Determining the competence of mountainous Mediterranean streams using lichenometric techniques

FREDERIC GOB[1], NICOLAS JACOB[2], JEAN-PAUL BRAVARD[2] & FRANCOIS PETIT[1]

1 *Laboratoire d'Hydrographie et Géomorphologie fluviatile, University of Liège Dept. of Geography, Allée du 6 Août, 2. 4000 Liège, Belgium*
fgob@ulg.ac.be

2 *University of Lyon 2, Louis Lumière 5600, 5 Avenue Pierre Mendès-France, 69676 Bron cedex, France*

Abstract This article deals with the application of lichenometry to the study of mountainous Mediterranean boulder-bed rivers, characterized by strong floods. Lichens present on blocks are a means of dating the reworking of this material, and therefore determining the maximal competence of floods. By associating the diameters of the blocks dated using lichenometry to the specific streampower of corresponding floods, several diameter/critical specific streampower relations for elements between 0.5 and 2.7 m were proposed. In this way several different relations were determined for the rivers studied, highlighting the uneven dissipation of energy due to the roughness of bed forms in these rivers.

Key words boulder bed rivers; flood events; lichenometry; Mediterranean streams; specific stream power

INTRODUCTION

Still relatively little is known about the fluvial dynamics of gorge sectors of mountainous Mediterranean streams, particularly as far as the mobility of gravel bed load is concerned. Yet, these environments offer an opportunity to calculate the specific streampowers necessary to mobilize generally coarse material (b axis > 1000 mm). However, these values are rarely available in the literature dedicated to this subject (Costa, 1983; Petit *et al.*, 2000). Moreover, it is interesting to be able to calculate the competence of flow in terms of specific streampower in order to understand the conditions in which riverbed features are formed. But processes remain difficult to study for a number of reasons: the absence of ancient descriptions or archives, the impossibility of observing the processes during flood conditions and the size of the alluvial material itself.

In an effort to overcome these difficulties, lichenometric techniques are employed for this study. These techniques are not widely applied to the study of watercourses, despite the fact that many authors have demonstrated their value in measuring hydraulic conditions (Gregory, 1976) or dating features, as has been shown in periglacial studies (Carling & Glaister, 1987; Macklin *et al.*, 1992; Maas *et al.*, 1998; Jacob, 2003). In a recent article, Gob *et al.* (2003) showed that lichenometry is a reliable instrument in determining the conditions for mobilizing coarse alluvial bed load. This technique is useful as it is easy to execute and especially because it provides information about past events that is not revealed by using radioactive, coloured or radio-emitting markers (Mussot, 1969; Ergenzinger *et al.*, 1989). Indeed, the study demonstrated that dating alluvial units (deposits, re-organization or stabilization) is possible over a period of at least 200 years (Jacob *et al.*, 2002).

STUDY AREA

Four rivers were selected; three on the eastern border of the Massif Central, the Chassezac, the Ardèche and the Loire, and the fourth in Corsica, the Figarella (Fig. 1).

