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Prédiction globale de la production de sédiments des bassins versants torrentiels

Bilans sédimentaires et application d'une méthode d'estimation des volumes de laves torrentielles

Stéphane Veyrat-Charvillon

Ce projet s'inscrit dans le cadre de recherches visant à prédire et estimer le volume sédimentaire des bassins versants torrentiels et en particulier le volume maximum pouvant être transporté par une lave torrentielle. Il fait suite au projet n°6 financé en 2000 par le Pôle Grenoblois sur les Risques Naturels, où l'étude du bassin versant du Manival et de sa dynamique sédimentaire avait permis de définir une méthode de prédiction des apports sédimentaires sur ce torrent. Le travail présenté ici comporte deux volets principaux :

-Une étude photogrammétrique sur le chenal du Manival montrant la possibilité d'utiliser des photographies d'archives comme source de donnée objective, fiable, et quantifiable ;

-Une application de la méthode sur deux autres bassins versants isérois : Le Merdarêt et Les Arches.

Ces travaux ont été valorisés pour le premier volet lors de la conférence sur le ravinement en montagne à Digne en octobre 2003 (Cf. actes en annexe), et pour le second volet dans le cadre d'un article proposé dans la revue internationale River Research and Applications (Cf. article en annexe).

Mesures photogrammétriques du Manival

Nous avons effectués des mesures topographiques en suivant une méthode d'échantillonnage adaptée aux torrents. L'imprécision de cette méthode de mesure est estimée à environ 6% du volume total calculé dans le chenal. De plus, le niveau de référence du fond, correspondant à un niveau maximum d'érosion d'une lave torrentielle, n'étant pas connu, nous avons déterminé deux niveaux de référence. Les volumes sont calculés à partir de ces deux hypothèses, l'une minimaliste et l'autre maximaliste, qui encadrent la valeur réelle du volume de sédiments stocké dans le chenal.

L'outil de mesure utilisé a été la stéréophotogrammétrie sur plus de dix dates de 1963 à 2000, à partir de documents photographiques existants. Ces photographies d'archives sont de qualités variables et ont des échelles différentes allant jusqu'au 1/30 000^{e}. Malgré cela l'incertitude finale sur les mesures est de l'ordre de 80 centimètres en écart-type, ce qui représente environ 6% du volume total calculé dans le chenal et permet donc la comparaison des états sédimentaires du chenal calculés aux différentes dates.

Pour améliorer la connaissance du niveau de référence du fond, nous avons voulu déterminer le niveau le plus bas du profil en long, toutes dates confondues. Dans ce cas, malheureusement, l'imprécision de mesure est maximum est peut atteindre trois mètres sur certains points. La seule certitude est que les erreurs sont toujours négatives puisque l'on sélectionne les minimums, donc le niveau minimum observé sur toute les dates ne peut pas être inférieur. Les résultats sur les volumes montrent qu'ils coïncident à peu près avec le niveau de référence le plus bas de l'hypothèse maximaliste et conforte donc l'idée qu'une lave torrentielle ne peut pas éroder à un niveau plus bas que ce profil de référence.

Application aux bassins versants du Merdarêt et des Arches.

Ces deux bassins sont du même type que celui du Manival et disposent également d'informations historiques suffisantes. Les bassins versants et les résultats de la méthode d'estimation des volumes sédimentaires sont décrits en détail dans l'article joint en annexe.

Les résultats restent approximatifs mais semblent être cohérents en particulier pour le torrent du Merdarêt où la méthode est validée grâce à un événement unique relativement important, alors que pour Les Arches la validation des résultats est plus difficile bien que la méthode montre l'intérêt de résultats objectifs et quantifiés.

L'amélioration de cette méthode passe en priorité par une meilleure connaissance du niveau de référence. Plusieurs voies de recherche peuvent être proposées : une analyse des niveaux minimum de la topographie du chenal, en particulier après le passage d'une lave torrentielle, à partir d'une base de donnée très fournie ; une étude en canal de laboratoire du niveau d'érosion d'une lave torrentielle entre deux points durs du profil en long ; ou éventuellement une approche géophysique (électrique, sismique, radar,…).

Par la suite la méthode doit être confrontée à de nombreux cas d'événements torrentiels afin de déterminer si l'ensemble du volume de sédiment stocké dans le chenal peut systématiquement être mobilisé. Il est possible que seules les zones de stockage temporaire soit à prendre en compte.

A terme, le type de torrents d'application pourrait être élargi en essayant la méthode sur un grand nombre de bassins versants torrentiels plus diversifiés.

ANNEXE 1 :

Résumé étendu de la conférence internationale

Ravinement en montagne :
Processus, Mesures, Modélisation, Régionalisation,
15 au 17 octobre 2003, Digne-les-Bains
(Alpes-de-Haute-Provence, France)

p.159-162

Etat sédimentaire d'un chenal à lave torrentielle : Méthode topographique d'échantillonnage et application photogrammétrique

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Sediment state of debris-flow channel :
Topographic methodology of measures and photogrammetry

We present here a part of a global research on debris-flow magnitude estimation. The current presentation focus on a methodology to characterise the amount of sediment stored in channels and also the use of historical photographs for aerial-survey by stereophotogrammetry.
The topographic method of measures is made of a long profile with equidistant 4 points cross-sections. Each cross-section is representative of 50 meters-long reach of the channel. To calculate the volume of each reach, the difference is made between a reference level and the topographic surface. The reference level is the lowest level where debris-flow can erode, and in the current method this level is estimated from fixed points inside the long profile. The accuracy of the method have been estimated by comparing results of the measures with detailed topographic survey made of 20-points cross-sections each 10 meters, and standard deviation correspond to about 6% of the total volume calculated.
This topographic methodology have been used on aerial photographs by photogrammetry. This tool was applied on about 10 past dates, but photogrammetry can also be useful for torrent survey with difficult or dangerous access. The scales of the archive photographs used are ranging from 1/15 000^{e} to 1/30 000^{e}, but results are suitable and permit to calculate sediment states of the channel for different past dates.

Dans le cadre plus large de recherches visant à prédire et estimer la production sédimentaire de bassins versants torrentiels, nous présentons ici une méthode d'échantillonnage optimisée permettant de calculer le volume de matériaux stockés dans un chenal où les laves torrentielles sont le mode de transport prédominant. Nous avons privilégié un outil de mesure topographique bien adapté à cette problématique : la photogrammétrie sur des couples stéréoscopiques de photographies aériennes.

La méthode d'échantillonnage est un peu plus élaborée que le levé d'un profil en long pour permettre le calcul de volume par addition de casiers sédimentaires. Ceci est permis grâce à la mesure de profils en travers équidistants. Nous sommes partis de profils en travers détaillés (une vingtaine de points) et rapprochés (tous les dix mètres environ) pour arriver à un échantillonnage topographique optimisé en diminuant le nombre de profils en travers et le nombre de points les définissants, tout en conservant des résultats acceptables. Pour calculer un volume, nous avons défini un profil en travers érodé par une lave et une section type déterminée par les points durs du profil en long (seuils naturels ou artificiels). Finalement, la méthode d'échantillonnage se compose de profils en travers équidistants de cinquante mètres et définis par quatre points, avec une marge d'erreur, dans la plupart des cas, de l'ordre de 20 centimètres en écart-type par rapport à la topographie de surface.

La stéréo-photogrammétrie nous a permis d'utiliser cette méthode sur plusieurs torrents mais surtout à différentes dates passées. Cet outil présente aussi l'avantage de pouvoir faire des mesures topographiques dans des zones trop dangereuses ou inaccessibles. Nous avons utilisé un restituteur numérique et des photographies aériennes d'archive à des échelles allant du 1/15 000^{e} au 1/30 000^{e}. Sur le torrent du Manival (Alpes du Nord – France), avec une dizaine de dates, la précision en altitude obtenue avec cet outil reste cohérente et nous permet de calculer des états sédimentaires du chenal pour chaque date.

Après la présentation de la méthode topographique d'échantillonnage adaptée aux torrents, nous exposerons son application à différentes dates par stéréophotogrammétrie sur des photographies aériennes. Ce travail montre qu'il est possible d'utiliser des données historiques objectives à travers des photographies d'archives ayant une échelle d'environ 1/30 000^{e}. Les résultats concernant la quantification sédimentaire du chenal torrentiel sont cohérents lorsqu'ils sont confrontés aux observations de terrain.

Méthode topographique d'échantillonnage.

Le principe général du calcul pour estimer le volume sédimentaire du chenal, est une différence entre un niveau de référence et la topographie de surface.

Le niveau de référence idéal doit correspondre, en théorie, au niveau maximal d'incision d'une lave torrentielle, au delà duquel elle ne pourra pas éroder. Dans la pratique ce niveau n'est pas connu. Nous avons donc proposé deux hypothèses théoriques, l'une minimaliste et l'autre maximaliste, toutes deux calées sur les points durs du profil en long (seuils naturels, barrages,…). De plus, notre base de données élaborée sur un torrent à partir d'une dizaine de dates nous a permis de sélectionner les niveaux les plus bas (toutes dates confondues) dans le profil en long pour élaborer un profil de référence « observé » plus proche de la réalité.

