

*Chapter 10*

**THE EFFECTIVENESS OF TORRENT CHECK DAMS TO  
CONTROL CHANNEL INSTABILITY:  
EXAMPLE OF DEBRIS-FLOW EVENTS IN  
CLAY SHALES**

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**ABSTRACT**

Debris flows consist of a fully saturated mixture of water, sediment and debris that can travel several kilometers. They are very dangerous phenomena claiming thousands of lives and millions of Euros each year over the world. One of the most effective techniques to manage torrential flood and debris-flow hazards is to construct series of check dams. While a huge amount of work has been performed on debris-flow triggering mechanisms, there are still few studies discussing the quantification of erosion by debris flows and the influence of the series of check dams on debris-flows scouring and deposition mechanisms. As well, theoretical and numerical work has been performed on the size, the shape and the structure of torrent check dams, allowing the definition of general design criteria; it is worth noting that less research has focused on the optimal location of these dams along the debris-flow track.

The first part of this chapter reviews the historical aspects of torrential mitigation in the French Alps; the second part presents some geomorphologic and kinematical characteristics of debris-flows events with a specific focus on the influence of check dams on scouring and deposition intensity. The third part proposes a methodological framework to evaluate the impacts of the number and the location of the check dams on the reduction of debris-flow intensity (in terms of flow thickness, flow velocity and volume). This framework is based on simple numerical calculations with a 1D debris-flow runout model. It is demonstrated that a few check dams located nearby the source area may decrease substantially the debris-flow intensity on the alluvial fans.

## 1. INTRODUCTION

Debris flows are found worldwide in various mountainous environments; they are a common type of mass movement and consist of fully saturated mixtures of water, sediment and debris that can travel, in a series of surges, several kilometers (Iverson, 1997). Observations of past events have revealed debris-flow velocities varying from  $0.5\text{m}\cdot\text{s}^{-1}$  to over  $20\text{m}\cdot\text{s}^{-1}$  (Goudie 1995; Hungr et al., 2001). Debris flows are widely recognized as one of the dominant geomorphic processes in steep mountainous terrain (Pierson, 1980; Costa, 1984; Johnson and Rodine, 1984; Takahashi, 1991; Scott et al., 1995; Corominas et al., 1996; VanDine and Bovis, 2002; Godt and Coe, 2007). The generic term “debris flow” can be broadly divided into “open slope debris flow” and “channelized debris flow” (Evans, 1982; Pierson and Costa, 1987).

This chapter addresses channelized debris flows only. Unlike other types of mass movements, the evaluation of the hazard requires, besides the prediction of the time occurrence and of the source material location, the assessment of the run-out susceptibility (e.g. O'Brien et al., 1993; Ayotte and Hungr, 2000; Laigle and Marchi, 2000; D'Ambrosio et al., 2007).

Debris flows most commonly mobilize from landslides, which occur when rainfall increases pore water pressure causing failure. However streamflow falling onto colluvium can also trigger debris flows (Johnson and Rodine, 1984). Various factors, including natural or human factors, influence debris flow activity (Figure 1).

The effects of debris flows are often catastrophic to the inhabitants. They can cause serious casualties and damages to properties. Impacts of debris-flow activity could potentially be reduced with the development of debris-flow mitigation actions (Figure 1). Debris-flow mitigation can be divided in (1) debris-flow forecast and (2) debris-flow protection. Classically, protection methods (Figure 2) can be broadly divided into passive and active control measures.

Passive measures are mainly land-use planning keeping the endangered areas free of settlements and infrastructure to prevent damages or public notification and education. Active methods of protection require some engineering once the hazard has been identified and assessed (VanDine, 1996); these methods start at the debris-flow source area and are continued through the debris-flow path down to the apex and the debris cone. They can involve remediation to reduce or eliminate the potential of a debris flow from occurring like reforestation (bio-engineering), or the design and construction of defence works to reduce the effects of the event (Figure 1, 2).

Considering this last point, one of the most important active protection works in order to reduce the debris-flow impact consists to modify the topography of the track by building series of check dams. Check dams are usually built in series in the transportation zone of a debris flow and/or on the debris-fan. In this chapter, we will discuss only check dams built near the source area or in the transportation zone; in such locations, check dams are used to: (1) minimize entrainment (essentially banks undermining, channel degradation and slope instabilities) along the stream (Figure 3A) and (2) reduce steep channel gradients locally in order to decrease the velocity and the kinetic energy (Figure 3B).

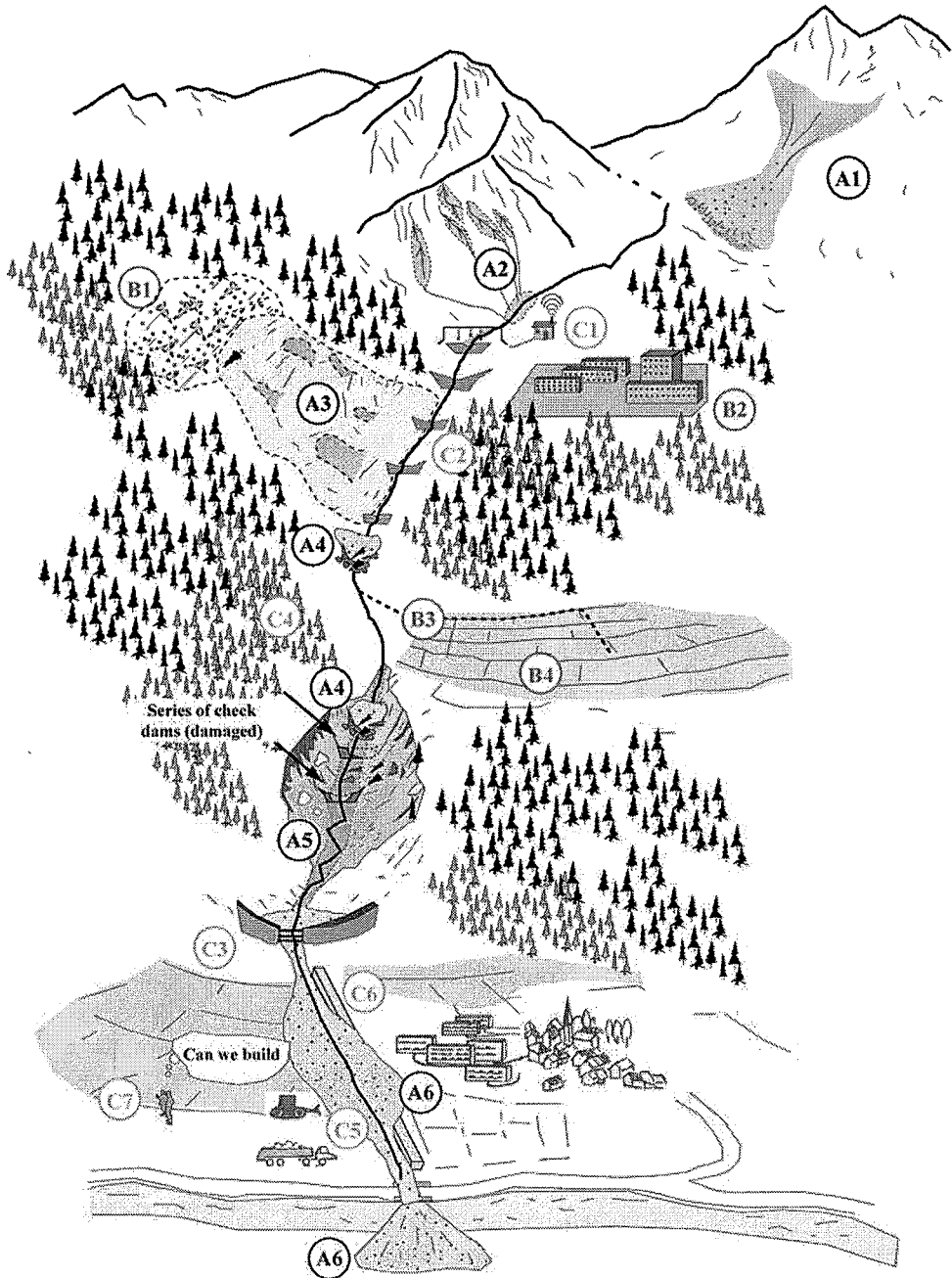


Figure 1. Concept of risk in a torrential watershed (modified from van Effenterre, 1982). A) Hydrological and geomorphological processes controlling the triggering/run-out/spreading of torrential event: (A1) active landslide (volume > 1000 m<sup>3</sup>), (A2) runoff, soil erosion and gully, (A3) area affected by several shallow landslides, (A4) Natural dam, (A5) bed incision, banks undermining and associated slope instabilities, (A6) overflowing and creation of a debris fan. B) Human impact on torrential hazard: (B1) deforestation, (B2) urbanization, (B3) defective drainage, water leakage and infiltration, (B4) abandonment of cultivated land, pasture and land degradation. C) Torrential mitigation actions: (C1) warning system, (C2) series of check dams, (C3) storage basin and straining structure, (C4) reforestation, (C5) periodic cleaning out of the storage systems, (C6) deflection walls, (C7) land use planning.

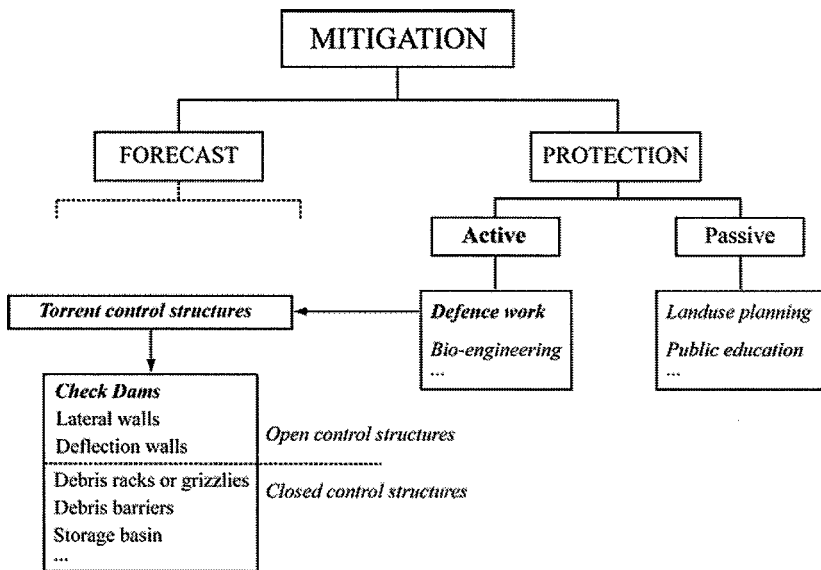


Figure 2. The mitigation concept (modified from Flageollet, 1988 and VanDine, 1996).