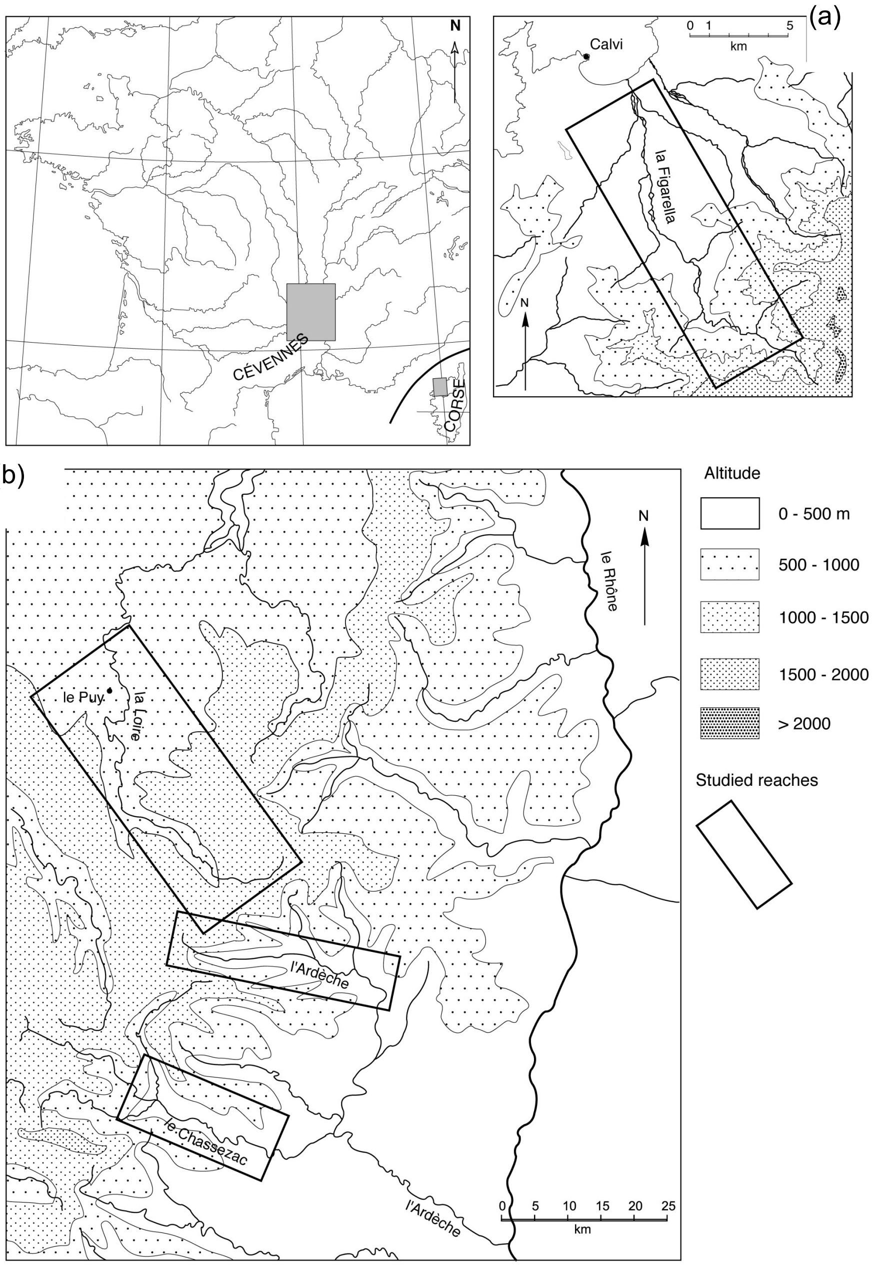

Fig. 1 Map showing (a) the Figarella River basin; (b) the Upper Loire, the Ardèche and the Chassezac basins.

Table 1 Characteristics of the river basins studied.

	Catchment area (km^2)	10 largest blocks max. diameter (m)	Mean slope ($m\ m^{-1}$)
Upper Ardèche R.	291	1.5	0.02
Upper Chassezac R.	507	2.9	0.014
Upper Loire R.	880	0.95	0.012
Figarella R.	50	3.2	0.05

The sectors chosen meet numerous conditions necessary for the successful application of lichenometry. Gravel bed sectors or sectors where the bed is composed of mobile blocks or coarse bed load were selected in order to refine mobility equations for elements greater than 1000 mm. The drainage basins of the rivers chosen are exposed to a Mediterranean or Peri-Mediterranean climate. Furthermore, the areas studied are found in mountainous or mid-mountainous regions. Generally, the substratum is crystalline and metamorphic with a predominance of granite and gneiss in the upstream part of the watercourse. In the selected areas, the slopes are steep and reach between 50 and 70% and the thalwegs have average longitudinal gradients of 0.012 to 0.05 $m\ m^{-1}$, but these values may reach 0.08 and 0.1 $m\ m^{-1}$ in the headwater basin (Table 1).

Hydrological characteristics and strength of streamflow

Episodes of violent autumn rainfall explain the strength of streamflow. In the Cèvennes, heavy rain may last for days. Rainfall totals of over 400 mm may be recorded, as occurred in September–October 1958, which witnessed 600 mm of precipitation (Fig. 2). Likewise, in October 1827, 972 mm of rain was recorded in 21 h at Joyeuse (Ardèche).