Concernant la forme de profil en travers la plus érodée, nous avons choisi une forme en « U » correspondant aux observations de transects après le passage d'une lave torrentielle.

La topographie de surface pourrait être mesurée de façon classique, mais notre but était de proposer une méthode « allégée », rapide et moins coûteuse, tout en gardant des résultats acceptables. Un levé de terrain précis, c'est-à-dire des transects équidistants de 10 mètres composés d'une vingtaine de points chacun, a servi de référence pour estimer la précision des résultats.

La diminution du nombre de transects correspondant à une équidistance entre eux de 50 mètres, donne une erreur d'estimation des volumes d'environ 4,5%.

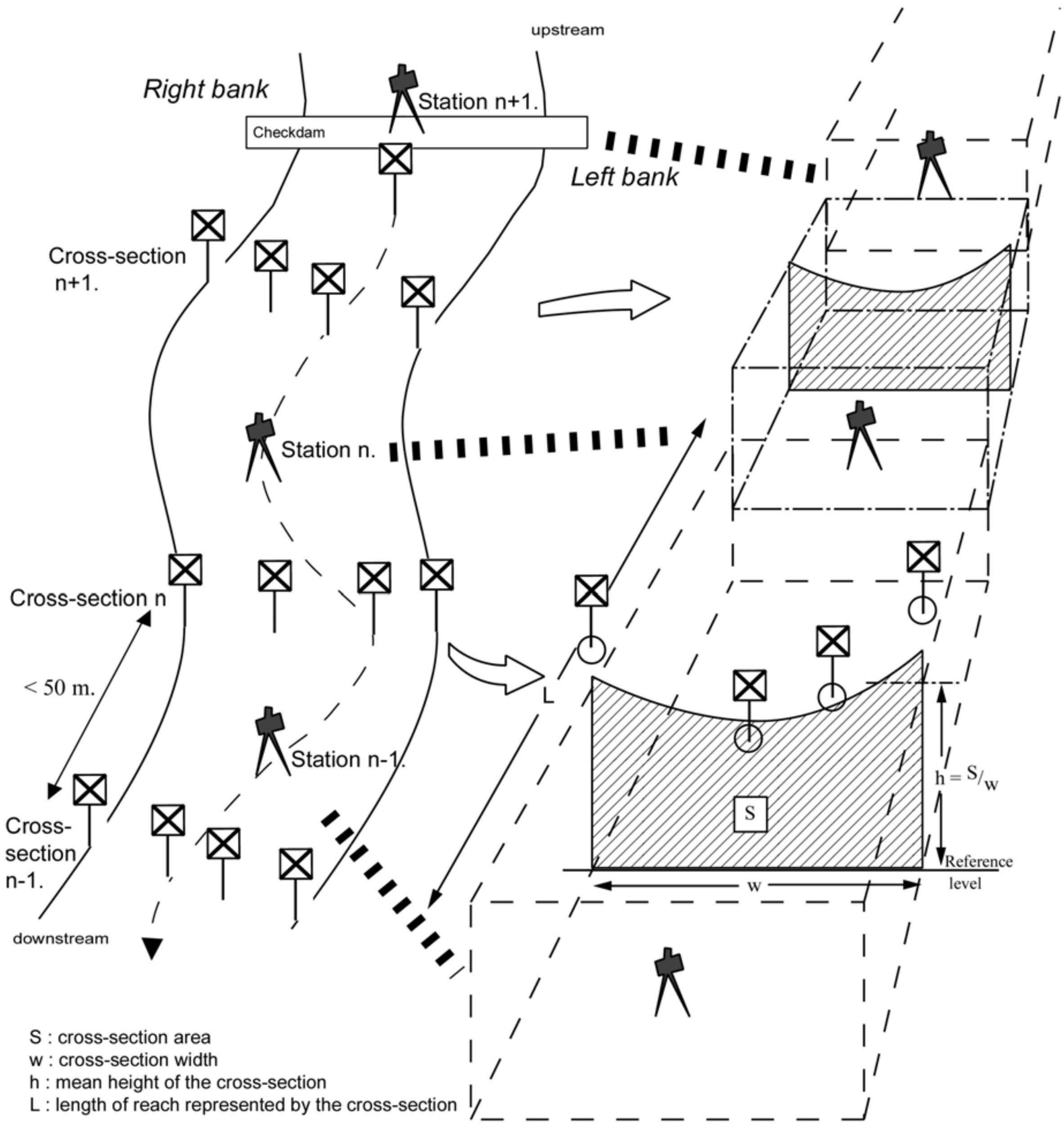

Figure 1: Ranging measures and volume calculation methodology (Veyrat-Charvillon, 2003).

Chaque profil en travers est quant à lui réduit à 4 points de mesure : chaque berge, le talweg, et le point haut de la partie centrale du chenal. Ces quatre points sont ensuite modélisés par une courbe de tendance polynomiale d'ordre 2 (calcul des moindres carrés), qui permet le calcul d'une intégrale comprise entre cette courbe et le niveau de référence. Pour obtenir le volume d'un bief représenté par le profil en travers, le résultat de l'intégrale est multiplié par la longueur du bief (Fig.1). Ainsi les différents casiers sédimentaires peuvent être additionnés pour calculer le volume total de sédiment accumulé dans le chenal. La comparaison de la hauteur moyenne entre le transect modélisé et le transect constitué de vingt points donne une marge d'erreur de l'ordre de 20 centimètres en écart-type, soit une erreur d'estimation sur les volumes d'environ 1,4%.

La méthode topographique d'échantillonnage a donc une marge d'erreur de l'ordre de 6%.

Utilisation de la photogrammétrie pour traiter des données historiques objectives.

Le choix de la stéréo-photogrammétrie comme outil de mesure topographique a surtout été déterminé par une volonté d'utiliser les données historiques objectives des photographies aériennes, bien que cet outil soit également très intéressant d'un point de vue économique, mais aussi pour des zones inaccessibles ou dangereuses. Sur le torrent du Manival, la dizaine de dates étudiée est représenté par des photographies de qualités et surtout d'échelles variables. En effets de nombreuses photographies sont à une échelle d'environ 1/30 000^{e}, ce qui réduit la précision des mesures.

Compte tenu de la qualité des documents disponibles que nous avons utilisé (exposition, échelle, contre-type, centrage de la zone d'étude), la précision altimétrique sur les images au 1/30 000^{e} peut être estimée par un calcul théorique à environ 1,3 mètre en écart-type.

Pour le torrent étudié, nous avons appuyé les couples stéréoscopiques sur de nombreux points durs recensés dans le profil en long. L'étude des résidus sur ces points durs nous permet d'effectuer une estimation de l'écart-type des mesures, qui est alors de 80 centimètres pour les photographies au 1/30 000^{e} (Fig.2), ce qui représente une erreur inférieure à 6% sur l'estimation des volumes. Bien entendu l'erreur est plus faible pour des photographies à plus grande échelle.

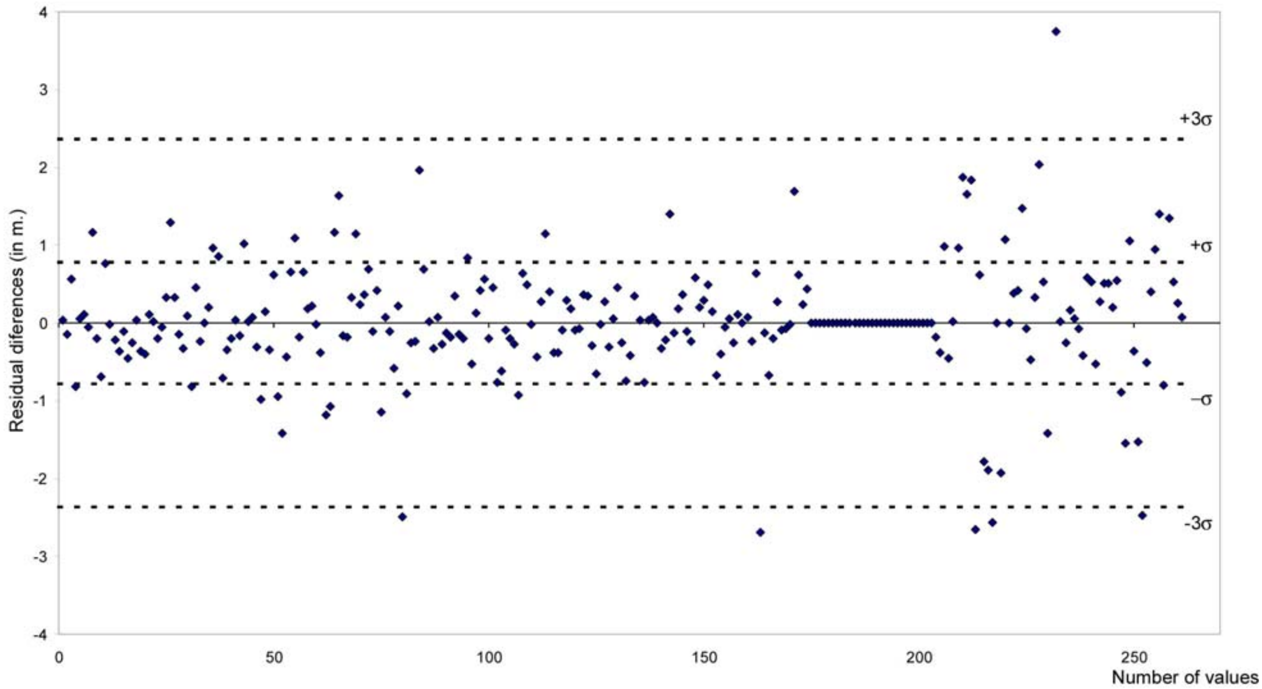

Figure 2: Error estimation of photogrammetric measures on historical photographs at 1/30 000 scale.

