DRAIX: A FIELD LABORATORY FOR RESEARCH ON HYDROLOGY AND EROSION IN MOUNTAIN AREAS

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RÉSUMÉ
Les crues des petits bassins versants de montagne à réponse rapide sont soudaines et fréquemment dévastatrices. Améliorer les connaissances sur le ruissellement, l'érosion et le transport solide dans ces bassins représente un intérêt stratégique du fait des conséquences des crues qui s'y produisent et des besoins pour le dimensionnement des ouvrages de protection. En France, dans les Alpes du Sud, les marnes du Jurassique, localement appelées "Terres Noires" affleurent sur de larges surfaces. Ces marnes noires sont très sensibles à l'altération et à l'érosion et sont très instables. Les mouvements de masse sont fréquents sur les pentes raides de marnes souvent fracturées. Ces phénomènes se traduisent par une topographie fortement incisée (badlands) et des transports solides intenses au cours des crues. Ces besoins de quantification des phénomènes et des effets des aménagements de protection ont conduit le Cemagref à équiper il y a une des sites de mesure sur de petits bassins versants des Alpes du Sud. Cinq petits bassins de superficie comprise entre 1300 m² et 1 km² ont été instrumentés pour la mesure des précipitations, des débits et des transports solides par charriage ou en suspension. Quatre bassins sont situés en zone dénudée avec des taux de couverture végétale variant de 21 % à 56 %, tandis que le dernier a été entièrement reboisé à la fin du XIX° siècle dans le cadre des travaux de restauration des terrains en montage (RTM). Un sixième bassin, le Bouinenc (20 km²), drainant les quatre bassins situés en zone dénudée a été équipé en 2007. Cet article présente l'équipement de ces bassins et résume les résultats obtenus sur les processus et facteurs de la formation des crues et de l'érosion.

ABSTRACT
The floods generated in small mountains basin are flash floods often devastating. Predicting runoff, erosion and sediment yield within mountainous catchments presents a strategic interest due to the consequences which arise from these phenomenons and the need for natural hazard mitigation engineering. In the Southern French Alps, the Black Marls formation covers a large area. These Jurassic marine black marls (Bajocian, Bathonian and Callovo-oxfordian) are very susceptible to weathering and erosion and very unstable. Mass movements are frequent in the steep and fractured slopes. It results in "badlands" topography with V-shape gullies and high solid transport, bringing heavily loaded floods downstream and silting up reservoirs. The need to quantify the phenomenon and the effect of the restoration strategies led the Cemagref to monitor a group of little basins in this area. Five basins with surface area ranging from 1300 m² to 1 km² have been equipped since 1982 for the measurement of rainfall, liquid discharge and solid transport, which can be both bedload and suspension. Four are situated in denuded areas with vegetation cover ranging from 21 % to 56 %; the last one was reforested at the end of the last century, within the frame of restoration works. A sixth basin, the Bouinenc (20 km²) is monitored since the end of 2007 and includes the 4 small basins of the badlands area. The paper presents the monitoring of the field site and summarizes the main results on the processes and factors of runoff and erosion.

1. GENERAL CONTEXT

The floods generated in small mountains basin are flash floods often devastating. Predicting runoff, erosion and sediment yield within mountainous catchments presents a strategic interest due to the consequences which arise from these phenomenons and the need for natural hazard mitigation engineering. In the Southern French Alps, the Black Marls formation, or "Terres Noires" in French, covers a large area. This formation is very susceptible to weathering and erosion. It results in "badlands" topography and high solid transport, bringing heavily loaded floods downstream and silting up reservoirs. These problems are particularly acute in the Durance basin where the erosion rates in the watersheds devoid of vegetation are the highest values in the world. The need to quantify the phenomenon and the effect of the restoration strategies led the Cemagref to monitor a group of little basins in this area (Cambon, Mathys *et al*. 1990).

