STATENS GEOTEKNISKA INSTITUT
SWEDISH GEOTECHNICAL INSTITUTE

Stability and run-off conditions

– Guidelines for detailed investigation of slopes and torrents in till and coarse-grained sediments

Karin Rankka
Jan Fallsvik

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– Guidelines for detailed investigation of slopes and torrents in till and coarse-grained sediments

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Preface

These guidelines for carrying out detailed investigations of the stability and run-off conditions in slopes and torrents in till and coarse-grained sediments, have been developed by the Swedish Geotechnical Institute (SGI).

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- Siegfried Sauermoser, Forsttechnischer Dienst für Wildbach und Lawinenverbauung, Innsbruck, Austria.
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Karin Rankka and Jan Fallsvik

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Summary

Introduction

This report is a guideline for detailed investigations of the stability and run-off conditions in slopes and torrents[1] in till and coarse-grained sediments. The guidelines are intended to serve as a guide not only for geotechnical engineers but also for the landowners and local and central authorities facing problems relating to such conditions.

The type of investigations needed varies considerably between the two types of movement, landslide and debris flow, that can occur in slopes and torrents. Hence, the report is divided into two parts; one for landslides and the other for debris flows.

In regard to both landslides and debris flows, the following main parts are described in this report:

- Field investigations
- Run-off conditions
- Calculation methods
- Documentation

Many areas with prerequisites for landslides and/or debris flows have satisfactory stability and therefore it is recommended that the investigations give a limited extent. The aim is to determine whether a real problem exists.

Mass movements in Sweden

Sweden has long experience of slope stability analysis in clay and silt sediments due to several large landslides that damaged railway tracks and other infrastructures in the early 20th century. General stability mapping of the landslide hazard in areas with clay and silt sediments has been carried out by the Swedish Rescue Services

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[1] A torrent is a gully-formed area in which a stream is flowing and this stream will sometimes transport soil material, as a debris flow, from higher to lower altitudes, see Chapter 2.2.1.

Agency since 1987. The mapping method is described by Fallsvik & Viberg (1989).

However, mass movements in Sweden also occur in slopes and torrents in till and coarse-grained soils such as gravel and sand. These mass movements are mostly triggered by long periods of rainfall or by heavy rainfalls. After heavy rainfalls in the 1990's, causing many problems in terrain with a sharp relief, a need for more knowledge and instruction concerning investigation methods to finding areas in danger was identified.

Two different types of mass movement, landslides and debris flows, may be found in these areas. These movements can be extensive causing severe impact and damage in the vicinity.

Detailed investigation of the landslide hazard

The detailed investigation of the landslide hazard aims at determining the slope stability in areas with potential risks of landslides and erosion. The slope stability is expressed mainly by a safety factor and by a description of the possibility of erosion and concentration of water.

The safety factor has to be calculated using well-proven computer programs. The data input to the calculations should be based on field investigations of the topography, the stratigraphy, the soil type, the groundwater and pore pressure situation, and the shear strength of the soil.

The investigation of the erosion hazard is based on a field investigation of the vegetation situation, the grain size distribution and the possibility of concentration of water flow. Boulders in the slope should also be investigated.

The requirements on safety factors differ depending on the type of land use, the hazards involved, the type of investigation performed (rough estimate, detailed or in-depth) and the type of stability analysis performed. The requirements are in general accordance with those used for investigating the stability conditions in clay, silt and sand sediments (see Swedish Commission on Slope Stability, 1995).

Detailed investigation of the debris flow hazard

In the case of torrents, there are mainly two types of problem; high water discharge, which may cause debris flow, and unstable slopes towards the bottom of the torrent.

The debris flow hazard thus depends on the volume and velocity of water and the volume of transportable soil material. Landslides in slopes towards the torrent may bring soil material and trees down to the bottom of the torrent, causing damming of the brook. During high discharges in the brook, this material may once again begin to move and cause severe erosion and damage downstream.

Detailed investigation of a torrent and its catchment area mainly consists of a determination of the run-off conditions, the design rainfall (involving rain intensity, duration and total amount of precipitation), the peak discharge and the available and transportable amount of solid material.

The run-off conditions determine how the rainwater will proceed after it has reached the vegetation or the ground. The conditions are influenced mainly by the geology, the soil type, the vegetation cover, the topography, the groundwater conditions, the type of precipitation and the shape of the catchment area. The different conditions are investigated from maps, air photos interpreted in stereo and a careful field study.

The precipitation conditions can be analysed from measurements performed by the Swedish Meteorological and Hydrological Institute, SMHI, close to the area. These measurements are, however, most often made only once a day and in the case of torrents mostly rainfalls with shorter duration, up to a few hours, are of interest. For such rainfalls, the Dahlström method (Dahlström, 1979) may be used. The possibility of a larger amount of rain at higher altitudes than the measuring level also has to be considered.

The peak discharge and its duration may be calculated with different empirical relations. The run-off conditions, rain intensity and size of the catchment area are input to these calculations. The transportation capacity of the debris flow may also be calculated using empirical relations. Mainly, the peak discharge and the inclination of the bottom of the torrent determine the transportation capacity. The amount of transportable soil material along the bottom and banks of the torrent also affect the transportation capacity. The amount and position of the material have to be evaluated in the field.

The calculations give the peak discharge and the amount of material that can be transported by a one debris flow for different positions along the torrent.

Documentation of the content and results of the detailed investigation

The content and the results of the detailed investigation should be documented in two separate reports:

- Report 1: Results of field and laboratory investigations.
- Report 2: Assumptions, analysis, calculations and, if there is a need for preventive measures, suggestions and rough estimates for type, position and design of such measures.

Chapter 1.
Introduction

1.1 BACKGROUND

In Sweden, most problems with mass movements have occurred in areas with clay and silt sediments. Landslides with the most severe consequences have occurred in quick clay areas. General stability mapping of the landslide hazard in areas with clay and silt sediments has been carried out by the Swedish Rescue Services Agency since 1987. The mapping method is described by Fallsvik & Viberg (1989).

However, mass movements in Sweden also occur in slopes and torrents in till and coarse-grained sediments like gravel and sand. These mass movements are mostly triggered by a long period of rainfall or by heavy rainfalls. After a number of heavy rainfalls in the 1990's, causing many problems in terrain with a sharp relief a need for more knowledge and instruction concerning investigation methods to finding areas in danger was identified.

Two different types of mass movement, landslides and debris flows, may occur in these areas. These movements can be very extensive, causing severe impact and damage in the vicinity. Even though mass movements in these soils most commonly occur in the least populated areas of Sweden, there is a need for a general stability mapping method and guidelines on how to carry out detailed stability investigations of these slopes. These methods and guidelines should as far as possible be analogous to the existing general stability mapping method for slopes in clay and silt sediments.

Areas in Sweden with prerequisites for landslides and debris flows in coarse-grained sediments are

- slopes with soil cover and an inclination greater than 17 degrees
- all gullies and torrents
- slopes with poor vegetation cover
- areas with scars from erosion, landslides and debris flows

Thus, by analogy, the stability investigations for slopes and torrents in till and coarse-grained sediments are planned to be performed in the following main stages:

- Preparatory study
- Stage 1 – General stability mapping
- Stage 2 – Detailed stability investigation
- Stage 3 – Projecting and design of preventive measures

The preparatory study and the general stability mapping are planned to be carried out on a municipal level. The preparatory study delimits the parts of the municipalities where the general stability mapping is to be carried out.

The purpose of the general stability mapping is to indicate where detailed investigations are required. On commission by the Swedish Rescue Services Agency (SRSA), the Swedish Geotechnical Institute (SGI) in co-operation with Chalmers University has developed a method for survey mapping (Stage 1) of slopes in till and coarse-grained soils, Viberg et al. (2004). The mapping method has a structure similar to the existing method for clay and silt areas. The objective of the mapping method is to identify areas in risk of landslides and/or debris flows and consequently where a detailed investigation is necessary.

The survey mapping method is intended to be used for slopes and torrents in till and coarse-grained sediments in Sweden. The most common soil to be mapped will be till, which comprises a large range of compositions – from fine-grained to stony and boulder-rich types. Talus formations and sand and gravel sediments will be rarer. Bedrock slopes are not included in the method.

Guidelines for detailed stability investigations (Stage 2) of mass movements in till and coarse-grained sediments are presented in this report. The corresponding direction for slope stability investigations in clay and silt sediments can be found in the Swedish Commission on Slope Stability, Directives for slope stability investigation, Report 3:95, (1995).

On behalf of SRSA, guidelines for project planning and design of preventive measures (Stage 3) have been developed by SGI. The guidelines are presented by Rankka & Fallsvik (2003).

1.1.1 SRSA funding for prevention of landslides and debris flows in till and coarse-grained sediments

The bodies responsible for performing and financing the detailed investigations are the landowners, e.g. affected municipalities, real estate owners and/or boards of road and railroad administrations as well as private land ownvers.

Nevertheless, on application, the SRSA can subsidise part of the costs for planning, designing and performing the preventive measures found to be necessary in Stages 2 and 3. Only municipalities can apply for subsidies.

1.2 OBJECTIVE

The guidelines given in this report are planned to be used for directing detailed investigations (Stage 2) in slopes and torrents in till and coarse-grained sediments in Sweden. The guidelines will form the course of action for both the landowners and those performing the detailed investigations.

Furthermore, the guidelines will form the basis for decision-making by SRSA on economic contribution towards necessary preventive measures.

Chapter 2.

Destructive mass movements

There are many types of flow or mass movement involving water and sediments that can occur on steep slopes and along torrents (for a definition, see Chapter 2.2.1) in mountainous and hilly areas. They include mud flows, debris flows, granular flows, flash floods, debris avalanches and landslides. The classification differs in the literature and it is relatively difficult for an untrained person to distinguish one phenomenon from another. In this report, we will concentrate on two types of mass movement; landslides and debris flows.

2.1 LANDSLIDES

Landslides are here defined as rapid mass movements where sliding occurs along a surface which, in till and coarse-grained soils, often is planar, although it may have other shapes. The sliding masses often come to a stop close to the bottom of the slide. They have more or less the same structure as before the slide, unlike debris flows that undergo extremely large deformations during the flow. If the water content is sufficient and the slope inclination very high, the masses may proceed downwards as a debris flow, see Chapter 2.2. A landslide that originates in rocky and granular masses and thus has a high content of granular material is often defined as a debris avalanche (Coussot & Meunier, 1996).

The sliding surface is mostly shallow, up to a few metres in depth, and is most often triggered by one or more of the following factors:

- high pore pressure in the soil due to intense rainfalls after periods of long-term precipitation and/or snow melt
- shear stress exceeding the shear strength of the soil
- a critical slope inclination
- thawing of frozen ground
- clear-cutting or insufficient vegetation cover
- human activity
- falling or rolling pieces of rock from the slope above

Landslides can occur both in slopes along the side of a torrent and in slopes not connected to torrents, i.e. so-called open slopes. Scars from landslides create possibilities of water infiltration, thereby increasing pore pressure and possibly causing new slides. Debris flows triggered by a landslide often cause intense erosion and create channels in the slopes. These channels form the basis for new torrents or gullies.

2.2 DEBRIS FLOWS IN TORRENTS

According to Coussot & Meunier (1996) a debris flow is an event during which a large volume of a highly concentrated viscous water-debris mixture flows through a stream channel. Debris flows usually follow pre-existing drainage ways, but can move down hill-slopes and across unobstructed fan surfaces in almost any direction because flows tend to build there own channels as levees form at the lateral boundaries of the flow (Costa, 1984). The flow can be extremely destructive and transport both large boulders and trees. The triggering factor for a debris flow is most often an intense rainfall in an area characterised by poor run-off conditions, thus leading to a very quick run-off and a high peak discharge in the stream. Because of sparse rainfall data in most mountain areas, the intensity or duration of precipitation required to mobilize side-slope materials is poorly known (Costa, 1984).

There are many types of water/debris mixture flow, differing mainly in regard to flow, sediment concentration, deposit structure and type of sediment. The classification of a debris flow according to its concentration of sediments differs in the literature, but values between 50 and 90% of total volume are given by Coussot & Meunier (1996). Flows with a volume of water above 40% are denoted stream flows (Lorenzini & Mazza (2004).

Coussot & Meunier (1996) also describe a debris flow as a transient flow with almost periodic surges and state that the velocity is approximately the same for the solid particles as for the water. On the other hand, in flash floods the coarsest solid particles have a mean velocity differing significantly from that of the water-solid suspension that flows around it. After a debris flow event, lateral levees left by the flood may be seen on the sides of the stream. Usually, such levees are not formed by landslides.

Along the same torrent, different types of water-debris mixture flow may occur depending on the precipitation (and thus the flow), the inclination and the available amount of material in different longitudinal sections.

Many different classification systems have been proposed by authors such as Varnes (1978), Costa (1984), Coussot (1992), Coussot & Meunier (1996), Hungr & Jakob (2005). According to Costa (1984) three principal types of flow appear depending on the amount of water, the current velocity, the bottom inclination of the torrent and the supply of loose soil material. These are:

1. **Water flood (flash flood, clear-water flood)** occurs when the volume and current of water are of such a magnitude that the soil material forms only a small part of the total volume. Suspended soil particles tumble downwards. When deposited, sediments are generally stratified and sorted to poorly sorted.

2. **A mud flood or hyperconcentrated flood** consists of a rapid water current containing a high amount of suspended soil particles, which is mainly transported downwards as a bedload. The trigger of a mud flood could be an extreme water current along a torrential creek-gully, which can bring into motion existing soil or debris accumulated along the gully. The bottom material originates in many cases from older landslides, debris flows or mud flood events, as well as from weathering, glacial transportation and alluvial transportation. When deposited, sediments are generally poorly sorted with a weak stratification and no sharp defined margins exist.

3. **A debris flow** consists of a more or less coherent viscous mass of soil and water in rapid movement down a slope or torrent. During the movement, the debris flow tends to increase in volume and the deposition process results in the formation of lobes with irregular surfaces (Lorenzini & Mazza, 2004). The trigger of a debris flow could be a severe water flow and/or a landslide in saturated soils higher up in the slope. When deposited, there is no separation of debris flows into solid and liquid components as in water and mud flows. Levees and lobes of poorly sorted debris are formed.

Some characteristics of the different types of the above mentioned flows are described in Table 1.

In the literature, mud floods and debris flows are often combined in the same group of flow types – "debris flows" – the vocabulary also chosen in this guide.

Material from a landslide deposited along the bottom of a torrent may, if the water current in the torrent on the particular occasion is high enough, be transported further downstream, following the torrent as a debris flow.

Table 1. Some characteristics of different flow types, after Costa (1984).

Flow type	Proportion of solid material [weight %]	Density [t/m^3]
Water flood (flash flood)	1 – 40	1.01 – 1.3
Mud flood (hyperconcentrated flows)	40 – 70	1.3 – 1.8
Debris flow	70 – 90	1.8 – 2.6

On its propagation, the debris flow causes erosion. As a rule, the debris flow creates an erosion channel along which additional soil material as well as parts of the present vegetation (turf, bushes, complete trees, logs, branches, etc.) will be loosened, broken and successively assembled by the debris flow. Along its path and in its final accumulation area, a debris flow can cause severe damage to buildings, structures, forests, fields, pastures and domestic animals, as well as loss of human life.

2.2.1 Definition of a torrent

A torrent is a gully-formed area containing a stream that sometimes will transport soil material, as a debris flow for instance, from higher to lower altitudes. In Austria, for instance, torrents are defined in law.

Torrents are most often formed in soil, in solid rock or in a deep and wide fissure between two mountains, due to repeating extreme high water discharge during intense precipitation. Torrents are often found in steep slopes in erodible till and coarse-grained soil material, see Figure 1. Torrents may also be formed by repeated debris flows in a scar from an earlier landslide.

