Mapping Sediment Transfer Processes Using GIS Applications

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Abstract

In alpine environments, debris flows are a very dangerous geomorphic process and the main sediment transport agent in mountainous watersheds. The vulnerability of many infrastructures built on debris fans becomes higher and higher due to increasing intense meteorological events. Causes and factors acting on debris flow triggering are complex and still partly ignored. In small alpine watersheds, topographic conditions and land cover often hinder accessibility to conduct complete field surveys such as geomorphological mapping. Hence, GIS applications using digital elevation models in ArcMap software can be used to analyse specificities of the hydrographical network and, hence, to evidence the localisation and the potential volumes of sediment supply zones. This paper presents some applications in a torrential watershed located on the right side of the upper Rhone river valley and an outline of the developed methodology.

1. Introduction

In alpine environments, floods and bed load transport like debris flows constitute one of the major sources of risk. As an example, in August 2005, an extensive flood event in Switzerland provoked economic losses of 2 billion euros. In small mountainous watersheds, channelised debris flows (or debris torrents) are the main sediment transport agent and a very dangerous geomorphic process (Sterling & Slaymaker 2007). In fact, many infrastructures built on debris fans become more and more vulnerable because of the occurrence of intense meteorological events. In Switzerland, this trend is particularly perceptible since the end of the 1980s. Indeed, catastrophic floods in 1987, 1993, 1994, 1999, 2000 and 2005 in different regions of the country are only the most important national events and do not include local events, for example during storm events. Causes and factors acting on debris flows triggering are complex and partly ignored, depending on meteorological (intensity and duration of rainfall, temperatures, snow cover), topographic (slopes), geomorphological ((in)activity of geomorphological processes, instabilities, particle size and thickness of glacial, gravitational, periglacial or fluvial deposits), thermal (permafrost evidence), geological (faults and lithological characteristics) and hydro(geo)logical (shape of the hydrological network, flow regimes, underground water circulations, glacier occurrence) parameters. All of these elements may be combined, so that it is difficult to define a typology of the events and to model and predict these phenomena. Nonetheless, there are three fundamental parameters acting on debris flow triggering: slope (generally steeper than 15°), water presence and sediment supply zones connected to a main channel or a stream (Zimmermann & al. 1997). The aim of this paper is to discuss the contribution of GIS tools for evidencing sediment supply zones in torrential systems. Spatial analyses performed on high-resolution digital elevation models (DEM) are considered to be a good alternative to field geomorphological mapping in dangerous and inaccessible areas.

2. Geomorphological mapping of sediment transfer processes

An analysis of a large panel of geomorphological maps and legend systems revealed that most of the studies undertaken deal with the establishment of simple landform inventories. Some of them have an approach based on natural hazards or phenomena (e.g. Kienholz 1978; Petley 1998; Grecu 2002; Gustavsson 2005) or on sediment production (Bardou et al. 2007), but few authors use GIS applications for geomorphological mapping, even if some simple data derived through GIS spatial analysis (slopes, aspect) might be of high interest in geomorphological mapping. In a previous papers (Theler et al. 2007), some inconsistencies of the global methodology used in hazard mapping in Switzerland were highlighted[1] (Theler et al. 2007; Theler & Reynard 2007), particularly in the geomorphological legend used to map fluvial phenomena (Kienholz & Krummenacher 1995). More precisely, we concluded that there was a need for more detailed information about the volumes of potentially mobilised sediments that are one of the most important parameters of channelised debris flow occurrence, especially in densely populated mountain regions with a high potential of natural hazards.

[1] A "phenomena" map is produced by using geomorphological field evidence. A colour scheme is given to each morphogenic process and different tones of colour or thicknesses of symbols allow the differentiation of the substratum type, the depth of gravitational processes and the evidence, relative age and size of processes. However, the recommended legend for mapping the phenomenon only gives a momentary vision of one single event.

