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# HYDROLOGY AND EROSION PROCESSES IN SMALL MOUNTAIN CATCHMENTS

## 25 YEARS OF OBSERVATION IN THE DRAIX EXPERIMENTAL SITE (FRENCH SOUTHERN ALPS)

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## ABSTRACT

Located in the Alps of south-eastern France, the experimental catchments of Draix were created in the period 1983-1984 and aim principally at studying mountain hydrology, erosion processes and corresponding protection devices. The substratum of the basins is black marls; a very erodible ground where erosion processes and sediment transport are particularly high, resulting in badlands topography with incised and very active gullies. Five small watersheds, from 1 000 m² up to 1 km² with various vegetation cover rates are equipped for rainfall, runoff and erosion measurements.  The sediment production is measured at the outlet of the catchments for each storm event: the coarser part of the sediment yield is measured in a sediment trap, the finer part is sampled at the gauging section or monitored continuously with an optical fibre sensor. The paper presents the monitoring strategies and devices used and summarize the main results on flood generation, erosion and solid transport.

**Keywords**: Erosion, Experimental catchments, Floods, Sediment yield, Solid transport

## INTRODUCTION AND 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 phenomena and the need for natural hazard mitigation engineering. In the Southern French Alps, the Black Marls formation 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 among the highest values recorded 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. The main goal of this observatory is to improve the prediction of the runoff and erosion response of small mountain catchments to climatologic inputs (precipitation and temperature), particularly for extreme events.

After several years of monitoring and research, focusing first on floods and sediment yield at the catchment outlets, improving the knowledge on the processes involved is now deemed necessary. A multidisciplinary group (GIS Draix) was created in 1999 to achieve this purpose, grouping 17 research teams belonging to 13 different research institutions and universities. In 2002, responding to a call of the French ministry of Research, the group obtained for the site the label as an Observatory for Environmental Research (ORE). More recently, in the frame of a national research project, a member of the GIS Draix group, the LTHE, monitored for discharge and sediment transport several larger catchments from 22 to 900 km² in the Bleone basin which include the Draix site. To ensure the link between the two different scales, a sixth site was instrumented by Cemagref, on the Bouinenc

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River (22 km²), in the village of Draix. The whole constitutes now the ORE Draix-Bléone observatory and bellows to the French Network of Basins Observatories (RBV).

## STUDY AREA AND MONITORED SITES

The Draix observatory is located 200 km South of Grenoble, near the little town of Digne Five basins have been equipped since 1983 for the measurement of rainfall, liquid discharge and solid transport (Fig. 1). These basins have different areas, from 1300 m² to 1 km². Four are situated in denuded areas and the last one, the Brusquet, was reforested at the end of the 19th century, within the frame of restoration works. 87 % of its surface area is now covered with a pine forest (Fig. 1 and Tab. 1).