2.2.2 Soil material distribution along the bottom of a torrent

Along the bottom of a torrent the inclination varies. On steep sections, the water current will be fast, and hence is characterised by high kinetic energy. Depending on the bottom inclination, torrents can be divided into three characteristic types of section with respect to the ability of the water current to generate and maintain a debris flow:

Eroding sections – On steep sections with a high discharge and erodible material along the bottom or the banks, erosion may bring soil in suspension, which can continue as a debris flow.

Figure 1. Torrent formation in Kittelfjäll, community of Vilhelmina. (Photo: K. Rankka)

Transport sections – On moderate steep sections the suspended soil material can remain in transport mode.

Deposit sections – In less inclined areas the suspended soil material will be deposited.

The type of section for a specific position in the torrent may vary depending on the seasonal and occasional stream discharge conditions. However, as to triggering and consequences of debris flows, the peak discharge conditions are of primary interest.

Chapter 3.

General description for guidelines on detailed investigations

In these guidelines, detailed investigation of the hazard of mass movements in slopes and torrents is divided into two main categories; landslides and debris flows. These two categories require different field investigations, different types of data input and presentations. A general description of the required detailed investigations is presented below.

3.1 LANDSLIDES AND SHALLOW EROSION IN OPEN SLOPES

The landslide and shallow erosion hazard is normally affected by the following parameters, which all require investigation throughout the area:

- the inclination of the slope
- the type, strength and depth of the soil
- the groundwater condition
- the type, cover, height and position of vegetation
- the possibility of infiltration of run-off water
- man-made features of the slope, such as ditches, culverts, roads and other structures.

The hazard is mainly presented as a factor of safety, F, as well as by a description of the possibility of erosion and concentration of water. The investigation identifies areas with a high landslide hazard and areas in danger of being hit by sliding masses or material transported by debris flows.

A more detailed description is given in Chapter 4.

3.2 DEBRIS FLOWS IN TORRENTS

The debris flow hazard in torrents is mainly affected by the volume of water and the peak discharge that can reach the torrent on a single occasion and the volume of soil material that is available to, and transportable by, the water flow. The debris flow hazard is therefore dependent on the following parameters, which all require investigation throughout the catchment area:

- size, shape and topography of the catchment area
- run-off conditions
- precipitation (amount, duration, intensity and return period)
- amount of soil material available to a debris flow
- peak discharge

To calculate the peak discharge, it is first necessary to determine the run-off conditions, which in turn will determine the proportion of the precipitation that will run off directly to the brook and the rate at which it will flow in different parts of the catchment area. The run-off conditions are determined by field investigation and empirical equations. The time it takes for the most remote water-droplet in the area to flow down to the lower parts of the area determines the duration of the design rainfall. The design rainfall has to be estimated based on measurements performed in or close to the area, preferably at different altitudes. The Swedish Meteorological and Hydrological Institute stores precipitation measurement records from about 800 stations spread throughout the country. The amount of precipitation falling within a short period of time, normally a few hours, can be determined using a method developed by Dahlström (Dahlström, 1979), see Chapter 6.4.

By conducting a field investigation, it is possible to evaluate the amount of soil material available for the peak discharge to transport further downstream. The transport capacity of the peak discharge may be determined with the aid of an empirical method.

The debris flow hazard is given by the peak discharge, the volume of transportable masses, the transport capacity of the peak discharge and the stability and erosion conditions in the surrounding slopes.

A more detailed description is given in Chapters 5, 6, 7 and 8.

Chapter 4.

Slope stability analysis

4.1 INTRODUCTION

The aim of a detailed investigation in slopes is to determine the slope stability of areas which have either been identified in general stability mappings as having potential landslide hazards or designated for new construction on or close to steep slopes. The slope stability is expressed mainly by a safety factor, as well as by a description of the possibility of erosion and concentration of water.

Many areas with prerequisites for landslides and/or debris flows have satisfactory stability and it is therefore recommended that the preparatory study will be given a limited scope. The aim at that stage is to determine whether a real problem exists.

In the general stability mapping, Stage 1, only slopes that fulfil all the following requirements are selected as areas in need of further investigation, see also Figure 2.

- Settlements within the areas. The buildings shall be situated closer than 250 m from the toe of the slope if the ground surface behind the crest of the slope is flat (inclination less than 2 degrees).
- Slopes with a minimum inclination of 17 degrees.
- Slopes with soil cover.

Note that in areas below the toe of the slope with an inclination larger than 2° material from a debris flow may remain in transport mode.

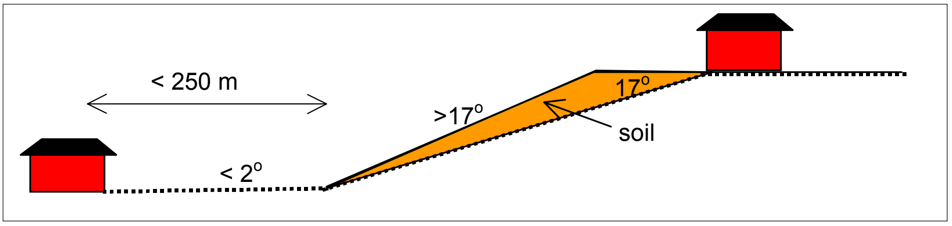


Figure 2. Areas in need of slope stability investigation.

These guidelines also apply to areas where exploitation is planned.

With the aid of rough calculations and topographical considerations, a number of critical sections are selected. In this selection, the slope inclination, the estimated soil depth, the vegetation cover and scars from earlier events are used as guides. The distance between two investigated sections over a potential landslide area should normally be less than 50 metres.

Field and laboratory investigations in these sections are intended to provide general information on the following parameters:

- Topography of the ground surface
- Soil conditions – soil type, soil layers, soil depth, geometry of underlying bedrock, bedrock outcrops
- Soil strength
- Groundwater and pore pressure conditions
- Soil moisture
- Vegetation – type and cover
- Traces of earlier landslides and erosion
- Boulders in dangerous positions

4.2 SHEAR STRENGTH IN TILL AND COARSE-GRAINED SEDIMENTS

The shear strength in coarse-grained tills and coarse-grained sediments is mostly regarded as a direct function of the effective normal stress, σ'_N, along the sliding surface and the friction angle, ϕ', according to the Mohr-Coulomb formula:

$$\tau = \sigma'_N \tan \phi'$$

The friction angle is not a constant but varies with mineral composition, relative density, stress situation, grain strength, grain shape and boundary conditions in the specific loading situation. The fact that the friction angle decreases with increasing normal stress should be taken into account in slope stability analyses. A dense multiple-graded soil has generally a higher friction angle compared to a single-graded soil, see Table 2.

The friction angle may be determined in laboratory tests, but it is most often determined through empirical relations. Different empirical relations are found in Larsson (1989a).

Table 2. **Schematic variation of friction angle in coarse-grained soils with grading and relative density. The values apply to cases with low normal stresses, i.e. shallow slip surfaces in slopes. At increasing normal stresses, the values of the friction angles approach those for a low relative density. (From Larsson, 1989a).**

Type of soil	Angle of friction, ϕ', at different relative densities		
	Low	Normal	High
Single-graded	27°	32°	37°
Medium-graded	29°	35°	41°
Multiple-graded	30°	37°	44°

The angle of friction can be derived empirically from the grading and the relative density, as outlined in Table 2. Tills are generally referred to as multiple-graded soils. Due to their genesis, being formed by and below the glaciers, they can normally be considered as having a high relative density. Exceptions are redeposited materials, such as slide or erosion debris. Sediments, like sand and gravel, have been deposited by water or gravitational processes. Gravitational processes mostly give rise to sediments with a low relative density, whereas water processes yield different densities. The relative density is the actual density in relation to the maximum density to which the material can be compacted.

In clay till (*Sw*: lermorän) both undrained and drained behaviour need to be investigated. The undrained shear strength may be determined by CPT, see Chapter 4.3.4, field vane or by pressuremeter (see Larsson, 2001).

The drained shear strength in fine-grained soils is most often determined by the Mohr-Coulomb formula:

$$\tau = c' + \sigma'_N \tan \phi'$$

Different empirical relationships for linking the undrained shear strength, c_u, the effective friction angle and the cohesion intercept, c', with other soil properties have been proposed by authors such as Jacobsen (1970) and Hartlén (1974). Tests performed by Larsson (2001) show that the empirical relations mostly used in Sweden for clay may be used also for clay till. The cohesion intercept, c', is then evaluated from the undrained shear strength as $0.1c_u$ and the friction angle is set to 30 degrees.

4.3 FIELD INVESTIGATION

Field investigations are both important and compulsory. They must be performed in accordance with recommended standard procedures, if such exist. Before the field investigation is carried out, a thorough introductory study should be carried out in the office.

4.3.1 Introductory study prior to field investigation

The introductory study prior to the field work consists of the following items:

- interviews with local inhabitants and persons representing local authorities
- retrieving reports from earlier geotechnical investigations (or others of interest) in the vicinity
- defining the extent of the area to be investigated
- survey of maps
- stereo air photo interpretation, including studies of traces from earlier slides and soil movements
- estimation of the number and distribution of field test sections and points

The survey of maps and air photos should follow the guidelines given in Chapter 8.3.

4.3.2 Levelling and positioning

For determination of the geometry of the ground surface, a levelling is performed. A map with an equidistance of 1 metre or less between the isometric lines may also be used, if available. All points to be investigated shall be positioned.

4.3.3 Groundwater and pore pressure

An assessment of the groundwater condition in critical parts of the slope area should be performed. Readings from open ground water pipes with filter tips installed in the soil layers should be used. The measurements should be carried out for a sufficiently long time to enable seasonal and temporary rain-induced variations to be studied and extreme values to be determined.

If only a few or no measurements of the ground water conditions can be carried out, the ground water conditions must be estimated by making cautious and unfavourable assumptions. The possibility of artesian ground water pressures has to be taken into account.

Wet sections in the slope subsurface and/or sections covered by water demanding plants may indicate high groundwater tables, see Chapter 5.2. In these sections, ground water measurements are of special importance.

4.3.4 Sounding and seismic measurements

Sounding or different types of seismic measurement should be used to determine the soil stratigraphy and the soil depth. The distance between the sounding test points along the profiles should normally not exceed 50 metres. One point should be located at the crest of the slope and one at the toe.

Soil-rock drilling and/or seismic reflection or refraction measurements may be used to determine the soil depth. For information on different types of seismic measurement, the reader is referred to for instance Möller et al. (2000) and Dahlin et al. (2001). Depending on the coarseness and stiffness of the soil layers, CPT or dynamic probing may be used in order to determine the stratigraphy in sand, gravel and fine-grained till.

In clay till, cone penetration tests, CPT, may sometimes be used. The CPT provides information on the stratigraphy and the shear strength parameters (both drained and undrained). In soils with a high heterogeneity, it is recommended that a relatively large number of tests be performed in order to obtain the variation and results that are representative for the bulk of the soil mass (Larsson, 2001).

Geotechnical investigations using a drill rig may be difficult to perform in steep slopes. In Austria, for example, excavators and drill rigs equipped with climbing rods and wires are used. When investigations are very expensive to carry out and a rough evaluation indicates that the stability is unsatisfactory, a cost-benefit analysis may show that it is more economical to relocate the endangered objects.

4.3.5 Sampling

Sampling should be carried out in all types of soil. Where it is possible to perform CPTs, the sampling can be reduced to what is required to verify the preliminary classifications from the sounding results. In some areas, sampling with a screw auger may be possible, whereas in other areas test pits must be dug in which the soil conditions can be further investigated. The test pits can be dug by an excavator equipped with climbing rods and wires.

The relative distance between the test points along the profiles should normally not exceed 50 metres.

4.3.6 Density determination

The density of the different soil layers may be measured with the aid of a water volume meter in the different soil layers in the test pits. A coarser estimation of the density of the soil layers can also be made according to Table 3. This estimation is based on the type of soil and the location of the groundwater table.

Table 3. 1 Typical bulk density values for sand, gravel and till in different ground water conditions. (After Larsson, 1989b).

Type of soil	Bulk density [t/m^3]	
	Saturated soil (ρ_m)	Soil situated above ground water level (ρ)
Sand and gravel	2.0 – 2.3	1.6 – 2.0
Till	2.1 – 2.4	1.8 – 2.3

4.4 VEGETATION, EROSION AND BOULDERS

The stability conditions in steep slopes are affected by the type and cover of vegetation as well as by the possibilities for concentrations of the water flow. A dense cover of shrubs and trees slows down the surface run-off and also reduces the pore pressures. Clear-cutting may therefore lead, after some time, to higher pore pressures and hence an increased hazard of slips and landslides. Removal of vegetation cover during construction in steep slopes should be performed with care since it may lead to surface erosion. It is of great importance that the run-off water be diverted to other areas until the vegetation is re-established. It is advisable to re-plant the vegetation before the next winter season. For further details of vegetation and run-off, see Chapter 5.

Wheel tracks in steep slopes may lead, and thus concentrate, water to sensitive areas. Scars from uprooted trees may introduce more water into the soil. These aspects have to be studied during the field investigation and the consequences analysed.

Large boulders in the area and the risk of boulders loosening and falling should be investigated.

4.5 LABORATORY INVESTIGATION

Laboratory investigations on samples taken in the field are performed mainly in order to determine the soil type (grain size distribution) and the natural water content.

4.6 EXTENDED INVESTIGATION

In the guidelines for slope stability investigations of clay, silt and sand sediments (see Swedish Commission on Slope Stability, 1995) also extended and supplementary investigations following the detailed investigation are described. These investigations aim at:

- giving the basis for a more thoroughly slope stability calculation
- giving the size of the area at risk
- giving the basis for a consequence analyses
- giving the basis for planning of preventive measures

For areas in till and coarse-grained sediments an extended investigation may include a determination of the pore pressure situation in the whole slope including its seasonal variation and prognosis of its extreme values. It may also include a deeper investigation of the soil properties, the presence and extension of layers and depth to bedrock. Such investigations are though not described in this report.

4.7 CALCULATION OF THE SAFETY FACTOR

Slope analyses are normally carried out by using well-proven computer programs. Slip surfaces of planar, circular and arbitrary shapes should be considered. For tills with considerable clay contents, e.g. clay tills, both drained and undrained behaviour should be considered (so called combined analysis) for each slice. For soil layers containing coarser types of till as well as sand or gravel, it is sufficient to perform drained analysis.

The drained and combined analyses should be carried out for the most unfavourable groundwater and pore pressure conditions.

4.8 RECOMMENDED SAFETY FACTORS

The recommendations concerning safety factors differ depending on the type of land use, the consequences involved, the type of investigation (rough estimate or detailed) and the type of stability analysis. The requirements are in general accordance with those used for investigating the stability conditions in clay, silt and sand sediments. However, there are a number of modifications relating to the difficulty of obtaining accurate and relevant shear strength properties in the types of soil considered in this document.

Depending on the direct consequences of a landslide for human life, buildings and structures, the slope stability calculations should be carried out with different requirements. Four different types of area depending on land use are employed:

- **New exploitation areas**
  When planning areas on, above, beside or below slopes with the intention of new exploitation with buildings and structures, i.e. dwellings, hotels, commercial areas, schools, industrial areas, roads, ski-lift installations, dams, major drainage systems, sewers and cables etc., the demands on the required safety factor (*F*) are the highest. Also rebuilding and extension of existing buildings and structures fall into this category.

- **Built-up areas**
  The requirements are slightly lower for areas that are already built-up, e.g. areas including present buildings and structures. However, these requirements are only applicable as long as there are no factors or actions that reduce stability. Restrictions therefore often have to be imposed.

