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Sediment supply and climate change: implications for basin stratigraphy

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ABSTRACT

The rate of sediment supply from erosional catchment to depositional basin depends primarily upon climate, relief, catchment slope and lithology. It varies in both time and space. Spatial changes in erosion rates due to variations in lithology are illustrated by contrasting rates of drainage divide migration away from faults of known ages. Time variations in relative sediment supply are extremely complex and vary widely according to the direction and magnitude of climate change. In many parts of the Great Basin and south-western USA, glacial maximum climates were characterized by higher effective moisture and the altitudinal downward spread of woods and forests. Sparse data from alluvial fans indicate reduced sediment supply, despite the increased runoff evident from higher lake levels. The situation in Mediterranean areas is less clear, with rival climatic scenarios for vegetation ecotypes predicting contrasting runoff. In order to test these latter we run Cumulative Seasonal Erosion Potential [CSEP] experiments for present-day and a variety of full-glacial Mediterranean candidate climates. The results indicate the likelihood of enhanced sediment supply and runoff compared to the present day during full-glacial times for a cool wet winter climate and a reduction in sediment supply and runoff for a full-glacial cool dry winter climate. We then explore the consequences of such phase differences in sediment supply, and sea and lake levels for the stratigraphy of sedimentary basins. Highstands and lowstands of sea or lake may be accompanied by greater or lesser sediment and water supply, as determined by the regional climate and the direction of climatic change. Thus marine lowstands are not necessarily periods of great transfer of coarse clastic sediments to shelves and deep water basinal environments. Unsteady sediment supply has greatest implications for alluvial systems, in particular the effect that changing relative supplies of water and sediment have upon river and fan channel incision.

INTRODUCTION

The rate of sediment supply exerts major controls on a basin's stratigraphic record (Galloway, 1989; Schlager, 1993). In the past few years geologists have tended to concentrate on exploring tectonic controls of relief and slope upon sediment supply. At the same time the occurrence of climate change during Quaternary times has been well established, together with increasing appreciation of its effects on the sedimentary record during earlier geological epochs (e.g. Perlmutter & Mathews, 1989). In particular, with the advent of sequence stratigraphic concepts, it is a matter of great importance to explore whether ups and downs of sea or lake level are accompanied by more or less sediment supply from continental catchments, i.e. do sea level and sediment supply change in-phase or out-of-phase? The rate of sediment supply to a sedimentary basin depends upon the rate of surface soil and rock erosion in the basin-bordering catchments, minus any sediment stored or otherwise exported, e.g. by wind. It is determined, in complex ways, by catchment geology, relief, slope and by the role of climate in determining vegetation and runoff.

Here we:

- outline major spatial and time controls on sediment production rates;
- review data on the variation of sediment supply and erosion rates with changing semiarid climate at different Quaternary time-scales;
- present results of modelling experiments on predicted sediment supply and runoff for full glacial and Mediterranean climates;
- indicate the likely stratigraphic consequences of variations in sediment supply and their implications for basin modelling;
- establish the role of sediment supply on the evolution of axial rivers

RATES OF SEDIMENT SUPPLY

General

Many authors, beginning with Fournier (1960), have addressed empirically the problem of modern sediment delivery and supply (e.g. Ahnert, 1970; Milliman & Meade, 1983; Pinet & Soriau, 1988; Milliman & Syvitski, 1992; Summerfield & Hulton, 1994; Ludwig & Probst, 1996; Hovius, in press). In such studies measurements of sediment discharge from large catchments (eliminating influences due to bedrock geology) are correlated with catchment variables such as mean gradient, relief, elevation, precipitation trends, temperature, etc. Such correlations are useful in determining the likely importance of various controlling parameters on regional scales. The lack of success of individual variables in explaining more than a bare majority of variance leads one to suspect that the complex nature of the whole process requires an integrated forward modelling approach; furthermore, one that takes vegetation and hydrological balances specifically into account. Forward models of sediment production and erosion allow estimates of relative sediment yield on regional or global scales, enabling the role of climate change to be explored from a firm scientific base. The Cumulative Soil Erosion Potential (CSEP) models of Kirkby (1995) and Kirkby & Cox (1995) are developments of earlier deterministic erosion models (Kirkby & Neale, 1987; De Ploey *et al.*, 1991). Briefly (see Appendix for more detailed summary), CSEP models consider that sediment discharge from catchment to basin is a function of two rates: soil production rate and soil transport rate. Both are controlled by the time-distribution of precipitation and temperature through the growth of vegetation and its role in the balance of apportioning incoming water between evapotranspiration and runoff (Fig. 1). The general trend of the model curves (Kirkby, 1995) compares well with previous empirical studies of the relationship between precipitation and sediment yield gained from areas where transport-limited conditions apply (e.g. Langbein & Schumm, 1958). They also accord with predictions of relative sediment yield provided by changing water balances. We use CSEP modelling to explore the likely effects of complex climate change on sediment yields later in this paper.

