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Internationale Kommission für die Hydrologie des Rheingebietes

International Commission for the Hydrology of the Rhine Basin

Methods for the Estimation of Erosion, Sediment Transport and Deposition in Steep Mountain Catchments

A contribution to the International Sediment Initiative of UNESCO/International Hydrological Programme

Eva Gertsch

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Foreword

Across the world, erosion, transport and sediment processes have significant social, economic and environmental impacts. Every year human lives are lost to erosion, landslides and debris flows. The negative impacts of erosion and sedimentation are further exacerbated by global changes associated with a rapidly growing population and increased vulnerability to severe climatic conditions, which increase soil erosion. E.g. the disappearance of perm frost regions in the mountains due to temperature raise causes an increase of loose material ready to be transported downwards.

Although the head water countries of the Rhine basin Switzerland and Austria have a long-term experience in handling natural risks, there are still significant gaps in baseline sediment data, in current knowledge and understanding of erosion and sediment transport processes.

To improve this situation during the last few years several research studies have been carried-out at the universities of Berne and Zurich with the aim to get better procedures for the estimation of erosion, sediment transport and deposition in steep mountainous catchments.

Two of these procedures are presented in this publication. The first method is developed by Dr. Christoph Lehmann with the title "Estimation of sediment yield in mountain rivers - A guideline for practical application". The second method is developed by Dr. Eva Gertsch and focuses on "Sediment delivery of alpine torrents - Process analysis and estimation method of debris flow".

The two methods have been only published in German and partly in French language. To facilitate the application of the methods by a broader audience the Swiss Federal Office for the Environment has agreed to set-up an English version of the two methods. The coordinators of the CHR have than decided to publish the English version in the framework of the CHR – Publication Series.
The summary of the publication is available in the form of a power point presentation, which also can be used for education and training purposes.

The publication is funded by the Swiss Federal Office for the Environment and is also a contribution to the International Sediment Initiative of UNESCO/International Hydrological Programme.

The CHR gives thanks to the authors, to all contributors, to the head of the Hydrology Division Dominique Bérod of the Federal Office for the Environment and to the CHR Secretary Eric Sprokkereef for their efforts related to the publication.

Prof. Dr. Manfred Spreafico, President of CHR

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1. Introduction

Manfred Spreafico

1.1 Geographical overview of Switzerland

Switzerland is located in the heart of Europe. The main route linking northern and southern Europe does run through it. Switzerland covers an area of 41285 km^2. The highest point is the Dufour Peak at 4634 m altitude, with an artic climate. The lowest point is Lago Maggiore, only 195 m above sea level. Here palm trees grow and the climate is Mediterranean. Ascona, located at the Lake Maggiore, and the Dufour Peak are only 70 km apart. This means that there is a great diversity in landscape within a small space.

Geographically, Switzerland is structured into three main regions:
- The Alps with 60%
- The Plateau (Midlands) with 30 % and
- The Jura with 10 % of the total area.

The average altitude of the Alps is 1700m. They provide a continental watershed, determining the climate and vegetation. The valleys of the rivers Rhone, Upper Rhine, Reuss and Ticino divide the mountain ranges.
The Plateau stretches from Lake of Geneva in the south west to the Lake of Constance in the north east, with an average altitude of 580 m. The Plateau is home of two thirds of the population. There are 450 people per square kilometre. Few regions in Europe are more densely populated. Most of Switzerland`s industry and farmland is concentrated in the Plateau.
The Jura, a limestone range, stretches from Lake of Geneva to Basle in the north. Located on average 700 m above sea level, it is a picturesque highland crossed by river valleys.Switzerland has 6 % of Europe`s stock of freshwater. There are more than 3000 km^2 of glaciers and firn located in the Alps. Switzerland is the water castle of Europe and provides water to the North Sea, Mediterranean Sea and to the Black Sea. In addition, Switzerland has over 1500 lakes.
Water is the only natural source in the country. Hydroelectric power supplies about 60 % of Switzerland`s electricity needs.
In regard to precipitation, Switzerland is located in a transition zone. In the western part, there is a strong influence of the Atlantic Ocean. Winds bring a lot of moisture into Switzerland and cause rainfall.

Figure 1.1 The 3 main regions of Switzerland: Alps, Plateau (flat land) and Jura

In the eastern part, there is an almost continental climate, with lower temperatures and less precipitation. The climate varies strongly from one region to another. The Alps act as climate divide. In the alpine and pre-alpine basins, rivers and torrents frequently cause severe damages. The causes of the damages are bed erosion, bank failure collapse, undercutting of constructions, channel displacement , debris flow deposits, landslides, inundations and river damming by debris from tributaries.

1.2 Sediment management in Switzerland

The floodwater and sediment management in Switzerland is based mainly on the Flood Protection Law of 1993. According to that law, a comprehensive danger assessment must be carried out first. The protective measures based on that assessment can be differentiated depending on the potential for damage. They should be balanced (floodwater protection combined with ecological requirements) and the residual risks should be limited.

The three parts of modern risk analysis, assessment and management

Risk analysis
- Identify hazards
- Determine processes
- Estimate damage potential
- Define impacts

→

Risk assessment
- Compare with other risks
- Compare with benefit
- Quantify risk as a function of hazard, vulnerability and value
- Risk acceptance

Risk management
- Define protection goals
- Develop solution concepts
- Plan measures
- Implement measures
- Handle remaining risk

The principles of risk analysis, risk assessment and risk management also apply for the sediment management of torrents. In the past, many protective measures were planned and implemented in Switzerland:

Preventive protection measures

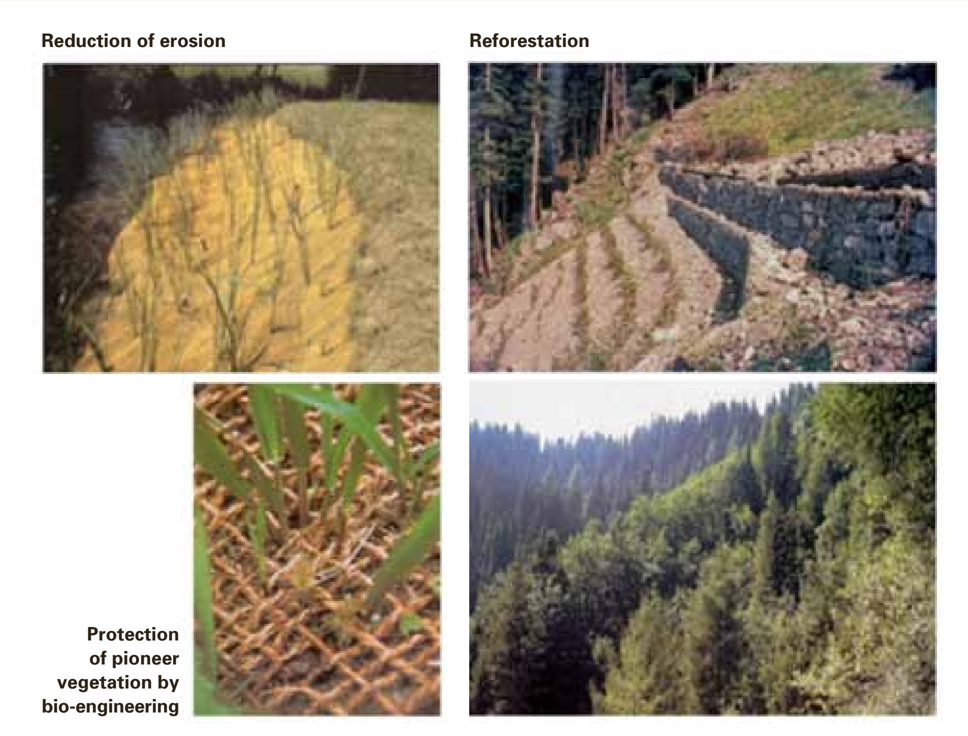
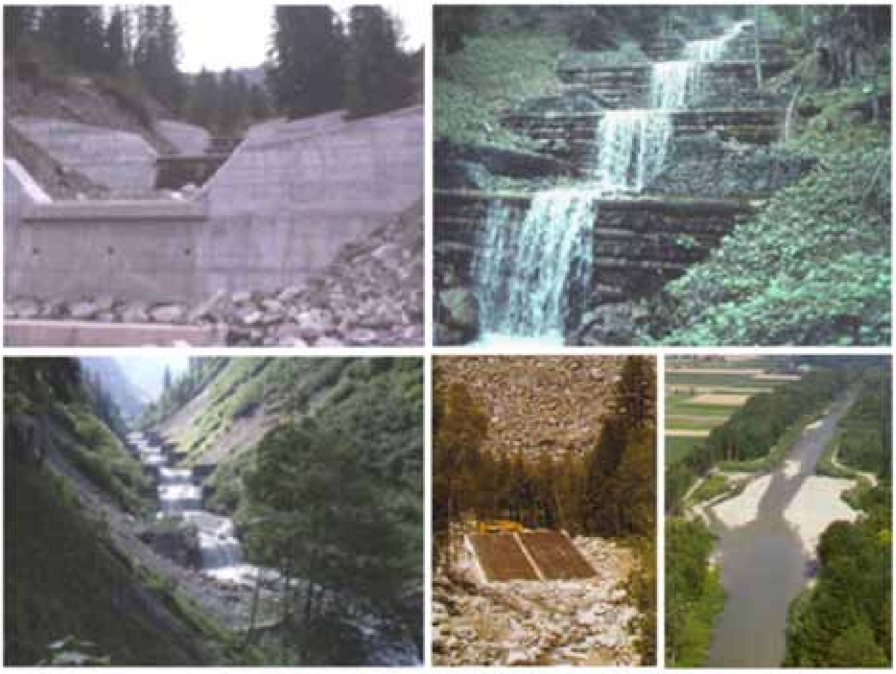


Figure 1.2 Erosion protection by reforestation and protection of vegetation by bio-engineering methods

Preventive protection measures, stabilisation of torrents



Check dams Debris flow breaker Opening of river

Figure 1.3 Stabilisation of torrents by check dams, debris flow breaker and river opening

Preventive protection measures with sediment retention basins

Fischlauwi Seedorf Filderenbach Hochybrig Berschnerbach Berschnis

Figure 1.4 Sediment retention by sediment retention basins

Hazard maps are importatnt instruments for flood protection.

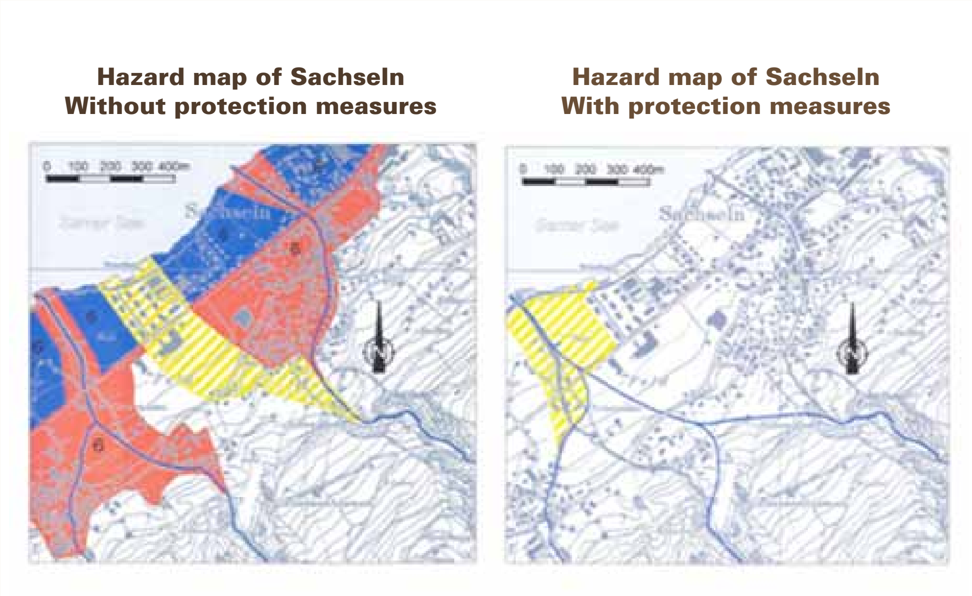


Figure 1.5 Hazard maps of Sachseln, canton of Obwalden (Swiss Federal Office for the Environment, CH-3003 Berne)

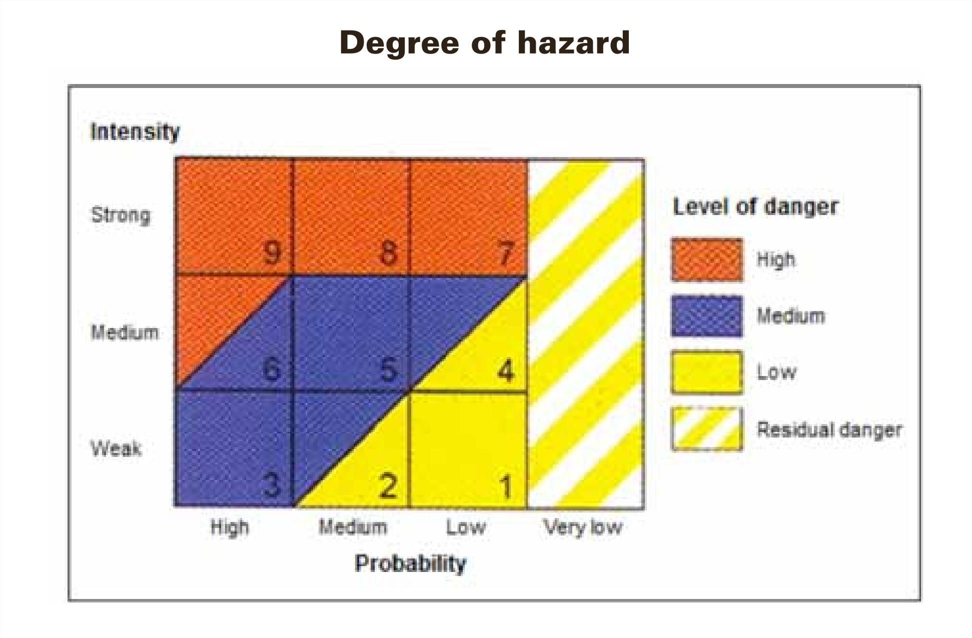


Figure 1.6 The 4 hazard categories used in Switzerland with consequences for building and zoning regulations (Swiss Federal Office for the Environment, CH-3003 Berne)

Thanks to these measures, considerable damages were able to be reduced. In the near future, many of these structural measures need to be renovated, improved or replaced by new protective measures. Improved bases for decision-making are needed for this purpose.
The mechanisms that are essential for the occurrence of damage events are generally known. However, the qualitative recognition of the various processes such as rising floodwaters, runoff build-up and concentration, transport of solid materials and the changes to the creek bed and to the creek suspensions connected to it is only partially possible. Despite much practical experience, there are wide knowledge gaps that need to be reduced.

1.3 Assessment of basic information

For the acquisition and assessment of basic information for the planning of protective measures, the knowledge of many parameters is required. An overview is presented in Table 1.1.
Debris transport trials in the laboratory and research stations such as the ones established by WSL in the alpine creek by Einsiedeln give important basic information. However, these scientific activities must be complemented by observations at the greatest possible number of torrents. For this purpose, Switzerland operates a nationwide network of sediment retention basins for the observation of total bedload.

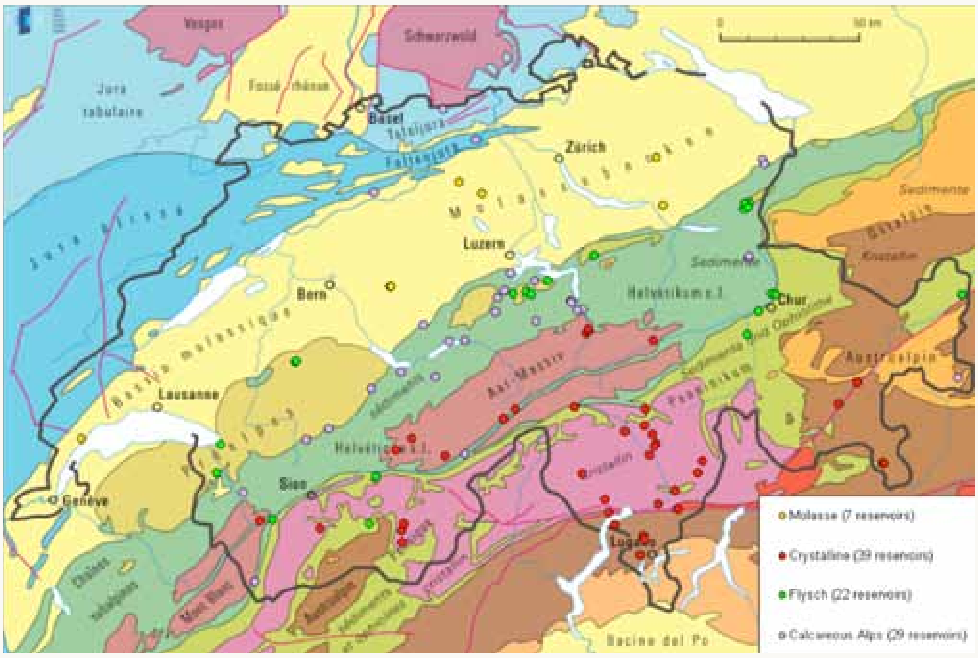


Figure 1.7 Overview of sediment retention basins for the observation of total bed load in Switzerland (A. Grasso, Swiss Federal Office for the Environment, CH-3003 Berne)

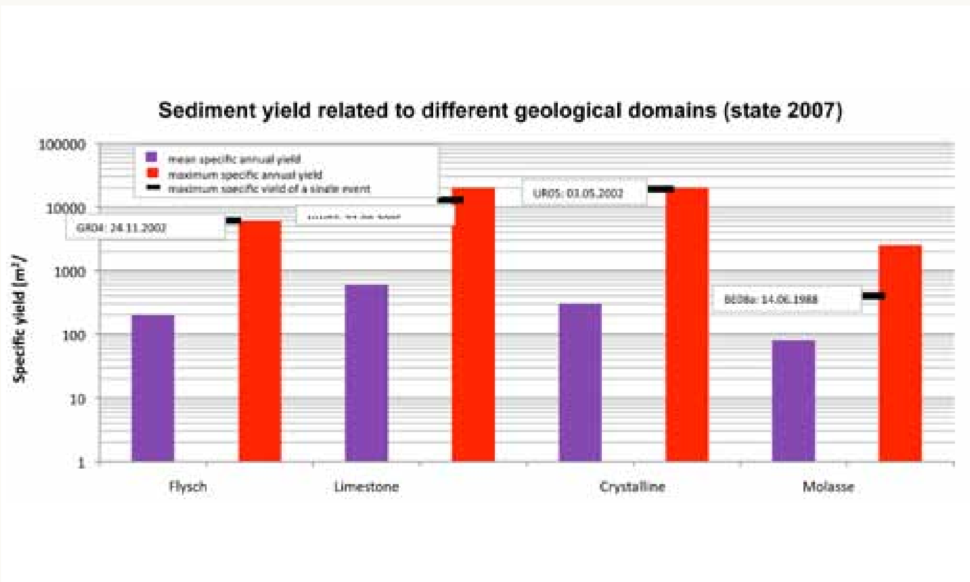


Figure 1.8 Analysis of the observation of total bed load gained by sediment retention basins, structured according to geological formations (blue = mean specific annual volume, red = maximum specific annual volume, black line=maximum specific volume of a single event). (A. Grasso, Swiss Federal Office for the Environment, CH-3003 Berne)

Uses/Goals of use	Desirable solid material observations	Further observations
Basic information for the solving of planning, structural and operational problems in the areas: **Hydraulic engineering** - Stabilization measures - Retention measures - Effects of torrents on their receiving waters **Traffic routes** - Creek crossings - Narrowings - Bridges **Residential water development** - Collections, crossings - Discharges - Protection of water resources **Utilization of water power** - Collections - Retention of debris, wood **Maintenance of drainage areas** - Maintenance and improvement of the usability of the drainage basin by agriculture and forestry - Drainage operations, reforestation projects **Landscape protection, usage planning, protection planning** - Danger recognition - Mapping of dangers - Risk matters - Warning of dangers	**Debris** - Debris potential - Greatest possible sediment transport (transport capacity) - Sediment transport in the case of special floodwater events - Hydrograph of the sediment transport - Particle size in the case of special floodwater events - Debris load of floodwaters of various sizes **Suspended sediment** - Concentration of suspended sediment - Ratio of runoff to concentration of suspended sediment - Suspended sediment loads **Solid material characteristics** - Particle distribution - Particle form and petrography - Specific gravity - Density of sediments - Material composition of debris flows **Floating debris** - Transported wood cubage per floodwater event	- Cross-section and length profile of the flowing waters and their changes over time - High water marks - Sediment cubage within and outside the channel - Slumping cubage along the channel - Water quality - Channel roughness - Torrent history - Morphometry - Geology - Ground cover - Land usage - Hydrology/meteorology - Geomorphology - Springs - Control factors for bedload balance

Table 1.1 Necessary and desirable basic information

The experiences of the past years show, that in addition to more and reliable observations we need sophisticated process oriented estimation methods for the determination of erosion, transport and deposition of sediment in mountainous basins. As a contribution to this demand two methods have been developed at the University of Berne and supported by the Swiss Federal Office for the Environment. These two methods will be presented here.

1.4 Basic processes in a torrent system

In a torrent system, many different processes interact and determine the sediment output of a mountainous basin. See Figures 1.9 –1.15.

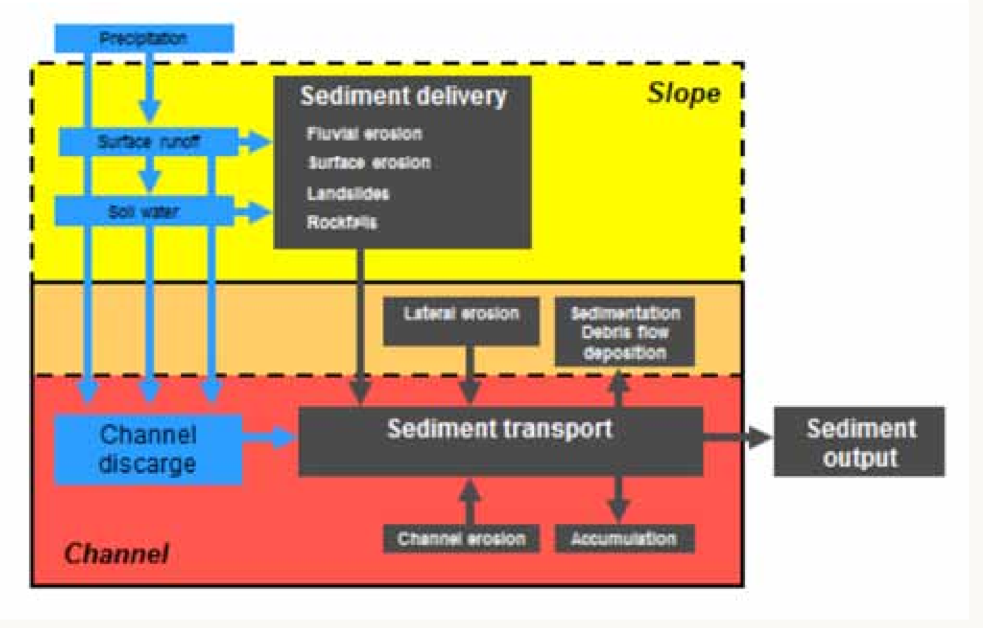


Figure 1.9 System of erosion, transport and deposition in a torrent system

Figure 1.10 Sediment delivery by fluvial erosion

Figure 1.11 Sediment delivery by landslides

Figure 1.12 Sediment delivery by landslide

Figure 1.13 Sediment transport and fluvial erosion

Figure 1.14 Sediment/debris deposition

Figure 1.15 Sediment deposition in channels

2. Estimation of Sediment Yield in Torrents - A guideline for practical applications

By Christoph Lehmann

2.1 Introduction

Bed load of large floods and debris flows regularly cause severe damage in the heavily populated areas of the Alps. Therefore, the planning, design and implementation of protective measures deserve a high priority. Despite high quality research efforts, there are still gaps remaining in the basic knowledge in the area of sediment yield assessment.
The recommendation for the assessment of sediment yield in mountain streams was elaborated between 1989 and 1992 (Lehmann 1993) and brought into a more applicable form with handbook and program for calculations during 1993 and 1996 (GHO 1996). The recommendation was a response to the requirements after the severe floods in 1987, which occurred in the central European alpine regions and specially in the Swiss Alps. These floods caused an immense need for repair works of infrastructure and hydraulic works in rivers and torrents. It also showed there was no operational tool for sediment assessment yet available.
The method can also be considered as a contribution to the understanding of mountain stream processes and describes the procedure for the assessment of a large future mountain stream event. The method was developed by the Geographical Institute of the University of Berne, Switzerland, in association with the former Swiss National Hydrological Survey of the Swiss Federal Office for Water and Geology, now Dept. of Hydrology in the Swiss Federal Office for the Environment. For the recommendation, it has been attempted to collect the current information into a practical guide for specialists who are familiar with hydrological, geological, geomorphological and hydraulic engineering issues and have specific problems to solve in the area of mountain stream processes. The recommendation consists of two volumes. Volume 1 contains a description of the method and volume 2 discusses the basic technical background knowledge. The calculations can be done with the aid of a computer program.
Since the recommendation has been published, a lot of field experience with it has been gained by various applicants in alpine environments. It had shown that the method has become quite a standard procedure for sediment assessment in Switzerland, namely for such applications as the elaboration of danger maps and the planning of protection measures. But it also showed that the simple estimation of the sediment yield does not yet meet all required demands for more sophisticated planning. So, by and by, more features have been introduced to the procedure such as the evaluation and calculation of river bed fluctuation and the use of more different and sophisticated hydrographs as input parameters.

