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The effect of ordering on the geomorphic effectiveness of hydrologic events

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Abstract. A certain confusion exists between geomorphic effectiveness as defined by Wolman and Miller (1960) and as defined by Wolman and Gerson (1978). The difference between the concepts is discussed and it is shown that both definitions are limited in practical application to specific cases. The problems of defining effectiveness are illustrated with reference to a theoretical analysis of some simple systems containing geomorphic threshold components. In particular it is shown that event interarrival times and event ordering may play an important role in governing the resulting "effectiveness" of an event.

L'effet du rangement sur l'éfficacité géomorphique des évennements hydrologiques.

Résumé. Il y a de la confusion entre les définitions de l'éfficacité géomorphologique suivant Wolman et Miller (1960) et cela de Wolman et Gerson (1978). On discute la différence entre les concepts, et on montre que les deux définitions sont limités en usage pratique en des cas individuels. Les problèmes de la définition de l'éfficacité sont illustrées en tenant compte de quelques systémes simples qui contiennent des composants des limites géomorphologiques. En particulier, on montre que les temps d'arrivés entre-évennements et leurs grandeurs peuvent jouer un rôle important en gouvernant l'éfficacité résultant d'une évennement.

NOTIONS OF GEOMORPHIC EFFECTIVENESS

The starting point of this paper is the study of Wolman and Gerson (1978), who investigated the geomorphic "effectiveness" of single hydrologic events and present a preliminary analysis of the relationship between the effectiveness of events "as formative agents of channels and hillslopes" and climatic zone. Wolman and Gerson imply throughout that it is the "catastrophic" event that is geomorphologically effective in this sense, making the point that such catastrophes may be relatively normal or common in many environments and that the rate of recovery of landform following such an event may be rapid.

Their paper represents a substantial shift in position of the generally accepted interpretation of the paper by Wolman and Miller (1960) and the concept of effectiveness contained therein. In the earlier paper Wolman and Miller concluded that

> "The effectiveness of processes which control many land forms depends upon their distribution in time as well as their magnitude. It cannot be assumed that simply because of their magnitude the rare or infrequent event must be the most effective. Analyses of the transport of sediment by various media indicate that a major portion of the work is performed by events of moderate magnitude which recur relatively frequently rather than by rare events of unusual magnitude" (p. 72).

Aided by a clear and memorable diagrammatic representation of this conclusion, Wolman and Miller's magnitude/frequency analysis of effectiveness has been disseminated widely throughout geomorphology (perhaps to the neglect of much more that Wolman and Miller wrote about the operation of threshold effects in geomorphic systems). This definition is, however, somewhat different from that of Wolman and Gerson who define effectiveness in terms of "the ability of an event or combination of events to affect the shape or form of the landscape". (p. 190). Wolman and Gerson note that the two definitions are not equivalent and that "the landforming result is only partly related to the mass of material moved". They also recognised that effectiveness in this sense must be related to the "recovery time" of the landscape in obscuring the effect of individual events (see also Anderson and Calver, 1977 for discussion of this point).

There has been a move then from defining effectiveness in terms of total work done, to effectiveness in terms of the production and persistence of land forms. The result, noting that there must be considerable overlap between the definitions, is likely to be an unsatisfactory confusion. In what follows it will be argued that effectiveness cannot be properly defined for low frequency, long persistence effects except in some simple cases. This holds for the former definition which is, in principle at least, capable of substantiation in quantitative terms (see for example Pearce, 1976). The latter definition contains a considerable subjective element and will be shown to be subsumed in the wider conceptual framework of geomorphic threshold systems.

However, it is possible to rationalise the difference between the definitions in fairly simple terms. As noted by Wolman and Miller in 1960, the first definition applies best to transport processes leading to depositional landforms and they cite a number of reasons to account for the lack of evidence of the effectiveness of moderate events in moulding erosive landforms. Wolman and Gerson are particularly concerned with such erosive landforms and especially with those involving relatively infrequent threshold effects. The presence of thresholds does not necessarily preclude an analysis of effectiveness in the magnitude/frequency terms of Wolman and Miller but it becomes increasingly difficult to evaluate the distributions involved as the thresholds become higher and occurrences of the threshold effects become more frequent. At some stage the definition of effectiveness offered by Wolman and Gerson will become an apparently suitable alternative.