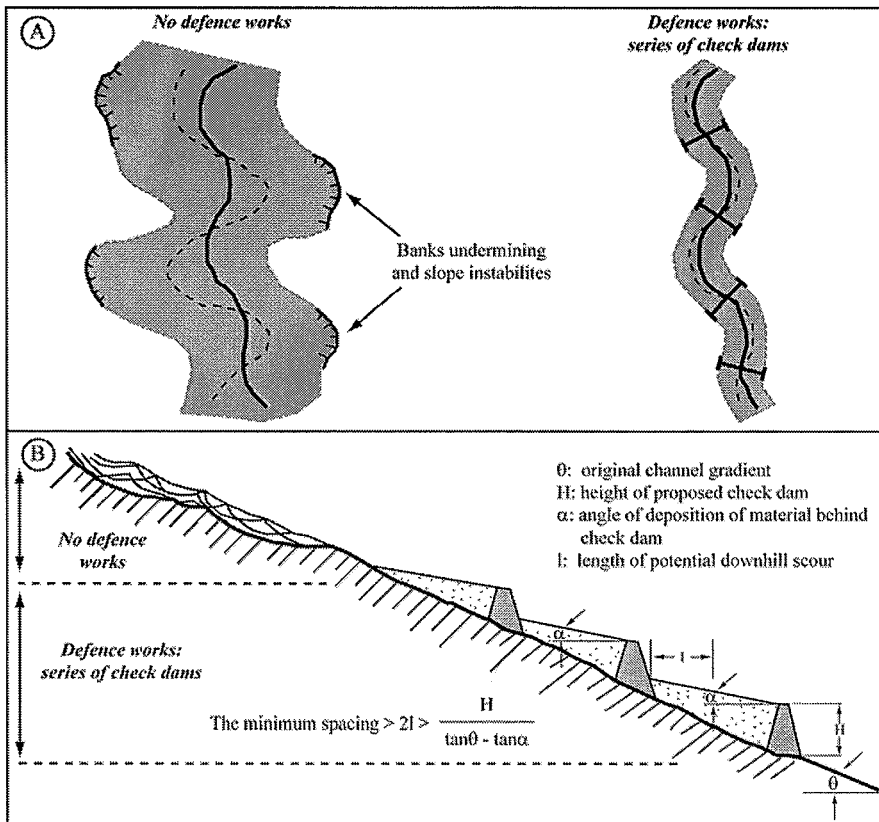


Figure 3. Usefulness of check dams to (A) minimize scouring phenomenon and (B) reduce channel gradients (modified from Deymier et al., 1994 and VanDine, 1996).

If considerable theoretical and numerical works have been performed on the size, shape and structure of torrential check dams, allowing the definition of general design criteria (Leys and Hagen, 1971; Eisbacher and Clague, 1984; Government of Japan, 1984; Heierli and Merk, 1985; Whittaker et al., 1985; Johnson and McCuen, 1989; Couvert et al., 1991; Armanini and Scotton, 1992; Chatwin et al., 1994; Deymier et al., 1994; Miyazawa et al., 2003), it is worth noting that less research has focused on the optimal number and location of these dams along the debris-flow track. For instance, some previous works have been focused on the spacing between check dams which depends on stream gradient, dam height, angle of deposition of material behind the dam, and downstream extent of potential scour. Chatwin et al. (1994) provide a formula for the spacing of check dams (Figure 3B). Nevertheless, there is still a lack for the optimal location and number of check dams to increase the efficiency of defence works.

The present chapter discusses some aspects of the effectiveness of torrent check dams to control channel instability through examples of debris-flow events in clay shales basins in the South French Alps. First an historical review of torrent check dams construction in the French Alps is presented. Then, some geomorphological and kinematical characteristics of two debris-flows events are discussed, with a specific focus on the influence of check dams on scouring intensity. Finally, a methodological framework, based on simple numerical calculations with a 1D debris-flow run-out model, to evaluate the impacts of the number and the location of the check dams on the reduction of debris-flow intensity is presented.

## **2. AN HISTORICAL OVERVIEW OF TORRENTIAL MITIGATION IN THE FRENCH ALPS**

During the 17<sup>th</sup> century in France, the forests were considered as an economic resource, especially for the construction of warships. Moreover, deforestation permits the extension of arable lands which were rare in mountainous region. These deforestations led to dramatic consequences with an important increase of land degradation and mass movement occurrence.

In France, the French Ministry of Agriculture and Forest is in charge to manage natural hazards and risks in mountainous areas. This dates back to 1860, when a special public service (RTM) was created by an act of the government as result of a flood disaster four years before. Indeed, a major hydrogeomorphological crisis occurs in 1856; intense thunderstorms have threatened the French Alps causing numerous severe floods. Two of the biggest French rivers, the Rhône River and the Saône River, caused such heavy life and property damage in the French Alps that neither the inhabitants nor the communities were able to deal with the aftermath.

From 1860 until today control measures are planned and performed by the RTM, because the interactions between runoff, erosion and torrential events on the one hand and vegetation, especially forest cover, on the other hand were already known (Figure 1). From the beginning the French RTM service tries to prevent or reduce mountainous hazards or their effects by a combination of different kind of watershed and land use management measures and technical defence works. Ten RTM offices were created for the all country, six in the Alps and four in the Pyrenees.

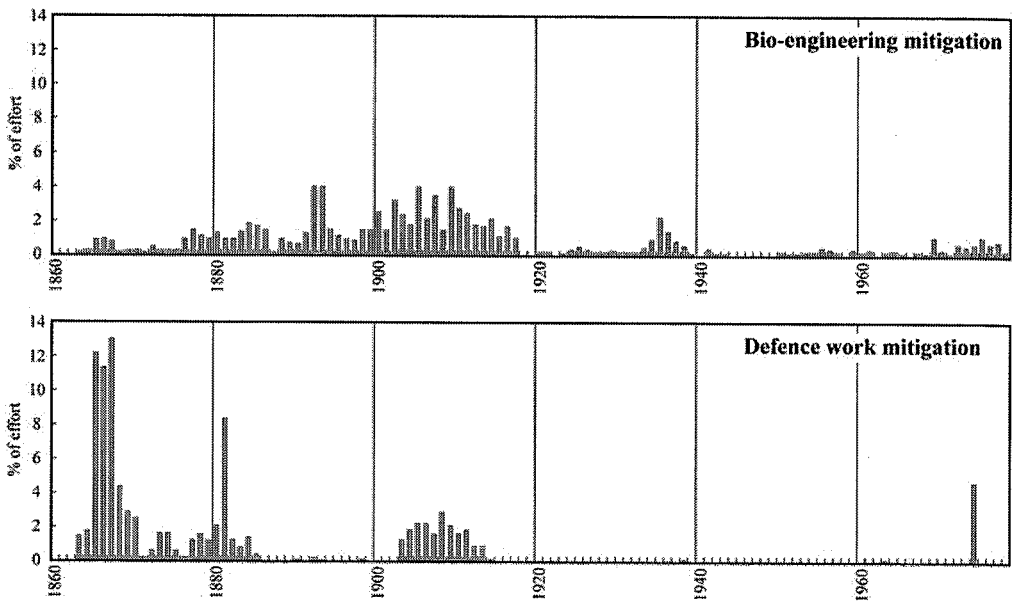


Figure 4. RTM effort from 1860 to 1940 in the South French Alps for (A) bio-engineering mitigation and (B) hydraulic engineering mitigation (in Liebault and Taillefumier, 2000).

The action of the RTM services has been conducted in three steps (Brugnot and Cassayre, 2002), (Figure 4):

- 1860 – 1882: a first law is adopted in 1860. This law creates “the RTM areas” which correspond to deforested regions that should be reforested. The main objective was to reforest 13,000 km<sup>2</sup> of bare soils. Additionally, the RTM service offers its technical support to local communities for the construction of technical countermeasures;
- 1882 – 1914: a second law is voted in 1882, it reinforced the RTM services through a considerable increasing of governmental funding. Gradually, the deforested areas are bought by the state. The construction of technical countermeasures (especially series of check dams) is increasing. Approximately one hundred torrents in the French Alps are equipped with defence works in 1905 (Figure 5);
- 1914 – 1940: the two world wars led to decrease governmental funding. The “RTM” services stop to build new series of check dams, but they still performed maintenance of the defence works and bio-engineering.

Most of the series of check dam built during these periods were masonry check dam made of dry stones (Figure 6A). This type of check dams have been progressively replaced by concrete check dams (Figure 6B, 7). Nevertheless, masonry check dams are still built nowadays in the French Alps and Pyrenees but mostly in the upper part of the torrential streams.

After the Second World War, the RTM policy enters into a long period (30 years) of inactivity. In fact, the national funding decreased substantially causing a lack of maintenance of all the defence works. Moreover, the RTM had severe difficulties to find workmen; most of them did not agree to work like hard labors.