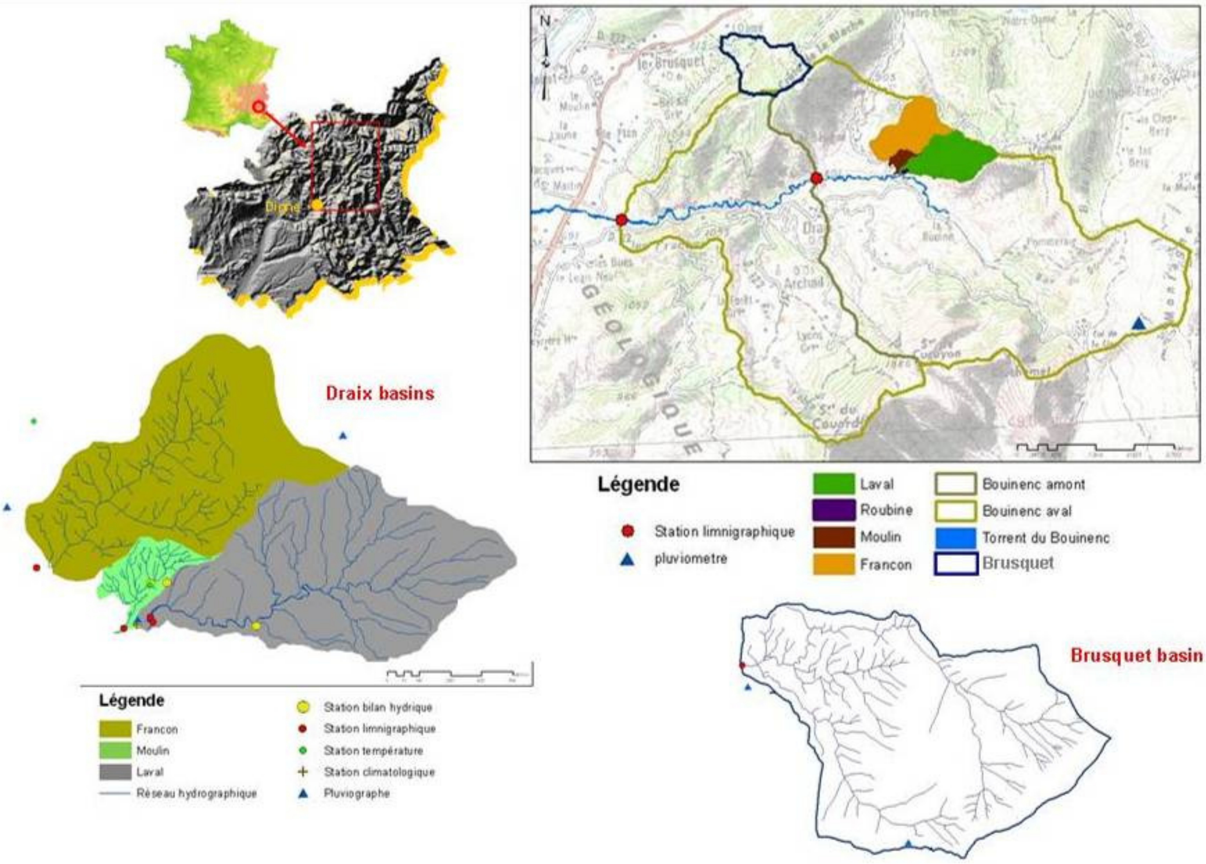


**Fig. 1** Location of the study area

**Tab. 1** Main characteristics of the monitored basins

| Basin name | *Area* (ha) | Denudation rate (%) | Average slope (%) | Elevation min-max (m a.s.l) | Observed since |
|---|---|---|---|---|---|
| Roubine | 0.133 | 79 | 75 | 850-885 | 1983 |
| Moulin | 8 | 54 | 30 | 850-925 | 1988 |
| Francon | 76 | 56 | 41 | 850-1140 | 1983-96 - 2008 |
| Laval | 86 | 68 | 58 | 850-1250 | 1984 |
| Brusquet | 108 | 13 | 53 | 800-1260 | 1987 |

The experimental site is 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 (Fig. 2).

The Roubine (0.13 ha) is a steep gully and can be considered as an elementary unit to observe erosion phenomenons (Fig. 2). The slope gradient of the main channel remains higher than 35 %. The Laval (86 ha) 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 (8 ha) is an intermediate scale basin which already has a small network of channels. The main stream, 300 m long, is 4 % steep.

The Francon basin was initially monitored in parallel to the Laval. The purpose was to compare the 2 basins for several years, then to conduct restoration works inside the Francon and observe the potential changes in the water and sediment response. But, the difficulties met in the Laval sediment trap management and the cost of the emptying procedures led to the progressive abandonment of the monitoring between 1990 and 1996. More recently, new experiments of bio-engineering restoration works have been conducted in the Francon basin which needed the evaluation of sediment fluxes exported and gave the opportunity to build a new sediment trap and monitor again liquid and solid discharge at the outlet of the basin.

*General view of the Roubine basin* *Gully in the Moulin basin* *Laval Basin from the crest*

**Fig. 2** Badlands topography in the Draix site

Seven rainfall recorders measure the precipitation at different locations, located in the lower as well as in the higher parts of the basins. Recently, a spectro-pluviometer (Thies Clima) was settled close to the Laval rainfall recorder in order to characterize the rainfall properties: this device gives each minute the raindrop grain-size and velocity distribution. This allows calculating the effective kinetic energy of the precipitation and makes possible to determine the type of the event (hail, snow, rain, etc….).

At the outlet of the basins, a gauging station with level recorders, samplers, optical turbidimeters and sediment traps allow the measurement of discharge, suspended and bedload sediment fluxes. Flow level, intending to calculate flow discharge, are measured in control section or calibrated gauging flumes, with level recorders of various type. Upstream the gauging stations, sediment traps protect the measuring devices from excessive sediment transport. These traps allow as well the measurement of the deposited sediment volumes by topographic methods after each flood. The fine sediment fluxes are calculated from the sediment concentration measurements in the gauging flume. Different processes are used: automatic samplers and optical fibre sensors (Fig. 3).

