ASSESSMENT TOOLS FOR MOUNTAIN TORRENTS: SEDEX© AND BED LOAD ASSESSMENT MATRIX

Hans Kienholz[1*], Eva Frick[2], Eva Gertsch[3]

ABSTRACT

In order to protect threatened settlements on debris fans or cones by hazard zoning and/or technical measures, the total amount of delivered solids [m^3] must be known for each event. Two approaches aiming at facilitating and standardizing such analyses for mountain torrents (watersheds < 10 km^2) were developed in Switzerland. Both methods require the examination of sequences of more or less homogenous channel sections and can be used for different event scenarios. The two procedures can either be applied sequentially or on their own. The first procedure, the "Gertsch method", is primarily based on GIS analyses of digitally available input data using two matrices (channel assessment and slope assessment). Once the data is put into the matrix (Excel sheet), the bed load budget per channel section and the total bed load at the fan apex are automatically estimated. The second procedure, SEDEX©, requires local field checks. The assessment of the channel is based on the division of each homogenous section into different channel, embankment and slope modules. SEDEX© systematically guides the user through the field work and all the steps of the analysis. A hand-held computer supports the data input and facilitates first calculations already in the field.

Key Words: Mountain torrents, Debris flows, Hazard assessment concepts and tools, Sediment supply, Awareness of uncertainty

INTRODUCTION

In the Alpine countries as well as in other parts of the world, many settlements are located on alluvial cones of mountain rivers or mountain torrents. By definition, debris and mud flows as well as fluvial bed load transportation may occur in mountain torrents. In order to protect the threatened settlements on the debris fans or cones by hazard zoning and/or technical measures, the probable peak flood [m^3/s] (water and solids) and the total amount of solids [m^3] per event must be known. Usually, these key data (in the following referred to as "apex key data") are required for the apex of alluvial fans or debris cones. The apex of a fan or cone is the place from where flooding and sedimentation may start to cause damage to people, settlements and other goods.

In most cases, however, there are no measured data available for runoff nor transportation of solids or debris flows. Therefore, the experts depend on qualitative and/or semi-quantitative estimations. While hydrological models (precipitation-runoff-models, etc.) provide more or

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less valuable data on water runoff, the difficulties in assessing the bed load transport rate [m^3/s] or the total amount of bed load or debris flow solids per probable and possible event [m^3] are immense.

The empirical formulas for the estimation of the total amount of bed load or debris flow solids (e.g. D'Agostino *et al.*, 1996) are usually developed for the conditions of specific regions (geology, climate, etc.) and are therefore transferable to other regions only under restrictions. Fluvial transport models (e.g. Rickenmann, 1990, Rickenmann *et al.*, 2006) are generally applicable to less steep channels, but not to steep channels with partially limited sediment production potential. However, there is some uncertainty about the correct specific input parameters for the considered torrent. Furthermore, most empirical methods, particularly transport models, only relate to fluvial transport and not to debris flow.

The above mentioned very important and valuable tools are applied by most experts. Yet in order to be able to make statements of a high spatial resolution about the processes and their intensities in settlement areas on alluvial cones of mountain torrents, the characteristics of each torrent have to be considered. For each torrent basically has its own character, disposition, history and its own conditions for development in the future. To meet the singularity of each mountain torrent, sufficient knowledge has to be acquired which can only be accomplished by field work in the particular torrent and by a combination of different diagnostic methods.