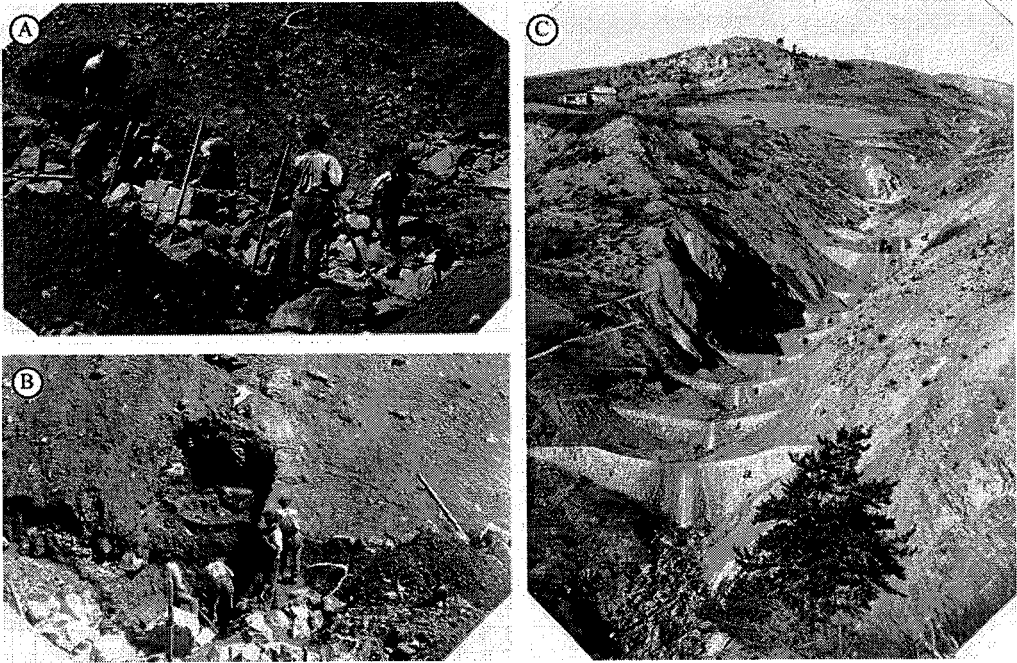


Figure 5. Construction of series of check dams in the Barcelonnette basin, South French Alps (A) and (B) Local inhabitants building a check dam in 1898 in the Faucon torrent, (C) A view on a series of check dams in the upper part of the Faucon torrent. (Courtesy of the RTM Services of Alpes-de-Haute-Provence).

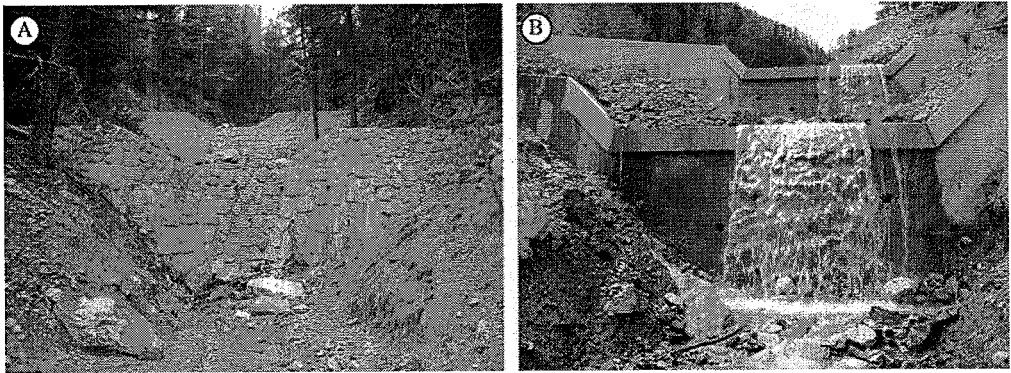


Figure 6. The two main types of check dams in the South French Alps: (A) photograph of a masonry check dam (Faucon torrent); (B) photograph of a concrete check dam (Champerousse torrent).

In parallel, during the past four decades (1960–2000), the French mountainous areas experienced major changes in population size, development patterns, economic conditions, and social characteristics. This is mostly related to the intensification of the tourism activity. These social, economic, and built-environment changes altered the French mountainous hazardscape in profound ways, with more people living in high-hazard areas than ever before. The strong development of specific equipments and accommodation spaces (ski resorts, hostels, holiday villages) increased the vulnerability of such mountainous areas. In the early 1970's two major events occurred:

- On February 10, 1970; an important snow avalanche killed 39 people in the ski resort of Val d'Isère;
- On April 16, 1970; a complex flow-type landslide threatens a youth hostel and killed 72 people (most of them were children).

These two catastrophic events had a huge impact on the French population. In 1971, the French government decided to redefine the tasks of the RTM services. Three new technical tasks were added to RTM: (1) participation in the elaboration of natural risks maps, (2) collaboration with the local authorities for urban planning and (3) providing information and knowledge to inhabitants concerning the prevention and rehabilitation in case of danger and disaster. Additionally, the RTM services get new national funding dedicated to the rehabilitation and maintenance of the defence works.

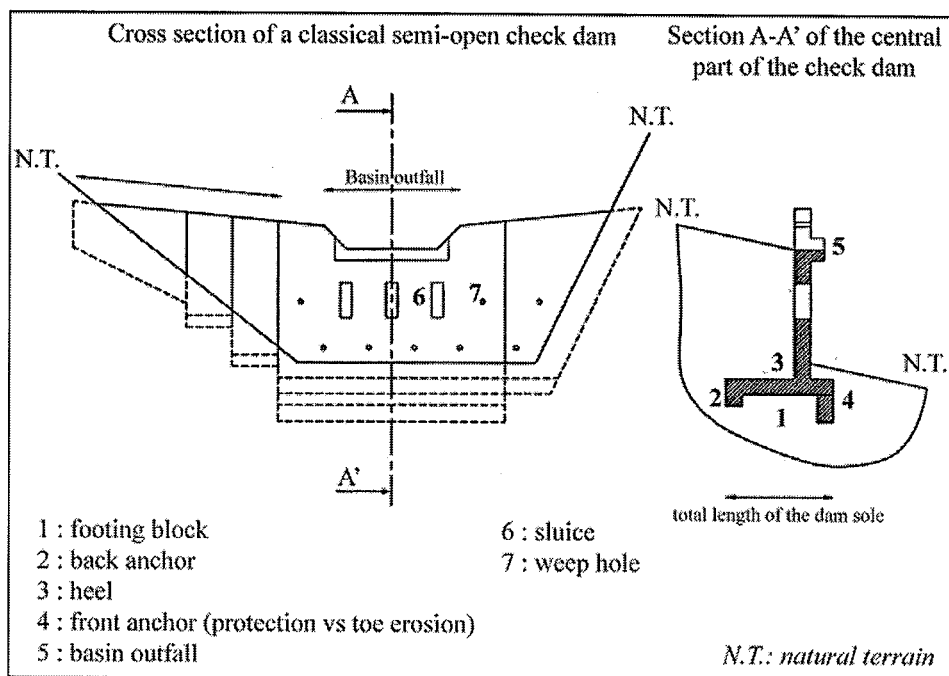


Figure 7. Sketch of a typical semi-open check dam (in Deymier et al., 1994).

### 3. INFLUENCE OF CHECK DAMS ON THE DYNAMICS OF DEBRIS FLOWS: EXAMPLE OF THE FAUCON TORRENT

The triggering of a debris flow has commonly described as occurring in one of two ways. The first considers the triggering of a debris flow as the result of a landslide that steadily transforms itself into a debris flow by liquefaction during its movement (Johnson and Rahn 1970). The second describes the triggering of a debris flow as a sudden failure of coarse debris in a high altitude channel or gully bed (Takahashi 1981). The input, or trigger, for this later mechanism stems from either snowmelt or intense rainstorms. The two ways of triggering mechanisms have been observed during two events which have occurred in the



Faucon torrent (South French Alps). During these two events, check dams conditions have played an important role on the debris-flow dynamics.

### 3.1. Study Site

The study was conducted within the Faucon torrent in the Barcelonnette basin, a steep, mountainous region. The Barcelonnette basin extends from 1100 to 3000 m a.s.l. (Figure 8), it is representative of lithological, geomorphological, climatic and landuse conditions observed in the South French Alps.

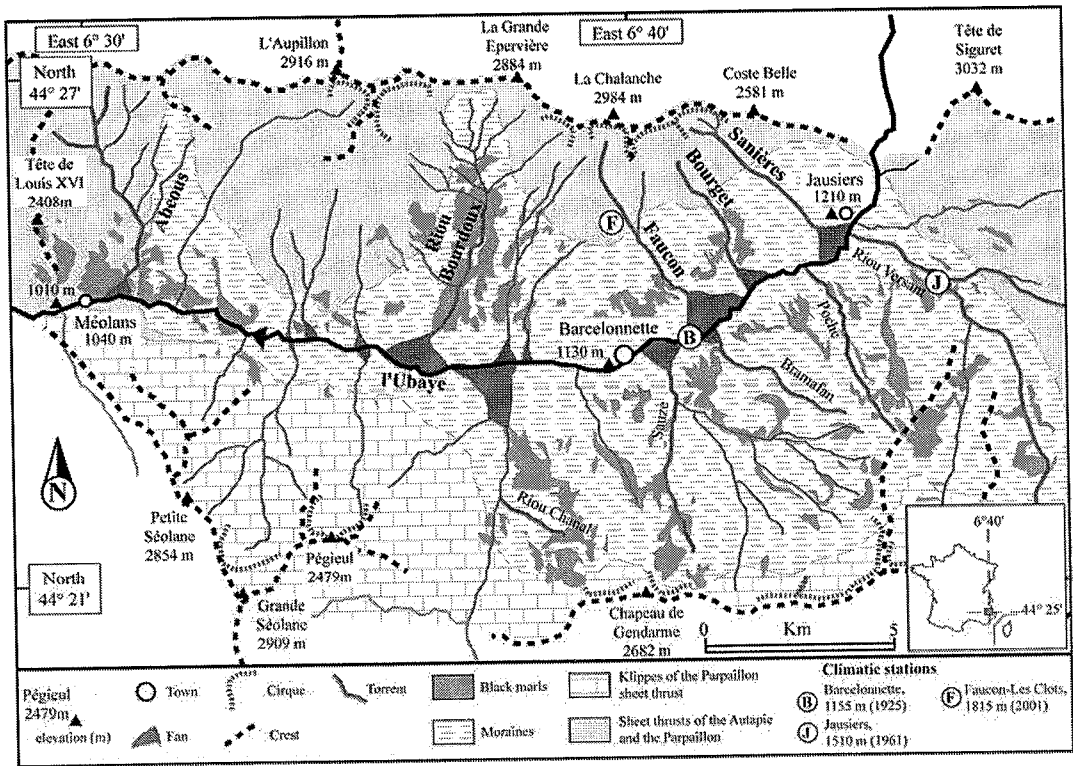


Figure 8. Morphological sketch of the Barcelonnette basin.