The main goal of this laboratory is to improve the prediction of the runoff and erosion response of small mountain catchments to climatological inputs (precipitation and temperature), particularly for extreme events. Several scientific questions can be identified:

- What is the spatial and temporal variability of rainfall at the scale of a small mountainous catchment?
- What is the hydrological response of these small catchments to these inputs?
- What are the sediment yield, storage and transfer processes on the slopes and in the network?
- What is the role of the vegetation cover in these processes?
- Will modifications in some of these processes reveal present climatic or anthropic changes?

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2. DRAIX BASINS: SITUATION AND DESCRIPTION

The experimental basins of Draix are located 200 km South of Grenoble, near the little town of Digne (figure 1). Five basins have been equipped since 1982 for the measurement of rainfall, liquid discharge and solid transport, which can be both bedload and suspension. These basins have different surface areas, from 1300 m² to 1 km². Four are situated in denuded areas with vegetation cover ranging from 21 % to 56 %; the last one was reforested at the end of the last century, within the frame of restoration works. 87 % of its surface area is now covered with a pine forest (Table 1).

Figure 1. Location and general view of the basins

Table 1. Main Characteristics of the basins.

Basin	Area	Vegetationc cover	Average slope	Elevation
	Km²	%	%	m a.s.l.
Roubine	0.0013	21	75	850-885
Moulin	0.09	46	40	850-925
Francon	0.73	56	41	850-1140
Laval	0.86	32	58	850-1250
Brusquet	1.08	87	53	800-1260

A new gauging station was installed in 2007 for the Bouinenc torrent which drains the denuded area close to the village of Draix (20 km², elevation range 800-2270 m).

2.1 Geomorphological context of the study area

The Roubine (1330 m²) is a steep gully and can be considered as an elementary unit to observe erosion phenomenons. The slope gradient of the main channel remains higher than 35 %. The Laval (0.86 km²) is composed of several sub-catchments draining into a channel about 1 km in length with a slope gradient ranging from 8 % to 4 %. The Moulin (0.09 km²) is an intermediate scale basin which already has a small network of channels. The main stream, 300 m long, is 4 % steep. The basins are located on Jurassic marine black marls (Bajocian, Bathonian and Callovo-oxfordian). This geological dark formation is very sensitive to weathering and erosion, very unstable and well represented in the South French Alps (Antoine *et al*., 1995). This results in the characteristic badlands morphology with V-shape gullies (Figure 1).

The mean annual rainfall is 900 mm. The area has a Mediterranean climate, an average of 200 days a year without rain and only 5 days with rainfall depth higher than 30 mm. Summers are dry with the odd short yet severe storm and the maximum precipitation occurs in two periods, April-May and September-October (Mathys *et al*., 2003). It is also a mountain climate with frequent freeze and thaw cycles in winter. The freezing-thawing, completed by the wetting-drying phenomenon, is the major process for black marl degradation in this environment and was observed in similar catchments in Vallcebre, Spain (Gallart *et al*., 2002). These processes, variable in intensity from one year to another, depend greatly on climatic conditions and are consequently good indicators of climatic change.

At the end of winter, a weathered layer, several cms thick, smoothes the slopes and the rills mostly disappear. During winter, without runoff, marl platelets fall due to gravity and they constitute stocks at the bottom of the slopes, which are ready for the first runoff event . Saturation of the weathered layer, by melting snow for example, may cause solifluction. On steep slopes, it generates small landslides and mudflows that supply sediments to the stream channels (Oostwoud Wijdenes and Ergenzinger, 1998). Consequently, the first major spring events cause floods with high sediment load. In summer and early autumn, severe storms provide material by concentrated runoff on the slopes. Once in the main channel, liquid and solid discharge are routed, according to the equilibrium between them: when the liquid discharge coming from the slopes contains only a little solid sediment, the flood is highly erosive and erodes the deposits of the previous floods. On the other hand, when there is too much sediment from the slopes, there is deposition. Debris flows occur on the slopes but they are rare in the main channel. Moreover, when they occur, they seem to stop suddenly as the channel slope gradient is far less than the hillslope gradient or else they are diluted and transformed into hyperconcentrated flows. So in general, the floods behave as hyperconcentrated flows. One problem is the lowering of the grain size of the solid transport due to the quick destruction of the marl stones and gravel by the turbulence of the flow, transforming bed-load into suspension.