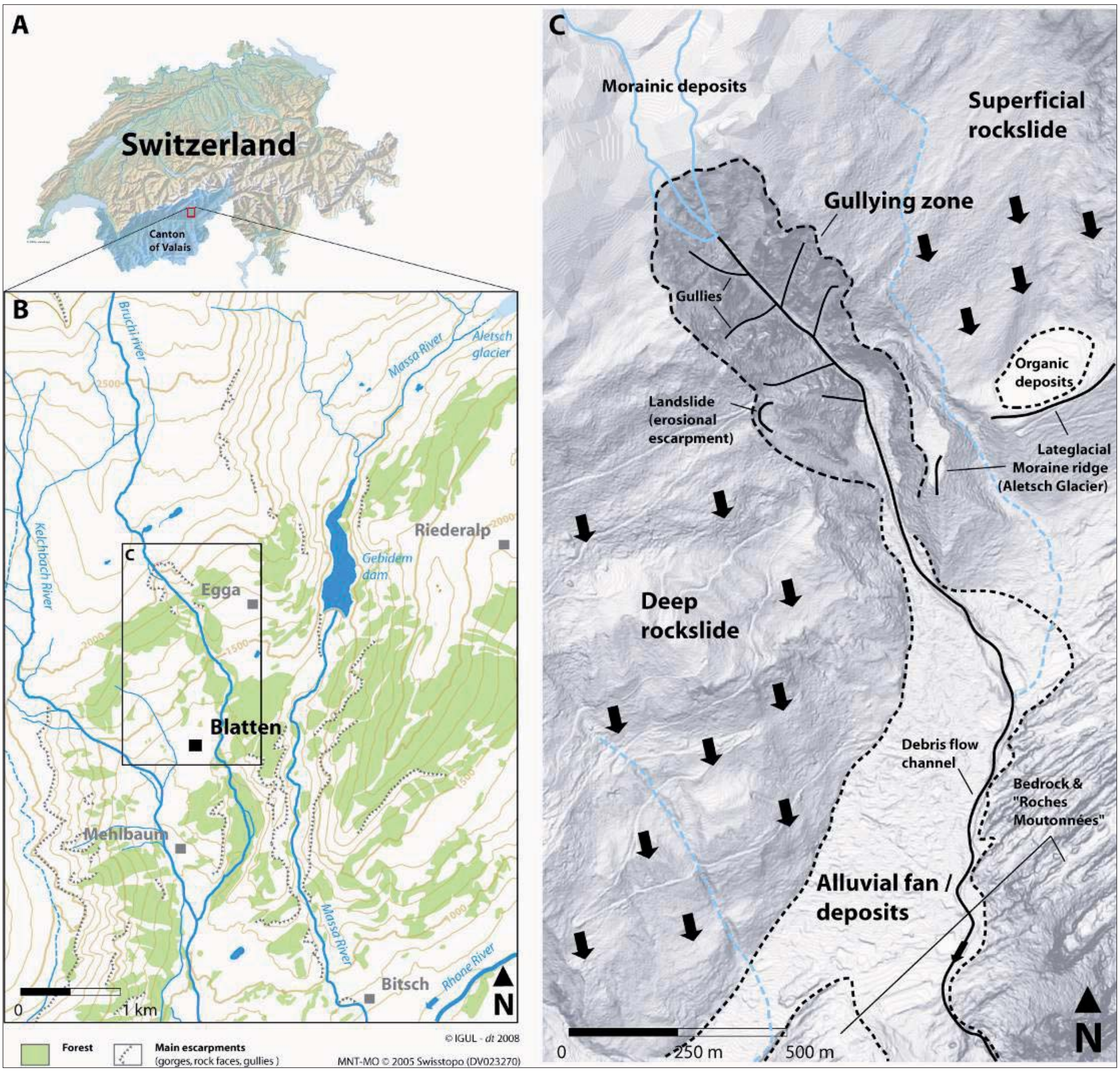

Fig. 1: Localisation map of the study site and main geomorphological features. MNT-MO © 2005 Swisstopo (DV023270)

Then, as return and frequency periods are often used in hydrological studies, we outlined that these parameters are quite random in small torrential watersheds where bed load transport phenomena are common and not always related to heavy rainfall. A better cartographic recognition of the slope system and especially the sediment transfer processes should improve the knowledge on hydrological hazards in alpine environments.

3. Research area: Bruchi torrent (Swiss Alps)

Because of time and financial restrictions, a perfect quantitative evaluation of the sediment storage in torrential systems is not the objective of our study[2], but a good cartographic recognition can help to understand and detect the problematic zones. Three sites, situated in the Canton of Valais (Switzerland) are currently being investigated: Bochtür (Agarn), Tsarmine (Arolla), and Bruchi (Blatten). This paper concerns only the latter.

The Bruchi torrent is located north–northeast of the village of Blatten bei Naters (Valais, Swiss Alps, 46° 22' N/7° 59' E) (Fig. 1). It is a perennial watercourse that is the main tributary of the Kelchbach torrent, which drains the right part of the Massa valley that was eroded by the Aletsch glacier, the largest glacier of the alpine range. The Bruchi torrent source is situated at about 2800 m a.s.l. in a depression under the Hohstock mountain (3226 m) (Fig. 1). The watercourse then meanders through pastures developed on granitic "roches moutonnées" belonging to the crystalline Aar massif. In contrast to typical torrential systems, the drainage basin corresponds to a highly gullied zone midfield of the watercourse (1600 – 2000 m a.s.l) (Fig. 1). Thus gullies take place in a slope characterised by mass movement fostering gneiss erosion and rockfalls. All the known debris flow events triggered from this instable zone. Archives of past events of the Bruchi torrent are rare and incomplete and

2 This paper provides results of a PhD thesis project called "Geomorphological mapping of sediment transfer processes in high mountain watersheds" (2007-2010).