- **Other areas**
  The requirements are even lower for areas containing only buildings and structures of less importance and which are visited by people only during daytime. This category involves local streets, parking lots, garages, secondary sewers and cables, parks, pedestrian and bicycle paths, sports grounds and ski pistes.

- **Open country**
  In open country areas, there are no demands.

  For unexploited slopes facing torrents, from which landslides can release soil masses that become involved in future debris flows, a geotechnical inspection and a rough estimate of the stability conditions and hence the volume of the masses involved in a possible landslide should be made. This is sufficient to form a basis for an estimation of the volume of soil masses available for transport by future debris flows in the torrent.

The recommended lowest safety factors (*F*) are given in Table 4 in a similar way to investigation of the stability conditions in clay, silt and sand sediments (see Swedish Commission on Slope Stability, 1995).

The recommended levels of the safety factor (*F)* may in some cases be slightly higher or lower depending on the amount of favourable and unfavourable prerequisites. Prerequisites that should be regarded are the type and amount of field and laboratory tests, the geometry and condition of the slope, ground- and pore water situations, the soil properties, the consequences of a slide, the type and extension of slope stability analyses. If a calculated F-factor is acceptable according to the table, no further investigation is normally required, provided that all the preconditions are fulfilled.

4.9 DOCUMENTATION OF RESULTS FROM THE INVESTIGATION

Recommendations for documentation of results from detailed investigations in slopes are presented in Chapter 9.1.

Table 4. Recommended safety factor (F) in different investigation stages depending on type of land use and slope stability analysis method. (Modified after Swedish Commission on Slope Stability (1995)).

Investigation stage	Soil Conditions	Intended or present type of land use			
		New exploitation	Present buildings and structures	Other areas	Nature areas (if the surrounding areas are not affected)
Geotechnical inspection and rough estimate	Till	Insufficient[1]	$F_{c\phi} > 1.50$	$F_{c\phi} > 1.45$	$F_{c\phi} > 1$
	Sand and gravel	Insufficient[1]	$F_{\phi} > 1.50$	$F_{\phi} > 1.45$	$F_{\phi} > 1$
Detailed investigation	Till	$F_{c\phi}$ and F_{COMB} > 1.45	$F_{c\phi}$ and F_{COMB} ≥ 1.40	$F_{c\phi}$ and F_{COMB} ≥ 1.40	$F_{c\phi}$ and F_{COMB} > 1
	Sand and gravel	$F_{\phi} \geq 1.35$	$F_{\phi} \geq 1.3$	$F_{\phi} \geq 1.3$	$F_{\phi} > 1$

[1] At least a detailed investigation has to be carried out for new exploitation.

Chapter 5.
Run-off conditions

The risk of erosion, debris flows and shallow landslides is dependent on the run-off conditions in the area. The run-off conditions determine how the rainwater will proceed after it has reached the vegetation or the ground, for instance how much of the water will be left in the crowns of the trees, how much will penetrate the soil or bedrock and how fast the rainwater will flow on the surface. The run-off conditions are influenced by the following parameters:

- vegetation cover (type, amount, evapotranspiration)
- topography and shape of the catchment area
- geology
- amount and location of brooks in the catchment area
- soil conditions (type, thickness, structure, pore volume, hydraulic conductivity)
- inclinations of slopes, of bottom of the torrent and of brooks (large and small scale)
- drainage and infiltration characteristics
- ground water and soil moisture content
- precipitation condition (intensity, duration and distribution over the year)
- land use (roads, ski pistes, artificial drainage, buildings, structures, meadows, forests)

It is obvious that the run-off conditions in a catchment area (see Chapter 5.1) are not constant but vary both during the year and with specific conditions. The run-off conditions are often expressed by a dimensionless run-off coefficient, which is described in Chapter 5.2. Furthermore, the amount of water that runs off directly into a brook may be calculated using various formulas, which are described in Chapter 5.5.

5.1 CATCHMENT AREA

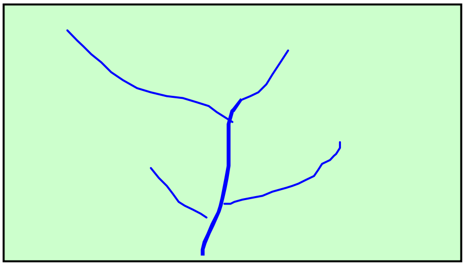
A catchment area is defined as the land area, usually horizontally projected, from which all run-off water enters the same stream, upstream of the point of interest. The boundary of the catchment area is called the watershed.

The watershed configuration, and hence the extent of the catchment area, can be illustrated by drawing a line by hand with guidance from the elevation contour lines on a detailed topographical map (a map which shows the inclination and height of the ground by elevation lines) with a scale of 1:20 000 or preferably larger and the differences between the elevation lines nor more than 10 meters. If a detailed digital topographical map is available, the watershed can be drawn by using the existing tools for construction of the watershed line in a– geographic information system , i.e. ARC-Info, MAP-info etc. The horizontally projected size of the catchment area, A, may be determined either with a planometer or, better, by using a GIS.

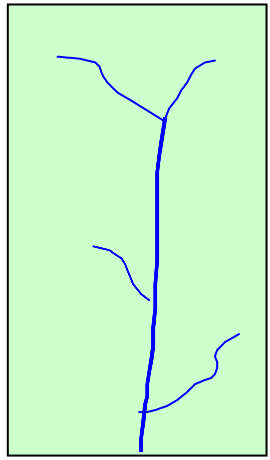
From a run-off point of view, a small catchment area (< 10 km^2) behaves in a different way to a large catchment area (> 100 km^2). Progressively smaller and steeper basins have the potential to transport an increasingly larger percentage of eroded material by mass-wasting processes such as debris flows (Costa, 1984). This is because of the following aspects:

- Rainstorms drop proportionally larger volumes of water on smaller basins
- Smaller basins are usually the highest, where snowpacks accumulate and can melt rapidly in the spring,
- Hillsides in smaller basins have steep slopes resulting in greater instability of surficial materials

The probability of a large catchment area being completely covered by a shower with a high intensity is low. The run-off from a small catchment area is also more sensitive to changes in land use. In larger catchment areas, this sensitivity will be suppressed due to a higher water storage effect in the watercourse, as well as in lakes and ponds. Also the shape of the catchment area plays an important role. Figure 3 shows two different shapes of catchment area. Provided all other conditions are the same, all the water from the long area will reach the stream much faster compared with the wide area. However, the flow will differ much more along the stream bed in the long area compared with the wide area. The highest run-off values are from heart-shaped catchment areas, since the water droplets have the same distance to flow from nearly every point in the catchment area (Sauermoser, 2004).



Wide-shaped catchment area



Long-shaped catchment area

Figure 3. Different shapes of catchment area.

5.2 RUN-OFF COEFFICIENTS

Most often, the run-off condition is expressed by a dimensionless run-off coefficient, Ψ, which is normally considered to have a constant value, although in reality this is usually not the case. The run-off coefficient expresses how much of the total amount of rainwater will run off directly over the surface (surface run-off) without infiltrating the soil or remaining in the tree crowns or in bushes. The coefficient is a number between 0 and 1, where 1 indicates that all rainfall runs off directly. The dimensionless run-off coefficient is used in different formulas and models for run-off calculations, see Chapter 5.5.

Mostly, the run-off coefficient is assumed to be independent of the rain intensity from the point when a constant run-off is reached. A constant run-off is reached after overcoming run-off delay effects at the beginning of the rain event, e.g. initial abstraction. Kohl & Markart (2002) showed that this assumption is valid for rain intensities from 30 to 120 mm per hour on research plots with sizes between 75 and 100 m^2. Recent experiments by Kohl & Markart for rain intensities of approximately 100 mm per hour covering larger areas (400 m^2), showed that generally this scheme fits and therefore the assumption seems realistic (Markart, 2004). For rain intensities below 10 mm per hour, they found that the run-off coefficient slowly increases with increasing rain intensity.

5.2.1 Typical values of run-off coefficients

Markart et al. (2004) presented results from artificial irrigation tests on slopes covered with different types of vegetation. Some typical values of run-off coefficients measured in their study are presented in Appendix A. The run-off coefficient varies widely depending on the type of vegetation, land use, penetrability of water through the ground surface, thickness of the soil layer and permeability of the soil layers. The highest run-off coefficients are found for thin and dense soil layers with a high moisture content and where the vegetation consists of grazed grasses, extensively used grassland containing a high amount of dead biomasses in the litter layer and short-growing herbs. A low surface run-off is achieved with shrubs, trees and a non-smooth soil surface. Dense soil, mostly found in clay-rich soils from crystalline mountains, leads to a high number of river channels and gullies, while porous soil, mostly found in limestone mountains, leads to a low number of river beds (Sauermoser, 2004).

Grazing is not recommended as erosion protection or on slopes where the run-off needs to be reduced. This is due to the fact that grazing most often leads to a dense grass cover that makes it difficult for the water to infiltrate the ground. The use of grazing as landslide protection is, however, suitable on slopes where the pore water pressure needs to be reduced. However, the grazing has to be planned carefully. Heavy animals, such as cows, often destroy the soil surface and form paths which can be the starting point for rain infiltration. A small number of sheep grazing for a brief period is to be preferred. Grazing may reduce the growth of unwanted species, such as nettle, raspberry and different types of brushwood, and thereby increase the possibilities for desired species to grow.

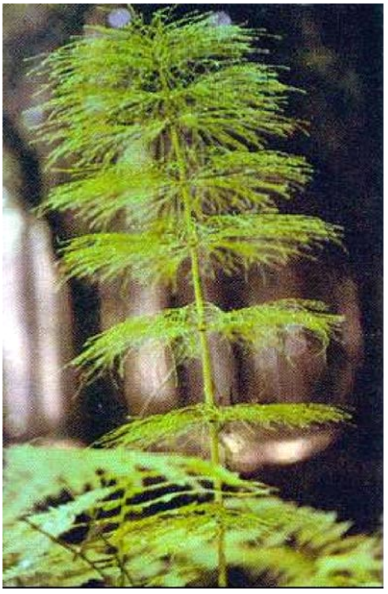
By looking at the different species growing in an area, an indication of the soil moisture content and run-off conditions may be obtained. Three-leaved rush (*Lat*: Juncus trifidus, *Sw*: klynnetåg) requires very little nourishment and prefers a dry and exposed habitat in the Swedish mountains, see Figure 4. However, most of the other species in the Juncus family, such as three-flowered rush (*Lat:* Juncus triglumis ssp triglumis, *Sw*: lapptåg) and two-flowered rush (*Lat:* Juncus biglumis *Sw*: polartåg), prefer wet soil conditions. The species mat-grass (*Lat*: Nardus stricta, *Sw*: stagg) forms a dense root system and acts like a thatched roof, thereby effectively preventing infiltration and giving a high run-off coefficient, Figure 5.

In the case of woody vegetation, many species from the salix family indicate wet soil conditions. Species found in Table 5, common in the Swedish mountains , all indicate a high moisture content and thus a high run-off coefficient. For areas outside the mountains an investigation of growing species and there requirement of water has to be analysed.

Table 5. Example of species common in the Swedish mountains (Fjällen), which prefer wet soil conditions.

	Species	
English name (Eng)	**Latin name(Lat)**	**Swedish name (Sw)**
Alpine saw-wort	Sausurea alpina	Fjällskära
Marsh marigold	Caltha palustris	Kabbeleka
Wood horsetail	Equisetum sylvaticum	Skogsfräken
Alpine garden angelica	Angelica archangelica ssp archangelica	Fjällkvanne
Three-flowered rush	Juncus triglumis ssp triglumis	Lapptåg
Bog bilberry	Vaccinium uliginosum ssp microphyllum	Odon
Greyleaf willow	Salix glauca	Ripvide
Tea-leaved willow	Salix phylicifolia	Grönvide
Globeflower	Trollius europaeus	Smörboll
Woolly willow	Salix lanata	Ullvide

Three-leaved rush (*Lat*: Juncus trifidus, *Sw*: klynnetåg). Photo: G. Markart



Wood horsetail (*Lat*: Equisetaceae sylvaticum, *Sw*: skogsfräken) are found on moist and often poor soils. Photo: G. Markart

Figure 4. Two species indicating high run-off conditions.

Figure 5. Mat-grass (Lat: Nardus stricta, Sw: stagg). (Photo: K. Rankka).

5.2.2 Choosing the right run-off coefficient

The catchment area has to be divided into sub-areas within which the run-off conditions can be regarded as equal. The run-off coefficients for each of these sub-areas have to be established. For implementation of the run-off coefficient concept in practice, it is often recommended to assign not exact run-off values but rather run-off classes to different soil and vegetation units (Markart et al., 2004).

The following aspects should be considered when choosing the run-off coefficients:

Vegetation

	Aspects	Effects of run-off	Run-off coefficient
Type of vegetation	Trees	Reduced amount of rainwater reaching the ground	Low
	Shrubs	Reduced run-off speed, increased infiltration capability	Low
	Grass	Increased run-off speed, reduced infiltration capability	High
	Herbs		
	Water-demanding species	Indicate high moisture content and thus a high run-off	High

	Aspects	Effects of run-off	Run-off coefficient
Vegetation cover	Dense	An area with a dense vegetation cover of shrubs and trees, well treated meadows and combinations of trees, shrubs and herbs. Not for extensively used grassland. These types of areas give good possibility for infiltration.	Low
	Sparse		High
Grazing, maintenance	Grazing	May both increase and reduce run-off, see Chapter 5.2.1. According to Markart et al. (2004), uniform grazing with light animals increases the run-off coefficient by approximately 0.1 – 0.2.	High and low
	Maintenance	To achieve the desired vegetation type and cover, maintenance of the area may be necessary.	Low

Soil and bedrock condition

	Aspects	Effects of run-off	Run-off coefficient
Type of bedrock	Presence of fractures of infiltration	Reduced run-off due to possibility	Low
	Weathered surface not smooth	Reduced run-off since surface is	Low
Type of soil	Coarse-grained	Reduced run-off since surface is not smooth	Low
	Fine-grained and mostly forms a smooth surface which increases run-off	Reduced possibility of infiltration	High
	Porosity – high	High porosity increases possibility of infiltration	Low
	Permeability – high	High permeability increases possibility of infiltration	Low
	Thickness – large	Large thickness increases possibility of infiltration	Low

Inclinations of slopes (large and small scale)

Steep slopes have both higher run-off coefficients and shorter run-off times compared to lesser steep slopes, all other factors being similar. For areas well covered by vegetation, the effect of inclination is, however, of minor importance (Markart, 2004). The average inclination of the slopes in the catchment area should be studied. Nevertheless, it is important not only to look at the average inclination but to identify possible depression points where water can be stored for shorter or longer periods. Occurrences of depression points reduce the run-off coefficient.

Drainage

Drainage channels that lead the water away from a slope reduce the run-off coefficient in the slope, but may increase the run-off coefficient for the whole area. It is of great importance for the channels to be designed correctly, to be cleaned and to be regularly checked regarding their function.

Soil moisture content

The surface run-off increases when the soil moisture content is high. During snow melt and after long periods of rainfall, the run-off coefficient is therefore often very high.

Artificial snow is stiffer than natural snow and thereby melts slower, which is both positive and negative. The positive effect is that less snow melts at the same time on warm days compared to natural snow. The negative effects are that more snow deposited on the slope has to melt and that the stiff artificial snow cover acts as a very high run-off area. Run-off water will overflow on top of the stiff snow cover and thereby run off very quickly. A run-off coefficient of about 0.9 can be assumed for run-off on artificial snow.