The basin is located in the dry intra-Alpine zone, characterized by (1) a mountain climate with a marked interannual rainfall variability ( $735 \pm 400$  mm over the period 1928-2005) and 130 days of freezing per year, (2) a continental influence with significant daily thermal amplitudes ( $> 20^\circ$ ) and (3) a Mediterranean influence with summer rainstorms yielding more than 50 mm.h<sup>-1</sup> on occasion. The basin is drained by the Ubaye River. Local slopes are characterized by a specific morphology:

- (a) At the upper part (1900 to 3000 m a.s.l.), slopes are steeper than  $45^\circ$  and consist of sheet thrusts of faulted calcareous sandstones. These slopes are often covered by non-consolidated debris varying in thickness between 0.5 to 5.0 m. Several debris tracks are affecting these slopes.

(b) At the lower part (1100 to 1900 m a.s.l.), gentle slopes (10-30°) consist of Callovo-Oxfordian black marls, mainly composed of fragile plates and flakes packed in a clayey matrix. Slopes are covered by various quaternary deposits: thick taluses of poorly sorted debris, moraines deposits and landslide debris.

These factors have given rise to the development of several mass movements (Flageollet et al., 1999), active torrential streams and debris tracks (Remaître et al., 2005a, 2008). Historical data concerning the torrential activity were collected in order to improve the current information about hazard. In the period between 1850 and 2005, 561 historical torrential events were found through the review of catalogues, newspapers, monographs, technical reports, bulletins and scientific papers (Figure 9, 10). The type and quality of information collected, and the methodologies used to analyze the data can be found in Flageollet et al. (1999) and Remaître (2006). The analysis has allowed verifying that flash floods (461 events) have been the most common types of torrential activity. 100 debris-flows have been recorded. The spatial distribution of historical debris-flows shows that they have occurred mainly in the torrents located on the south-facing slope of the Barcelonnette basin. Indeed, 90% of the debris-flow events were recorded in five torrents (Figure 9): Riou-Bourdox, Sanières, Faucon, Bourget and Abeous.

The Faucon torrent is a tributary of the river Ubaye and it is one of the most active streams in the Barcelonnette basin (Figure 11). The channel is 5500 m in length and its mean slope is more or less 12° ranging from 50° (headwater basin) to 3° (debris fan). Altitudes range between 2984 and 1130 m a.s.l.

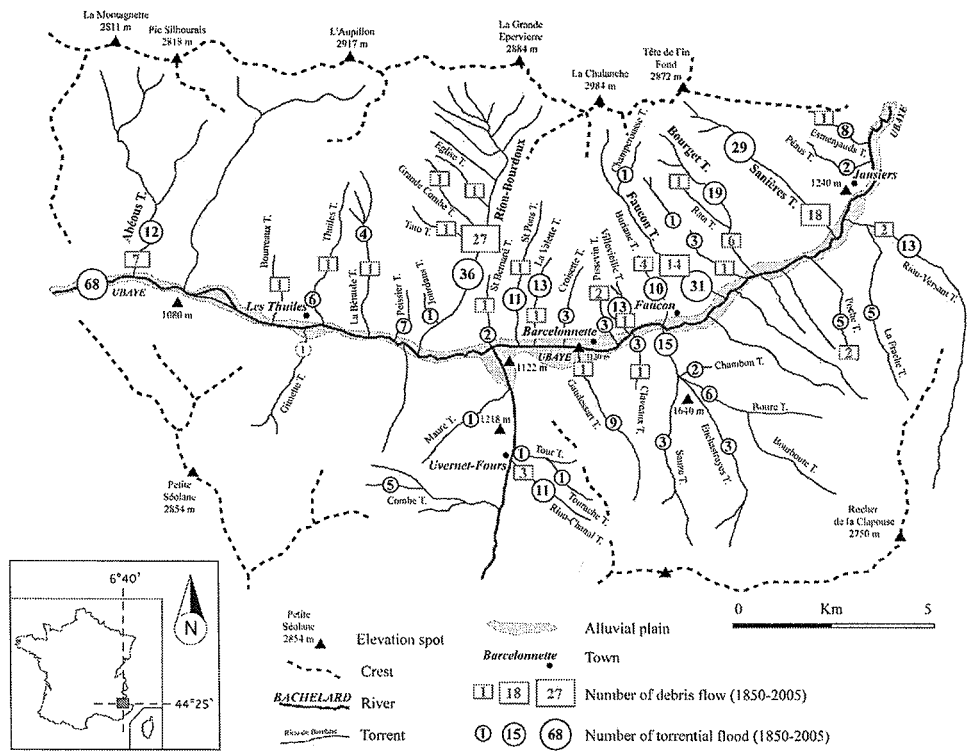


Figure 9. Map of the torrential activity in the Barcelonnette basin.

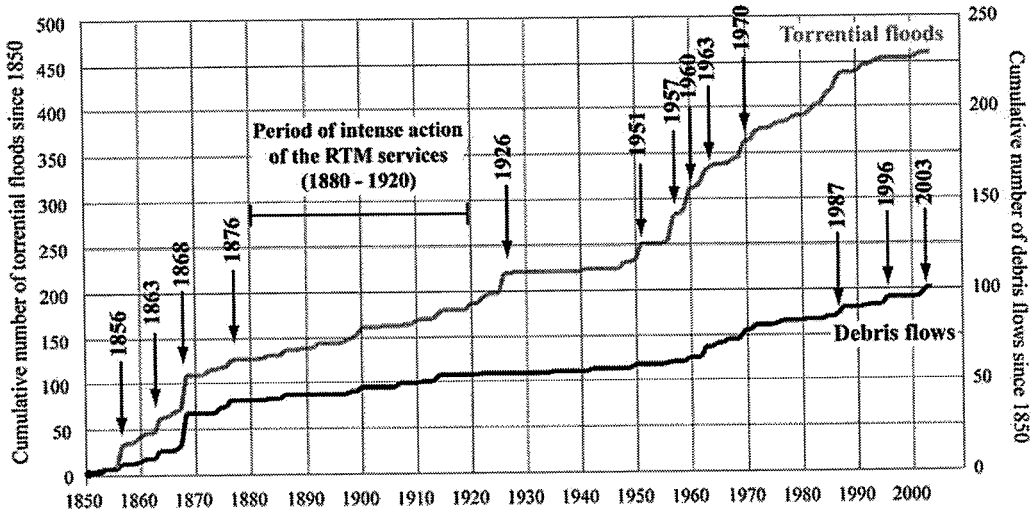


Figure 10. Torrential activity in the Barcelonnette basin (1850-2004). Torrential floods and debris flows have been considered.

The Faucon torrent exhibits a steep gradient (ranging from step-pools to waterfalls), a bed-rock channel with gorge and cascading sections and a basal debris fan. Channel morphology is characterized by two main types of cross-section, a V-shaped profile and a flat-floored cross profile. It contains abundant sediment (including multiple streamflow and debris-flows deposits), and has significant slope-channel coupling (scree and shallow stream-side landslides).

Since 1850, fourteen major debris flows have occurred in the torrent. In order to prevent flooding, authorities have built a hundred check dams on the torrent since the 1890's; but only a half of them are still efficient. Two main types of check dams can be observed: concrete check dams and masonry check dams. Three major events have occurred in the two last decades; two debris flows in 1996 and 2003 and one torrential flood in 2002 (Remaître, 2006; Remaître et al., 2005a, 2008, 2009). The check dams have been inventoried in a GIS database. For each dam, several characteristics have been recorded like the type, the size, and the year of construction. A sample of the database is available in Remaître et al. (2008); the complete database is available on request.

### 3.2. Methodology

Two detailed case studies of debris-flow events are presented here. In each case, the debris flow took place in the Faucon stream. Each of the events reveals strong relations between the debris-flow kinematic and the conditions of the series of check dam before the event that allow a better understanding of the processes involved in debris-flow generation (initiation and scouring). The erosional and depositional processes have been analyzed through a methodology associating detailed morphological mapping and sedimentological analysis of both the source material and the debris-flow deposits.

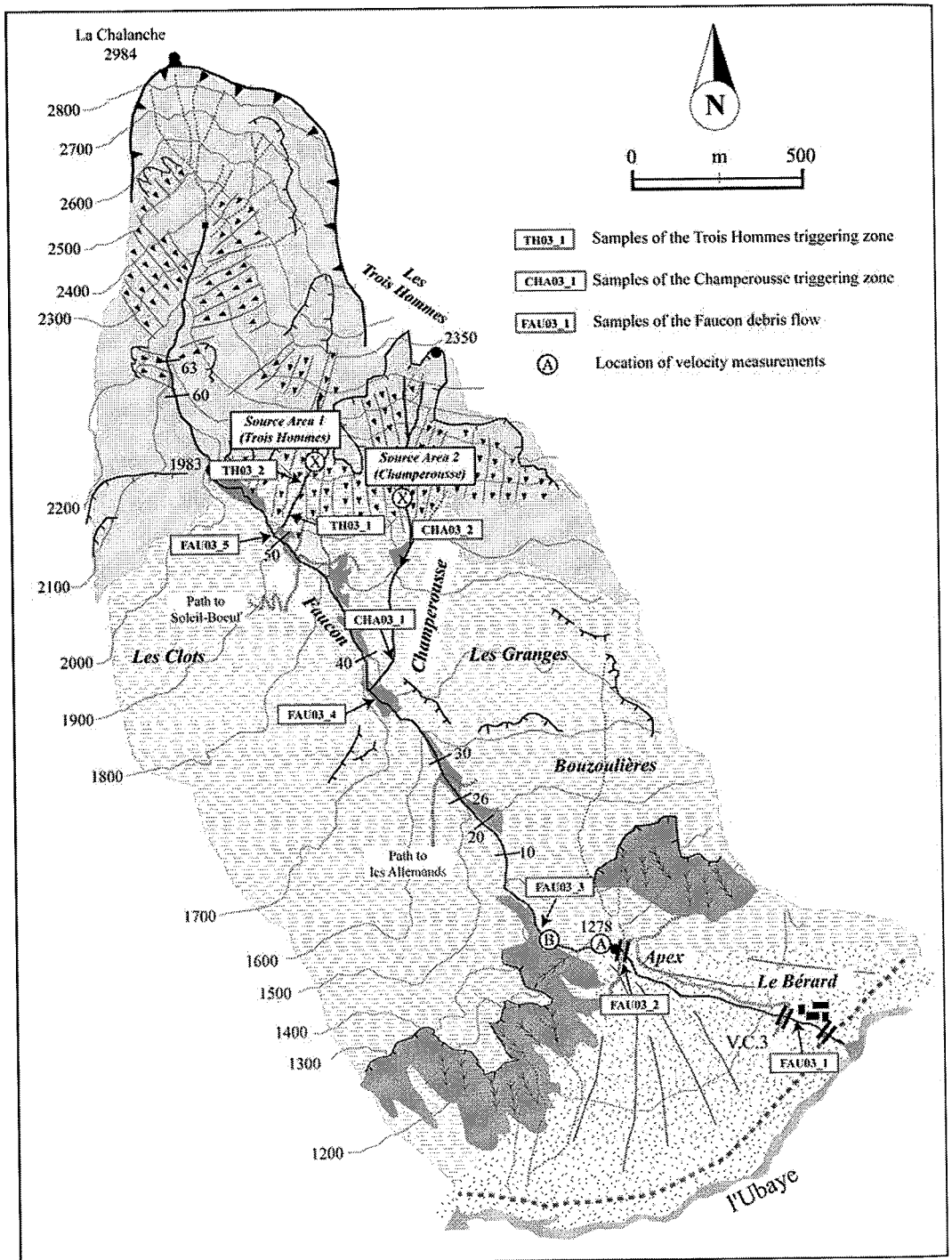


Figure 11. Morphological map of the Faucon watershed.