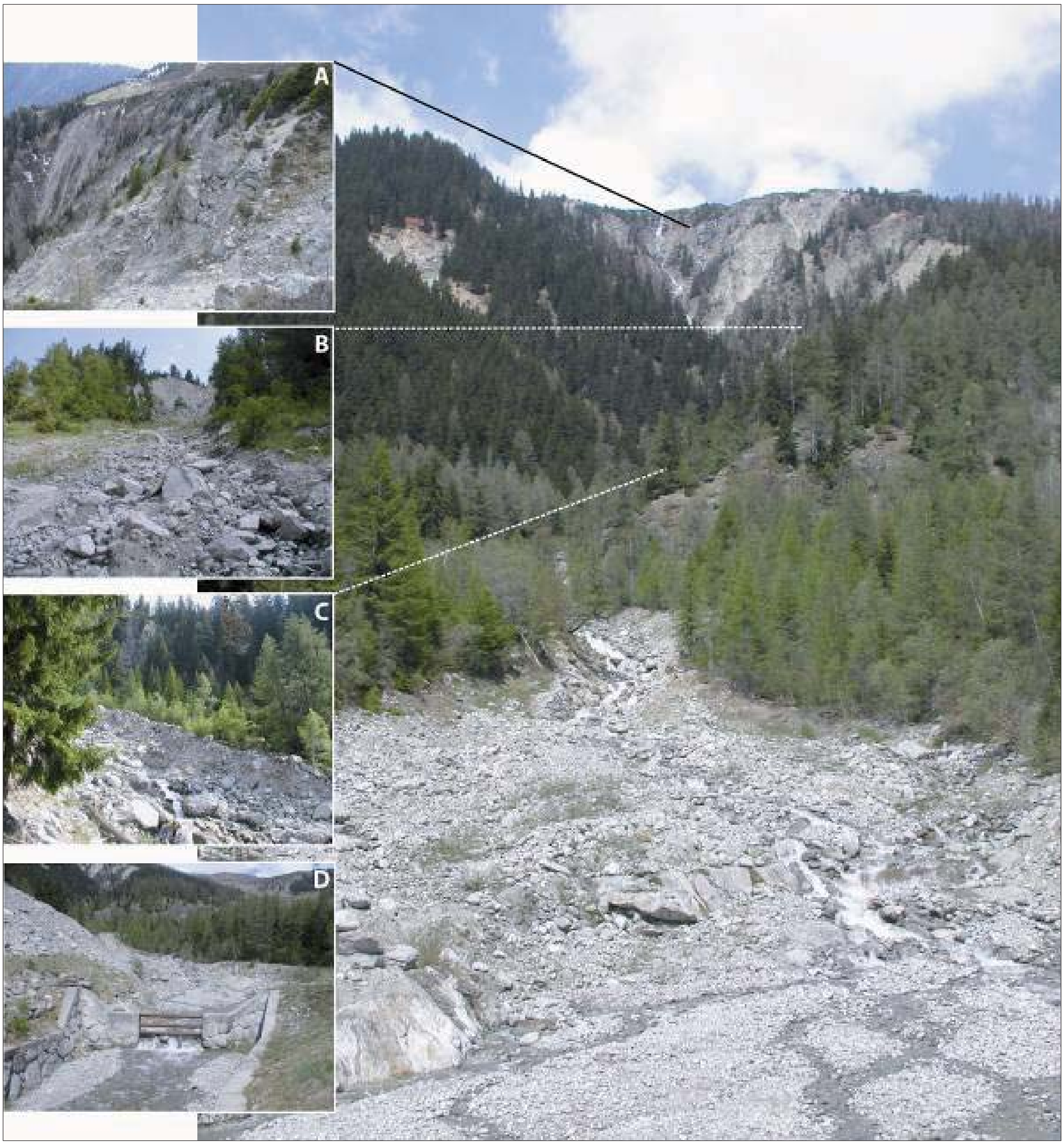

Fig. 2: General view upstream of the three parts of the torrential system of Bruchi with zooms on different parts of the watershed. A: Fractured rocks at the top of the drainage basin; B: lateral supply of sediments by debris flows triggering on a landslide; C: lateral levee in the channel (transport zone); D: deflection dam and sediment bars on the alluvial fan. Zone "B" shows characteristics of a landslide and an erosional escarpment where small debris flows are triggered. The problem is how to map this kind of zone at large scale: is it an erosion or an accumulation zone? Actually both processes are often superposed in the field and complicate distinction of erosional and accumulation landforms. Pictures: David Theler, April 2007.