2.2 Hydrology and erosion monitoring

Five rain recorders located in the lower, intermediate and higher parts of the basins measure the precipitation. At the outlet of each catchment a set of devices allows the measurement of liquid discharge and sediment transport (figure 2). A gauging station, with a calibrated flume (V-shape or Parshall flume) is equipped with different type of level recorders (floating device, ultrasonic sensor, radar sensor, numerical rule). Upstream of this flume a sediment trap retains the coarse material. The volume of deposited sediments is measured by topographic methods after each flood. This method gives a global amount of bedload transported material for a flood or a small group of consecutive floods. The trap is emptied when it becomes full of sediments or after most of the events for the small Roubine trap. In the gauging flume, an automatic sampler takes samples during floods with a program referring to both the level of water and the time lag between two samples: this gives a discontinuous estimation of fine solid transport during the flood. Since 1995, prototypes of optical fiber sensors have been used in the Laval and Moulin stations. This device measures sediment concentration of the flow using back scattering properties of the mixture (Mathys *et al*., 1999). It is accurate, highly resistant to the hard conditions of mountain torrents, but sensitive to the particle size distribution of the suspension. So, both continuous measurements with the optical device and discrete values obtained with the sampler are used to determine the sediment load throughout the flood. As a result, instant concentration with discharge allows one to calculate the suspended sediment yield of the flood. Recently, commercial backscattering optical sensors have been settled on the Roubine and the Bouinenc station, but the response of these sensors is nor longer reliable over 150 g/l.

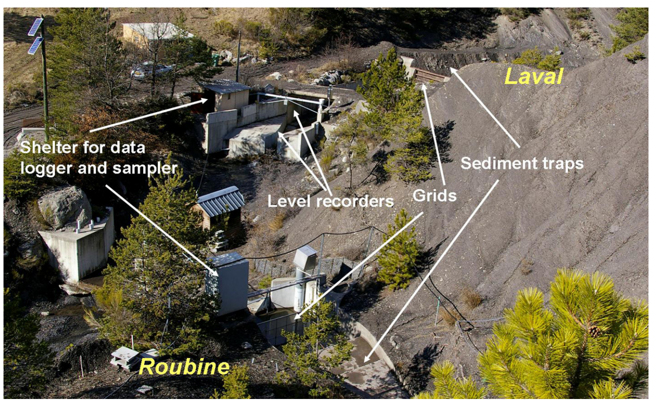

Figure 2. Measurement station at the outlet of the catchments

Other measurements are conducted to complete the observed parameters of the research site:

- Climatological data (air temperature and humidity, wind speed and direction, solar radiation)
- Soil hydraulic properties (piezometers, TDR probes, capacity probes, tensiometers) in different soil types
- Soil temperature at different depth (0 to 24 cm) with different aspect (north and south facing) and position on the slope length
- Rainfall drops properties (size distribution and velocity) with a spectro-pluviometer

Since 2004, a specific monitoring is realized on a landslide which occurred in 1999 and blocked up the main stream of the Laval, 600 m upstream the gauging station. This equipment has been completed in 2006 in order to observe the water fluxes in the mass movement: piezometers, TDR, tensiometers, soil water content capacity probes, lysimeters. In addition, an area of the divide between Laval and Moulin catchment is investigated since 2006 for the study of water circulation in the fractured marls and its role on mass movement triggering. 20 self potential probes, 8 capacity probes, 4 tensiometers, 5 piezometers, 4 soil temperature sensors, 4 TDR. Five boreholes were drilled down to -25m to study the structure and the discontinuities of the marly slopes.