The effects of climatic change on Quaternary to Holocene river geomorphology are well documented (see Rose *et al.*, 1980; Knox, 1983; Starkel, 1983; Schumm & Brakenridge, 1987; Bull, 1991; Vandenberghe, 1995) but there has been no accompanying systematic quantitative study of changes in the magnitude of sediment supply from catchments to sedimentary basins. The chief control is probably exerted through the complex relationship between mean annual temperature, precipitation and catchment vegetation, following the general lines of the CSEP model. Following the approach of Bull (1991), vegetation is seen as both contributor to bedrock-sediment/soil transformation and as modulator of runoff and sediment erosion. Studies of modern sediment delivery rates recognize the major problems in interpretation of these as 'natural', due not only to measurement uncertainties but, more importantly, to the effects of deforestation, cultivation, river training and damming. There is a great need for imformation on prehuman time variations in delivery rates from different catchments along the lines of recent investigations into changing rates of denudation (Nott & Roberts, 1996). Methods for dealing with this problem require calculation of the volume of sediment derived from catchment or delivered to the basin (Ibbeken & Schleyer, 1991; Collier *et al.*, 1995). 1D deposition rates alone (calculated from magnetostratigraphic sections, for example) are not sufficient to estimate or even indicate changing rates of sediment supply because of the spatial variability of deposition and, more importantly, the loss of sediment from 'open' basins. Another problem is extensive periodic Quaternary incision.

Due to geologically rapid climate changes in the Quaternary, information at a variety of time-scales is required to assess the various influences of climate, vegetation and humans. The relevance of these various estimates will vary according to the nature of the investigation proposed. For example, the determination of erosion rates relevant to geophysical models for basin margin deformation requires data on a long time-scale, perhaps over 10^6–10^7 years such as that provided from Australia by Nott & Roberts (1996). Students of fluvial architecture, on the other hand, require data on changing rates of sediment delivery over time spans of the order 5–100 kyr so that they can try to distinguish between climatic, sea level and tectonic origins for fluvial cycles (e.g. Blum, 1993). Finally, archaeological, geomorphological and environmental studies often require information on decadal to thousand year time-scales.

Nonuniformity vs. unsteadiness

In light of the difficulties of establishing 'universal' laws for sediment supply, it may be argued that it is not the absolute magnitude of the sediment supply that matters but rather the relative rate or the rate of change of supply. The hydrological basis of changing relative rate was the basis of Schumm's classic (1968) speculation on how sediment supply may have varied through geological time. We must distinguish here spatial and/or time changes in sediment supply. Spatial changes in supply (nonuniformity) within sedimentary basins in a given climatic regime result from contrasts in catchment geology and tectonic evolution, particularly the effects of fault or fold propagation and landscape growth (see Jackson & Leeder, 1994; Jackson *et al.*, 1996; Gupta, 1997). Changes in supply over time (unsteadiness) may also result from tectonics, from unroofing of successively deeper substrates (Colombo, 1994), but are most importantly the result of changing climate.