These conditions account for the formation of powerful flood waves, whose discharge often reaches or exceeds 1000 m^3, for example 2200 $m^3\ s^{-1}$ for the Chassezac in 1958. Steep longitudinal slopes allow very rapid propagation of the flood peak downstream, at a speed of 12–15 $km\ h^{-1}$ for the Ardèche and the Chassezac. Interestingly, surface speeds of 10 $m\ s^{-1}$ were measured on the Chassezac in 1958 (Guilhot, 1959). In Corsica, episodes of heavy rain produce flashfloods whose discharges exceed 150 $m^3\ s^{-1}$. Such streamflows are characterized by very high specific streampowers. The average values are around 3000–5000 $W\ m^{-2}$, while in the narrowest sectors, these rivers may reach values of up to 1000 $W\ m^{-2}$.

METHODOLOGY

The techniques traditionally used to evaluate bed load transport are difficult to undertake and are not generally effective in the type of river selected for this study. Based on natural markers, lichenometry allows the mobility of coarse material to be estimated and facilitates the study of past morphogenic floods and exceptional flood events.

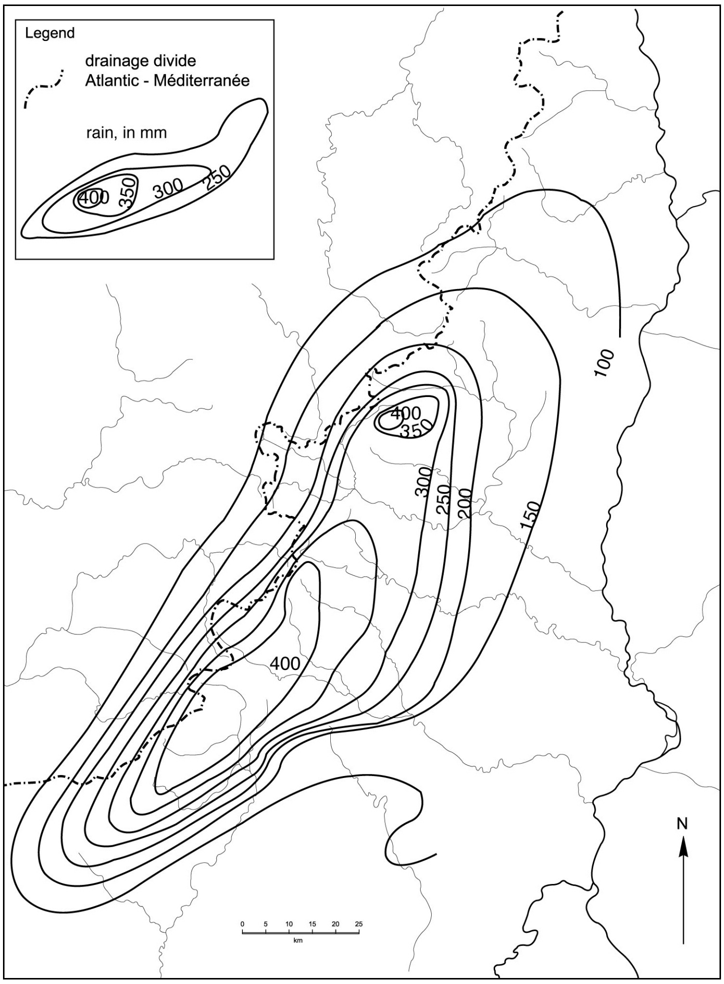

Fig. 2 Precipitation recorded between the 29th and the 30th of September 1958 on the Cévennes. This type of very heavy rainfalls creates very powerful floods

Definition of lichenometry and working hypothesis

Grove (1988) defined lichenometry as "a method of dating based on the assumption that the largest lichen growing on a given substrate is the oldest individual and that, if the growth rate for a given species is known, the maximum lichen size will provide a minimum age for the substrate". In fluvial environments, one considers that lichen present on blocks is destroyed during floods when the elements are mobilized. Following the flood, a new generation of lichen may begin to grow and, subsequently, by identifying the age of the lichen, the date of the mobilizing flood may be established.

Sampling in the selected riverbeds involves measuring the diameter of the largest thalli present on each block and also recording the intermediate axis of the blocks. Then, using a lichen growth curve, the last time that the blocks were moved may be dated and the hydrological parameters (specific streampower) of the morphogenic flood may be related to the diameters of the mobilized elements. An exhaustive chronical of hydrological events must be available so that the flood events and the mobilizations indicated by the lichen may be correctly corresponded.