Precipitation (intensity, duration and time of the year)

As mentioned earlier, Kohl and Markart (2002), found that the run-off coefficient increases with increasing rain intensity up to about 10 mm per hour. For higher intensities the values are fairly constant. When choosing a suitable value for the run-off coefficient, the possible types of rain in the area should be studied. The possibility of intense precipitation during snow melt and after long periods of rainfall (mostly during the autumn) also has to be taken into account.

Land use (roads, ski pistes, meadows, artificial drainage, buildings, structures, forests)

Different types of land use have a significant effect on the run-off coefficient. The construction of a ski piste, for example, destroys the soil structure and vegetation cover, and thereby most often increases the run-off coefficient. It may take years and a great deal of effort to achieve good infiltration again.

Scars from wheels and ditches not protected from erosion may be the starting point for a debris flow. Roads have high run-off coefficients since the soil has been compacted.

5.2.3 Examples of run-off coefficients from Sweden

No direct measurements of run-off coefficients in catchment areas have been performed in Sweden. Indirect measurements were carried out in the catchment areas of Bergebäcken and Fjällvallen in the municipality of Åre by Wilén et al. (1993). The catchment areas, each with a size of about 0.65 km^2, are characterised by:

- relatively flat slopes
- lack of deep gullies and valleys
- vegetation in the direction from the lower altitudes with spruce forest, birch forest, heather moors and a bare mountain region above the tree-line
- a number of ski pistes in the catchment area of Bergebäcken
- depression points, small ponds

Average run-off coefficients for the whole catchment areas were estimated by measuring the precipitation and the water discharge in the central brooks. The coefficient for Bergebäcken was estimated to be 0.36 and for Fjällvallen 0.41. The coefficients were estimated as average values for precipitation during the summer months of 1989 to 1991.

A detailed investigation of the run-off and stability conditions in Mörviksravinen in the municipality of Åre, was performed by SGI in 2003 on commission from the municipality of Åre (see Rankka & Fallsvik, 2003 and 2004). The run-off coefficient used in the investigation varied between 0.15 and 0.6, with a mean value of 0.3.

5.3 RUN-OFF VELOCITIES

The run-off velocity in a catchment area depends on the inclination of the slopes and the stream bottom, the type of vegetation cover, the smoothness and roughness of the ground surface and the cross-section area of the brook. The run-off velocity has to be determined in order to decide what rain duration to use in calculating the design water discharge.

The run-off velocity of interest is the velocity of the most remote raindrops in the catchment area during their flow down to the point of interest, for instance the selected position of a sedimentation dam. The time it will take for these drops to run through the catchment area, down to the dam, the run-off time, determines the duration of the rainfall to be used as design rainfall, see Chapter 6.3.

The run-off velocity may differ between flows in natural streams, channels and surface run-off.

5.3.1 Run-off velocities in natural streams and channels

Calculations according to Manning formula for channel flow
According to the Manning formula, the velocity of water at fully developed turbulent steady flow in pipes or channels can be calculated as:

$$v = MR^{2/3}\sqrt{I} \qquad \text{[m/s]}$$

where M = Manning coefficient [m$^{1/3}$/s]
R = A/P [m^2/m]
A = wet area [m^2]
P = wet perimeter [m]
I = bottom gradient [height/length]

The Manning formula requires the flow to be unaffected either by damming below the place of interest or by overcritical flow above. The formula requires measurements of the wet area (width and height of flow) and the wet perimeter during earlier debris flows. If no measurements have been made during the earlier debris flow, traces in the river bed may be found and investigated to obtain relevant data, but only for a few weeks after the event.

The use of the Manning formula in the context of brooks may be discussed since, among other things, it has been developed for clean water. According to Rickenmann

(1999) the mean velocity of debris flows and clear water can, however, be described in an initial approximation with almost the same formulae. The values should be accepted with caution and used only to obtain an estimate of the flow velocity.

One difficulty with the Manning formula is the choice of the Manning coefficient, M. Zeller (1974) recommends values of 5 to 25 for the Manning coefficient in steep, rocky natural terrain. Zeller's guidelines are used by the Forsttechnischer Dienst für Wildbach und Lawinenverbauung in Austria (Sauermoser, 2004). Chow (1959) and French (1985) presented extensive tables of values for the Manning coefficient for various types of channels, streams and rivers. A few of these values useful in the case of natural streams are presented in Table 6. Rickenmann (1999) mentioned that the peak flow velocity of debris flows may be estimated with a Manning coefficient equal to 10.

Table 6. Some values of the Manning coefficient according to French (1985) for natural streams

Description of stream	Manning coefficient, M
Mountain streams, no vegetation in channel, banks usually steep, trees and brush along banks submerged at high stages	
- Bottom: gravel, cobbles and few boulders	20 – 25
- Bottom: cobbles with large boulders	14 – 20
Streams on plains	
- Clean, straight, full stage, no rifts or deep pools	30 – 33
- Very weedy, reaches, deep pools or floodways with heavy stands of timber and underbrush	6 – 10

Rickenmann (1999) suggests a semi-theoretical value of the Manning coefficient, M, as a function of the flow as:

$$\frac{1}{M} = 0.077(Q)^{1/15} \qquad [-]$$

where: Q = water or debris flow [m^3/s]

The factor 0.077 is based on debris flow records from Italy, Switzerland, USA, China and New Zealand. With the formula suggested by Rickenmann, a flow value of 4 m/s gives a value of the Manning coefficient of 12.

According to experiences in Austria, the Manning formula generally gives excessive velocities in calculations of debris flow velocities in brooks. For this reason, in Austria, a velocity higher than 6 m/s is never used (Sauermoser, 2003). It should also be taken into account that during high flood, the flow consists of both water and debris, which gives a low velocity in comparison with clean water.

An adjustment of the formulas and values given above to Swedish conditions is desirable.

Calculations based on the transverse inclination of the stream surface in a bend

The flow velocity in a natural stream or in a channel can be determined empirically using a formula suggested by Haiden (Sauermoser, 2004). The formula is based on the transverse inclination, due to centripetal acceleration, of the stream surface, which occurs when the water flows through a bend. The velocity is calculated as:

$$v_{\max} = \sqrt{\frac{h \cdot g \cdot r}{s}} \qquad \text{[m/s]}$$

where h = the vertical uplift of the water, according to Figure 6, [m]
s = the width of the flow, according to Figure 6, [m]
r = the bending radius of the brook at the point of observation, [m]
g = gravity acceleration [m/s^2]

The mean water flow velocity in the section is determined as:

$$v_{mean} = \frac{v_{\max}}{2} \qquad \text{[m/s]}$$

and the flow:

$$Q = A \cdot v_{mean} \qquad \text{[m}^3\text{/s]}$$

where A = cross section area, according to Figure 6, [m^2]

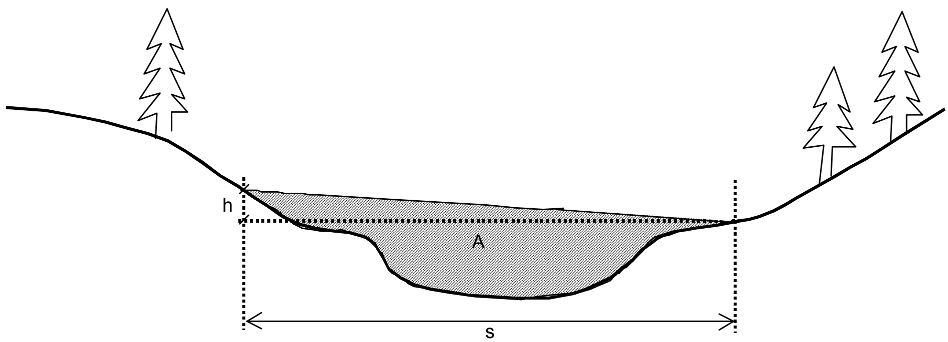


Figure 6. Section for determination of flow velocity and flow.

The use of the formula suggested by Haiden requires that traces in the brook from earlier events can be measured, see Chapter 8.6.

Measurements of run-off velocities

Run-off velocities in natural streams may be measured during heavy rainfalls. The measurements have to be related to the intensity and duration of the precipitation.

Wilén et al. (1993) gives results from measurements of water discharges in the brooks of Bergebäcken and Fjällgårdsbäcken in the municipality of Åre. The measurements were made using a V-shaped Tomson weir and took place continuously during the snow-free periods of 1989-1991. The results were related to the amount, duration and intensity of precipitation. The mean flow velocity throughout the catchment areas was found to be 0.08 m/s (mean value for both brooks). The catchment areas are characterised by uniform moderately inclined slopes with no gully or valley formation, some flat and some wet areas with high water storage capacity and relatively good vegetation cover.

Values according to experiences

According to Sauermoser (2002 and 2003) the flow velocity for catchment areas formed like a gully with steep slopes can be estimated to be approximately 2 m/s. This velocity corresponds to a mean value for the conditions along the brook, through areas of talus, forest areas with water saturated soil, and moors.

Calculation of flow during earlier events

The flow (m^3/s) in different sections along the brook may be calculated if the velocity and wet area have been determined. The calculation of high water flow is presented in Chapter 5.5.

5.3.2 Run-off velocities on a natural ground surface

The run-off velocity on a natural ground surface, outside streams, is dependent on the same factors as the run-off conditions (see Chapter 5). Measurements of the run-off velocity on natural ground surface may be performed using trace substances, such as fluorescence.

5.4 RUN-OFF TIME

The run-off time is the time it takes for the most remote water droplet to run (or more strictly: which takes the longest time to run) through the catchment area to the point of interest, for instance to a sedimentation dam. The run-off time, T, may be calculated as the run-off distance, L, for the most remote droplets, divided by the run-off velocity, v, using the formula:

$$T = \frac{L}{v} \qquad \text{[s]}$$

where: L = run-off distance [m]
v = run-off velocity [m/s]

Alternatively, the run-off time may also be calculated according to different empirical formulas. According to Bergtahler (1986) the run-off time may be calculated as:

Hampel: $T = 27.8 \cdot A^{0.5}$ [minutes]
Kreps: $T = 52.2 \cdot A^{0.4}$ [minutes]
Kirpich: $T = 0.0195 \cdot L^{1.155} \cdot H^{-0.385}$ [minutes]

where: A = catchment area down to the selected dam position [km^2]
L = run-off distance from the outermost part of the catchment area [m]
H = difference in altitude between the outermost part of the catchment area and the point of interest [m]

The Hampel and Kreps formulas have been developed for situations in the inner area of the Alps with moderate rain intensities and large catchment areas. The Kirpich formula has been developed for very heavy precipitation values in the Alps.

5.5 FORMULAS FOR RUN-OFF FLOW

The so called rational method (also called the Zeller method) is one of the simplest and best known methods routinely applied in hydrology (Kohl & Markart, 2002) for run-off calculations. The rational method expresses the peak run-off flow, HQ, in a specific position along the brook as:

$$HQ = \psi \cdot I \cdot A \qquad [\mathrm{m^3/s}]$$

where ψ = run-off coefficient [–]
I = rain intensity [m/s]
A = catchment area [m²]

The rational method is valid for heavy rainfall and therefore requires a good knowledge of the rain intensity and duration for short periods (Sauermoser, 2002). Such precipitation records are seldom available and an estimation procedure has to be used, see Chapter 6.

For precipitation with long duration, about 24 hours, in large catchment areas, a method suggested by Hampel may be used. According to Hampel (1984) the peak run-off flow may be calculated as:

$$HQ = 0.4 \cdot \psi \cdot h_{150} \cdot A^{0.5}\left(1 - \frac{H_u}{2400}\right) \qquad [\mathrm{m^3/s}]$$

where ψ = run-off coefficient [–]
h_{150} = rain height for rainfall of long duration with 150-year return period [mm]
A = catchment area [km²]
H_u = height above sea level for lowest part of the torrent [m]

Both the Hampel and Zeller methods are empirical equations constructed for a situation applying to specific places. Calculations of run-off flow should therefore always be checked against flow records, see Chapter 5.3.1.

5.6 RUN-OFF DISTANCES

The distances over which the masses may be transported depends on the bottom inclination and on the grain size distribution within the flow. Rickenmann (1999) gives a simplified formula for the possible transportation distance, L_f, from the apex of the fan:

$$L_f = 15 \cdot V_s^{1/3} \qquad \text{[m]}$$

where: V_s = solid material volume [m^3]

Rickenmann (1999) points out, however, that the formula should not be used since the scatter between predicted and observed values is too high. Sauermoser (2004) says that this formula is not used in practice. In Austria, the run-off distance is set to the point where the torrent reaches the main, usually perpendicularly oriented, stream unless the flow has left the channel somewhere along the debris cone (Sauermoser, 2004).

Chapter 6.

Precipitation

6.1 INTRODUCTION

In most cases, debris flows following torrents are triggered by heavy rainfalls, e.g. rainfalls with a high intensity, especially if they follow a long period of rain or snow melt.

Typically, the cause of precipitation is uplift of warm air, e.g. a vertical movement, of a warm mass of air within the atmosphere. Condensation of water vapour and hence formation of clouds and further rain is often due to these different types of uplift. Briefly, in the context of uplift of warm air masses, the following physical conditions are important:

- Warm air is lighter than cold air.

- The ability of an air mass to contain water vapour is reduced through lowering of the air temperature.

- At higher altitudes the air pressure is lower. When an air mass is moving upwards, it will adopt the same pressure as the surrounding atmosphere. When the air pressure decreases, also the temperature will decrease and hence the atmosphere's ability to contain water vapour also decreases. The water thereby condenses into water droplets forming clouds, and further to precipitation.

- Condensation and, higher up, freezing of cloud droplets causes the release of latent heat, which warms the air and amplifies the vertical motions.

In general, three different types of precipitation due to uplift are distinguished: convective, orographical and frontal uplift, see Figure 7. These are described in the following sections.

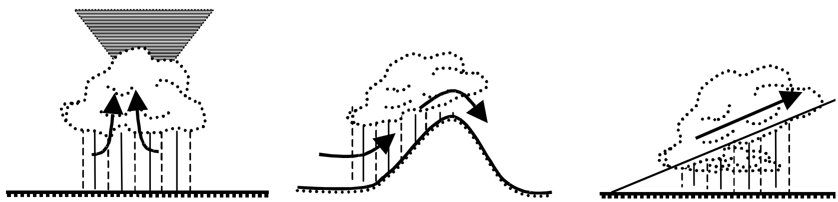


Figure 7. The three main types of precipitation.

6.2 DIFFERENT TYPES OF PRECIPITATION

6.2.1 Convective precipitation

On sunny days, the subsurface is heated by solar radiation. In its turn, the heated subsurface warms the lower parts of the atmosphere. However, different parts of the landscape, such as forests, grasslands, lakes etc., are heated by the sun to different degrees, depending on their different reflective abilities. Over these areas where the subsurface becomes relatively warmer, also the lower parts of the air mass will become warmer than in the surroundings. Therefore, on warm days, so called convection cells are formed in the atmosphere where the relatively lighter warm air is forced upwards. The vertically lifted warm air will be chilled due to the lower air pressure (see above), leading to condensation of air moisture, and thereby the development of cumulonimbus clouds, generating showers that may be combined with thunder.

The cumulonimbus clouds give rise to a high precipitation intensity. However, the clouds will follow the present general wind direction in the area, and because cumulonimbus clouds have a small horizontal size, the convective type of rain normally has a relatively short duration, from a few minutes to 2 – 3 hours.

6.2.2 Orographical precipitation

In hilly terrain and mountainous regions, precipitation may also be triggered by so called orographical[2] uplift. In this case, an air mass is forced to higher altitudes due to the topography, i.e. the wind blows the air over the mountain ridge. For the same reason as in convective cells, the uplift results in condensation, creating water drops and hence rain fall, often heavy once.

