,000 maps for the whole investigation area,
- DTM2
  based on the digital 5m contour lines provided by Vegagerðin for parts of the area along the investigated section of road no 76, and
- DTM3
  based on a combination of DTM1 and DTM2.

The elevation data of the 5m contours was used where available. At the margins of these areas a 100 m wide buffer zone with the averaged elevation data of the two DTMs was formed. For the remaining part of the investigation area the elevation data of DTM1 was used.
This improved DTM provided the basis for modelling the investigated processes, which guarantees a high quality of the modelling results for the areas around the road.

3.3 Aerial Photographs/Orthophotos

The following black and white aerial photographs covering the whole investigation area were available at the Institute of Geography, University of Innsbruck: Landmælingar Íslands Fjarkönnunardeild, flight N 07.08.1994, pictures 0965, 0967 - 0968, 0972 - 0979, 1043 - 1054, 1059 - 1071, 1137 - 1138, 1140 - 1144.

Stereo pairs of these aerial photographs provided the basis for mapping the geomorphological processes relevant to the assessment of the natural hazard potential for the whole investigation area before going into the field.
Orthophotos of a resolution of 1.0 m were produced from these photographs at the Institute of Geography, University of Innsbruck. The pictures were scanned with a resolution of 1500 dpi using a specialized Heidelberger Topaz scanner. Digital orthophotos were produced from the scanned aerial photographs by means of the software PCI OrthoEngine on the basis of the DTM1 (see 3.2).

For the areas around the road digital colour orthophotos with a resolution of 0.5 m were provided by Vegagerðin: Straumnes-Siglufjörður *.tif *dxf *.dgn DVD 27-10-2004.HSH.

The mosaic of the digital colour orthophotos provides the background for the the 3D-views of the investigated road sections and the detailed maps of the results.

3.4 Meteorological Data

There are three meteorological stations operated by Veðurstofa Íslands in or close to the investigation area: Sauðanesviti (66°11.112'N, 18°57.204'W, 30 m a.s.l.), Skeiðsfoss (66°00'N, 19°01'W, 84 m a.s.l.) and Siglunes (66°11.626'N, 18°50.585'W, 8 m a.s.l.). The locations of these stations are shown in Fig. 1.
Precipitation measurements from these meteorological stations were used to determine the design precipitation for the discharge modelling (see 4.2).

3.5 Reports

Þorstein Sæmundsson, Halldór G. Pétursson og fl. 2004. Kortlagning á sígi á Siglufjarðarvegi um Almenninga. Áfangaskýrsla.

Ágúst Guðmundsson, Walter Fahrnberger, Haraldur Hallsteinsson 2001. Siglufjörður - Ólafsfjörður. Veggöng um Héðinsfjörð. Yfirlit yfir jarðfræði Tröllaskaga og aðstæður til jarðgangagerðar. Jarðfræðistofan ehf. Unnið fyrir Vegagerðina.

Jarðfræðistofa ÁGVST, BAH Ráðgjöf 1999. Greinargerð um aurskriðu úr Kóngsnefi í Fljótum.

Jónas Elíasson 1998. Útreikningar á flóðum. Verkfræðistofnun Háskóla Íslands, Vatnaverkfræðistofa.

Hafliði Hafliðason 1982. Jarðfræðiskýrsla vegna jarðsigs á Almenningum við Siglufjörð.

Sæmundsson et al. (2004) give a detailed description of the sagging processes for the part of road no 76 around Almenningur (see 4.1). The report by Jarðfræðistofa ÁGVST, BAH Ráðgjöf (1999) is an investigation of a specific mass movement in this area. Hafliðason (1982) describes the geological situation for this road section.

Guðmundsson et al. (2001) give an overview of the geology for Tröllaskagi in general and for the planned tunnel between Siglufjörður and Ólafsfjörður.

The paper by Elíasson (1998) includes an estimation of daily precipitation values for Iceland which was used in the discharge modelling (see 4.2).

4 Investigated Processes and Applied Models

As stated in the objectives (see 1) this investigation of the natural hazard potential focuses on processes which are characteristic for alpine mountain areas, i.e.:

- rockfall and sagging
- flooding and debris flows
- avalanches

Due to these specifications and the requirements of the regional scale and the resulting detail in the determination of areas affected by natural hazard processes an approach was adopted which has been developed in the Eastern Alps in recent years. In addition to the natural hazard zone maps on the planning level with scales = 1:10,000 a preceding regional scale overview level with scales = 1:25000 has recently been introduced in Austria, Germany and Italy. The basics for this were developed in the research project EGAR (*Nutzungs- und funktionsorientierte Beurteilung von Einzugsgebieten hinsichtlich Wildbächen, Lawinen und Wasserhaushalt zur nachhaltigen Entwicklung und Sicherung des Siedlungs- und Wirtschaftsraumes auf regionaler Ebene*, i.e. user-orientated operational assessment of catchments with regard to torrents, avalanches and water balance as a contribution to sustainable development and safety of areas of settlement and economic activities on a regional scale), which was financed by the European Union.

This approach aims at increasing the efficiency and effectiveness in natural hazard management by maximizing the use of existing data (maps, reports, scientific investigations etc.) and reducing time-consuming and expensive fieldwork to a minimum. Modellings which are specially adapted to the requirements of a regional scale guarentee comprehensible, reproduceable and comparable results, which help to assign priorities in the planning of measures.
The EGAR approach has been extensively applied in Austria, Germany and Italy since. These investigations have followed a generally standardized procedure with adaptions to the specific situations and requirements in each country.

The procedure is based on maps of the geomorphological processes on a scale of 1:25,000, which were produced by means of aerial photograph interpretation and checked in the field. These maps distinguish between the following process groups:

- water related
- fall
- slide
- flow/creep

As to their activity the process groups are classified as:

- active
- inactive
- inactive assumed

The maps further indicate different process areas, i.e.:

- erosion area
- transport area
- accumulation area
- not specified

The mapping results are shown in two maps (see Appendix A2, Map 1 and Map 2). Due to the specific situation for the investigated section of road no 76 from Siglufjörður to Straumnes the process groups were adapted as follows:

- rockfall and sagging
- flooding and debris flows
- avalanches

4.1 Rockfall and Sagging

Processes

Rockfall and sagging are gravitational processes, i.e. mass self movements dominated by gravitation and thus can be distinguished from processes of mass transport. While e.g. Abele (1974) differentiated between *Bergsturz* (landslides > 1 million m³), *Felssturz* (rockfall with a volume of 1 m³ to 1 million m³) and *Steinschlag* (rockfall < 1 m³), Laatsch and Grottenthaler (1972) distinguish between slow and fast processes.

For this assessment rockfall comprises all processes of gravitational movement of rock masses with a volume in the dimension of m³, which follows e.g. what Evans and Hungr (1993) defined as fragmental rockfall or rockfall.

In contrast to these sudden fast gravitational mass movements sagging belongs to the slow processes.

Objective and procedure

Objective of this investigation was the determination and outline of areas of rockfall hazard for the section of the road no 76 from Siglufjörður to Straumnes.

For the areas around the road potential starting areas of rockfall processes and the apices of the talus cones were mapped based on stereo pairs of the aerial photographs (see 3.3). These maps were checked and completed in the field. S*tumme Zeugen* as defined by Aulitzky (1992) were used as the main indicators for the range of the rockfall processes.

The ground-truthed maps were digitized and transferred to a GIS dataset, which was the basis for modelling the range of the rockfall processes using the model GRID-rock.

Model approach

Heim (1932) observed that the line connecting the source area and the head of the accumulation area of a rockfall shows a characteristic inclination. Depending on how the lines connecting these two points are defined, different slope angles can be measured (see Fig. 8):

- the geometric gradient (*Geometrisches Gefälle* according to Heim, see Fig. 8), i.e. the angle of gradient of the line connecting the crest of the source area and the most distal point of the accumulation area (Heim 1932) in the geometric gradient model, and
- the shadow angle (see Fig. 8), i.e. the angle of gradient of the line connecting the apex of the talus cone and the margin of the shadow in the shadow-angle model (Evans and Hungr 1988, 1993).

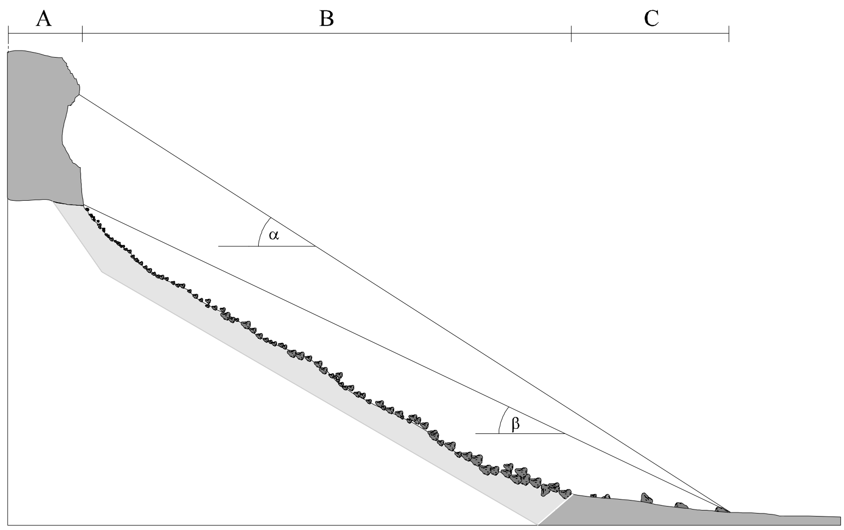

Fig. 8: Geometric gradient (a) and shadow angle (ß). A: source area, B: talus cone, C: shadow = according to Evans and Hungr (1993) that area at the end of the talus cone where debris no longer covers the ground completely (Meißl 2001, 133).

In geometric terms, the models can be described as follows: Each pixel at the upper margin of the talus slope forms the apex of a cone whose generator (line that connects the apex and base of the cone) has a characteristic gradient that has been determined during model calibration. The boundary of the danger zone is located where these cones meet the terrain surface and thus the rockfall paths on the surface.

For this investigation the shadow-angle model was used, which provides more reliable results on the regional scale (Meißl 2004 pers. comm.).

Model GRID-rock
GRID-rock (Grid based Trajectory Rockfall Model) is a two-dimensional model to calculate the range of rockfall processes on a regional scale. Like the grid based trajectory avalanche model (GRID-aval) it is based on the approach of Lied and Bakkehoi (1980) and determines the maximum range in a topographic-statistical way. The model describes the range of a rockfall by means of the shadow angle ß (see Fig. 8).