Statistics of residuals on the fixed points	
Number of values	261
Mean	-8.71163507445E-015
Median	0
Variance	0.631130218325732
Average deviation	0.493049523865456
Standard deviation (σ)	0.794437044910251

Cohérence des résultats.

L'utilisation combinée de la méthode topographique d'échantillonnage et des mesures de stéréophotogrammétrie sur des photographies d'archive au 1/30 000^{e} donne une imprécision des résultats sur les volumes estimés d'environ 12%. Toutefois, la confrontation de ces résultats avec les observations de terrain recueillis auprès des services de la Restauration des Terrains de Montagne en charge de la gestion des risques torrentiels est cohérente. Voici quelques unes de ces observations :

-en 1970, les dépôts d'une lave torrentielle importante survenue un an et demi auparavant sont encore visibles,

-en 1975, la gestion différente des sédiments du chenal par divagation explique bien les grosses quantités de matériaux stockées dans la partie aval du chenal,

-en 1993, les barrages sont bien visibles dans le chenal en corrélation avec une faible charge sédimentaire,

-en 1996, le rapport de suivi technique des ouvrages du chenal par les techniciens du service de la RTM (illustré de photographies) mentionne des accumulations sédimentaires dans de nombreux biefs…

ANNEXE 2 :

Manuscrit soumis à River Research and Application (10 p., 7 figures, 2 tableaux)

Application of a Geomorphological Method to Predict Debris Flows Volumes on Two Alpine Torrential Basins

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Keywords: torrential system, field experimental studies, geomorphology, stereoscopic photogrammetry, topography, debris flows, predictive method, hazard mitigation tool.

ABSTRACT: This paper describes how a method based on geomorphological concepts and topographical measures which can enable practitioners to predict the volume of sediment transported by chanalized debris flows, has been tried on two torrents of the French North-Alps: Le Merdarêt and Les Arches.
For this kind of torrent, well known to have produced debris flows in the past, the main sediment yield comes from the upper part of the catchment made of limestone-marl mixed escarpment rock. Depending on specific time scales relative to each geomorphological processes, sediments are more or less rapidly stored in several particular reaches in the channel, named Temporary Storage Areas (TSA). These sediments stored in TSA are then available to feed debris flows.
To validate the estimation results this study is based on: (1) Recent events data collected by the RTM, the French Governmental Agency in charge of natural hazards mitigation, (2) Stereo photogrammetry on IGN (Geographic National Institute) aerial photographs with a numerical stereo-restitutor, and (3) Field survey including topographical measurement with a laser range-finder and an electronic compass.
The purpose of this method is to give a tool to assess deposited volumes on the alluvial fan during a large torrential event. This study shows coherent results in agreement with data and field survey. This method allows us to provide estimates of sediments potentially available for debris flows, corresponding to the sediment volume of the largest event, at any one time. In the future, this method could certainly be extended to different watersheds with debris flow events.

1 INTRODUCTION

Debris flows can be considered as a significant natural hazard in the Alps and in many other mountainous areas. Torrential disasters causing property damage and loss of human lives have occurred frequently in the past. The aim of this paper is to describe the use of a method which was developed on the Manival torrent. This method seems to be an interesting way to estimate the overall potential debris flow volume. The lack of a reliable method to estimate volume is a problem for engineers who need to manage torrential hazard mitigation: on the one hand, most global models are empirical and statistical and so, cannot be used in any other parts of the world without large fluctuation in the results (Laigle and Marchi, 2000, Marchi, 1999); and on the other hand, research on debris flow rheology and mechanics is still in process (Iverson, 1997) but, due to the complexity of torrent systems relatively few studies can currently provide a workable tool for engineering design.

In the whole catchment, many geomorphological processes contribute to recharging channels. Depending on specific time scales relative to each geomorphological process, sediments are more or less rapidly stored in several parts on slopes (Peiry, 1990, Tricart, 1960) and in particular in reaches in the channel, where they are then available for debris flows. Debris flow events are therefore controlled not only by exceeding a local climatic threshold, but also by factors such as terrain instability and ruggedness, which control debris supply and the channel recharge rate. During an event, the magnitude of the debris flow is then mainly determined by the volume of material dragged along the channel (Davies et al., 1992, Fannin and Rollerson, 1993), so channels must be recharged with material before a large debris flow can reoccur.

Although sediment supply and the channel recharge rate are important factors controlling debris flow activity, these aspects have received little attention to date. In this study, we show a method which has been tested on two other torrent basins, the Arches and the Merdaret, which have the same characteristics as the Manival torrent. Before presenting the two watersheds, the main lines of the method developed on the Manival torrent will be summarized (Veyrat-Charvillon, 2003). Then results of measures, from aerial photographs by stereoscopic photogrammetry and volume estimations before debris flows occurred in Le Merdarêt and Les Arches torrents,are presented. Using topographic fieldwork measures taken after the events a diachronic permits us to discuss of the method's reliability compared to event information.

2 THE GEOMORPHOLOGICAL METHOD USED

2.1 *Essentials of the method*

The geomorphological method used here is based on two main points:

-It follows a stability concept

-It is applicable on a certain type of torrent.

The stability concept (Peiry, 1988, Schumm, 1977, Zimmermann et al., 1997) explains how a torrent system works (Cf. Fig. 1). Long periods of time with little apparent torrential activity alternate with torrential events, which could carry downstream large amounts of material by debris flow. Three factor allow this phenomenon: (1) predisposition parameters, which could increase and decrease over a long period of time, such as a basin area or channel length. These parameters only indicate if the basin is already close or not to the instability threshold. (2) sediment supply variables, such as the channel recharge rate. These are the main variables, because the more they increase, the closer the basin is of the instability threshold. (3) hydroclimatic events, which are short in time but could rapidly destabilize the system. The magnitude of an event is mainly determined by the volume of material dragged along the channel and not only the volume of the initiating event (Davies et al., 1992, Fannin and Rollerson, 1993), so channels must be recharged with material before a large debris flow can reoccur.

According to such authors as Bovis and Jakob (1999), Carson and Kirkby (1972), Stiny (1910), it is important to separate torrents into two groups (Cf. Fig. 2): catchments where sediment supply is limited (weathering limited systems) and catchments where sediment supply is unlimited (transport-limited systems). The second group, with a hydrological dominant extrinsic threshold, appears, for example, in torrents where channels are incised into thick glacial drift or into pyroclastic deposits around an active volcano. To use the geomophological method in the North Alps, we studied only torrents from the first group, with a morphologic dominant intrinsic threshold, which is why sediment yield dynamics and torrential sediment dynamics have definitly become the most important factor of the torrential system.

To estimate debris flow volume, it is most important to study and calculate the quantity of sediment temporarily stored inside the channel because the debris flows will be fed by this material. That is why we did not try to quantify each geomorphological process rate on slopes.

2.2 *Principle of the method*

Determining the potential volumetric state of channel sediment is based on a reference level through the channel length, which is representative of the lowest level for debris flow erosion. Once this calculation has been done, it is possible to calculate a volume between this reference level and the topographic surface. This volume represents the sediment potential store in the channel which could feed a debris flow.

At the moment, two hypotheses are being considered to determine the reference level (Cf. Fig. 3). (1) The level going straight from the top of the downstream profile length hard point - a check dam or escarpment rock - to the bottom of the next upstream hard point. (2) The second hypothesis uses a lower level, taking into account a maximum erosion slope observed downstream from the sediment trap where all the sediment is stopped. The real reference level is between these two hypotheses.

The topographic surface level is measured with a length profile and cross-sections which divide the channel into homogeneous reaches (especially for slope and width), using either classic field topographic measures with successive station progress or stereo-photogrammetric measures on aerial photographs. Then it is possible to summarize each reach volume for the total length of the channel.

2.3 *Reference Level*

The cross-section reference shape used is a U-shape following vertical or subvertical banks observed in the field and described by different authors (Aulitzky, 1982, Johnson, 1970, Lavigne and Thouret, 2000, Thouret et al., 1995). This is particularly exact just after a debris flow, but the verticality also depends on the material. Usually the substratum is deep enough below the channel, but the U-shape choice may over estimate volumes upstream when the method is used in the ravines (with a natural v-profile made of rock).