### 3.2.1. Geomorphological Observations

Herein, the debris-flow volume variations along the flow track have been carefully estimated. Indeed, knowledge of the volume is fundamental for the hazard assessment on the alluvial fan. The estimation of the volume has been realized on the basis of a field survey before and after the debris-flow event. A two-step methodology has been adopted:

- 1) A general appraisal between the volume of the source area and the volume of the deposits in the channel and the debris fan/cone;
- 2) A more detailed study of the debris-flow volume variations during the run-out based on the volume estimation for each torrential stretch. In order to simplify the volume calculations, morphology of the debris-flow (Figure 12A) and check-dams location and characteristics (Figure 12B) have been implemented in a GIS.

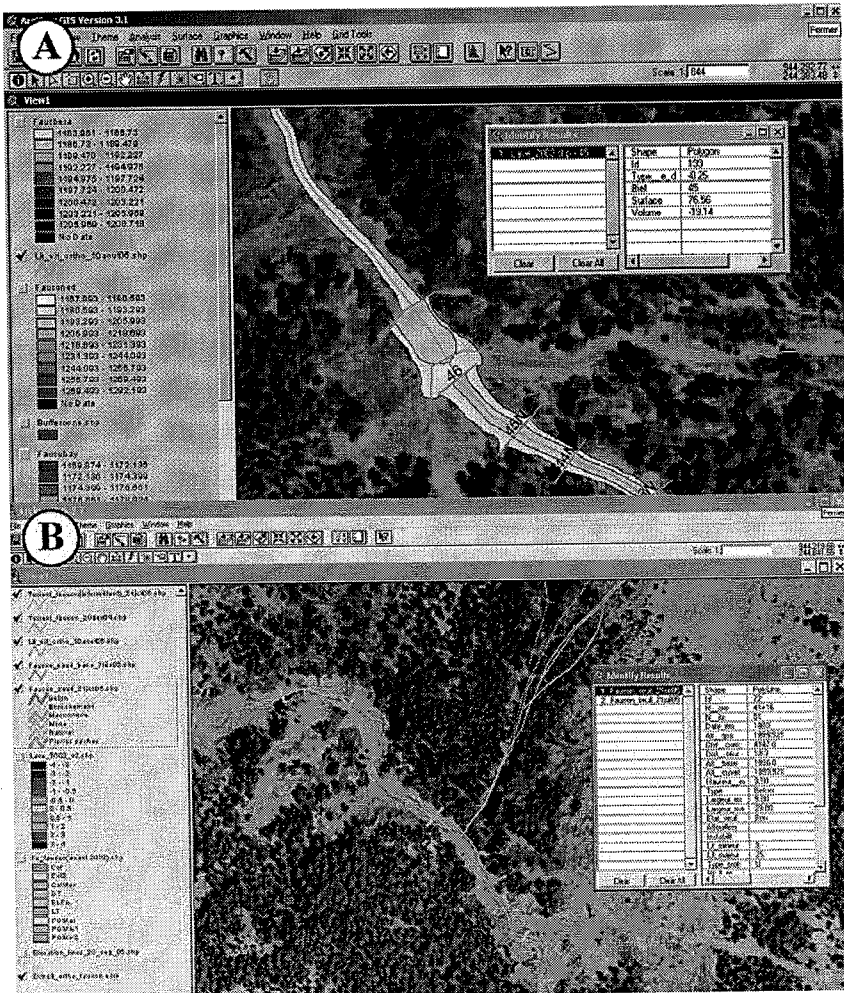


Figure 12. GIS database of the Faucon torrent. (A) Morphology of the 2003 debris flow (height of deposits and scouring depth), (B) Check dam location and characteristics.

### 3.2.2. Material Characterization

The sedimentological properties of the debris-flow deposits have been investigated in order to:

- (1) Define the evolution of the debris-flow characteristics during the run-out in terms of grain-size distribution;
- (2) Identify the main outcropping surficial formations involved in these events.

For the 1996 debris flow, five samples of debris-flow matrix have been collected (Remaître et al., 2005a). For the 2003 event, nine samples of debris-flow matrix were gathered at widely spaced locations along the main axis of the debris-flow event (Figure 8). Debris-flow deposits were sampled at 20 and 50 cm depth; the average weight of the samples was about 50 to 150 kg. All samples were oven dried and sieved from less than 20 mm to 0.050 mm, the fraction > 20 mm has been measured and characterized (petrography) in the field. The proportion of fines (<0.050 mm) was analyzed by laser diffractometry. Some additional samples were collected using the sand replacement method in order to define the bulk density (dry and wet). A complete description of the methodology and results can be found in Remaître et al. (2005b) and Remaître (2006).

## 3.3. RESULTS

### 3.3.1. The 1996 Debris-Flow Event: Influence of Check Dams on the Triggering

On Monday August 19, 1996, between 4:00 and 6:30 p.m. in the middle Ubaye valley, a debris flow was triggered by an intense and local thunderstorm. Indeed no rainfall was recorded by the pluviograph located at the Faucon alluvial fan. Several inhabitants provided eye-witness descriptions of debris flow.

They describe flowing masses of muddy-bouldery debris, first moving with pulsating waves "slower than a running man", and then rushing downward at high speed. According to eye-witnesses and the French Forest Office, the total duration of the event was about 2 ½ hours. The debris flow caused moderate damage and the main road across the alluvial fan was cut for several hours.

Concerning the interpretation of the 1996 debris-flow event, the reader must keep in mind that all the field observations were collected two years after the event. Thus, all the interpretations have to be carefully considered.

This warning is also valid for the analysis of run-out and deposition. Nevertheless, the sampled debris-flow site showed good preservation of flow track/levee curvature and shape. Additional observations and data concerning the characteristics of the 1996 event (rheology, sediment budget, back-calculated velocities and discharges, run-out modeling) can be found in Remaître et al. (2005a, b).

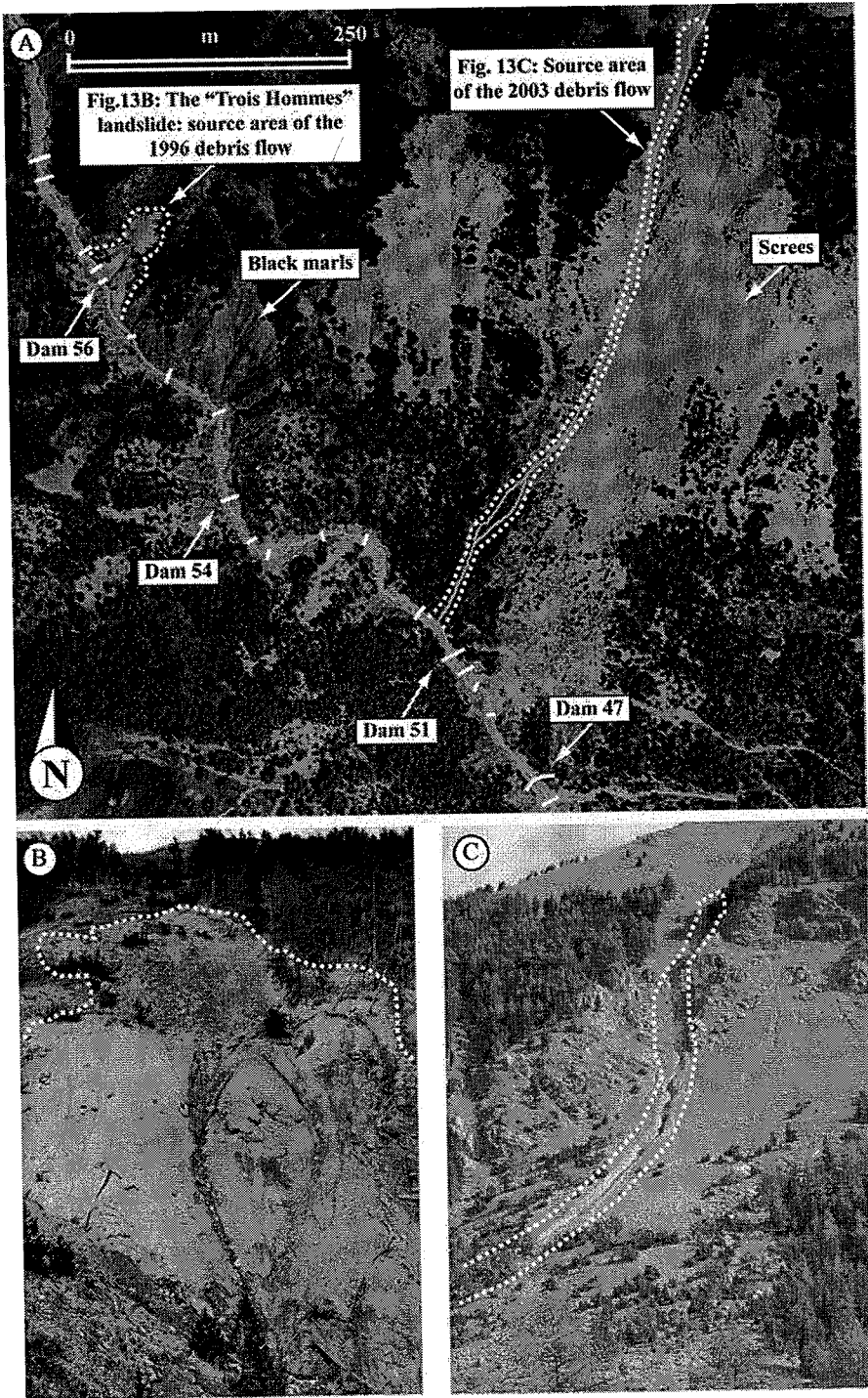


Figure 13. The source areas of the 1996 and the 2003 debris flows at the Faucon torrent. (A) Orthophotograph of the upper part, (B) photograph of the landslide which is consider to be the source area of the 1996 debris flow, (C) photograph of the 2003 debris- flow source area in a scree talus.