The current version of the model calculates the range of rockfall processes starting from a given line by means of an estimated slope. This estimated slope describes the loss of energy of the rockfalls during the gravitative process. Thus the difference between the real slope of the terrain surface and the estimated slope gives the corresponding kinetic energy, which, in a following step, can be used as input data for the modelling of the rockfall paths. The angle ß is determined on the basis of a statistical analysis of known rockfall events.
The starting line is defined by the mapped apices of the talus cones.
The rockfall paths are determined by means of a vector-orientated model on the basis of orientation and slope data from the digital terrain model. The output of this modelling is a sequence of points in three-dimensional coordinates.
The model requires the following input data (format ESRI GRID ASCII):

- digital elevation model
- slope
- orientation
- starting line (grid cells)

The influence of topography on the calculated rockfall paths is determined by a weighting factor (topoweight). A topoweight value of 1 stands for a motion close to that of a ball while a very high value represents the motion characteristics of water. A further model parameter (widening) defines the lateral extension of the rockfall from the calculated paths. In model calculations made so far a topoweight value of 10 and a widening of 0.005 have given good results.
A shadow angle of 26° as suggested by Meißl (1998, 2004 pers. comm.) was used for the calculations.
Possible over-estimations of the range of rockfall processes by this model are balanced by the fact that in Iceland the ground is frozen over long periods of time.
Fig. 9 shows an example of the modelled rockfall paths and the extent of the accumulation area, which is the outer boundary of all cells reached by the rockfall paths.

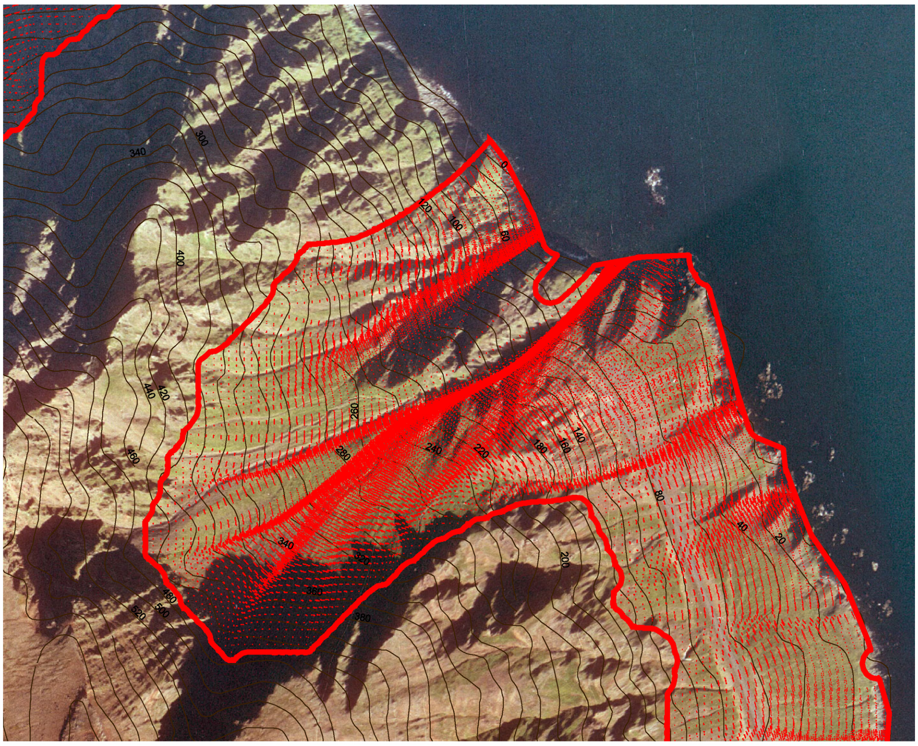

Fig. 9: Modelled paths and accumulation area of a rockfall

Results

Based on the findings in the field and the modelling results 16 sections of rockfall hazard could be identified in the investigated part of road no 76 from Siglufjörður to Straumnes (see Table 1). These areas are also shown in the overview in Appendix A2, Map 3 and in detail in Appendix A2, Map 4 and Map 5.

No	Road km from Siglufjörður
1	0.25-0.57
2	0.65-0.95
3	1.03-2.17
4	3.03-3.94
5	4.25-4.67
6	5.29-5.70
7	5.92-5.94
8	6.11-6.89
9	7.91-7.98
10	8.25-9.15
11	9.39-9.77
12	10.27-10.61
13	10.68-10.75
14	11.14-11.33
15	13.08-13.24

Table 1: Areas of rockfall hazard in road no 76 from Siglufjörður to Straumnes

The areas of rockfall hazard mostly lie in road sections 911, 912 and 921 between Siglufjörður and km 13.25 (see Fig. 10, Fig. 11 and Fig. 12). Altogether almost 7 km or half of this northern three sections are areas of rockfall hazard. Especially the parts of road no 76 between Siglufjörður and the southern exit of the tunnel and from the northern exit of the tunnel to the northernmost point (i.e. section 911) are almost entirely affected by rockfall processes. Areas of rockfall hazard also cover extensive parts of section 912, while in section 921 these areas are limited to four comparatively short parts of the road.

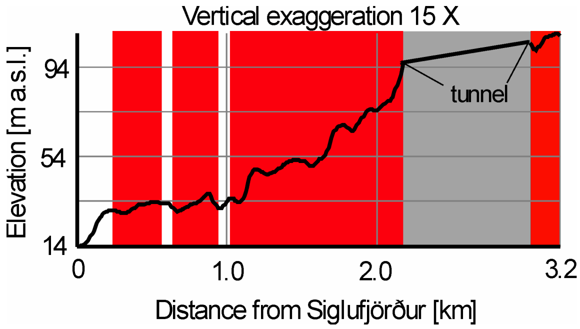

Fig. 10: Areas of rockfall hazard in road section 911: km 0-3.2 – Siglufjörður to the northernmost point of road no 76

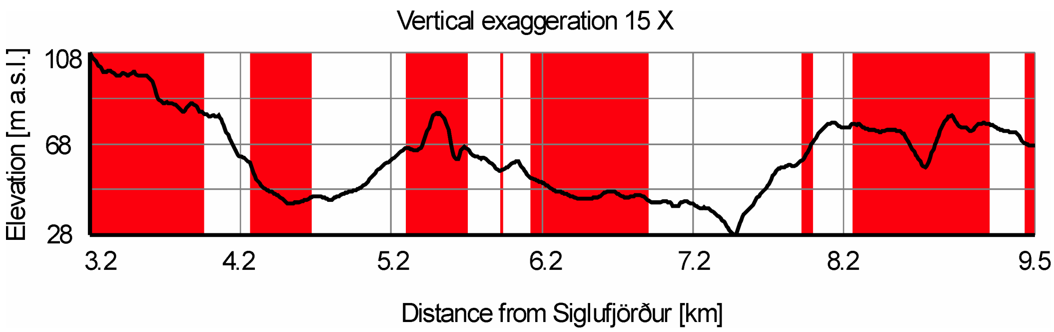

Fig. 11: Areas of rockfall hazard in road section 912: km 3.2-9.5 – northernmost point of road no 76 to Skriðnavík

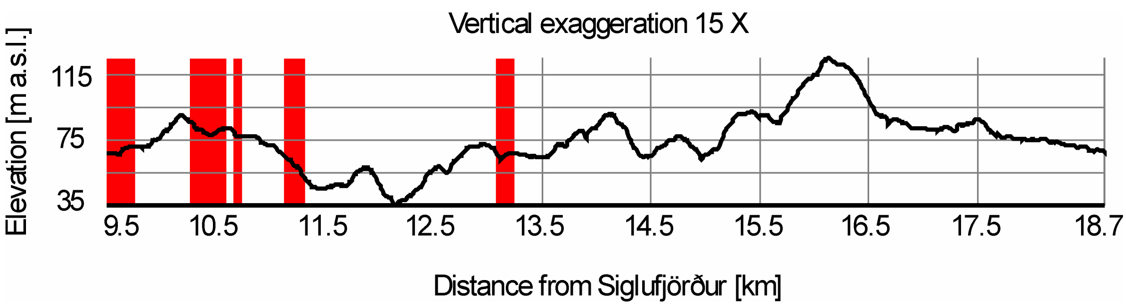

Fig. 12: Areas of rockfall hazard in road section 921: km 9.5-18.7 – Skriðnavík to south of Hraun

West of km 13.25 the slopes along road no 76 are less steep and less high. There are steep and high slopes in road section 941, which are, however, too far away from the road to cause a hazard by rockfall material from these slopes for the road in this section.

The part of road no 76 between km 10.1 and km 18.2 around Almenningur is affected by intensive sagging processes, which are causing considerable damage to the road (see Fig. 13). There is a frequent change between active and inactive areas over short distances. The processes in the section of Siglufjarðarvegur around Almenningur were investigated in detail by Sæmundsson et al. (2004).

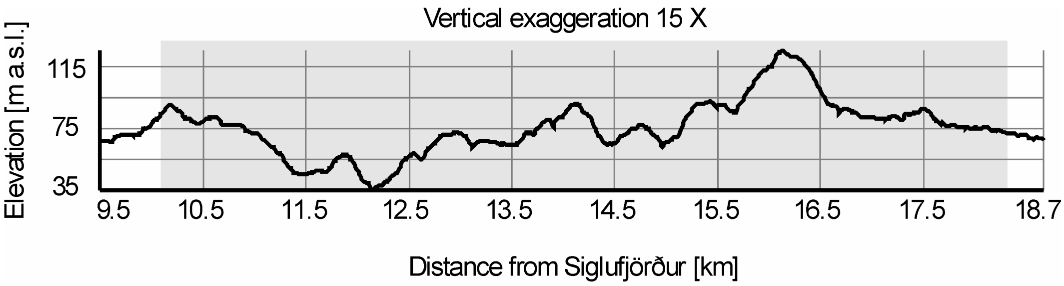

Fig. 13: Areas of sagging hazard in road section 921: km 9.5-18.7 – Skriðnavík to south of Hraun

4.2 Flooding and Debris Flows

Processes
Precipitation and infiltration capacity of an area determine the surface runoff, which forms the stream network. The distribution and size of the streams thus depend both on hydrological and geological-topographical conditions.
With a drainage that is usually very variable the streams are mainly formed by the discharges and the transported solids of extreme floods of a long recurrence period.
Roads crossing such streams thus need hydraulic structures which allow free discharge of these floods. The discharge capacity of these structures is mainly determined by the full cross-section area and the in- and outflow conditions.
In steep streams with bed slopes > 20% and sufficient sediment supply the fluvial transport of solids can turn into a hyperconcentrated discharge or a debris flow, which is characterized by a rapid flow of a papascent mixture of water and solids. If the afflux of water is high debris flows can also be triggered by local slips or sagging processes on the slopes.