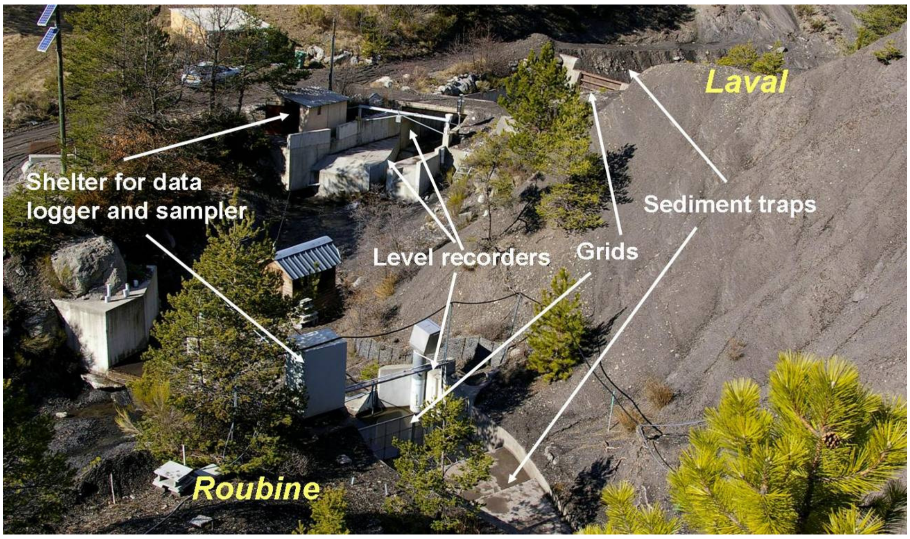


**Fig. 3** Gauging stations at the outlet of Laval and Roubine basins

A climatologic station records air temperature, humidity, solar radiation, wind speed and direction. Soil temperature is recorded in two stations with sensors at different depth, aspect and slope locations. Four soil hydrological stations with TDR, tensiometers, piezometers and humidity capacity probes are settled in different environmental contexts: abandoned rangeland, badlands slopes and landslide

## MAIN RESULTS ON FLOOD GENERATION, EROSION AND SOLID TRANSPORT

### Climatological and geomorphological context of the study area

Mean annual rainfall is 900 mm with 200 days a year without rain and only five days with rainfall depth exceeding 30 mm. 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 more intense precipitation is concentrated between June and September (Fig. 4). For example, July and August do not register the maximum mean rainfall depth but the maximum of intense precipitation which are highly erosive. The area experiences 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 (Regues et al., 2000). These processes, variable in intensity from one year to another, depend greatly on climatic conditions and are consequently good indicators of climatic change.

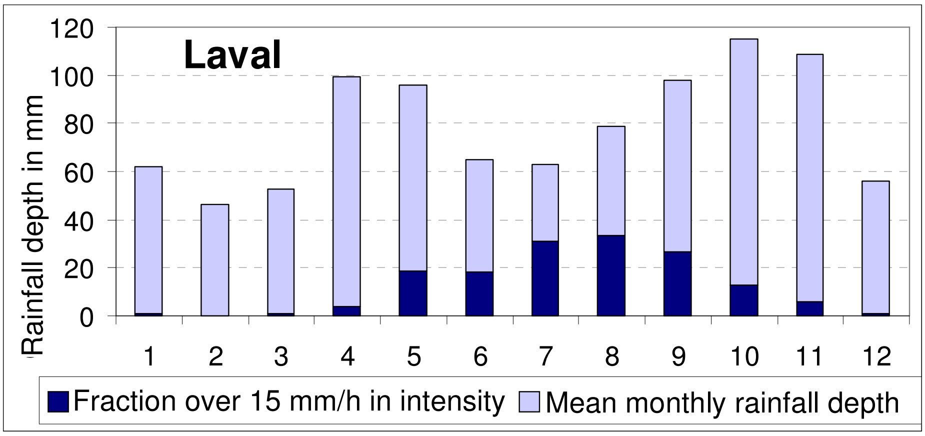


**Fig. 4** Monthly rainfall depth distribution

At the end of winter, a weathered layer, several centimeters 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 solifluxion. On steep slopes, it generates small landslides and mudflows that supply sediments to the stream channels. 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.