THE VARIABILITY OF EFFECTIVENESS

We can further reconsider these definitions of effectiveness in terms of the supply and transportation of materials by geomorphic processes. Sediment transportation by rivers is a particular case where the Wolman and Miller definition appears to work quite well. Processes such as this operate relatively frequently and are low threshold processes in the sense that there will usually be some geomorphic work done even by low magnitude events. However, there is evidence to suggest that, at least in humid temperate rivers, the transport of sediment during events of moderate magnitude is frequently supply limited, and that the amount transported may then depend on the time of occurrence of an event relative to preceding high magnitude events that effectively release sediment for later transporation (see Wolman and Gerson, 1978, Figure 6 and Newson, 1980, Figure 9). This suggests that the ordering of events may be significant and that the supply of sediment may be governed by high threshold (relatively infrequent) effects that may qualify as being effective in modifying landforms under the Wolman and Gerson definition. Note also that ordering of events may be important where the persistence of an effect is considerably modified by a later perhaps larger event.

Further reference to Newson (1980) reveals some more complications in the variability of effectiveness. Newson reports the effects of two floods of similar magnitude but differing in intensity, in the River Severn catchment, Plynlimon, Wales. The first (1973) flood had a longer duration of less intense rainfall and the higher flood peak. This was classified as a hill-slope forming event in that several landslips were generated and the observable effect on the channel was slight. The second more intense event (1977) was classified as a channel forming event in that there was far greater evidence of channel modification by erosion and deposition, while slope failures were notably absent. The events were therefore effective in different ways. However, Newson notes that the distinction in respect of the channel processes is somewhat misleading in that in both cases similar amounts of material were transported out of the catchment, large bedload traps being filled to overflowing by both events.

IMPLICATIONS FOR THE DEFINITION OF EFFECTIVENESS

This last study poses some intriguing questions in the present context. First, given that both events were similarly effective (in the Wolman and Miller sense) in removing material from the catchment, which storm was the most effective (in the Wolman and Gerson sense) in terms of channel formation? The first, with a higher peak discharge and flow durations above a given threshold level, in which the lack of obvious channel alteration may be an indication that the longer duration of high flows allowed a more integrated response; or the second, in which the effects on the channel were more obvious but where the material left as shoaled and sometimes armoured deposits in the channel bed by the shorter duration of high flows may indicate some retrogressive effects? Secondly, would the hillslope failures that were a feature of the 1973 event have occurred in the 1977 event in the absence of the earlier event, or was the period of wetting preceding the storm core in 1973 necessary to initiate slope failure such that an <u>upper</u> threshold of intensity, limiting hillslope failures, may have operated in 1977? Thirdly, was the supply of material to the channels by slope failure in the 1973 flood a prerequisite of the channel form response in the 1977 flood?

At our present state of knowledge it is obviously difficult if not impossible to answer these questions. However, the implications as regards the discussion of effectiveness can be considered. It is the argument here, on the basis of evidence such as that above, that both definitions of effectiveness must allow that it is an extremely variable quantity on the space and time scales of observations of current geomorphological processes.

Consider for example the case of the decreasing amounts of sediment transported by lesser flows following a major flood. The greater the variability of material transported by an event of given magnitude in the case where transport is supply limited then the longer the period of study required to properly evaluate Wolman and Miller's magnitude/frequency/effectiveness distributions, since it is necessary to integrate not only over a sample from the distribution of magnitudes, but over a sufficient sample of assemblages of consecutive magnitudes. The quantitative aspect of this definition of effectiveness is thereby reduced in significance and one is left only with the hypothesis that moderate events of relatively frequent occurrence do the most geomorphic work, even though they may be dependent on material supplied by events of greater magnitude. As a result the sting in the tail of Wolman and Miller's fairy tale (1960, p.73) becomes more pointed. It should be noted, however, that these reservations will be most important as one moves upstream to smaller upland catchments. Downstream, as catchment area increases, the effects of individual events will be buffered by storage in the channel and adjacent flood plain, while the regular supply of (sorted) sediment from upstream ensures that the supply limitation on transport may be less important.

Consider also the implications of Newson's study in the River Severn catchment which might be considered as a case of complex response (Schumm, 1977). It is clearly difficult to evaluate the Wolman and Miller definition of effectiveness for the high threshold hillslope phenomena in this case. It is similarly difficult to evaluate the Wolman and Gerson definition of effectiveness faced with the possibility of such complex response. It is suggested that, certainly in upland areas, such complex response will be the rule rather than the exception, and that the time scales required to statistically average such response into a meaningful geomorphological interpretation are in many environments sufficiently long to preclude this form of analysis. Instead, analysis in terms of the more general concepts of threshold systems should be considered. This will be illustrated by reference to a simple model of a geomorphic threshold system.