Objective and procedure
Objective of this investigation was the determination and outline of areas of flooding and debris flow hazard for the section of the road no 76 from Siglufjörður to Straumnes.
The assessment of the flooding hazard was based both on a hydraulic calculation of the relevant flow conditions and on a hydrological discharge model.
The flooding and debris flow hazards were modelled using the program PROMAB-GIS, which was developed in collaboration by i.n.n. GmbH & Co KG, the Institute of Geography, University of Innsbruck and the alpS Centre of Natural Hazard Management (see e.g. Schöberl et al. 2004).

Flood modelling
Based on the analysis of the official precipitation measurements available for the investigation area design precipitation values were determined. Together with the runoff coefficients which were derived from the maps of the geomorphological processes (see 4), the latter provided the basis for modelling the discharge hydrographs and the flood peaks.

Analysis of official precipitation measurements
There are two stations with precipitation measurements operated by Veðurstofa Íslands in the investigation area (see Fig. 1), i.e. Sauðanesviti (66°11.112'N, 18°57.204'W, 30 m a.s.l.) and Skeiðsfoss (66°00'N, 19°01'W, 84 m a.s.l.). The station at Siglunes (66°11.626'N, 18°50.585'W, 8 m a.s.l.) lies only little east of the investigation area of and was therefore included in the analyses.
Daily precipitation sums are recorded at these stations. There are no measurements of a higher temporal resolution. The length of the records varies from station to station, altogether the measurements cover the period from 1961 to 2004.
A comparison of the monthly 24h-precipitation maxima (Table 2) gives the highest values for Skeiðsfoss with 24h-precipitation maxima of up to 91.3 mm. It further shows that the highest 24h-precipitation values are mainly recorded from July to October.

Skeiðsfoss			Sauðanesviti			Siglunes		
P	Y	M	P	Y	M	P	Y	M
91.3	1982	8	86.4	1994	10	64.4	1963	7
82.0	1974	7	79.9	2002	6	58.5	1983	9
73.7	1991	11	49.3	1995	10	51.1	1984	5
73.2	1991	10	44.6	1992	9	49.5	1986	9
59.7	1982	10	43.2	1994	6	49.3	1985	10
58.8	1983	1	41.9	2000	3	48.5	1962	6
58.1	2004	9	41.6	2002	9	45.5	1981	9
56.5	1992	6	40.8	1990	6	44.7	1965	1
55.2	1995	10	39.4	1997	9	44.6	1963	9
54.4	1992	9	39.3	1993	7	43.1	1974	9
53.6	1974	8	37.8	2001	10	40.7	1970	9
52.0	1994	10	37.3	1999	9	40.0	1973	10
51.5	1988	8	37.1	1992	6	39.3	1985	7
50.8	1989	3	36.0	1991	10	38.2	1973	8
50.8	1985	10	34.8	2004	3	38.0	1964	10
49.7	2001	10	33.6	1999	5	37.9	1975	1
48.1	2001	8	32.9	2000	9	35.7	1977	3
47.4	1998	7	32.3	2000	8	35.3	1975	12
47.4	1984	9	32.2	1997	10	34.5	1964	8
46.2	1987	9	32.0	1991	9	33.5	1967	10

Table 2: Ranking of the 20 highest monthly 24h-precipitation maxima for the stations Skeiðsfoss, Sauðanesviti and Siglunes (P = precipitation [mm], Y = year, M = month)

The maximum 24h-precipitation value according to these measurements (i.e. station Skeiðsfoss, August 1982, 91.3 mm) gives an arithmetical precipitation intensity of 3.8 mm/h. Considerably higher intensities, however, have been observed for short precipitation events in Iceland.

Data on precipitation events of less than 24h duration
There are no standardized and regular precipitation measurements of a higher than daily resolution for the investigation area. For single extreme precipitation events, however, measurements within the 24h period are available. Thus Morgunblaðið from 21/9/2004 reports maximum precipitation intensities of 10 to 15 mm/h for an extreme precipitation event in the Ólafsfjörður area between 18/9/2004 0:00 am and 21/9/2004 12:00 pm according to measurements from Veðurstofa Íslands. More detailed information on the length of the period during which these precipitation intensities were measured is however not given.
Analyses of precipitation data from Eskifjörður in eastern Iceland gave precipitation intensities of 20 mm/h for a duration of 5 h and an annuality of ca. 100 a (Jensen and Sönser 2002). A comparison of the daily precipitation values in eastern Iceland and the investigation area shows that the measured daily precipitation is at least 20% lower in the Siglufjörður area than in eastern Iceland. If the precipitation intensity is reduced by the same factor the resulting value is 16 mm/h, which is in good agreement with the measurements quoted by Morgunblaðið.

On this basis a precipitation event of a duration of 5 h and a constant intensity of 15 mm/h was used as design precipitation for the discharge calculations.

Determination of the flood peaks
This is a rough estimation of the maximum discharge for the defined precipitation event (design precipitation). The flood peak was calculated by means of the Rational Formula. The

precipitation values were combined with the runoff coefficients for each cell (10 x 10 m) rather than as averages for parts of the catchments. The annuality of the resulting flood discharge is equal to that of the design precipitation.
The direct application of the Rational Formula without accounting for the factor time for the determination of the flood peak is mainly due to the long duration of the precipitation event. It can be assumed that within 5 h all parts of the affected catchments contribute to the discharge. The estimation of the flood peak thus needs to be based on the whole catchment area.
The map of the runoff coefficients (see Appendix A2, Map 7 and Map 8) was produced on the basis of aerial photograph interpretation and supplementing investigations in the field. The main focus was placed on mapping the geomorphological processes in the catchments (see Appendix A2, Map 1 and Map 2). A runoff coefficient was determined for each process area. In a second step, the land cover and soil/vegetation in the investigation area were assessed and the runoff coefficients based on the geomorphological processes modified accordingly where necessary. The map of the runoff coefficient areas was finally digitized by means of a Geographical Information System (GIS) and combined with the design precipitation (Rational Formula).

Hydraulic calculations
The focus was placed on estimating the discharge capacies of the bridges and pipes in the investigated section of road no 76 from Siglufjörður to Straumnes and compare them with the expected flood discharges of the corresponding streams.
The discharge processes through bridges and pipes are complex with a number of possible flow conditions. The relevant conditions for the investigated hydraulic structures were determined in the field. Thus the flow conditions could be reduced to two cases:

Case 1: free-surface inlet flow
This condition holds as long as the water depth in front of the culvert does not exceed 120 % of the height of the barrel and the tailwater level does not control the flow of the outlet side.
For this case the hydraulic capacity can be estimated by means of equation 1 according to Chanson (1999).

Equation 1: $Q_{K1} = C_1 \cdot w \cdot \sqrt{g} \cdot h_1^{1.5}$

C_1 = 0.438 for circular culverts and C_1 = 0.490 for box culverts
where Q_{K1} is the free inlet flow discharge capacity [m^3/s], h_1 the water depth of the approach flow, g gravitational constant 9.81 m/s^2 and w [m] the culvert width

If the flood peak exceeds Q_{K1} the flow backs up and the entrance gets submerged.

Case 2: submerged entrance flow
The back up can rise as long as the elevation of the road is not exceeded. This case can be calculated by means of equation 2.

Equation 2: $Q_{K2} = A \cdot \sqrt{\frac{2 \cdot g \cdot h}{1 + z_e + z_r}}$

where Q_{K2} [m^3/s] is the outflow discharge capacity, A [m^2] full cross-section area of the culvert, g [9.81 m^2/s] gravitational constant, h [m] pressure head above the culvert centre, $?_r$ friction loss coefficient, $?_e$ entrance loss coefficient. The friction loss is calculated according to the Darcy-Weisbach Equation with friction coefficients ? of 0.02 for concrete walls and 0.05 for corrugated sheets.

Flooding of the road can occur if the discharge capacity Q_{K2} for the highest possible back up without flooding is smaller than the expected flood peak. For these cases it additionally needs to be checked if the water can flow alongside the road to a neighbouring pipe of a higher discharge capacity.

Debris flow modelling

The stream network was calculated by means of the program PROMAB-GIS on the basis of the DTM3 (see 3.2). This network was then reduced to streams with catchments of at least 100 cells of 100 m² each (= 1 ha).

By combination with the slope dataset the bed slope was determined for each stream section. Two slope classes and corresponding hazard levels were distinguished:

- Debris flow hazard level 1
  is based on experience from the Alps with bed slopes > 20%. These are streams which can produce debris flows under unfavourable conditions.
- Debris flow hazard level 2
  indicates streams with bed slopes = 20% which can produce debris flows under extremely unfavourable conditions (worst case assumption).

Results

Flooding

The section of road no 76 from Siglufjörður to Straumnes crosses 67 bridged or piped streams (see Table 3). The main characteristics of these bridges and pipes (size, design, slope of the pipe) were recorded in the field. Photographs of the most important bridges and pipes can be found in Appendix A1.

The positions of the bridges and pipes were measured in the field by means of a D-GPS. Thus these data could be directly transferred to a digital GIS dataset. In combination with the digital road data the positions of the bridges and pipes in the vertical section of the road (road km) were determined.

As a basis for the discharge modelling the vertical sections and several cross sections of the most important streams were measured in the field up- and downstream of the bridges or pipes. Additional vertical and cross sections were derived from the DTM2 (see 3.2).

For 24 major streams crossing road no 76 between Siglufjörður and Straumnes (see Table 4) the discharges were modelled (case 1: free inlet flow).

For catchments 18, 19 and 20 flood peaks between 0.8 and 3.1 m³/s were modelled. There are no pipes for these streams under road no 76, however, which causes a potential flooding hazard for the road in these areas.

Catchment 10 was investigated in detail. In this catchment, which has an area of 150.6 km², there is a power station with a reservoir which has a strong influence on the discharge. The retention of the discharge was calculated as follows. The start-up time for the 5 h design precipitation event was determined synthetically by means of the equation of Kirpich. The discharge hydrograph was routed using the continuity equation for unsteady flow. The results are shown in Fig. 14. There is a significant reduction of the flood peak from 250 m³/s to 12 m³/s, which reduces the total discharge from 334 m³/s to 96 m³/s. A similar but less significant retention of the discharge by a lake can be found in catchment 5. As the discharge capacity of the stream at the bridge of road no 76 is much higher than the expected flood peak a specific calculation of the retention was not necessary for the assessment of the flooding hazard in this case.