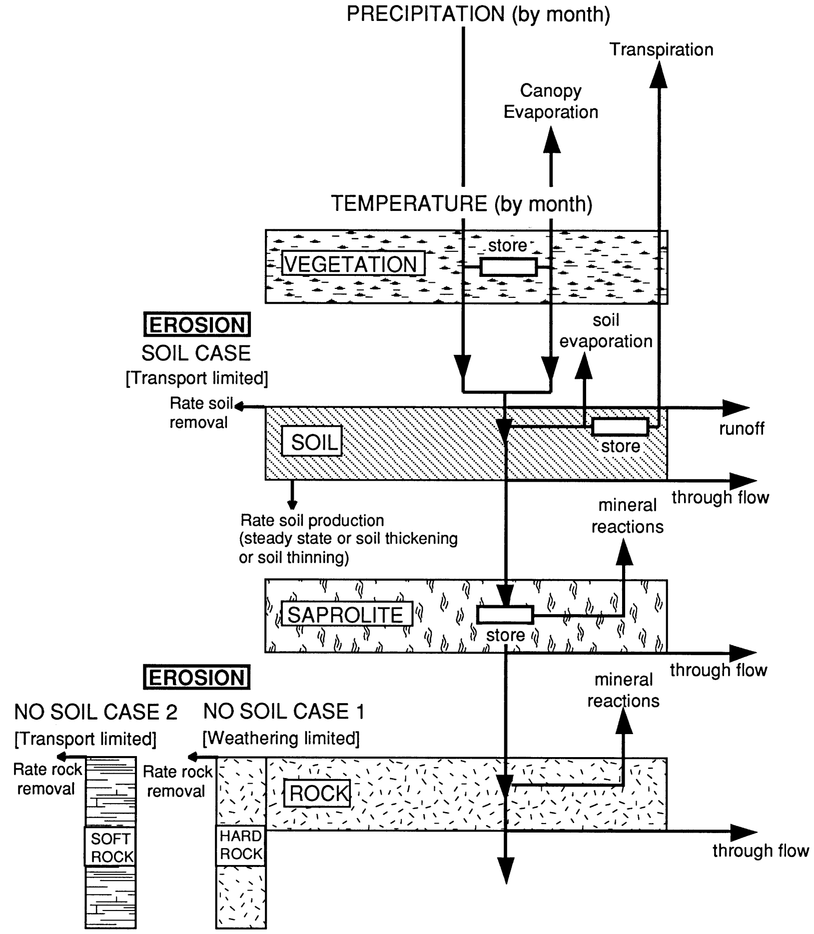

Fig. 1. Simple flow diagram for water interactions between vegetation, soil, saprolite and bedrock. Erosion results once surface runoff exceeds some critical value. For soils and for 'soft' bedrock, erosion rates are transport limited in the sense that they depend nonlinearly upon the magnitude of runoff. Mass movements from catchment slopes are considered to be part of this case, since it may be argued that once the slope-derived gravity flow reaches a stream course the rate of removal depends upon the magnitude of runoff. For 'hard' bedrock, erosion rates are weathering limited in the sense that they depend upon the availability of weathered material for transport.

Notwithstanding their success in predicting relative erosion trends, CSEP models ignore the nature of the geological substrate, local and regional variations in catchment rock type and in the rate of mineral reactions with changing water and vegetation. Such factors often lead to marked nonuniformity of sediment supply from basin margin catchments (Heusch & Milliés-Lacroix, 1971; Woodward, 1995). This may be an important local and regional constraint because the basin analyst is often concerned with the behaviour of features like alluvial and submarine fans which may be fed by catchments composed of lithologies of different weatherability. Thus for individual catchments at smaller scales the general problem of estimating erosion rates must be approached by considering transport- and weathering-limited conditions for different rock types (Fig. 1). Although difficult to quantify, 'hard' rocks are, crudely, those where chemical weathering is needed to break down the rock to erodeable soil or saprolite. 'Soft' rocks are those where physical weathering and/or direct erosion by runoff or gravity is predominant, without the necessity of soil formation for erosion, although a soil will often be present nevertheless. Studies of catchments dominated by one or the other of 'hard' and 'soft' rocks along faults of known age allow crude estimates of the spatially variable rates of sediment supply and drainage divide retreat.

In an example from southern Greece illustrated in Fig. 2, the active Skinos–Psatha normal fault has an estimated age of around 1 Ma (Leeder *et al.*, 1991; Collier *et al.*, 1992). Since that time a number of catchments have developed in the gradually uplifting footwall to the fault, feeding their sediment and water discharges into the marine Alkyonides Gulf to the north. Large catchments excavated in 'soft' Neogene marls, sandstones and conglomerates record up to 8.3 km drainage divide migration (8.3 mm yr^{-1}) from the fault line during this time. By contrast, smaller catchments developed in Mesozoic limestones and serpentinites indicate much slower divide migration (3.25 mm yr^{-1}) and therefore lower mean export of sediment (Fig. 2). There is clearly scope for further work along these lines in other areas where the age of fault initiation may be determined. For example, spatial variations during Holocene times might be estimated by considering the volumes of sediment deposited by individual fans on dated features such as abandoned lake shorelines (see Jackson & Leeder, 1994; their Fig. 3).