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2 Orography, that part of physical geography, which deals with different aspects connected to a sharp subsurface relief like mountains, hills, slopes etc

6.2.3 Frontal precipitation

A front constitutes the boundary between two air masses with different temperatures. There are cold fronts and warm fronts depending on the direction in which the different air masses migrate. In both cases, the warmer and hence lighter air mass will be forced up over the colder and heavier air mass. Here again, the uplift results in condensation, creating water drops and hence rain. However, in this case the rain will have a long duration but a moderate or low intensity.

6.2.4 Combination of precipitation types

When a front reaches a mountain range or hilly terrain, the effects of frontal uplift and orographical uplift will be combined, so the rain intensity will be higher on the slopes which are directed to the windward side. On the slopes on the leeward side, however, the rain intensity will be relatively lower.

However, a case of more intense precipitation is the combination between convective and orographical precipitation. The latter may occur when a powerful convective cell, containing warm and humid air of tropical origin, is moved by a strong wind upwards over hilly terrain or the slopes of a mountain ridge. In this case, the precipitation may reach very high intensities, although the duration is often short or moderate.

6.3 DESIGN PRECIPITATION

To estimate the risk of debris flows and to judge their maximum volumes, the design precipitation for the chosen return period has to be established. Three factors have to be determined regarding the design precipitation: the return period, the duration and the intensity.

6.3.1 Return period for design precipitation

The return period states the time within which the chosen rain intensity and duration will occur once, statistically. For instance, a return period of 50 years means a rainfall that will occur once in 50 years, statistically.

The return period has to be decided for each project, but it is advisable to choose a period of at least 100 years. In Austria, for instance, a return period of 150 years is often used in detailed investigations but for hazard mapping a return period of 100 years is used.

6.3.2 Design duration

To establish the design precipitation, the so-called design duration must be known for the selected catchment area. The design duration equals the run-off time required for the "drop of water", which has the longest way (or strictly; which takes the longest time to pass) through the catchment area. Chapter 5.4 describes how to calculate the run-off time.

6.3.3 Precipitation records

To determine the design precipitation based on precipitation records, it is important that the measurements have been carried out in a place that is representative also for the catchment area in mind. The place should be close to the catchment area, at the same altitude and on the same side of high mountains, etc. Furthermore, precipitation records should have been kept for several years.

Information on the precipitation conditions for short durations is rather sparse in most mountain areas. The Swedish Meteorological and Hydrological Institute (SMHI) has performed long series of measurements of precipitation in its nationwide network of weather stations. About 800 stations with precipitation measurements were in operation at the beginning of 2001 (Alexandersson & Karlström, 2001). Most of them, more than 700, are manually read stations and readings are performed only once a day, so there is a lack of information concerning the duration of short rainfalls. However, many of the stations have been used for precipitation measurements since the 19th century. The weather stations are unevenly spread over the country, with a higher density in the southern part of Sweden. If they had been evenly spread, the average distance between the stations would have been 23 km. In the most northern part, however, the distances may be more than 60 km.

Furthermore, it is possible that the closest weather stations are not positioned at sites that are representative. The three main types of precipitation described above, in particular the combination between orographical and convective rains, generate different precipitation conditions locally in the landscape. Due to the orographical uplift, more rain will most probably fall on the higher altitudes within a catchment area. Thus, for the specific purpose of gathering local information on the precipitation conditions (rain height and duration) at different altitudes within a selected catchment area, often the data from weather stations is not sufficient.

6.4 RECOMMENDATIONS

Different approaches may be used in handling the problems outlined above. In Sweden, a method for calculating the regional distribution of intense precipitation with duration from 3 minutes to 96 hours with return periods of up to 10 years (extrapolation up to, for instance, 100 and 150 years is possible) has been developed by Dahlström[3] (1979). The method is based on continuous time series of precipitation records carried out at a number of places in Sweden together with monthly regional distribution of convective precipitation and annual mean precipitation in the area studied. The method requires either precipitation data from a weather station with measurements made once a day between the years 1931 and 1960, or a coefficient for different regions in Sweden. Subsequently, the method has been somewhat modified to give a better fit to measured values and longer return periods. On request, SMHI can perform calculations according to the Dahlström method for selected areas, precipitation duration and return periods.

In areas with large altitude differences within the catchment area, it is recommended to find extra and more local sources of precipitation data. Occasionally, the precipitation may have been measured by local agents other than SMHI, such as local authorities, ski piste operators, fire brigades, local military staff, researchers, consultants, contractors etc. and even private persons interested in meteorology. Otherwise, the investigator has to perform his own series of measurements, preferably at different altitudes in the catchment area. These measurements should be carried out for at least two years.

These extra measurements performed at a minimum of one extra altitude will form the basis for modelling the precipitation at any other altitude.

SMHI has analysed differences in monthly mean rain heights at different altitudes for a number of places in Sweden (Alexandersson, 2003). As an average, an increase of 7% per 100 m of altitude, is given as a guideline. However, it is not recommended to transfer this value to precipitation with short duration, since slowly moving frontal rainfall gives a more significant increase in precipitation amount with altitude, compared with showers (heavy rains with short duration). Showers in warm fronts at high altitudes are more insensitive to topography differences, but they sometimes cause very heavy cloudbursts (Alexandersson, 2004).

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3 The equations used in the Dahlström-method are briefly described in APPENDIX C

In Austria a similar method as the Dahlström method is used to estimate the regional distribution of intense precipitation with short duration (Gattermayer, 2004).

6.5 EXAMPLE OF DESIGN PRECIPITATION FOR MÖRVIKSÅN IN ÅRE

The Dahlström method has been applied to the catchment area of Mörviksån in Åre. The altitudes within the catchment area range from 380 to 1450 m above sea level. The closest SMHI weather station is situated in Duved, about 15 km west of Mörviksån, at almost the same altitude as the lower parts of the selected catchment area. The design duration for a rainfall was calculated as 60 minutes, and hence the design precipitation for the return period of 150 years was calculated by SMHI as 46 mm according to the modified Dahlström method.

Due to the effects of the orographical uplift, a higher precipitation was estimated to fall at higher altitudes. Long-term precipitation records had never been carried out at higher altitudes within, or in the vicinity of, the catchment area. However, precipitation measurements had been carried out by Wilén et al (1993) during the snow-free period of the years 1990 – 91 simultaneously at two sites – on the shore of Lake Åre in the lower part of the catchment area (altitude 380 m) and in Ullådalen 8 km west of the catchment area (altitude 695 m). On most precipitation occasions, these measurements indicated a higher amount of precipitation in Ullådalen than in Åre. With these measurements as guidance for short duration rainfalls, a precipitation increase of 2% per 100 m of altitude change was estimated up to 1000 m altitude. Over that altitude, no further increase in rain intensity was estimated.

Chapter 7.
Masses transported by a debris flow

The amount of masses transported by a debris flow will depend on the available soil masses in the torrent and the transportation capacity of the debris flow.

7.1 AVAILABLE MASSES

There is no existing method for determining the exact amount of available masses for a debris flow. The calculation of mass volume should comprise two parts:

- Available masses that can be transported in one debris flow
- The total sediment potential in the torrent, i.e. the total mass volumes that are available for repeated debris flows.

7.1.1 Available masses that can be transported in one debris flow

The available masses have to be estimated in the field. The amount of debris that can be transported is a function of the critical shear stress in the riverbed during a high flood and it is primarily connected to the inclination, see Chapter 7.3. The debris masses come from bank erosion along the sides of the brook, bottom erosion along the bottom of the brook and material that may reach the brook by landslides and debris flows from the surrounding slopes. By studying traces from former debris flows the amount of eroded material can be estimated.

Fine-grained material is more easily carried by water than by coarse-grained material. Therefore, the availability of masses in deposits made up of fine-grained material should be regarded as higher than that from coarse-grained deposits. It is important to determine the depth to bedrock. Places where the soil depth is limited, where the brook flows on bedrock or bedrock is found in the slopes, should be marked.

For slopes facing the torrent, the stability has to be calculated roughly, see Chapter 4. For slopes that are found to be unstable, the amount of material that could reach the brook has to be estimated. It is also necessary to take into account the number of landslides that might occur during the same time rain fall.

The estimated available material in Mörviksån in the municipality of Åre is given in Table 7. One part of Mörviksån is shown in Figure 8. Traces from earlier erosion can be seen along the right side of the brook. Material has been deposited along the bottom and on the left side (from the photographer) of the brook during earlier debris flows. This material may be further transported during a high flow.

Table 7. Estimation of available masses for one section in Mörviksån.

Type of erosion	Available masses	Comments
Bank erosion	≈2 m^3/m	Depth and width 1.5 m each, left side
Bottom erosion	≈1.5 m^3/m	Depth 0.5 m with an average width of 3 m
Landslide, debris flow from side slopes	0	The possibility of landslide material reaching the brook is limited

Figure 8. The stream Mörviksån.

7.1.2 Total sediment potential

The material sources for debris flows in a catchment area may in some places be almost endless, while in others the sources are limited. In some catchment areas, the potential is very high, much higher than the amount that can be transported in one event, and it is therefore to be expected that there will be many more events in the future. A rough estimate of the total sediment potential in the catchment area should therefore be given.

Knowledge of the total amount of masses is essential when plans are being made for suitable preventive measures. Check dams, for instance, are built to prevent the brook from eroding deeper along its bottom. The soil depth along the torrent should therefore be investigated. If the material along the bottom is limited there is no need for check dams.

7.2 DEPOSITION AREAS

Generally, the bottom inclination varies along the stream within the catchment area. Material eroded and transported in one place may, on its way further downstream, enter an area where the inclination is lower. A lower inclination means that the transport capacity of the water decreases and some of the transported material may settle. Some places along the stream are therefore erosion areas, while others are deposition areas. The amount of material that is settled in the deposition areas will depend on the bottom inclination, the type of bottom material, the water flow (volume and velocity), the cross section area and the size and shape of the transported material.

The inclination of the bottom of the stream has to be determined. This may be done using maps, preferably with high resolution and contour lines having an equidistance of 1 metre. During a field investigation, it is important to measure the bottom inclination and to mark deposition as well as erosion areas, see Chapter 8.6.

The examples shown here in Figure 9 and Figure 10 are from deposition areas along Mörviksån in Åre and in the Stor-Grova gully in Kittelfjäll.

Figure 9. Deposition area in Mörviksån. (Photo: K. Rankka).

Figure 10. Deposition area in Stor-Grova in Kittelfjäll (Photo: J. Fallsvik)

7.3 TRANSPORTATION CAPACITY

The amount of material that can be transported by the water flow (see Chapter 5.5) depends on the bottom inclination, the grain size distribution, the high water discharge and the duration of the high water discharge.

Methods for estimation of the transport capacity have been suggested by different researchers.

Ikeya (1989) suggested that the total volume of transported sediment, V_s, be calculated as:

$$V_s = 18 \cdot \sqrt{HQ \cdot A} \qquad [m^3]$$

where: HQ = high water discharge $[m^3/s]$
A = the part of the catchment area that has a bottom inclination of the river bed greater than 10 degrees $[m^2]$

Ikeya´s method is useful for catchment areas between 0.5 and 5 km^2. The factor 18 is based on measurements of debris flows in Japan. According to other researchers, the inclination is the most important factor for transport capacity. Therefore, Ikeya's formula may be questionable.

Hampel has suggested different methods of calculating the transport capacity for a debris flow. One method is based, among other things, on the inclination and grain size distribution of the alluvial fan and the longitudinal distance for bed load transport (transportation of material along the bottom of the torrent). The total volume of transported sediment, V_s, is calculated according to the equation given on the next page (see Hampel, 1969 and 1980).

The abrasion coefficient is a factor accounting for the abrasion (weathering) of soil particles during the bed load transport. Over a long bed load transport distance, the particle size will become smaller due to weathering and thus the volume of the sediment transported will be reduced. The Central Alps are built up mostly from crystalline bedrock and the Chalk Alps are built up from limestone. The equation is based on a precipitation with a return period of 100 years and a duration of 24 hours. It is also based on readings referring to a torrent with an altitude of about 2 300 m. The estimation of the mean grain size and the abrasion is difficult and hence the formula has not been widely used (Sauermoser, 2004).

$$V_s = 10^{\frac{A \cdot h_{100}\left(1-\frac{h}{2300}\right)\left(\frac{I-55\cdot d_a^{1.65}}{3.6}\right)^{\frac{1}{0.42-0.4d_a}}}{c^a}} \qquad [m^3]$$

where: A = catchment area [km²]
h_{100} = rain height with a return period of 100 year [mm]
h = height above sea level for outflow of water course on alluvial fan [m]
d_a = mean grain size in alluvial fan [m]
a = longitudinal distance for bed load transport [km]
I = inclination of the alluvial fan [height/length]
c = abrasion coefficient (Central Alps: 0.66, Chalk Alps: 0.80)

Another method of determining the total volume of sediment that may be transported, V_s, by the high water flow suggested by Hampel (see Hampel, 1990) is given as:

$$V_s = 2.5HQ \cdot I^{0.6}\left(I - \frac{m \cdot d_m}{12.1 \cdot h}\right) \cdot T \qquad [m^3]$$

where: I = bottom inclination of stream [height/length]
HQ = high water flow [m³/s]
m = factor according to Table 8
d_m = mean grain size [m]
h = height of discharge [m]
T = time of duration of precipitation [s]

Table 8. Factor m according to Hampel (1990).

Bottom inclination, I	0.0	0.1	0.2
Factor m	1	0.8	0.5

Hampel found that the width of the river bed and the depth of the flow have far from the same influence on transport capacity as inclination and therefore he reduced his formula to one variable – inclination. According to Hampel (1990), a simplified calculation of the total volume of sediment that may be transported, V_s, by the high water flow when the inclination exceeds 5% may then be derived as:

$$V_s = 250 \cdot I^{1.6} \cdot HQ \cdot T \qquad [m^3]$$

where I = bottom inclination [height/length]
T = time of duration for precipitation [s]
HQ = high water flow [m^3/s]

Most often, the bottom inclination, I, varies along the stream. This means that the transportation capacity also differs. When calculating the transport capacity using the methods suggested by Hampel, it is therefore inadvisable to use the mean inclination of the bottom. Instead, a longitudinal section of the bottom should be drawn and based on the need to divide the stream into parts with almost the same inclination. The transport capacity for each part may then be calculated. The length of the different parts should be at least 40 metres.

It has to be pointed out that all the equations presented are empirical and are based on situations at specific places in Austria or Japan. The results should therefore be taken cautiously and always compared with measured volumes from earlier events.

Chapter 7.3.1 presents results from calculation of transport capacities for Mörviksån in the municipality of Åre.

7.3.1 Example of calculated transportation capacity

Calculation of the total volume of sediment that can be transported to the alluvial fan in a high water flow with a return period of 100 years has been performed with the aid of a number of methods for Mörviksån. The results are given in Table 9. The results show large differences between the methods. It is important to understand that the calculation of total sediment transport capacity is approximate and gives only a rough estimate of the possible amount of material that can be transported. The calculated values should always be compared with measured volumes from earlier events.

As a comparison to the calculated values of transport capacity, some figures from the debris flow in June 2003 are given. According to the municipality of Åre, about 3000 m^3 of soil material was excavated after the event from the sedimentation dam, the channel and surrounding areas, while another 1 000 – 2 000 m^3 was estimated to have flowed into Åresjön. The precipitation was statistically a 20-year event according to the Dahlström method, see Chapter 6.4.

Table 9. Sediment discharge capacity for Mörviksån according to different methods.