The first hypothesis (Cf. Fig. 3(1)) for the reference level in the length profile gives minimum volume estimations. The straight line between two successive check dams (or escarpment rock in the channel) theoretically corresponds to a dynamic equilibrium slope gradient (profile a). It is possible, in certain reaches when check dams are far from each other, for sediment to be eroded below this level. On the other hand, this reference level is easy to use to compare the different states of the sediment.

The second hypothesis (Cf. Fig. 3(2)) is the lowest reference level, i.e., the debris flow cannot erode below this level. In theory, the maximum limit can be modeled by two straight lines representing slopes between check dams: a horizontal line downstream and a vertical line upstream (profile b). In fact, in nature, the maximum erosion slope exists downstream of the sediment trap because all the sediment discharge is caught (profile c). This field maximum erosion slope is still too extreme for the channel upstream, where sediment discharge is much more substantial. That is why this second hypothesis (profile d) uses two slopes as medium slopes between the maximum erosion slope observed (profile c) and the dynamic equilibrium slope (first hypothesis: profile a). The maximum erosion slope is observed downstream where the channel is not too steep, so to use it upstream, a proportion with the general slope of the main channel parts is calculated. Also, to simplify, the downstream slope of the maximum erosion slope is considered to be horizontal.

2.4 *Topographic Range*

An optimal field measure range was estimated comparing with precise topometric data made of a 20-point cross-section every 10 meters in the length profile. Taking into account the topographic instrument, each cross-section was separated by 50 meters or less if the slope change (check dam) (Cf. Fig. 4). For cross-section used, the risk of error is then about 4,5%.

Inside the cross-section, only 4 points remain necessary: both banks, thalweg, and the highest point in the middle 40% of the channel (Cf. Fig. 4). These 4 points allow us to calculate a good estimation of the section area between the reference and the topographic level. From section areas, a statistical analysis of the comparison between the mean height of detailed cross-section and the mean height calculated, on about 40 different types of cross-sections shows an uncertainty of less than 25 cm. For the kind of torrents studied this is equivalent to 2,5%.

Between cross-sections, stations complete the length profile, which is made alternatively of cross-section thalweg point and station point. The length between two stations limits cross-section representativeness. When a check dam or rock escarpment is found, measures are taken downstream and upstream of it (Cf. Fig. 4).

2.5 *Volume calculation taking account of slope gradient*

All the following computing might be more or less automated. In our case, some macro commands programmed with *VisualBasic* language on the software *Excel*, made the data processing semi-automatic.

Four steps allow to calculate a volume of sediment stored all the long inside the channel:
-defining reference length profiles
-computing surfaces of cross-sections
-computing length of each reaches
-computing volume of each "boxes", which are representative of reaches.

First, the bottom level must be defined as a reference level. Two reference levels have been used (see reference profiles in §.2.3..(Both of them are based on hard points in the length profile as escarpment rock, check dam, ford, apparent rock,… Most hard points can be rapidly identified on the field, but sometimes it is possible that some of them would be completely buried and not visible. In this case, some other ways are possible: using past (aerial) photographs, using some historical data, or doing a seismic prospection. Of course, the best reference level integrates all the length profile hard points. The reference length of profile 1 is made of straight lines between hard points, whereas the reference length of profile 2 follows the outline proposed in profile d (see §.2.3). In order to calculate the profile d an intermediate point as been used with the following coordinates:

$$x_I = \frac{x_B - \tan\beta . y_B - \tan\beta . \tan\alpha . x_A + \tan\beta . y_A}{1 - \tan\beta . \tan\alpha}$$

$y_I = \tan\alpha\ (x_I - x_A) + y_A$ with x, distance on the length profile and y, elevation.

Second, each cross-section made of four points is modelized by a curved line ($y = ax^2 + bx + c$). The surface of cross section (S) is then computed by the integral between the curved line and the bottom reference level. It is also possible to compute a mean height (h) by using the width (w): $h = \frac{S}{w}$.

Third, the length of each reach (L) represented by cross-section is defined by the two station measuring points located immediately downstream and upstream of the cross-section.

Fourth, each reach of the torrent channel can be modelized by a box (Cf. Fig. 4). Volume of boxes (V) are computed as follow: $V = L . w . h$ or $V = L . S$

Finally, to obtain the total sediment volume available in the channel to feed a debris flow, boxes are added together. Downstream boxes, where the mean slope gradient is lower than 8°, are not used. Indeed lower slope gradient area are deposit areas (as sediment traps or part of a debris fan) or areas where the debris flow slows down so much that no more sediment of these areas could feed a debris flow (PWRI, 1984, Rickenmann, 1997).

3 THE APPLICATION OF THE METHOD ON TWO SIMILAR TORRENTS: LE MERDARET AND LES ARCHES

3.1 *Choice of torrents*

Two groups of criteria have been followed to choose torrents: (1) *The torrents* must resemble the Manival torrent were the method was elaborated, especially with reference to the same sediment working system; (2) Some data are necessary to validate the method: aerial photographs of past dates and data describing past debris flow events.

For these torrents, sediment recharge is essential in the instability process. *The torrents* are included in the morphologic dominant intrinsic threshold group. The working torrential activity can determine some types of torrents (Richard, 1996). These torrents have their sediment yield located in the upper part of the catchment area with scree, rock fall, or stone fall slope processes. The torrents chosen have the same geologic and lithologic features: rock layers bent and cracked which alternate b hard limestone layer and softer marl layer. Landslide processes have been avoided because they involve a different type of torrential activity.

As much information as possible is necessary to validate the results of the method on the two other torrents. It is essential to have two channel sediment states at two different dates, to know the torrential events which happened between these two dates. In France, aerial photographs are centralized by the national geographic institute (IGN), and torrent data are often collected by a national forestry service in charge of natural hazard mitigation in mountain (RTM). The RTM service makes an event index card each time that a consequent debris flows occur, with some descriptions: date of event, climatic conditions, deposit area, start area, volume estimations, injuries,…

Also we had to take in account that field study is difficult to work because of steep slopes, friable rocks, or stone fall, so a torrent basin must have a possible and safe access.

3.2 *Brief presentation of torrents*

These two torrents are located in the French North Alps south of Grenoble (Cf. Fig. 5).The Le Merdarêt torrent has developed in limestone and schist between the Ecrin and Taillefert mountain ranges and Les Arches torrent is very deep on the east side of the Vercors mountain range. Like many torrent watersheds, they have three characteristic parts: (1) the upper-part or upper basin, where most of the sediment and water from the slopes is collected by the torrent channel; (2) a flow channel, quite short with gorges; (3) the debris fan where sediments settle down and increase the debris fan, according to the overflow from the main channel.

The basin areas studied cover about two to three square kilometres. Elevation for the Le Merdarêt basin ranges from about 1 300 to 2 400 meters high, while the channel is about 2 100 meters long up to 1 800 meters high, and for the Les Arches basin ranges from about 1 000 to 1 950 meters high, whereas the channel is about 2 500 meters long up to 1 500 meters high. In the upper basin both have one or two major affluent ravines. Precipitation is not well known for these torrents because of the lack of pluviometric data in this mountain area, but some stations at lower elevation show mean annual precipitations ranging of 780 to 1400 mm.

The lithology and geology of upper basins are favorable to sediment yield and do not permit much vegetation cover. From top to bottom the Le Merdarêt lithology is: limestone with schist (Carixien-Lotharingien), marly limestone (Domerien), marly limestone and marl (Toracien), whereas the Les Arches lithology is: yellow limestone (urgonien), grey limestone (barremien inf.), grey schist of Chichilianne (hauterivien), alternation of grey limestone and blue marl (hauterivien). Debris fans are quaternary fields with torrential and glacial deposits.

To protect people and infrastructures downstream against torrent hazards, the RTM agency planted many trees on bare slopes where it was possible and built a number of check dams in ravines and channels and maintained them to stabilize the length profile and the slopes, which has thus resulted in a lower sediment yield. It also built some dykes along the channel and sediment traps, and there moves regularly, sediment deposited both in sediment traps and inside the channel as needed, to avoid any overflows.

In the Le Merdarêt torrent, 50 check dams were built between 1904 and 1933. By 1904, the Le Merdarêt debris fan and the Les Pâles debris fan from the torrent next to it, were often connected, according to the overflow from each channel. Trees have been planted on the debris fan, but it was not possible to do so upstream in the large upper basin. After 1958, a 275 meters dyke was erected upstream of the road (on the debris fan) on the left bank of the torrent to protect villages. Now, a few check dams have been added, and two sediment traps with a capacity of about 10 000 m3 each. The Les Pâles torrent has been diverted into the Le Merdarêt channel, but the Les Pâles has also a 10 000 m3 sediment trap (Cf. Fig. 6(A)).