3. MAIN RESULTS ON FLOOD GENERATION, EROSION AND SOLID TRANSPORT

3.1 Hydrology

Summer precipitation comprises very few rain showers: occasional storms providing 20–60 mm of precipitation. The periods of April-May and September-October are much rainier, with monthly rainfall reaching 100 mm, and October is usually the wettest month. The floods observed are violent with very high peak discharge. The highest flood monitored reached 20 $m^3 s^{-1}$ as peak flow for only 0.86 km of basin area. The floods are very flashy on Laval, Roubine and Moulin. On Laval, the raising time is shorter or equal to 20 minutes and within this time the discharge raise in the gauging station from zero up to 2 to 10 $m^3 s^{-1}$: (for example, from 0 to 5 $m^3 s^{-1}$ within 11 minutes in July 1995). When observations of rainfall depths which do or do not cause runoff are plotted against dry period duration, "rainfall threshold curves" can be defined. It is interesting to note that in the Laval basin, most falls of rain greater than 9 mm can cause runoff whereas at Brusquet, after a long dry period even 25 mm of rain may not. The maximum threshold is about 9 mm for Laval and about 30 mm for Brusquet. The rainfall-runoff diagrams of figure 3 illustrate the contrasting responses of the forested and unforested basins to a rainfall event.

Investigations on environmental water tracing (chemical and isotopic) were carried out. Direct surface transfer of event water was the dominant flow mechanism at peak flow. This large contribution was not dependant of antecedent soil moisture conditions. Nevertheless, significant participation of subsurface water has been observed over the flood events even at peak discharge. This contribution was greater in the case of wet antecedent conditions. In a dry context, subsurface water was shown to be mostly new water whereas pre-event water could contribute to the flow in wet conditions. A deep groundwater reservoir may take part in the pre-event component in the larger basin (Laval) but in Roubine and Moulin, pre-event water was mostly made of short mean residence time water (from previous rainfall events) originating from sporadic, shallow hillslope reservoirs (Cras *et al*, 2007).

3.2 Role of the superficial deposits

To improve the knowledge of the mechanisms which induced “flash floods” (more or less delayed) it is necessary to know the water storage capacities and their distribution within this heterogeneous basin. A detailed mapping and a geometrical and hydrodynamical characterisation of the superficial deposits has been conducted. Weathering of black marls with clayed shale facies leads to superficial formations of variable nature and thickness, depending on local structural and topographic conditions. They consist of several superposed layers, whose density and compactness increase with depth: (i) the loose detrital cover, made of locally produced clasts or colluvial material sensitive to erosion, (ii) the regolith of marl, more or less fragmented, (iii) the compact lower regolith, keeping the marl structure but not its cohesion, (iv) the bedrock at the bottom, which is very compact, structured and cohesive (figure 4).

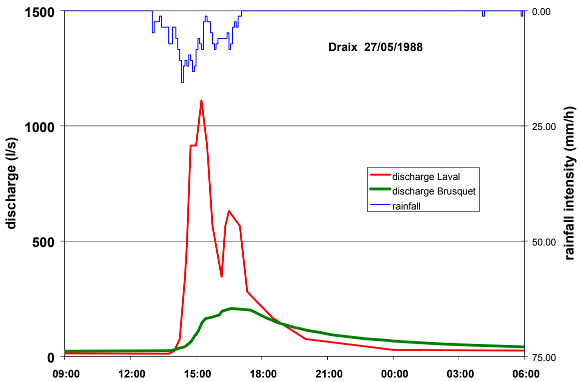

Figure 3. Contrasting responses of Laval and Brusquet to a rainfall event

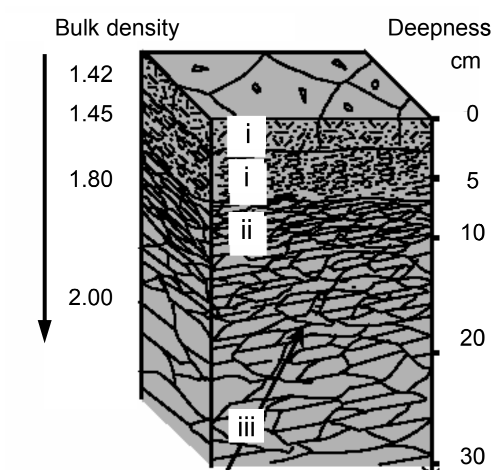

Figure 4: Composition of the weathered layer

Penetrometric tests were carried out along longitudinal and transversal transects crossing gully systems at several representative sites to estimate and map the large spatial variations in thickness of the weathered marl profile. The weathered marl profile thickness is (i) maximum on crests, because of a more efficient lateral decompression; (ii) homogeneous on gully sides, as a result of both vertical weathering and lateral transit; (iii) minimum in talwegs, which are more frequently scoured (Maquaire et al.,2002, Esteves et al., 2005).