Growth curve

Rhizocarpon geographicum l.s. was chosen for this study. This species of lichen is widely used by geomorphologists as it is common and easy to identify. The age of the thalli is determined by measuring their diameter and comparing this to the growth curve of the species being considered. Lichen growth curves are generally obtained indirectly, by measuring a large number of lichen on artificial substrates, whose age is already known: tomb stones, bridges, monuments, standing stones. Growth is determined by the environment (humidity, exposure, etc.) and therefore varies according to the regions studied (Fig. 3). The choice of envelope curve and the principles of building and applying a growth curve were presented and discussed in a recent publication (Jacob *et al.*, 2002).

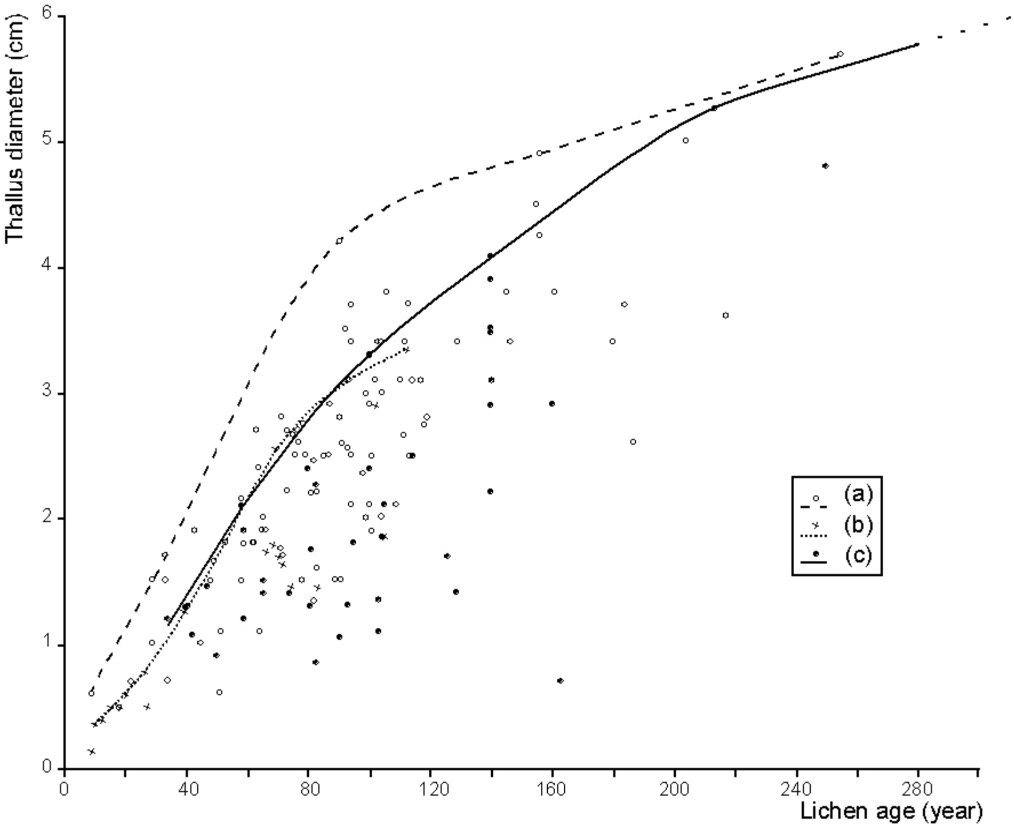

Fig. 3 *Rhizocarpon geographicum* growth curves in (a) Haute Loire, (b) the Cévennes and (c) Corsica.

Lichen populations in river beds may be closely correlated with major hydrological events in each basin. Size-frequency diagrams (Fig. 4) highlight these different populations, indicating their age and associating them with hydrological events. In the case of the Upper Loire, the elements making up the bed are regularly mobilized. The narrow width of the valley means that ancient deposits have not been stored: the traces of the oldest floods date to 1943.