only concern two periods (1905-1907) and four events after 1987 (Bollschweiler et al. 2007). Dendrogeomorphological investigations on 401 trees were carried out by Bollschweiler et al. (2007) to retrace spatial and temporal extension of old debris flows. They highlighted 53 different natural levees and 164 frontal lobes. Eleven previously active channels were identified and almost forty events were recognised between 1867 and 2005. In order to prevent future damage to infrastructures (roads, buildings, etc.) caused by debris flows, protection measures were undertaken in the late 1970s (debris retention basin and deflection dam) and the banks of the main channel were reinforced. After significant overbank sedimentation on 4 July 2001 caused by several debris flows, the existing retention basin and the deflection dam were enlarged (Bollschweiler et al. 2007).

4. Outline of methodology

Regarding topographic conditions, accessibility of sites, land cover (vegetation) – that can hide some processes and landforms – in mountainous environments and the expected level of cartographic details, traditional geomorphological mapping based on field surveys becomes difficult sometimes. Topographic attributes derived from DEM are, therefore, more and more often used in geology and in geomorphology (Van Asselen & Seijmonsbergen 2006). Hence, GIS applications in ArcMap software using digital elevation models can be used to analyse the specificity of the hydrographical network and, moreover, to evidence the localisation and the potential volumes of sediment supply zones.

4.1. DEM and ArcGIS tools

Since 2000, the Federal Office of Topography (swisstopo) provides two types of digital elevation models based on very high accuracy laser measurements (one replicating land surface with soil, vegetation and buildings called "MNS" and the other showing gross topography, only below 2000 m a.s.l., called "MNT-MO"). The precision is about ± 150 cm for the first model and ± 50 cm for the second one, with, for both of them, a density of points of 1/m^2 (swisstopo 2007). The global approach consists in simulating the hydrographic network and then delineating sub-watersheds in the sediment source zone where debris flows or bed load transport phenomena are triggered. Generally, the triggering area corresponds to the drainage or contributing area, but in our study site, it is located midfield of the stream. We describe the different steps here.