The method described below can be used to solve problems like the following according to Figure 2.1:

- Determination of the volume of sediment transported to a certain point during a flood of a defined recurrence intervall (e. g. about 100 years). The volume estimations serve as fundamentals for example for the design of sediment retention basins.
- As the total load is known, the hydrographs with the necessary flood control storage may be determined.
- As the fluvio-morphological character as well as the sediment load of the said river stretch is known, minimum channel transversal profiles required to avoid overflow can be determined.

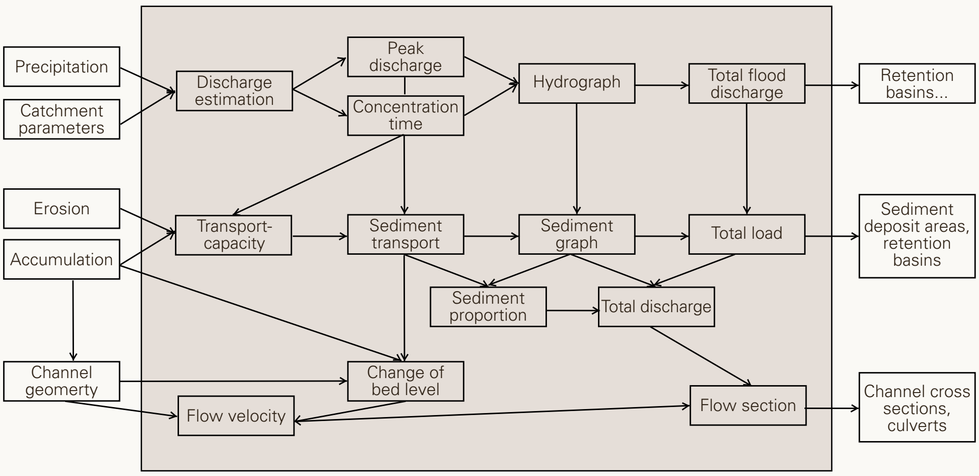


Figure 2.1 Use of the estimation method to solve hydraulic problems

2. 2. Fundamentals and explication of the model conception

2.2.1. The catchment processes for sediment delivery

The sediment volume that reaches the fan of a mountain stream depends on the available sediment potential, transport process and the deposits in the mountain stream. A sketch of a torrent system shows Figure 2.2.

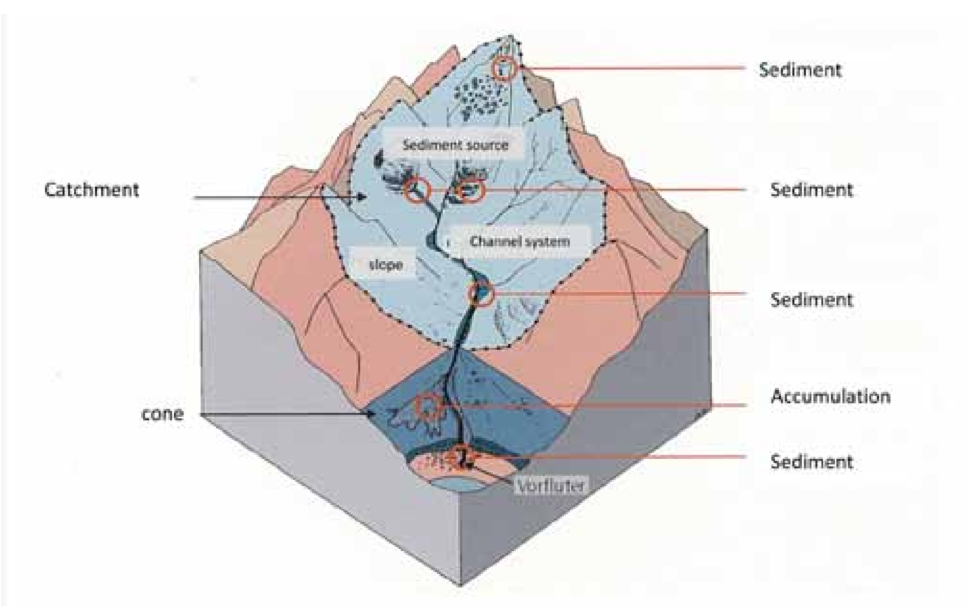


Figure 2.2 Simplified system of a torrent

The catchment of a torrent comprises slopes, gullies and the channel system, which includes a main and eventually several side channels. It includes also the processes described in table 2.1. The composition of the catchment influences the processes which govern sediment production, sediment delivery and sediment transport. Most torrents flow over an alluvial cone before entering to the receiving stream.

For the estimation of the sediment budget of a torrent catchment the following processes can be distinguished:

- Production an mobilization of sediments
- Sediment delivery into the channel
- Sediment transport within the channel
- Accumulation of sediment in an aggrading reach, on the cone or in a sediment retention basin
- Sediment input into receiving stream.

The transport process within the channel is an important issue regarding sediment yield at the cone. There are many ways to transport sediment in channels from "normal" sediment transport to high concentrated flows, to mud flows and finally to high energy debris flows transporting the sediments downstream like an avalanche. As a simplification, only sediment transport and debris flows are distinguished in the method.
Sediment transport is regarded as the process transporting sediment material along the channel and water is the transport medium. The criteria for sediment transport is a low slope channel of not more than 10 % inclination and typical issues e. g. like accumulation terraces and limited erosion within the channel. Also the size of transported components is limited (see Figure 2.3). Sediment transport can be with restrictions calculated by formulas.
Debris flows include material like boulders, wood, fine material and water as a highly energetic mixture. Criteria for debris flow channels are the high slope of more than 15 to 20% inclination, high erosion capacities in the channel and transport of large boulders as well. The transport is avalanche-like. Typical issues of debris flows are the wall like transversal accumulations (levées), and the bobsleigh-run-similar rounded channel cross-sections in the slopes (see Figures 2.4 and 2.5). There is no general applicable way to calculate sediment transport by debris flows.
Mudflows consist of a mainly fine material mix and also occur in mountainous regions and show a similar behavior like debris flows concerning their lateral accumulation walls (levées, Figure 2.6).

Figure 2.3 Sediment transport channel, Grosse Melchaa, canton of Obwalden. At the right side there is an accumulation terrace with relatively small components as fluvial deposit

Figure 2.4 Debris flow channel with levees, Melbach, canton of Nidwalden

Figure 2.5 Debris flow channel in the slope, Melbach, canton of Obwalden

Figure 2.6 Mudflow in the Edisriedbach, canton of Obwalden. The lateral deposits consist of fine material.

Sediment delivery into a channel is composed by several processes, each of them has it's own characteristics.

The following processes are involved at the sediment mobilization and -delivery into the channels:

- Erosion (depth erosion, lateral erosion, gully erosion, erosion preliminary in channels) and transport of debris material by floods or debris flows.
- Erosion and transport of debris material by landslides
- Relocation of material by rock fall (rock and stones)
- Transport of sediment material by avalanches (Table 2.1).

Any of these processes can be recognized in the field by it's typical erosion scar shapes (Table 2.1).

Sediment delivery by…	**Process**	**scar shape**
1. Fluvial erosion	Depth erosion	V-shaped scar
	Lateral erosion	Bank scar
	Gully erosion	Gully scar
2. Landslides and creep movements	Landslide	
	- Rotational slide	Rotational scar
	- Translational slide	Translational scar
	Rockslide	
	Sacking	
	Creep movements	
3. Fall processes	Stone fall	
	Rock fall	
4. Avalanches	Snow- and avalanche erosion	

Table 2.1 Sediment delivery by characteristic erosion processes and scars

The extent of the erosion is governed by various coupled factors:

- Channel geometry. On one hand the longitudinal profile with the slope and location of the local erosion base are of importance, on the other hand the particularity of the cross- section.
- Resistance of the channel bed and embankments.
- Water flow (discharge and flow velocity).
- Bed load transport with the characteristics of the hardness and granulometry of the transported components.
- Erosion capacity of the debris flow.

2.2.2. Relevance of the sediment sources

The relevance of sediment source for sediment delivery into the channel depends on several factors outlined below. They are also shown in Figure 2.7.

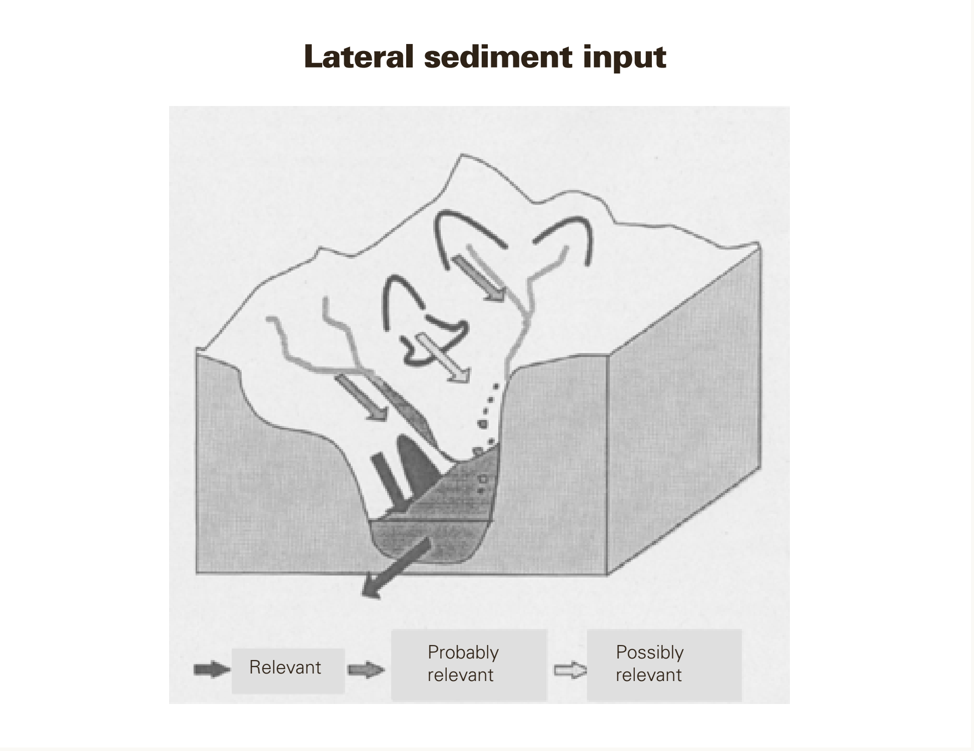


Figure 2.7 Relevance of sediment sources

For the sediment delivery, sediment sources with specific characteristics are relevant. The contribution of each of the sediment sources to the mobilized sediment volume depends primarily on the material and on the position of the sediment source in relation to the channels. These two factors determine the moment of the sediment delivery into the channel. The moment of sediment delivery is regarded in relation to the flood event (Table 2.2).
Important are only sediment sources consisting of loose material. One has to decide, to what extent the sediment source concerned is linked to the channel, respective whether its material reaches the channel during the flood. Three groups of sediment sources are differentiated:

- Channel bed
- Embankment. These sediment sources are in the sphere of influence of the flood. The material is eroded directly by the flood or slides into the channel due to undercutting.
- Slope. Sediment sources in the slope area are not in the direct sphere of influence of the flood. The material arrives the channel by independent slope processes such as slides or by gullies. Here it is to be particularly examined whether the material reaches the channel during the flood event.

The significance of a sediment source can be judged using the following two criteria:

Material composition
Sediment sources consisting of loose material are important. Those originating from bedrock are less important, unless the rock is easily erodible and slat, as the sediment discharge in the channel (e.g. from a rock slide) is not directly related to a flood event in the mountain stream.

Location of the sediment source
The location of the sediment source and transport path of the material in the channel sediment sources of loose material lying near the channel will be eroded during an event and are to be considered of great importance. Mountain streams with large sediment sources in the channel area tend to be especially active. As a rule large sediment volumes are to be expected.
The transport path for sediment sources outside of the channel area is important. Large sediment sources such as talus cones, open erosion scars, etc. are meaningful when their material is able to directly reach the mountain stream via side channels or gullies.
For sediment sources that do not have a direct path of connection to the channel, the slope gradient plays an important role. If the gradient of the slope is less than 30°, then the material tends to come to rest on the slope from where it can be eroded at a later time.
The location of the sediment source in relation to the channel will decide whether the delivery of the solids into channels takes place in a 'direct' or 'indirect' way.

Direct:
For sediment sources within the close range of the channel, i.e. in direct range of influence of the flood. The mobilization of solids is not linked to a certain triggering precipitation. They are only controlled by the tractive forces of the flood. Sediment sources in direct outreach of the channel are 'certainly relevant' (Figure 2.7).
Indirect:
For sediment sources out of the reach of the channel:
- The sediment input will be channeled by gullies. Sediment sources, whose material reaches the channel by gullies are 'probably relevant'. The solids reach the channels by steep slopes and an unbent longitudinal profile.
- The sediment input is not channeled through the free slope. These sediment sources are 'possibly relevant'. The solids reach the channels as a rule on steep slopes with a stretched longitudinal profile.

The way between the sediment source and the channel is thus playing a key role (Figure 2.8).
- The steeper the terrain and the less graded the longitudinal profile, the greater the chance that material reaches the channel alone by gravitational processes
- the less shear stress by water is needed to transfer solids into channels, the bigger the probability that sediments reach the channels before the flood or debris flow event.

Time of sediment delivery
The sediment delivery into the channel can either take place during or between the floods. The time of the sediment delivery into the channels will - regardless of precipitation considered - be set through the material and the location of the sediment source.

Sediment source / process of sediment delivery	**Sediment delivery between the time of the floods**	**Sediment delivery during the flood event**
loose material channel bed	never	always
bed rock channel	never	rarely
weakly consolidated channel bed	never	often
bank failures	rarely	often
low depth landslides	mostly	often
deep landslides	mostly	rarely
rockslides	mostly	rarely
rock fall	mostly	rarely
stone fall	mostly	rarely
gully erosion	mostly	often

Table 2.2 Time of sediment delivery in regard to the flood

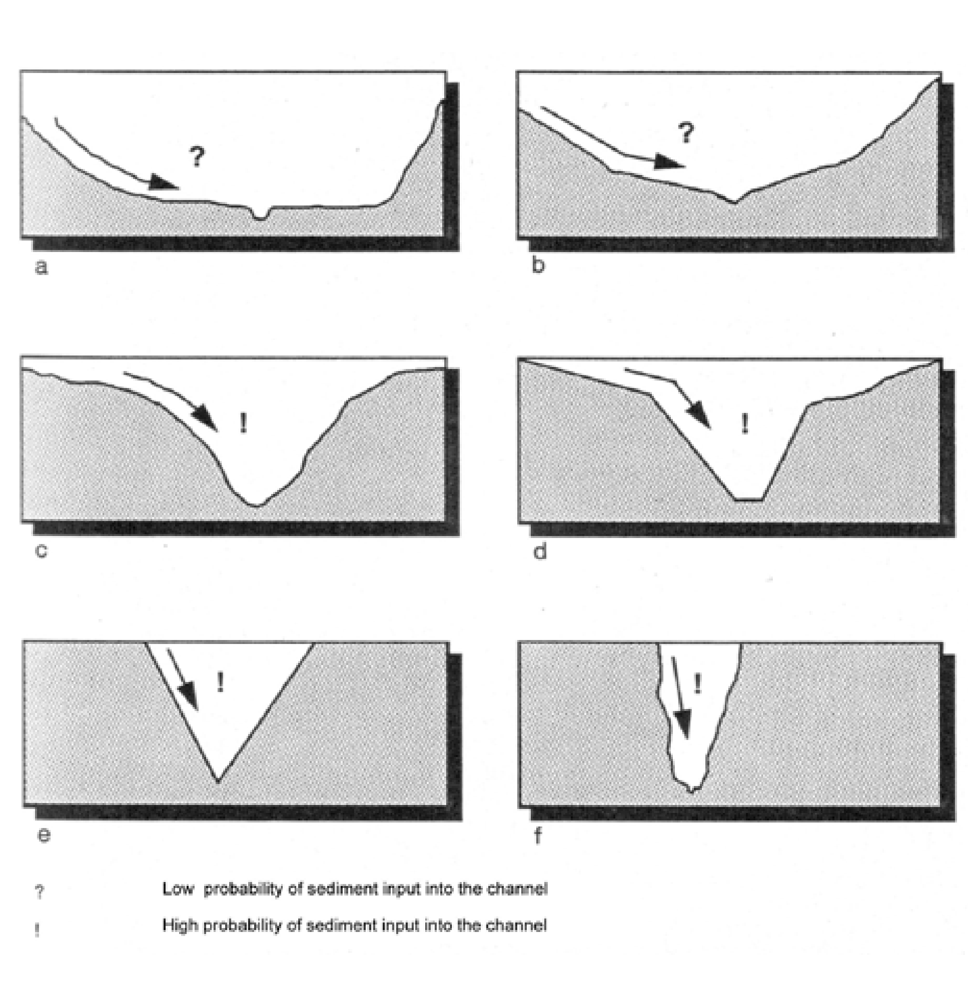


Figure 2.8 Importance of the travel paths of sediment into the channel

2.2.3. Sediment potential

The sediment potential is defined as the amount of erodible solids that can be mobilized during a specific event. That means that the term does not cover all the available loose material in the catchment area. The assessment of the sediment potential in the terrain is carried out through a classification of the relevant sediment sources. The source of the erodible material is very important, as sediment originates to a large extent from the channel and the adjacent embankments. So in general, only a small part of the catchment area delivers sediment to the channel and is therefore of importance to sediment yield. The sediment transport process is made up of bed load transport and debris flow. Debris flows do transport much higher amounts of sediment and in general cause greater damage in endangered areas. Also important are areas of accumulation in and around the channel, where sediment can be deposited during an event. In this case the deposited material will not reach the cone.

2.3. The Procedure

With this method the sediment yield of an event can be assessed in the following manner (Figure 2.9):

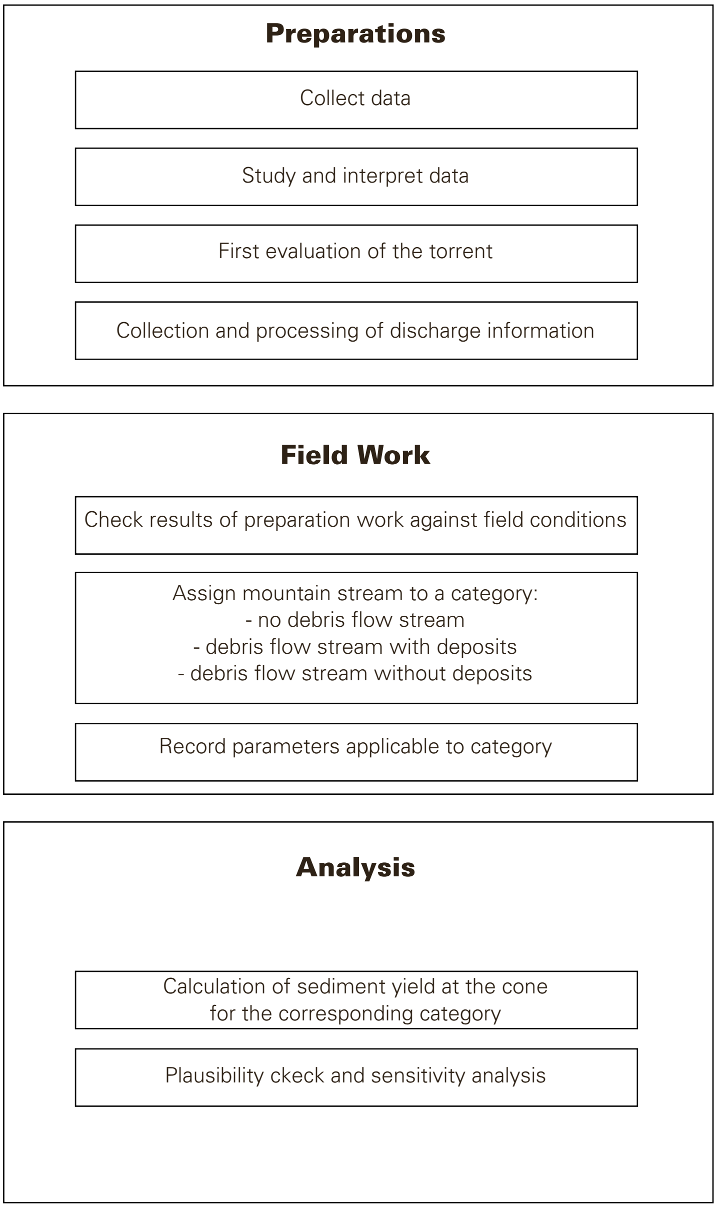


Figure 2.9 Overview of the steps required for the assessment of sediment yield

2.3.1. Preparations

Aim of the preparations is getting to know the catchment and to carry through a first evaluation of the processes involved. The question whether the channel is debris flow prone or not plays a special role in this.

The main part of the preparation work can be done in the office and involves the following (Figure 2.9):

- A preliminary examination of the transport process which involves an ascertainment of the mountain stream’s capability for debris flows, using available documentation, descriptions of past events, maps and aerial photographs.

The torrent can be assigned to several categories which depend on the transport process:

- No debris flow torrent.
  Calculation of the sediment potential, the accumulation potential and the transport capacity can be done.
- Debris flow prone torrent with accumulation possibilities.
  Procedure for debris flow estimation with accumulations is to be carried out.
- Debris flow torrent without accumulations.
  A sediment potential assessment has to be done.
- Eventually debris flow torrent.
  The transport process cannot yet be determined. Until there is no final clarification, the procedure includes the one for no debris flow torrents as well as for debris flow torrents with accumulation possibilities.

- A pre-selection of the most important sediment sources that can be determined using maps and aerial photographs.

- For „no debris flow mountain streams" and in the case that no measurements are available: construction of simplified hydrographs to calculate the sediment transport capacity of the channel.

- First evaluation of transport processes and sediment yield according to Figure 2.11 and Table 2.3.

This first evaluation shown in Figure 2.11 consists of several steps of application of criteria, which will finally lead to the determination of specific sediment yield. With the aid of Table 2.3, the specific sediment yield can be transformed to an absolute sediment yield. The specific sediment yield is derived from flood and debris flow events, which occurred in the past and of which the sediment volumes are known (Figure 2.10).

For each of the evaluation steps an element of influence has to be considered with "yes" or "no", starting with the development and maintenance of debris flows, to decide if the evaluated torrent is debris flow prone or not (considering criteria of development of debris flows as water and loose material availability, gradient etc.).

Further on, the existence of large sediment sources, rock sections in the main channel and retention possibilities along the channel are regarded to finally determine the category of specific sediment yield ("very small to very large") to which the torrent will be assigned.

With the aid of Table 2.3 the tentative sediment yield can be assessed.

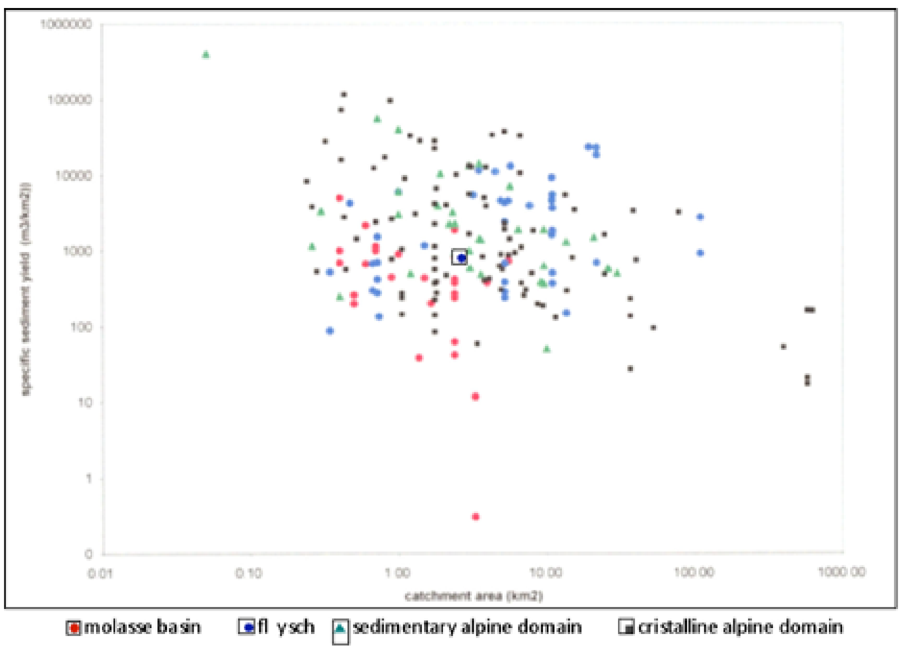


Figure 2.10 Specific sediment yields in 4 geological categories of past events in Switzerland

The first estimation of the specific sediment yield divides the sediment yield into five size groups:

1. Very small:
Usually with no debris flow torrents without large sediment sources with retention space for sediments and/or also with longer channel stretches of bedrock. The average slope is less than 20%.

2. Small
No debris flow torrents with no large sediment sources, with however less distinctive retention areas and/or rock stretches.

3. Medium
Usually with no debris flow prone torrents with large sediment sources without larger retention areas and without longer rock stretches. Likewise with debris flow prone catchment areas without large sediment sources, but with retention areas and/or rock stretches.