THRESHOLD SYSTEM MODELS

The concept of a threshold system model can be used to demonstrate the variability of effectiveness, and why in some cases high magnitude events will have little effect on the form of the landscape if the system state is such that the event does not trigger the threshold response of the system. Dury (1973), for example, reports the lack of effects of the (estimated) 1000 year flood on the River Ouse, Northamptonshire. It need not be expected that a flood of very long recurrence interval should be effective in the Wolman and Gerson sense, provided that the resilience or threshold resistance of the system is great enough. In fact, where the system is developing gradually over time, the threshold may be crossed during an event of relatively moderate magnitude (but note that it may also require an event of increasing magnitude). Schumm's illustration of this concept treats the threshold as static over time (see Figure 1a); more generally, it may be better to consider that the threshold changes over time (Figures 1b, 1c) and, perhaps, varies dynamically with the magnitude and intensity (and perhaps timing) of the generating event in some complex manner.

The minimum requirements for a model are as follows:

(1) A component specifying the distribution of event magnitudes (only hydrologic events will be considered here).

(2) A component specifying the interarrival times between events.

(3) A component specifying the state of the system in terms of its resilience or resistance to change as it develops over time, in terms of the event magnitude required to initiate a threshold change, and the effect of a given threshold exceedence.

As an example, such a model has been fitted to a short period of data on bank erosion on the River Exe in Devon, England (Hooke, personal communication). This data is summarised in Figure 2, where the dotted line describes a representative relationship between effect (in terms of mean erosion) and threshold exceedance expressed in terms of flood peak discharge in the Exe at Thorverton. A 13 year record of peak discharges at Thorverton, greater than 97 m^3s^{-1} (an average of 4.8 storms per year) is available from the Flood Studies Report (NERC, 1975) and has been used to specify the distributions of event magnitudes and arrival times required by the model.

For a model defined with a fixed threshold of erosion (and erosion/exceedance relationship), interarrival time and event ordering have no effect on amounts of erosion. For the case of Figure 2, all simulated points would plot on the dotted line. If however, a random threshold of erosion is introduced, the ordering of events does become significant, and if a time variable threshold is introduced, both ordering and interarrival times will affect the "effectiveness" of a given magnitude of event. This second case has been used to illustrate the effect of ordering using the following procedure.

(1) Using Monte Carlo simulation, 100 storm peak discharges and 100 interarrival times (totalling 21.4 years) were randomly selected from the respective distributions for the River Exe at Thorverton.

(2) A functional representation of changing threshold of erosion was specified arbitrarily (Figure 3) in this case representing a simple decay of bank strength over

time. The thresholds were scaled upwards in comparison with the observed data of Figure 2 so as to be within the range of the available peak discharge data. However, the same relationship between exceedance and erosion (as shown in Figure 2) was used.

(3) Keeping the same sequence of arrival times, the 100 storms were run in different random orders and cumulative erosion rates were calculated for each run. This step was repeated 500 times.

(4) Mean cumulative erosion and the variance for the 500 replicates were calculated at each storm occurrence. The results are shown in Figure 4.

The high variance at intermediate times is a result of both the effects of ordering and the sampling variance of the events. However, at the end of the period some convergence is expected due to the limitations imposed by the fixed distribution of 100 events. If ordering were unimportant (e.g., the fixed threshold case) the variance at the end of the period would be zero. Figure 4 shows therefore that ordering can have a significant effect and that considerable variability of effectiveness is to be expected as a result of even a simple deterministic variability in the system. Naturally, other factors that have not been considered in this simplistic analysis will be pertinent to the real data. Effects such as seasonality or spatial inhomogeneity may reinforce the importance of ordering, others such as impact on a large number of representative sites may reduce it.