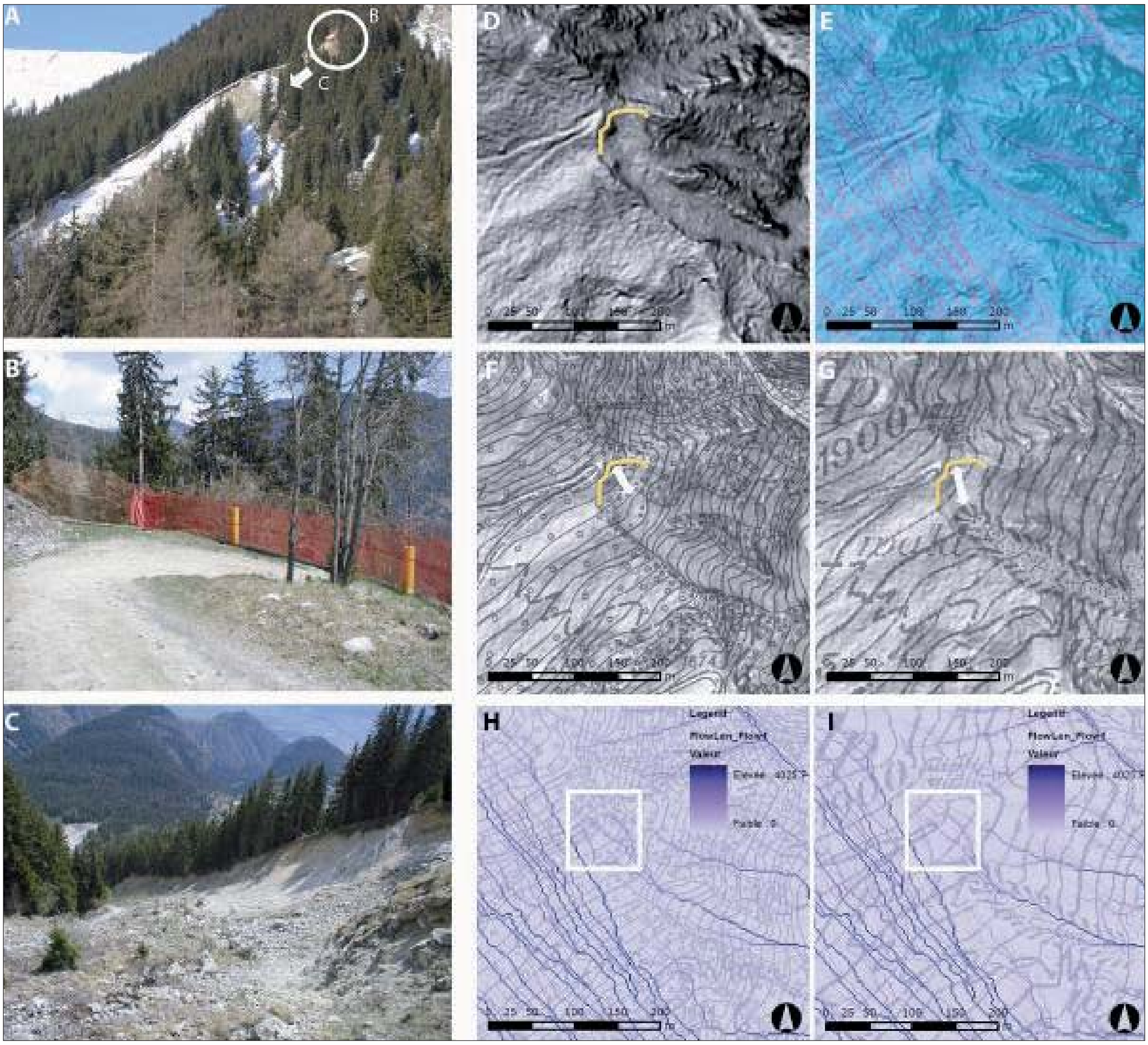

Fig. 3: Use of "Flow_Length tool" on "MNT-MO" DEM applied in a small landslide acting as a sediment supply zone. A: View of the scarp from the monitoring station (picture: David Theler, February 2007); B: Detailed view of the forestry road safety net; C: View downslope of the landslide. D to I: excerpts of the aerial view of the landslide with - hillshade and scarp (D), - hillshade and Flow_Length (E), - hillshade and topographic map (1982) at 1:10,000 scale (F), - hillshade and topographic map (1986) at 1: 25,000 (G), - topographic map (1982) at 1:10,000 scale and Flow_Length (H), - topographic map (1986) at 1:25,000 scale and Flow_Length (I) . MNT-MO © 2005 swisstopo (DV023270).

First the "Hillshade" function greatly enhances the visualization of a surface for analysis or graphical display – especially when using transparency – by determining illumination values for each cell in a raster and thus, obtaining the hypothetical illumination of a surface. The "Fill" tool fills sinks in a surface raster to remove small imperfections in the dataset. It creates an elevation grid without depressions that will be used for the other steps. The tool "Flow direction" creates a raster of flow direction from each cell to its steepest downslope neighbour. The output of the Flow Direction tool is a raster map whose values range from 1 to 255. The "Flow accumulation" tool calculates the accumulated flow at a point. As the accumulated weight of each cell is based on the flow coming from the upper related cells, this phase is based on the "Flow Direction raster map". As explained in the ArcGIS Help "if no weight raster is provided, a weight of one is applied to each cell, and the value of cells in the output raster will be the number of cells that flow into each cell. Cells of undefined flow direction only receive flow; they will not contribute to any downstream flow". The accumulated flow is based on the number of cells flowing into each cell in the output raster. Output cells with a high flow accumulation constitute areas of concentrated flow and can be used to identify stream channels, and hence, potential erosion and transfer zones. The "Snap Pour Point" tool is used to ensure the selection of points of high accumulated flow when delineating drainage basins using the Watershed tool. Snap Pour Point will search within a snap distance around the specified pour points for the cell of highest accumulated flow and move the pour point to that location. Before using this tool, it is necessary to create pour points (shapefiles) that will determine the watershed. This step is realised by displaying the Flow Accumulation raster. They correspond to the watershed exit, which is the lowest point along the boundary of the watershed. Finally, the "Watershed" tool allows us to determine areas that drain water (and other substances like sediments) to a common outlet as concentrated drainage. This area is normally defined as the total area flowing to a given outlet or pour point.

The above description is just a non-exhaustive overview of some tools that can help the geomorphologist working in difficult environments. Other tools have to be used, like the "Flow Length" tool, whose primary use is to calculate the length of the longest flow path within a given basin (Fig. 4). Using the "UPSTREAM" option, it usually allows the time of concentration of a basin in flood studies to be calculated. In our study, it proves to be better than the Flow Accumulation option, because it allows existing and potential gullied zones and sub-drainage basins to be defined more precisely. It also allows us to predict the evolution of dynamic zones like gullies, by analysing the lag between the DEM and old topographic maps. An example is given below for a small landslide acting as a supply zone in the catchment area of the Bruchi.