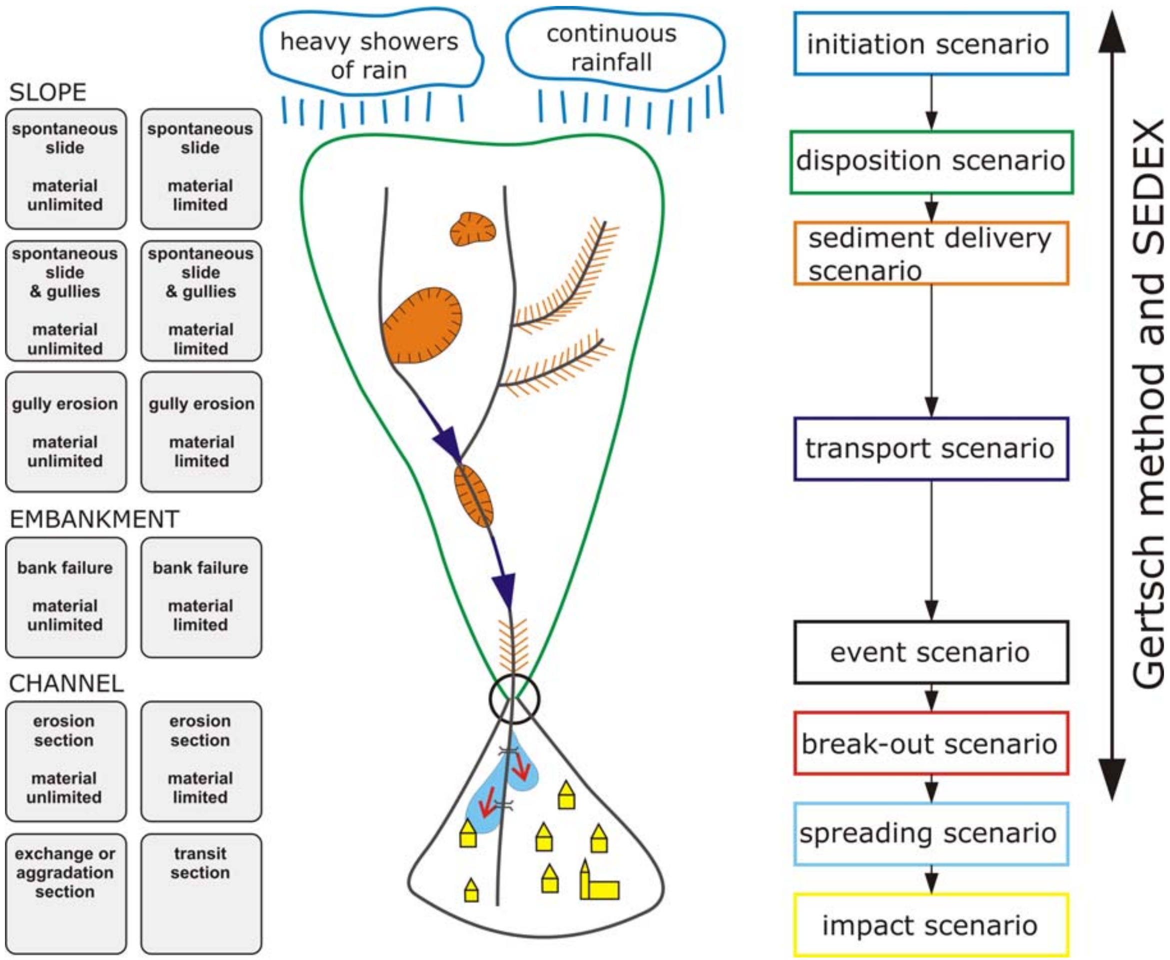

Fig. 1 Catchment and debris fan of a typical mountain torrent (schematic). Indication of different sections and different types of bed load sources. On the left: List of 12 modules as used in the SEDEX© procedure

In plain terms: To reach the required level of detail, it is indispensable to acquire ample knowledge of the terrain. To some extent this can be achieved by means of remote sensing and GIS methods or based on possibly existing documents such as geological maps or descriptions in projects for control structures. However, an evaluation in the field is indispensable in the majority of cases. It is essential that the field work is done by experienced experts with a pronounced understanding of the governing processes.

The authors have been dealing with this subject for a longer time. In the last years they have concentrated on the development of methods which work towards the goal of determining the apex key data in a correct, comprehensible and, regarding time and effort, economical way. A first approach initiated by our research group was published later on by Spreafico *et al.* (1996). Subsequently, two approaches for mountain torrents with watersheds smaller than 10 km^2 were developed in Switzerland in order to facilitate and standardize such analyses: SEDEX© (acronym for SEDiments and EXperts) and the Bed Load Assessment Matrix (called Gertsch method). SEDEX© is mainly supported by the Civil Engineering Office of the Canton of Berne (TBA BE) and the Gertsch method by the Swiss Federal Office for the Environment (FOEN). The major preliminary outlines for the two procedures were already reported during their status nascendi at Interpraevent 2008. Both methods require the examination of sequences of more or less homogenous channel sections and can be applied to different event scenarios (different probabilities and magnitudes). The Gertsch method and the SEDEX© procedure may either be applied sequentially in combination or individually.

It has to be mentioned that both methods rely on long-term experience as well as on hard data: In order to obtain reliable reference data, FOEN has promoted several event analyses during the last decades (Bezzola and Hegg, 2007 *and* 2008) as well as a purposive study about the caracteristics of 58 mountain torrents in the Alpine parts of Switzerland and the total amount of solids [m^3] on the occasion of real events (e.g. Gertsch and Kienholz, 2008, Gertsch, 2009) in these torrents (cf. Fig. 2).