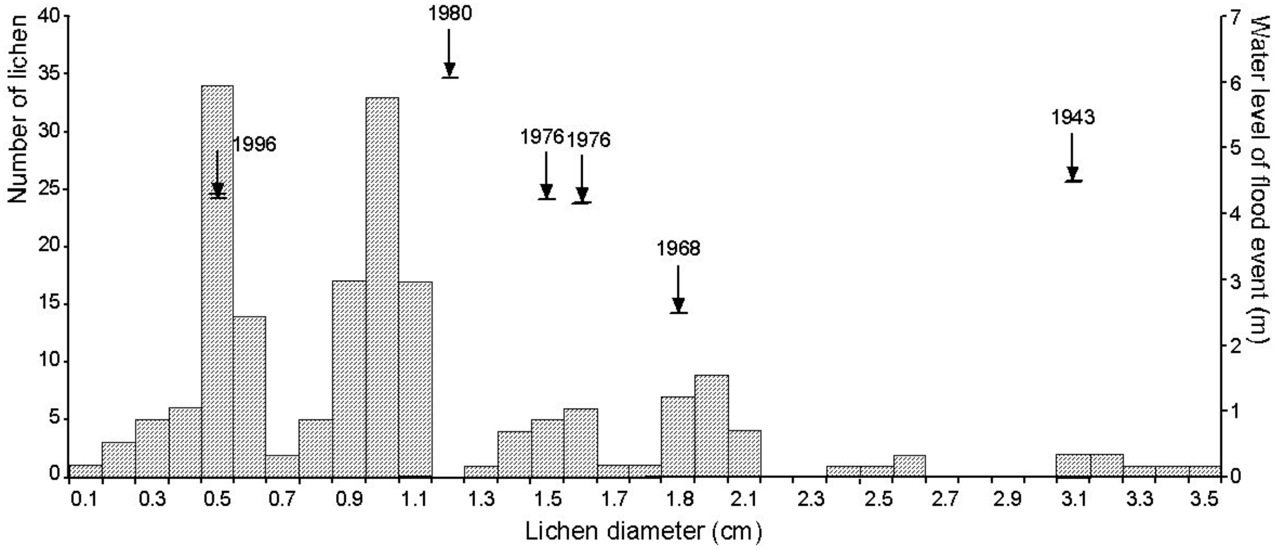

Fig. 4 Size-frequency diagram of *Rhizocarpon geographicum* population in the Upper Loire. Water levels have been recorded at the gauging station of Brives (close to le Puy-en-Velay). One can see a good correlation between the peaks of thalli and flood events.

Characteristics of the bed load studied and the critical specific streampower

The aim of this study is to determine the maximal competences of mountainous Mediterranean torrential rivers. This involved investigating the discharge required to mobilize the largest elements. To these ends, in each case we only considered the average of the ten largest particles mobilized (which corresponds to the D_{95} at least) or the largest element mobilized.

The researchers worked with specific streampowers which are increasingly used to study the dynamics of hydrosystems (Fergusson, 1981; Vanden Berght, 1995; Gintz *et al.*, 1996). Specific streampower is relatively easy to use as only the widths, slopes and discharges are considered in the equation:

$$\omega = (\rho\, g\, Q\, s)/w \qquad (1)$$

where ω is the specific streampower (W m^{-2}), Q the discharge ($m^3\ s^{-1}$), s the slope of the water surface (m m^{-1}) and w the width (m). The widths were measured on site by taking the width at the bankfull discharge or, in the case of gorge sectors, using the width constrained by rock surfaces. The slopes were calculated using maps or large scale plans when these were available.

The final elements necessary to calculate specific streampower are discharges. These were provided by la Direction Régionale de l'Environnement (the regional directorate of the environment) for the regions of Corsica, Rhône-Alpes and Auvergne. The discharges measured at the gauging station were extrapolated for the study sites using the equation for modest sized basins, based on the area of the valley sides (Bravard & Petit, 1997):

$$q = Q\,(a/A)^{0.8} \qquad (2)$$

where q is the discharge sought, Q the discharge measured at the station ($m^3\ s^{-1}$), a the

Table 2 Critical flood discharges used.

	Year	Discharge at the gauging station ($m^3 s^{-1}$)
Upper Ardèche River	1977	1465
($290 km^2$)	1982	1315
	1992	1900
Chassezac River	1890	3250
($510 km^2$)	1899	2200
	1907	2750
	1958	2250
	1980	2960
	1995	1460
Upper Loire River	1980	2000
($880 km^2$)	1996	1300
Figarella River	1973	153
($28 km^2$)	Q_3	50

area of the basin upstream from the sector studied and *A* the area at the station (km^{-2}). The discharge values for past flood events were identified through historical research.

Table 2 gives the list of floods that were highlighted using the size-frequency diagram for the different rivers studied. It should be added that due to the rarity of hydrological data on the Figarella, for the purposes of this study, blocks without lichen were considered to be regularly reworked. To calculate specific streampowers, the discharge of the 3-year flood (i.e. the amount of time necessary for blocks to be colonized by lichen) was taken. With regard to blocks without lichen in the Chassezac, account was taken of the fact that an 18-year flood had occurred 5 years before the measuring campaign was undertaken.