Method	Input	Sediment discharge capacity, V_s [m^3]	Reference	Comments
Ikeya	HQ = 14 m^3/s A = 3.34 km^2	76 000	Modified after Bertilsson & Persson (1995)	63% of A is classified as rock and the volume is corrected for this.
Hampel First equation	6 < I < 8 % 0.72< c <0.80 h_{100} = 88.1 mm A = 4.4 km^2 a_d = 420 asl a = 1.7 km d_a = 2 mm	16 000 – 37 000	Bertilsson & Persson (1995)	The value of the inclination of the alluvial fan strongly influences the results.
Hampel Third equation	HQ =14 m^3/s T = 60 minutes	11 000	Rankka & Fallsvik (2003, 2004)	Return period 150 years

Chapter 8.

Field investigation in torrents

8.1 INTRODUCTION

A field investigation of the entire catchment area has to be carried out both for the torrent and for the surrounding slopes within the same catchment area. The purpose of the investigation is to:

- estimate the amount of transportable soil material
- investigate traces of earlier incidents
- investigate the run-off conditions
- investigate erosion, transportation and deposition areas, and
- establish contacts with people living or working in the area

If information on past debris flow events is available (or can be gathered), this is the most reliable source for a detailed investigation (Rickenmann, 1999). A field investigation should therefore be performed directly after an event or, if that is not possible, during the snow-free period of the year, preferably during a high flow. An investigation directly after an event provides much valuable input to the design criteria:

- the type of soil transported by the debris flow
- an estimate of the amount of transported material, for instance from the amount of excavated material in the deposition area
- an estimate of the velocity of the debris flow in different parts of the brook derived from measurements of the highest water level (see Chapter 5.3)
- unstable areas along the brook and in slopes indicated by scars
- the run-off distance of the debris flow along the alluvial fan
- the direction of the debris flow
- information from people living in the area (see Chapter 8.7).

However, a field investigation is important and necessary even if it is not performed directly after a debris flow event. Before the field investigation is carried out an introductory study should be undertaken in the office.

8.2 INTRODUCTORY STUDY PRIOR TO FIELD INVESTIGATIONS

An introductory study in the office prior to the field investigation is aimed at planning the investigation and determining points of interest for a more detailed investigation. The planning includes aspects such as the way in which different parts of the catchment area are reached and the number of days required. The work consists of a survey of maps and photos, route preparation and preparation of measuring instruments and other equipment.

8.3 SURVEY OF MAPS AND PHOTOS

The extent of the catchment area of the whole brook has to be determined and marked on a map with a scale preferably of 1:5000, but no smaller than 1:20 000. The extent may be determined from ordinary topographical maps, but an airial photo investigation in stereo provides better accuracy. Below is presented a list of suitable maps and the parameters that can be determined from them.

8.3.1 Topographical or similar maps

Topographical maps with a scale of 1:50 000 (called "Topografisk karta") are available from Lantmäteriet (the Swedish Land Survey). Other maps with larger scales, preferably 1:10 000 (for instance "Fastighetskartan"), may also be available from Lantmäteriet. The municipality may also have its own large-scale maps. The maps are studied in order to determine the following parameters:

- extent of the catchment area
- topography
- brooks
- wetlands
- land use
- infrastructure

8.3.2 Black and white aerial photos

An investigation of stereo aerial photos (vertical projection and stereo models) may yield valuable information if performed by a skilled person. Airial photos are available with different scales and different ages from Lantmäteriet. Most common are the photos with a scale of 1:30 000 taken from a height of 4600 metres ("normalhöjdsbilder"). However, the best results are obtained from photos with a scale of 1:10 000 taken from a height of 2000 metres. The following aspects may be studied from aerial photos:

- topography
- bedrock, soil type and soil cover
- scars and deposits from landslide, erosion, debris flow and talus
- extent of the catchment area
- wetlands
- land use
- infrastructure
- vegetation (cover and type)

8.3.3 Geological maps

Geological maps are available from the Swedish Geological Survey (Sveriges geologiska undersökningar). For southern Sweden and the coastline of Norrland, the maps have a scale of 1:50 000. For other regions, the scale varies between 1:200 000 and 1:250 000. The following aspects may be studied from geological maps:

- type of soil and bedrock
- thickness of soil deposits
- bare rock

8.3.4 Geomorphological maps

Geomorphological maps are available for some parts of the Swedish mountainous area as well as for some other places. Some are distributed by the University of Stockholm (Naturgeografiska institutionen) and others by the Swedish Geological Survey. The scale of the maps varies. The following information is given on the geomorphological maps:

- scars and deposits from landslides, erosion, debris flows and talus
- type of scar and deposit (levée, loobe, alluvial fan, bank erosion/bottom erosion, talus etc.)
- recent deposits or deposits from the last ice age
- river bed system
- inclination
- wetlands, springs

8.3.5 Infrared (IR) coloured aerial photos

Infrared (IR) coloured photos are available from "Lantmäteriet". IR photos with stereo models enable the same information as for black and white aerial photos to be extracted, but the IR photos offer better possibilities for detection and analysis, especially of vegetation, moisture and bare rock.

8.3.6 Ortho-photos

Ortho-photos are often used by the municipality for land use planning and visualisation of planned roads or buildings. These photos provide the following information of interest:

- vegetation cover (if in colour)
- infrastructure and buildings
- bare rock or soil
- ponds
- brooks

8.4 ROUTE PREPARATION

The field investigation should always start from the highest point of the catchment area and proceed downwards. The reason is that it is easier to understand the processes going on in the catchment area if the investigator follows the same route as the water. If the main brook is divided into several small brooks, each brook should be followed from the source to the mouth. It should be noted, however, that not only the brook area/areas should be investigated but the whole catchment area.

The information and points of interest found during the survey of different maps should be marked on a map with a scale no smaller than 1:10 000. To make it possible to refer to a specific point along the brook, the brook should be divided into several parts, each with a length of 100 metres. The division starts at the lowest point of the brook. A mark is drawn on the map at a distance of 100 metres from this point, which is called hectometre 1. Marks are then placed at intervals of 100 metres from hectometre 1 and numbered consequently. If the main brook divides into smaller brooks, these should have their own hectometre divisions. A division of Mörviksån is given as an example in Appendix B.

Ways of reaching different parts of the catchment area should be investigated in advance. Some parts may be accessible by car or by chair lifts. Many parts are probably only accessible on foot or by horse. In any case, a walk from the top to the bottom of the catchment area will be necessary.

8.5 MEASURING INSTRUMENTS AND OTHER EQUIPMENT

The recommended measuring instruments and equipment that should be brought for the field investigation are described in Table 10.

Table 10. Recommended measuring instruments and equipment for a field investigation.

Type of equipment	Purpose
Measuring tape	Extent of scars, width of brook, traces of highest water level, distances, available masses.
Folding rule	Depths, widths.
Inclinometer	Inclination of slopes and torrent. Very light models are available.
Distance meter*	Distances, facilitate referring to position on map.
Altimeter*	Altitude, facilitate referring to position on map.
Camera	Take numerous photos, important for documentation and memorising.
Binoculars	Investigation from a long distance.
Spade	Soil sampling.
Manual sound	Soil depth and stratigraphy in the upper layer.
Maps in plastic folder and notebook	Describe and mark investigated points of interest.

*A high resolution GPS (0.5 m resolution) may be used instead.

8.6 FIELD INVESTIGATION METHODOLOGY IN TORRENTS

As pointed out earlier, the field investigation starts at the highest point of the catchment area and proceeds downwards. All points marked during the desk investigation should be investigated in the field, see Figure 11. It is of great importance that all the points investigated will be marked on the map and described with a reference to the hectometre value (for instance, hm 13.5 indicates 1350 metres from the lowest point in the area investigated).

Figure 11.
Field inspection at the location of an earlier landslide in a torrent. (Photo: K. Rankka)

Table 11 presents parameters suggested for investigation in the field. It may be used as a check list during the field investigation.

The need for determination of soil depth, grain size distribution with depth, and ground water conditions has to be considered. For slopes not directly threatening settlements by a landslide, it may be sufficient to estimate the soil depth in the field and to investigate the grain size distribution and ground water condition in the upper layer. A spade and manual sound are suitable for this purpose. For slopes directly threatening settlements more detailed investigations are required, see Chapter 4. As for the soil depth at the bottom of the brook, it is sufficient to perform an estimation in the field and to make a map survey. If the soil depth is estimated to be great, it will be necessary to determine the exact depth and grain size distribution before the construction of any preventive measures, such as check dams and sedimentation dams.

8.7 DISCUSSION WITH CITIZENS, LAND OWNERS AND STAFF AT THE MUNICIPALITY

People living in or near the area may have valuable information on aspects such as earlier events, precipitation and soil condition. An interview with these people may be a good investment. Landowners should be contacted to obtain information on clear-cutting and other forest work planned.

Staff at the municipality should be contacted at an early stage of the investigation. Often they have maps and information of significant value for the investigation. They may also have experience of construction works and results from earlier geotechnical investigations in or close to the area.

Table 11. Parameters to be investigated in the field.

Position in area	Parameter	Purpose
Area with small inclination	Soil – grain size distribution at surface,	
	approximate thickness	Run-off (velocity, water storage capacity)
	Bare rock – position and extent	Run-off
	Wet areas	Capacity for water storage
	Inclination	Mass transport capacity, slope stability
Steep slopes (see also Chapter 4)	Inclination	Slope stability
	Soil – grain size distribution, thickness	Slope stability, shear strength, sources of material that may be brought to the brook. Soil sampling should be performed.
	Groundwater, pore pressure	Slope stability
	Vegetation (type, position and condition)	Run-off, critical areas, wet areas, vegetation limit altitude.
	Traces	Unstable areas, erodible soil
	Trees – types, position, inclination	Inclined trees may indicate slope movements (drunken forest). Tree and forest level.
	Streams, ditches	Run-off, ground water condition, possibility of gully formation and thereby debris flows
	Avalanche tracks	Run-off, possibility of gully formation
Brook	Inclination of the whole longitudinal section	Calculation of velocity, transportation capacity, slope stability
	Trees – condition, position and inclination (also fallen trees)	Possibility of falling trees that can block the brook and cause damming. Inclined trees may indicate slope movements (sometimes called drunken forest).
	Amount and type of available masses in bottom and along sides	Available masses, transport capacity, possibility of blocking of the brook
	Traces from earlier events Erosion, debris flows, deposition	Unstable areas, erodible soil, sources of next debris flow, deposition areas
	Wet areas, ponds, lakes	High pore pressure, possibility of water storage, rapid run-off
	Soil/bedrock	Sources of mass movements, water flow velocities, erodibility,
	Width, water flow height during earlier events and possible highest water level	Calculation of water flow velocity and capacity

cont. next page

Table 11. Continued.

Position in area	Parameter	Purpose
Alluvial fan	Inclination, extent	History of earlier events, input to calculation of transport capacity
	Soil condition, stratigraphy, soil depth	History of earlier events, sources of new mass movements
	Settlements	In danger
Bridges	Bottom inclination	Velocity of stream
	Size	Flow capacity
Roads	Ditches – size and position	Capacity, is drainage going to the right place
	Run-off	Derivation of run-off water
Culverts, pipes	Bottom inclination	Velocity of stream
	Size	Flow capacity
Ski pistes	Vegetation cover	Run-off, indication of wet areas
	Drainage	Right place and way
	Soil condition	Slope stability, erosion
	Inclination	Slope stability, erosion

Chapter 9.
Documentation of the detailed investigation

The detailed investigation should be documented in two separate reports:

- **Report 1**: Results of field and laboratory investigations.
- **Report 2**: Interpretations, evaluations, analysis, calculations and, if there is a need for preventive measures, suggestions and rough estimates for type, position and design of such measures.

Since the detailed investigation often forms an important basis for purchasing contractors when performing preventive measures, it is practical to report the results of the investigations in two separate documents.

9.1 LANDSLIDES

9.1.1 Report 1

In this report, the introductory study prior to the field investigation and the field investigation carried out on the slope should be described and documented. A description of the documents used in the introductory study should be given, e.g. maps, aerial photos, earlier investigations etc. Also the results should be presented. The results of the field and laboratory investigations should be presented in drawings – ground plan and sections with a geotechnical legend.

9.1.2 Report 2

In this report, all interpretations, evaluations, analysis, calculations, data and, if there is a need for preventive measures, suggestions and rough estimates for type, position and design of such measures are given. The following documentation should be provided:

- A technical fact sheet for slope stability investigations, see Table 12.
- Detailed description of all calculations.
  The data used and the results of calculations for the sliding surfaces found to be most critical. For rough estimates based on calculations carried out “by hand”,

the parameters and diagrams used should be reported. If computer programs are used to ensure the possibility of following and analysing the calculations, the following information should be reported:
- the computer program (name)
- calculation method (drained, undrained, combined, Janbu, Bishop, etc.)
- search routines used for the most critical sliding surface
- input data
- offprints from the calculations

• Drawings showing calculated sections, soil layer geometry used and values of shear strengths used, pore pressures and densities as well as other parameters essential for the calculations such as external loads and surface water levels. Also the sliding surface found to be most critical should be presented in the drawings
• Description of the need for preventive measures and the type, position and design (size, height, inclination, etc.) of them.

Table 12. Technical fact sheet for slope stability investigations (3 pages). (Modified after the Swedish Commission on Slope Stability, 1995).

STABILITY CONDITIONS IN SLOPES IN TILL AND COARSE-GRAINED SEDIMENTS

Technical facts for slope stability investigations — **Page 1**

Object

Date

Extent

Geotechnical investigations — Number of sections:

Field investigations

Sounding			Sampling		Density	GW cond.	Seismic measurement	
CPT	DP	SR penetr.	Aug. sampl	Test pits	Water volume meter.	GW pipes	Refraction	Reflection

Laboratory investigations

Routine	Triaxial test	Shear test

Pore pressure conditions

Hydrostatic: GWL, see sketch no:

Non-hydrostatic: see sketch no:

External water levels:

Cracks in dry crust::

Eventual divergence between measured pore pressures and water levels:

Stability calculations — Number of sections:

Calculation method		Type of analysis		Type of sliding surface		Computer program	
Diagram (D)		Undrained (U)		Planar (P)		Slope/W	
Bishop (B)		Drained (D)		Circular (Ci)		Beast	
Janbu (J)		Combined (C)		Combined (Co)		Other	
Spencer (S)							
Morgenstern & Price (MP)							

Page 2

Interpretations and evaluations

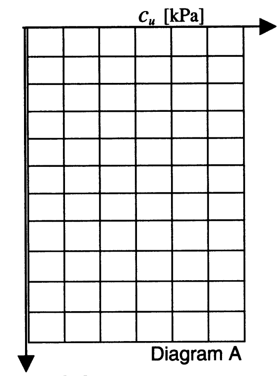
Geometry, soil stratigraphy, density and external loads , see drawing no:

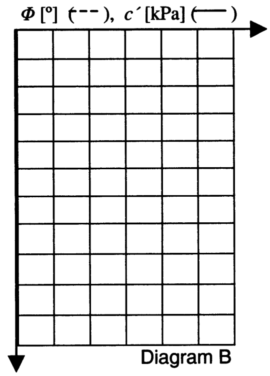
Shear strength

Conditions for calculation according to diagram A or B.
Given parameters related to:

- ☐ Subsurface
- ☐ Datum level

Conditions for calculation, see drawing no:





Results

Section	Calculation method						Analysis			Sliding surface			Safety factor			Comments
	D	B	J	S	MP		U	D	C	P	Ci	Co	F_c	$F_{c\Phi}$	F_{comb}	

Explanation/Instructions to technical fact sheet for slope stability investigation   Page 3

Object

Specify client, county, municipality, place, locality and project/register number. Also specify the stability investigation stage.