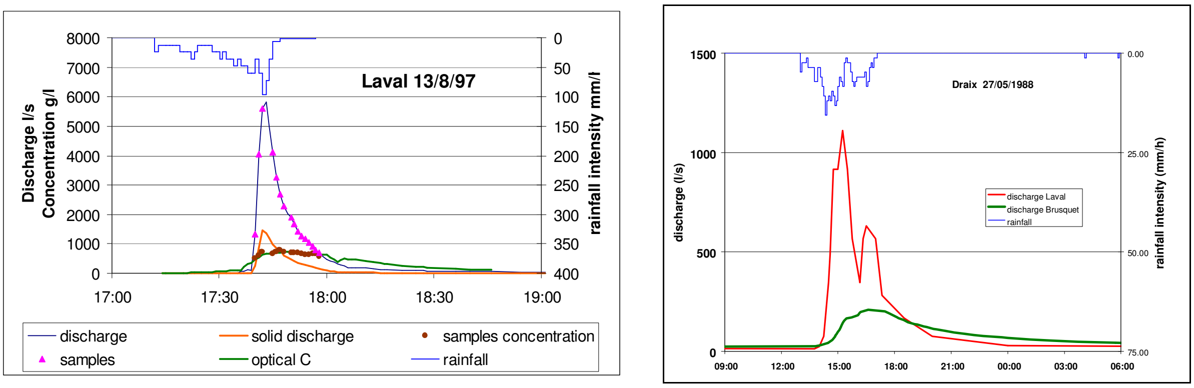
*1/09/1993 deposits in the Laval channel after several floods*

*30/09/1993 : bedrock outcrop in the same reach after a long and high flood*

**Fig. 5** Deposition and scouring processes in the main channel

## Flood generation

The floods observed are violent with very high peak discharge. The highest flood monitored reached $20 m^3/s$ as peak flow for only 0.86 km² 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. For the Laval catchment, within this time the discharge raises in the gauging station from zero up to 2 to 10 $m^3s^{-1}$. Contrasting responses are observed in the forested basin (le Brusquet) : the raising time is much longer (20 to 60 min), the peak flows 5 to 10 times lower.



*a) Flashy and heavily loaded flood in the Laval Basin*

*b) contrasting responses of Laval and Brusquet to a rainfall event*

**Fig. 6** Rainfall-runoff schemes in the Draix basins

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 maximum flood registered (08/09/1994) reached 20 m$^3$s$^{-1}$ in the Laval basin and 2 m$^3$s$^{-1}$ in the Brusquet. The specific ten years return period peak discharge is evaluated to 20 m$^3$s$^{-1}$ km$^{-2}$ for the Laval to 60 m$^3$s$^{-1}$ km$^{-2}$ for the small Roubine basin. For the Brusquet, the forested basin, it remains around 2 60 m$^3$s$^{-1}$ km$^{-2}$ (Mathys, 2006). Analysing the Laval peak discherge series for the 1097-2000 period, Graff (2004) observed that the highest peaks were observed for storm events ranging 20 to 30 mm in 1 hour, when preceded by small rainfalls. The runoff coefficient for the high floods remains moderate and close to the mean value (42%).

By natural tracer methods, Cras et al. (2007) showed the existence of deep contributions to flow at the outlet. The black marls, often considered impermeable are able to store and water. Indeed, the detailed analysis of the components of the flow by isotope geochemistry shows for some events a clear contribution of the pre-event water. But this behavior is variable from one event to another. For example, for two successive floods in May, the first signal measured in the flow is very close to the rain signal while during the second, 10 days later, the pre-event component gradually becomes dominant along the flood event. In the small Roubine catchment, on a late summer event, hydrograph decomposition leads to a main event water contribution to the first flood peak with a very high rainfall intensity and pre-event water contribution to the second peak with a more moderate rainfall intensity.

### Erosion and sediment yield

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 gl$^{-1}$ and can reach 800 gl$^{-1}$ (August 1997). The maximum measured concentration is 420 g/l for the Moulin and remains under 300 gl$^{-1}$ for the Roubine. On the Brusquet, the maximum concentration is 35 gl$^{-1}$ and for most of the floods, it remains under 10 gl$^{-1}$.