Table 3: Bridges and pipes in road no 76 from Siglufjörður to Straumnes

No	Road km	Stream (see Appendix A2, Map 8)	Catchment [ha]	Size (width, height/diameter) [cm]	Design	Slope of the pipe [%]	Photograph(s) (see Appendix A1)
10	0.7	23	71	32	concrete pipe		1208-1209
20	3.2			77	corrugated iron		1232-1233
30	4.3			45	concrete pipe		1239-1240
40	4.8	21	243	360, 420	corrugated iron pipe	5.0	1241-1246
50	5.8			105	corrugated iron pipe		
60	6.9			45	corrugated iron pipe		1252
70	7.1			60	corrugated iron pipe		1256-1258
80	7.5	25	810	370, 410	corrugated iron	7.0	1259-1262
90	8.1			50	corrugated iron pipe		1263-1265
100	8.4			25	iron pipe		1266-1268
110	9.5			60	corrugated iron pipe		1272-1275
120	12.7	17	317	190, 170	concrete pipe	7.0	1285-1286
130	12.9			49	corrugated iron pipe		1436-1437
140	13.1	16	45	60	corrugated iron pipe		1440-1441
150	13.5			74	corrugated iron pipe		1442-1443
160	13.9			60	corrugated iron pipe		1444-1449
170	14.2			74	corrugated iron pipe		1452-1454
180	15.0	15	242	200	corrugated iron pipe	5.0	1455-1461
190	15.1	14	234	90	corrugated iron pipe	8.0	
200	15.3			45	corrugated iron pipe		1462-1464
210	17.7	13	242	90	corrugated iron pipe	15.0	1467-1471
220	17.9			85	corrugated iron pipe		
230	18.1			72	corrugated iron pipe		1472-1474
240	18.2			80	corrugated iron pipe		
250	18.3			60	corrugated iron pipe		
260	18.4			60	corrugated iron pipe		
270	18.5			0			1476-1477
280	18.6			0			
290	18.7			74	corrugated iron pipe		1478-1479
300	18.9			60	corrugated iron pipe		
310	19.4			70	corrugated iron pipe		1480-1485
320	19.6			55	concrete pipe		1486
330	20.5	12	2458	500	corrugated iron pipe	5.0	1487-1489
340	21.3			55	concrete pipe		
350	22.7			80	corrugated iron pipe	5.0	1490-1492
360	23.3			60	concrete pipe		
370	23.6	11	3418	1200, 500	concrete bridge	2.0	1493-1494
380	24.4	10	15063	2200, 150	concrete bridge	1.0	1501-1502

No	Road km	Stream (see Appendix A2, Map 8)	Catchment [ha]	Size (width, height/diameter) [cm]	Design	Slope of the pipe [%]	Photograph(s) (see Appendix A1)
390	25.5			30	corrugated iron pipe		1503-1504
400	25.7			50	corrugated iron pipe		
410	25.8			130	corrugated iron pipe		1505-1506
420	26.2			50	corrugated iron pipe		1507
430	26.4			50	corrugated iron pipe		1508-1510
440	26.8	9	198	155	corrugated iron pipe		1511-1512
450	27.3			155	corrugated iron pipe		
460	28.6			35	concrete pipe		1513-1514
470	28.6			105	corrugated iron pipe		
480	28.7	8	220	62	corrugated iron pipe		
490	29.2			40	corrugated iron pipe		
500	29.6	5	8750	4000, 1060	concrete bridge		1515-1520
510	31.1	7	182	80, 110	concrete pipe		1521
520	31.2	6	35	80, 110	concrete pipe		
530	31.5			50	iron pipe		1522
540	32.0			50	concrete pipe		
550	32.3			62	corrugated iron pipe		
560	32.5			0			
570	32.6			30	concrete pipe		
580	32.7			0			
590	32.8			50	corrugated iron pipe		1523
600	33.7	1	203	80, 100	concrete pipe		
610	34.1			50	concrete pipe		
620	34.2			38	concrete pipe		
630	34.4	2	47	80, 105	concrete pipe		1525-1526
640	35.5	3	350	200, 200	concrete pipe		
650	36.7	4	1604	200	corrugated iron pipe	2.0	1531
660	37.8			62	corrugated iron pipe		

Table 4: Modelled discharges (case 1: free inlet flow) of the major streams crossing road no 76 between Siglufjörður and Straumnes

Pipe/bridge (see Table 3)	Road km	Catchment (see Appendix A2, Map 8)	d [m]	w [m]	Number of openings	Shape	C_1	h_1/d	h_1 [m]	**Q_{K1} [m³/s]**	**Q_{peak} [m³/s]**	Status
10	0.7	23	0.32	0.32	1	oval	0.438	1.20	0.38	**0.1**	**1.6**	submergence see case 2
40	4.8	21	4.30	3.70	1	oval	0.438	1.20	5.16	**64.1**	**5.8**	no flooding
80	7.5	25	4.30	3.70	1	oval	0.438	1.20	5.16	**64.1**	**17.0**	no flooding
no	10.0	20	0.00	0.00	1	oval	0.438	1.20	0.00	**0.0**	**1.6**	flooding
no	10.3	19	0.00	0.00	1	oval	0.438	1.20	0.00	**0.0**	**0.8**	flooding
no	12.1	18	0.00	0.00	1	oval	0.438	1.20	0.00	**0.0**	**3.1**	flooding
120	12.7	17	2.00	1.70	1	oval	0.438	1.20	2.40	**9.4**	**6.0**	no flooding
140	13.1	16	0.60	0.60	1	oval	0.438	1.20	0.72	**0.5**	**0.9**	submergence see case 2
180	15	15	2.05	2.05	1	oval	0.438	1.20	2.46	**10.9**	**4.7**	no flooding
190	15.1	14	0.90	0.90	1	oval	0.438	1.20	1.08	**1.4**	**4.8**	submergence see case 2
210	17.7	13	1.00	1.00	1	oval	0.438	1.20	1.20	**1.8**	**5.1**	submergence see case 2
330	20.5	12	4.30	5.70	1	oval	0.438	1.20	5.16	**79.6**	**58.0**	no flooding
370	23.6	11	5.26	11.80	1	box	0.490	0.65	3.42	**114.5**	**78.0**	no flooding
380	24.4	10	3.20	21.00	1	bridge	0.490	1.00	3.20	**184.5**	**96.0**	no flooding - peak discharge reduction due to reservoir retention
440	26.8	9	1.55	1.55	1	oval	0.438	1.20	1.86	**5.4**	**4.4**	no flooding
470	28.6	8	1.05	1.05	1	oval	0.490	1.20	1.26	**2.3**	**5.4**	submergence see case 2 (470 and 480 act together for catchment 8)
480	28.7	8	0.62	0.62	1	oval	0.438	1.20	0.74	**0.5**	**5.4**	
500	29.6	5	10.60	18.00	1	bridge	0.490	0.65	6.89	**499.6**	**252.0**	no flooding
510	31.1	7	1.10	0.80	1	box	0.438	1.20	1.32	**2.0**	**3.3**	submergence see case 2
520	31.2	6	1.10	0.80	1	oval	0.438	1.20	1.32	**2.0**	**0.7**	no flooding
600	33.7	1	1.00	0.80	1	oval	0.438	1.20	1.20	**1.6**	**4.5**	submergence see case 2
630	34.4	2	1.05	0.80	1	oval	0.438	1.20	1.26	**1.8**	**0.8**	no flooding
640	35.5	3	2.00	2.00	1	oval	0.438	1.20	2.40	**10.2**	**7.8**	no flooding
650	36.7	4	2.00	2.00	2	oval	0.438	1.20	2.40	**20.4**	**39.0**	submergence see case 2

d: diameter or height of pipe/bridge
w: width of pipe/bridge
C_1: shape dependent constant
h_1: water depth of the approach flow
Q_{K1}: free inlet flow discharge capacity
Q_{peak}: expected flood peak

Table 5: Modelled discharges (case 2: backup flow) of the major streams crossing road no 76 between Siglufjörður and Straumnes

Pipe (see Table 3)	Road km	Catchment (see Appendix A2, Map 8)	d [m]	w [m]	Open-ings	h [m]	h/d	?$_e$	?	l_r [m]	?$_r$	v [m/s]	**Q_{K2} [m³/s]**	**Q_{peak} [m³/s]**	Status
10	0.7	23	0.32	0.32	1	1.5	4.69	0.5	0.02	25.0	1.56	3.10	**0.2**	**1.6**	flooding
140	13.1	16	0.60	0.60	1	1.5	2.50	0.5	0.05	20.0	1.67	3.05	**0.9**	**0.9**	no flooding
190	15.1	14	0.90	0.90	1	1.5	1.67	0.5	0.05	20.0	1.11	3.36	**2.1**	**4.8**	no flooding - residual discharge drains to 180
210	17.7	13	1.00	1.00	1	3.0	3.00	0.5	0.05	20.0	1.00	4.85	**3.8**	**5.1**	flooding
470	28.6	8	1.05	1.05	1	2.0	1.90	0.5	0.05	20.0	0.95	4.00	**3.5**	**5.4**	no flooding - residual discharge drains to 500
480	28.7	8	0.62	0.62	1	2.0	3.23	0.5	0.05	20.0	1.61	3.55	**1.1**	**5.4**	
510	31.1	7	1.10	0.80	1	3.0	2.73	0.5	0.02	20.0	0.43	5.53	**4.9**	**3.3**	no flooding
600	33.7	1	1.00	0.80	1	2.0	2.00	0.5	0.02	20.0	0.45	4.49	**2.8**	**4.5**	flooding
650	36.7	4	2.00	2.00	2	3.0	1.50	0.5	0.05	24.5	0.61	5.28	**33.2**	**39**	flooding

d: diameter or height of pipe
w: width of pipe
h: tolerable pressure head above the pipe centre with no flooding of the road
?$_e$: entrance loss coefficient
?: Darcy-Weisbach coefficient
l_r: lenth of pipe
?$_r$: friction loss coefficient
v: mean flow velocity
Q_{K2}: outflow discharge capacity
Q_{peak}: expected flood peak