RESULTS

The blocks studied range in size from 0.5 to 3.2 m inclusive. Observations show that the coarsest particles may be mobilized at maximal specific streampowers. In the case of the Chassezac, 7000 W m^{-2} is necessary to remobilize particles with a b-axis of 2 m. Figure 5 shows the relations between the size of elements and the streampower necessary to mobilize them for each river. The dots correspond to the largest elements mobilized by a given flood at each site. The size-critical streampower relation is represented by the envelope curve which allows the dots corresponding to blocks smaller than that which the river may mobilize, to be excluded. In this way, the maximal competences of floods may be defined for the four rivers considered.

Table 3 summarizes the results, indicating the range of diameters considered and the specific streampowers developed, as well as the relation that may be determined for each river studied.

Two groups of curves may be distinguished (Fig. 5). Those for the upper Ardèche and the Haute Loire are quite close and seem to follow on from the relations put forward by Costa (1983) and Williams (1983). It should be noted that Costa also uses an envelope curve, while Williams uses straight line regression. The other relations determined for the Figarella and the Chassezac are notably different: their position on

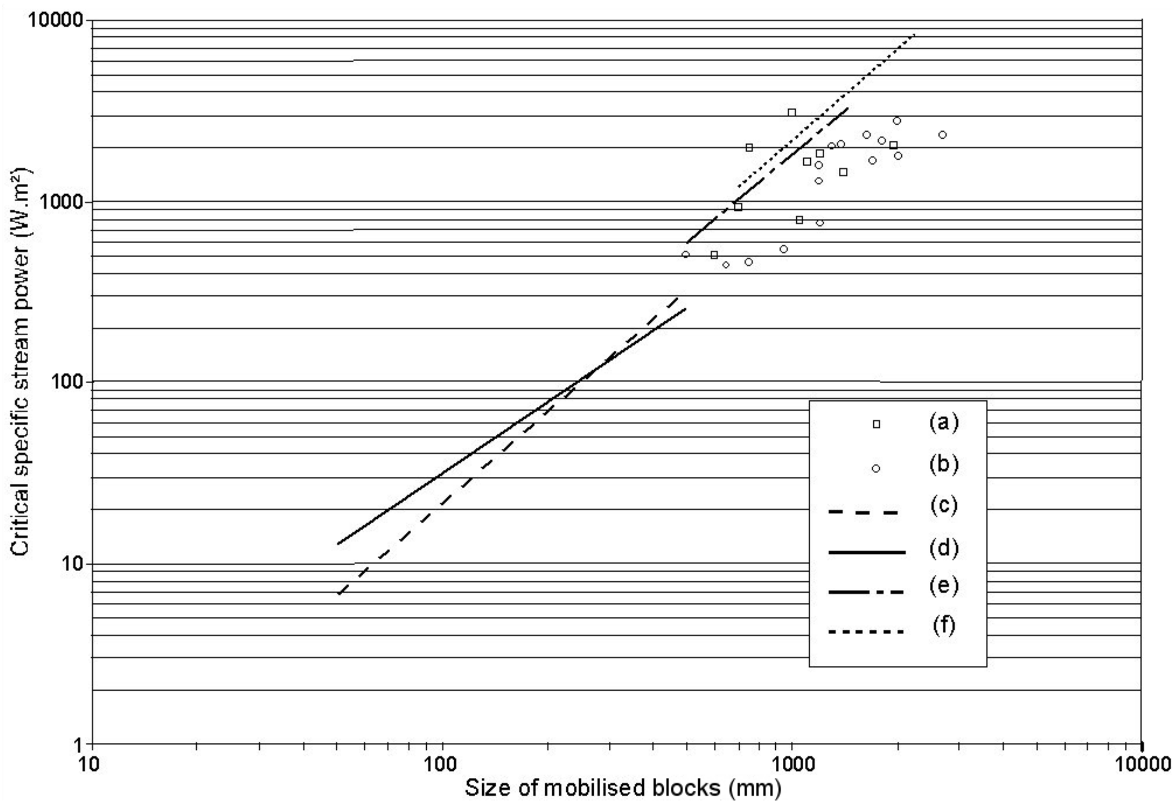

Fig. 5 Relation linking the Critical stream power and the diameter of mobilized blocks in several mountainous boulder bed rivers: (a) Upper Loire, (b) Upper Ardèche, (c) rivers of Colorado (Costa, 1983), (d) observations from literature (Williams, 1983), (e) Figarella River (Gob *et al.*, 2003), (f) Chassezac River (Jacob, 2003).