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 m3 (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: only the highest discharges are able to transport much sediment to the outlet. For the lower discharges, most of the sediment eroded from the rare eroded areas are trapped behind the vegetation barriers on the slopes or in the secondary channels.

**Tab. 2** Characteristic values concerning sediment transport during floods (1985-2010)

| | Laval | Moulin | Roubine | Brusquet |
|---|---|---|---|---|
| Suspended Sediment Concentration(gl$^{-1}$) | | | | |
| common | 100-350 | 100-200 | 50-150 | <10 |
| maximum | 800 | 420 | 300 | 30 |
| Deposit for one event (m$^3$) | | | | |
| common | 100-400 | 2-20 | 0.05-0.5 | - |
| maximum | 700 | 44 | 5 | 17 |

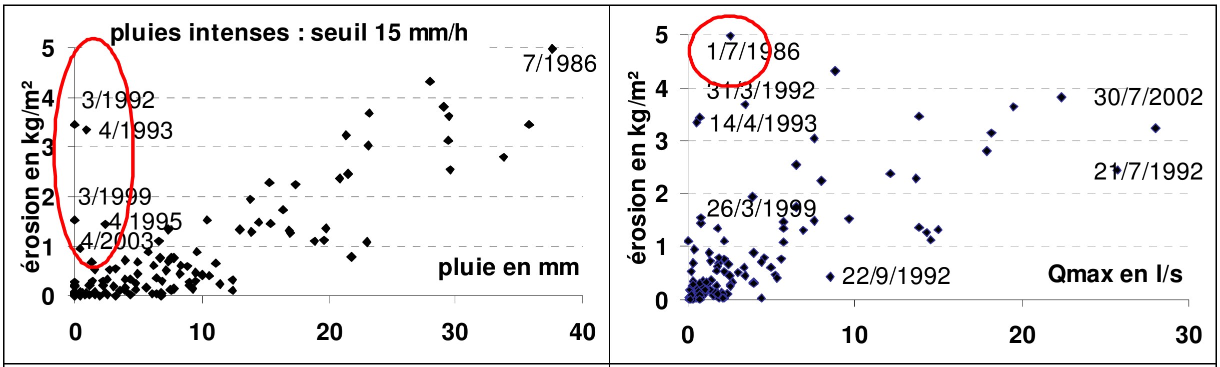
The annual sediment yield reaches very high rates, 115 t ha$^{-1}$ year$^{-1}$ (11.5 kg m$^{-2}$year$^{-1}$)r for the Laval, with an important variation from one year to another (minimum 44, maximum 220). A great part of the annual production is often due to only a few storms in the year. On the forested Brusquet basin, the variability from one year to another is much higher and the maximum value (2.2 t ha$^{-1}$ year$^{-1}$, 1994) is ten times the minimum (0.2 t ha$^{-1}$ year$^{-1}$, 1995).

### Factors of the erosion response of the catchments to a rainfall event

The long time series available make possible the observation that the sediment yield (bedlaod, suspension and total load) at the outlet of a basin is highly variable and non linear from one event to another. Similar rainfall inputs can produce very different yields and threshold effect are often evidenced. A spatial scale effect is also observed.

- **At the small gully scale (Roubine catchment)**

There is a positive global relationship between the parameters of rainfall and erosion. But the scatter is important and for similar rainfall depth responses vary by a factor of 4 may be observed. Moreover, there is a group of episodes whose strong production can not be explained by precipitation. All these events occurred in spring (Fig. 7a): the weathered mantel was very thick because of freezing–thawing processes in winter and debris accumulation in the gully bottom. The first floods in spring are able to mobilize these platelets and transport it to the sediment trap. The dispersion is even greater if one refers to the flow: the range of sediment yield for low an exceed 1 to 5 and for a wide range of discharge one can get identical responses. A last point is different in this graph: it is a strong hailstorm of July 1986 (Fig. 7b).



*a) relationship between rainfall (pluie en mm) and erosion. The rainfall amount corresponds to the fraction which occurred with an instant intensity over 15 mm h$^{-1}$*

*b) relationship between peak discharge (Qmax) and erosion*

**Fig. 7** Factors of sediment yield in the Roubine basin

The sediment yied at the outlet of the basin is the sum of suspended sediment yield and bedload. The fine material (represents in average 15-20% of the total yield. However, this proportion is extremely variable and it reaches 40% for strong episodes (Fig. 7, left). In order to analyze the role of high discharge in highly productive, we plotted the proportion of fine sediment in the total (Ratio SSY/TSY) versus the peak discharge of each event (Fig. 7, right). We observed that for high flow rates the ratio of is high and generally greater than 20% but we can meet even higher values for lower discharges. So, the explaining factor is not the sediment transport capacity of the flow but rather the availability of fine materials that controls the largest ratio of suspension.