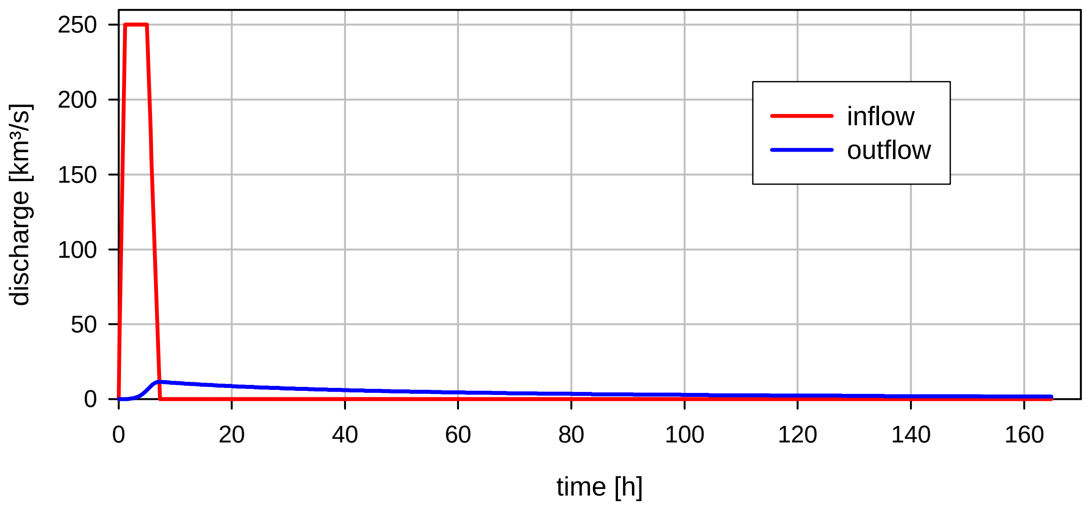

Fig. 14: Modelled discharge hydrographs of Fljótaá at the in- and outflow of Stífluvatn (lake retention)

In further nine catchments the modelled flood peaks are higher than the discharge capacities of the respective hydraulic structures. For these cases an additional hydraulic modelling (case 2: backup flow) was made (see Table 5).
Based in these calculations the pipes for the streams in catchments 1, 4, 13 and 23 cause a potential flooding hazard for road no 76. Similar problems could be expected for the pipes of the streams in catchments 8 and 14, which can, however, drain the excess water through other pipes.

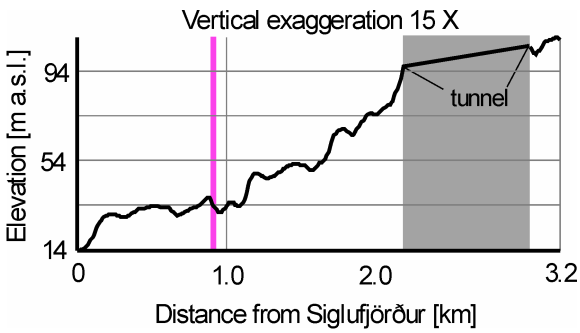

Fig. 15: Areas of flooding hazard in road section 911: km 0-3.2 – Siglufjörður to the northernmost point of road no 76

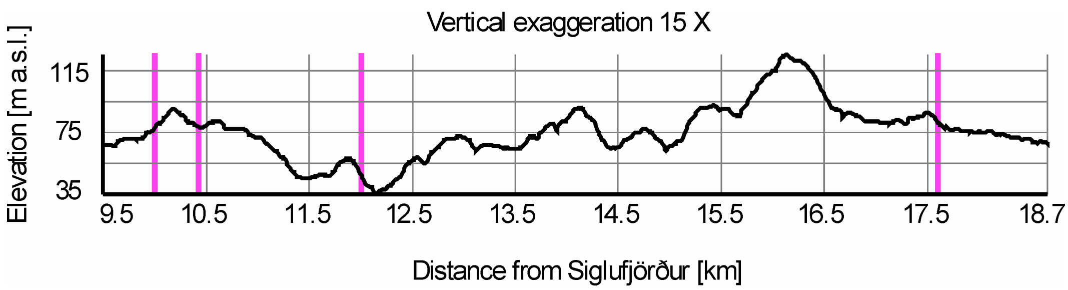

Fig. 16: Areas of flooding hazard in road section 921: km 9.5-18.7 – Skriðnavík to south of Hraun

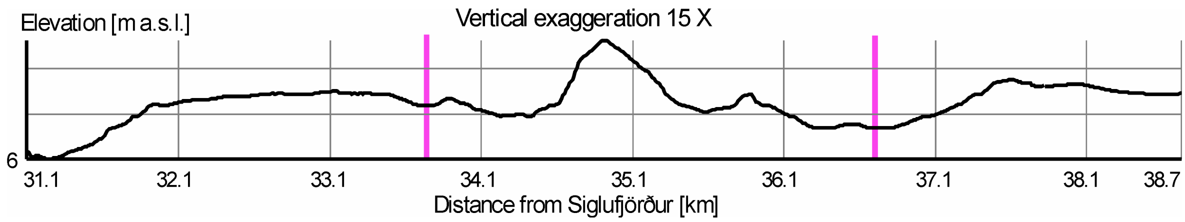

Fig. 17: Areas of flooding hazard in road section 941: km 31.1-38.7 – pipe 510 to crossroads to Straumnes

Debris flows

In the investigated part of road no 76 between Siglufjörður and Straumnes there are 103 areas of debris flow hazard. 59 of these are areas of debris flow hazard level 1 and 44 areas of debris flow hazard level 2 (see Table 6). These areas are also shown in the overview in Appendix A2, Map 9 and in detail in Appendix A2, Maps 10 to 14.

Road km	Debris flow hazard level	Road km	Debris flow hazard level	Road km	Debris flow hazard level	Road km	Debris flow hazard level
0.07	2	5.93	1	11.51	2	17.90	1
0.28	2	6.29	1	11.58	2	18.07	1
0.38	1	6.39	1	11.70	2	18.15	1
0.49	1	6.53	1	12.15	2	18.23	1
0.52	1	6.57	1	12.65	2	18.29	1
0.56	1	6.60	1	12.98	2	18.37	1
0.62	1	6.66	1	13.01	2	18.53	1
0.67	1	6.76	2	13.08	2	18.58	1
0.94	1	6.86	2	13.31	2	18.66	1
1.03	1	7.02	2	13.37	2	21.13	1
1.43	1	7.05	2	13.48	2	21.20	1
1.55	1	7.09	2	13.74	2	21.60	1
1.70	1	7.28	2	13.89	2	21.79	1
1.84	1	7.71	2	14.07	2	21.93	1
1.99	1	7.87	1	14.15	2	21.96	1
2.07	1	7.95	1	14.46	2	22.04	1
3.13	1	8.83	1	14.96	1	31.30	2
3.34	1	9.13	1	15.01	2	31.49	2
3.50	1	9.16	1	15.09	2	31.70	2
3.79	1	9.89	2	15.66	2	32.47	2
3.86	1	10.40	1	16.65	2	32.83	2
4.20	1	10.92	1	16.81	1	32.96	2
4.34	2	10.94	1	17.03	2	33.73	2
4.89	2	11.00	1	17.66	1	34.37	2
5.22	1	11.10	2	17.73	1	34.48	2
5.64	1	11.44	2	17.83	1		

Table 6: Areas of debris flow hazard (debris flow hazard levels 1 and 2) in road no 76 from Siglufjörður to Straumnes

Like the areas of rockfall hazard the areas of debris flow hazard lie mostly in road sections 911 and 912 (see Fig. 18 and Fig. 19). Due to the steep mountainsides close to the road nearly all streams that can produce debris flows in these sections have bed slopes > 20% before they cross of the road and therefore were assigned to debris flow hazard level 1. This means that debris flows can reach the road in these areas under unfavourable conditions and, due to the sudden fast character of these processes, may not only damage the road but are also a hazard for goods and people on it.

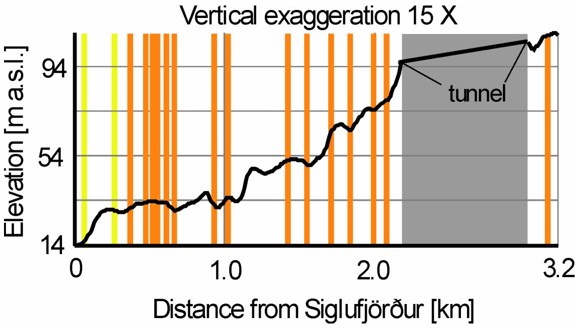

Fig. 18: Areas of debris flow hazard (debris flow hazard levels 1 and 2) in road section 911: km 0-3.2 – Siglufjörður to the northernmost point of road no 76

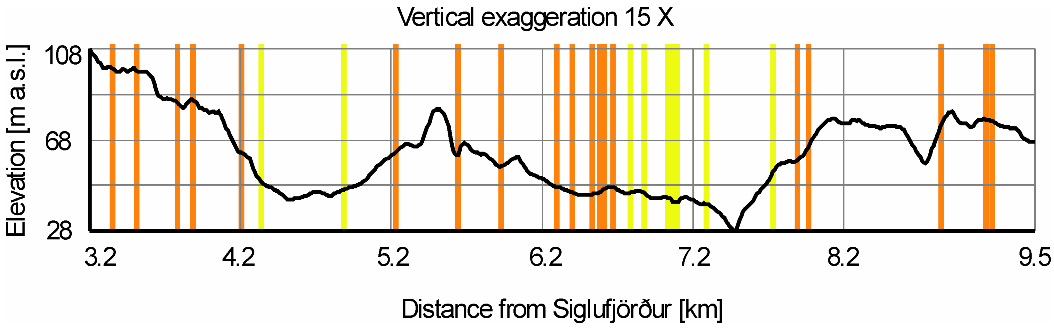

Fig. 19: Areas of debris flow hazard (debris flow hazard levels 1 and 2) in road section 912: km 3.2-9.5 – northernmost point of road no 76 to Skriðnavík

In adjacent section 921 the road also crosses many streams that can produce debris flows (see Fig. 20). 18 of these belong to debris flow hazard level 1, though the slopes are generally less steep and further away from the road in this section. Most of the streams in section 921 have bed slopes belonging to debris flow hazard level 2. This means that only under extremely unfavourable conditions there is a debris flow hazard for the road in these cases.