In the Les Arches torrent, only a few check dams are present: one in the lower part on the debris fan, made in 1970, is 1.7 meters high; an other one in the upper basin made in 1976, is 5.4 meters high, and was consolidated in 1979 by an other check dam now largely damaged. In 1993, a large check dam was built at the downstream extremity and a sediment trap was dug out behind it. From there to the gorges, on the debris fan, a long and high dyke protects the village. The channel width is then about 20 meters, but most of the time the water flow is contained in a few meters in the middle of the channel. At the top of this long reach (top of the debris fan) is a 340 meter long area which is very wide, between 30 to 60 meters, and less steep than the upstream reach. This wide area could be considered as a kind of sediment trap (Cf. Fig. 7(A)).

3.3 *Results on Le Merdarêt torrent*

3.3.1 *Data used*

Among the recent torrential events which occurred in the Le Merdarêt torrent, the event of the 24th July 2000 was described by the RTM technicians. During this event, many check dams (28) were damaged and two of them fell down. The road was also buried by debris flow deposit. Each sediment trap was filled by about 10 000 m3 of sediment. At this time, debris flow in the Le Merdarêt torrent was estimated at about 20 000 m3. In the Les Pâles torrent, all the sediment was trapped in the sediment trap and no material went from there to the Le Merdarêt.

Two days before, the 22d July 2000, aerial photographs were taken and are now available at the IGN. The scale is about 1/25 000e. These photographs were used to make the topographic measures by the stereo photogrammetric technique. It was then possible to use the geomorphological method to estimate the maximum volume of a possible debris flow before the event of the 24th of July.

3.3.2 *Volume results*

Following the method, the volume computation of the sediment trap downstream which has a slope gradient lower than 8° (or 14%) was not taken into account.

Results for the two bottom reference level hypothesis are:

-using the reference length profile 1: 19 684 m^3,

-using the reference length profile 2: 64 048 m^3.

The risk of error of the method with the use of photographs is about 12%. The real volume is between about 20 000 m^3 and 64 000 m^3 (around 42 000 m^3). It represents the maximum volume which can be transported by a debris flow.

The figure 6(B) shows that an important sediment volume is stored in the channel between 440 meters and 760 meters, and some reaches upstream with more than 2 000 m^3 of sediment stored whereas the sediment traps doesn't seems to be completely empty.

3.3.3 *Channel Temporary Storage Areas (TSA)*

During an event, sediments are not incised uniformly all along the channel. Some reaches work as a sediment reservoir. We named them channel Temporary Storage Areas (TSA). TSA are very important for the sedimentary dynamic of torrents because water discharge is very low for most of the time and sediment moves mostly by pulsation when a debris flow occurs. Theoretically, this is explained very well by the conceptual graph, applicable on any time or space scale.

The best way to detect TSA is to study channel slopes. In fact, channel TSA seem to be located at concave parts of the length profile but these parts, however, are difficult to see on length profile graph. For this reason, the length profile residual graph was studied (Cf. Fig. 6(C)). This graph is made by calculating the difference between the straight line from minimum elevation to maximum elevation on the one hand, and the length profile on the other hand. It must be read from upstream (right) to downstream (left) and each difference of the slope gradient shows a concave or a convex part of the length profile. To study in detail a shorter part of the length profile it is possible to make a new length profile residual graph on a shorter distance. Also, when TSA are located on the graph, they are easily visible in the field.

On the graph of figure 6(C), TSA are shown. The most evident are sediment traps, whereas it is more difficult to define TSA located in reaches with many check dams.

The state of channel TSA is very important: if a TSA is full of sediment it will probably feed the debris flow, but if a TSA is "empty" debris flow can fill it and may slow down. Often sediment traps are the biggest TSA.

3.4 *Results on Les Arches torrent*

3.4.1 *Data used*

Like the other torrent, we have looked at the recent events. Three debris flow events of medium deposit volume have been used: a 6 000 m^3 event of September 1998, a 10 000 m^3 event of July 1999, and a 10 000 m^3 event of August 2000. These volumes have been estimated inside the sediment trap.

The same stereo photogrammetric technique as the Le Merdarêt torrent study has been used on July 1998 photographs from IGN.

3.4.2 *Volume results*

The result of the method have been computed with data from 1460 meters upstream, with a slope gradient higher than 8° (or 14%).

Results for the two bottom reference level hypothesis are:

-using the reference length profile 1: 17 483 m^3,

-using the reference length profile 2: 57 811 m^3.

The maximum volume of sediment which can be transported by a debris flow at 1998, was between about 17 500 m^3 and 57 500 m^3 (around 38 000 m^3).

For the particularly wide area located at the debris fan apex, we examined a width of 20 meters because we consider, due to the channel morphology, that debris flow could not drag sediment all over the 60 meters wide of this area. Therefore the calculation was made for a width of 20 meters so that the result is plausible. This unusual torrent emphasizes that field work is necessary.

The figure 7(B) shows a larger amount of sediment volume on the debris fan apex, at a distance between about 1600 meters to 1900 meters. Downstream, lower slope gradients favor debris flow deposits so that there is an enormous quantity of sediment because on the weaker slopes the debris tends to settle or at least slowing down.

3.4.3 *Channel Temporary Storage Areas (TSA)*

We have proceeded in the same way as before and used a length profile residual graph. The sediment trap is an evident TSA, but there are small convex zones although the TSA is in fact largely concave.(Cf. Fig. 7(C)).

4 DIACHRONIC ANALYSE BEFORE AND AFTER DEBRIS FLOW EVENTS AND DISCUSSION ABOUT THE METHOD USED

4.1 *Estimation of debris flow volumes and prediction of maximum volume possible in July 2001*

The same method has been used to manage volume calculation, using field topographic measures taken in July 2001 with a laser range-finder (*Impulse 300*) and an electronic compass (*Mapstar*). Both reference length profiles are kept the same.

The calculation of the volume of the debris flow between the 2 dates is based of the overall total of the channel and substation allowed us to calculate the difference between the total channel volume in 2001 after debris flow events and the total channel volume in 2000 for the Le Merdarêt torrent (1 event), and the total channel volume in the 1998 for the Les Arches torrent (3 events). Figure 6(D) and 7(D) show the length profile evolution for each torrent.

All these results, and also predictions of maximum debris flow volumes possible in 2001, i.e. the volumes of the upper reaches which have a slope gradient higher than 8°, are presented in table 1 for the Le Merdarêt torrent, and in table 2 for the Les Arches torrent.

4.2 *Workability of the method*

4.2.1 *Comparison of event informations and event volumes calculated*

For the Le Merdarêt, the July 2000 event description mentions debris flow deposit at sediment traps of about 20 000 m^3 and in a few reaches. Calculated volume gives a result of about 11 000 m^3. Most of the measures have been taken between the two sediment traps, then this result must be compared with the approximately 10 000 m^3 stored in the lower sediment trap. We can consider that volume calculated fits well with information about the event. Figure 6 presents the length profile evolution between 2000 and 2001, which fits well with TSA.

For the Les Arches, the period observed is longer with 3 debris flows. Events information gives a total of 26 000 m^3. But the difference volume calculated is of about -14 000 m^3. This means that, between 1998 and 2001, the channel torrent was recharged by about 40 000 m^3. The high rate of sediment yield for this torrent is possible considering the upper basin morphology and might be linked with the frequency and non negligible magnitude of the latest events. The length profile comparison represented on the graph of figure 7, shows a more important accumulation in the lower part, whereas for upper reaches with slope gradient higher than 8° the channel has been recharged by only 3 500 m^3.

4.2.2 *Comparison of predicted maximum volumes and events volumes*

For the event in the Le Merdarêt, the predicted maximum volume was from about 20 000 m^3 to 64 000 m^3 and the total debris flow volume estimation was more than 20 000 m^3. In 1998, predicted maximum volume for the Les Arches torrent was from about 17 500 m^3 to 57 500 m^3 , and the 1998 debris flow had a volume of about 6 000 m^3, while the next debris flow had a volume of about 10 000 m^3. Although debris flow event was relatively important for this torrent, the results are still coherent because they predict the biggest event possible which rarely occurs.

Result volumes are also coherent with each torrential basin morphology. For example, the upper basin of the Les Arches is smaller and volume prediction fairly modest in fact what seems to append is that debris flows are small but more frequent. This would correspond to the information received as they have been 3 debris flows in 3 years.

Obviously, after an important debris flow the new predicted maximum event volume decreases because a part of the sediment stock inside the channel has been used by the debris flow.

4.2.3 *Difficulties encountered by using the method*

The main difficulty in this study came from the utilisation of two different measuring techniques (photogrammetry and “rapid” field topography). They had different accuracy and it was difficult to fit both measures together with steady points.

The second difficulty was to determine all of the hard points necessary for reference levels design. Field work was essential to see most of them, and to locate some others from lithologic features. Generally historical information on the torrent (check dams building, events descriptions,…) are also very useful to complete or validate the location of hard points. In some part of the torrents, seismic prospective may have been done.