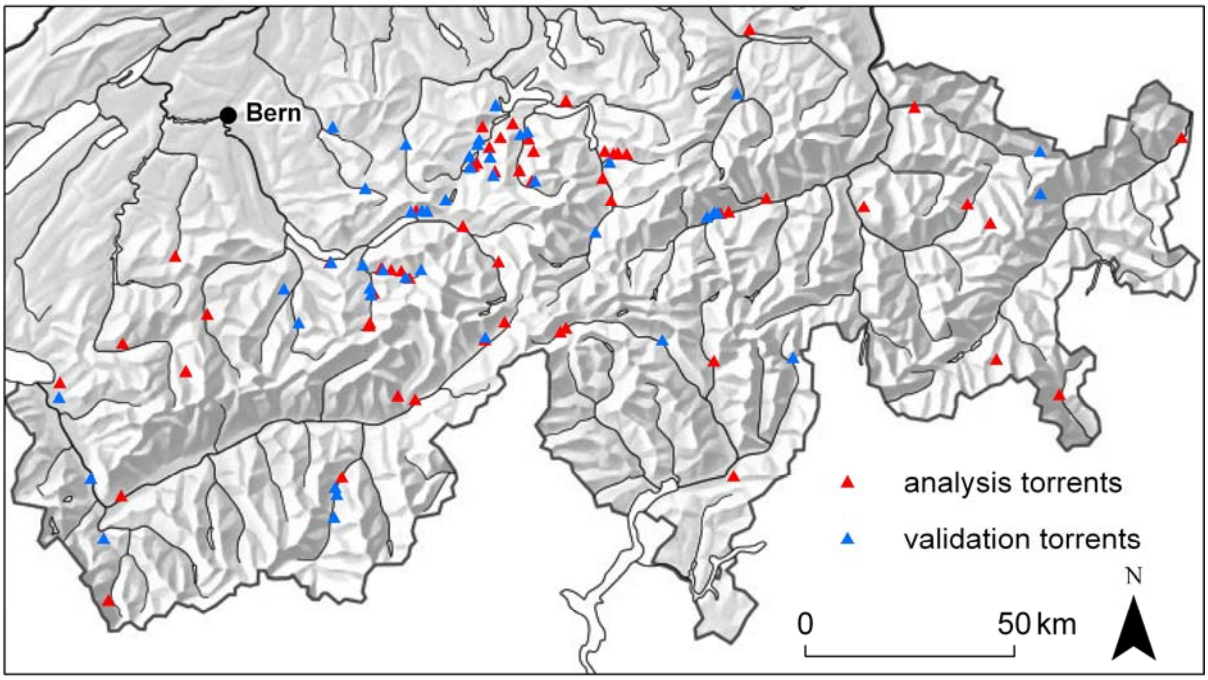

Fig. 2 Location of the 58 analyzed mountain torrents and the 43 catchments used for the validation of the Gertsch method in the Alpine parts of Switzerland

SIMILARITIES BETWEEN THE TWO METHODS

Both methods pursue the same goals: a reliable and comprehensible determination of the apex key data.

Common features of the two approaches are:

- Definition of the required level of detail (depending on the job order and the needs of the client)
- Division of the channel in homogenous sections, considering criteria such as gradient, properties of the torrent bed and of the adjacent slopes, torrential function of the section (erosion, transit, bed load exchange, deposition)
- Separate examination of the sediment sources in the stream bed and on the adjacent slopes
- The main emphasis is put on the inspection of the sediment production potential in the sediment sources. The inclusion of the transport rates is rather subordinate. In both methods, a difference is made between "material limited" (e.g. shallow soil cover on bedrock) and "material unlimited" (e.g. huge fluvio-glacial deposits).
- Consideration of different scenarios
- The target audience of both procedures is experts who already have a sound understanding of the processes taking place in mountain torrent systems relating to sediment budgets. Detailed manuals were developed for both procedures, though, which can be used as kind of textbooks for less experienced people.

Both procedures have to be linked with methods to assess for example general characteristics of the torrent, runoff conditions and records of historic events. As both methods are used in practice to assess the hazardous activities of mountain torrents, the approaches have to be applicable to a catchment within a short time. This implies that they have to be handy and very efficient

While the Gertsch method allows for an approach rather on an overview scale (based on remote sensing) as well as for a relatively detailed procedure (in-depth field work), SEDEX© focuses primarily on detailed field work.

THE GERTSCH METHOD

The aim of the Bed Load Assessment Matrix, the so-called "Gertsch method", is the assessment of bed load deliveries for extreme events (recurrence interval > 100y). The starting point for the development this procedure was the analysis of 58 events in different mountain torrents, which occurred in Switzerland after 1987. 52 of these events were related to debris flows and 6 events to fluvial sediment transport (for more details see Gertsch and Kienholz, 2008, Gertsch, 2009). The Gertsch method was developed and calibrated on the basis of these 58 detailed event analyses (cf. Fig. 2) and then validated by means of 20 additional events and 23 existing assessments, which had been carried out previously by other experts on the occasion of hazard zoning for hazard maps. The procedure is described in detail in Gertsch (2009) (German) and soon, a short form user's manual will be published (English) (Spreafico *et al.*, in prep.).