4. Large
Debris flow prone torrents with large sediment sources, but with retention areas and/ or rock stretches.

5. Very large
Debris flow prone torrents with large sediment sources, but without retention areas and/or rock stretches.

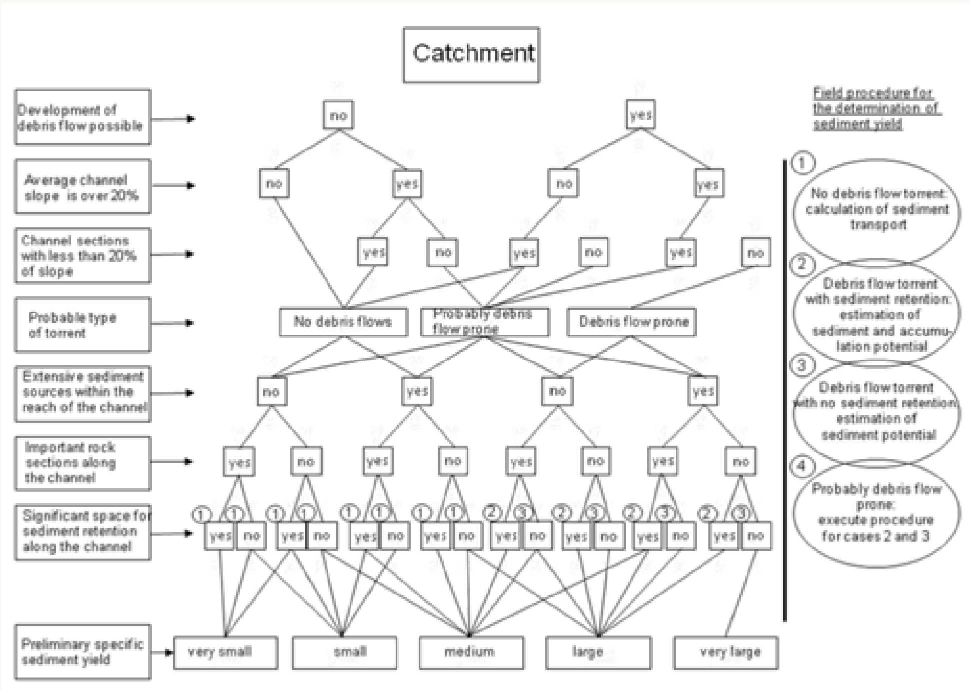


Figure 2.11 First evaluation of transport process and specific sediment yield in a catchment

Specific yield (m³/km²)	Molasse basin 10 km² - 1 km²	Flysch	Limestone 10 km² - 1 km²	Crystalline 10 km² - 1 km²
very small	20 - 100	150	200 - 800	400 - 3.000
small	50 - 200	1.500	500 - 1.000	800 - 5.000
medium	150 - 500	5.000	1.000 - 5.000	1.500 - 15.000
large	500 - 1.500	10.000	2.000 - 10.000	3.000 - 30.000
very large	(800 - 3.000)	20.000	3.000 - 30.000	8.000 - 80.000

Table 2.3 Specific sediment yields according to 4 geological categories

In the molasse basin, the limestone and crystalline alps the specific sediment yield decreases with increasing catchment area (see also Figure 2.10). Due to the available data, this observation is not valid for flysch catchments.
The multiplication of the value with the catchment area surface, interpolated from the table, results in the order of magnitude of the possible sediment yield.
For example for a 5 km^2 catchment in the limestone alps, which due to Figure 2.11 a "small" specific sediment yield was assigned, 3.750 m^3 (rounded approx. 4.000 m^3) is a realistic value (from column "Limestone" and the line "small" results a value of approx. 750 m^3/km^2). Extrapolations for catchment areas over 10 km^2 are to be accomplished only with caution. Below a catchment area surface of 1 km^2 one should not extrapolate. This rough estimation serves primarily as a check for the later results from the field elevation. Under no circumstances the application of the Figures 2.10 and 2.11 as well as Table 2.3 may replace a detailed field evaluation!

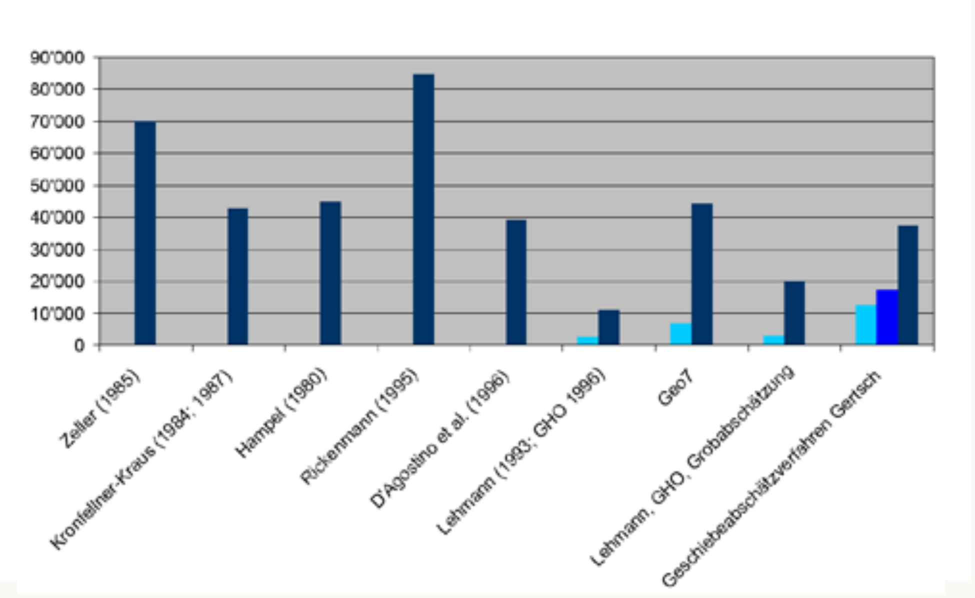


Figure 2.12 Results of sediment yield estimations by various methods

Figure 2.12 shows the results of sediment yield assessment by various methods from literature which were applied for the Steinibach, Canton Lucerne. The area of the Steinibach is 4.4 km^2 mainly consisting of marl and sandstones. In upper regions there is also some limestone to be found. The channel network is widely branched and consists of a large number of small gullies besides the main channel. Medium slope of channels is about 18 %.
The sediment yield assessments show a large variation of possible results between 2.500 and 85.000 m^3, which corresponds to a factor of 34! The discrepancy between the results would even be larger if the scope of discretion in choosing the parameter values would have been regarded in the examples of Figure 2.12! The regional constraint of some of the methods is also not regarded in Figure 2.12.
As a conclusion to this, it might be stated that sediment assessment methods should never be applied without a detailed field investigation.
With the summary of the findings from the preliminary work, a first evaluation of the torrent is possible. A first picture develops primarily over the historical aspects of the torrent, mainly on the basis of documents regarding the past torrent events as well as past measures in the catchment area. Some knowledge of the present situation and the current processes is compiled by means of map- and aerial photo interpretation. Thus a first determination of the transport process can take place, and also a rough estimation of the sediment yield can be accomplished. With these preliminary results, the procedure for the field work can be planned.

2.3.2. Field work

a) Goals and overall investigations

The field work serves the following goals:

- Clarification if the torrent is debris flow prone, if this is not already cleared free of doubts on the basis of the preliminary work.
- Survey of the basic data for the computation of the sediment transport capacity (with no debris flow torrents).
- Estimation of the sediment potential of the determining sediment sources.
- Estimation of the volume of possible deposits along the channel.

In the field the following investigations have to be carried through:

- Assessment of the channel’s capability for debris flow, in case that this is not known.
- Division of the mountain stream into channel sections. In each channel section the following has to be undertaken:
  - Estimation of the sediment potential of the main sediment sources.
  - Estimation of the possible depositions.
  - Mapping-out of cross sections with slope, bed width and the key numbers of granulometry d90 d50 d30 of bed material for „no debris flow mountain streams“. These parameters are used in the calculation of the transport capacity.

During the collection of the data better results are obtained according to experience, if the torrent is inspected upward instead of in flow direction. The channel is constantly divided into individual sections during the investigation upstream. The evaluations take place separately for these individual sections.

The individual sections are selected in such a way that they cover approximately uniform distances from approx. 100 to 300 m length and contain similarities concerning the sediment transport process, bed condition, channel width and gradient. The bounds of a section are selected when obvious changes of the character (e. g. transition from bed rock channel to a loose material channel), of the channel geometry and of the gradient are observed (see Figure 2.13).

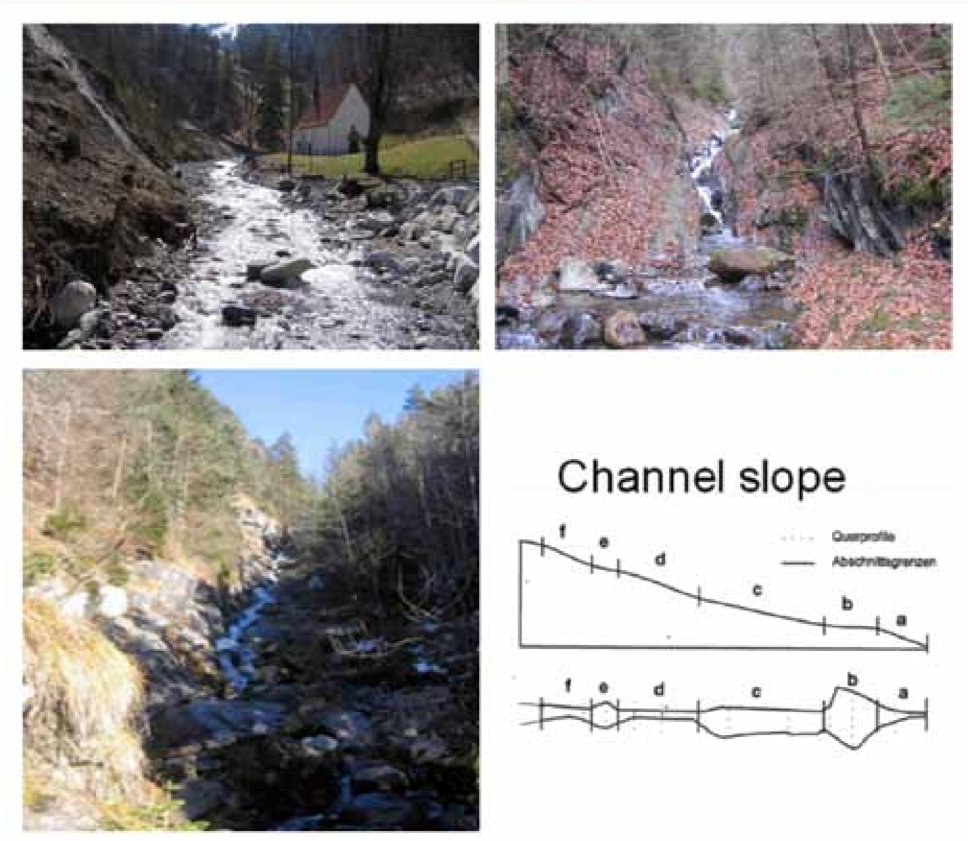


Figure 2.13 Determination of channel sections and “cross sections” according to slope and channel width

The torrent must be investigated at least up to the place,
- of the highest relevant sediment source
- where further up in the catchment area no larger material entry takes place,
- where the catchment area regarding the sediment potential is manageable and therefore no complete investigation has to be carried through,
- where the channel starts to be divided into many small gullies, which mobilize for their part only a small and very limited sediment potential and therefore there is only a punctual check necessary
- the transportation capacity is not sufficient to transport the available sediment (e.g., long channel section with small downward gradient).

b) Evaluation if a torrent is debris flow prone

EVALUATION AT THE CONE

Important information, if the torrent is debris flow prone, can be already found on the cone:
- Downward gradient.
  The downward gradient must exhibit at least 5%.
- Characteristics of the longitudinal profile.
  The longitudinal profile of mainly the smaller cones is convex. Concave cones and flat downward gradient are referring to not debris flow prone channels respectively they indicate that the places concerned were not reached so far by debris flows.
- Structure of the cone surface.
  Debris flow cones often exhibit a pronounced relief and are strongly structured. These characteristics can be also due to other processes, e.g. to rockfall!
- Characteristics of the gullies on the cone.
  Debris flow gullies are often again overgrown by vegetation. They are often deeply radical and mostly recognizable by an "U"-shaped cross section. If they are not or only little eroded, debris flow gullies show as special characteristics lateral parallel embankments, so-called levées. Between the two levées of recent events the vegetation is often practically intact.
- Shape of accumulations.
  The deposits of debris flows are lengthwise, tongue-shaped and show a clear delimitation to the environment. A steep deposit front (debris flow head) is characteristic.
- Composition of material.
  On the cone there are often above average large and edge-rounded blocks. If the deposits of a debris flow are still very young and the traces still intact, the following additional characteristics are typical: a very sharp border of the solid deposits mostly exists to the intact environment.
  The individual components are neither vertically nor horizontal laminated, as this is the case with fluvial deposits. There are no grain size decreases against the edge of the deposits.

INVESTIGATIONS IN THE CATCHMENT

The most important issues for debris flows in a catchment are:
- Traces in the channel:
  - Levees, i.e. lateral embankment-like deposits of coarse-grained unsorted material
  - Deposition of larger, edge-rounded boulders parallel on both sides of the channel, at the edge of embankments (thus clearly over the channel bed).
  - Individual edge-rounded blocks in the channel, which are visibly larger than the remaining bed material. Although the channel after a debris flow is often empty-swept, it can occur that individual larger blocks remained on the channel bed. Or, what is also possible, they rolled later out from the levees. Boulders without rounded edges origin from slope processes (landslide, rockfall).
  - Edge-rounded boulders as elements of older embankments may be part of an old debris flow.
  - Mostly still recognizable U-shape of the cross section of the channel bed.
- Traces outside of the channel:
  Indications for debris flows outside of the main channel are to consider particularly in slopes and larger loose material accumulations (glacier aprons, talus slopes, moraines etc.).
  - Typical debris flow gullies
  - Levees. They can be partly intact (covered by other processes) or be eroded.
  - Debris flow heads.
  - U-shaped transverse profiles of side channels and gullies.

SPECIAL CHARACTERISTICS:

Apart from the evaluation of traces the evaluation of risk factors is necessary, which can increase the probability of debris flows. To be specially named:
- Glacier lakes with the possibility of outbursts
- Check dams with increased danger of failure. This is particularly to consider with older and insufficiently maintained constructions. Debris flows arise above all if several check dams break down practically at the same time.
- Possibilities of clogging (bottle-necks, drift wood etc.).

c) General procedure for the estimation of sediment potential

The evaluation of the parameters for the determination of the sediment potential to be mobilized, for the computation of the transport capacity and for the estimation of the possible sediment volumes are to be accomplished for each channel section. The analysis of the bed material cannot be accomplished for each channel section in most cases, because of the large expenditure. So the values from other channel sections upwards shall be used.

For the estimation of the sediment yield the most important sources of sediment have to be specified and their contributing volumes must be identified. The sediment sources are classified primarily according to their position regarding the channel, in second line by lithological characteristics (see also chapter 2.2.2).

For each sediment source the volume of the mobilizable material is to be estimated. Since however not the entire volume of the sediment source reaches the channel according to experience, because due to obstacles, material remains partly in the sediment source. Therefore, the volume of the sediment source is reduced with a reduction factor. This reduction factor contains a value between 0.1 and 1 (10% resp. 100% of the material considered will be transported off). With channel bed and embankments it has to be regarded that debris flows achieve higher erosion rates and thus larger volumes will be eroded.

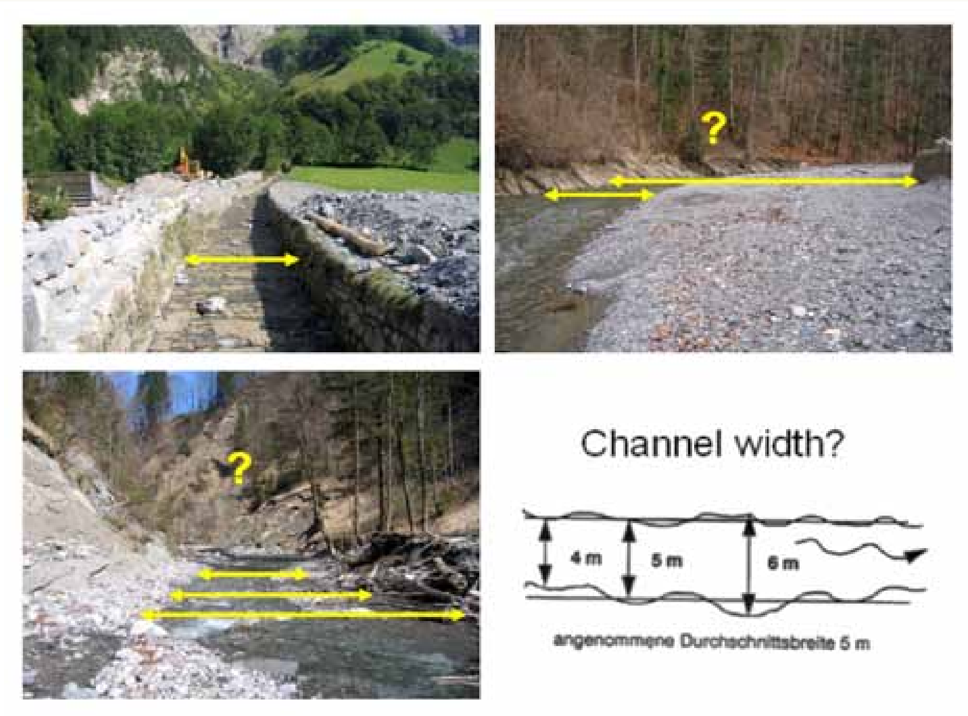


Figure 2.14 Determining of average channel width

For erosion of the channel bed:

For the channel bed the mobilizable sediment volumes can be determined as follows (see Figure 2.14):

- Specify the total length of the channel section by estimating or measuring.
- Determine the average width of the channel bed within the section (Figure 2.14).
- Estimation of the erosion depth:
  The erosion depth can be locally very different. In the procedure an overall value for the erosion depth is therefore used. Empirical values for the erosion depth are:
  - For debris flows.
    In the channel, the relationship erosion depth / channel bed width may reach 1:5. In slopes, erosion depths are in the relationship up to 1:3 as realistic assumption. It is important to note that these assumptions are overall values and must be adapted to local conditions according to each case (downward gradient, obstacles).
  - For bed load transport:
    In the channel, depending upon local conditions, a relationship erosion depth / channel width from approx. 1:10 to 1:12 can be assumed. These values depend on the bed material and the down ward gradient. Experience indicates that the depth erosion may correspond to the granulometry value of “d90” of the bed material.

Erosion of embankments:
For the embankment the mobilizable volumes of the embankments on the left and on the right channel side are separately estimated. One proceeds as follows:

- Determine the length of the channel section
- Specify the height to the erodable embankment
- Frequently the material is eroded up to the upper edge of the embankment, provided that this is not too far away from the channel. As an orientation, existing traces of older scars will help. Realistic average values might amount to up to approximately 6 meters, in individual cases also more. Thereby also local conditions (for instance the presence of stabilizing trees or rock) are to be considered.
- Estimation of erosion depths (figure 2.15):
  Erosion rates depend particularly on the material of the embankment (fig 16). It depends also from the influence of stabilizing elements (trees, coarse material etc.). It is to be noted that - also with the embankments - debris flows may erode larger volumes than normal bed load transport.
  - For debris flows no absolute values can be indicated, since erosional force is strongly material dependent. Up to a half meter higher values than with normal bed load transport occur however easily.
  - With bed load transport an average of 50 cm of erosion depth might not be exceeded, even if locally far higher values already occurred.
- Calculation of the erosion volume of a single sediment source (Figures 2.16 and 2.17). The computation of the erodible volume of individual sediment sources is practically alike as with the embankment. Often the surface of a the sediment sources can be approximated also with a triangle form (Figure 2.17).

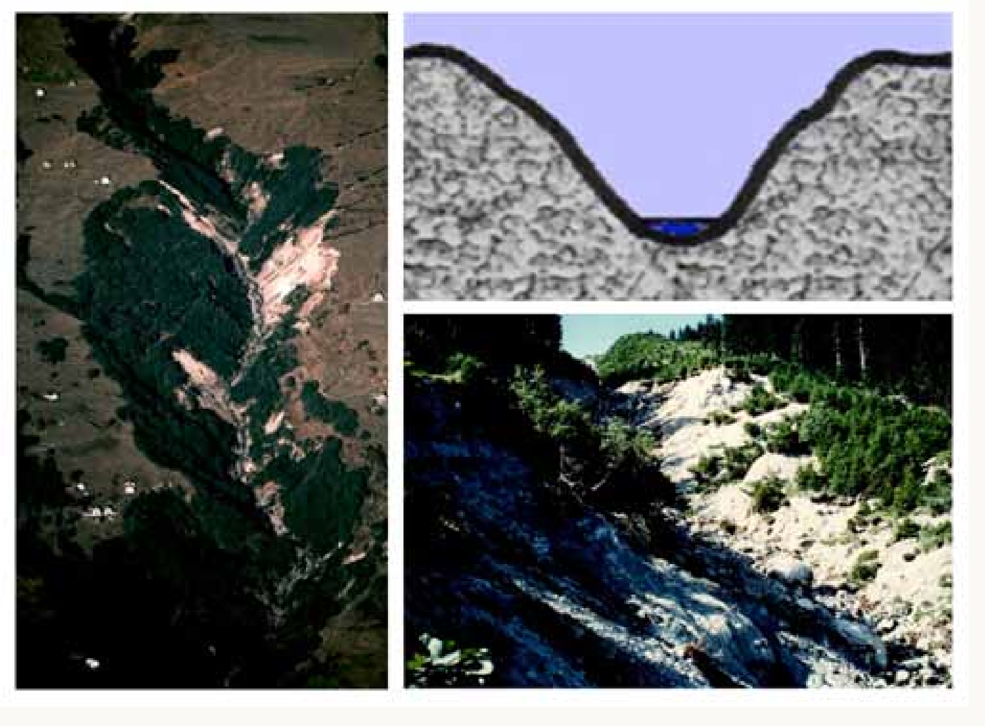


Figure 2.15 Depth erosion in torrents

Estimation of sediment accumulation in the channel (Figure 2.18):
The accumulation volume in the channel section results from the product of the length of the deposit distance with the deposit width and average deposit thickness. Deposits are to be expected with an increase of the channel width and / or with locations with reduced downward gradient. The maximum place available for deposits must be assessed for each individual case. Furthermore it is to be remembered that deposits increase the channel downward gradient and that the deposited material may extend further channel upwards. Besides the channel deposits it has to be considered that there are deposits also outside the channel.

For each channel section, the erodible sediment volumes are added (figure 2.19). The distribution of the volumes to the cross sections, for the transport calculations, will be finally done in the frame of the analysis.
Distribution of the solid potential in the channel section: In direction of flow of the torrent from left to right the sediment potential amounts at cross section a to 279 m^3, at cross section b to 330 m^3, at c to 370 m^3 and finally at d to 100 m^3.

Figure 2.16 Different processes of sediment input

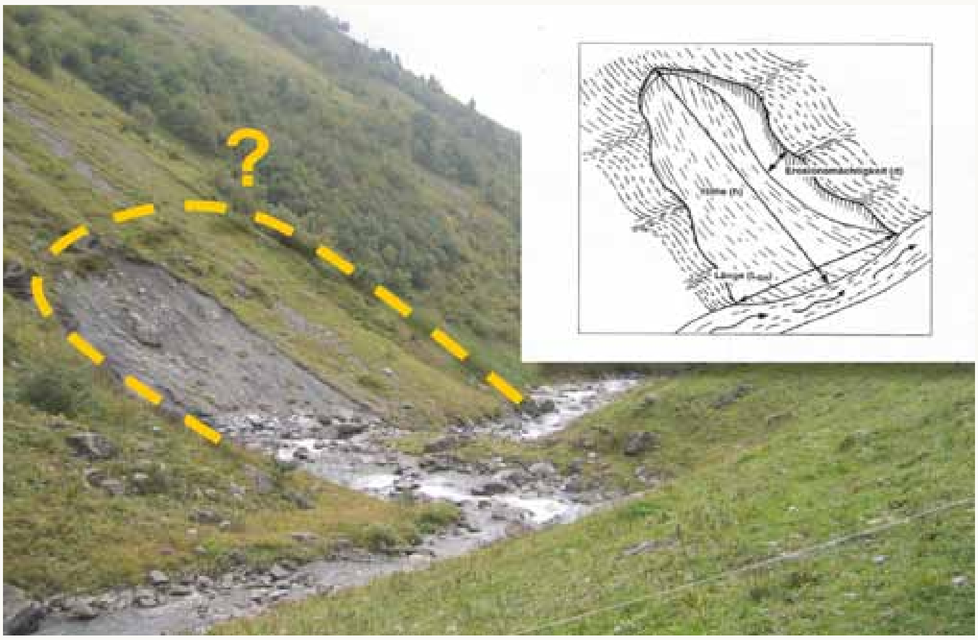


Figure 2.17 Single sediment source, approachable to a parabolic o triangle shape

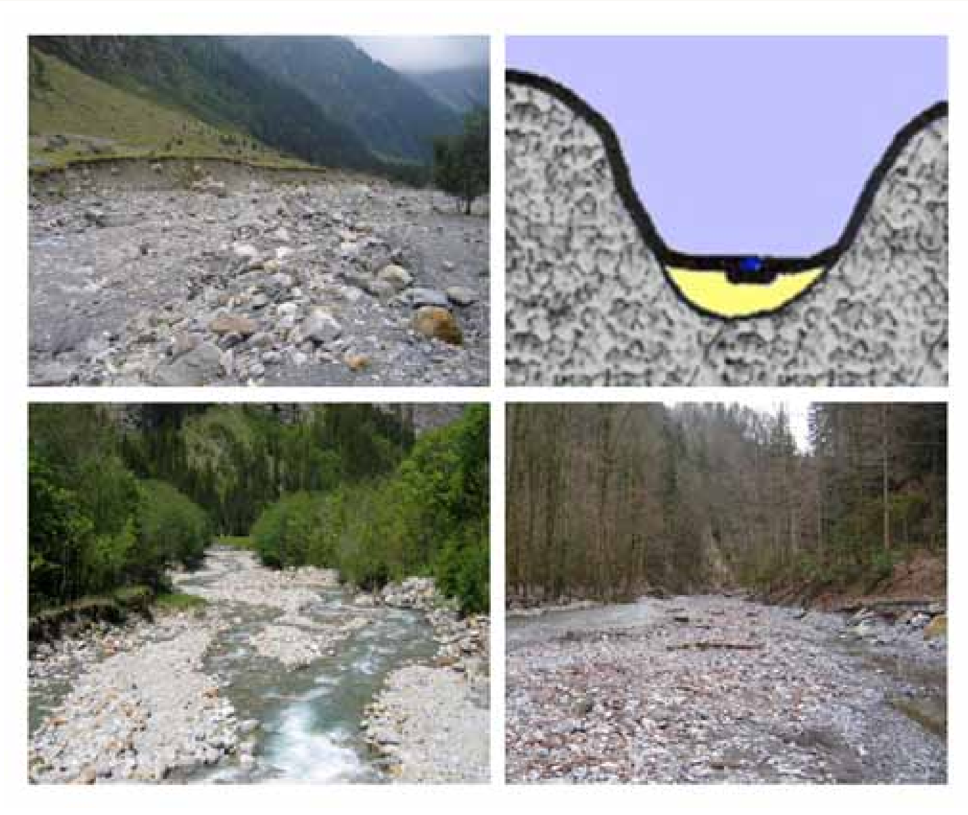


Figure 2.18 Accumulation stretches in a torrent

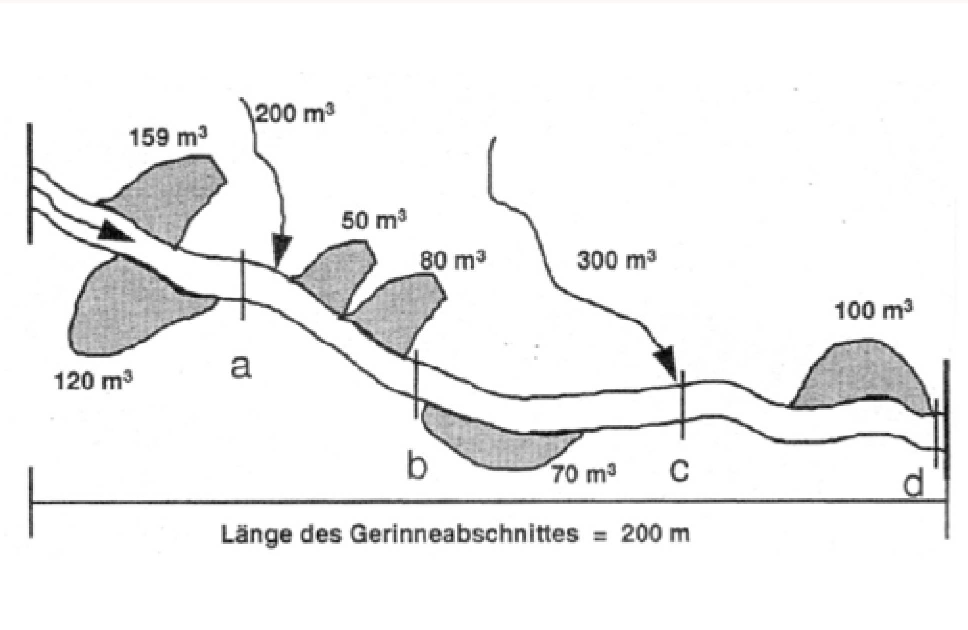


Figure 2.19 Distribution of sediment potential in a channel section

2.4. Analysis

Back in the office an analysis of the data can be carried out that involves a detailed calculation of the sediment yield and a check of the field investigation (plausibility check).