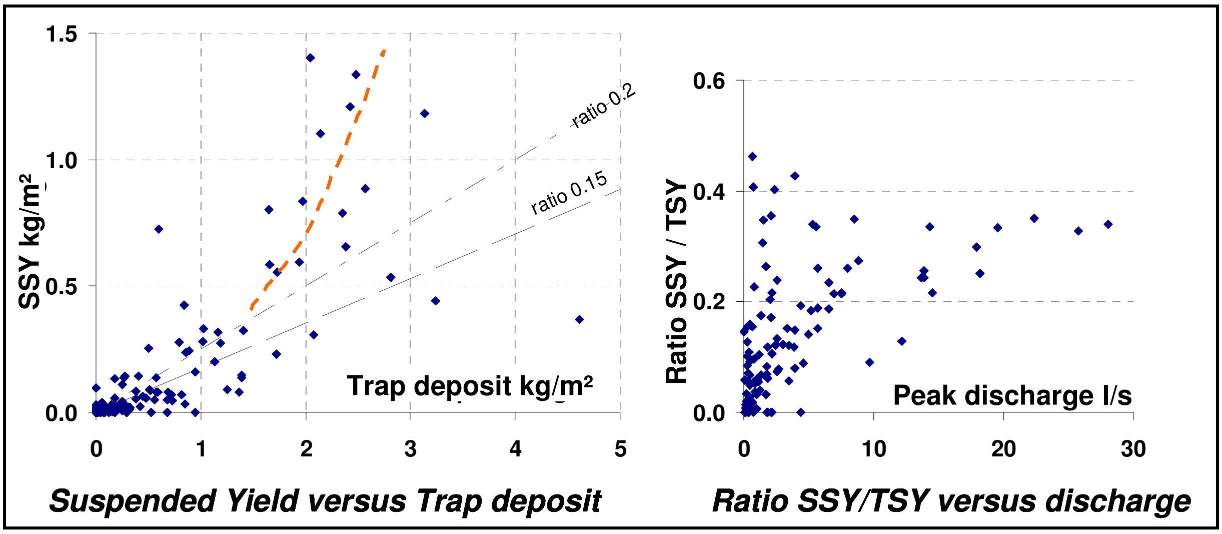
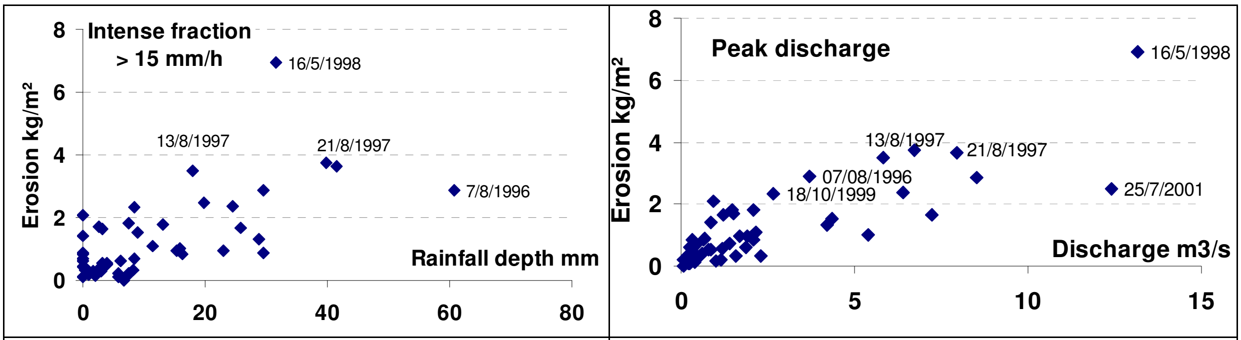


**Fig. 8** Ratio between suspended load and bedload for Roubine

The analysis conducted on the rainfall-runoff-erosion data and the field observations allows us to propose an erosion conceptual erosion model at the gully scale in marly badlands catchments: a seasonal pattern is involved with the renewal of the weathered mantel in winter, substantial displacement of material with spring events, high production of numerous and intense summer storms, and a decrease in sediment availability in autumn.