The assessment system of the Gertsch Method

The sequence of operations proposed by the Gertsch method is illustrated in Fig. 3.

The input data can be completely collected through GIS analyses, field work or a combination of both. Hazard assessments for hazard indication maps, which only have a survey character,

can be exclusively done in GIS or Excel. In contrast, for hazard zoning at the local level, field work is indispensable. In the following, the procedure is described in detail.
Similar to SEDEX© (see further down) the channels within the considered torrent catchment are subdivided into **homogenous** (gradient, sources of solids, runoff and characteristics of adjacent slopes) **channel sections.** Ideally, this delineation can be made with basic digital data using GIS. If necessary, the results have to be verified in the field.

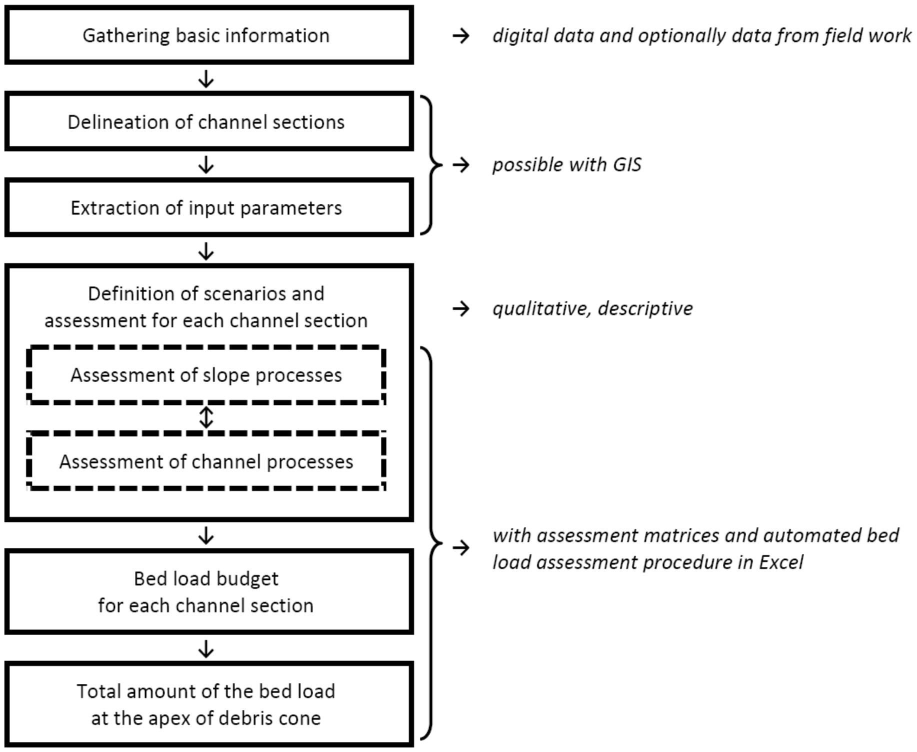

Fig. 3 Sequence of operations according to the Gertsch method

Afterwards, the required input parameters for each channel section (area of catchment contributing to the process, channel geometry, supply of solids from within the channel and from the slopes) are determined This step can be mainly done with GIS, too. In addition, some of the data are compared to those of the section lying above and used to calculate a "gradient relation" (increasing or decreasing gradient) and a so-called "local" and "accumulated energy index". The local energy index provides a strongly simplified measure of the buildup of kinetic energy: In steep sections with "limited material" or rock (cf. Chapter *Similarities between the two methods*), where high velocities can develop, the local energy index is positive. In contrast, it is negative in erosional sections with unlimited unconsolidated material where major parts of the energy are converted into friction and heat energy instead of kinetic energy. For the mobilization of solids in the channel section, which needs to be assessed, the summation of the local energy indices $E\text{-}I_{GA}$ of the above lying sections of the channel is crucial. The measure for this summation is the accumulated energy index $E\text{-}I_{akk}$. Thus, the "local conditions" on the one hand and the "conditions above" are considered (cf. Fig. 4).

Now, the user has to think about qualitatively possible event scenarios and define them. According to the Gertsch method, the analysis of so-called "negative factors" (possible state and process transitions, bifurcation effects) plays an important role in the assessed channel section itself and also in the channel and slope sections lying above.