4.3 *Possible improvement of the method*

The results of the method are approximate but seem to be coherent. It is particularly true on the Le Merdarêt torrent which has been a simple case study with a single debris flow and measures just before the event and after it. Whereas on the Les Arches torrent, the method shows objective results which means that the channel have been largely recharged and not only dragged by debris flows.

The weak point of the method is certainly the uncertainty of the reference level. To improve our knowledge of it, different ways are possible: a first way could be to experiment in a laboratory with the incision features made by a debris flow; a second way is to use a large data base of channel topography to analyse the lowest levels observed, especially after a debris flow.

The method could be improved by making the result more precise in comparison with reality. When the method gives a maximum event volume, it assumes that debris flow will incise all long inside the channel to the bottom reference level. But it is also possible that debris flow could never take off all this volume but only a part of it. Perhaps only TSA volumes or few TSA volumes have to be taken in account. To improve the method in this way, a large amount of torrent measures are needed.

Finally, it will certainly possible to extend this method to other types of torrents, but to do this the method must be tested on many of them.

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Date	2000		2001		Volume of debris flow (+) and recharge (-)	
Reference profile	1	2	1	2	1	2
Volume estimation for the maximum debris flow (using upper reaches with slope gradient >8° (in m^3)	**19 684**	**64 048**	**6 463**	**50 826**		
Potential volume stored in all reaches (in m^3)	25 009	82 179	14 155	71 324	**10 854**	**10 854**

Table 1: Le Merdarêt torrent volumes estimations.

Date	1998		2001		Volume of debris flows (+) and recharge (-)	
Reference profile	1	2	1	2	1	2
Volume estimation for the maximum debris flow (using upper reaches with slope gradient >8° (in m^3)	**17 483**	**57 811**	**21 101**	**61 429**		
Potential volume stored in all reaches (in m^3)	-20 192	264 062	-6 013	278 241	**-14 179**	**-14 179**

Table 2: Les Arches torrent volumes estimations.

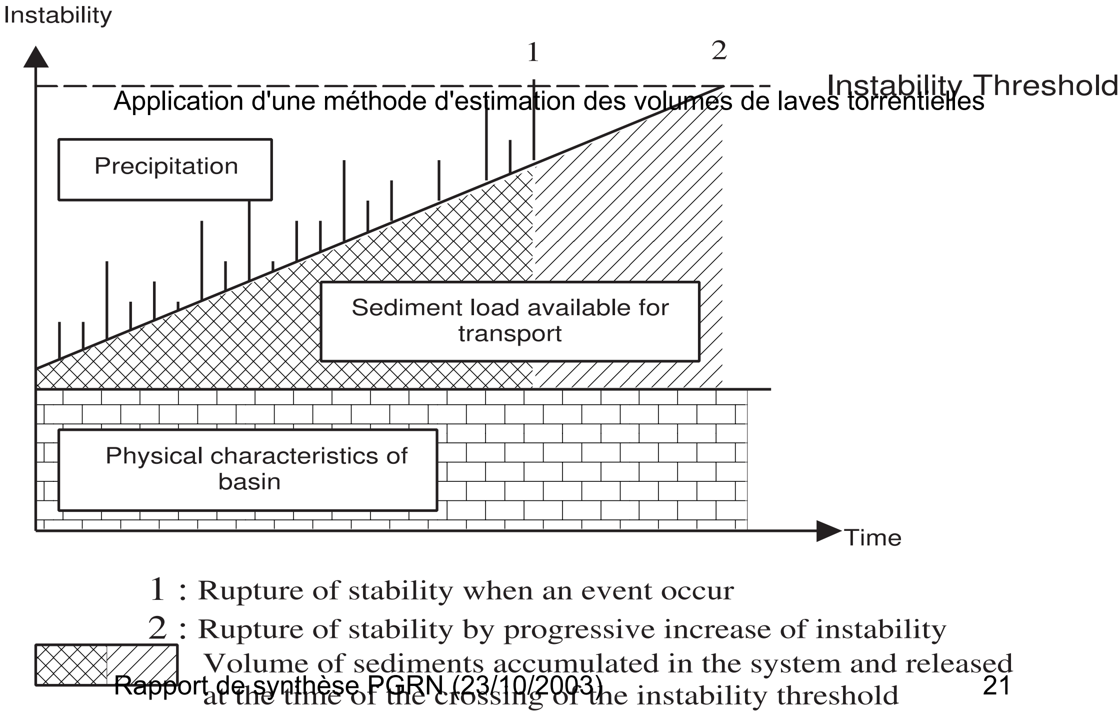

Figure 1: A stability concept graph (from Schumm, 1973 and Heward, 1978, modif.).