For each channel section the following is calculated (see also Figure 2.20):
- the sediment potential
- the sediment transport capacity using the hydrograph (not applicable for „no debris flow mountain streams")
- the volume of possible deposits
- and for each cross section moving downstream the difference between the sediment potential and the transport capacity taking into consideration the deposits. These differences are then summed together to create a sediment budget. At the last cross section the volume of the sediment yield at the cone is found (figure 2.20).

The example in figure 2.20 shows the schematic operational sequence of the computations. 10.000 m^3 arrives cross section 1. The sediment potential between cross sections 1 and 2 amounts to 3.000 m^3, 2.000 m^3 can be potentially deposited. Since with cross section 2 the sediment transport capacity amounts to 14.000 m^3, the entire summed 13.000 m^3 can be transported downstream. With cross section 3 the sediment transport potential amounts to 11.000 m^3. The estimated sediment potential between cross section 2 and 3 is 2.000 m^3, so that the entire potential volume amounts to 15.000 m^3 at cross section 3. So 4.000 m^3 have to be accumulated to achieve the 11.000 m^3 corresponding to the sediment transport capacity at cross section 3. Like this, every section is sediment balanced, and at the end, the sediment yield at cross section 4 is 15.000 m^3.

In the case of debris flow mountain streams, these calculations cannot be done in such a detail. There is no way of calculating the transport capacity of debris flows.

For each channel section, the sediment and deposit potential is recorded just the way it is described in chapter 2.3.2. The only difference is that the sediment budget is directly made for each channel section without applying any calculation of sediment transport capacity.

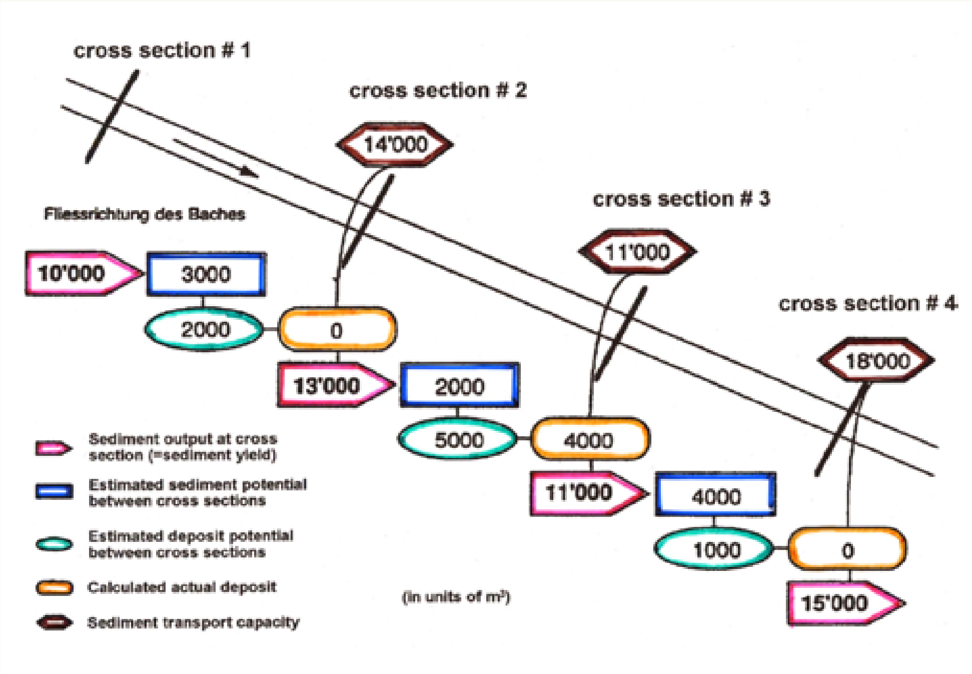


Figure 2.20 Determining the sediment yield in torrents

2.5. Results from the Calculations

Figure 2.21 is also a schematic example representation. The flow of the stream from cross section no. 21 down cross section 1 is plotted in the diagram. The larger natural deposit points (to be observed at cross sections 19, 18, 13, as well as 8, 7 and 2) reduce the sediment yield and it can be seen that transport capacity would allow more sediment to be transported in the middle section (cross sections 17 to 10) of the torrent.

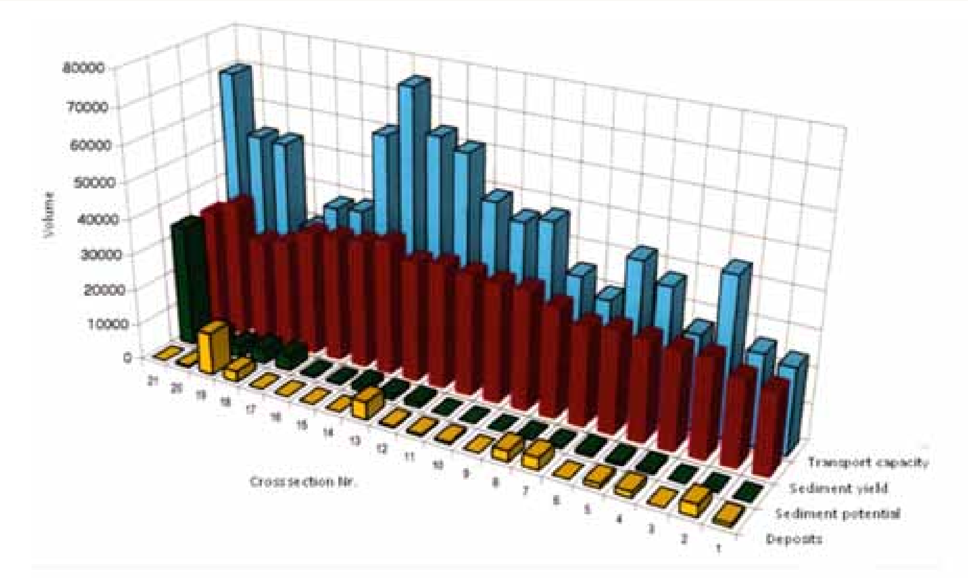


Figure 2.21 Sediment transport during a large event in the Guppenruns, canton of Glarus

So it is possible that a lot of material could be deposited at the fan (cross sections 2 and 1) and cause damage there. It was shown that planning a bed load deposit area near cross sections 8 and 7 together with further retaining measures (near cross sections 14 - 12) can drastically reduce the sediment yield of a large event which would practically prevent a possible damming of the Linth.

In Figure 2.22, the relation between water content and solid material shows, if there are any boundary conditions for debris flows surpassed. If the solid material exceeds 25 - 30% of total volume, the probability for debris flow is quite high. In the case shown above, the proportion solids to water does not exceed 10%, what means, it is quite unlikely that a debris flow might form along the channel.

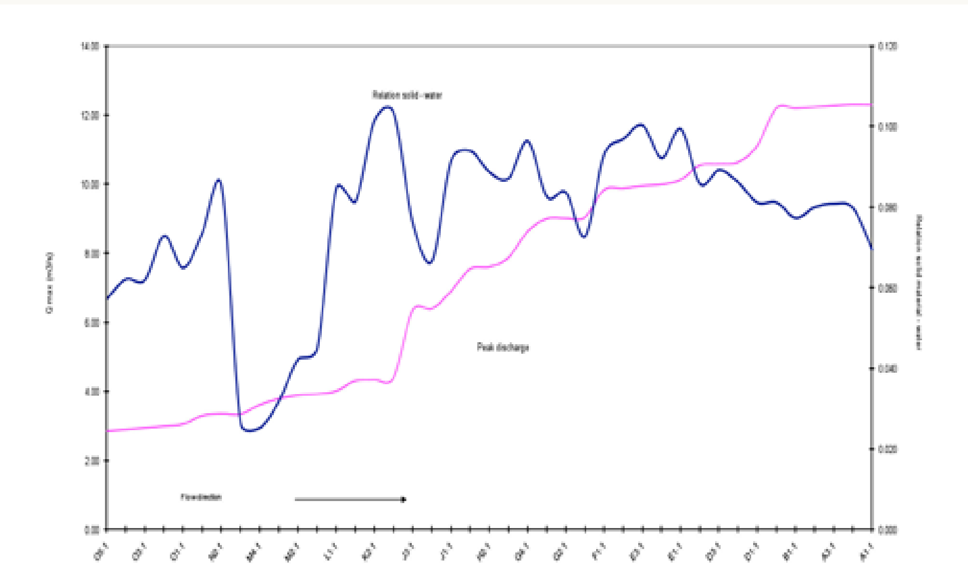


Figure 2.22 Relation between water content an solid material along a torrent.

2.6. Examples

In the following an application is demonstrated. Each case is usually concerned with a certain problem. Many cases require the design for sediment retention basins. Also the question whether a channel for water and transported sediment is large enough even in case of channel bed elevations is often to be solved.
The first example shows the evaluations for a project for sediment retention in the Lütschine river, Bernese Oberland in Switzerland.
In October 2000, a large flood event transported some 20.000 m^3 of material to the reaches of the small village of Stechelberg. Before undertaking some countermeasures, a study should investigate sediment yield in each of the tributaries and sediment transport of large flood events in the Lütschine river (Figure 2.23). The main question was to know if an event like the one of October 2000 could easily be repeated and what could be the river behavior in the future, especially regarding climate change.

In addition, a sediment retention basin had to be pre-designed. Therefore, various variations and scenarios of sediment input, channel width designs and channel gradient had to be calculated to find the most economical solution of sediment retention.

Example of bed evaluation in the Lütschine and in the Massabach

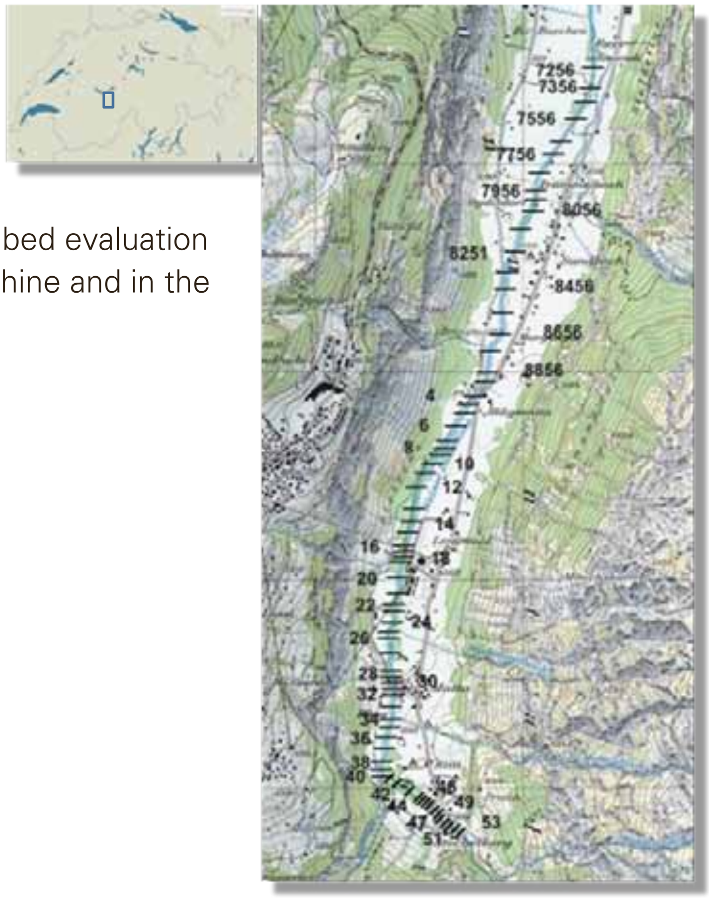


Figure 2.23 Location and cross sections for the sediment yield assessment in the Lütschine, Bernese Oberland

The sediment yield into the Lütschine is primarily caused by the torrents south of Stechelberg, depending on the distribution of local storms. A scenario which causes flood discharge at rare recurrence intervals in all torrents simultaneously into the Weisse Lütschine is rather unrealistic on account of the findings made in the study.
The greatest sediment load occurs when the two largest tributaries simultaneously transport material into the Weisse Lütschine.
Therefore, one must count for the future that large sediment transport comparable to the one of the fall 2000 event will occur again, but not every 10 to 20 years. A recurrence interval from available data is difficult to derive, especially considering effects of climate change. But events of a recurrence

interval of about 50 to 100 years depending on scenario will probably transport 20 - 30.000 m^3 of material or even more. On account of glacier withdrawals (uncovered debris cones), the frequency of the corresponding events would however increase in the future.

On account of the small transport capacity of the Weisse Luetschine, a high sediment load induces deposits by force. These deposits occur in different places along the Lütschine. Bed elevations caused by the deposits provoke flooding of neighboring settlements and cultivated land (Figure 2.24). Besides retention areas, which alone are not sufficient as protection measures, it was planned to support some natural deposit places in the river by application of technical measures, such as a reinforced local river widening, serving as a periodic sediment retention place.

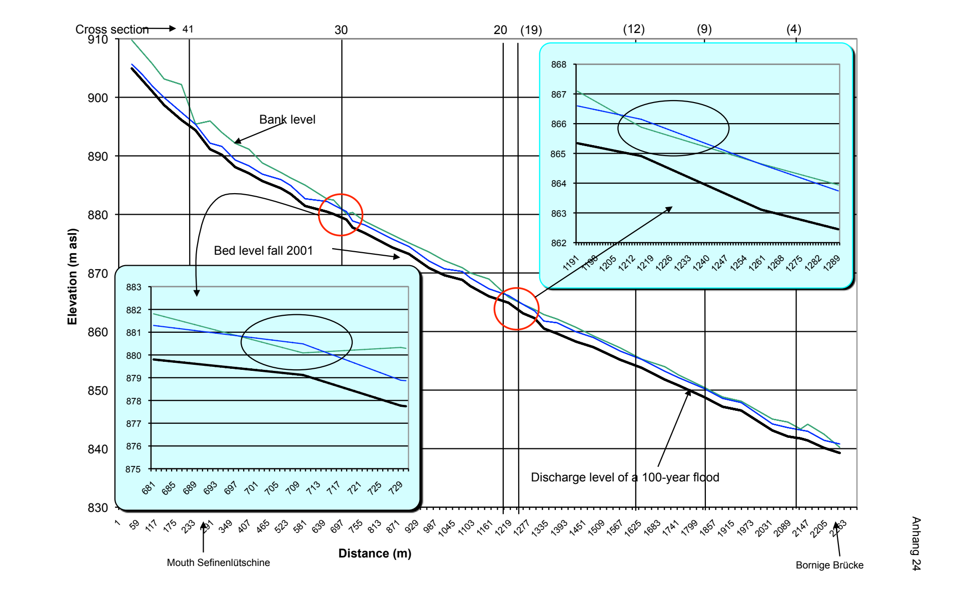


Figure 2.24 Bed- and water level in the case of an event of 100 year recurrence interval indicating potential places of river outbursts

For the retention basin, which should have been situated between cross sections 46 and 40 in Figure 2.25, the sediment volume had to be reduced as much as possible to prevent channel bed elevations due to further accumulations downstream at cross sections 23 - 10. Here material input had to be as low as possible because of the relatively low sediment transport capacity in this river section. The natural situation as shown in figure 2.25 proved that in the critical channel section between cross sections 23 and 10, the sediment volumes still are around 8.000 m^3, what is too high for the respective transport capacity and will cause accumulations and hence a channel bed elevation. The consequence would be an overflow because of the now insufficiently large cross section.

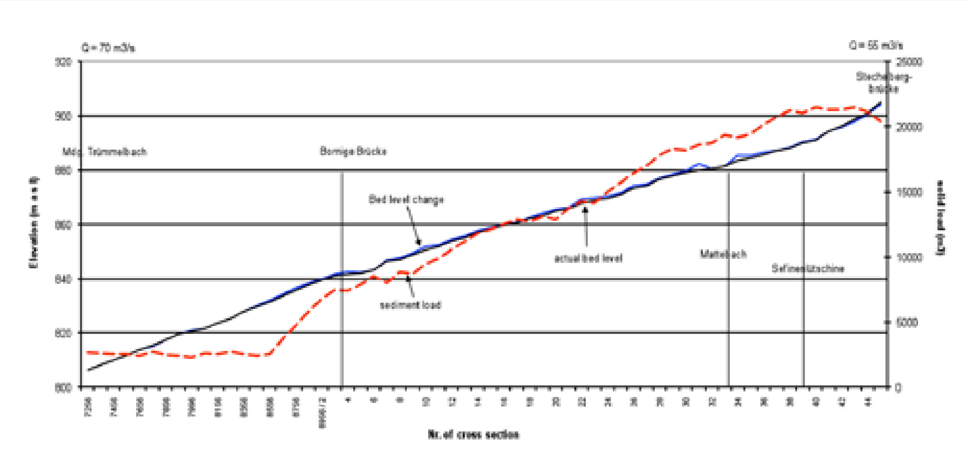


Figure 2.25 Assessment of sediment yield and bed level change in the Luetschine

Another example, the Grönbach Merligen at Lake Thun, Bernese Oberland, deals with the question of the total discharge of a debris flow (Figure 2.26). The debris flow's sediment volume for an event with a recurrence interval of 300 years and it's peak discharge was assessed by different assumptions. For the evaluation of possible debris flow discharges, the discharge hydrograph of the lowest cross section was used. This is actually not completely correct, since a debris flow develops further above, but the calculations should be on the safe side. The hydrograph was simplified as a simple triangle. Figure 2.26 can be interpreted as follows:

At the beginning of the discharge the sediment potential is still completely available (possible debris flow load = sediment potential at it's maximum, left side in the diagram, figure 2.26) respectable no material is transported yet (sediment load = 0). In accordance with rising discharge the sediments transport capacity increases, respectable the transported sediment quantity increases, therefore the maximal possible debris flow load decreases. If the peak discharge is reached, the debris flow cannot reach more than 15.000 m^3 of sediment reach, since a certain part of the potential is already removed. At the end of the hydrograph, theoretically still another debris flow can develop and move downstream, but only with very small magnitude (missing discharge!!). Due to clogging along the channel causing break-outs this is however possible.

For the determination of the peak discharge of the debris flow a sediment- water- relationship must be specified. According to literature, this relation can achieve up to against 10:1 (volume: specific weight of the mixture of approx. 2.5), but this is however not justified for the available case (low downward gradient in the lowest part of the torrent, many deposit possibilities etc.). Further on, this would result in a theoretical total discharge of nearly 500 m^3/s, already for the event with a recurrence interval of 100years!). The basis for the computations is therefore a solid-water relationship of 1:1. This results in a maximum discharge of 120 m^3/s for the 300-year event in the pessimistic case. However, the probability for such a scenario is very small. Particularly for the very rare 300-year -recurrence interval event, the probability that the debris flow meets the discharge peak just in the same time, even doubling it hereby, is very small. Moreover, this assumption lies outside of the dimensioning defaults for hydraulic measures.

120 m^3/s are therefore also quite unrealistic to assume, regarding the facts that there is a forest with stable trees as obstructions to a freely flowing debris flow discharge, and that no traces exist of older events of that magnitude.

Regarding figure 2.26, the total peak discharge of a debris flow might be more in the range of about 80 m^3/s, which still seems to be high, but not unrealistic as a short peak. The channel capacity in the settlement area is still not large enough to have a debris flow of this magnitude passed through. As the most promising countermeasure, a retention basin just upwards the settlement will break peak discharges and reduce sediment yield. As usual in mountainous areas, only little space is available for the construction of a retention basin at the fan apex.

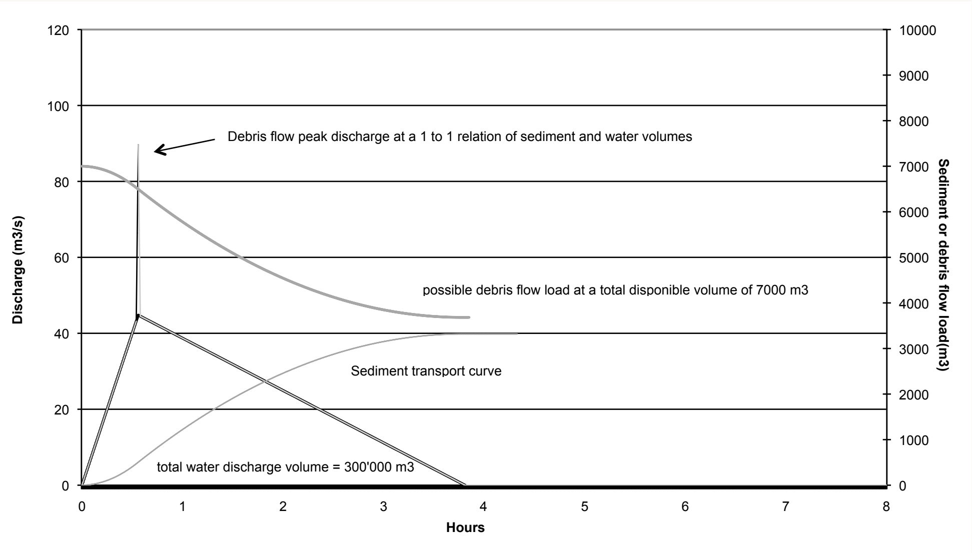


Figure 2.26 Debris flow load and peak discharge assessment for a debris flow in the Grönbach, Bernese Oberland

The retention volume of a possible bed load sedimentation place can be smaller due to the danger constellation for the settlement than the resulting sediment yield. According to findings from the danger map 10.000 m^3 can pass the channel practically without causing damage outside the channel. The retention volume of the basin can therefore correspond to approximately the difference of total sediment yield of 15.000 m^3 minus 10.000 m^3 passing the channel. The defaults of the Swiss federation require a protection goal adjustment for closed settlements by a recurrence interval of 100 years with limited protection on rarer events (BUWAL 1999, BWG 2001). Hence, a construction with approx. 5.000 m^3 might already serve his purpose for a majority of all cases.

2.7. Conclusion

The assessment of sediment yield for a specific event using the presented method can be systematized and is reproducible. The method makes it possible to record the sediment transport at practically any point in the channel and to determine the yield. Through variation of selected parameters, such as precipitation or sediment potential, it is possible to simulate various recurrence intervals and developments of an event. As well, the consequences of the expected sediment yield at the fan can be assessed. Further on, special questions like minimum channel dimensions or assumptions for debris flow peak discharge can be assessed. This leads to new possibilities for the planning and dimensioning of hydraulic engineering changes as well as for the elimination of danger zones.
The method has been tested on many examples and carried out in regions such as the Himalayan mountains and latin american volcanoes. It has been shown that the necessary investigations require a good understanding of the ongoing processes in a mountain stream and so should only be carried out by an experienced specialist.