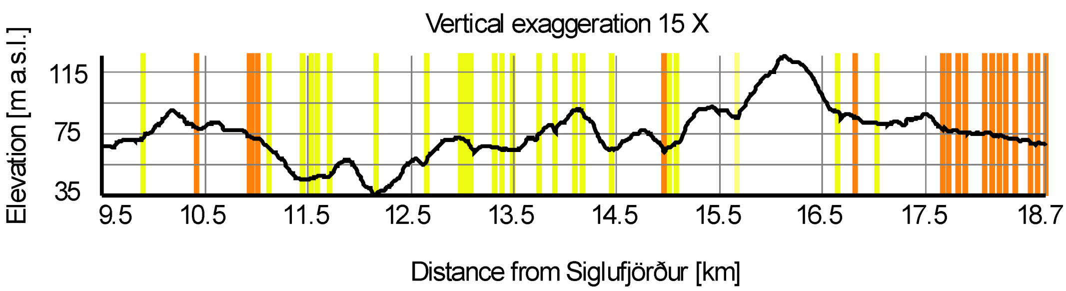

Fig. 20: Areas of debris flow hazard (debris flow hazard levels 1 and 2) in road section 921: km 9.5-18.7 – Skriðnavík to south of Hraun

In road sections 931 and 941 (see Fig. 21 and Fig. 22) the debris flow hazard is comparatively small. There are seven small but steep streams with debris flow hazard level 1 in section 931. In section 941 there are nine streams with steep upper sections, which under extremely unvafourable conditions (debris flow hazard level 2) can lead to debris flows getting over the less steep lower sections and reaching the road.

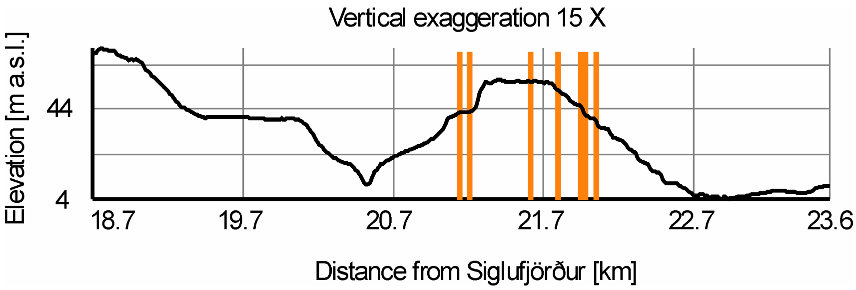

Fig. 21: Areas of debris flow hazard (debris flow hazard levels 1 and 2) in road section 931: km 18.7-23.6 – south of Hraun to Ketilás

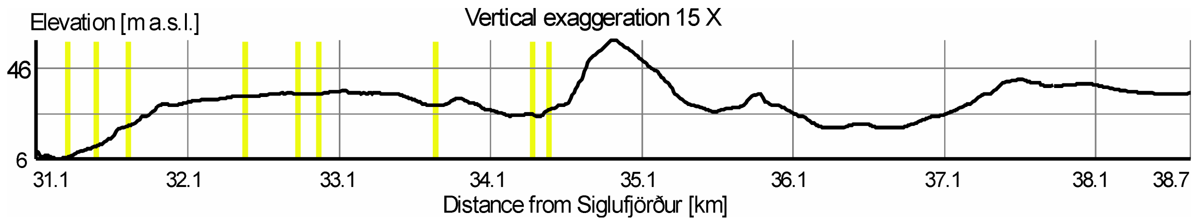

Fig. 22: Areas of debris flow hazard (debris flow hazard levels 1 and 2) in road section 941: km 31.1-38.7 – pipe 510 to crossroads to Straumnes

4.3 Avalanches

Process

Avalanches are defined as the fast motion of snow masses on slopes. As for the process areas there is a distinction between the starting area, the transport area (avalanche track) and the accumulation area.

Avalanches are caused by failures of the snow cover. The start can be spontaneously, when the cohesion of the snow cover is weak (i.e. as powder or loose snow avalanches) or after longer metamorphosis and settlement with strong coherence of the snow cover as slab avalanches. Factors affecting the stability of the snow are the terrain (slope, curvature, roughness, orientation, elevation), the vegetation and climatic conditions (precipitation, wind, radiation, temperature).

Objective and procedure

Objective of this investigation was the determination and outline of areas of avalanche hazard for the section of the road no 76 from Siglufjörður to Straumnes.

For the areas around the road potential starting areas of avalanches were mapped based on stereo pairs of the aerial photographs (see 3.3). These maps were checked and completed in the field. Boulders deposited by the avalanches were mapped as indicators for the extents of the accumulation areas.

The ground-truthed maps were digitized and transferred to a GIS dataset. The starting areas were checked and partly expanded by means of a disposition model. This dataset of potential avalanche starting areas was the basis for modelling the accumulation areas using the model GRID-aval.

In a further step the modelled avalanche accumulation areas were printed out and checked against the background of the topographic maps and colour orthophotos (see 3.1 and 3.3). The checked and corrected data provide the basis for assessing the avalanche hazard for the investigated road section.

Model

The avalanche model GRID-aval (Grid based Trajectory Avalanche Model) is a two-dimensional model to calculate the run-out distance of flow avalanches on a regional scale. It is based on the approach of Lied and Bakkehoi (1980) and determines the maximum run-out distance in a topographic-statistical way. The model describes the run-out distance of an avalanche by means of an angle a which is a function of the angle between the starting point and the point at which the avalanche track reaches an angle of 10°.

The current version of the model calculates the run-out distance of an avalanche starting from a given line by means of an estimated slope. This estimated slope describes the loss of energy of the avalanche during the flow process. Thus the difference between the real slope of the terrain surface and the estimated slope gives the corresponding kinetic energy, which, in a following step, can be used as input data for the modelling of the flow paths. The angle a is determined on the basis of a statistical analysis of known avalanche events.

The starting line is defined by means of a disposition analysis which mainly uses functionalities of Geographical Information Systems (GIS). On the regional scale, the most important criterion for this determination is the slope of the terrain. Potential starting lines are defined as the upper boundaries of areas with slopes between 28° and 50°.

The avalanche track is determined by means of a vector-orientated model on the basis of orientation and slope data from the digital terrain model. The output of this modelling is a sequence of points in three-dimensional coordinates.

The model requires the following input data (format ESRI GRID ASCII):

- digital elevation model
- slope
- orientation
- starting areas (grid cells)

The influence of topography on the calculated avalanche tracks is determined by a weighting factor (topoweight). A topoweight value of 1 stands for a motion close to that of a ball while a very high value represents the motion characteristics of water. A further model parameter (widening) defines the lateral extension of the avalanche from the calculated tracks. In model calculations made so far topoweight values between 5 and 7 and a widening of 0.005 have given good results.

Avalanche modelling for Iceland

The estimated slope a was determined on the basis of the statistical analysis of 45 avalanche events in Iceland by Jóhannesson (1998).This investigation gives a mean value for a of 23.62° with a standard deviation of 3.19° (a = 23.62°, s = 3.19°, n = 45). The minimum value for a in the Siglufjörður area (n = 7) is 21°. On this basis an estimated slope of 23.62° (mean) and a lower limit of 20.43° (mean minus one standard deviation) were used in the calculations.

Fig. 23 shows an example of the modelled avalanche tracks and the extent of the accumulation areas, which are the outer boundaries of all cells reached by the avalanche tracks, for avalanche hazard levels 1 and 2 respectively.

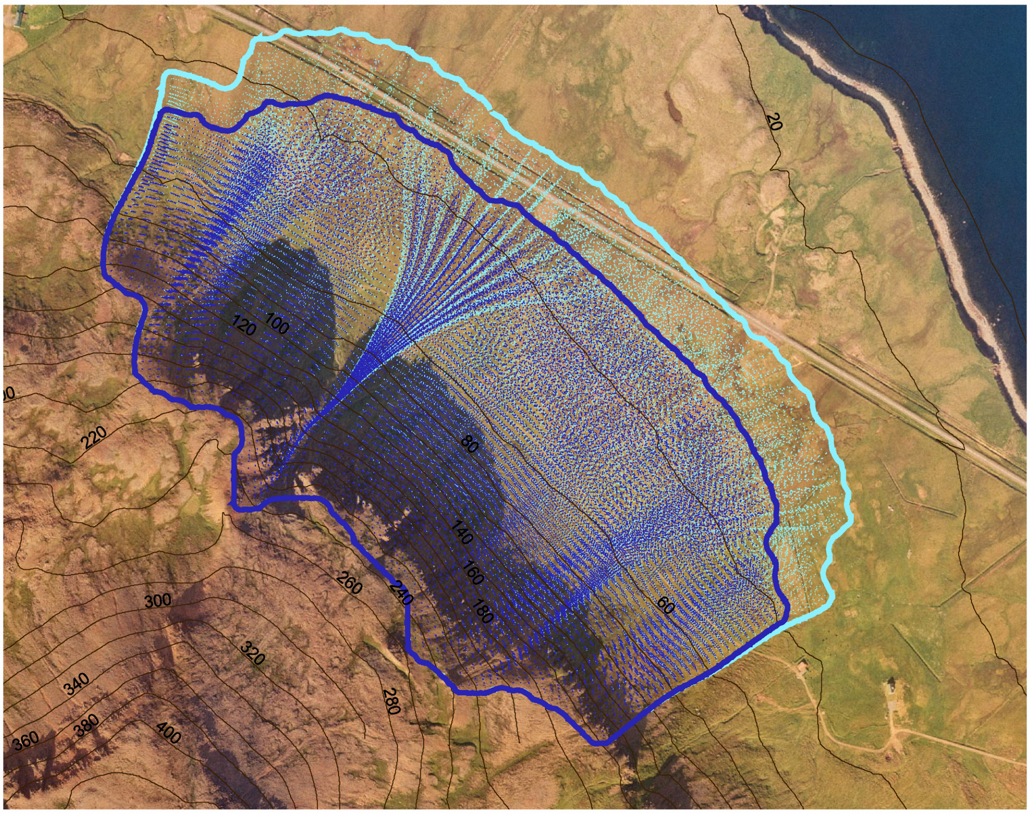

Fig. 23: Modelled avalanche tracks and accumulation areas for avalanche hazard levels 1 and 2

Based on the findings in the field and the modelling results two avalanche hazard levels can be distinguished:

- Avalanche hazard level 1
  is based on an estimated slope of 23.62°, which is the statistical mean of the analysis of 45 avalanche events in Iceland by Jóhannesson (1998). Areas of avalanche hazard level 1 can be reached by avalanches under unfavourable conditions.

- Avalanche hazard level 2
  is based on an estimated slope of 20.43°, which is the mean minus one standard deviation in the analysis by Jóhannesson (1998), and indicates areas that can be reached by avalanches under extremely unfavourable conditions (worst case assumption).