IMPLICATIONS FOR GEOMORPHIC PROCESS STUDIES

An analysis of geomorphic systems in terms of threshold concepts reinforces the criticisms made of the notions of geomorphological effectiveness of hydrological events. In particular, we should expect a variability of both measures of effectiveness due to the intensity characteristics of a given magnitude of event; the dynamic change of geomorphic thresholds with event magnitude and intensity; and the ordering and arrival time of events. Ordering may be particularly important to the persistence of effects where different processes responding to different threshold effects interact. Geomorphic systems are characterised by variability at all time and space scales below the level of morphological classification. The possibility of predicting such variability is likely to decrease as the frequency of occurrence of an effect (landslip, bank erosion, boulder movement, initiation of trenching, etc.) decreases. The concept of geomorphic thresholds allows such variability to be an explicit part of data analysis. However, it is recognised that this form of analysis is easier in theory than in practice. Magnitude, intensity and arrival times would all appear to be variables that may be measured relatively accurately (although the obviously simpler difficult of relating a given magnitude and intensity of rainfall to the corresponding magnitude and intensity of stream discharge is a problem that continues to tax mathematical hydrologists!). Complex geomorphic thresholds are also not measured simply.

Indeed it has been common to use magnitude/intensity measures as threshold surrogates (see for example, Harvey, 1977; Hughes, 1977). In that case, there is again a danger of ignoring the dynamic nature of the processes involved. It should be the aim to approach geomorphic thresholds in terms of the dynamic characteristics of the processes operating and the mechanical characteristics of the materials on which they operate. Some progress in this direction has already been made but will in many cases require a theoretical basis to link the small scales of measurements to the larger time and space scales of significant landform change.

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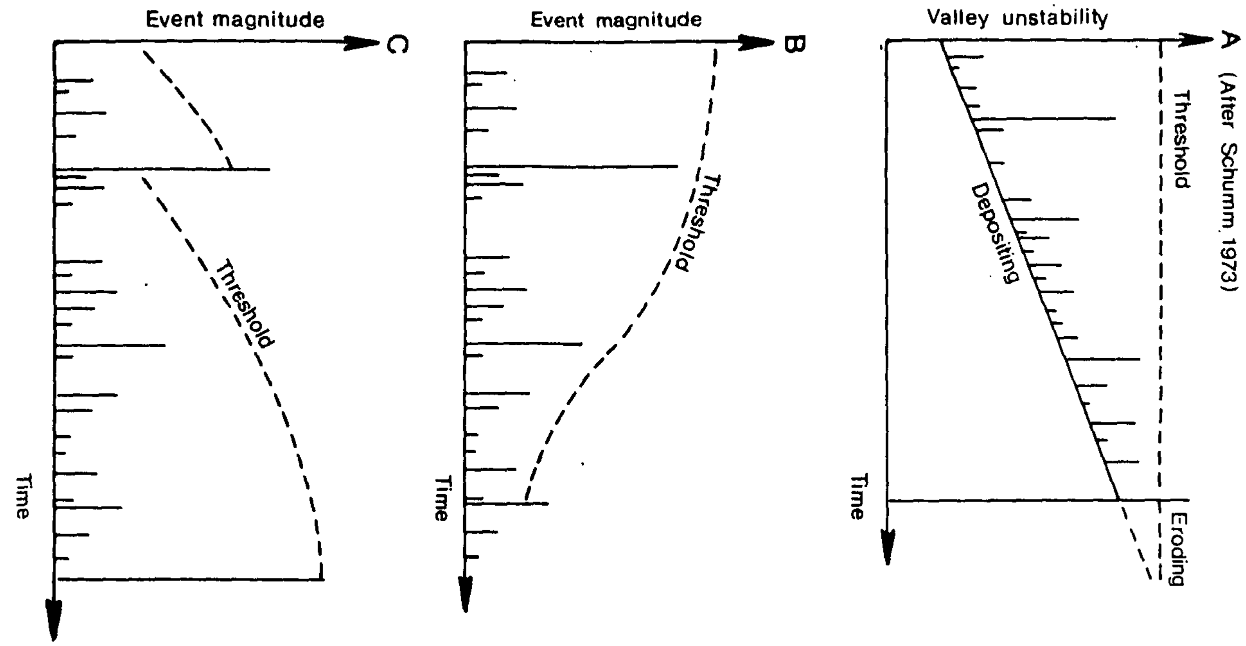

FIGURE 1. Geomorphic threshold concepts.
a) constant threshold (after Schumm, 1977)
b) falling threshold
c) rising threshold