3.3 Erosion processes on the slopes

A slope subject to erosion and gullying have been monitored on four plots with a topomicromètre laser© to follow the evolution of the slopes surface and to quantify eroded volumes. Other complementary installations were used to measure movements of marly deposit in talwegs. (profilograph and deposit pit). During the year 2002/2003, various weathers show the extreme irregularity of the submediterranean climate, which generate sudden erosive phases followed by long lull periods. What emerges is three morphoclimatic periods representing 90% of the annual total erosion: the winter season (frost and thaw), the summer (violent storms) and intermediate season with a predominance of the autumn (stormy shower disturbances) (Rovera and Robert, 2005).

In order to analyse the rainfall-runoff behaviour of the mudstone slopes, rainfall simulations were conducted on small plots 1 m² in area. Four different local geomorphologic conditions were selected for the experiments: (a) steep slope parallel or (b) perpendicular to the bedding, (c) moderate slope and (d) gravel-covered surface, both parallel to the bedding. Under moderate intensities (12-25 mm h^{-1}), in dry conditions, runoff was low or negligible. Runoff increased slightly when the interval between rainfall simulations was reduced to 30 min. In this case, a few grams of sediment were eroded, whereas no erosion was observed in dry situations. Under high-intensity conditions, runoff began quickly and the runoff coefficients were high (20-50%). Erosion was notable, but remained low. During natural rainfall events, in particular summer storms with short periods of high intensity (more than 100 mm h^{-1} in 5 min) substantial erosion activity occurred (more than 700 g m^{-2} on all the plots for a rainfall event of 54 mm) The rainfall intensity over the short duration and the kinetic energy of the raindrops were the main factors influencing particle detachment and movement (Mathys *et al*., 2005).

3.4 Erosion and organic matter

The work carried out deals with the problem of the incorporation of fossil Organic Matter (fOM) in the supergene cycle by considering weathering processes and its possible implications for the carbon cycle (source or sink). OM has been examined in the different compartment: bedrocks, alterites, soils and river. 60 samples, collected in these different compartments, have been subjected to petrographic (palynofacies), geochemical (Rock-Eval pyrolysis) analysis as well as artificial bacterial degradations. Results confirm firstly the contribution of reworked organic matter in modern fluxes and suggest that such analysis can also give information concerning the characterization of eroded bedrocks and the erosional processes such as river bank erosion and runoff (Copard *et al*; 2006).

3.5 Sediment transport

The sediment supply occurs during storm events. Table 2 presents a summary of the erosion measurements. During the floods the measured sediment concentration for the Laval is frequently higher than 300 g/l (or kg m^{-3}) and can reach 800 g/l (August 1997, June 2005, figure 5). The maximum measured concentration is 420 g/l for the Moulin and remains under 300 g/l for the Roubine. On the Brusquet, the maximum concentration is 35 g/l and for most of the floods, it remains under 10 g/l.

Figure 5: Highly concentrated flow in the Laval station

Table 2: Characteristic values concerning sediment transport during flood (1985-2006)

	Laval	Moulin	Roubine	Brusquet
Concentration (g/l)				
frequently	100-350	100-200	50-150	<10
maximum	800	420	300	30
Deposit for 1 event (m³)				
frequently	100-400	2-20	0.05-0.5	…
maximum	700	44	5	17