Results
In the investigated part of road no 76 between Siglufjörður and Straumnes there are 18 areas of avalanche hazard level 1 (see Table 7) and 25 areas of avalanche hazard level 2 (see Table 8). These areas are also shown in the overview in Appendix A2, Map 15 and in detail in Appendix A2, Maps 16 to 18.

The areas of avalanche hazard level 1 mostly lie between Siglufjörður and km 13.32, i.e. in road sections 911, 912 and 921 (see Fig. 24, Fig. 25 and Fig. 26). Altogether more than 7 km or more than half of this northern three sections can be reached by avalanches under unfavourable conditions. Especially road sections 911 and 912 from Siglufjörður to Skriðnavík are almost entirely areas of avalanche hazard level 1 with 14 avalanche tracks, some of which very broad, crossing this part of the road.
Similar to the areas of rockfall hazard, the areas of avalanche hazard level 1 in section 921 are limited to four comparatively short parts of the road.

No	Road km from Siglufjörður
1	0-0.39
2	0.88-1.08
3	1.39-1.46
4	1.50-2.00
5	2.08-2.17
6	3.19-4.43
7	4.79-5.03
8	5.09-5.29
9	5.39-5.66
10	5.71-5.73
11	5.88-7.32
12	7.45-7.48
13	7.58-7.99
14	8.53-9.20
15	9.54-9.82
16	11.09-11.41
17	12.22-12.39
18	13.05-13.32

Table 7: Areas of avalanche hazard level 1 in road no 76 from Siglufjörður to Straumnes

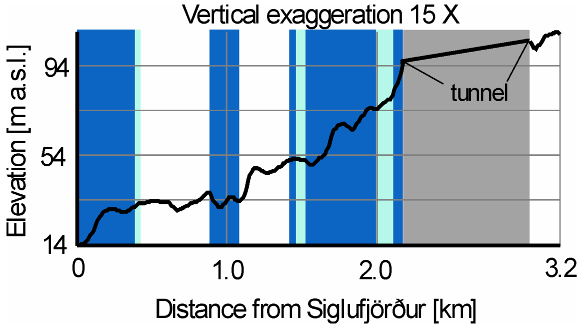

Fig. 24: Areas of avalanche hazard (avalanche hazard levels 1 and 2) in road section 911: km 0-3.2 – Siglufjörður to the northernmost point of road no 76

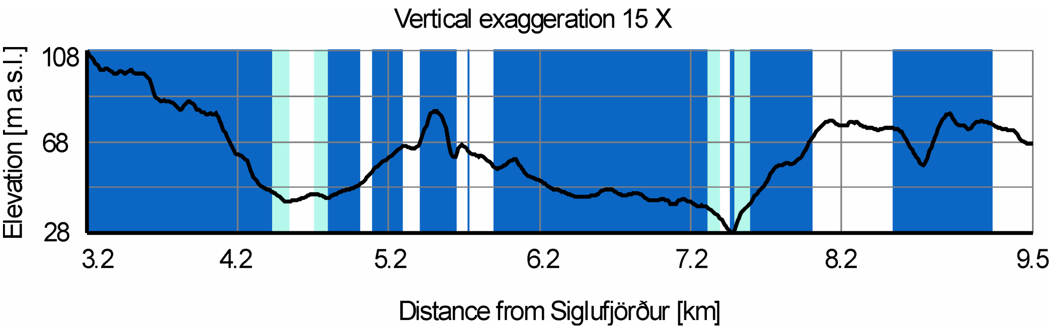

Fig. 25: Areas of avalanche hazard (avalanche hazard levels 1 and 2) in road section 912: km 3.2-9.5 – northernmost point of road no 76 to Skriðnavík

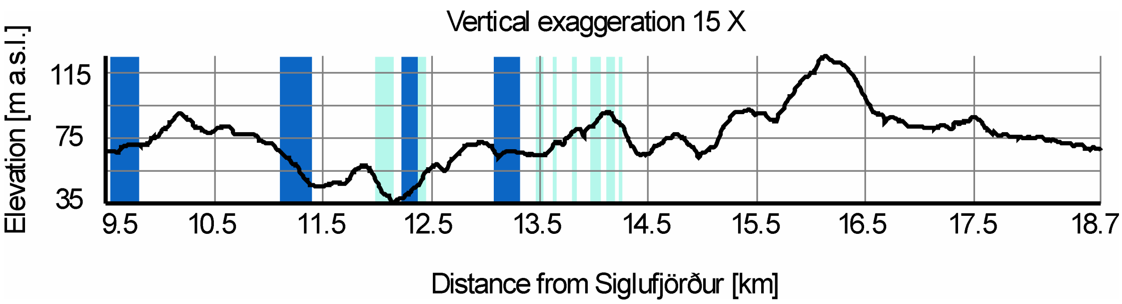

Fig. 26: Areas of avalanche hazard (avalanche hazard levels 1 and 2) in road section 921: km 9.5-18.7 – Skriðnavík to south of Hraun

West of km 13.32 the slopes along road no 76 are less steep and less high. There are steep and high slopes in road section 941. These are, however, so far away from the road that the modelled accumulation areas for avalanche hazard level 1 of the four potential avalanches in this section do not reach the road.

The modelled accumulation areas of avalanches for avalanche hazard level 2 are generally larger than those of avalanche hazard level 1. The areas of avalanche hazard level 2 thus usually form a band around the areas of avalanche hazard level 1 (see Fig. 23).
For road sections 911, 912 and 921 this means that more than 8 km of the road can be reached by avalanches under extremely unfavourable conditions (worst case assumption). While in road sections 911 and 912 with their extensive areas of avalanche hazard level 1 there are only small further areas of avalanche hazard level 2, ten additional avalanches reach the road in section 921 under the conditions of avalanche hazard level 2. The total extent of the areas of avalanche hazard level 2 in this road section remains however limited (see Table 8).

No	Road km from Siglufjörður
1	0-0.42
2	0.88-1.08
3	1.38-2.17
4	3.17-4.54
5	4.69-5.06
6	5.11-5.30
7	5.39-5.66
8	5.71-5.73
9	5.86-7.38
10	7.43-8.03
11	8.52-9.23
12	9.50-9.82
13	11.08-11.44
14	11.96-12.15
15	12.21-12.46
16	13.03-13.35
17	13.45-13.52
18	13.61-13.63
19	13.77-13.83
20	13.95-14.05
21	14.10-14.18
22	14.21-14.24
23	31.99-32.66
24	35.74-35.76
25	35.83-35.85

Table 8: Areas of avalanche hazard level 2 in road no 76 from Siglufjörður to Straumnes

Three further areas of avalanche hazard level 2 lie in road section 941 (see Table 8 and Fig. 27).

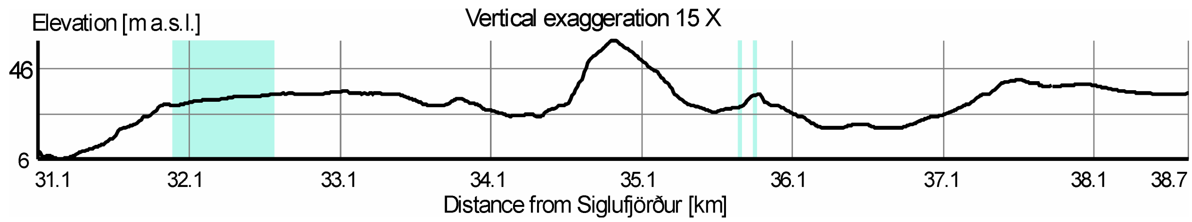

Fig. 27: Areas of avalanche hazard (avalanche hazard level 2) in road section 941: km 31.1-38.7 – pipe 510 to crossroads to Straumnes

5 Assessment

The investigation of the processes rockfall, sagging, flooding, debris flows and avalanches covered the main natural hazard processes for the section of road no 76 from Siglufjörður to Straumnes. As the investigated road section lies in an essentially alpine environment these alpine natural hazard processes can be regarded as characteristic for such areas.

Based on the detailed evaluation of the specific processes and the resulting natural hazards for the investigated road sections (see 4) a comprehensive assessment of the natural hazard potential for road no 76 from Siglufjörður to Straumnes was made.
This assessment revealed that the six defined road sections (see 2) are very different as to the relevant natural hazard processes and the resulting natural hazard potentials.
The results of the comprehensive assessment are presented both as vertical sections for the specific road sections (see Figures 28 to 32) and as an overview map for the investigated part of road no 76 from Siglufjörður to Straumnes (see Appendix A2, Map 19).
These figures and maps show the hazard areas of the specific natural hazard processes in comparison.

The road sections which are most affected by natural hazard processes are sections 911 and 912, i.e. the part of road no 76 from Siglufjörður to Skriðnavík (see Fig. 28 and Fig. 29). Except for the part through the tunnel in section 911, the road almost everywhere lies in areas of rockfall, debris flow or avalanche hazards in these sections. This is due to the fact that most parts of the road cross steep slopes and are therefore very exposed. While the debris flow and avalanche hazards are subject to specific climatic conditions and can thus be reduced by adequate measures, this is difficult for the rockfall hazard as rockfall processes, though their intensity may vary temporally (e.g. during melting periods), can occur spontaneously almost any time.
In addition to these rockfall, debris flow and avalanche hazards there is an area of flooding hazard caused by a pipe of an insufficient discharge capacity at km 0.7 in road section 911.