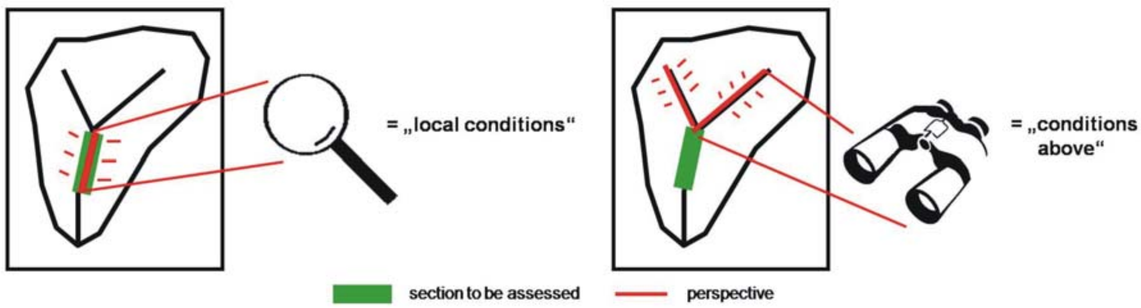

Fig. 4 Analysis of the channel section from a local (on the left side) and a broader perspective, putting the focus on the above lying sections (on the right side) (from Gertsch, 2009)

Negative factors are special processes or combination of processes which can trigger particularly large destructive debris flows. They can lead to extreme erosion rates both in the channel sections where they originate and in the sections below. Negative factors act as threshold processes in the whole torrent system by which the mobilized sediment loads can be multiplied considerably.

For each scenario a bed load assessment is carried out. For this purpose, the input from the slope into the channel as well as the processes and the displaced cubatures of sediments in the channel are quantitatively assessed for each channel section. The tools used in this step are an assessment matrix for the slope processes and another one for the channel processes. The quantitative estimation of the bed load budget for each channel section is made depending on the defined event scenario. To provide an overall impression and an overview of the tools, the Channel Assessment Matrix is shown in Fig. 5. However, it is not intended to illustrate the matrix in detail on this occasion. The structure of the matrix is briefly explained below.

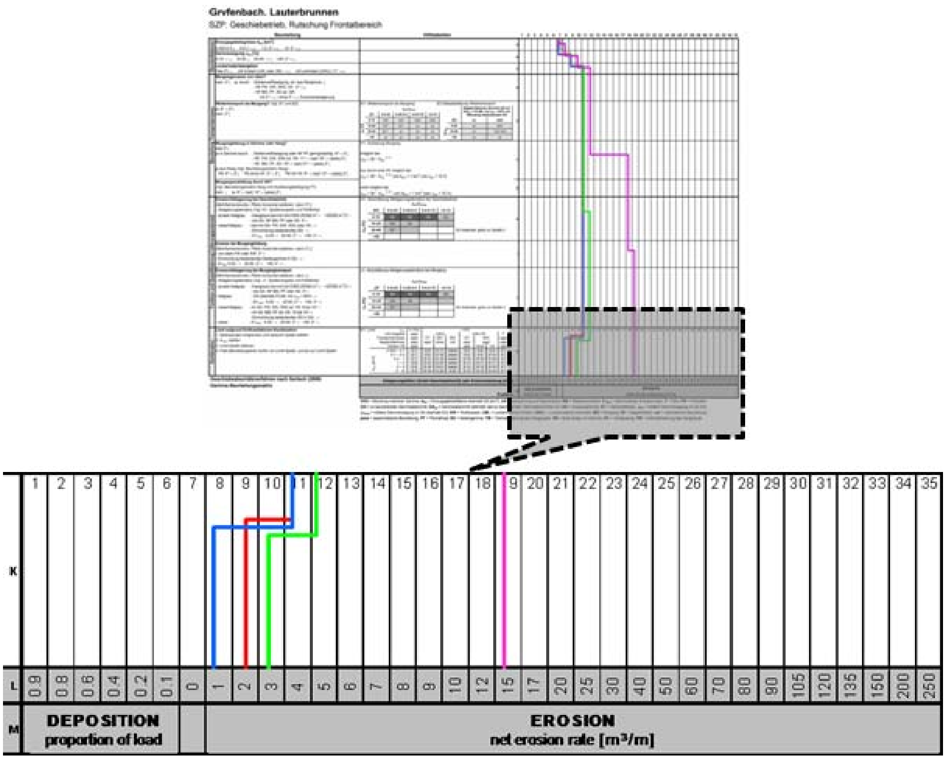

Fig. 5 Channel Assessment Matrix. The further the assessment curve shifts towards the right side, the higher the expected erosion rate is (after Gertsch, 2009)

The Channel Assessment Matrix to be applied to each channel section is divided into three parts:

- The left part is dedicated to the assessment and consists of four paragraphs with several lines of assessment criteria, out of which single ones have to be considered for each channel section depending on the prevailing conditions.
- The central section includes assistance tables, which simplify and limit decision-making during the evaluation of the left part of the table.
- The right part comprises the actual assessment matrix in which the graphical representation of the assessment is displayed. The appraisal is documented by means of an assessment curve. Assessment criteria promoting erosion cause a shift of the curve towards the right in the matrix, factors promoting deposition effect a displacement towards the left. Depending on the final location of the assessment curve, the result is the quantification of the expected erosion rate and the deposition in the channel section respectively.