UNSTEADY SEDIMENT SUPPLY RATES, WESTERN USA

Opportunities for integration at various Quaternary to Holocene time-scales arise in the western USA where alluvial fan accumulations overlie Pleistocene lavas of

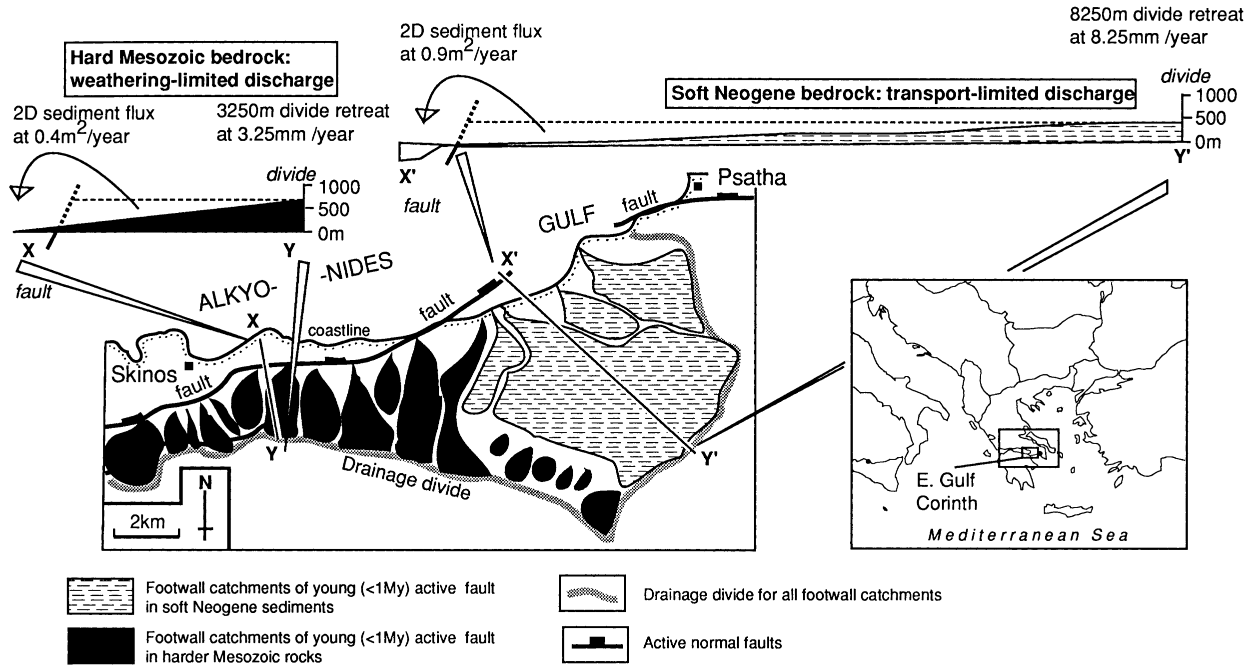

Fig. 2. The active coastal Skinos-Psatha normal fault in the eastern Gulf of Corinth has an estimated age of around 1 Ma (Leeder *et al.*, 1991). Since that time a number of catchments have developed in the gradually uplifting footwall to the south of the mapped fault, feeding their sediment and water discharges into the marine gulf to the north. Large catchments (dashed shading) excavated in 'soft' Neogene sedimentary rocks record up to 8.25 km drainage divide migration (8.25 mm yr^{-1}) from the fault line during this time. By way of contrast, smaller catchments developed in Mesozoic limestones and serpentinites (black shading) indicate much slower divide migration (about 3.5 mm yr^{-1}) and therefore lower mean export of sediment to the marine gulf.