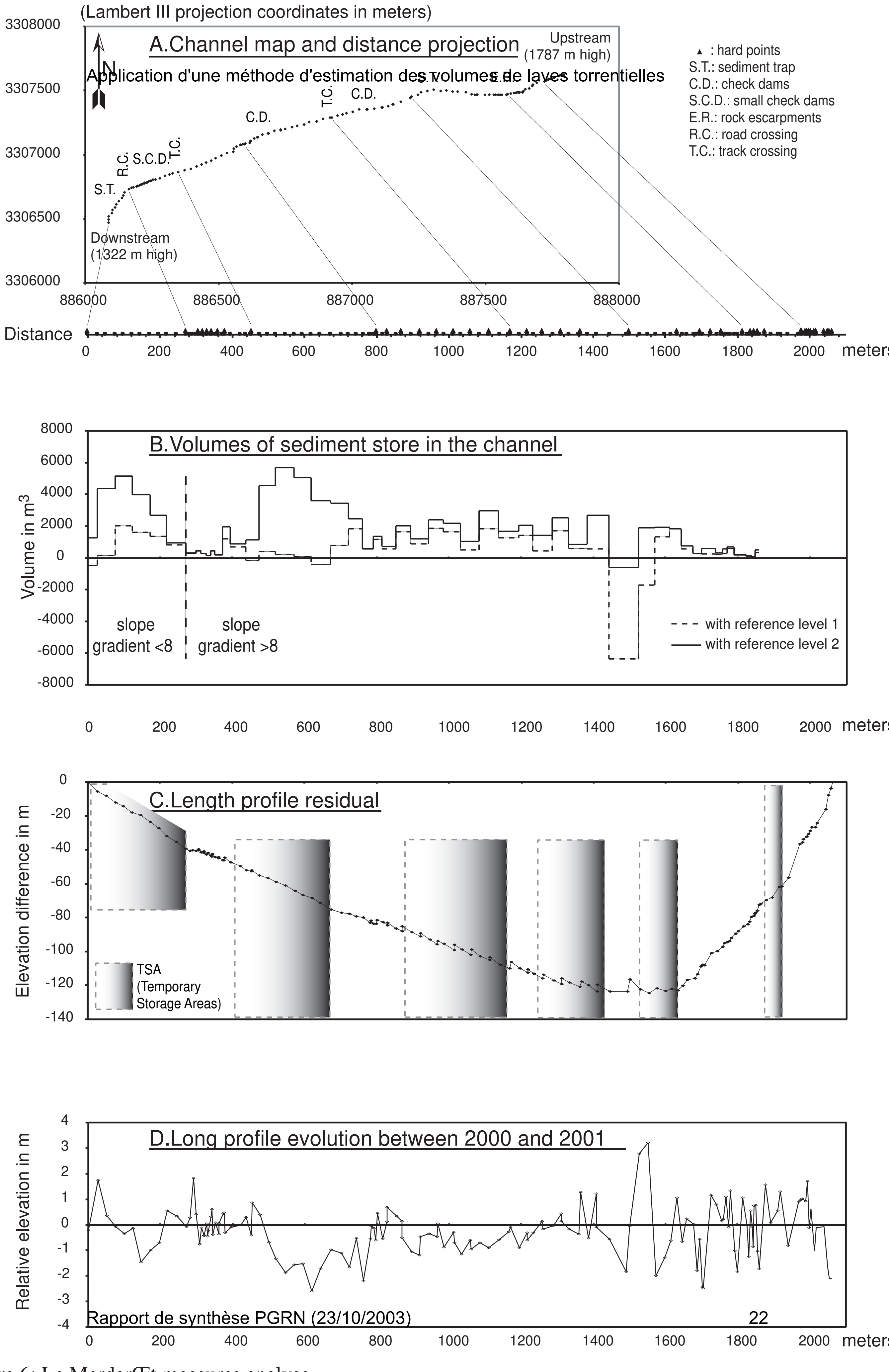

Figure 6: Le MerdarŒt measures analyse

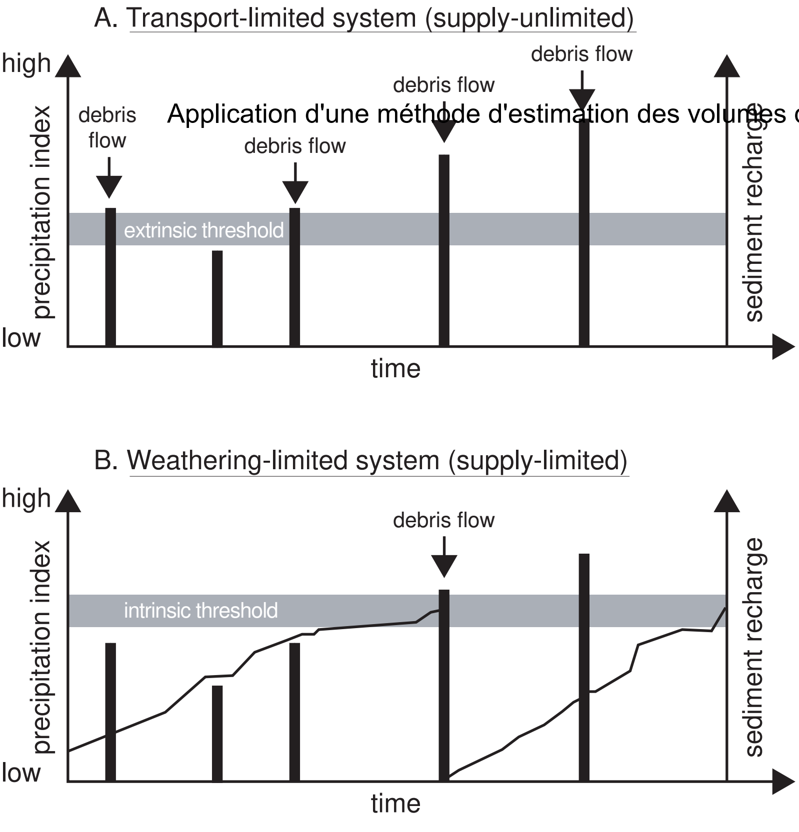

Figure 2: transport-limited (A) with morphologic dominant intrinsic threshold and weathering-limited (B) with hydrologic dominant extrinsic threshold concepts applied to the occurence of debris flow events. Bars indicate precipitation, curved rising lines indicate cumulative sediment recharge (from Bovis and Jacob, 1999).

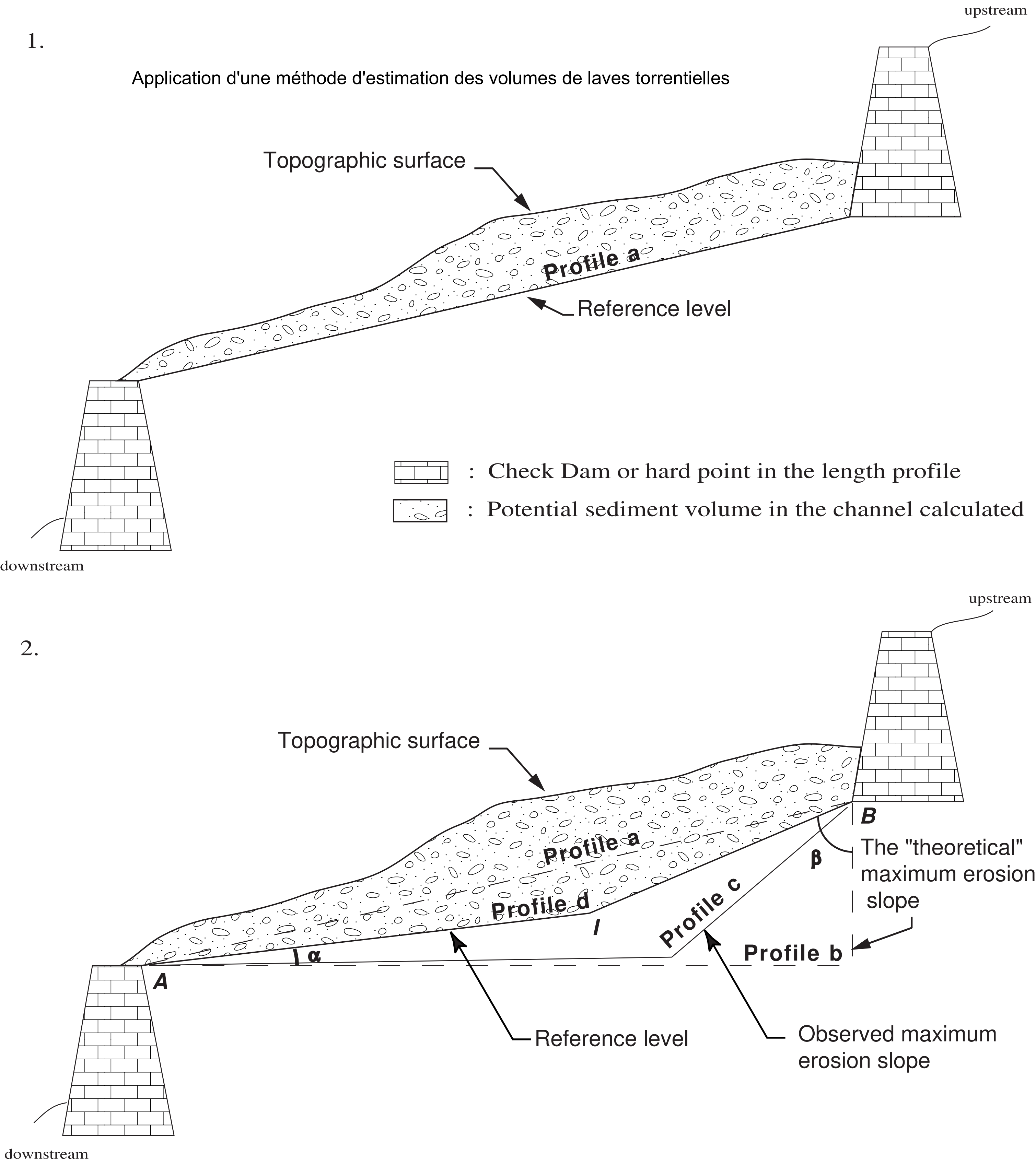

Figure 3: Reference levels, (1) first hypothesis: reference level as a dynamic equilibrium slope gradiant, (2) second hypothesis: reference level between the equilibrium slope gradiant and the observed maximum erosion slope (from Veyrat-Charvillon, 2003).

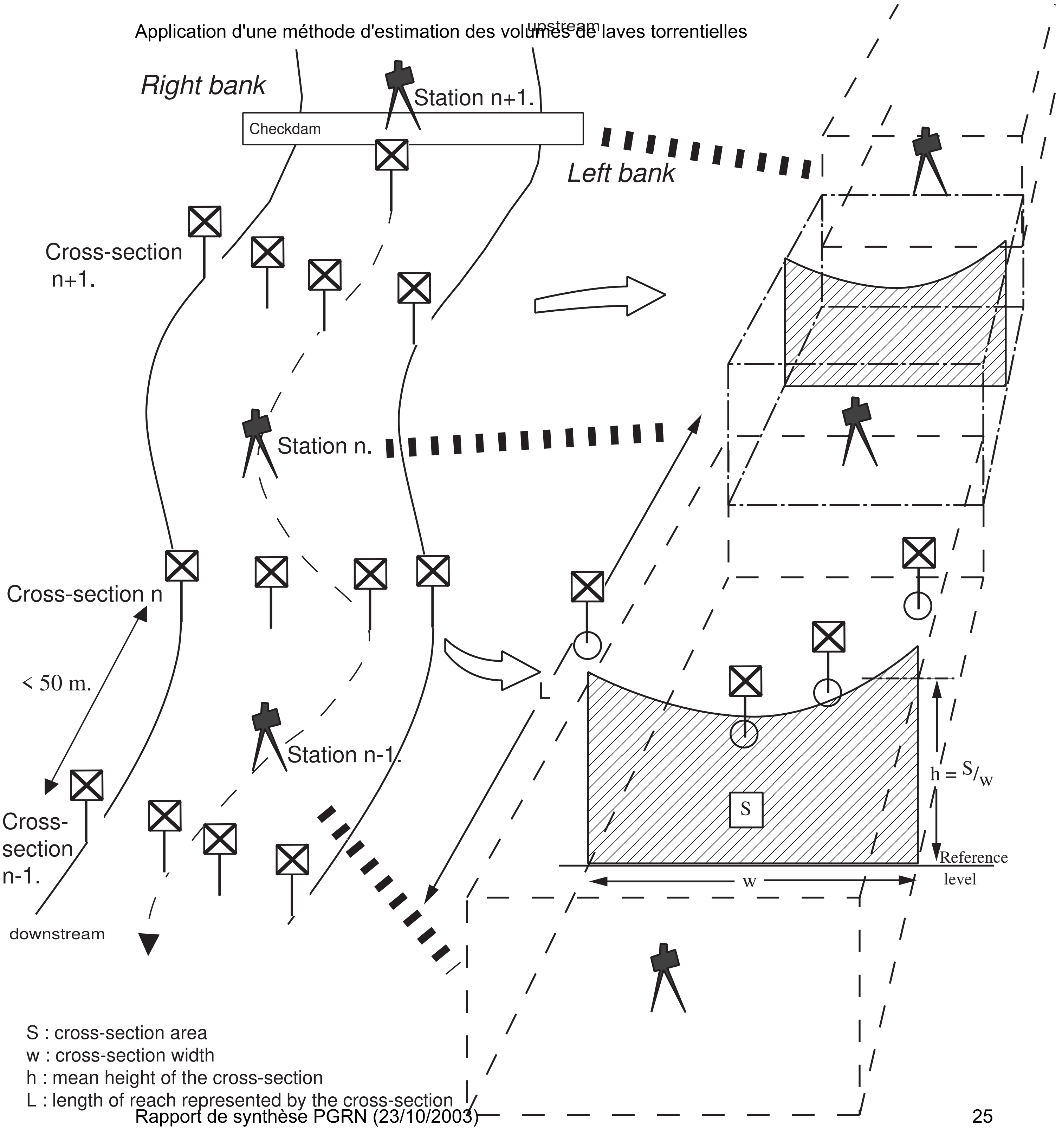

Figure 4: Ranging measures and volume calculation methodology.