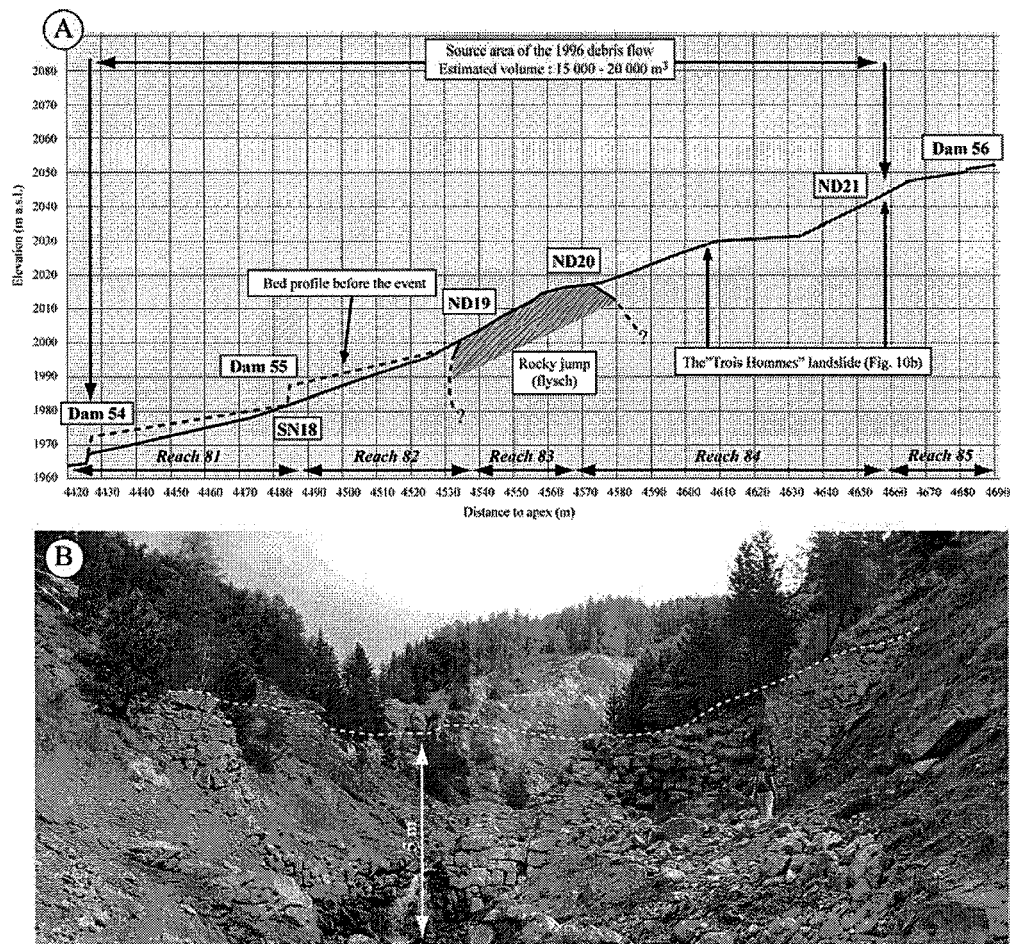


Figure 14. Morphology of the source area of the 1996 debris flow. (A) Bed profile of the Faucon torrent between check dam 54 and check dam 56. This area is considered as the main source area of the 1996 debris flow. (B) Photograph of check dam 54. Field observations suggest that his failure caused the triggering of the 1996 event.

Field evidences and aerial photographs study suggest that the debris-flow source area was located in the upper part of the torrent (above 2100 m a.s.l.), between check dam 54 and check dam 56 (Figure 13A):

- Check dam undermining and channel scouring in this area is particularly strong and reached nearly 5 m depth at check dam 54 (Figure 14B). Check dams 54 (Figure 14A), 55, 56 and 57 are completely destroyed. These check dams correspond to dry stone masonry type and they were built in 1880. Some vestiges of the wings are still visible, but the central part almost completely disappeared;
- An important quantity of debris fulfilled the channel. These debris mostly consist of coarse materials (some blocks exhibit a volume  $> 1 \text{ m}^3$ ) and various vegetable debris (mostly tree trunks). Such type of debris and morphology is characteristic of a natural dam collapse. The thickness of these debris decreases upstream;



- Mud splatters were observed on the tree trunks located on both sides of the channel. These mud splatters testify that the thickness of debris trapped by the temporary dam was at least 5 m.

These observations are in agreement with a dam breach which could have triggered the debris flow. The grain-size analysis of the source material and the debris-flow deposits suggest that the material involved in the debris-flow triggering had two sources:

- 1) A strong channel scouring was observed. Upstream of check dam 54, the channel was incised and widened. There is evidence of multiple temporary stream blockages, especially between the check dam 55 and the natural dam 21;
- 2) A hillslope sediment source which consist of a shallow landslide located near the check-dam 56 and affecting the “Trois Hommes” slope (Figure 13B). The analysis of an aerial photograph taken in May 1996 shows that the “Trois Hommes” shallow landslide occurred between May 1996 and August 1996.

The volume of the landslide and the volume of scoured sediments in the reaches located between check dams 54 and 56 range between 15'000 and 20'000 m<sup>3</sup> (Figure 14A). The main causes for the triggering of the 1996 event are associated to (a) the occurrence of a severe thunderstorm, (b) the occurrence of a shallow landslide, (c) the failure of the check dam 54. In this case, the general bad condition of the check dams 54, 55 and 56 is perhaps responsible for the debris flow triggering.

### **3.3.2. The 2003 Debris-Flow Event: Influence of Check Dams on Scouring Intensity**

In this section, only the run-out stage of the 2003 debris-flow event will be considered. Nevertheless, some information about the triggering and the spreading stage are provided in order to discuss the sediment budget of the debris flow. Additional observations and data of the characteristics of the 2003 debris flow (rheology, sediment budget, back-calculated velocities and discharges, run-out modeling ...) are detailed in Remaître et al. (2008, 2009).

On Monday August 5, 2003, between 6:00 and 8:00 p.m., a debris flow occurred. This event has been triggered on two specific spots on the east flank of the Faucon catchment: the Trois Hommes area (Figure 13C), and the upper part of the Champerousse torrent. For both cases, the morphology of the source area corresponds to a strong incision in scree slopes. The volume of the Trois Hommes debris-flow ranged approximately from 4000 to 5000 m<sup>3</sup>, while the volume of the material in the source area of Champerousse ranged from 6000 to 7500 m<sup>3</sup>. Unlike the Trois Hommes event, all the material did not reach the Faucon torrent; in fact 3000 m<sup>3</sup> of material has been trapped by the check-dams network. The observations at the Trois Hommes slope and the Champerousse torrent indicate that the source volume ranges from 7500 to 9500 m<sup>3</sup>, a value of 8500 m<sup>3</sup> can be considered.

On the upper part of the debris fan/cone, most of the deposited debris has filled the channel; the debris flow has started to spread below the VC3 Bridge (Figure 11). Mudlines and splatters of fine-grained liquid sediments along both sides of the path revealed a nearly

constant cross-sectional area (20 to 30 m<sup>2</sup>). Field measurements and evidences of the residents indicate that the event evolved into 5 surges, for a time interval ranging between 2 and 5 minutes. These debris-flow surges filled progressively the channel; the last surge overflowed and caused the occlusion of the VC3 Bridge. Eyewitnesses indicate that the debris-flow height of the last surge reached 5 to 6 m. Most of the debris spread over the left bank, causing some substantial damages on five houses. Some residents were in their houses as the overflowing occurred but remained uninjured. The thickness of the debris deposits ranged from 1.0 to 2.0 m. Moreover, the debris flow also breached the main road of the valley; the traffic was stopped during several hours and remained difficult for three weeks while authorities cleaned the channel and the fan. We have measured the area and the depth of the deposits both in the channel and on the fan. Length, width and depth were recorded and mapped. Total volume of debris-flow deposits was estimated to be 45,000 m<sup>3</sup> on the debris fan and 15,000 m<sup>3</sup> in the upper channel.

Channel scour is responsible for the great difference between the 8500 m<sup>3</sup> of the two source areas and the 60,000 m<sup>3</sup> of the total volume. The length of the debris-flow track is about 3500 m, with a slope gradient of about 15°. Several areas of scouring were observed, they are mainly located in the 1996 debris-flow deposits area. The channel scour rate amounts to 15 m<sup>3</sup>.m<sup>-1</sup>. This value is in agreement with values observed by other authors in various geological environments (Hungur et al., 1984; Jibson, 1989; Jakob et al., 2000). Observations of the channel after the event indicate that the scour depth ranges between 0.5 and 4 m.

The most intense scour depth was observed at the toe of some check dams (Figure 15), as a result of regressive channel erosion. Field evidences show that 26 check dams were scoured or partially destroyed by the 2003 event.