The maximum deposit for one flood in the Laval sediment trap was 700 m^3 during a thunderstorm with hail in July 1986 and it is frequently over 400 m^3). On Moulin basin, the maximum deposit was 44 m^3 (November 94) and on the Roubine, 5 m^3 (default value, 8/9/1994). In the Brusquet sediment trap, the deposits for one flood are usually too small to measure. The annual volume in the trap ranges from only 5 to 35 m^3. However, in September 8th and November 11th 1994, when the 2 highest floods of the observation period occurred, the deposits reached 12 and 17 m^3, respectively. This shows the threshold effect in erosion processes of this basin: the higher discharges are able to transport much more sediment to the outlet (Mathys et al., 2003b). The events with moderate rainfall intensity (less than 50 mm h^{-1} in 6 minutes) produce low deposits (less than 1 m^3) in the Roubine sediment trap but can carry more than 600 m^3 in the Laval sediment trap when they are associated to a high rainfall depth. Figure 6 illustrates the role of two factors (intense fraction of the rainfall depth and peak discharge) on the Laval sediment yield at the event scale

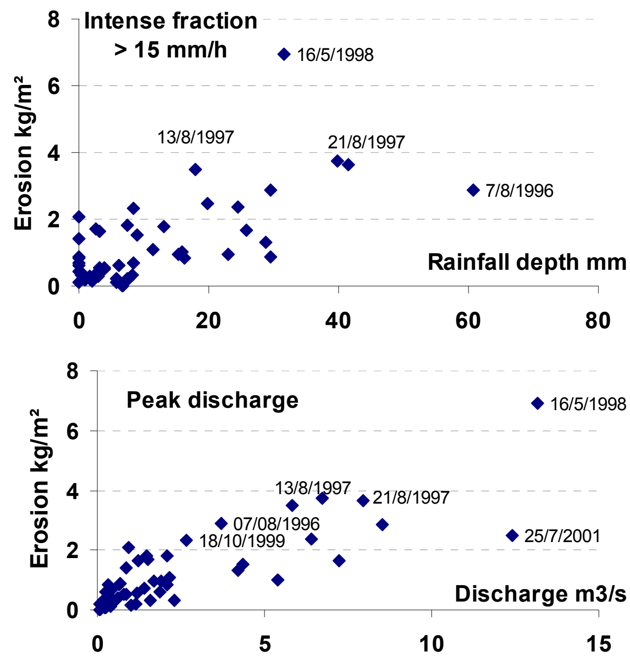

Figure 6: Factors of the sediment yield at the event scale

On the 3 catchments of the badlands zone, we compared the sediment yield measured in the sediment trap to the total amount including the fine material yield downstream of the trap, deduced from the measurements in the gauging station. We observed that, on average for the flood events, in the Roubine 85 % of the material (in weight) is stocked in the trap while only 40 % is deposited in the Laval trap. This proportion of coarse material is about 42 % for the Moulin watershed. This shows a scale effect in the sediment production : at the Roubine scale, ablation on the slopes is the dominant process. At the Laval scale, the coarse material from the slopes and gullies is submitted to deposition, scouring and transport processes and the proportion of fine sediment gets higher. The small catchment of Moulin, which is only 0.09 km² in area, has already a notable channel network in which these channel processes are active.

A seasonal cycle of deposition and scouring in the channel network has been identified and appears as a key process for erosion response in badlands catchments:

- In winter, freezing-thawing cycles generate a thick mantel of weathered material which fills the rills of the previous year and smoothes the slopes. Due to steep gradients, detritic material is accumulated at the foot slopes, in gullies and streams

- In spring, the first storms move the material accumulated in the rills and small mudflows occur on steep slopes. If the runoff is sufficient in the drainage network the accumulated materials of the foot slopes are transported at the outlet. If not, they increase the stocks in the reaches.
- In summer, the intense storms, especially when they contain hail, move sediments both in the rills and in the inter-rills. As a consequence the floods are heavily loaded both with coarse and fine material. Even if the production is high at the outlet, the flood is too short to export all the material and the stocks in the reaches increase considerably (Figure 7, top).
- In autumn, the lower intensities and the decrease in weathered material availability produce less erosion on the slopes. The clearer flows from upstream are able to load with sediments stocks and scour intensively the deposits in the reaches (Figure 7, bottom).