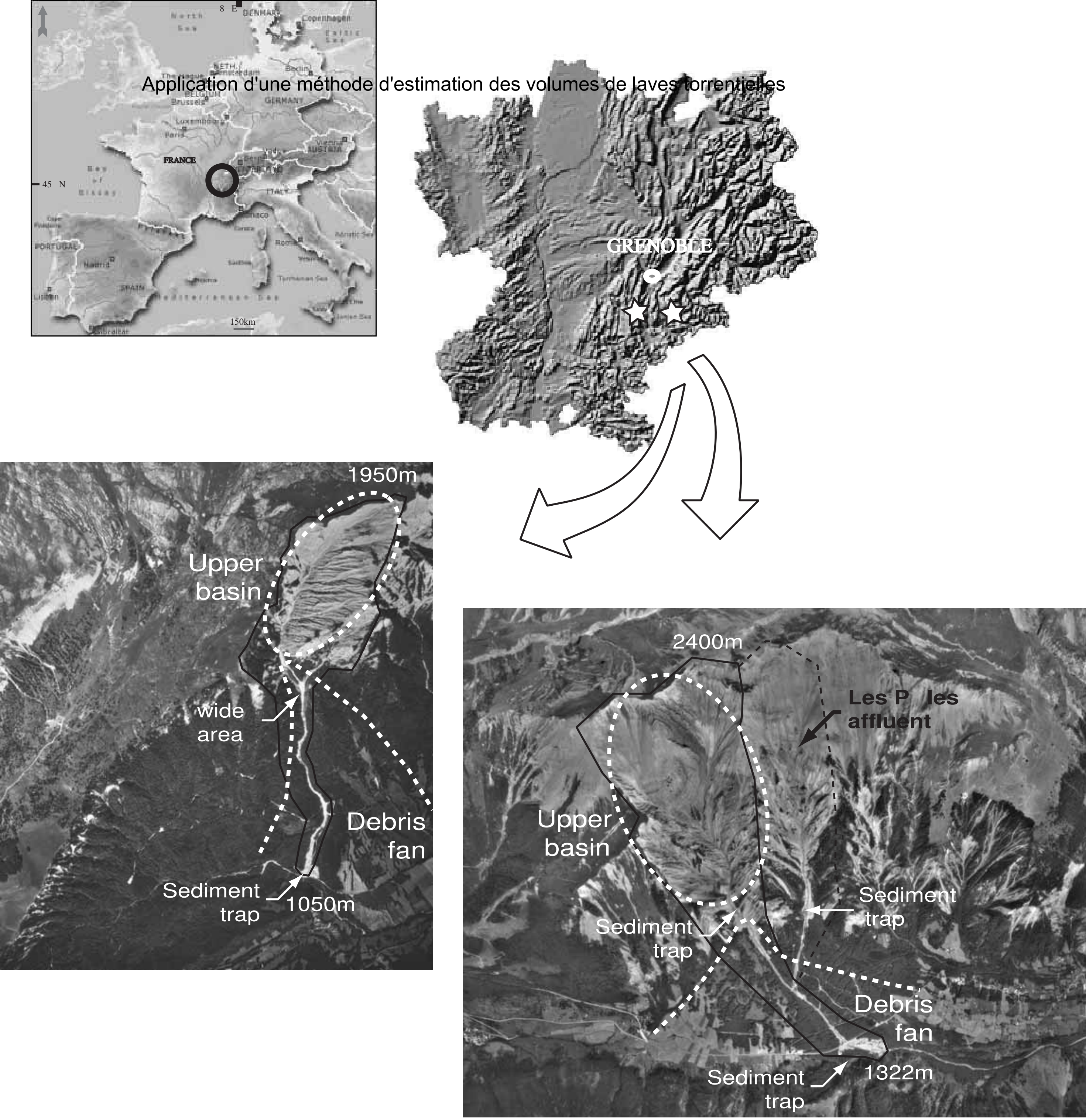

Figure 5: Location of the two torrents studied, Les Arches (left) and Le MerdarŒt (right). Aerial 1998 and 2000 photographs have been bought at IGN.

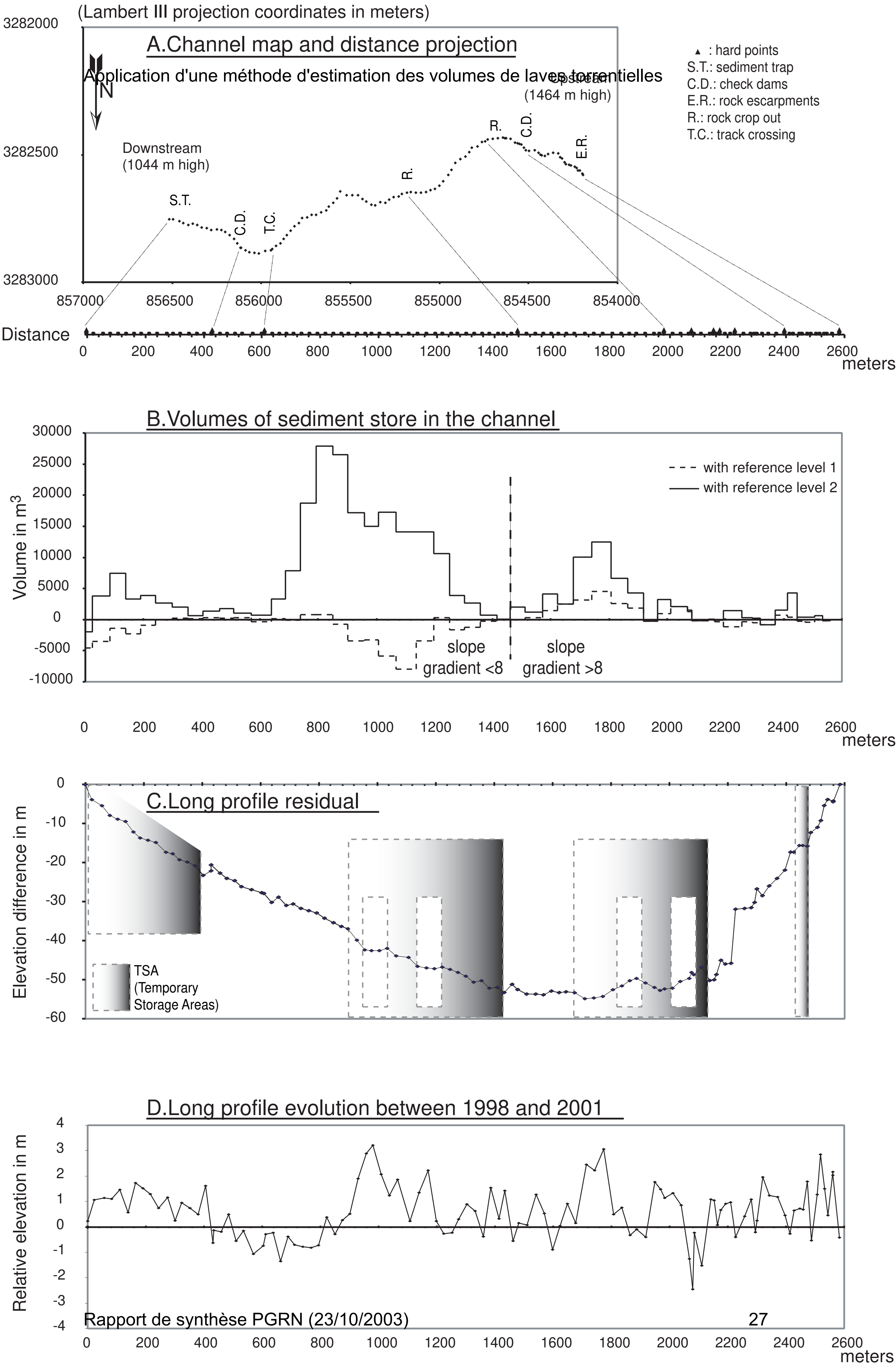

Figure 7: Les Arches measures analyse