- **At the small catchment scale (Laval and Moulin data)**

In the Laval basin there is a greater dispersion of sediment yield results than on Roubine when referring to the variables of precipitation (Fig. 8a). For example, in August 1997, 2 successive storm events (13/8/1997 and 21/8/1997) yielded the same amounts of sediments although the first rainfall depth is 2 times lower: this flood occurred after a dry autumn in 1996 and a calm spring with no notable flood event: this first flood could easily mobilize a great amount of sediment stocked in the basin. In contrast, the dispersion diminishes when referring to the peak flow of the episode (Fig. 8b). These results highlight the importance of transport mechanisms by the flow to explain the production of erosion at this scale.



*a : relationship between rainfall and erosion. The rainfall amount corresponds to the fraction which occurred with an instant intensity over 15 mm* $h^{-1}$

*b): relationship between peak discharge and erosion*

**Fig. 9** Factors of sediment yield in the Laval basin

At the small basin scale, the suspended sediment transport becomes dominant in the measured fluxes, reaching 50 to 60% in the Moulin and 60 to 70% in the Laval. There is a lower dispersion in Laval than previously mentioned in Roubine, although some exceptional events show ratios that exceed 85% (Fig. 9).

The ratio of fine sediment in the total sediment yield evidences strong seasonal pattern (Fig. 9).

There is a sharp decrease in the proportion of fine from September to December. This pattern somewhat follows the pattern of intense precipitation we highlighted in Fig. 4. We can assume that the fine sediment transport at the outlet is directly linked to the erosive power of the rainfall on the slopes. The fine sediment produced is then quickly transported at the outlet while during these intense events, even if a great amount of bedload is transported, the exceed in bed material is stored in the channel network and delivered later in the autumn.