The pictures of figure 7 illustrate 2 phases of this cycle in the Laval channel. Several storms in summer and one intense event in July 2002 filled most of the torrent reaches. Less erosive events and long lasting floods in autumn were then able to transport these temporary stocks to the downstream reaches and to the sediment trap (800 m3 of deposit in November

The annual sediment yield reaches very high rates with an important variation from one year to another. The lowest value (1989) corresponds to the driest year of the observation period. For the dry period from 1989 to 1991, the mean value is 9.4 kg m^{-1} $year^{-1}$, while for the whole period the mean is 13.6 kg m^{-1} $year^{-1}$. The highest value, 27.7 kg m^{-1} $year^{-1}$ does not come from the highest rainfall depth but from the highest rainfall with intensity above 5 mm h^{-1} and the highest energy. A great part of the annual production is often due to only a few storms in the year. In 1986, the sediment supply of the thunderstorm with hail in July represents the 35 % of the annual sediment yield.

Regarding the area devoid of vegetation in each catchment, the annual erosion rate is 17.3 kg m^{-1} on the Roubine basin, 17.5 kg m^{-1} for the Laval and only 10.6 kg m^{-1} for the Moulin (the slopes are much less steep on this last basin). These rates represent a mean equivalent ablation of 12 mm of the weathered layer or 6 mm of bedrock.

On the forested Brusquet basin, the variability from one year to another is much higher and the maximum value (1994) is ten times the minimum (1995). In 1994, most of the erosion was due to 2 major events that were the 2 highest values of the series. The specific sediment yield of Brusquet is 170 times lower than on Laval and remains 35 times lower even if reported to the bare area. The geological unit of the marls is not exactly the same but even if we take into account a difference in erodibilty, we can assess that a great part of the material eroded in the areas with active erosion never reached the outlet of the catchment during the observation period. The basin obviously has a different behaviour for the erosion phenomenon during exceptional events. The increase in the connectivity between the slopes and the channel network may play the main role in this case (Mathys *et al*., 2005a).

- 03/08/2002: deposit after summer storms

- 21/11/2002: bedrock outcrop in the same reach after autumn long lasting floods

Figure 7: Deposition and erosion processes in the channels

4. ONGOING RESEARCH AND PERSPECTIVES

The present researches are focusing on a few points:

- Hydrological comparison between the forested (Brusquet) and un-forested catchments (Laval)
- Experimentation and evaluation of the role of the vegetation on sediment production and sediment transport (Francon)
- Study of the fossil organic carbon fluxes in the river systems
- Analysis of rainfall-runoff-infiltration processes in weathered black marls
- Study of the water circulations in fractured rocks and its role on mass movement triggering
- Detailed topographic surveys (LiDAR) and tests of their relevance to study erosion processes and surfaces evolutions
- Study of the material degradation in the drainage network and of the relation between bedload and suspension
- Study of the transfer of sediments to the downstream river systems.

In order to understand how sediment fluxes are delivered to the river systems downstream, the monitoring of larger catchments is now undertaken with embedded catchments from 20 km² up to 900 km². A second station will be equipped in 2008 on the Bouinenc for 36 km² of drainage area. In 2007, several gauging stations with continuous monitoring of suspended sediment concentration have been settled in the Bleone river basin which includes the Draix site by another team of the Draix research group, the LTHE (University of Grenoble).

The research carried out on this site highlighted the need to take into account how the different parts of the basin function: hydrological, geomorphological and phyto-ecological processes. The processes and factors identified are consistent with the results derived from other sites in the Mediterranean area. The modelling approaches used to study the basins of Draix were limited by how inadequate the representation was of the runoff and sediment yield processes on the slopes and how difficult it was to take their spatial variability into account. Additional monitoring and experiments are therefore necessary to improve the knowledge on these phenomena and the factors influencing them, so that modelling can produce more accurate results.

The work on this topic requires a multidisciplinary approach, already possible within the GIS Draix group which was created in 1999, grouping 16 research teams from 11 institutions (Universities and research centres). However, new collaborative efforts with other teams, in France and in other countries, will enrich this research.