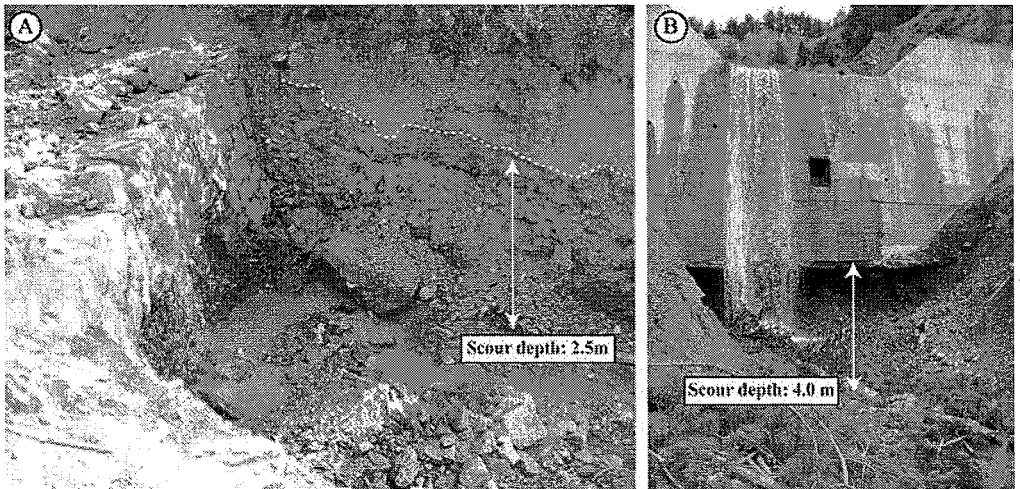


Figure 15. Example of two scoured check dams after the 2003 debris flow event.

The 2003 event started as a granular flow, bulked increased in fine elements by incorporating marly sediments along the debris-flow track and transformed into a muddy debris flow (Remaître et al., 2008). Such process has been observed during the 1996 event (Remaître et al., 2005a). In order to analyze more precisely relations between the 2003 debris-flow kinematics and the morphological factors of the torrential stretches, the spatial evolution

of the sediment budget and conditions of the check dams before the 2003 event have been compared (Figure 16).

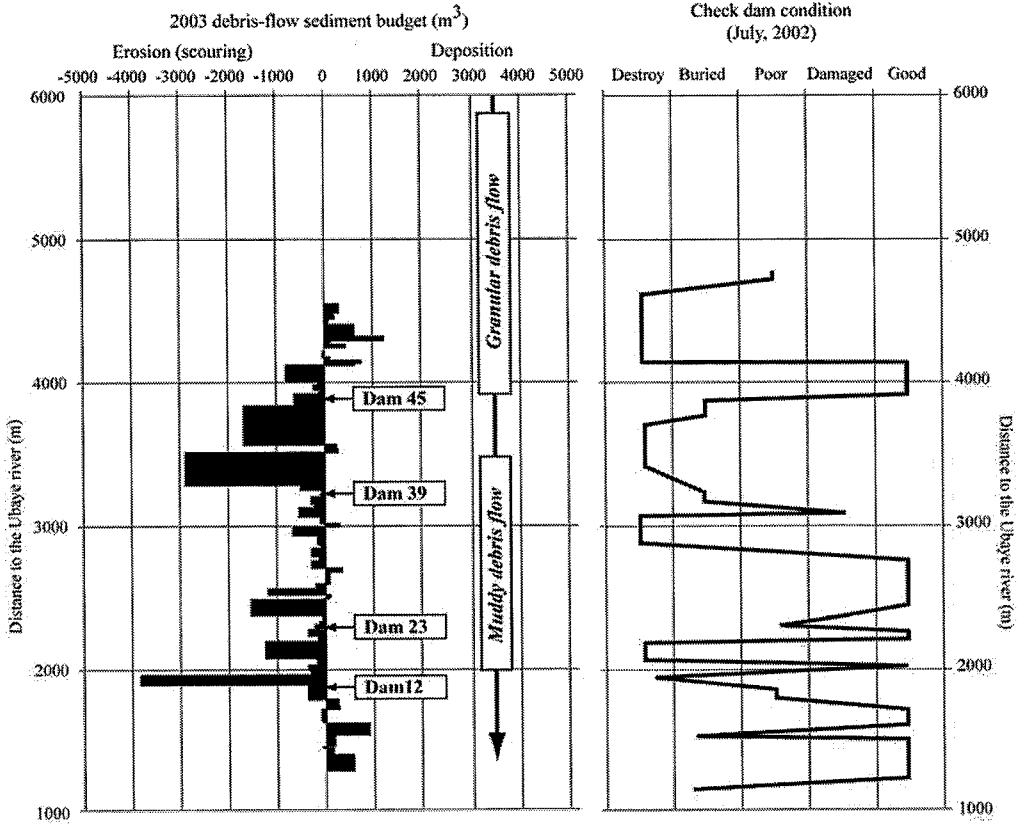


Figure 16. The 2003 debris-flow event at Faucon torrent: sediment budget and check dam conditions.

Results show a correlation between the volume of scoured sediments and the condition of the check-dams. Indeed the two main areas where the bulking was particularly intense (between check dams 45 and 39 and between check dams 23 and 12), are characterized by a general bad conditions of the check dams (buried or destroyed). These stretches do not exhibit a steep longitudinal profile, the average slope of the torrent in these areas is about 7-9°.

It could be expected that the steepest stretches would be characterized by an intense scouring during the event, but this was not always observed in the field. In fact, the stretches characterized by an intense scouring have been fully or partially filled by the 1996 debris-flow deposits (Remaître et al., 2005) and the 2002 streamflow deposits (Remaître, 2006) producing a large source of ‘available’ sediments for the 2003 debris flow. Relations between the 1996, the 2002 and the 2003 events seem to be very close. The spreading and the overflowing on the fan of the 2003 event were much more important than in 1996, although the volume of both events was very close. This must be put in relation with the occurrence of the streamflow in 2002 which filled the lower stretches located on the debris/fan producing an increasing of the bed profile level and a decreasing of the flow sections.

The example of the 2003 event shows the fundamental role of the series of check dams on the scouring and the enlargement of the debris-flow volume during its run-out. The general

bad condition of the check dams and the presence of large available material (deposits from the previous events) have both contributed to increase the intensity of the debris flow.

#### **4. INFLUENCE OF CHECK DAMS ON DEBRIS-FLOW RUN-OUT INTENSITY: A MODELING APPROACH**

In this section, some modeling exercises have been carried out to evaluate numerically the influence of the number and the location of the check dams on the debris-flow run-out intensity (in term of flow thickness, flow velocity and volume). The JDFM-1D model (van Asch et al., 2004), is used to simulate the run-out of the debris flow. The constitutive equation used in the model is a simplified 2-parameters viscoplastic rheology. The model uses the Janbu force diagram to resolve the force equilibrium equations; a Bingham fluid rheology is introduced and represents the resistance term.

The JFDM-1D model can take into account the amount of material entrained by the flow along the path (scouring) in order to increase the final volume deposited. According to Rickenmann et al. (2003), the intensity of the scouring is assumed to be a function of the integrated mean shear stress of the debris-flow mixture which passed through sections of the torrent, and is controlled by the slope gradient, the volume and the density of the mixture which enters this section. Therefore, breaking the energy of the flow in the earlier stage of the debris-flow event kinematics would reduce the total amount of entrained material. A complete description of the model can be found in van Asch et al. (2004) and Remaître et al. (2008).

The model has been calibrated both on the debris-flow events that occurred in 1996 and 2003 at the Faucon stream. Influence of the check dams on the debris-flow intensity is quantified taking into account several check dams configurations (number and location) as input geometrical parameters.

##### **4.1. Modeling Scenarios**

For each modeling test, the same triggering scenario has been used based on the observations after the 2003 event. A volume of 5000 m<sup>3</sup> of material has been considered, which corresponds to one of the source area (Trois Hommes area). The rheological characteristics of the debris-flow material can not be changed during the run-out. Therefore, we considered that the flow exhibits viscoplastic behaviour for the entire simulation. The source area is located at the upper part of the profile (point A on Figure 17) while the check point (point B on Figure 17) location corresponds to the upper part of the fan where the flow-track shows a clear flattening of the slope gradient. The run-out distance is approximately 4000 m.

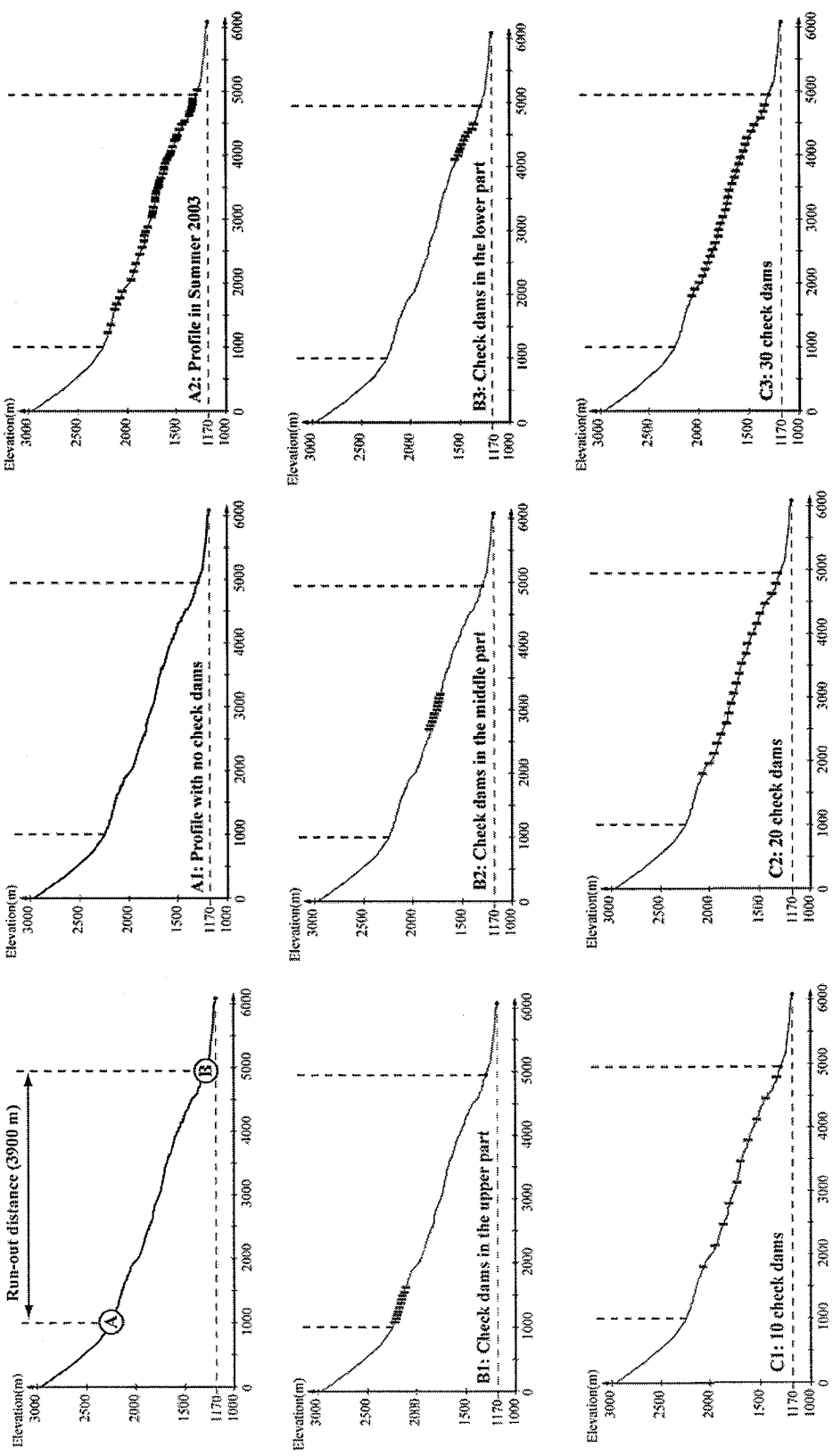


Figure 17. Settings of the three modeling scenarios. The bed profile corresponds to the one of Faucon torrent.