Table 3 Table showing the equation $\omega_0 = a\, d_i^b$ where ω_0 represents specific stream power (W m^{-2}) and d_i the size of the mobilized elements (mm).

	a	*b*	Block size range (m)
Upper Ardèche	0.1238	1.29	0.65–2.7
Chassezac (Jacob, 2003)	0.025	1.647	0.7–2.3
Upper Loire	0.6069	1.09	0.6–1.9
Figarella (Gob *et al.,* 2003)	0.0253	1.62	0.9–2
Costa (1983)	0.009	1.69	0.5–1
Williams (1983)	0.079	1.3	0.1–1.5

the graph shows that for blocks with equivalent diameters, greater critical specific discharges are required for mobilization than in the Ardèche and the Loire.

DISCUSSION

The rivers may be classed into two distinct groups, even though their hydrological regimes and the material being considered are comparable. As the energy necessary for mobilization to occur is higher in the gorges of the Figarella and the Chassezac, one may interpret that a greater amount of energy is dissipated by the roughness of the bed resulting from skin friction and form drag from individual bed particles (Wohl, 2000). The bed morphology may account for this roughness of features. In the Chassezac, meanders are numerous, which is not the case in the other rivers. Added to this are irregularities and depressions cut into the bedrock. In the Figarella as in the Chassezac (see Table 1), there are very coarse blocks. In each case, this may be explained by a combination of factors: (a) The structural conditions: the joints are widely spaced in the granite outcrops of these river basins, facilitating the liberation of large blocks (Valadas, 1984). In Corsica, freeze-thaw action at the headwater, which lies at a very high altitude, helps account for the large number of coarse blocks. Moreover (b), the evolution of the beds since the late-glacial period has been marked by the evacuation of the inherited pebble sheet, which has resulted in the formation of paving. Indeed, with time sediment sorting has rendered bed load reworking more and more difficult. In both valleys, the largest blocks were mobilized by exceptional floods at the end of the 19th century, but ordinarily, are stable.

This is not the case in the Ardèche and the Haute Loire, where the material is of more modest size, for different structural reasons. In the Ardèche, the inherited pebble sheet has not been completely evacuated due to the width of the alluvial plain. The Loire and the Ardèche have more rectilinear beds and a smoother and better sorted bed load. One may hypothesize that a smaller proportion of energy is taken up by the roughness of the bedforms (Petit *et al*., 2000).

CONCLUSIONS

This paper underlines the value of lichenometry in the study of hydrology, and its advantages in relation to traditional techniques. Indeed, lichenometry allows a rapid evaluation of the mobility of deposits. The long lifespan of the thalli allow former floods and certain exceptional events to be recorded. In this way, the time period available for study is considerably wider than that provided by the use of colour or radio-emitting markers. Finally, it is possible to work with a large number of blocks as lichen is a natural marker. Lichenometry is an efficient instrument for the study of boulder-bed rivers and the morphogenic effects of extreme stream flows. However, precautions are necessary in employing this tool: for organisms sensitive to their surroundings, the field of application is limited to boulder beds in open torrential environments (without a canopy of trees).

Through lichenometry, size-streampower relations may be developed for blocks whose diameter is greater than that presented in the literature so far. Indeed, this study has allowed the sedimentary dynamics of very active mountainous Mediterranean streams to be better understood and quantified. Finally, the results suggest that in these rivers, the roughness of the bed consumes a large amount of energy. The presence of lichen, or in other words the presence of markers indicating ancient flood episodes, is linked to the preservation of river features. When the material remains relatively stable, as in the Chassezac, or when the large alluvial plain allows for changes in the course of the channel, as in the Ardèche, features that were laid down during the first half of the 19th century remain conserved.

Acknowledgements This study has benefited from the support of the "Programme Tournesol" and bilateral agreements between the Communauté Française de Belgique and the Ministère francais des Affaires Etrangères. Frédéric Gob is financed through a grant offered by the F.R.I.A. of the Communauté Française de Belgique. Comments made by Paul Carling improved this paper.