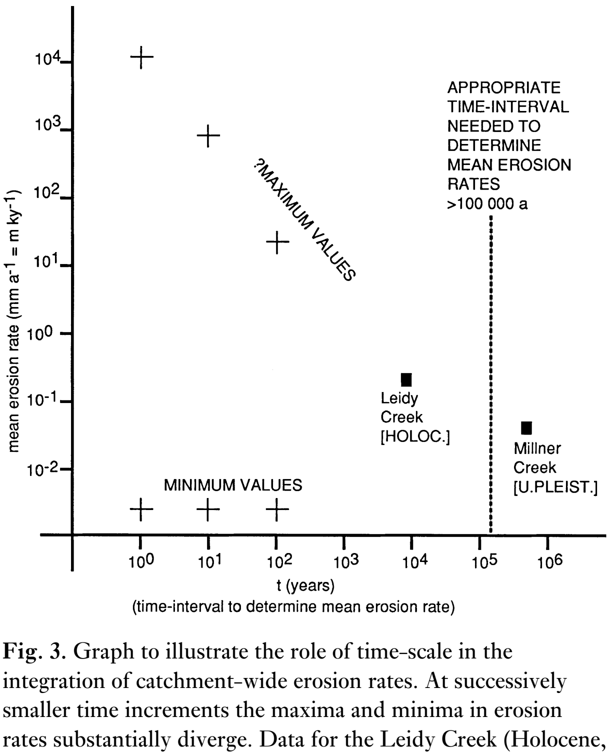

Fig. 3. Graph to illustrate the role of time-scale in the integration of catchment-wide erosion rates. At successively smaller time increments the maxima and minima in erosion rates substantially diverge. Data for the Leidy Creek (Holocene, 11 ka) and Millner Creek (Upper Pleistocene, 800 ka) catchments derived and discussed in the text.

known age (Beaty, 1970; Leeder, 1991) or where Holocene fan lobes have been carefully mapped and sampled (Reheis *et al.*, 1996). In the Great Basin and adjacent areas of the South-West, generally wetter and cooler glacial maximum climate (Thompson *et al.*, 1993) often enabled soil formation to develop under patchy or more continuous tree cover and a diverse subcanopy of grasses and scrub over the whole altitudinal range of many catchments (reviews in Grayson, 1993). Important stratigraphic investigations on Leidy Creek alluvial fan in Fishlake Valley, Nevada – California (Reheis *et al.*, 1996) indicate virtual shutdown of fan deposition and development of thick draping soils during the late Pleistocene glacial maximum. It is inferred that at this time fan surfaces were essentially bypassed as fan channels incised in response to reduced sediment supply and increased runoff. The Holocene trend to higher temperatures, aridity and dominance of summer convective precipitation has caused treelines to rise substantially and the incidence of debris flow deposition from poorly vegetated catchment slopes onto alluvial fans to increase. It is possible to use the data of Reheis *et al.* (1996) to compute an estimate of Holocene sediment discharge. Modelling the Holocene fan sediment as a basinward tapering wedge with a maximum thickness of 10 m yields a mean fan volume of 0.196 km^3, giving a mean Holocene (post-11 ka) sediment discharge from the catchment of