In the model, the series of check dams influence the intensity of the debris-flow through topographic variations of the flow track (slope angle). For the scenario A, the height of check dams corresponds to the height observed in the field in July 2003. For the scenarios B and C, a 5m height has been considered for all the check dams. Three main run-out scenarios have been tested (Figure 17):

- (1) Scenario A: effect of the check dams on the intensity of the 2003 debris-flow. This scenario is a kind of “back analyses”. We compare modeling results for two configurations of debris-flow pathway; a profile with no check dams (A1), and the profile with the check dams observed before the 2003 debris-flow event;
- (2) Scenario B: effect of the location of check dams on the intensity of a debris flow. Three configurations of check dams location were tested: check dams located in the upper part of the torrential pathway (B1), in the middle part (B2) and in the lower part (B3);
- (3) Scenario C: effect of the number of check dams on the intensity of a debris flow. Three configurations of check dams number were tested: a profile with 10 check dams (C1), a profile with 20 check dams (C2) and a profile with 30 check dams (C3).

## 4.2. Modeling Results

For each scenario, the maximal flow height, the maximal velocity and the total volume of debris where analyzed and compared (Figure 18).

For the scenario A, logically, the intensity of the debris flow is decreasing when the torrent is equipped with check dams. The maximum flow height is decreased from 5.95 m (A1: no check dams) to 2.21 m (A2: 75 check dams), while the maximum velocity is decreased from  $1.58 \text{ m.s}^{-1}$  (A1) to  $0.53 \text{ m.s}^{-1}$  (A2). The total volume of the debris-flows is decreasing from  $69,000 \text{ m}^3$  (A1) to  $33,000 \text{ m}^3$  (scenario A2).

The run-out modeling results for the Scenario C show a decrease of the flow intensity. The decrease is particularly strong between the scenario A1 (no check dams) and the scenario C1 (10 check dams): decreasing of the maximal velocity, the maximal flow height and the volume are respectively 29% ( $1.58$  to  $1.12 \text{ m.s}^{-1}$ ), 25% ( $5.95$  to  $4.41 \text{ m}$ ) and 26% ( $69,000$  to  $51,000 \text{ m}^3$ ); while the decreasing is gently moderate when the number of check dams is increasing (scenarios C1, C2 and C3). For instance, between the C1 and the C3 scenarios, decreasing of the maximal velocity, the maximal flow height and the volume are respectively 11% ( $1.12$  to  $1.00 \text{ m.s}^{-1}$ ), 7% ( $4.41$  to  $4.12 \text{ m}$ ) and 10% ( $51,000$  to  $46,000 \text{ m}^3$ ).

The comparison of debris-flow intensity for the three cases (B1, B2 and B3) indicates that the location seems to have a strong influence on the debris-flow intensity. Indeed, the differences are significant between the B1 scenario (dams located on the upper part) and the B3 scenario (dams located on the lower part): decreasing of the maximal velocity, the maximal flow height and the volume are respectively 37% ( $1.19$  to  $0.74 \text{ m.s}^{-1}$ ), 36% ( $4.97$  to  $3.18 \text{ m}$ ) and 33% ( $62,000$  to  $41,000 \text{ m}^3$ ).

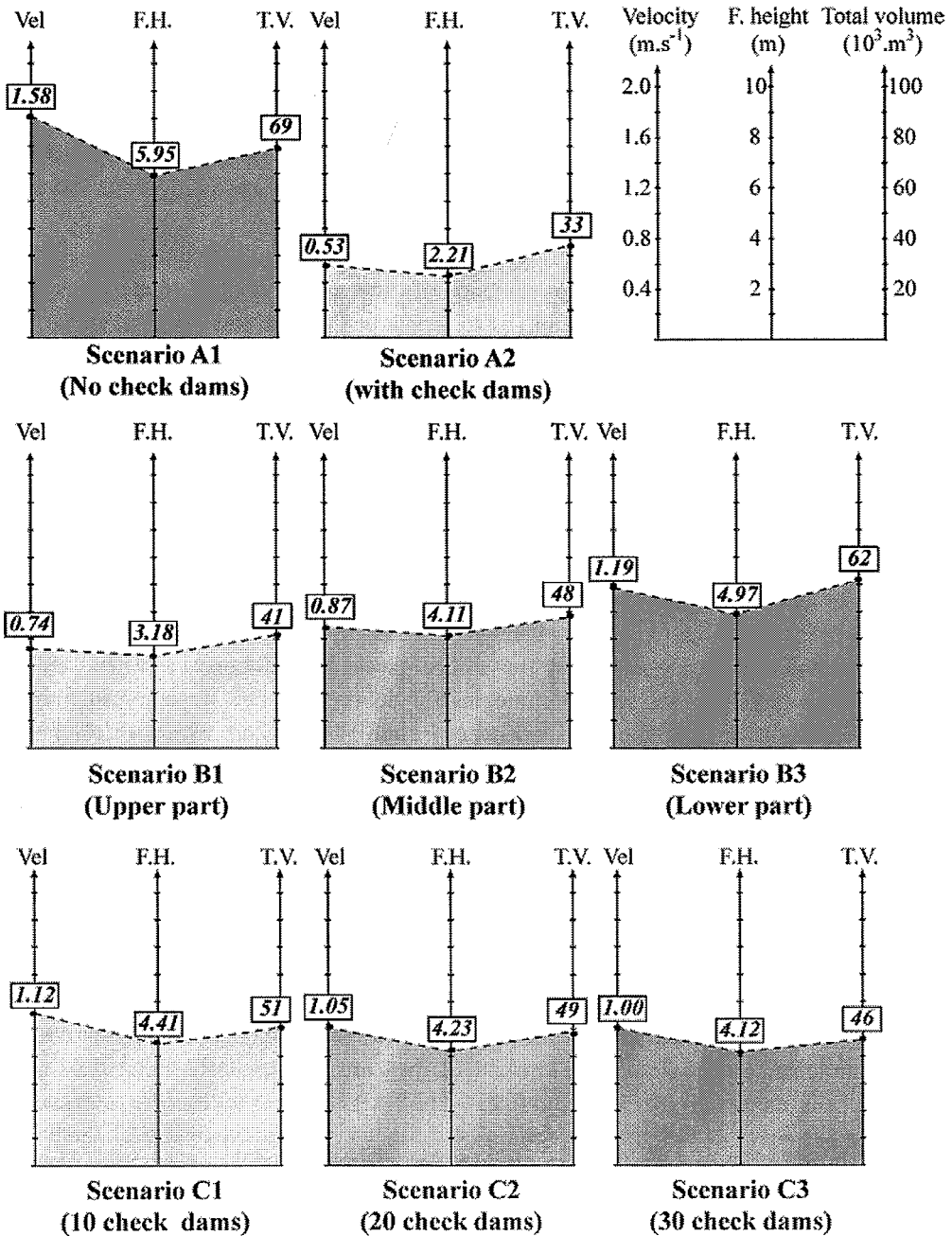


Figure 18. Results of the three modelling scenarios.

### 4.3. Discussion and Conclusions

The sensitivity analysis of the relative influence of, on one hand the number of check dams, and on the other hand the location of the check dams shows interesting results. The simulation which provides the lowest debris-flow intensity corresponds to the case where the

check dams are located at the upper part of the flow track (Scenario B1), near the source area. These results suggest that a relative small number of check dams located near the potential source areas could be very efficient by breaking early the energy of the debris-flow. For this reason, additional river engineering measures could be proposed, such as construction of new check dams in the upper reaches of the Faucon torrent. These conclusions are valid for a debris flow that exhibited a muddy behavior; some additional modeling tests have to be provided for granular debris-flows.

This new approach opens a new direction for future research. Additionally work remains to be done in order to (i) analyze the influence of other check dam characteristics (height, width) on the debris-flow intensity and (ii) to develop a robust and efficient methodology which can be applied for routine debris-flow hazard assessment.

## CONCLUSION

Studies of debris flows throughout the world indicate that many factors have been responsible for the triggering and the run-out of debris. Numerous studies have demonstrated that rainfall, lack of vegetation and other factors had a strong influence on debris-flow processes. It is ridiculous to relate a single parameter, such as intensity of rainfall or landcover to the occurrence of debris flows in a given area (Johnson and Rodine, 1984). During the two last centuries several strategies for debris flow risk management have been developed to fight against the consequence of such phenomena which threaten all the mountainous areas, although with different intensity and recurrence. The strategies include hazard and risk zoning methods, non-structural measures and defence works.

As it concerns the last point, the experience gained and the results obtained in several countries encourage the use of defence work to improve the safety of vulnerable elements and inhabitants. The role of series of check dams in regulating torrential and hillslope processes is fundamental. The results reported here indicate a strong relation between debris-flows triggering and run-out processes and the characteristics of series of check dams, particularly those located in the upper basin near the source areas. These series of check dams have to be specifically suited to the character of the debris flow, the resources, and equipment available for the maintenance of the structure. Indeed, if they are not regularly cleaned or repaired, series of check dams can increase significantly both (i) the probability of occurrence of an event and (ii) the volume of an event through scouring processes. Nevertheless there is still a great benefit to use series of check dams but their conditions have to be checked carefully by the authorities. This is particularly true in clay-shale basins where debris-flow scouring can be very intense.

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