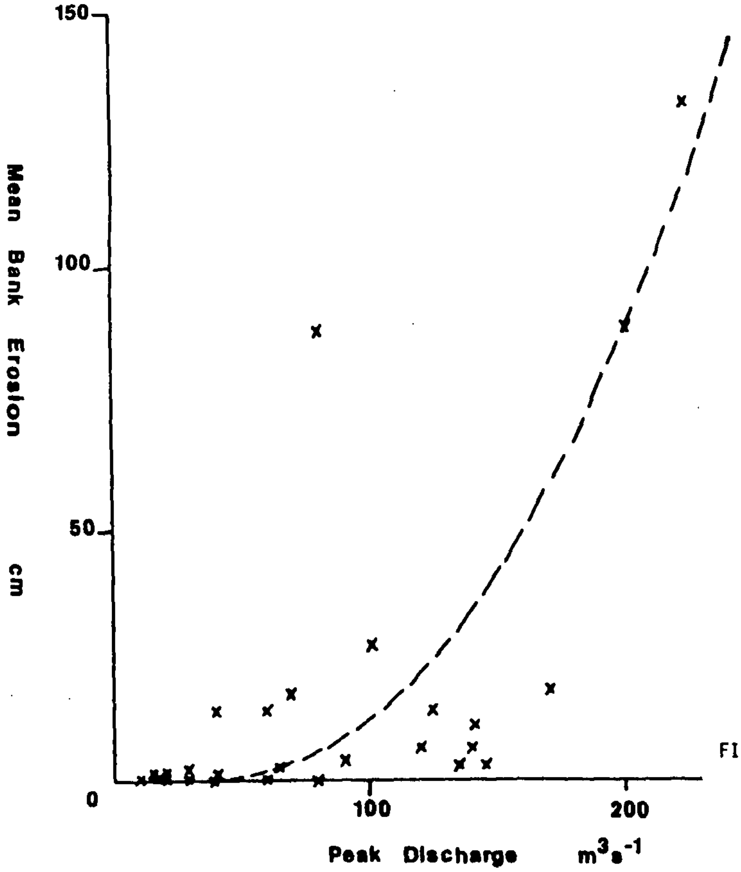

FIGURE 2. Average bank erosion $\bar{e}$ at River Exe Site D, plotted against peak discharge, q, at Thorverton. The dotted line describes the curve

$$\bar{e} = 0.0035\ (q-t)^2\ \text{cm}$$

where t is a 'threshold of erosion' (= 40 m^3s^{-1}). Data supplied by Janet Hooke.

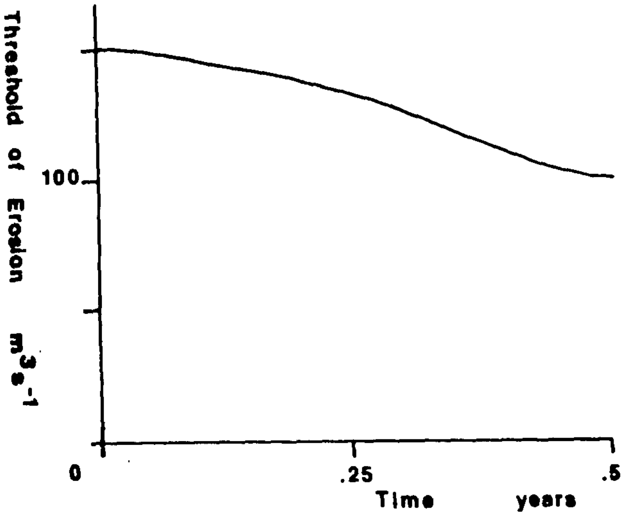

FIGURE 3.

Variable threshold of erosion assumed in model runs.