ACKNOWLEGMENTS

Since 1999, the researches are conducted within the "Groupement d'Intérêt Scientifique, GIS Draix, Etude de l'érosion en montagne". This summary owes the different research teams many results and information. We thank all the scientists of this group.

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REFERENCES

Antoine, P., Giraud, A., Meunier, M. and Van Asch, T., 1995. Geological and geotechnical properties of the "Terres Noires" in southeastern France: Weathering, erosion, solid transport and instability. *Engineering Geology*, 40(3-4): 223-234.

Cambon, J.P., Mathys, N., Meunier, M. and Olivier, J.E., 1990. Mesures des débits solides et liquides sur des bassins versants expérimentaux de montagne. Hydrology in mountainous regions, Lausanne, CHE, August 1990(193): 231-238

Copard, Y., Di-Giovanni, C., Martaud, T., Alberic, P. and Olivier, J.E., 2006. Using Rock-Eval 6 pyrolysis for tracking fossil organic carbon in modern environments: Implications for the roles of erosion and weathering. *Earth Surface Processes and Landforms*, 31(2): 135-153.

Cras, A., Marc, V. and Travi, Y., 2007. Hydrological behaviour of sub-Mediterranean alpine headwater streams in a badlands environment. *Journal of Hydrology*, 339(3-4): 130-144.

Esteves, M., Descroix, L., Mathys, N. and Marc Lapetite, J., 2005. Soil hydraulic properties in a marly gully catchment (Draix, France). *CATENA*, 63(2-3): 282-298.

Gallart, F., Llorens, P., Latron, J. and Regues, D., 2002. Hydrological processes and their seasonal controls in a small Mediterranean mountain catchment in the Pyrenees. *Hydrology and Earth System Sciences*, 6(3): 527-537.

Maquaire, O. et al., 2002. Caracterisation des profils de formations superficielles par penetrometrie dynamique a energie variable : application aux marnes noires de Draix (Alpes-de-Haute-Provence, France): Characterisation of alteration profiles using dynamic penetrometry with variable energy. Application to weathered black marls, Draix (Alpes-de-Haute-Provence, France). *Comptes Rendus Geosciences*, 334(11): 835-841.

Mathys, N., Bergougnoux, L. and Olivier, J.E., 1999. Sediment Measurements in Small Mountainous Badlands Catchments: Experiments and Results from Experimental Catchments of Draix, (Alpes-de-haute-Provence), France, ASCE's 1999 international water resource engineering conference. Water resources into the new millenium: past accomplishments, new challenges, Seattle, USA, August 8-12 1999, pp. 10.

Mathys, N., Brochot, S., Meunier, M. and Richard, D., 2003a. Erosion quantification in the small marly experimental catchments of Draix (Alpes de Haute Provence, France). Calibration of the ETC rainfall-runoff-erosion model. *CATENA*, 50(2-4): 527-548.

Mathys, N., Richard, D. and Grésillon, J.M., 2003b. Non-linearity in erosion response of a small mountainous and marly basin: the Laval in the Draix experimental catchments, South East, France, *Hydrology of the mediterranean and semi-arid regions*, Montpellier.

Mathys, N., Esteves, M. and Gresillon, J.M., 2005a. Seasonal rhythms of sediment deposition and scouring in the Laval and Moulin channel networks (experimental basin of Draix, France). *Technical Documents in Hydrology*, UNESCO IHP-VI., No. 77: pp. 127-132.

Mathys, N., Klotz, S., Esteves, M., Descroix, L. and Lapetite, J.M., 2005b. Runoff and erosion in the Black Marls of the French Alps: Observations and measurements at the plot scale. *CATENA*, 63(2-3): 261-281.

Oostwoud Wijdenes, D.J. and Ergenzinger, P., 1998. Erosion and sediment transport on steep marly hillslopes, Draix, Haute-Provence, France: an experimental field study. *CATENA*, 33(3-4): 179-200.

Rovera, G. and Robert, Y., 2005. Winter climatic conditions and periglacial erosion processes in the marly bad-lands of Draix (800 m, French southern Alps). *Géographie Physique et Quaternaire* 59(1): 31-48