3. Sediment delivery of alpine torrents - Process analysis and estimation method

By Eva Gertsch

3.1 Introduction

The debris evaluation process according to Gertsch (2009)[1] that is presented here was developed in Switzerland between 2004 and 2009 in the context of the dissertation project "Debris delivery of alpine torrent systems in the case of major events". The project was financed by the Federal Office for the Environment (FOEN) and by the Geographic Institute of the University of Bern (GIUB). Technical support was provided by the Group for Operational Hydrology (GHO), Particulate Material Division.

The research project strove toward two goals. The first goal, a contribution to a better process understanding of the bedload balance of steep torrent catchment areas, was achieved through the detailed analysis of 58 major events that had occurred in the Swiss Alps with recurrence periods ≥ 100 years. These newly acquired results formed the basis for the second goal, the development of a debris assessment process for practical use.

The following report, after a short introduction to the necessary bases for the process understanding, presents the new debris assessment procedure as an overview and strongly summarized. The goal is to give an overview for the development and to show the principal procedure. In order to implement it in specific cases, it is essential to consult the detailed dissertation.

In this report, Chapter 2 is dedicated to the theoretical background of the assessment procedure.
In Chapter 3, the technical data for the procedure are shown; in Chapter 4, the procedure is explained, starting from the application principle. Chapter 5 gives a brief overview of the specialties of the procedure.

In the report, the masculine form is used for all general personal statements. It is obvious that women are also meant thereby.

1 *Gertsch, E. (2009) Debris delivery of alpine torrent systems in the case of major events – Event analyses and development of an evaluation system. Inaugural dissertation of the philosophical natural sciences faculty of the University of Bern. Geographic Institute of the University of Bern. Download the dissertation in German: http://www.zb.unibe.ch/download/eldiss/09gertsch_e.pdf*

3.2 Theoretical background of a torrent system and relevant impact factors

3.2.1 The torrent system

Torrent systems are complex due to the great multitude of relevant impact factors and processes. To take this complexity into account, a system-based approach was chosen both for the evaluations of the major events being analysed and for the development of the debris assessment procedure.

A system includes a system boundary, multiple system elements and interactions between these system elements. Strong stress, moreover, can lead to triggering effects in unstable systems.

If these system characteristics are carried over to a torrent, the following system components are standard (cf. Fig. 3.1):

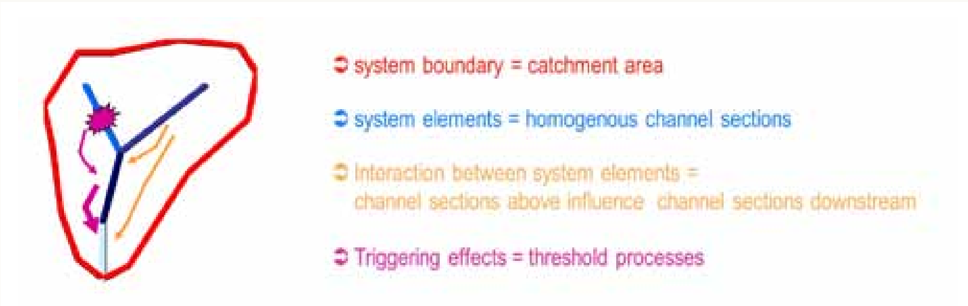


Figure 3.1 Torrent system

System boundary
In torrent systems, the system boundary is given normally above by the geographical boundary of the catchment area and below, in the case of bedload considerations, by the cone neck (cf. Fig. 3.1, red).

System elements
System elements are various homogenous channel sections (as regards median channel slope, loose material supply and drainage supply), inclusive of their adjacent slopes (cf. Fig. 3.1, blue).

Interactions between system elements
The homogenous channel sections correlate reciprocally. Thus, the interactions in the torrent system are one-sided and given by the topography.

Channel sections that lie higher in the catchment area affect channel sections that lie below them (cf. Fig. 3.1, orange arrows). Channel sections that lie lower affect the sections above them only in exceptional cases, namely in the case of retrogressive erosion. The highest channel sections (hereinafter called “first sections”) are not influenced by other system elements. All channel sections that do not lie at the highest point (hereinafter called “underlying sections”) are influenced by other system elements.

Trigger effect in the system
In connection with major events in torrent systems, the stability of this system is important. Major events are rare events with extraordinary event processes. Depending on the type of system, exceeding a threshold can cause a trigger effect that triggers new, worse and more extreme reactions within the system than under normal circumstances. Thereby the existing interactions between the system elements can be changed (cf. Fig. 3.1, violet arrows).

3.2.2 Relevant perspectives and impact factors of a torrent system

The investigations in the project have shown that the processes occurring during major events are strongly intertwined, spatially and functionally, and are interrelated. If the processes that play out in an individual system element (channel section) are to be understood and evaluated in an interconnected way and with sufficient regard for their complexity, various angles and impact factors connected to them in the entire system must be considered (cf. Ch.3.2.2.1 to Ch.3.2.2.3).

3.2.2.1 Characteristics of the system elements - local location factors

A first step is to consider the characteristics of the system element (channel section) to be understood.

Emblematically, the expert stands in the channel section to be evaluated, holds a magnifying glass, and observes the conditions in this subspace, the homogenous channel section, in a focused way. These conditions in the system element/channel section are referred to collectively with the term "local location factors". Relevant impact factors of this viewpoint lie both in the slope and in the channel.

These conditions in the system element/channel section are referred to collectively with the term **"local location factors".** The relevant impact factors of this viewpoint lie both in the slope and in the channel.

Figure 3.2 Local location factors

Impact factors in the slope

The normative impact factors of the viewpoint "local location factors" in the slope are:

- ***Slope angle:*** The angle of the slope is a very important impact factor for the disposition of slope processes, especially slides.
- ***Loose material and its characteristics:*** Both the geologic-tectonic qualities and the loose material characteristics exercise an essential influence on the occurrence and triggering of slides.
- ***Ground cover:*** The ground cover, especially forest, affects the slope stability through hydrologic and mechanical processes.

Impact factors in the channel

The impact factors of the viewpoint "local location factors" in the channel determine very generally the disposition for sediment mobilisation in the channel, but also over the debris flow capacity of the channel section. For this purpose, the following are normative:

- ***Supply of loose material:*** Only if mobilisable loose material is available in the channel can bedload be mobilised. Three classes are distinguished for the supply of loose material:
  Rock (R): Channel sections in solid bedrock, in which no mobilisable loose material is available.
  Limited loose material (LML): With limited loose material, there is a limited amount of loose material in the channel bed. However, the bedrock is not near the surface. One speaks in this case of "sediment-limited" conditions. Channel sections with transverse structures also belong to this category.
  Unlimited loose material (LMUL): Here there is a nearly inexhaustible supply of mobilisable loose material.
- ***Drainage supply:*** A sufficiently large discharge volume is a basic requirement for sediment mobilisation and transport in the channel. As a strongly simplified amount for the drainage supply, the area of the catchment area ACA [km^2] above the channel section can be seen as an impact factor. This is a strongly generalized amount of the area on which rain falls before and during an event and of the discharge arising from it.
  For smaller values, the the catchment area can have a limiting effect on the sediment mobilisation; one speaks of "discharge-limited" conditions. The small discharge volume is indeed able to mobilise bedload, but the transport capacity is limited and is not able to reach the total debris potential. Discharge-limited relationships occur in steep torrents mostly in the upper part of the catchment area or on flat stretches.

- ***Channel slope:*** *The channel slope J_{GA}* [%] is a normative factor for the topographic energy, from which the erosion power of the water-debris mix in the channel results. Smaller values mean a very limited flow power, which can lead to depositions. Large values fulfil the disposition toward erosion.

3.2.2.2 Interactions between system elements - Conditions upstream

In a second step, for underlying sections that can be influenced by other system elements, the effects of the system elements that lie upstream from the system element/channel section are clarified.

Emblematically, the expert stands in his own channel section, takes the binoculars out of the rucksack and looks out at the slopes and the channel of the upper catchment area (cf. Fig. 3.3).

The consideration of the upstream channel sections, which influence the observed channel section through various effects, is summarized under the term **"conditions upstream"**. These can be divided into erosion-limiting and erosion-supporting impact factors.

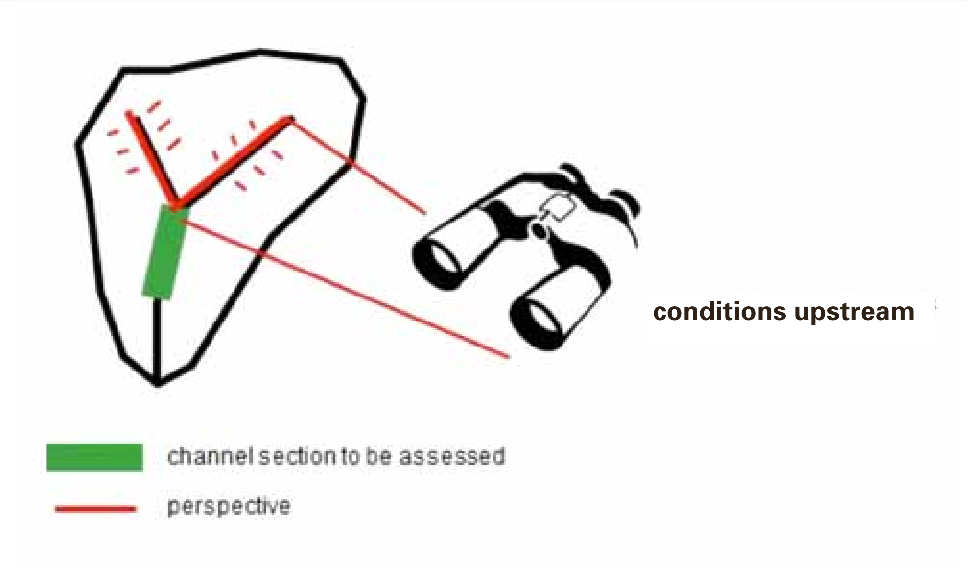


Figure 3.3 Conditions upstream

Erosion-limiting impact factors

- ***Flattening compared to upstream channel sections:*** Flattenings have a great influence on the transport capacity and can be considered important key points during major events. The transport rates are lower with lower slopes, and it can result in deposition processes. As a measure of such reductions in the transport capacity, the relationship of the channel slope in the channel section J_{CS} [%] to the channel section immediately above it J_{CSup} [%] can be chosen. If the slope remains the same, the ratio J_{CS}/J_{CSup} is equal to 1; with convex conditions it is >1, with concave conditions <1.
- ***Slope input in upstream channel sections:*** The amount of delivered material [m^3] from the slope in upstream channel sections is also an important factor. Large amounts of debris input from the slope can lead to the conditions in the outlet area of the slope processes in the channel to change from sediment-limited to discharge-limited instead, in that an inexhaustible sediment potential in the channel is created. The transport capacity is thereby fully reached at this location and is no longer available for the debris mobilisation in underlying channel sections.

Erosion-supporting impact factors

- ***Debris flow transport process from above:*** An important impact factor is the transport process that comes from the channel section immediately upstream. If a debris flow comes out of the upstream channel section, and if this can be transported further due to local location factors, greater erosion forces are to be reckoned with when only sediment is displaced from above by fluvial sediment flow. It is also decisive for the mobilisation of debris input from the sides through slope processes whether a debris flow or fluvial sediment flow predominates, since debris flows can mobilise significantly more loose material delivered from the slope into the channel.
- ***Channel confluences upstream:*** If two channels converge with one another, an underlying channel section receives an increased discharge supply, which can lead to increased erosion force with unlimited loose material supply. The further down in the catchment area these confluences are, the greater their influence can be. This applies especially when the partial catchment areas of the

individual channels are similar in size and have a similar form, since the discharge peaks during a major event can thereby occur at roughly the same time.

- ***Erosion force from above:*** Very simply put, in torrent systems, bedload is mobilised by the conversion of potential energy (topographic energy) of the water-sediment mix to kinetic energy (speed) and heat energy (through friction). The speed is chiefly responsible for the mobilisation of sediment in the channel. Great speeds mean great erosion force. During the erosion of bed material and through the transport of sediment, larger portions of the topographic energy are converted to heat and friction rather than speed. By contrast, in steep, rocky channel sections that are strongly sediment-limited and where the bed is not very rough, the proportion of topographic energy converted to speed rather than heat is comparatively larger. This effect is comparable to a smooth slide on which things can slide down faster than on a rough surface with a similar slope. The result is that in steep, rocky channel sections, high speeds can build up and downstream from such channel sections, greater erosion force is available, which can cause especially great channel erosion. The situation is similar, but in significantly lower amounts, after deposition stretches. Sediment is left behind, and thereby the friction loss is lowered in favour of speed.

  As a simplified value for this phenomenon, the local energy index $E\text{-}I_{CS}$ was developed. It describes per channel section these "erosion force-building" or "-diminishing" relationships and is calculated from the factors of loose material supply, angle and length of the channel section. In steep, sediment-limited channel sections in which high speeds can build up, the local energy index $E\text{-}I_{CS}$ is positive. In erosion sections in unlimited loose material, in which greater proportions are converted by friction to heat rather than to kinetic energy, it is negative.

  Now normative for the viewpoint "Conditions upstream" is the summing up of the local energy indices $E\text{-}I_{CS}$ of the upstream channel sections along the channel until the entrance into the channel section is to be evaluated. The value for this summary is the accumulated energy index $E\text{-}I_{acc}$. The larger the value of the accumulated energy index $E\text{-}I_{acc}$ becomes, the greater is the speed in a channel section and thereby also the free transport capacity. The smaller the value of $E\text{-}I_{acc}$ is, the slower the speed and thereby the more strongly diminished is the transport capacity. If a high accumulated energy index $E\text{-}I_{acc}$ enters a steep channel section in unlimited loose material, it can cause an especially high erosion force.

3.2.2.3 Trigger effects in the system - Negative factors

A third step deals with considering the slope and channel sections both in the system element/channel section and those that influence/lie upstream from the system element with regard to potential trigger effects.

Emblematically, the expert stands in the channel section to be evaluated. After he thinks he knows the functioning of this system through the previous reflections, he searches out special locations and configurations that hide in themselves the potential for trigger effects (cf. Fig. 3.4). It is helpful for this purpose for him to make cross-comparisons to major events that have occurred in his past experience.

The consideration of such potential trigger effects that can move the system toward another reaction is summarized with the term **"negative factors"**.

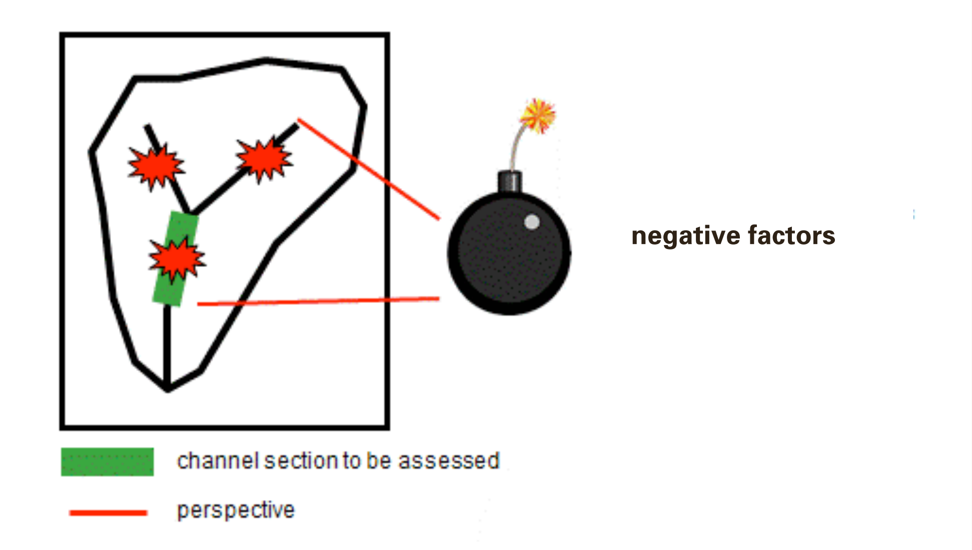


Figure 3.4 Negative factors

Negative factors are special configurations or processes that, as a rule, lead to triggering particularly large and destructive debris flows. They can lead to extreme erosion forces both in the channel section in which they have their source and in underlying channel sections. Negative forces act as threshold processes in the overall torrent system. The mobilised debris loads can thereby be increased many times over.
In the research project, eight negative factors were defined. They can be divided into four each of "sediment-affecting negative factors" and "discharge-affecting negative factors."

Sediment-affecting negative factors
Negative factors that affect sediment are characterized by the fact that they set a large sediment yield in motion in a small space on the slope or in the channel, thereby triggering a debris flow. The requirement is a steep jam horizon made of rock, ice or loose material that has a layer of a strong loose material deposit. The triggering can occur through a water oversaturation of the loose material deposit, through soaking currents between the jam layer and the loose material deposit or through a combination of the two. The following 4 sediment-affecting negative factors were defined (cf. Tab. 3.1).

Discharge-affecting negative factors
Discharge-affecting negative factors distinguish themselves through an extreme discharge that is strongly concentrated with regard to space and/or time and that can arise through various causes: Special channel network geometry, outbreaks of floodwaters, temporarily jammed water or a discharge input from outside the system boundary through underground waterways. The 4 negative factors thus defined are (cf. Tab. 3.2):

3.2.3 Combination of the impact factors

In Chap. 3.0 to Chap. 3.2.2, the impact factors of the various viewpoints were presented individually. Torrent systems are complex, however, and the impact factors of all viewpoints to be considered can be regarded only in their combination and in their complex interplay. Normative for the type and the extent of the ongoing debris processes in a channel section to be evaluated is the combined effect of all impact factors of the three viewpoints in the system. Every channel section thereby experiences a unique combination of impact factors and is therefore to be considered as an individual.

In this way, the various impact factors can mutually:
- ***combine:*** The erosion force from a debris flow in a channel section with a high channel slope in loose material (local location factors), for example, is amplified by an increased accumulated energy index (conditions upstream) due to a steep rock stretch above the section.
- ***compete:*** For example, if a flood wave occurs due to the breakout of a water pocket in a glacier (negative factor), its erosion force can be weakened under certain circumstances by the low channel slope in the very flat glacial forefield (local location factor).
- ***inhibit:*** A destructive debris flow can indeed come down into the channel (e.g. due to a negative factor), but if the bed consists of solid bedrock (local location factor), no erosion is possible.

The above examples show the complex interplay of the various impact factors. It also becomes clear that the various impact factors do not have the same weight in every situation or combination.

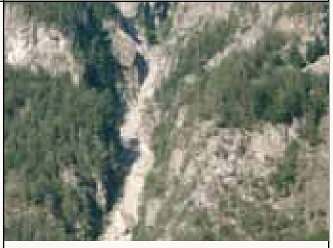
Slight fissure in bastion moraine (BM) Debris flow trigging on the front of a steep bastion moraine: During the mobilisation, soil liquefaction takes place in the water-saturated moraine deposit up to the jam horizon of ice or loose material. Due to the steepness of the initial phase, it may combine with slide processes along the jam horizon. The requirement is a steep bastion moraine in the glacier forefield with a steep jam horizon of dead ice, permafrost or consolidated loose material in the moraine body. The triggering occurs after long-lasting intensive precipitation and is usually limited to the summer and early fall months.	 *Photo: Flotron AG Meiringen*
Slight fissure in defrosting permafrost (PF) Debris flow triggering in the active defrosting layer of a permafrost area: The mobilisation consists of a soil liquefaction of the water-saturated defrosting layer of the permafrost from the jam horizon at the border area to the frozen underground, possibly combined with slide processes along the jam horizon. The requirement is a steep scree slope in the permafrost area with an active defrosting layer and connection to a channel. The triggering occurs via long-lasting intensive precipitation and is usually limited to the summer and early fall months.	 *Photo: Geotest AG and belop gmbh*
Removal at steep, more resistant jam horizon in channel (AS) Debris flow formation through removal of a thick loosely deposited loose material layer at a steep, more resistant jam horizon from bedrock or loose material in the channel. Various mechanisms come into question as the mobilisation process. Soil liquefaction of the loose material deposit and progressive erosion at the surface, but also a seeping out of the water in the loose material body and reappearance at the lower end of the rock couloir with debris flow formation through retrogressive erosion. Apparently, the triggering of the whole process is supported by smaller gliding processes along the jam layer. The requirement is a steep (>60%) channel that is several meters wide, either a rock couloir that is filled with a thick loose material layer or a channel in loose material that has an impermeable layer of loose material underneath (e.g. consolidated moraine material). The triggering can occur either with long-lasting precipitation (possibly combined with intensive snowmelts) or with storms with strong preceding soil moisture.	 *Photo: Eva Gertsch*
Spontaneous discharge of a major slide (MS) Debris flow formation through a spontaneous discharge of a slope slip with a volume > 20,000 m^3: The mobilisation in the slope occurs through a water oversaturation of the loose material body, concentrated water seepage or intensive soaking currents of slope water and thereby a reduction of the shear stability. The movement occurs along the glide surface in the channel. There either the debris flows stream directly in the channel as a mudslide or a blockage of the channel cross-section occurs and thereby the process becomes the negative factor "logjam." The requirement is slopes with an angle between 20° and 45° with direct connection to a channel, which has from formation on a powerful layer of loose material on a significantly structured glide surface of bedrock or loose material. The triggering occurs after long-lasting intensive precipitation, mostly supported by a high soil moisture beforehand and/or strong snowmelt.	 *Photo: Eva Gertsch*

Table 3.1 Sediment-affecting negative factors

Breakout of floodwaters (FW) Spontaneous breakout, independent of precipitation, of above-ground or underground jammed water and thereby formation of a floodwave: Due to the spatially and time-wise strongly concentrated discharge, a debris flow formation is possible, but not necessary. In this case, a debris flow formation due to soil liquefaction is not necessary in the channel section in which the floodwaters break out, but under certain circumstances only in the next underlying section that fulfils the requirements for formation of a debris flow. Floodwaters could arise under various conditions: 1. Above-ground lake where the dams become unstable and break; the discharge is stopped by avalanche snow, ice or wood and suddenly breaks through; or a large amount of rock, loose material, ice or snow spontaneously falls into the lake from the slopes on the sides. 2. Other impoundments of water (e.g. in glaciers in the form of water pockets, subglacial lakes or at the wall base of rock walls through avalanche snow or ice) that break out suddenly due to the hydraulic pressure. The triggering occurs independently of precipitation.	 *Photo: Stefan Zingg*
Concentrated exit of fissure water (KW) In the case of long-lasting intensive precipitation, the storage areas in complex fissure systems can fill up strongly, which can temporarily lead to changed underground water currents and to concentrated fissure water exits at the surface. These exits form an additional discharge input both locally at the exit point and in the system as a whole. The mobilisation of sediment and potential formation of a debris flow mostly does not occur directly in the channel section in which the fissure water exits in concentration, since these often lie in the area of rock bands that serve as a jam horizon. The debris flow formation often occurs only in the next underlying section that fulfils the requirements for a debris flow triggering based on its local location factors. The triggering occurs after long-lasting intensive precipitation.	 *Photo: Obwalden Canton Police*
Confluence of multiple channels at one point (3HG) A special configuration based on the water network is given when multiple (>2) channels flow together at one point into an actual main channel. Thereby a sudden multiplication of the discharge occurs locally, which can lead to a major debris flow in unlimited loose material. The debris flow triggering due to soil liquefaction and mobilisation occurs directly at the point at which the channels converge. Due to the suddenly much higher discharge, a step between the individual supply channels and the combined main channel can form after the debris flow formation. The requirement is a channel network with common confluence of more than two channels at one point in unlimited loose material. The more similar in size and form the catchment areas of the individual channels are the stronger effects this phenomenon can have. The triggering is possible both during storms and during long-lasting intensive precipitation.	 *Photo: Flotron AG Meiringen*
Breakthrough of a logjam (LJ) If the channel is blocked during an event due to a jam of snow, ice, wood or loose material, the water masses build up behind this blockage and an increase in the hydraulic pressure occurs. If this pressure becomes too great, a sudden breakthrough of the jam can occur. In the case of a sudden breakthrough, the onrush of the floodwaters that have broken through mobilises both the blockage and bed material from the channel and flows on as a debris flow. The requirement is a blockage of the channel during a high water event and the existence of a larger backup area in the channel. The triggering can occur both during storms and during long-lasting intensive precipitation.	 *Photo: Eva Gertsch*

Table 3.2 Discharge-affecting negative factors

With the development of the debris assessment procedure presented in Chap. 3.3 and 3.4, an attempt was made to take these complex relationships into account. It was defined on the basis of the extensive analyses of major events that occurred at the most varied thresholds and limit values that cannot be exceeded with certain impact factor combinations. These formed the calibration basis for the debris assessment procedure.

3.3 Technical data regarding the debris assessment procedure

3.3.1 Development and validation

The debris assessment procedure presented here was developed from 58 major events that occurred in the time frame from 1987 to 2005 in the Swiss Alps and that were analysed in detail. It was validated by 20 further past major events on one hand and on the other hand by 23 evaluations of debris loads that were carried out during danger assessments.

3.3.2 Target audience/users

The target audience for application of the debris evaluation procedure are experts from the practice (geologists, geomorphologists, engineers) who are confronted with debris assessments in torrents in their daily work. Because the debris assessment process, especially for scenario building, requires an active approach and thought process, a certain level of experience and an existing process understanding is essential for users and is the basic requirement for a successful application.

3.3.3 Statements and area of applicability

With the debris assessment process, bedload balances in channel sections as well as the total debris load at the cone neck of steep torrents can be evaluated depending on specifically defined scenarios for major events. A major event is defined as an event with a recurrence period of ≥ 100 years.

The process can be used in pre-alpine and alpine torrent systems with an area of the catchment area < 10 km² and a median channel slope of > 10%.

3.3.4 Statement accuracy and duration of the execution

The debris assessment procedure can basically be carried out at two different processing levels, the "desk-based procedure" and the "field-supplemented procedure." They differ in the required time expenditure for execution and in the accuracy of the statement (cf. Tab. 3.3 and also Chap. 3.4.2).