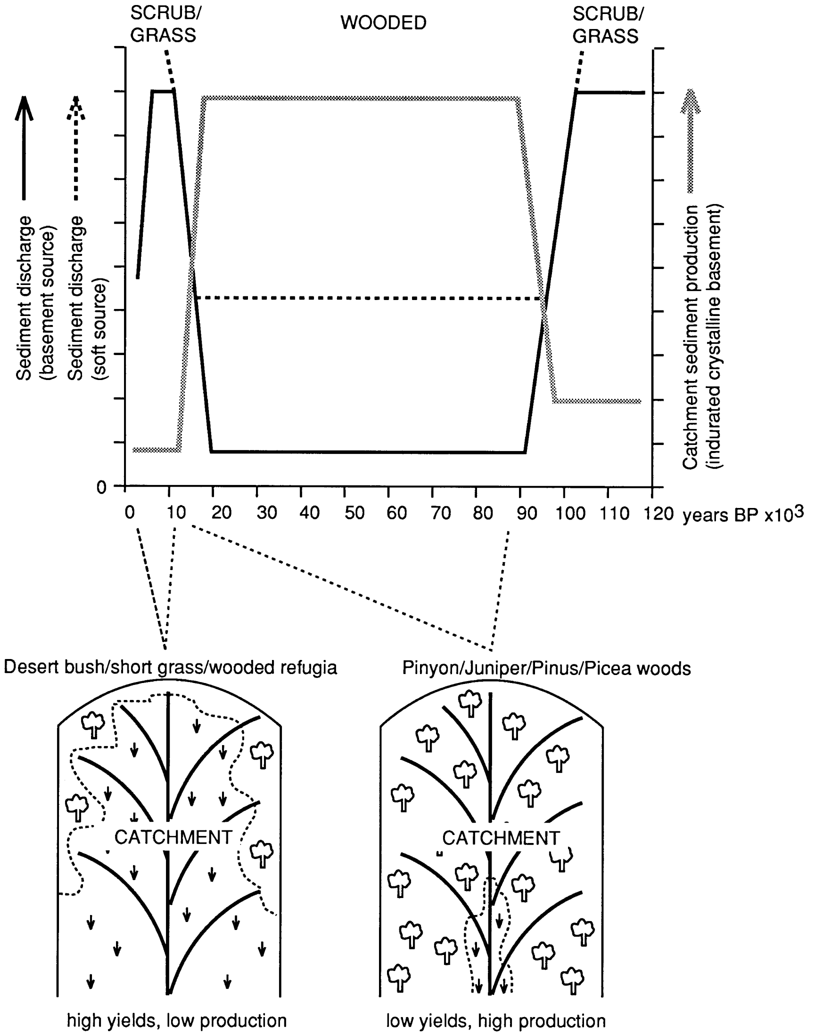

Fig. 4. Cartoon graph to show general trends in vegetation, sediment production (i.e. the rate of *in situ* production of soil from hard bedrock for weathering-limited transport conditions) and sediment discharge (for both weathering and transport-limited conditions) across an eccentricity time band for Great Basin climates. The graph is indicative only and unscaled, ignoring the changes that have undoubtedly occurred at precessional and tilt timeband frequencies.

some 17 820 m^3 yr^{-1}. The mean denudation rate needed to achieve this discharge for the whole 60.3-km^2 catchment over the past 11 kyr is around 0.26 mm yr^{-1} (Fig. 3), after allowance for sediment porosity but neglecting chemical denudation and any contribution to axial sediment flux.

Beaty (1970) provides rare data on a several 100-kyr time-scale from Millner Creek fan and catchment that lie adjacent to Leidy Creek over the watershed of the White Mountains of northern California. The fan overlies the well-dated 700-kyr Bishops Tuff erupted from Long Valley caldera and is inferred to have originated at that time. Holocene fan channel and lobe deposits are dominated by debris flow deposition and little sediment today escapes the confines of the fan to escape as axial discharge, i.e. the system approximates to a sink. Beaty (1970) calculated the total fan volume above the tuff as some 1.73 km^3, giving a mean annual late Quaternary sediment discharge from catchment to fan of some 2460 m^3 yr^{-1}. We calculate the mean denudation rate for the whole 35.5-km^2 Millner Creek catchment over the past 700 kyr as a very low 0.06 mm yr^{-1}, after allowance for sediment porosity but neglecting chemical denudation (perhaps up to 10%?) and assuming no axial sediment loss. This result is integrated over at least seven full glacial/interglacial cycles and might be considered to be 'robust' in terms of possible use in longer time-scale geophysical or whole basin modelling studies for semiarid Great Basin conditions (Fig. 3). It compares well with cruder previous estimates from fan volumes in Dixie Valley, central Nevada (Leeder, 1991), but sheds no light on time variations of sediment delivery at the scale of individual glacial and interglacial cycles.

Despite the crudity of the analysis it can be seen that the value for Holocene sediment supply to Leidy Creek fan is significantly higher ($> \times 4$) than the longer term rate from Milner Creek. We cautiously infer that these differences in mean rates of supply between geologically and climatically comparable catchments are due to significant unsteadiness over the contrasting time integrals involved. Figure 4 attempts to chart the changing relative magnitudes of sediment production and discharge with time in an area such as the Great Basin over the late Pleistocene to Holocene interval. Superimposed on the broad trends indicated in Fig. 4 will be shorter period cycles in the relative magnitude of sediment and water