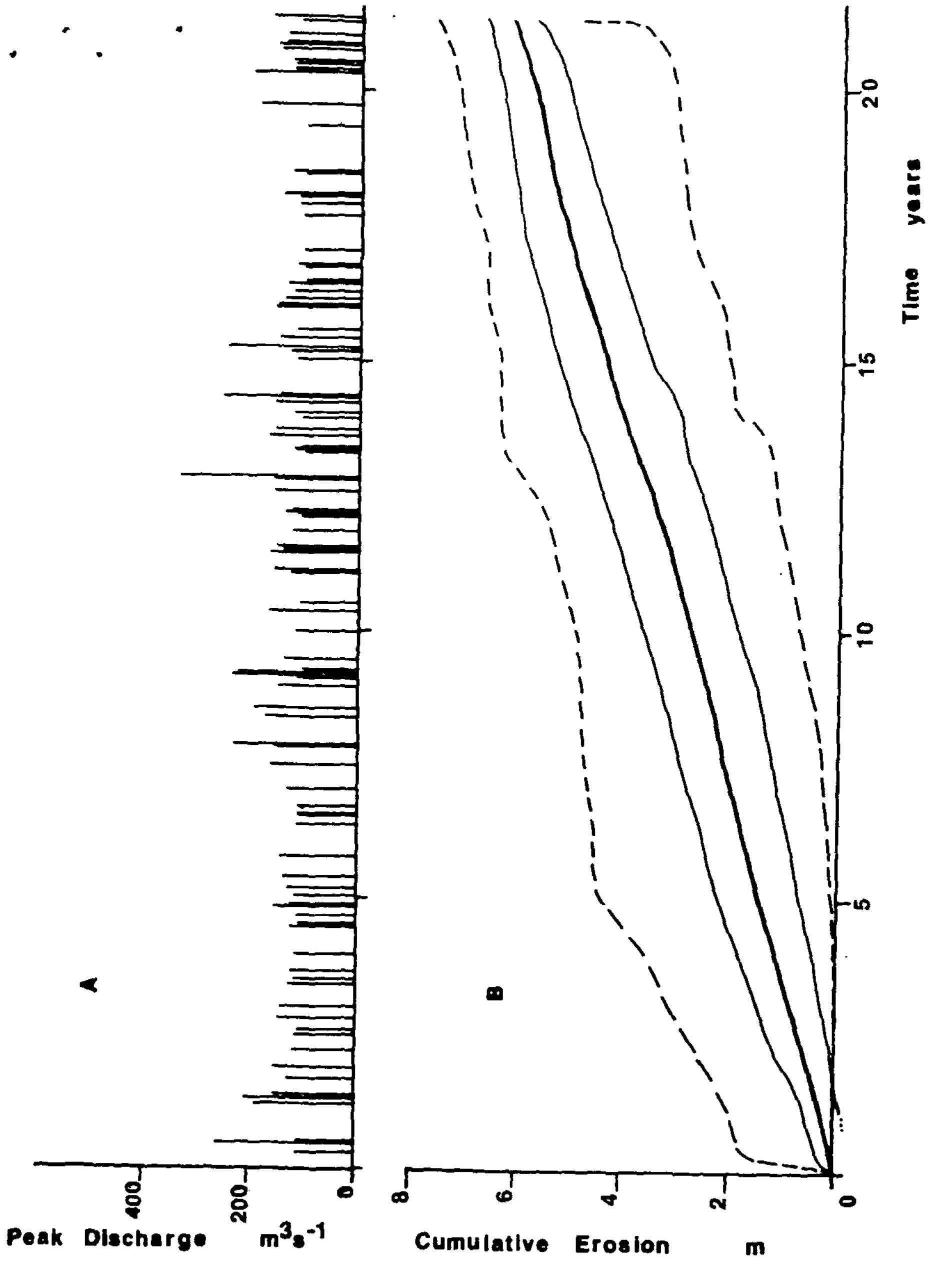

FIGURE 4. a) Randomly generated sample of 100 storms used in analysis of effect of ordering.
b) Cumulative erosion curves for 500 replicate orders for same 100 storms. Solid lines are mean ± 1 standard deviation, dotted lines are maximum and minimum values over all runs.

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Methods for assessing lake Pleistocene and Holocene erosion history in glaciated mountain drainage basins

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Abstract. Methods for assessing late Pleistocene and Holocene erosion history of previously glaciated, mountain drainage basins are described. The main objective is the recognition of chronological sequences of geomorphic surfaces and their buried or exhumed correlatives. Once identified, geomorphic surfaces may be mapped and assigned ages based upon radiocarbon dating and upon surficial weathering features, such as rock surface weathering and soil profile development. Geomorphic surfaces of glacial moraine and associated landforms provide a relative age base which is the key to inter- and intra-drainage basin correlations. Maps showing the distribution of geomorphic surfaces and aggrading scree surfaces depict the erosion history of drainage basins.

Methodes d'estimation de l'evolution de l'erosion dans les bassins de drainage des glaciers de la fin du pleiostocene et de l'holocene.

Résumé. Des méthodes d'estimation de l'évolution de l'érosion dans les bassins de drainage soumis à la glaciation en montagne durant la fin du pléiostocène et de l'holocène sont décrites. L'objectif