	Processing depth/Procedure	
	Desk-based	**Field-supplemented**
Duration of execution	2 hours	2 days
Statement accuracy	Danger index map grade	Danger map grades

Table 3.3 Execution time and statement accuracy of the procedures

3.3.5 Requiered software

The extraction of the required input data for the execution of the debris assessment procedure occurs ideally with GIS. Advantages of this software are that individual work steps can be automated and that the processing time is thereby reduced. In principle, however, the input data can also be gathered conventionally and without GIS.

The execution of the debris assessment can be carried out by hand, using the evaluation matrices below. However, to enable an efficient and reasonable application, a Microsoft Excel table calculation template was programmed, with which the evaluation is largely automated.

3.3.6 Transferability to other mountainous regions

The debris assessment procedure was developed and tested from major events in the Swiss Alps. An application in the neighbouring alpine countries is apparently possible in principle.

Due to the system-based process as well as the process-oriented setup, the debris assessment procedure can also be carried over to mountainous areas on other continents in principle. However, a calibration for these mountainous areas is necessary. Differences exist, especially climatic (precipitation) and geological (type, amount, and properties of the available loose material). It is also conceivable that additional negative factors are possible in other mountainous areas. Before an application of the debris evaluation process in another mountainous area, therefore, it would be imperative to carry out tests and further investigations.

3.4 Debris assessment process

3.4.1 Overview of the work steps

A flow chart of the debris assessment procedure is shown in Fig. 3.5. The individual work steps are described in detail below. Here a rough overview is given first.

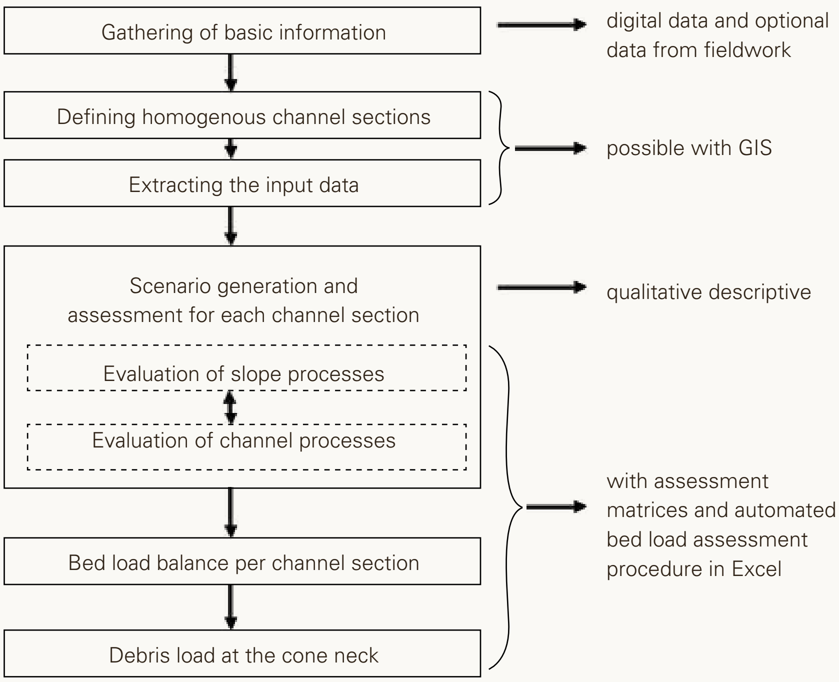


Figure 3.5 Flow chart of the debris assessment procedure

In a first step, the basic information gathering occurs, which takes a different form depending on the planned process or degree of detail of the debris assessment. Then one has to define and mark off the debris-relevant channel sections. Next, the required input parameters are extracted per channel section. Then the user has the task of creating and defining possible event scenarios. These are then processed per channel section with the help of various evaluation instruments for the slope processes and for the channel processes. From these occurs a quantitative evaluation of the bedload balance per channel section. Finally, the bedload balances of all channel sections up to the cone neck are summed up, resulting in an evaluation of the debris load at the cone neck (cf. Fig. 3.5.).

3.4.2 Gathering of basic information

For the gathering of basic information, all existing information regarding the catchment area is gathered and supplemented with the expert's own research and records.

On one hand, information is needed for scenario building. This information includes an event cadastre of the catchment area, which provides important indicators of processes already observed in the torrent in question. Interviews with residents and people who know the area can occur as a supplement, since these can contain valuable information and observations.

On the other hand, information is needed for debris assessment. Here the information gathering is oriented toward the planned method, or in the end effect toward the desired statement accuracy and the available financial means. **Required basic information and statement accuracy in connection with the method.** The required basic information is presented in Tab. 3.4.

	Method	
	Desk-based	**Field-supplemented**
Required basic information	**From digital base data:** • Basic map information • Aerial photo/orthophoto • Digital elevation model • Ground cover • Geologic information ↓	**From digital base data:** • Basic map information • Aerial photo/orthophoto • Digital elevation model • Ground cover • Geologic information **SUPPLEMENTED WITH FIELD RECORDS:** • Probability of mobilisation and potential delivery volumes from slope processes • Loose material supply in the channel at all relevant channel sections • Local deposition points that are not visible in the digital elevation model • Gen. "silent witnesses" ↓
Statement accuracy	**Danger index map grade**	**Danger map grade**

Table 3.4 Required basic information and statement accuracy in connection with the method

For the desk-based method, the entire processing occurs exclusively based on digital input parameters without supplemental fieldwork. The statement accuracy is thereby limited to the danger index level. The results of the debris assessment are not sufficient to form a basis for a danger assessment in the context of danger maps or dimensioning of protective structures in this case, since they do not meet the minimum level of detail needed.

For the field-supplemented method the digital input parameters are supplemented by field records, which significantly improves the accuracy of the statement. For this purpose, records regarding triggering probability and expected debris entry due to slope processes must be made in the terrain. The loose material supply in all of the channel sections is documented. Potential local deposition stretches are also located. In this case, statements at the level of danger maps can be made with the debris assessment procedure. The evaluated debris loads can thus be used as the basis for a rough danger mapping. For the planning of protection plans and protection structures, the evaluations offer important basic information, but as a rule, more extensive, detailed processing or investigations are needed.

3.4.3 Defining homogenous channel sections

The definition of homogenous channel sections can occur from the digital basic data, ideally using GIS. However, it is also possible without GIS.

First, the entire debris-relevant channel network is defined. After that, it is analysed from top to bottom with regard to potential boundaries of the channel sections. The criteria for determining a boundary of a channel section are:

- **Channel network:** When larger side channels converge, a channel section is bounded.
- **Channel slope:** When the ratio of the channel slope changes, a channel section is bounded. It should be noted here that to some degree the classes 0-10%, 10-20%, 20-40% and > 40% can be separated from one another.
- **Supply of loose material:** When the conditions of the loose material supply change, a channel section is bounded. These are differentiated into the classes LMUL (loose material unlimited), TS (transverse structures, blockages), LML (loose material limited) and R (solid bedrock).

Essentially, in a torrent system of < 10 km^2, a maximum of twelve channel sections should be marked off. In addition, apart from channel sections with a channel slope < 10%, no channel sections < 100 m in length should be marked off if possible. This limitation should have the result that one generalizes "generously" and focuses on the essentials. In the case of torrent systems with large catchment area sizes, this rule can lead to isolated side channels not being taken into account. The experience with event analyses has shown that with increased catchment area sizes, not all side tributaries are still active. The channel sections should then be numbered from top to bottom, i.e. such that channel sections with lower numbers always flow into channel sections with higher numbers.

3.4.4 Extracting the input data

After the channel sections are defined, the input parameters needed for the assessment procedure are extracted per channel section and processed in such a way that they appear in a list as input values. This can also be done using GIS. The required input parameters per channel section are:

- Channel section number
- Horizontal length l of the channel section [m]
- Area of the catchment area above the channel section at the highest point of the channel section A_{CA} [km^2]
- Loose material supply in the channel section, in the classes: Loose material unlimited (LMUL); structures, blockages (TS); loose material limited (LML); rock (R)
- Median slope J_{CS} [%] in the channel section
- Local energy index E-I_{CS} and accumulated energy index E-I_{acc}
- Ratio of the channel slope in the channel section to that in the upstream channel section J_{CS}/J_{CSup}

3.4.5 Scenario generation

In order to be able to work with the debris assessment procedure presented here, experts must first decide what event scenarios they would like to work through. For this purpose and this procedure, scenarios should be defined for major events with a recurrence period of ≥ 100 years.

"Due to the great multitude and complexity of the potential process occurrences, the danger assessment must be done by working with scenarios. Scenarios are representative for potential events and event sequences. In connection with natural dangers, scenarios serve to present a representative sample of possible dispositions, trigger conditions and processes and potential events and event chains. Scenarios mean simplification and limitation to the essentials. Scenario generation means in the first step a search for important potential event chains.
Despite good scientific bases, good evaluation and calculation models and technical helps, the clearest possible representations of the potential process flows are finally normative for the quality of danger evaluations. In other words: The quality of danger assessments stands and falls with the selection and consideration of adequate scenarios" (Kienholz et al. 2008[2]).

The expert should explicitly define multiple different scenarios and rank these intellectually as well as by expected yield. Here the considerations of potential negative factors receive special weight. These purely qualitative scenarios form the basis for the further work. In addition, a debris assessment is made per scenario, and for each channel section, the slope input into the channel as well as the type, process, and debris yield shifted thereby in the channel are quantitatively evaluated. The evaluation steps needed for this process are shown in the following chapters.

3.4.6 Evalutation of slope processes

3.4.6.1 Overview

For the evaluation of the slope processes, a quantitative evaluation of the debris volume that is delivered from the slope into the channel and transported further in the channel occurs for each channel

2 *Kienholz, H., Gosteli, H., Fässler, M., Aeberhard, S. (2008). Specialist technical analysis of the basic information regarding dangers. In: Bezzola, G.R., Hegg, Ch., eds. (2008). Event analysis of the flood of 2005, Part 2 – Analysis of processes, measures and basic danger information. Federal Office for the Environment (FOEN), Swiss Federal Research Institute for Forest, Snow and Landscape (WSL). Environmental Science No. 0825, Bern and Birmensdorf.*

section. For this purpose, the first step is to evaluate the yield delivered from the slope into the channel using field records and/or GIS queries (cf. Chap. 3.4.6.2). In the second step, the evaluation of what portion of this cubage from the slope can be transported further in the channel occurs (cf. Chap. 3.4.6.3). To do so, a slope evaluation matrix was developed that provides a mobilisation factor in the channel as a result. This is multiplied by the debris input from the slope (Chap. 3.4.6.2), and the result is the volume of debris mobilised from the slope in the channel section under consideration in m^3.

3.4.6.2 Determination of the cubage delivered from the slope
First, for every individual channel section, an evaluation occurs regarding the debris input from the slope into the channel.

For the "field-supplemented method," this evaluation is made on location. Thereby, evidence such as slides that had already occurred, small terrain forms, obliquely placed trees, tension cracks, wet spots, etc., are taken into account. The trigger probability and thereby delivered yield is determined by survey and implemented as input values in the evaluation procedure.

For the "desk-based method," this is not possible. The only evidence for the evaluation comes from the topographic maps, orthophotos and the event cadastre as well as queries and filters from existing digital basic data that describes the slope with regard to the "local location factors" (e.g. slope angle, loose material supply and distance from channel). Aids for such queries can be found in the dissertation (Gertsch, 2009).

3.4.6.3 Mobilisation of the slope input into the channel
After the cubage delivered from the slope into the channel section under consideration has been defined, the evaluation proceeds to the mobilization of this delivered cubage in the affected channel section. For this purpose, a slope evaluation matrix was developed (cf. Fig. 3.6 and Fig. 3.7).

3.4.6.3.1 Structure of the slope evaluation matrix
The slope evaluation matrix is divided horizontally into one evaluation block apiece per delivery yield class. The class limits lie at 1,000 m^3, 2,000 m^3, 5,000 m^3, 10,000 m^3 and 20,000 m^3 (cf. Fig. 3.6 blue). Per channel section, one such block is processed for the evaluation.

Vertically, the slope evaluation matrix is divided into two parts:
- In the left part, a rough estimation occurs (cf. Fig. 3.6, orange, and Chap. 3.4.6.3.2)
- In the middle to the right portion, a fine estimation occurs (cf. Fig. 3.6, red, and Chap. 3.4.6.3.3), the result of which is presented graphically with the evaluation line. At the bottom, there is a quantification block (cf. Fig. 3.6, violet), where the mobilisation factor appears as a result based on an evaluation line (cf. Fig. 3.6, green, and Chap. 3.4.6.3.3).

3.4.6.3.2 Rough estimation
With the estimation of the delivered cubage from the slope (cf. Chap. 3.4.6.2), the user selects the corresponding evaluation block in the slope matrix and carries out the evaluation of the mobilisation of the slope input in the channel section roughly for the moment.

The rough estimation regarding the mobilisation of the slope input in the channel section occurs in the left part of the evaluation matrix. For the rough evaluation regarding mobilisation of cubage delivered from the slope into the channel, the local location factors of the area of the catchment area A_{CA} and channel slope J_{CS} of the channel are needed. It is basically true that with larger catchment areas (= larger drainage supply) and a steeper channel, larger amounts of debris from the slope input can be mobilised in the channel. For this purpose, a specially adapted diagram was developed for each delivery yield class. The area of the catchment area A_{CA} is entered on the X axis and the channel slope J_{CS} on the Y axis. The corresponding values of the channel section are entered in the diagram. An initial rough estimation regarding mobilisation can be read from the diagram:

- In the **white** area, the conditions in the channel section, based on the channel slope and catchment area size, are so supportive of mobilisation that it can be assumed without further clarification that the entire volume from the slope is fully mobilised in the channel.
- In the **light grey** area, conditions are uncertain, and the rough estimation cannot state definitively whether the entire cubage can be mobilised in the channel or not. The fine estimation must there fore occur.
- In the **dark grey** area, the conditions of the channel slope and the catchment area size are limiting in such a way that, in principle, a partial mobilisation is to be reckoned with. How large this is must also be determined here with the fine estimation.

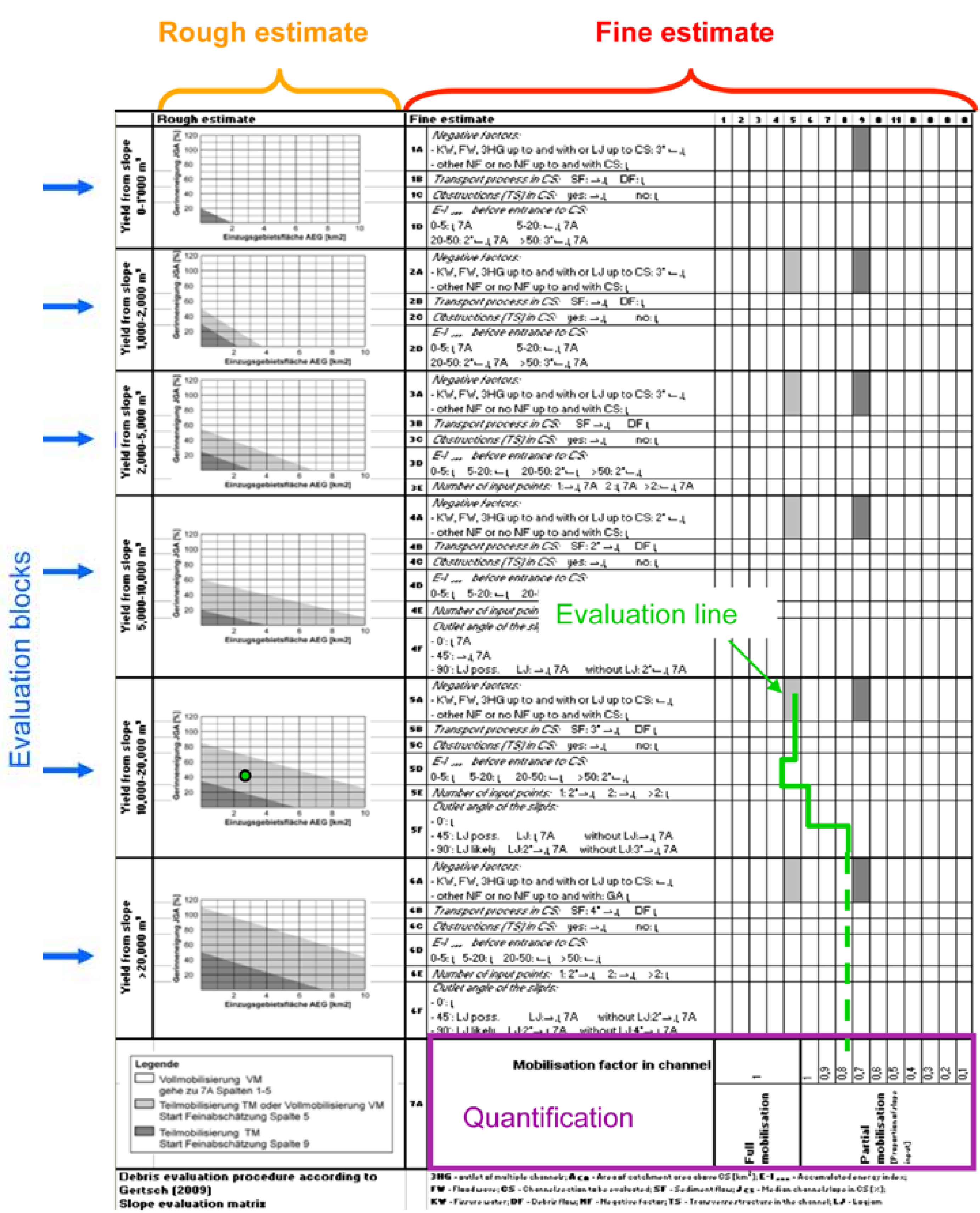


Figure 3.6 Overview of slope evaluation matrix

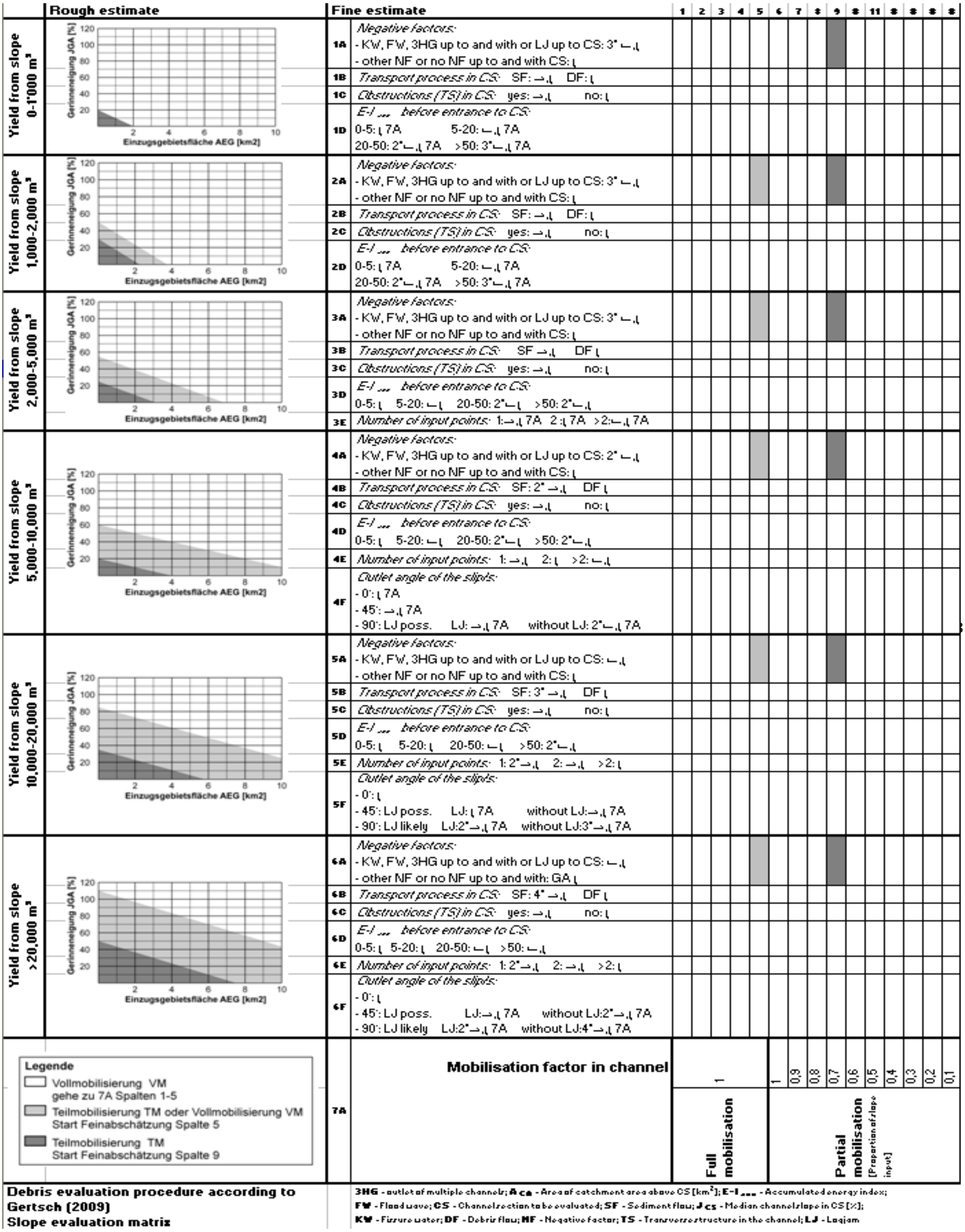


Figure 3.7 Slope evaluation matrix in detail

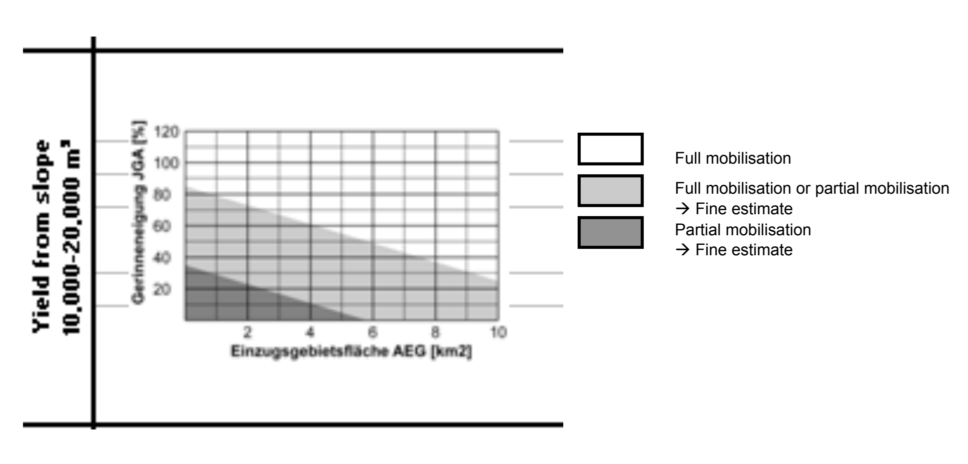


Figure 3.8 Rough estimation in the slope evaluation matrix

The limits of these areas are different for each yield class and shift upward with increasing yield volumes. In other words, for the same conditions regarding catchment area size and channel slope in the channel section, a full mobilisation is more likely to occur with a small debris input from the slope than with a large debris input.

3.4.6.3.3 Fine estimation

The fine estimation occurs on the middle to the right side of the evaluation matrix. It contains more lines per cubage-class block from the slope, in which the relevant impact factors affecting the mobilisation in the channel are incorporated as evaluation criteria (cf. Fig. 3.9). These consider the impact factors of the local location factors in the channel, conditions upstream and all predominant negative factors.
For the evaluation, the user works line by line and the result per line is graphically depicted with an evaluation line in the grid of the matrix (cf. Fig. 3.9). Depending on the evaluation, the evaluation line in the matrix shifts to the left, to the right, or not at all. These shift values are given in the evaluation criteria by arrows.→ means that the line must be moved 1 field to the right in the evaluation matrix, 3*→ three fields to the right. ↓ means that the evaluation line must be shifted one line down and thereby bypass the next evaluation criterion. Arrows to the left basically mean rather a full mobilisation of the slope input in the channel, arrows to the right rather a partial mobilisation.
The start cell in the evaluation matrix for the fine estimation depents on the result of the rough estimation. If the rough estimation lies in the light grey area, the start occurs more to the left (column 5), so more to the side of a full mobilisation. In the dark grey case, it lies further right (column 9), since already from the beginning one reckons with a partial mobilisation.

Overall, the following impact factors are considered and weighted:

- Discharge-affecting negative factors above or in the channel section: if these exist, they act more fully mobilising.
- Transport process in the channel of flows coming from upstream or formed by this slope process: debris flow transport is more fully mobilising, sediment flow more partially mobilising.
- Blockages in the channel: Due to the stepped length profile, these have a more partially mobilising effect.
- Accumulated energy index $E\text{-}I_{acc}$ in the channel section: High $E\text{-}I_{acc}$ values have a more fully mobilising effect.
- Number of input points of the slope input into the channel section: Division by space and time into multiple input points is more fully mobilising, individual slides more partially mobilising.
- Confluence angle of the debris entry from the slope compared to the channel axis: This has an effect on possible jams and thereby on the mobilisation. Jams are more fully mobilising, while the presence of no jams has a more partially mobilising effect.

It is important to note that both the number and the weight of the various impact factors vary by yield class. Whereas with small delivery yields the impact factors of channel slope, catchment area size, transport process, drainage-affecting negative factors and accumulated energy index $E\text{-}I_{acc}$ are most definitive, the delivery of larger volumes makes the impact factors of number of input points and confluence angle more important. This circumstance is considered in the evaluation in that not all impact factors are evaluated in every fine estimation of the various delivery yield classes and the shifting amounts to right or left, in the direction of full or paritial mobilisation, are not equally strong for every class.