Extent – Geotechnical investigations

Soundings	CPT = Cone penetration test DP = Dynamic probing SR penetr. = Soil-rock penetration test
Sampling	Report the number of levels where samples have been collected Aug. sampl = Auger sampler
Density measurements	Water vol. = Water volume meter
Ground water measurements	Report the number of ground water pipes
Laboratory investigations	Report the number of tests Routine = Routine test on disturbed soil samples, e.g. soil type, water ratio (w) and liquid limit (w_L)

Interpretations and estimations

For each section, describe the input data values used in the computer calculations by specifying the geometry, any external loads and the geotechnical conditions

Geometry	On a separate drawing, specify the geometry and soil layer stratigraphy used so that co-ordinates and breakpoints can easily be recognised
Soil strength	If a general soil strength has been used for the entire soil profile, it should be reported in the diagram on Page 2. Otherwise, the soil strength variation used should be specified on separate drawings as for geometry, see above.
Pore pressures	The pore pressure distribution used should be clearly specified on a separate drawing. Also specify clearly the connection between measured values at the specific test points in the field and the pore pressure distribution used. Further, specify surface water levels used, whether any dry crust has been judged to have cracks and whether these cracks have been judged to be full of water.

Results

For each calculated section, specify the lowest safety factor (F). The most critical slip surface should also be given on a drawing.

9.2 TORRENTS

9.2.1 Report 1

In this report, the introductory study prior to the field investigation and the field investigation carried out in the torrent should be described. The report should contain four parts.

1. Introductory study prior to field investigation

In this part, a description should be given of the documents used in the introductory study: maps, air photos, earlier investigations, etc. Also a short description of the results should be presented.

2. Description of the run-off conditions in the catchment area

A careful description of the run-off conditions in the whole area should be presented. Table 13 may serve as a guide for the description. Note that the conditions should be described for all the different parts in the area, not as mean values for the whole area. The catchment area is normally divided into different sub-areas where the run-off conditions can be regarded as equal.

Table 13. Parameters influencing the run-off conditions. Each sub-area should be described.

Parameter	Description
Vegetation cover	Type, amount, evapotranspiration
Topography,geometry of the catchment area	Inclinations of slopes and bottom of torrent (large and small scale), shape of the catchment area and sub-areas
Soil conditions	Type, thickness, structure, pore volume, hydraulic conductivity
Drainage and infiltration characteristics	Position, type, possibility of damming/blocking
Ground water and soil moisture content	Wet areas, water-demanding plants, storage capacity of run-off water, estimated groundwater table
Brooks	Amount, size, inclination and position
Land use	Type (roads, ski pistes, artificial drainage, buildings, structures, meadows, forests, grazing, etc.)

3. *Signs of earlier events*

Signs of earlier events found in the field should be marked on a map with a scale no smaller than 1:10 000 according to the legend given in Figure 12. A description of the amount of soil masses that have slid or been transported during earlier events should be given. As an example, the signs of mass movements found in Mörviksravinen, municipality of Åre, are given in Appendix B.

If traces of the high water level in the river bed during an earlier event have been investigated, the results and the position of traces investigated should be described and documented. The description should consist of a written part and section drawings of the wet areas, see Figure 13.

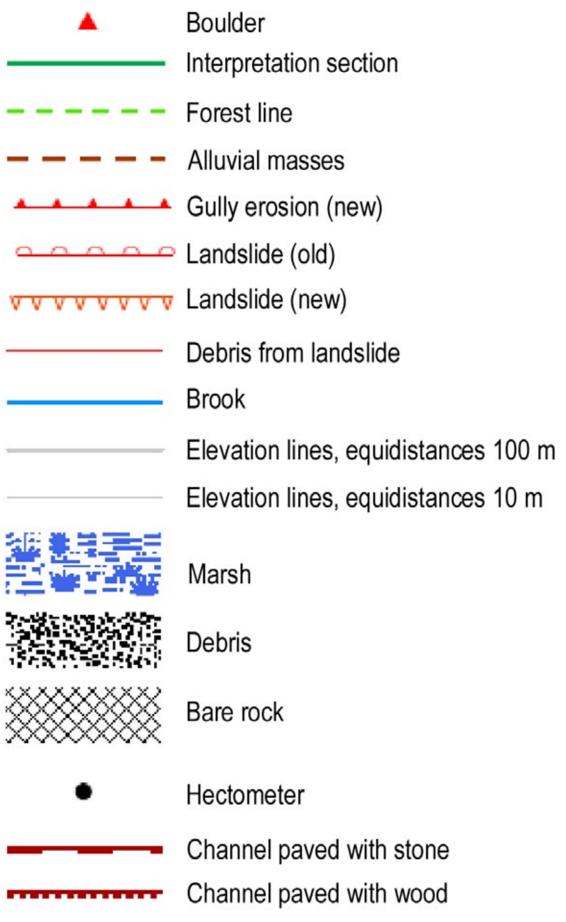


Figure 12. Legend for maps used for documentation of the stability and run-off conditions in torrents.

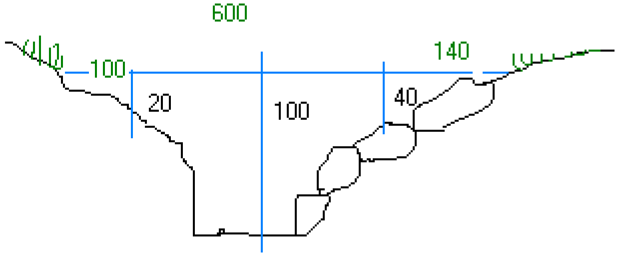


Figure 13. Wet area, A, for one section investigated in Mörviksravinen, Åre kommun (after Rankka & Fallsvik, 2003). Distances in cm.

4. Available soil masses in the torrent

A careful description of the available soil masses in each hectometre division should be given. The description should also involve an estimation of the amount of material that can be transported in one event, based on traces from earlier debris flows and estimations made in the field.

5. Description of field tests

If field tests using test pits, sounding, seismic measurements, soil sampling or groundwater measurements have been carried out, they should be described. The description should consist of a written part and a map and cross-sections showing the results.

Also a description of measurements of precipitation and run-off, if taken, should be given.

6. Discussions with citizens, landowners and staff in the municipality

The results from discussions with people in the vicinity are given.

9.2.2 Report 2

In this report, all interpretations, evaluations, analysis, calculations, data and, if there is a need for preventive measures, suggestions and rough estimates for type, position and design of such measures are given. The following documentation should be provided:

- A technical fact sheet for torrents, see Table 14.
- Detailed description of all calculations (data, interpretations, evaluations, analysis, methods, results)

- Description of the need for preventive measures. Type, position and design (size, height, inclination, etc.).

Table 14. Technical fact sheet for torrents. (Modified after the Swedish Commission on Slope Stability, 1995)

STABILITY AND RUN-OFF CONDITIONS IN TORRENTS IN TILL AND COARSE-GRAINED SEDIMENTS

Technical fact sheet

Object Date:

Torrent

Total length	(m)	Mean inclination		Earlier known events	
Height difference	(m)	Main soil type		Type	When (year)

Geotechnical investigations* Number of sections:

Field investigations / **Laboratory investigations**

Sounding		Sampling		Density	GW pipes	Seismic		
Type	Number.	Type	Number	Water volume meter	Number	Type	Type	Number

Run-off conditions

Catchment area			**Run-off velocity [*v*]**		**Run-off time [*T*]**	
Total size (km^2)			Manning		Hampel	
Sub-areas			Transv. incl		Kreps	
Number	Size (km^2)	Run-off coefficients	Measurements		Kirpich	
			Other		T=L/v	
					Other	
			Run-off flow [*HQ*]			
			Rational			
			Hampel			
			Other			

Precipitation / **Slope stability, rough calculation***

Measurements		**Calculations**		Shear strength		Type of analysis	
Performer		Return period (year)		GW condition		Slip surface	
Position		Duration (minutes)		Density		Method	
Altitude		Intensity (mm/h)		Safety factor			
Correction for altitude [x]		Method [x]					
		Dahlström	Other				

** For explanation see Table 12.*

References

References to literature mentioned in the report

Alexandersson, H. & Eggertsson-Karlström, C. (2001). Temperaturen och nederbörden i Sverige 1961-1990. Referensnormaler – utgåva 2. Meteorologi, nr 99. Swedish Meteorological and Hydrological Institute, Norrköping.

Alexandersson, H. (2003). Personal contact. Swedish Meteorological and Hydrological Institute, Norrköping.

Alexandersson, H. (2004). Personal contact. Swedish Meteorological and Hydrological Institute, Norrköping.

Bergtahler, J. (1986). Anwendungsbereich der Hochwasserformeln, Wildbach und Lawinenverbau, Zeitschrift 103, 50 Jahrgang.

Bertilsson, Å. & Persson, B. (1995). Erosionsrisker i Åre-Duved området. Examensarbete 1995:9, Avdelningen för mark- och vattenresurser. Institutionen för anläggning och miljö. Kungliga Tekniska Högskolan. Stockholm.

Chow, V., T. (1959). Open-channel hydraulics. McGraw-Hill. Tokyo

Costa (1984). Physical geomorphology of debris flows. *In* Developments and applications of geomorphology. Eds Costa, J., E., & Fleisher, P., J. Springer Verlag.

Coussot, P. (1992). Rheologie des laves torrentielles. Collection Etude, Serie Montagne, no 5. Grenoble.

Coussot, P. & Meunier, M., (1996). Recognition, classification and mechanical description of debris flows. Earth-science Reviews 40.

Dahlin, T., Larsson, R., Leroux, V., Svensson, M. & Wisén, R., (2001). Geofysik i släntstabilitetsutredningar. Statens geotekniska institut. Rapport 62. Linköping.

Dahlström, B. (1979). Regional fördelning av nederbördsintensitet – en klimatologisk analys, (Title in English: Regional distribution of precipitation intensity – a climatological analysis). Byggforskningen, Rapport R18:1979.

Fallsvik, J. & Viberg, L. (1989). Early stage landslide and erosion risk assessment – a method for a national survey in Sweden. Arbeitstagung – Erdwissenschaftliche Aspekte des Umweltschutz, Vienna.

French, R. H., (1985). Open Channel Hydraulics. McGraw-Hill.

Gattermayr, W. (2004). Personal contact. Wasserwirtschaft, Amt der Tiroler Landesregierung, Innsbruck.

Hampel, R. (1969). Geschiebetrieb und Ausgleichgefälle in Wildbächen. Wildbach und Lawinenverbau 33.

Hampel, R. (1980). Geschieberechnung für Gefahrenzonenplane in Wildbachgebieten. Proceedings International Society Interpraevent.

Hampel, R. (1984). Der Aufbau von Hochwasserformeln. Wildbach und Lawinenverbau. Zeitschrift, Sonderheft, Juni 1984. 48 Jahrgang. Imst.

Hampel, R. (1990). Geschiebefracht und Geschiebetrieb, Wildbach und Lawinenverba. Zeitschrift 114, August 1990, 54 Jahrgang. Imst.

Hartlén, J. (1974). Skånska moränlerors hållfasthets- och bärighetsegenskaper. Avhandling. Chalmers Tekniska Högskola. Institutionen för geoteknik med grundläggning. Göteborg.

Hungr, O. & Jakob, M. (2005). Debris-flow hazard and related phenomena. Springer Praxis Books.

Ikeya, H. (1989). Debris flow and its countermeasures in Japan. Bulletin of the International Association of Engineering Geology, no 40. Paris.

Jacobsen., M. (1970). Strength and deformation properties of preconsolidated moraine clays. Danish Geotechnical Institute, Bulletin No 27. Copenhagen.

Kohl, B. & Markart, G. (2002). Dependence of surface runoff on rain intensity – results of rain simulation experiments. Flood Estimating Conference. Bern.

Larsson, R. (1989a). Hållfasthet i friktionsjord. Information 8. Statens geotekniska institut. Linköping.

Larsson, R. (1989b). Jords egenskaper. Information 1. Statens geotekniska institut. Linköping.

Larsson, R. (2001). Investigations and load tests in clay till. Report 59. Statens geotekniska institut. Linköping.

Lorenzini, G. & Mazza, N. (2004). Debris flow – Phenomenology and rheological modelling. WIT Press.

Markart, G., Kohl, B.,Soiter, B., Schauer, T. Bunza, G., Stern & R. (2004). Provisorische Geländeanleitung zur Anschätzung des Oberlächenabflusses auf alpinen Boden-/Vegetationseinheiten bei konvektiven Starkregen. Research report. Bundesministerium für Land- und Forstwirtschaft, Umwelt und Wasserwirtschaft. BFW-Dokumentation; Schrifenreihe des Bundesamtes und Forschungszentrums für Wald, Wien.

Markart, G. (2004). Personal contact. The Austrian Federal Institute for Forest Research, Innsbruck.

Möller, B., Larsson, R., Bengtsson, P.-E. & Moritz, L. (2000). Geodynamik i praktiken. Statens geotekniska institut. Information nr 17. Linköping.

Rankka, K., Fallsvik, J. (2003). Förstärkningsåtgärder för slänter och raviner i morän och annan grov sedimentjord. Räddningsverket. FoU rapport. Karlstad.

Rankka, K., Fallsvik, J. (2003). Detailed investigation of the stability and run-off conditions in the catchment area of the stream Mörviksån. Swedish Geotechnical Institute. Commission No 11802. Linköping. (made on commission from the municipality of Åre).

Rankka, K., Fallsvik, J. (2004). Detaljerad utredning av stabilitets- och avrinningsförhållanden i Mörviksravinens avrinningsområde, Åre. Statens geotekniska institut. Uppdrag nummer 11802. Linköping. (Utförd på uppdrag av Åre kommun).

Rickenmann, D. (1999). Empirical Relationships for Debris Flows. Natural Hazards 19, pp 47-77. Kluwer Academic Publisher.

Sauermoser, S. (2002). Personal communication. Forsttechnischer Dienst für Wildbach und Lawinenverbauung, Innsbruck, Austria.

Sauermoser, S. (2003). Personal communication. Forsttechnischer Dienst für Wildbach und Lawinenverbauung, Innsbruck, Austria.

Sauermoser, S. (2004). Personal communication. Forsttechnischer Dienst für Wildbach und Lawinenverbauung, Innsbruck, Austria.

Swedish Commission on Slope Stability (1995). Directives for Slope Stability Investigations, Report 3:95. Linköping.

Varnes, D.J. (1978). Slope movement types and processes. In Landslides, Analysis and Control. Transportation Research Board. Special Report 176. Washington DC.

Viberg, L., Fallsvik, J., Rankka, K., Sällfors, G. & Gustafsson, M. (2004). Översiktlig kartering av stabilitetsförhållandena i raviner och slänter i morän och grov sedimentjord. Metodbeskrivning. FoU rapport, Räddningsverket. Karlstad.

Wilén, P., Eurenius, L. & Anderberg, J. (1993). Avrinning och erosion i Åredalen. Slutrapport. VBB Viak AB och Geo Information consult AB. Östersund.

Zeller, J. (1974). Starkniederschläge und ihr Einfluss auf Hochwasserereignisse Bericht Nr. 126. Eidg Anstalt für Forstliches Versuchswesen, Birmensdorf.

Suggestions for further studies

Davies, T. (1997). Using hydroscience and hydrotechnical engineering to reduce debris flow hazards. First international conference on Debris Flow Hazards Mitigation: Mechanics, prediction and assessment. Edited by Cheng-lung Chen. San Francisco.

Fiebiger, G. (1997). Structures of debris flow countermeasures. First international conference on Debris Flow Hazards Mitigation: Mechanics, prediction and assessment. Edited by Cheng-lung Chen. San Francisco.

Hampel, R. (1984). Der Aufbau von Hochwasserformeln. WLV Zeitschrift, Sonderheft, Juni 1984. 48 Jahrgang. Imst.