The bed load budget of the considered channel section is calculated by adding the solid delivery from the slopes (results from assessment matrix for slope processes, not depicted here) to the cubature mobilized in the channel (cf. Fig. 5). In the case of deposition the budget is negative, in the case of erosion it is positive. Finally, the total amount of bed load at the apex is estimated by summation of the results delivered from all the channel sections.

THE SEDEX© APPROACH

SEDEX© stands for SEDiment and EXperts. This tool supports the **field work** of experts who need to assess the apex key data of mountain torrents. It concentrates on the estimation of sediment deliveries for defined recurrence periods and event probabilities, respectively.

Products of SEDEX©

SEDEX© consists of four different products:

- A field manual with all the necessary checklists for the field work. This concise compendium contains all the information required for the data acquisition.
- The more detailed version of this manual – the office manual – gives specific instructions and serves as a reference book.
- Another important element is the PDA-program provided to guide the user systematically through all the assessment steps in the field. By using it, the consultant can benefit from a consistent documentation and from a saving of time since all the results are calculated automatically.
- An additional desktop version of the program is designed to display the existing data and assist the user in the interpretation of the calculated results. Since in the PDA-version the display space as well as the calculation capacity is limited, the desktop version offers better analysis tools.

The SEDEX© procedure

Similar to the Gertsch method, the procedure to assess a torrent according to SEDEX© is based on the fragmentation of a mountain torrent into sections with defined characteristics. In the field, channel, embankments and slopes are divided into relatively homogeneous sections, which are further subdivided into 12 so-called modules (cf. Fig. 1). They are mainly defined by the possible process types. In contrast to the Gertsch method, embankments and slopes are considered separately.

In the following the SEDEX© procedure is outlined step by step.

Step 1
The expert starts to work bearing **preliminary basic scenarios** of relevant courses and magnitudes of events in mind. He/she usually defines three basic scenarios based on preparative work (study of maps, available meteorological and hydrological data, reports about former events, etc.), his/here experience and last but not least on field work. A scenario outlines a possible sequence of sub-processes and is composed of an initiation, a disposition, a sediment delivery and a transport scenario (cf. Fig. 1). Thus, the expert for example may decide to consider the following basic scenarios for a certain torrent:

- Debris flow initiated by heavy showers of rain combined with activation of lateral gullies and shallow landslides (e.g. = reference scenario, assumed recurrence interval ≈ 100y);
- Debris flow initiated by continuous rainfall combined with additional reactivation of a dormant deep-seated landslide within the catchment (e.g. assumed recurrence interval >> 100y)
- Fluvial transport initiated by heavy showers of rain with activation of some bed load in the river bed and some unstable embankments only (e.g. assumed recurrence interval < 30y)

Step 2
Following the same principles as in the Gertsch method, the channels within the considered torrent catchment are subdivided into **homogenous channel sections** during field work (cf. Chapter *Similarities between the two methods*).

Step 3
Within each section, **channel**, **embankments** and **slopes** are considered. To all of them different types of so-called modules are assigned, which are mainly defined by the possible process types (cf. Fig. 1 and Fig. 6). The channel in the considered section is described by one of four SEDEX© modules (cf. Fig. 1 and Fig. 6). The embankments and the slopes on the left and on the right are characterized separately by two (embankments) respectively six (slopes) **SEDEX© modules**. Almost each SEDEX© module contains per se already some information about the process and the approximate availability of solids ("material limited" or "material unlimited") that could be mobilized by erosion or landslides. This enables the expert to characterize a mountain torrent by considering the amount of contribution to sediment delivery from the different modules.