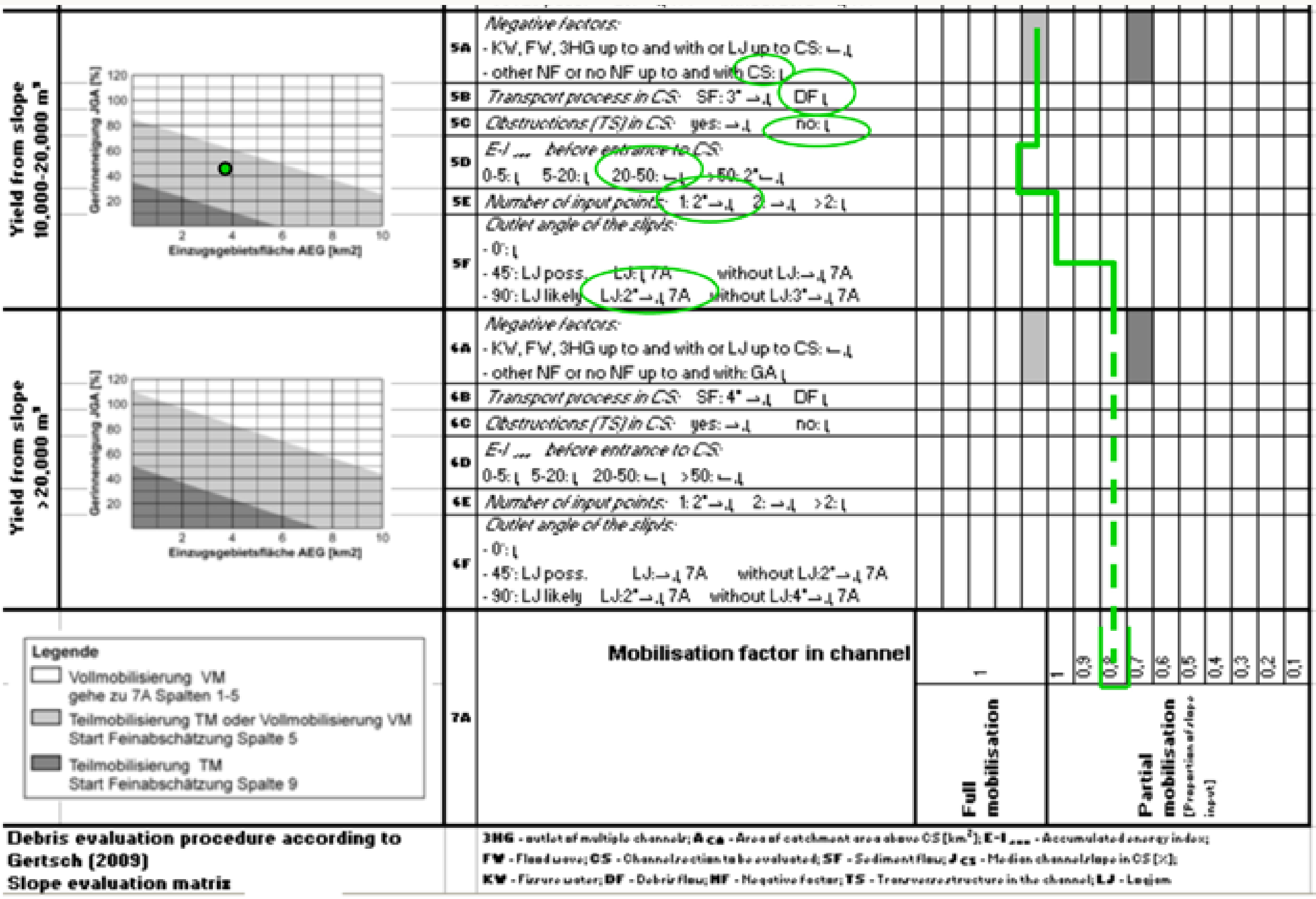


Figure 3.9 Fine estimation with the slope evaluation matrix

The further to the left one places the final evaluation line in the evaluation matrix, the more likely it is that the entire yield is fully mobilised in the channel. The result of the slope evaluation matrix is finally the mobilisation factor, which is needed for the quantification. It can be read at the end of the evaluation at the very bottom of the evaluation matrix. For a full mobilisation, the factor has the value 1. The entire yield delivered from the slope can be mobilised in the channel. For a partial mobilisation, the mobilisation factor determines the portion of the debris delivered from the slope that can be moved on in the channel.

3.4.6.4 Quantification

For the quantification, the mobilisation factor is multiplied by the yield delivered from the slope (cf. Chap. 3.4.6.1 and Fig. 3.9). The result is the debris volume mobilised from the slope in the channel section. If the debris input from the slope is 4.000 m^3, then, and the mobilisation factor in the channel is 0.8, 3.200 m^3 is mobilised in the channel.

3.4.7 Evaluation of channel processes

3.4.7.1 Overview

The evaluation of the channel processes also occurs per channel section. For this purpose, based on the defined scenarios, the eroded or deposited debris volume from the channel bed is estimated in m^3. This estimation occurs via a channel evaluation matrix, which is presented in the following chapters.

3.4.7.2 2 Erosion or deposition volumes per channel section

3.4.7.2.1 Structure of the channel evaluation matrix

The channel evaluation matrix is divided vertically into three parts (cf. Fig. 3.10):

- The left part is the evaluation portion and consists of four blocks with multiple lines for evaluation criteria. From these, individual lines are processed per channel section as needed (cf. Fig. 3.10, blue).
- The middle section contains supplementary tables, which are needed for the decision making for the evaluation in the left portion (cf. Fig. 3.10, orange).

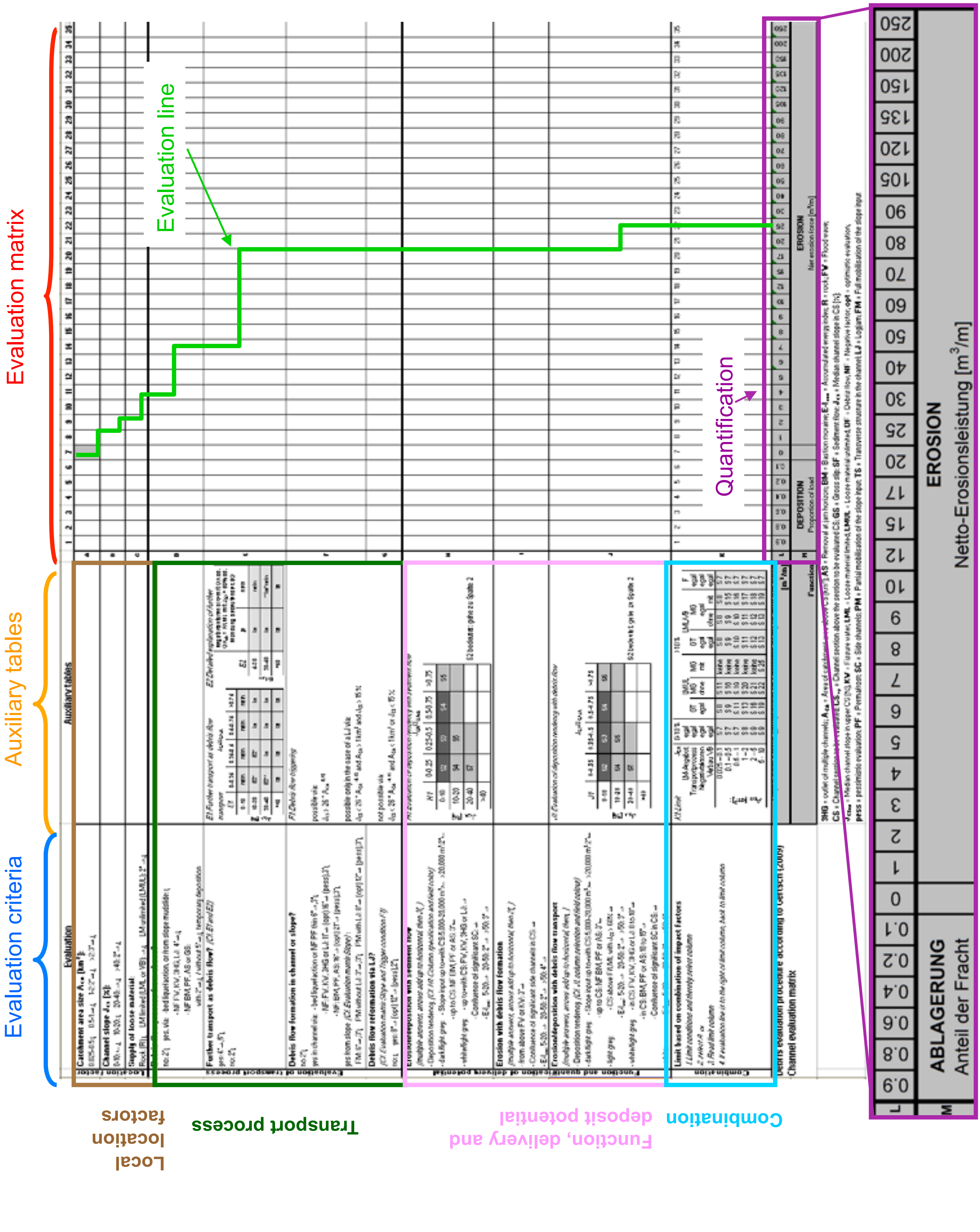


Figure 3.10 Overview of channel evaluation matrix

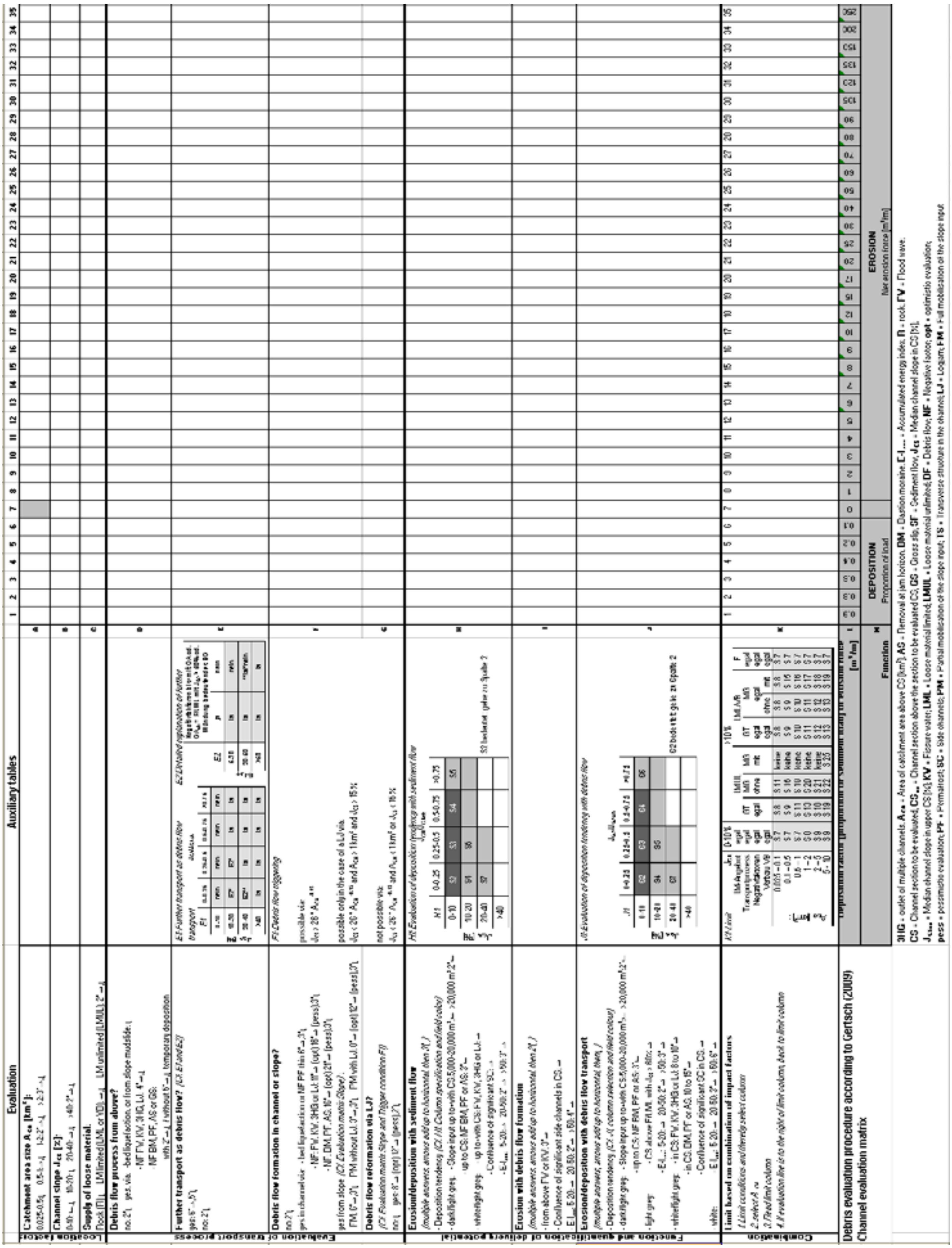


Figure 3.11 Channel evaluation matrix in detail

- The right part consists of the evaluation matrix, i.e. the graphic representation of the evaluation (cf. Fig. 3.10, red). For this purpose, an evaluation line documents the evaluation based on arrows for the evaluation criteria, according to the same principle as with the fine estimation of the slope evaluation. As a result, depending on the location of the end point of the evaluation line, a quantification of the expected erosion force or deposition ratio in the channel section occurs. The further to the right the end point of the evaluation line occurs on the evaluation matrix after the entire evaluation, the more erosion force occurs in the channel section. If the evaluation line is far to the left at the end, loose material is deposited, and the deposition factor is given (cf. Fig. 3.10, violet).

The evaluation blocks of the channel evaluation matrix, arranged horizontally and to be handled in different ways, contain in summary the following themes and aspects:
- Local location factors: The local location factors are integrated into the evaluation in the first block.
- Evaluation of transport process: In the second block, the transport process in the channel section is defined.
- Function and quantification of the delivery or deposition potential: In the third block, one evaluates for a given transport process which function the channel section has (erosion or deposition). Thereafter, the delivery or deposition potential of debris in the channel is evaluated.
- Combination: In the fourth block, the consideration of the impact factor combination occurs. If one of the important impact factors has such a strong limiting effect that it prevents or minimizes all the other impact factors, this can be identified here and the estimation can be adjusted.

For every channel section, an evaluation is undertaken and depicted with a separate evaluation line. In this process, the results of the slope evaluation matrix are incorporated into the channel evaluation matrix.

3.4.7.2.2 Evaluation of local location factors (Lines A through C in Fig. 3.11)
The evaluation of local location factors occurs on the basis of the absolute values of the input parameters area of catchment area A_{CA} [km^2] (Line A) and channel slope J_{CS} [%] (Line B) as well as the classification of the loose material supply in the channel section (Line C).

The assumption is that for increased catchment area size (= larger discharge supply), greater channel slope (= greater speed) and unlimited loose material supply, a higher disposition for erosion is basically to be reckoned with. The shift values for the evaluation line, which are also represented here by arrows to left (more deposition tendency) or right (more erosion tendency), are therefore directed the more to the right the higher values of A_{CA}, J_{CS} and LM supply apply for the channel section.

The start of the evaluation line in the evaluation matrix occurs in column 7. This is the "neutral" column, with which the state in regard to the quantification in the lowest block lies between deposition and erosion with an erosion force of 0 m^3/m.

3.4.7.2.3 Evaluation of transport process, function, deposition or delivery potential (Lines D through J in Fig. 3.11)
In the second and third block, the transport process in the channel section, the function during the major event and potential for deposition or delivery are determined based on the various relevant impact factors, considering all viewpoints (local location factors, conditions upstream and negative factors). Not all impact factors are always relevant. In addition, these can have a differing weight depending on the situation. Therefore, an evaluation catalogue (Lines D to J) was put together, from which answers must be given for the relevant criteria depending on the conditions in the channel section. Depending on the conditions in the channel section and on the scenario, the user enters the relevant evaluation criteria for the channel section or the relevant evaluation lines in the matrix. The basis of this selection of relevant evaluation criteria is the decision tree in Fig. 3.12.

The first question in the decision tree (cf. Fig. 3.12) regarding a "debris flow from above" (Line D in the channel evaluation matrix in Fig. 3.11) must be answered in every case. If this question is answered with "no," the question (Line F) regarding whether or not in any case a new debris flow can form in the current channel section presents itself. If "yes," the channel section is evaluated according to the erosion-supporting factors in the trigger line of the debris flow (Line I); if "no," according to the erosion-supporting or -limiting impact factors for sediment flow (Line H).

By contrast, if the first question (Line D) can be answered with "yes," the next question is whether the debris flow from above even can be transported further in the present channel section and whether it should be transported further (Line E). If yes, the evaluation of the erosion-supporting and -limiting factors for debris flow transport occurs in Line J. If no, a debris flow stop occurs in the channel section. If a "debris flow from above" stops in the channel section, this does mean that normally no new debris flow can be triggered in the channel itself; however, under certain circumstances, a new formation is possible due to a jam. This is explained in Line G. If no new debris flow formation is

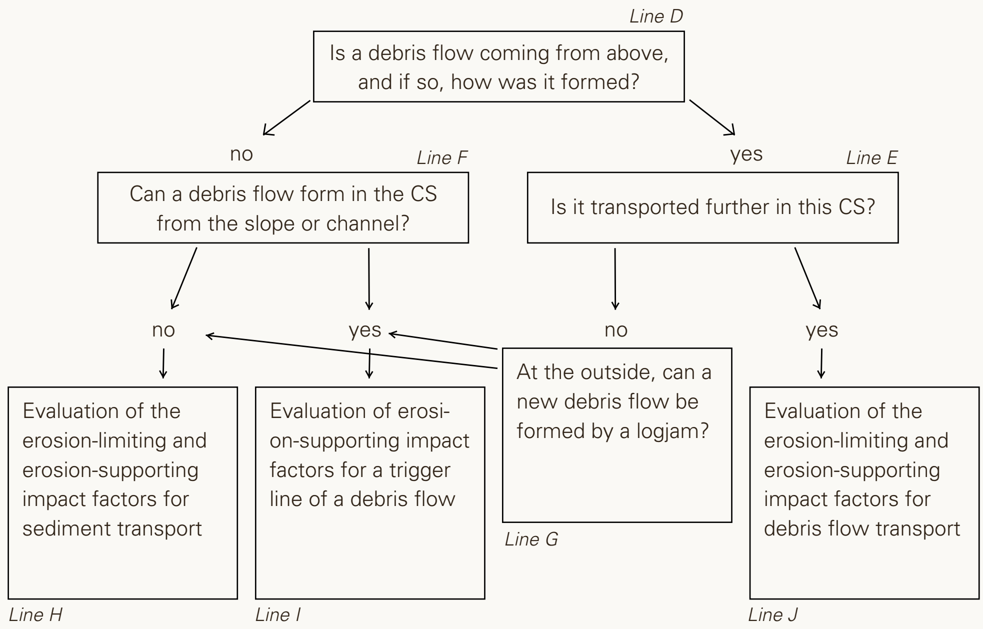


Figure 3.12 Decision tree as basis for selection of the relevant evaluation criteria (CS = channel section)

possible, the evaluation of the erosion-supporting and -limiting factors occurs for sediment flow (Line H). In the other case, the evaluation occurs for trigger lines of debris flows (Line I).
The user does not need to search out the relevant evaluation criteria himself by using the decision tree in Fig. 3.12; rather, in the channel evaluation matrix, he will be led directly to the next relevant question by the vertical arrows through his answers per evaluation criterion.

Below, the procedure in the individual evaluation lines of the entire catalogue is presented in sequence:

Line D - Debris flow process from above? (cf. Fig. 3.11 and Fig. 3.12)

The question in Line D is whether a debris flow comes from an upstream channel section (cf. Fig. 3.12). In the first sections as well as in underlying sections above which sediment flow dominates, this question is answered with "no." In underlying sections above which a debris flow was already formed, the answer is "yes." Then the mechanism by which this debris flow arose is requested from upstream. Three possible answers may be chosen. For the first option, the classical formation mechanisms of soil liquefaction or continuation from a slope slide are the trigger. In the second option, the triggers are the discharge-affecting negative factors floodwaters (FW), fissure waters (KW), multiple convergences (3HG) or blockage (LJ). In the third possible answer, the triggers are the sediment-affecting negative factors of bastion moraine (BM), permafrost (PF), clearance on jam horizon (AS) and major slide (MS). For these sediment-affecting negative factors, there is then a differentiation of whether there are temporary deposits made between the trigger point and the current channel section.
The assumption is that classical debris flows from soil liquefaction or from continuations from the slope have a lesser erosive effect than debris flows triggered by negative factors. Therefore, no horizontal shift is made in the evaluation matrix. For the debris flows triggered by negative factors, by contrast, there is a shift to the right, in the direction of stronger erosion force.

Line E - Further transport as debris flow? (cf. Fig. 3.11 and Fig. 3.12)

With the question in Line E, whether a debris flow coming from above can be transported further in the channel section under consideration is explained. The options "yes" or "no" are available to select as answers.Two supplemental tables were developed as a basis for the decision. They consider both the median angle of the channel section J_{CS} and the ratio J_{CS}/J_{CSup}, which gives evidence of flattening. The investigations have shown that a debris flow is better transported further the steeper the channel section is and the less flattening there is compared to the upper channel section. In uncertain cases, the additional impact factors of accumulated energy index $E\text{-}I_{acc}$, possible negative factors and confluences of significant side channels are requested. For high values of $E\text{-}I_{acc}$, negative factors and the confluence of a significant side channel, a further transport is to be expected in any case.
For a further transport of a debris flow, a shift occurs in the matrix to the right, in the direction of erosion.

Line F - Debris flow formation in channel or slope? (cf. Fig. 3.11 and Fig. 3.12)

If in Line D the question “Does a debris flow come down from above?” is answered with “no,” in Line F the evaluation follows regarding whether a new debris flow can form in the channel section to be evaluated and, if so, by what formation mechanism.

As an aid for deciding whether a debris flow triggering is even possible in the channel section, supplemental formulae are available that were developed during the investigations. These take into account the local location factors of median channel slope J_{CS} and area of the catchment area above the channel section A_{CA}.

Depending on the scenario defined by the expert, various formation mechanisms can be selected for the debris flow triggering in the channel, which mean various weights or shift amounts to the right in the direction of erosion. On one hand, the classical soil liquefaction with a small shift to the right can be chosen; on the other hand, one can choose system-tipping negative factors, which by definition cause especially erosive debris flow and therefore have a greater weight toward the right. Here one can also choose between an optimistic and a pessimistic variant.

For debris flow formation from the slope, the results from the slope evaluation matrix are transferred and distinguished according to the mobilisation in the channel: Fully mobilised (FM), partially mobilised with logjam (PM without LJ) and partially mobilised with logjam (PM with LJ). The logjam scenario effects a stronger shift to the right, in the direction of erosion.

Line G - Debris flow reformation due to logjam? (cf. Fig. 3.11 and Fig. 3.12)

If the question “Further transport as debris flow?” was answered in Line E with “no,” the debris flow stops. If a debris flow is stopped, the decline is so flat that in principle, no new debris flow can form from soil liquefaction or most of the negative factors in the channel. However, the investigations have shown that with such flat conditions, under certain circumstances, namely if a logjam forms in the channel and breaks through, debris flows can form nevertheless. In other words, if the conditions for a further transport as debris flow are only barely missed, the possibility always exists that a new debris flow can form due to a logjam. The conditions for this are predetermined in a supplemental formula. The user therefore has the options “no” or “yes” as answer options. For “yes,” an optimistic and a pessimistic variant can be selected.

Line H - Erosion-supporting and erosion-limiting impact factors for sediment flow (cf. Fig. 3.11 and Fig. 3.12)

If the evaluation result is that in the channel section, either no debris flow can form or a debris flow from above is stopped and cannot form a new flow due to a blockage, this means that in the channel section the transport process “sediment flow” predominates. The next question should now clarify which function in this channel section is to be expected (erosion or deposition) and how large the mobilisation or deposition potential is.

The evaluation is made regarding whether one must reckon with a tendency toward deposition or erosion. This occurs via a supplemental table. Through a comparison of the channel slope JCS with the ratio to the channel slope in the upper channel section J_{CS}/J_{CSup}, the first step evaluates the tendency of the function of the channel section. The flatter the channel section and the greater the flattening compared to the upstream channel section, the greater the deposition tendency. The greater the deposition tendency is, the further to the left the evaluation line shifts in the matrix. For erosion, the evaluation line remains at the original place.

For the delivery potential with erosion stretches, the normative impact factors are not the same as for the deposition potential. For this reason, a second step for the further evaluation brings in various impact factors depending on the result in the supplemental table:

- For the evaluation of channel sections with strong deposition tendencies, any erosion-limiting impact factors are considered in order to estimate the extent of the deposition.
- For channel sections that are in the grey area between deposition and erosion, both erosion-limiting and erosion-supporting impact factors are considered. Erosion-limiting impact factors draw the evaluation line to the left in the direction of deposition, while the erosion-supporting impact factors draw the line to the right in the direction of erosion.
- For channel sections in which only erosion is to be dealt with, the focus lies with the evaluation of the erosion-supporting impact factors. They all lead to a shift to the right in the direction of erosion. The more strongly they are pronounced and the more of these factors are active, the stronger is the shifting.

Line I - Erosion-supporting impact factors with debris flow triggering (cf. Fig. 3.11 and Fig. 3.12)

In channel sections in which a debris flow is triggered, no deposition tendencies dominate. For the evaluation of the erosion force, only erosion-supporting impact factors play a role. These include any floodwaters or fissure water exits that come from above and now lead to a debris flow triggering, confluences of significant side channels or increased E-lacc values. In Line I, these erosion-supporting impact factors lead to a shift to the right.

Line J - Erosion-supporting and erosion-limiting impact factors for debris flow (cf. Fig. 3.11 and Fig. 3.12)

In all channel sections in which a debris flow comes from above that can in principle be passed on in the channel section, the evaluation of the erosion-supporting and the erosion-limiting impact factors also occurs here now. The procedure and the supplemental tables are basically the same as those in Line H for the sediment flow transport process, so they will not be explained in more detail here. The difference from Line H lies in the impact factors and their weighting.