4.2. Field investigations

In addition to field geomorphological mapping, aerial photograph interpretation and DEM analysis, different methods are used to estimate sediment fluxes and denudation rates, as proposed in the SEDIFLUX manual for debris flows environments (Beylich & Warburton 2007) or by Schrott et al. (2003). These complementary measurements should confirm results obtained by GIS applications. At the Bruchi site, reference coloured lines, painted stones and wooden markers were installed in the summer of 2007. In June 2007, a monitoring station was installed, with a pluviometer, a thermometer and a camera that takes a picture of a sector of the watershed every day. Moreover, at the Bochtür site (site 2), 34 blocks were marked for calculating displacement rates by using real time kinematics GPS. The results obtained by field survey are not discussed in this paper.

4.3. Geomorphological mapping within GIS

The insertion of geomorphological maps in GIS is not always easy because of the high number of different landforms, the complex graphics used in classical geomorphological maps, and the rather poor graphical tools of some GIS software (Schoeneich et al. 1998; Gentizon et al. 2001). Nevertheless, recent graphical improvements in GIS software now offer new possibilities in geomorphological mapping within GIS environments (Gustavsson et al. 2006) and even more possibilities in estimating sediment volumes stored in some geomorphological reservoirs (Otto 2006). Nevertheless, it may be very difficult to quantify differences in sediment yields using a geomorphological map drawn with a morphogenetic approach (Schoeneich 1993), because this kind of mapping distinguishes the different landforms according to the processes, but not according to the intensity and frequency of current processes. This problem may be illustrated with three examples. Firstly, in alpine areas, rock glaciers and talus screes containing permafrost potentially represent large storage systems of unconsolidated materials, where collapses or debris flows may occur. The ice content and its distribution within the landform, as well as the thermal regime of ice and sediment, are important factors influencing the triggering processes; geomorphological mapping based only on field observation is not sufficient for evidencing the importance of these factors. The second example concerns moraines that are also important sediment storage systems. Old morainic deposits (Glacial Maximum, Lateglacial) do not have the same sedimentary dynamics as contemporary or Little Ice Age deposits, not covered with vegetation and sometimes rich in ice; morphogenetic mapping is again not sufficient for distinguishing potentially mobilised sediment volumes. The last example concerns the relationship between weathering and the position of the landforms within the watershed. Zimmermann et al. (1997), Bardou (2002) and Veyrat-Charvillon & Memier (2006) demonstrated that the contribution to debris flows by current gravitational accumulations resulting from rock alteration depend on the position of the weathered outcrop in the catchment (connected or not to the watercourse). These examples demonstrate that geomorphological maps