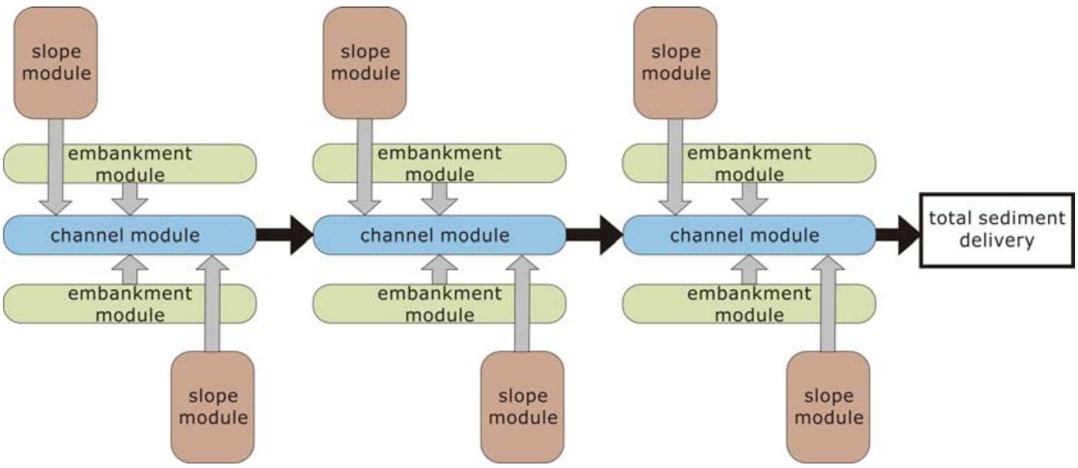

Fig. 6 Schematic diagram of sediment delivery from slope, embankment and channel modules of a sequence of sections (after Frick *et al.* 2008)

The SEDEX© modules, which per se already characterize the process, get further evaluated by assigning a degree of activity and an estimated sediment delivery to them (step 4). The determination of the probability of activation for a certain event is supported by so-called activation checklists in SEDEX©. These are observation tools, which guide the user step by step through the necessary deliberations. For this purpose, qualitative and semi-qualitative characteristics are displayed in such a manner that the user can evaluate the results of his/her observations in summary.

ACTIVATION-CHECKLIST FOR LATERAL GULLIES					
Indicators of stability	Grain size	mostly transportable	at least locally transportable		
	Bed armoring	mainly loose components	slightly armored	highly armored	
	Consolidation	unconsolidated, loose		consolidated	strongly consolidated
	Vegetation on embankment	no vegetation cover		(almost) closed vegetation cover	
	Vegetation on toe of embankment	no vegetation cover		vegetation cover	
	Reliability of constructions	low		limited	high
Indicators of erosivity	Cross section	V- or U-shaped	trapezoid, rectangle		trough-shaped
	Formation	by debris flow or erosion			by landslides
	Incision into slope	deep			not deep (<0.5 m)
	Longitudinal section of the gully	distinctly stepped, falls		even	
	Catchment basin		large catchment basin	small catchment basin	
Traces of processes	Traces of erosion in the gully	distinct or numerous traces of erosion	indistinct or only few traces of erosion		
	Scars on embankment	open scars		overgrown scars	morphology characterized by hollow molds
		easy to activate (at least locally)	generally stable; however almost full scarification possible during extreme events		very stable (at least locally)

Fig. 7 Checklist for the assessment of the activity of lateral gullies; the further left the appropriate statements are in the table, the higher the assumed activity is (for more details see Frick *et al.* 2008)

Especially for the spontaneous slide modules it has to be checked additionally if in the considered scenarios the mobilized masses can reach the channel in a timely manner -that is to say during the flood or debris flow event.

Step 4

In this step a quantitative estimation of the sediment delivery is made for each considered module and reference scenario. When it comes to erosion processes or land sliding, the cubature of material carried away depends on the resistance of the unconsolidated material as well as on the local tractive force of the water. As for landslides, the quantity of the soil in motion is regulated by the characteristics of the underground and the water balance. SEDEX© provides checklists for the estimation of the sediment delivery. The proposed mode of calculation for all the modules is based on geometrically simple scar and erosion forms or rather predefined cross-sectional areas which approximately represent the natural processes. The quantification of erosional processes of the SEDEX© module "embankment erosion, left-hand side of the channel" for a considered torrent section is the result of the multiplication of [erosion thickness] x [embankment height] x [reduction factor]. The reduction factor (from 0 to 1) allows to consider if only parts of a certain torrent section suffer from embankment erosion. The total cubature of one section results from the sum of the sediment deliveries of all modules (channel, embankments and slopes).

From this step on, SEDEX© asks the expert to deal with uncertainty and scope of discretion in his/her appraisal. Thus, the range of uncertainty for the estimated sediment delivery has to be indicated as positive or negative variance of the assessed cubature in %. Such ranges of uncertainty are especially high for modules in unlimited unconsolidated material, modules with a capacity to deliver considerable volumes of sediments, slope modules, exchange or aggradation sections or given the possibility that huge amounts of material could be delivered due to the failure of check dams.

Step 5
The results of the analysis of every single module are brought together and used to assess the total sediment delivery potential of the torrent. The summation of the sediment cubatures of all the different sections of a torrent produces a provisional result for the sediment delivery at the apex for the three basic scenarios.

Step 6
However, it still has to be assessed if the sediment transport capacity in each section is high enough to transport the sediment delivery from the sections above any further downstream. In transport-limited sections (= "exchange or aggradation sections", cf. List of modules in Fig. 1) the sediment delivery, which can be transported during one event, has to be calculated based on transport capacity formulas (e.g. Rickenmann, 1990) or estimated on site based on expert opinion. The provisional sediment delivery at the apex of the cone is calculated for the three basic scenarios by simply balancing all the modules.