Heumader, J. (2000). Technical debris-flow countermeasures in Austria – a review. Debris-Flow Hazards Mitigation: Mechanics, prediction and assessment. Rotterdam.

Hübl, H. (1995). Muren: Prozesse und Ablagerungsformen. Bedeutung für die Gefahrenzonenplanung Diss. Universität für Bodenkultur, Wien.

Hungr, O., Morgan, C. & Kellerhals, R. (1984). Quantitative analysis of debris torrent hazards for design of remedial measures. Canadian Geotechnical Journal, 21, pp 663-677.

Interpraevent. International Research Society. Homepage http://www.wasser.ktn.gv.at/interpraevent/index_en.htm

Kettl, W. (1984). Vom Verbauungsziel zur Bautupenentwicklung – Wildbachverbaaung in Umbruch. Wildbach und Lawinenverbau. Zeitschrift. 1984. Wörgl.

Markart, G., Sauermoser, S., Kohl, B. & Stern, R. (2002). Land use change and the effect of mountain forests in Alpine catchments. Proceeding of the symposium "Ecological and economic benefits of mountain forests". Innsbruck.

Rankka, K. (2002). Slå rot och väx upp eller Vegetation som förstärkningsmetod. Litteraturstudie. FoU rapport. Räddningsverket. Karlstad.

Smart, J. (1983). Sediment transport on steep slopes. Mitteilungen der Versuchsanstalt für Wasserbau, Hydrologie und Glaziologie, Nr 64. Zürich.

VanDine, D.F. (1996). Debris Flow Control Structures for Forest Engineering. Res. Br., B.C. Ministry of Forests Research Program, British Columbia, Work Paper 08/1996.

APPENDIX A

Examples of run-off factor classes for typical regions in alpine areas are given in the following pages. The run-off factor classes translated to run-of coefficients are given in Table A1. The values have been evaluated by Markart et al. (2004) from tests on slopes in Austria. All photos are from the paper by Markart et al (2004). Permission for publishing the photos and values has been given by the authors.

Table A1. Run-off factor classes translated to run-of coefficients

Run-off factor class	Run-off coefficients
1	0 – 0.10
2	0.11 – 0.30
3	0.31 – 0.50
4	0.51 – 0.75
5	> 0.75

1) Spruce-wood without ground-covering undergrowth

Type of soil	Use	Hydrologic characteristics	Run-off factor class
Silicate brown earth, coarse grained, loose	None	Wetting resistance after drying up	2
Like above, however surface layer consolidated by cattle footstep	Pasture	Wetting resistance after drying up, infiltration prevented by cattle footstep, infiltration in pores or through columns of root tubes	3

2) *Forest stand with afforestation by spruce, larch and cembran pine (partly grazes, partly with broom heath)*

Type of soil	Use	Hydrologic characteristics	Run-off factor class
Talus with silicieous (rich in silica) brown earth, coarse grained, loose, soil on slope debris	None	Almost no wetting resistance due to dense undergrowth, coarse grained soil with loose structure, rapid infiltration into deeper soil layers	1

3) *Spruce-wood with adenostyles (Lat: Adenostyles alliariae, not found in Sweden)*

Type of soil	Use	Hydrologic characteristics	Run-off factor class
Gleyic soil on carbonaceous substrate, mean to large soil depth, high amount of fine particles, cohesive	None	Coarse grained soil with high amount of fine particles gives low possibility of infiltration, infiltration primarily only though macro pores (e.g. tubes made by worms and other animals.)	4

4) Open slope (coarse-grained, loose)

Type of soil	Use	Hydrologic characteristics	Run-off factor class
Slope debris, coarse-grained, small portion of fine particles, not compacted (see picture)	None	High conductivity and/or permeability during heavy rainfalls	1

5) *Heather moor (Lat:Calluna vulgaris, Sw: ljung) in combination with mat grass (Lat: Nardus stricta, Sw: stagg) and dwarf-shrubs (covering less than 50% of the area)*

Type of soil	Use	Hydrologic characteristics	Run-off factor class
Shallow to middle deep brown earth and/or podsol, high portion of coarse grained particles, loose skeleton reaching top of soil, area covered by mat grass < 50%	No	Mat grass limits the infiltration (straw roof effect)	3
As above, however high portion of fine particles	Pasture	Mat grass limits the infiltration (straw roof effect), no preferential infiltration ways since the portion of fine particles is high and therefore high run-off capacity	4

6) Alpine meadow with edelweiss (Lat: Leontopodium alpinium). Short pasture in the middle of summer and/or early autumn)

Type of soil	Use	Hydrologic characteristics	Run-off factor class
Deep-brown earth, loose, upper soil shows crumbly blocky structure	Hayfield, pasture (2 weeks a year)	Small run-off potential in the spring and early summer, grazing in late summer leads to a compaction of the topsoil	3
As above, crumbly structure more pronounced	Hayfield	Small run-off potential	2

7) *Alpine meadow with dwarf willow (Lat: Salix herbacea, Sw: dvärgvide) with short pasture in the middle of summer and/or early autumn*

Type of soil	Use	Hydrologic characteristics	Run-off factor class
Shallow to mean deep brown earth, partially graded	Hayfield, short pasture, intensively maintained (fertilised and drained.)	Small to middle run-off potential in spring and early summer, increased run-off in late summer due to grazing (footstep damage) and agriculture activities (soil compression)	3
As above	Hayfield, short pasture, no maintaining, intensively grazed	High to extreme run-off potential due to mat of roots in the uppermost soil layers	4 – 5

8) Graded skipiste with plants indicating high humidity e.g. rushes (Lat: Juncus, Sw: tåg) and thistles (Lat: Cirsium, Sw: tislar)

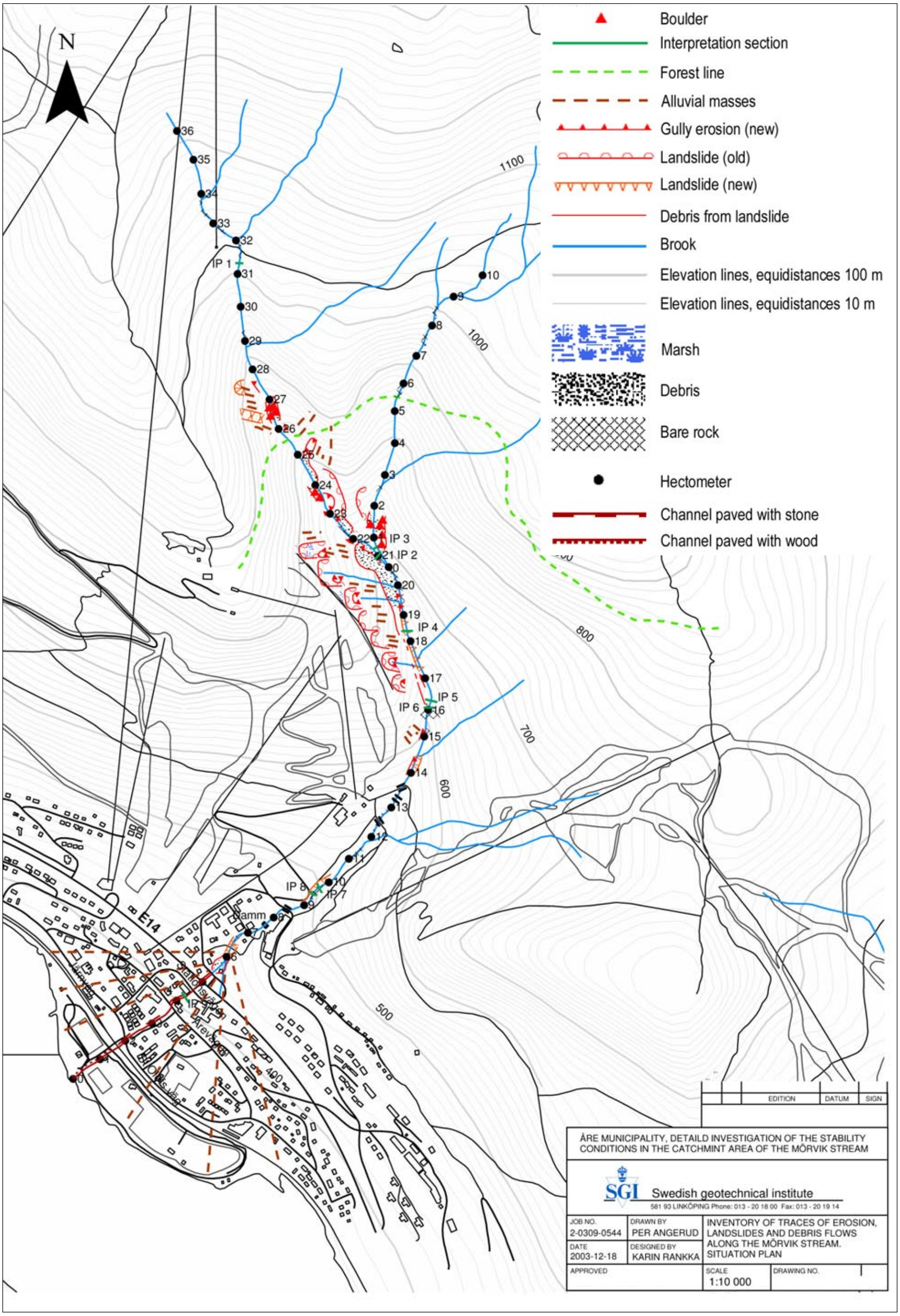
Type of soil	Use	Hydrologic characteristics	Run-off factor class
Middle deep Anthrosol[1], silty- sandy, gleyic soil, slope water course, at least partly permanently wetted	Ski piste, grazed	Poor retention capacity during heavy rain falls due to high moisture content. Very high run-off potential	4 – 5

[1] Anthrosol: Soils that have been modified profoundly by human activities, for example partial removal, cutting and filling and waste disposal.

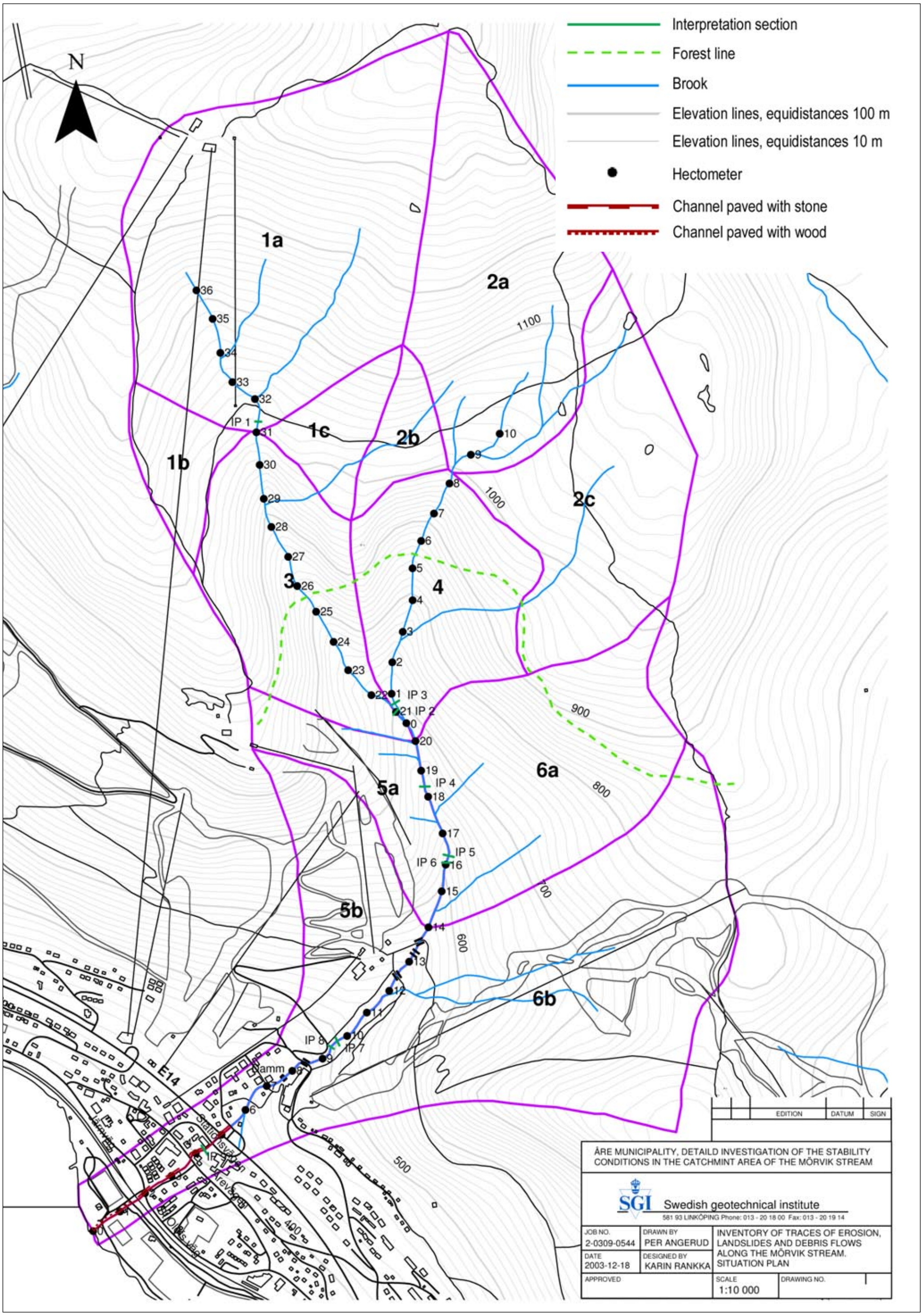
9) Grassland with mat grass (Lat: Nardus stricta, Sw: stagg) under thin snow cover (10 to 25 cm), fully wetted

Type of soil	Use	Hydrologic characteristics	Run-off factor class
Middle deep podsol-like soil	Ski piste	During the stage when the snow is melting and the snow layer is completely damp a high saturation of the uppermost soil layer is reached giving a direct run-off during heavy rain falls.	5

APPENDIX B



Plan showing results from field investigations in the Mörviksravinen torrent, municipality of Åre. (From Rankka & Fallsvik, 2003).



Plan showing the catchment area of Mörviksån (borderline in red) and a division of the total area into 10 sub areas (1a – 6b).

APPENDIX C

In the **Dahlström method** (see Dahlström, 1979), a so-called regional parameter, *Z*, has been developed to reflect the pattern of convective precipitation in Sweden. Series of precipitation from the different weather stations have been analysed, using stations read both continuously and once daily. The regional and time-dependent patterns of intense precipitation have been related to each other. The following formula has been developed for calculating statistics on precipitation intensity and duration. The formula gives the precipitation intensity standardised to the period 1931-60 with a duration of between 3 minutes and 96 hours and return periods of between 1 month and 10 years (extrapolation up to, for instance, 100 and 150 years is possible).

where $F(x, T, Z)$ = precipitation intensity [mm/h]

x = duration of the precipitation [h]

T = return period [months]

Z = regional parameter given for different regions in Sweden or calculated (see below)

$$A(T) = 1.7 \cdot T^{0.47} - \frac{1}{T}$$

$$Z = 0.5 \cdot (N_7 + N_8) - N_v$$

where N_7, N_8 are mean precipitation in the two months with the highest frequency of convective precipitation (mostly July, August).
N_v is the mean precipitation in the month with a lower shower activity than in the summer (mostly May)

$$B(T) = 0.32 - \frac{0.72}{T+3}$$

$$C(x) = 1 + 0.1 \cdot \frac{x - 0.167}{|x - 0.167| + 0.01}$$

$b' = -0.72$

However, in special regions :

$$A(T) = 1.9 \cdot T^{0.47} - \frac{1}{T} \quad \text{and } b' = -0.68$$

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