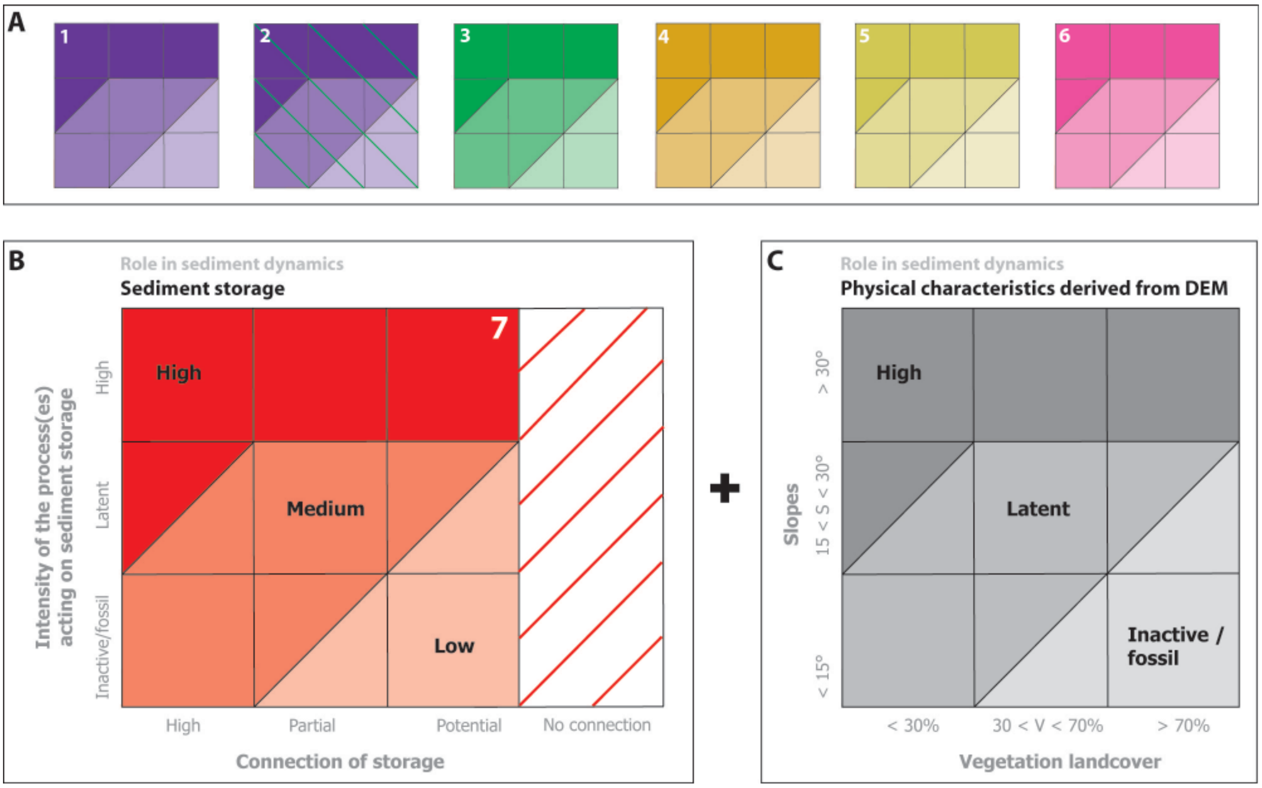

Fig. 4: Two matrixes depicting the importance of the sediment storage in the global sediment dynamics. AB: Sediment storage differentiated depending of the morphogenesis. 1: Glacial sediment storage (morainic deposits and ridges); 2: Fluvio-glacial sediment storage (fluvio-glacial deposits and kames); 3: Fluvial sediment storage (debris fans, alluvial deposits, natural levees etc.); 4: Gravitational sediment storage (talus screes, landslides, rockslides etc.); 5: Organic sediment storage (different types of soils); 6: Periglacial sediment storage (rock glaciers, talus screes etc.) and 7: "Structural" sediment storage (free faces, rock escarpments). C: Physical characteristics derived from DEM (slopes and vegetation). For example, high altitude screes (pink matrix) where traces of debris flows are visible will be classified as sediment storage of high importance because of the potential of unconsolidated material that could be mobilised by overflow. Free faces directly connected to a main debris flow channel, without vegetation and composed by highly fractured rocks will be drawn in dark red.

are only basic information for sediment transfer evaluation and that processing within a GIS (e.g. classification of landforms according to their dynamics or their position in respect to the watercourse) opens new opportunities for a more quantitative use of classical geomorphological maps.

In this study, two matrixes were established (Fig. 4) – inspired by hazard mapping in Switzerland (OFAT et al. 1997) – in order to compare the importance of the (or several) storage in each sub-drainage basin. The nature of the sediment storage is differentiated depending on its morphogenesis (Fig. 4A). A distinction is made between glacial, fluvial, fluvio-glacial, gravitational, organic and structural sediment storages. We consider free faces or rock escarpments on fractured or much folded rocks, which have quite the same behaviour as unconsolidated materials, as structural storages (Fig. 4B). The colours (Fig. 4AB) used to represent the morphogenesis of the sediment storage are the same as in the IGUL geomorphological legend (Schoeneich 1993). For this purpose we use a typical panel of colours in reference to principles established in the 1960's (Joly 1962) and recommended for unifying geomorphological mapping legends[3]. Connections of the sub-basin(s) with the main catchment area are also taken into account. Vegetation landcover is derived automatically from MNS and MNT-MO, as well as slope distribution (Fig. 4C). Homogenous polygons between vegetation land-cover and slopes are derived from GIS spatial analysis. Information is entered in the second matrix to characterise the role of the sediment storage in the global sediment dynamics.

We present two examples of sub-basins influenced by debris flows here (Fig. 5).

[3] Currently, there are almost as many geomorphological legend systems as geomorphologists! Few of them use the official colour system rigorously i.e. pink for periglacial landforms and processes, light blue for karstic ones, dark green for fluvial ones, beige for gravitational ones, red for structural features etc. Choices of colours also depend on the type of information contained in the map: morphogenesis, morphochronology, morphodynamics etc.