Step 7
This step is about verifying the collected data. On the one hand, incomplete or wrong entries producing an error message have to be corrected. On the other hand, checklists provide indications of module characteristics or combinations which can result in different courses of events. Thus, the user is assisted in his/her deliberation whether additionally any other scenarios than the basic scenarios have to be considered.

Step 8
By means of the estimated ranges of uncertainty per module, basic sensitivity analyses can be conducted which allow the expert to define the relevant range of cubatures for a certain scenario under specification of the range of uncertainty.

Additional remarks on the procedure according to SEDEX©

Considering different event sizes, it is important that not only the sediment quantities are adapted but also different processes are taken into consideration. For instance, the scenario for the reference event of a torrent (e.g. recurrence interval ≈ 100y) can be based on a mud flow, whereas the scenario for a smaller event (e.g. recurrence interval ≈ 30y) just comprises fluvial sediment transport. These and similar considerations about the process scenarios basically have to be made separately for each module in each channel section. Afterwards the corresponding conclusions concerning the probabilities of initiation and finally the estimation of the sediment delivery for each scenario have to be drawn. In addition to the demand to specify the ranges of uncertainty, this is one of the advantages of SEDEX©: The expert is prompted to take the two or three different basic scenarios into consideration for each channel section and each module.

A specially designed **PDA-program** is another very helpful tool, although its use is not mandatory. The possibility of working in the field with a PDA instead of paper has been appreciated a lot by the users. The PDA-program guides the expert systematically through all the assessment steps in the field. By using it, the consultant can benefit from a consistent documentation and from a saving of time since all the results are calculated automatically. An additional **desktop version of the program** is designed to display the existing data and assist the user in the interpretation of the calculated results.

SEDEX©, similar to the Gertsch method, offers much **flexibility** in respect of the depth of processing and the completeness of the documentation. The mentioned checklists are supporting tools, which can, but don't have to be used. Experienced experts can do without them and save time. In this case the documentation of the considerations will be a little less complete, though.

Verification of applicability of SEDEX©

For the development of SEDEX© it was essential that the method was constantly being reviewed by experts from science, administration and the private sector as well as by students on the occasion of workshops, test runs and case studies. Their criticisms and suggestions were continuously integrated into SEDEX©. The consulted experts confirmed that using SEDEX© enhances the quality and efficiency of an assessment. The visualization of the results and the simple overviews are regarded as being beneficial for the expert as well as for the communication of the results towards the client. It is particularly decisive for the continuation of projects (e.g. the design of countermeasures), whether the results and the associated uncertainties are comprehensibly accounted for by the expert. Furthermore, the traceability and the transparency of the results were considered as advantages of SEDEX©. Firstly, because SEDEX© improves the comparability of reports from different experts. Secondly, because it increases homogeneity within a single assessment by promoting a consistent documentation - for instance with the data input into the PDA-program.

CONCLUSIONS

The two procedures presented in this article, the Gertsch method and SEDEX©, were both developed in a relatively independent manner to meet the need of improving the assessment of natural hazards related to mountain torrents and debris flows (cf. Fig. 1). Both methods are currently in the implementation phase and need to prove themselves worthwile in practice. As mentioned at the beginning of this article, they can either be used on their own or combined with each other. In sequential use, the Gertsch method allows for a first quick, GIS-based assessment of the possible sediment load and supports the definition of basic scenarios which can be used in SEDEX© later on. In a second step, field work is done mainly with SEDEX©. If possible the same channel sections should be used, but if necessary they can also be further subdivided. The data collected in the field with SEDEX© are then used as an improved input for the Gertsch method, with the help of which the assessment is carried out a second time. Finally, the results have to be compared and discussed.

At present, the rating of the two procedures is carried out in a different manner:

- The evaluation of the Gertsch method relies on the fact
  - that it is, in compliance with common scientific procedures, based on more or less accurate data about sediment load during 58 real events
  - that it was verified independently by means of 20 events and 23 additional assessments in other mountain torrents.

  The analysis of these data has shown that the Gertsch method delivers good results for the conditions in the Swiss Alps, especially if the data collected in the field are included in the calculations.

- The possibilities of verifying SEDEX© on the basis of concrete events were limited so far. However, this will be possible with ample use of this method in the coming years. As opposed to that, the procedure was intensively tested during the development phase and test runs by 19 experts with different levels of experience and diverse professional backgrounds between 2005 and 2008. These experts consistently concluded that the procedure delivers realistic results. This very fact allows for the cautious conclusion that the chosen path is viable.

Of course the two procedures, which will be individually published in detailed manuals in 2010, still have to pass the practical test in a larger operational use.

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