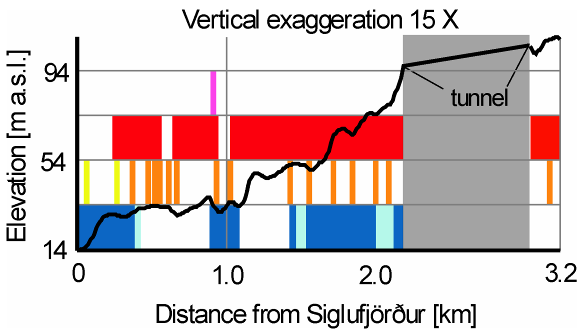

Fig. 28: Areas affected by natural hazard processes in road section 911: km 0-3.2 – Siglufjörður to the northernmost point of road no 76

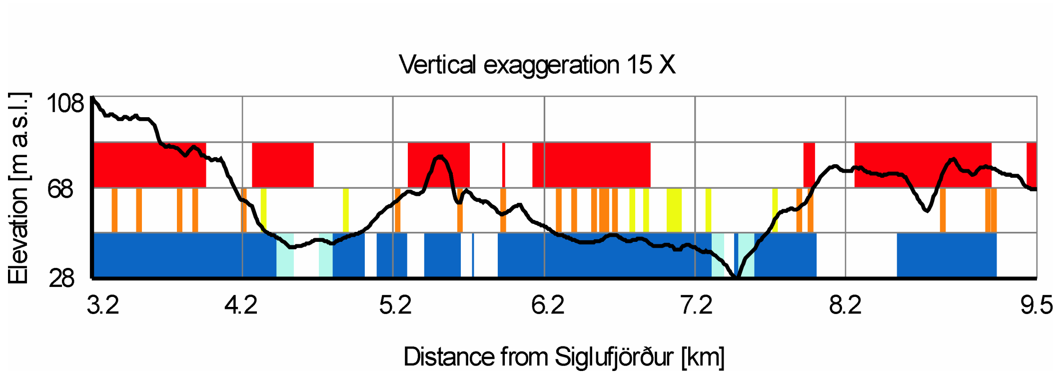

Fig. 29: Areas affected by natural hazard processes in road section 912: km 3.2-9.5 – northernmost point of road no 76 to Skriðnavík

The natural hazard processes rockfall, debris flows, avalanches and flooding also affect road section 921 between Skriðnavík and south of Hraun (see Fig. 30). Due to the less high and less steep terrain and the greater distance of the slopes from the road in this section the rockfall, debris flow and avalanche hazards are much lower than in sections 911 and 912. On the other hand the part of road no 76 between km 10.1 and km 18.2 around Almenningur is affected by intensive sagging processes, which are causing considerable damage to the road. In addition to this there are four areas of flooding hazard by streams with missing or too small pipes in road section 921.

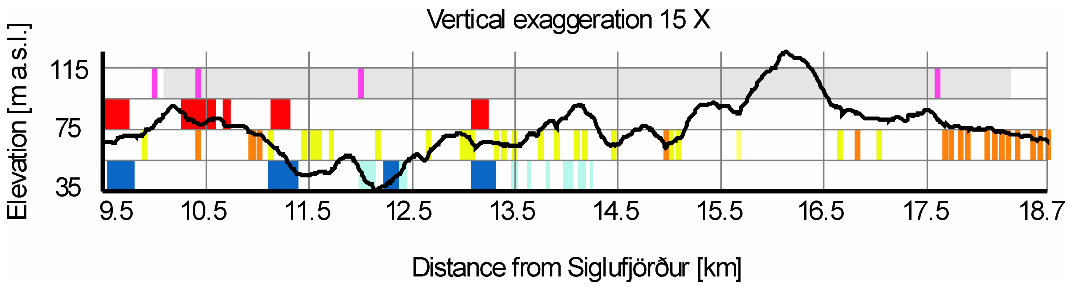

Fig. 30: Areas affected by natural hazard processes in road section 921: km 9.5-18.7 – Skriðnavík to south of Hraun

In the southern three road sections 931, 932 and 941 from south of Hraun to Straumnes the natural hazard potential is generally much lower than in the northern sections of the investigated part of road no 76.
Road section 931, except for very limited areas of debris flow hazard (see Fig. 31), is not affected by alpine natural hazard processes.

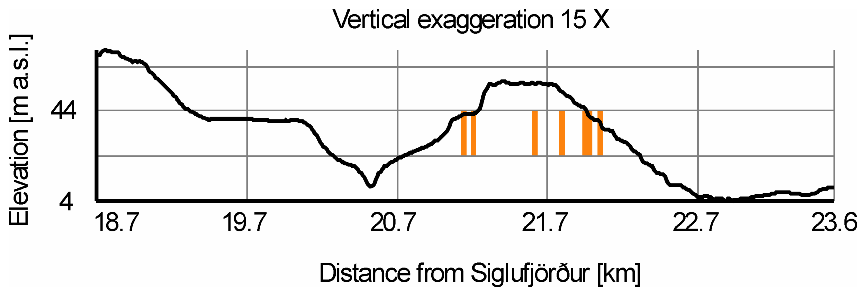

Fig. 31: Areas affected by natural hazard processes in road section 931: km 18.7-23.6 – south of Hraun to Ketilás

In section 932 from Ketilás to km 31.1 road no 76 is not affected by alpine natural hazard processes.

In road section 941 from km 31.1 to Straumnes (see Fig. 32) there is a limited natural hazard potential by avalanches and debris flows. These avalanche and debris flow processes, however, can reach the road only under extremely unfavourable conditions (worst case assumptions). Two further areas in this road sections are areas of flooding hazard due to pipes of insufficient discharge capacities. Compared to road sections 911, 912 and 921, however, the natural hazard potential in section 941 is very small.

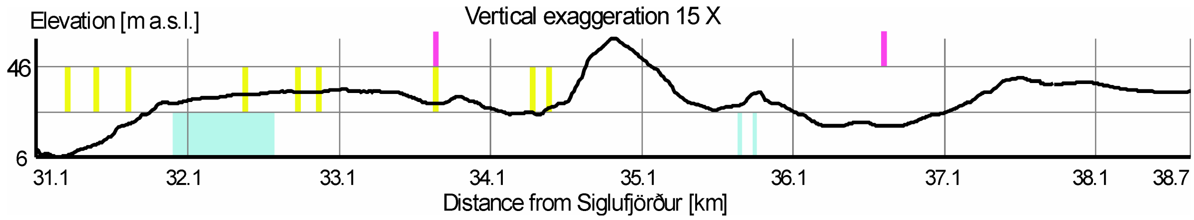

Fig. 32: Areas affected by natural hazard processes in road section 941: km 31.1-38.7 – pipe 510 to crossroads to Straumnes

6 Recommendations

The results of this regional scale assessment of the natural hazard potential for road no 76 from Siglufjörður to Straumnes allow the following recommendations:

- Substantial parts of the Icelandic public road network e.g. in central northern Iceland, northwestern and eastern Iceland lie in alpine mountain areas and are affected by characteristic natural hazard processes.
- A standardized regional scale approach is practical to determine, analyse and assess the natural hazard potential on rural roads and guarentees comprehensible, reproduceable and comparable results, which help to assign priorities in following detailed investigations and the planning of measures.
- This approach maximizes the use of already existing data, most of which is available at the offices of Vegagerðin and Veðurstofa Íslands, and reduces time-consuming and expensive fieldwork to a minimum. Investigations following this approach are thus feasible and affordable for all classified rural roads in Iceland.
- The developed approach can be applied to other areas to investigate and assess the generalized natural hazard situation for the Icelandic public road network as a whole.

For the natural hazard management the results of this assessment need to be combined with road data (e.g. current and expected traffic volume for various timescales, road clearing and maintenance costs for problematic road sections). This allows to determine the natural hazard risk for specific road sections and cost benefit analyses as a basis for decisions on protective measures.

As the data on the natural hazard potential need to be constantly updated a special information system meeting these requirements is being developed and will be presented to Vegagerðin in April 2005.

7 References

Abele G. 1974. Bergstürze in den Alpen. Wissenschaftliche Alpenvereinshefte, 25, München.

Aulitzky, H. 1992. Die Sprache der „stummen Zeugen“. Internationales Symposion Interpraevent, 6, 139-174, Bern.

Chanson H. 1999. The Hydraulics of Open Channel Flow. London.

Elíasson J. 1998. Útreikningar á flóðum. Verkfræðistofnun Háskóla Íslands, Vatnaverkfræðistofa.

Dracos T. 1980. Hydrologie, Eine Einführung für Ingenieure. Wien, New York.

Evans S.G., Hungr O. 1988. Engineering evaluation of fragmental rockfall hazards. In: Bonnard C. (ed.), Landslides, Proceedings of the 5th International Symposium on Landslides in Lausanne, 1, 685-690, Rotterdam.

Evans S.G., Hungr O. 1993. The assessment of rockfall hazard at the base of talus slopes. Canadian Geotechnical Journal, 30, 620-636.

Guðmundsson Á., Fahrnberger W., Hallsteinsson H. 2001. Siglufjörður - Ólafsfjörður. Veggöng um Héðinsfjörð. Yfirlit yfir jarðfræði Tröllaskaga og aðstæður til jarðgangagerðar. Jarðfræðistofan ehf. Unnið fyrir Vegagerðina.

Hafliðason H. 1982. Jarðfræðiskýrsla vegna jarðsigs á Almenningum við Siglufjörð.

Heim A. 1932. Bergstürze und Menschenleben. Zürich.

Jarðfræðistofa ÁGVST, BAH Ráðgjöf 1999. Greinargerð um aurskriðu úr Kóngsnefi í Fljótum.

Jensen E., Sönser T. 2002. Process orientated landslide hazard assessment for Eskifjörður. Veðurstofa Íslands Report 02014, VÍ-ÚR10, Reykjavík, April 2002.

Jóhannesson T. 1998. Icelandic avalanche runout compared with topographical models used in other countries. Norwegian Geotechnical Institute, 203, 53-64.

Laatsch W., Grottenthaler W. 1972. Typen der Massenbewegungen in den Alpen und ihre Klassifikation. Forstwissenschaftliches Centralblatt, 91/6, 309-339.

Lied K., Bakkehøi S. 1980. Empirical calculations of snow-avalanche run-out distance based on topographical parameters. Journal of Glaciology, 26, 165-177.

Meißl G. 1998. Modellierung der Reichweite von Felsstürzen. Innsbrucker Geographische Studien, 28, Innsbruck.

Meißl G. 2001. Modelling the runout distances of rockfalls using a geographic information system. Zeitschrift für Geomorphologie, N.F., Suppl.-Bd. 125, 129-137.

Naudascher E. 1987. Hydraulik der Gerinne und Gerinnebauwerke. Wien, New York.

Sæmundsson Þ., Pétursson H.G. og fl. 2004. Kortlagning á sígi á Siglufjarðarvegi um Almenninga. Áfangaskýrsla.

Schöberl F. 1998. Zur Hydraulik von Fliessgewässern im alpinen Bereich, Beitrag zum ÖWAV-Ausschluss „Gestaltung von Fließgewässern am Schwemmkegel im dicht besiedelten Raum“. Veröffentlichung des Instituts für Wasserbau, Universität Innsbruck. Innsbruck.

Schöberl F., Stötter J., Schönlaub H., Ploner A., Sönser T., Jenewein S., Rinderer M. 2004. PROMABGIS: Ein GIS-basiertes Werkzeug für die Ermittlung von Massenbilanzen in alpinen Einzugsgebieten. Internationales Symposion Interpraevent, 3, 271-282, Riva.

Schröder R.C.B. 1994. Technische Hydraulik, Kompendium für den Wasserbau. Wien, New York.