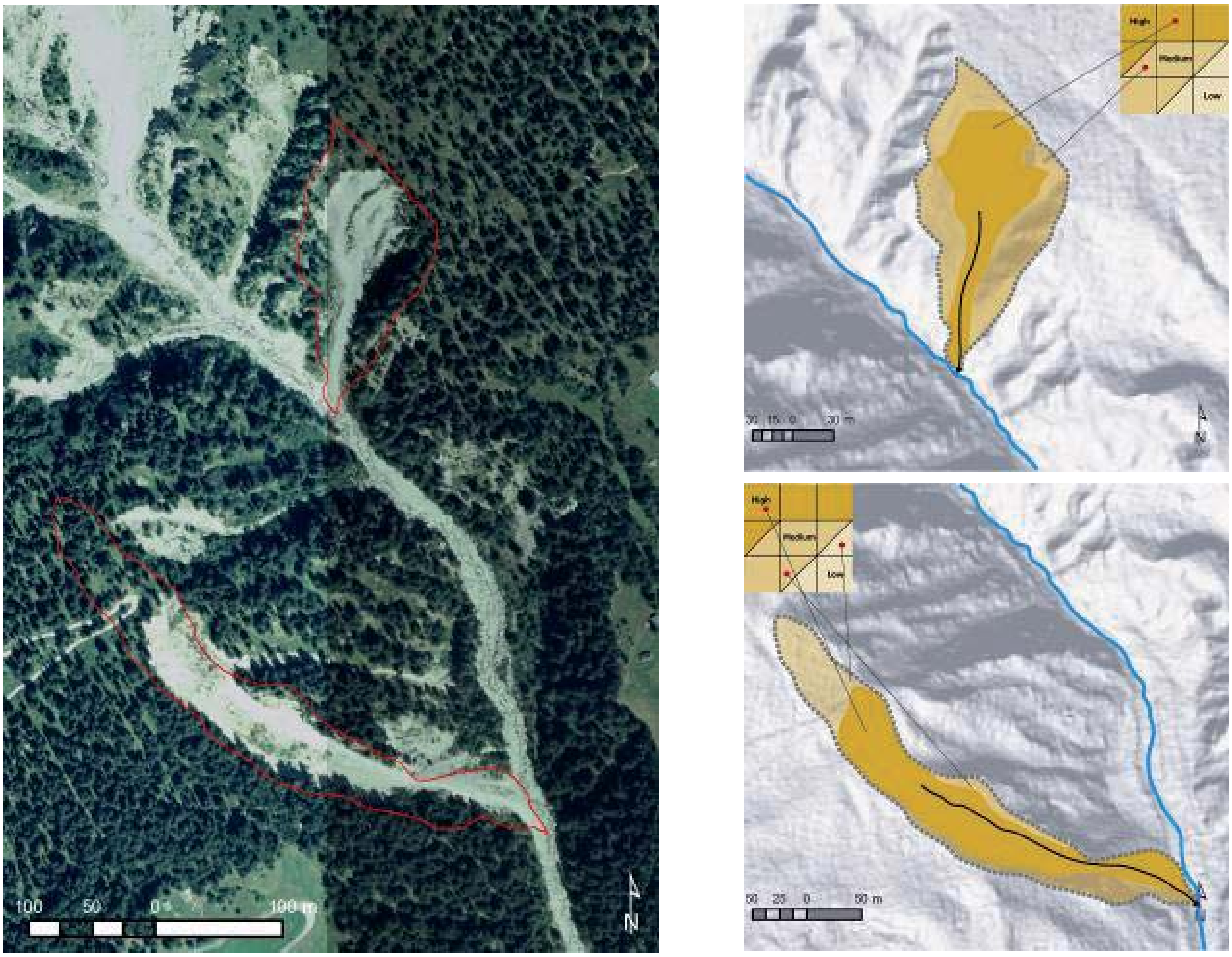

Fig. 5: Two examples of mapping sub-basins influenced by debris flows. Colours represent gravitational accumulations. Black arrows depict debris flow channels. MNT-MO © 2005 swisstopo (DV023270) and Swissimage © 2005 (DV023268).

5. Research perspectives

This simple approach provides another geomorphological approach of slope systems. Slope distribution analysis has to be performed to evidence specifically deposit and transfer zones and hence to map transitory deposits. The matrixes presented above are not definitive and have still to be tested in a complete drainage area especially for gravitational processes that have not the same behaviour as debris flows and interfluves where superficial overflow is the dominant process. Estimations of potential sediment volumes that may collapse in the main channel or transported by geomorphological processes are still not effective. Mapping of transitory deposits as natural levees has to be developed. Finally, results will be compared to field investigations and monitoring stations measurements and photogrammetric analyses will be carried out on pictures taken every day by a camera on a sector of the gullying zone.

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