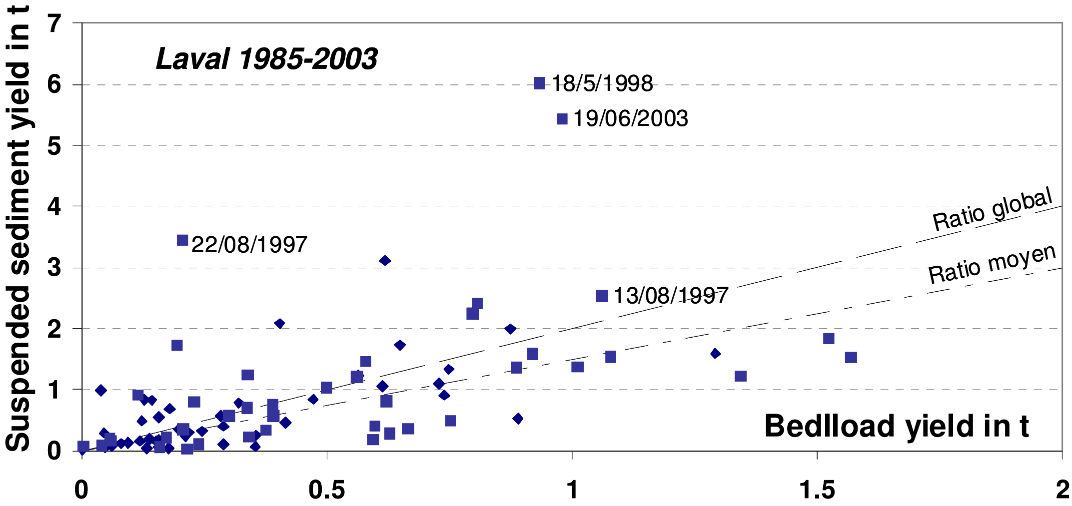


**Fig. 10** Ratio between suspended load and bedload in the Laval basin

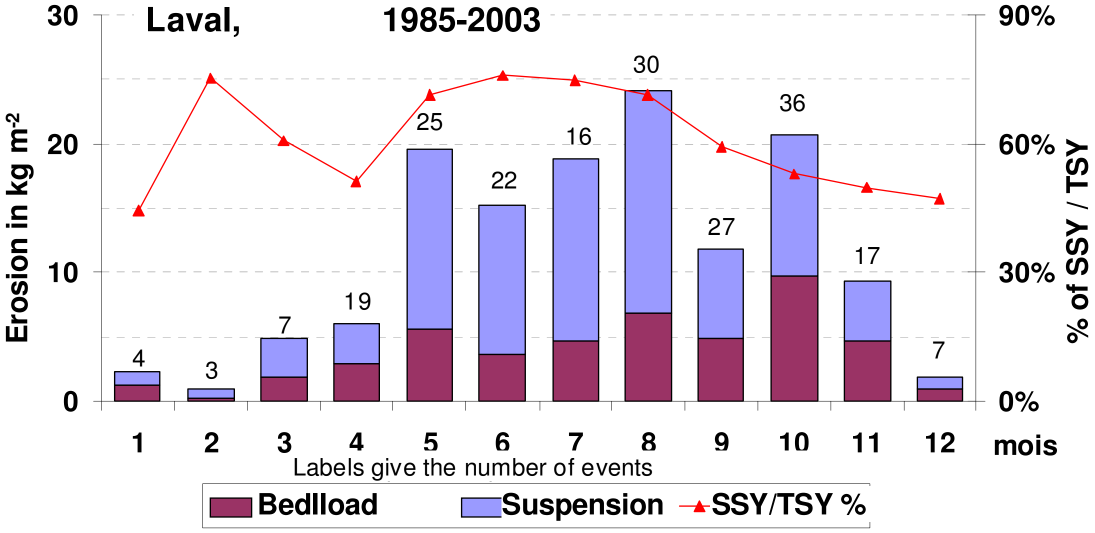


**Fig. 11** Seasonnal pattern of the bedload/suspension ration for the Laval basin

## A seasonal model of sediment production

Field observations and data analysis through the 25 years of monitoring allows building a conceptual model of erosion production in such 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.

**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.

The seasonnal deposit and scouring processes in the reaches was surveyed during several seasons and the first attempts of rainfall-runoff-erosion modelling gave good preliminary results (Mathys et al., 2003, Mathys, 2006). Therefore, the high variability of the response observed and the complexity of the processes involved make necessary the detailed monitoring of the different compartments of the system.

## ONGOING AND INNOVATIVE MONITORING IN THE DRAIX BASINS

In order to increase the comprehension of the hydrologic and erosion processes acting in this environment, new devices or surveys have been settled in the recent years. The spectro-pluviometer (disdrometer) showed a good agreement with rain gauges for the evaluation of the rainfall depth. The links between rainfall event characteristics and kinetic energy are studied and may lead to a regional formula for estimation with simple parameters as rainfall intensity. Scour chains were installed in 80 cross sections in the Moulin channel network, allowing a very precise calculation of the sediment stocks variations inside the basin. In 2011, a Reid-type recording slot bedload sampler was installed just upstream the Moulin gauging station. In collaboration with the Lausanne University, a detailed topographic survey of the Roubine basin with a terrestrial Lidar is conducted since 2009. In addition, a video camera has been installed in 2011 to get visual information on the slopes and the sediment trap during storm events. In order to understand how suspended sediment fluxes are delivered to the river systems downstream, the monitoring of larger catchments were undertaken since 2008 with embedded catchments from 20 km² up to 900 km² and the Draix observatory has been extended to this network and constitutes now the Draix-Bléone Observatory

## CONCLUSION AND PERSPECTIVES

The Draix-Bleone observatory tries to respond to the demand of knowledge for integrated watershed management. These responses must particularly take into account possible changes in the climate and its impact on the liquid and solid flows in streams. Hydrological risk prevention, in the case of the basins of the Southern Alps, includes the risks associated with the transfer of large amounts of sediment during heavy floods. The impact of sediment transport has to be analysed at two levels. In the uplands areas, near the outlets of the steep basins, loaded flows expose populations and infrastructures to a risk. Downstream, the transported sediments are deposited in the beds and potentially increase the risk of over flooding. The sediments are also deposited in reservoirs reducing their life and their economic viability.

From the plot or gully scale to the small catchment scale (a few square meters to a few square kilometers), the "Draix-Bléone" observatory therefore focuses on understanding of elementary processes of erosion and their interactions. At the scale of large river basin (tens to hundreds of square kilometers), the issue concerns the conditions of transfer flow of liquid, solid and dissolved. The ERO-Draix Bléone represents a unique site in France to study hydrology, erosion and sediment transfer in the mountains. The multidisciplinarity of the research groups involved in the monitoring tasks and the scientific work will allow the observatory to carry out its objectives. Such environmental research need to maintain the monitoring on a long period, decades if possible.

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