REFERENCES

Bravard, J. P. & Petit, F. (1997) *Les cours d'eau: dynamique du système fluvial*. A. Colin, Paris, France.

Carling, P. A. & Glaister, M. S. (1987) Reconstruction of a flood resulting from a moraine dam failure using geomorphological evidence and dam break modelling. In: *Catastrophic Flooding* (ed. by L. Mayer & D. Nash) (18th Annual Geomorphological Symposium, Miami University, Ohio), 181–200.

Costa, J. E. (1983) Palaeohydraulic reconstruction of flashflood peaks from boulder deposits in the Colorado Front Range. *Geol. Soc. Am. Bull.* **94**, 986–1004.

Ergenzinger, P., Schmidt, K .& Busskamp, R. (1989) The pebble transmitter system (PETS): first results of a technique for studying coarse material erosion, transport and deposition. *Z. Geomorphol.* **33**, 503–508.

Ferguson, R. I. (1981) Channel forms and channel changes. In: *British Rivers*. (ed. by J. Lewin), 90–125. G. Allen & Unwin, London, UK.

Gintz, D., Hassan, M. A. & Schmidt, K. H. (1996) Frequency and magnitude of bedload transport in a mountain river. *Earth Surf. Processes Landf.* **21**, 433–455.

Gob, F., Petit, F., Bravard, J. P., Ozer, A. & Gob, A. (2003) Lichenometric application to historical and subrecent dynamics and sediment transport of a Corsican stream. *Quatern. Sci. Rev.* **22**, 2111–2124.

Gregory, K. J. (1976) Lichens and the determination of river channel capacity. *Earth Surf. Processes Landf.* **1**, 273–285.

Grove, J. M. (1988) *The Little Ice Age*. Methuen, London, UK.

Guilhot, R. (1959) Note sur les crues de septembre-octobre 1958 dans le bassin du Chassezac. *Mémoires et Travaux de la Société Hydrotechnique de France* **1**, 60–65.

Guillot, P. (1959) Aspects hydrométéorologiques des crues cévenoles des 30 septembre et 4 octobre 1958. *Mémoires et Travaux de la Société Hydrotechnique de France* **1**, 50–59.

Jacob, N. (2003). Les Vallées en gorges de la Cévenne vivaraise, Montagne de sable et château d'eau. PhD Thesis, Univ. Paris IV-Sorbonne, France.

Jacob, N., Gob, F., Bravard, J. P. & Petit, F. (2002) Croissance du lichen *Rhizocarpon geographicum l.s.* sur le pourtour nord-occidental de la Méditerranée: observations en vue d'une application à l'étude des lits fluviaux rocheux et caillouteux. *Géomorphologie. Relief, Processus, Environnement* **4**, 283–296.

Maas, G. S., Macklin, M. G., Warburton, J., Woodward, J. C. & Meldrum, E. (1998) A 300 years history of flooding in an Andean mountain river system: the Rio Alizos, southern Bolivia. In: *River Basin Sediment Systems: Archives of Environmental Change* (ed. by D. Maddy, M. G. Macklin & J. C. Woodward), 297–324. Balkema, Rotterdam, The Netherlands.

Mackling, M. G., Rumsby, B. T. & Heap T. (1992) Flood alluviation and entrenchement: Holocene valley-floor development and transformation in the British uplands. *Geol. Soc. Am. Bull.* **104**, 631–643.

Mussot, R. (1969) Intérêt de l'utilisation des traceurs radioactifs dans la recherche en morphologie fluviale. *Bulletin de l'Association de Géographes Français,* **373/374**, 459–466.

Petit, F., Perpinien, G. & Deroanne, C. (2000) Détermination des puissances spécifiques critiques dans des rivières à charge de fond caillouteuse. *Revue géographique de l'Est* **40**, 59–65.

Valadas, B. (1984) Les hautes terres du Massif Central français, contribution à l'étude des morphodynamiques récentes sur versants cristallins et volcaniques. PhD Thesis, Univ. Paris-I, France.

Van den Berght, J. H. (1995) Prediction of alluvial pattern of perennial streams. *Geomorphology* **12**, 259–279.

Williams, G. P. (1983) Paleohydrological methods and some examples from Swedish fluvial environments. *Geogr. Ann. A* **65**(3-4), 227–243.

Wohl, E. E. (2000) *Mountain Rivers*. Water Resources Monograph 14. AGU, Washington, USA.