3.4.7.2.4 Evaluation of the impact factor combination (cf. Fig. 3.11)

In the channel section, only as much sediment can be mobilised as the most limiting impact factor of the impact factor combination allows. In the preceding assessment steps, the debris delivery potential was evaluated on the basis of a separate accumulated consideration of all individual impact factors. Now, however, one still has to consider their combined effect and to evaluate whether one of these factors combined with the other factors forms a limit that subjects the debris mobilization in the channel to a certain limit value. The most extreme form of such a limit is a channel section in bedrock. A strong debris flow can come down from above; the channel section can be extremely steep and the erosion supporting factors can be huge: where there is no loose material for mobilisation, nothing can be mobilised. However, there are also other, less obvious limits, e.g. based on the catchment area or the discharge supply. If in a channel section all requirements for the formation of a debris flow due to soil liquefaction are available, a very small catchment area and thereby a limited runoff leads to a modest erosion force due to its limited transport power despite the actual large potential for erosion. Such effects must be considered now in the fourth block of the evaluation matrix.

In this block, a supplementary table is used to consider the total impact factor combination. Through the evaluation of all relevant impact factors according to a firmly defined series, a limit of the erosion force that cannot be exceeded by the given combination of impact factors can be worked out. If the prior evaluation of the erosion force based on the separate consideration of the individual impact factors (evaluation columns A-J) is below this defined limit, the evaluation can be taken over as such. If, by contrast, it lies above this defined level, the evaluation must be corrected based on the combination of impact factors. The evaluation line is shifted to the left in this case, to the column of the erosion force defined in the supplementary table.

3.4.7.2.5 Quantification (cf. Fig. 3.11)

After the evaluation of the channel processes in the channel section, the quantification occurs. From the column in which the evaluation line occurs in the evaluation matrix according to Line K, the quantification follows in Line L. In the columns 1 to 6, the channel section lies in the deposition range, in column 7 in the transit range, and in columns 8 to 35 in the erosion range (cf. Fig. 3.13).

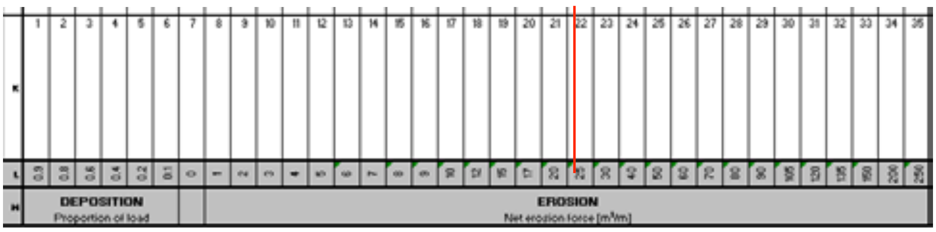


Figure 3.13 Quantification

In the deposition range, the deposition factor is used as the value for the quantification in Line L. The deposition factor lies between 0 and 0.9. It is the value for the portion of sediment from the debris load coming down from above the channel section that is deposited in the channel section. A deposition factor of 0.4 with a debris load from above the channel section of 10.000 m^3 means that only 4.000 m^3 of sediment is deposited in the channel section. For the bedload balance of the channel area in a deposition section, the total debris load from the upper channel sections must be known and multiplied by the deposition factor.

In the transit and erosion area, the erosion force m³/m is used in Line L as the value for the quantification. In this case, the value reaches from 0 to 250 m³/m. To calculate a bedload balance in the channel, this value must be multiplied by the length of the channel section. If the erosion force is thus 12 m³/m and the channel section is 230 m long, the sediment volume mobilised from the channel bed in the channel section is 2,760 m³.

3.4.8 Bedload balance per channel section

For the bedload balance in the channel section, the slope input calculated with the slope evaluation matrix and mobilised in the channel and the erosion amount or deposition yield calculated from the channel evaluation matrix are added. In the case of deposition, the balance is negative; for erosion, it is positive.

3.4.9 Debris load at the cone neck

Now one has to add these bedload balances of all channel sections up to the cone neck. Then the evaluation and quantification for the selected scenario is completed and the debris load at the cone neck is known.

It is recommended to calculate further scenarios. In so doing, both optimistic and pessimistic scenarios should be calculated. Doing so gives a limitation on the bandwidth of potential event loads. For the final tally of the debris load at the cone neck, it is advisable to round roughly or even to give the debris load in a range. Doing so avoids a precision of the evaluation becoming fictitious through very exact numbers that do not exist as such.

3.4.10 Automated evaluation process

The work steps for the quantitative evaluation of the scenarios using the evaluation matrices for the slope input and the channel processes and the pulling together for the bedload balance per channel section and debris load at the cone neck were automated with a simple programming in Microsoft Excel. This enables a quick, comprehensible and largely automated application.

Eingabemaske

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Szenariobeschrieb:	SZP, Murgänge und Hangprozesse
Bearbeiter/in, Datum:	Eva Gertsch, 18.11.2008
Anzahl Gerinneabschnitte:	6
Vorgehensweise: GIS Raster Feld-ergänzt "1" GIS-Vektor Feld-ergänzt "2" GIS-Raster Schreibtisch-basiert "3" GIS-Vektor Schreibtisch-basiert "4"	1

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11	1	0					3	0.0151	3	1296	885	433	48.9	985.248	1				#DIV/0!	#DIV/0!
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13	3	2	1	2			4	0.1387	1	863	726	132	18.2	737.902	0.4				#DIV/0!	#DIV/0!
14	4	1	3				5	0.3394	1	731	115	11	9.6	115.525	0.5				#DIV/0!	#DIV/0!
15	5	1	4				6	0.3456	1	720	131	23	17.6	133.004	1.8				#DIV/0!	#DIV/0!
16	6	1	5				Kegelhals	0.8603	3	697	732	199	27.2	758.568	1.5				#DIV/0!	#DIV/0!
17	7											#NV	#NV	#NV	1				#DIV/0!	#DIV/0!
18	8											#NV	#NV	#NV	1				#DIV/0!	#DIV/0!
19	9											#NV	#NV	#NV	1				#DIV/0!	#DIV/0!
20	10											#NV	#NV	#NV	1				#DIV/0!	#DIV/0!
21	11											#NV	#NV	#NV	1				#DIV/0!	#DIV/0!
22	12											#NV	#NV	#NV	1				#DIV/0!	#DIV/0!
23	Kegelhals									498		#NV	#NV	#NV	1				#DIV/0!	#DIV/0!

Figure 3.14 Input masks in the automated process

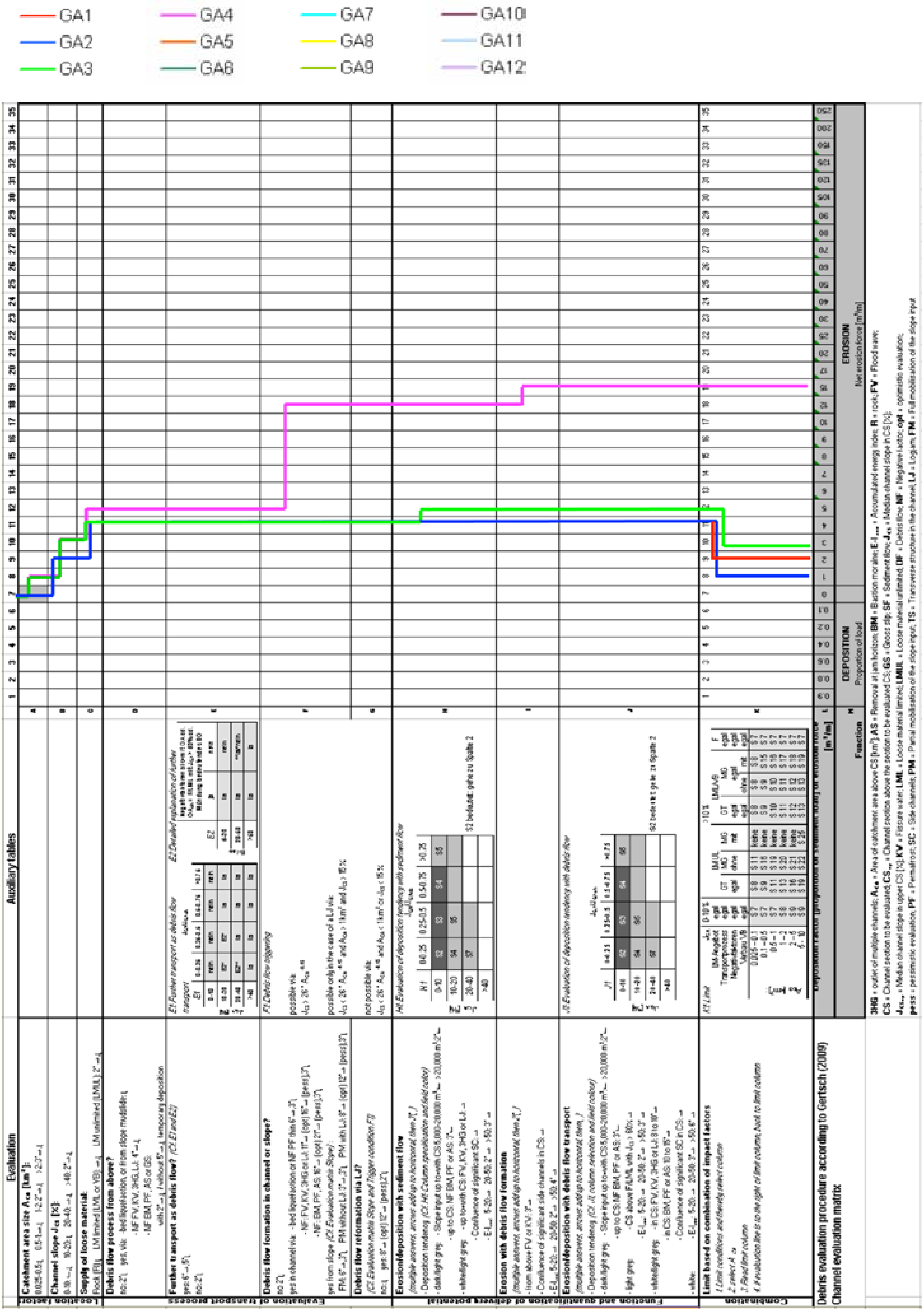

Figure 3.15 Example of a completed channel evaluation matrix

The following tools are implemented here:
- Input masks: Here all minimally required input parameters per channel section can be entered (cf. Fig. 3.14). A few of these (e.g. local and accumulated energy index, flattening ratio J_{CS}/J_{CSup}) are automatically calculated from the other input parameters.
- Evaluations of slope and channel: By means of an interactive matrix analogous to the evaluation matrices, the slope input and the channel processes are evaluated for each channel section. In this process, the requests for decision finding from the auxiliary tables in the channel evaluation matrix run automatically in the background and the result is presented as support.
- Graphic of slope and graphic of channel: The evaluation matrices with the evaluation lines for slope and channel are automatically presented, each in a graphic, and can thus be directly transferred into a report (cf. Fig. 3.15).
- Upshot of the evaluation: The evaluations per channel section and the total load at the cone neck are displayed in a table at the end.

3.5 Specialties of the debris evaluation procedure

In comparison to existing debris assessment procedure, the above procedure shows the following specialties and strengths:
- The debris assessment procedure closes a methodological hole in the existing debris assessment processes in that it focuses on the major events, that is, events with a recurrence period of ≥ 100 years.
- The debris assessment procedure presented here was calibrated to a large number, to 58 major events that really occurred in nature and validated by an equally large number of further events (20) and evaluations (23). It is thus scientifically well founded, developed and tested.
- The system-based approach used in this debris assessment procedure, with the inclusion of the relevant impact factor combinations networked both spatially and functionally, is new compared to existing evaluation procedures. The complexity of torrent systems and the individuality of individual channel sections is taken into account by the networked procedure that thinks in relationships.
- The debris evaluation procedure presented here is very strongly process-oriented. Thereby, thanks to the large number of major events analysed, especially with regard to the transport process of a debris flow, new process mechanisms like the negative factors or the accumulated energy index could be defined and incorporated. These have a normative influence on the bedload balance in individual channel sections.
- That various event scenarios could be recalculated using the debris assessment procedure answers the current standard for procedure during a danger assessment in a torrent.
- Depending on the question and the statement accuracy required by it, the depth of processing of the assessment procedure can be adjusted. In the case of a low processing depth, the application occurs with the desk-based procedure, for a greater processing depth with the field-supplemented procedure. Thereby, the procedure can be optimally adapted to the processing time available depending on the question and the cap on expenses. This is a significant advantage for application in practice.
- The application of the debris assessment procedure is independent of software availability. Thus, the scanning for the required input parameters can occur both with GIS and (in principle) without a GIS. The automated debris assessment procedure is made available as simple Excel worksheets and can thereby be carried out by anyone, as long as he/she is an expert in the field and has sufficient experience in the process understanding of the bedload balance in torrent systems.

4. Outlook

4.1 State of the art and missing knowledge

With regard to the general state of knowledge respecting bedload balance in torrent systems, the existing uncertainties still gives rise to a serious need for action. There are indeed various physical evaluation formulae for calculation of debris loads. However, these were developed under strongly simplified conditions in the laboratory and mostly are not able to depict the complex and very heterogeneous conditions within a small space in a real torrent channel. The engagement with the bedload in a torrent requires good understandings of the process and relationships. Better knowledge regarding these debris processes in torrent systems can be achieved through various means:

Event analyses:
Real-life events give us the best information regarding bedload balance in torrents. A large amount of information can be acquired here by extensive event documentation and analyses. In this process, the

question arises as to where in the catchment area by what processes how much debris is mobilised and transported to the cone neck. It is very important that trained experts are employed for this documentation and these analyses. Only through their experience, their good process understanding and the ability to classify and describe past events through cross-comparison with other places and events can these data, which are most valuable in and of themselves, later give rise to an effective application. For this reason, sufficient financial means must be made available for the event documentation and, for example, the conducting of a systematic event cadastre.

Systematic measurement of debris loads in torrents:
Worldwide, discharge measurements have been carried out in rivers and streams for a long time. As a result, long measurement series are available for statistical evaluation and thereby evaluation of flood peaks. By contrast, there are practically no measurement series on debris loads. The reason lies on one hand with insufficient funding and on the other hand with the technical difficulty of measuring debris loads at all. Despite these difficulties, the so-called "GHO debris measurement network" was established in Switzerland in 1987. It is the only measurement network in which systematic data on debris loads in torrents of the Swiss Alps area is collected. The principle of the measurement network is very simple. The respective clearance yields of the existing sediment collectors in 100 torrents are stored in a database and observed over time. These data are supplemented by topographic surveys regarding the predominant debris processes in the respective catchment areas. The data of this measurement network become the more valuable for an improvement of the process understanding the longer the measurement network is maintained and continued. Through this monitoring, in particular, new knowledge regarding annualities of debris loads in the widest variety of torrent systems can be gathered.

Research:
Basic research for improvement of the process understanding is also important. Already for the transport process of debris flows, where many questions remain open, investigations in test areas such as the Illgraben in Wallis (WSL) provide important new results. Also, improved technical possibilities for measurement and recording of debris transport during events, as they are developed (for example) in the test area Spissibach Leissigen of the Geographic Institute of the University of Bern, can provide important new information here. It is further worth mentioning model and laboratory trials regarding debris transport, as they are carried out, for example, at the Research Institute for Hydraulic Engineering of the ETH Zürich or at various universities of applied science.

4.2 Transfer of the methods to other mountainous regions

The methods have been applied in various mountainous regions such as catchments in Austria, Nepal, Pakistan, and Central America. Table 4.1 shows what elements of the methods can be transferred and what needs additional adaption.

Topic	Method Lehmann	Method Gertsch
Discharge calculations	with reservation (Rainfall data; catchment characteristics)	
Sediment transport	yes	
Granulometry	yes	
System oriented approach		yes
Process oriented approach		yes
Implementatin of local disposition Bed load supply	yes	yes
Channel gradient	yes	yes
Catchment area above		no (climate)
Implementation of channel conditions upstream Energy-index		yes
Implementation of negative factors		yes

Table 4.1 Transfer of methods to other mountainous regions

General Information about the International Commission for the Hydrology of the Rhine basin (CHR)

The CHR is an organization in which the scientific institutes of the Rhine riparian states develop joint hydrological measures for sustainable development of the Rhine basin.

CHR's mission and tasks:

Extension of knowledge of the hydrology of the Rhine basin through:
- joint research
- exchange of data, methods and information
- development of standardized procedures
- publications in the CHR series

Making a contribution to the solution of cross-border problems through the formulation, management and provision of:
- information systems (CHR Rhine GIS)
- models, e.g. models for water management and the Rhine Alarm Model

Co-operating countries:

Switzerland, Austria, Germany, France, Luxembourg and The Netherlands.

Relationship with UNESCO and WMO:

The CHR was founded in 1970 following advice by UNESCO to promote closer co-operation between international river basins. Since 1975 the work has been continued within the framework of the International Hydrological Programme (IHP) of UNESCO and the Hydrological Water Resources Program (HWRP) of WMO.

For more information about the CHR, please visit our website at: www.chr-khr.org

Publications of CHR

CHR/KHR (1978): Das Rheingebiet, Hydrologische Monographie. Staatsuitgeverij, Den Haag / Le bassin du Rhin. Monographie Hydrologique. Staatsuitgeverij, La Haye. ISBN 90 12017 75 0 (out of print)

CHR reports

I-1 GREBNER, D. (1982): Objektive quantitative Niederschlagsvorhersagen im Rheingebiet. Stand 1982 / Prévisions objectives et quantitatives des précipitations dans le bassin du Rhin. Etat de la question en 1982 (out of print)
I-2 GERHARD, H., J.W. VAN DER MADE, J. REIFF, L.P.M. DE VREES (1983): Die Trocken- und Niedrigwasserperiode 1976. (2. Auflage 1985) / La sécheresse et les basses eaux de 1976 (2ème édition, 1985). ISBN 90 70980 01 0 (out of print)
I-3 HOFIUS, K. (1985): Hydrologische Untersuchungsgebiete im Rheingebiet / Bassins de recherches hydrologiques dans le bassin du Rhin. ISBN 90 70980 02 9 (out of print)
I-4 BUCK, W., R. KIPGEN; J.W. VAN DER MADE, F. DE MONTMOLLIN, H. ZETTL, J.F. ZUMSTEIN (1986): Berechnung von Hoch- und Niedrigwasserwahrscheinlichkeit im Rheingebiet / Estimation des probabilités de crues et d'étiages dans le bassin du Rhin. ISBN 90 70980 03 7 (out of print)
I-5 TEUBER, W., A.J. VERAART (1986): Abflußermittlung am Rhein im deutsch-niederländi¬schen Grenzbereich / La détermination des débits du Rhin dans la région frontalière germano hollandaise. ISBN 90 70980 04 5 (out of print)
I-6 TEUBER, W. (1987): Einfluß der Kalibrierung hydrometrischer Meßflügel auf die Unsicherheit der Abflußermittlung. Ergebnisse eines Ringversuchs / Influence de l'étalonnage des moulinets hydrométriques sur l'incertitude des déterminations de débits. Résultats d'une étude comparative. ISBN 90 70980 05 3 (out of print)
I-7 MENDEL, H.G. (1988): Beschreibung hydrologischer Vorhersagemodelle im Rheineinzugs¬gebiet / Description de modèles de prévision hydrologiques dans le bassin du Rhin. ISBN 90 70980 06 1 (out of print)
I-8 ENGEL, H., H. SCHREIBER, M. SPREAFICO, W. TEUBER, J.F. ZUMSTEIN (1990): Abflußermittlung im Rheingebiet im Bereich der Landesgrenzen / Détermination des débits dans les régions frontalières du bassin du Rhin. ISBN 90 70980 10 x (out of print)
I-9 CHR/KHR (1990): Das Hochwasser 1988 im Rheingebiet / La crue de 1988 dans le bassin du Rhin. ISBN 90 70980 11 8 (out of print)
I-10 NIPPES, K.R. (1991): Bibliographie des Rheingebietes / Bibliographie du bassin du Rhin. ISBN 90 70980 13 4 (out of print)
I-11 BUCK, W., K. FELKEL, H. GERHARD, H. KALWEIT, J. VAN MALDE, K.R. NIPPES; B. PLOEGER; W. SCHMITZ (1993): Der Rhein unter der Einwirkung des Menschen. Ausbau, Schifffahrt, Wasserwirtschaft / Le Rhin sous l'influence de l'homme. Aménagement, navigation, gestion des eaux. ISBN 90 70980 17 7 (out of print)
I-12 SPREAFICO, M., A. VAN MAZIJK (Red.) (1993): Alarmmodell Rhein. Ein Modell für die operationelle Vorhersage des Transportes von Schadstoffen im Rhein. ISBN 90 70980 18 5
I-13 SPREAFICO, M., A. VAN MAZIJK (réd) (1997): Modèle d'alerte pour le Rhin. Un modèle pour la prévision opérationnelle de la propagation de produits nocifs dans le Rhin. ISBN 90 70980 23
I-14 EMMENEGGER, CH. ET AL. (1997): 25 Jahre KHR. Kolloquium aus Anlaß des 25jährigen Bestehens der KHR / 25 ans de la CHR. Colloque à l'occasion du 25e anniversaire de la CHR. ISBN 90 70980 24 x
I-15 ENGEL, H. (1997): Fortschreibung der Monographie des Rheingebietes für die Zeit 1971-1990 / Actualisation de la Monographie du Bassin du Rhin pour la période 1971-1990. ISBN 90 70980 25 8
I-16 GRABS, W. (ed.) (1997): Impact of climate change on hydrological regimes and water resources management in the Rhine basin. ISBN 90 70980 26 6
I-17 ENGEL, H. (1999): Eine Hochwasserperiode im Rheingebiet. Extremereignisse zwischen Dez.1993 und Febr. 1995. ISBN 90 70980 28 2 (out of print)
I-18 KOS, TH.J.M., H. SCHEMMER, A. JAKOB (2000): Feststoffmessungen zum Vergleich von Messgeräten und Messmethoden im Rhein, 10-12 März 1998. ISBN 90-36953-54-5
I-19 BARBEN, M. ET AL. (2001): Übersicht über Verfahren zur Abschätzung von Hochwasser¬abflüssen - Erfahrungen aus den Rheinanliegerstaaten. ISBN 90-36954-11-8
I-20 KRAHE, P., D. HERPERTZ (2001): Generation of Hydrometeorological Reference Conditions for the Assessment of Flood Hazard in large River Basins - Papers presented at the International Workshop held on March 6 and 7, 2001 in Koblenz. ISBN 90-36954-18-5
I-21 KRAHE, P. ET AL. (2004): Entwicklung einer Methodik zur Analyse des Einflusses dezentraler Hochwasserrückhaltemaßnahmen auf den Abfluss des Rheins. ISBN 90-36956-74-9
I-22 BELZ, J.U. ET AL. (2007): Das Abflussregime des Rheins und seiner Nebenflüsse im 20. Jahrhundert - Analyse, Veränderungen, Trends. ISBN 978-90-70980-33-7
I-23 GÖRGEN, K. ET AL. (2010): Assessment of climate change impacts on discharge in the River

Rhine Basin. Results of the RheinBlick2050 project. ISBN 978-90-70980-35-1
I-24 STEINRÜCKE, J., B. FRÖHLINGS, R. WEIßHAUPT (2012): HYMOG - Hydrologische Modellierungsgrundlagen im Rheinsgebiet. ISBN 978-90-70980-00-9

Katalog/Catalogue 1 SPROKKEREEF, E. (1989): Verzeichnis der für internationale Organisationen wichtigen Meßstellen im Rheingebiet / Tableau de stations de mesure importantes pour les organismes internationaux dans le bassin du Rhin. ISBN 90 70980 08 8

Reports under the auspicien of the CHR

II-1 MADE, J.W. VAN DER (1982): Quantitative Analyse der Abflüsse / Analyse quantitative des débits (out of print)
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II-12 SCHÄDLER, B. (Red.) (1997): Bestandsaufnahme der Meldesysteme und Vorschläge zur Verbesserung der Hochwasservorhersage im Rheingebiet. Schlußbericht der IKSR Arbeitseinheit 'Meldesysteme / Hochwasservorhersage' Projektgruppe 'Aktionsplan Hochwasser' / Annonce et prévision des crues dans le bassin du Rhin. Etat actuel et propositions d'amélioration. Rapport final de l'unité de travail 'Systèmes d'annonce / prévision des crues' Groupe de projet 'Plan d'action contre les inondations'. ISBN 90 70980 27 4
II-13 DRÖGE, B., H. HENOCH, W. KELBER, U. MAHR, T. SWANENBERG, T. THIELEMANN, U. THURM (1999): Entwicklung eines Längsprofils des Rheins. Bericht für die Musterstrecke von Rhein km 800-845. Arbeitsgruppe 'Sedimenttransport im Rhein' Projekt 3. ISBN 90 70980 29 0
II-14 MAZIJK, A. VAN, CH. LEIBUNDGUT, H.P. NEFF (1999): Rhein Alarm Modell Version 2. 1. Erweiterung um die Kalibrierung von Aare und Mosel. Kalibrierungsergebnisse von Aare und Mosel aufgrund der Markierversuche 05/92, 11/92 und 03/94. ISBN 90 70980 30 4
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II-17 SPREAFICO, M., R. WEINGARTNER ET AL. (2002): Proceedings International Conference on Flood Estimation, March, 6-8, 2002 Berne, Switzerland. ISBN 90-36954-60-6
II-18 BRONSTERT A. ET AL. (2003): LAHoR - Quantifizierung des Einflusses der Landoberfläche und der Ausbaumassnahmen am Gewässer auf die Hochwasserbedingungen im Rheingebiet. ISBN 90-70980-32-0
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