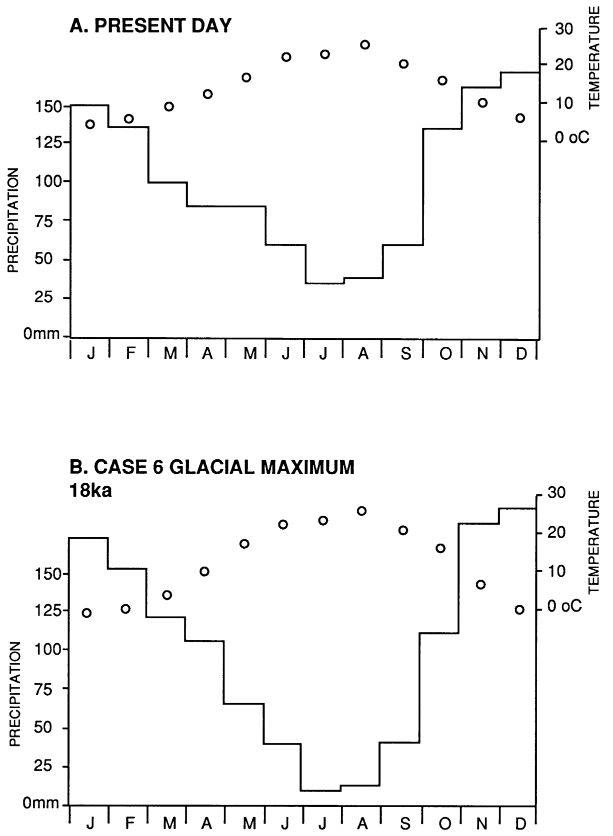

Fig. 5. Climatic data (from Prentice *et al.*, 1992) used in our CSEP experiments. Present-day monthly climatic data (Fig. 5A) for the Lake Ioannina area of northern Greece and for the same area for the Case 6 glacial maximum (18 ka) data (Fig. 5B, see also Table 1).

supply such as those documented from the southern High Plains by Toomey *et al.* (1993), Blum (1993) and Laird *et al.* (1996)

MODELLING MEDITERRANEAN SEDIMENT SUPPLY AND CHANGING CLIMATE

Around much of the northern Mediterranean there is pollen evidence for periodic major changes in later Quaternary vegetation at eccentricity and, to a lesser extent, precessional time-scales (Tzedakis, 1993). Glacial maxima were characterized by widespread development of treeless steppe and the interglacials by Mediterranean forest (e.g. Suc, 1984; Tzedakis, 1993). The direct evidence of the glacial vegetation indicates cooler climatic conditions with some additional evidence from the presence of chenopods and other central Asian floras for 'aridity' (Smit & Wijmstra, 1970; Wijmstra *et al.*, 1990). Climate and water balance models (Prentice *et al.*, 1992; our Fig. 5) for the Ioannina area, together with more controversial evidence for higher lake levels (see discussion of Tzedakis, 1994), suggest cooler temperatures with similar yearly rainfall to the present day for glacial maximum times, but with an increase in winter runoff. In order to illustrate the possible effects of changing water balance upon erosion rates and sediment supply we have modelled the modern climate and various possible glacial maximum (18 ka) climatic scenario from Prentice *et al.* (1992) in CSEP computational experiments (Figs 5 and 6; Table 1).

Table 2. CSEP modelling results for northern Mediterranean late Pleistocene glacial maximum and Holocene (Today) interglacial climate scenarios. The base case climatic details are outlined in Table 1 and graphically expressed in Fig. 5. The other climatic scenarios are comparative to Today: Runs 1–3 have only Temperature changed; Run 1 (cold winter) – 6 °C cooler December–March; 3 °C cooler April, November; Run 2 (cold year-round) – 6 °C cooler all months; Run 3 (cold summer) – 6 °C cooler June–September; 3 °C cooler May, October. Runs 4–6 have both temperature and precipitation changed; Run 4 (cold wet winter) – as case 1 but 20 mm per month wetter November–April; Run 5 (cold wet winter, cool dry summer) – as case 1 but 20 mm per month wetter November–April; 20 mm drier May–October. Run 5A (cold dry winter, dry summer) is a new case set up by us to test the cold/arid scenario, it is as case 5 but 20 mm drier November–April. Data of base runs for Today and 18 ka are given in Table 1.

Climate	1	2	3	4	5	5 A	6	Today
CSEP	5.7	0.02	0.6	10.8	13.1	7.0	15.6	12.4

The graphs of Fig. 6 show the values of output once

Table 1. Climate data (see also Fig. 5) used for base case CSEP modelling runs of northern Mediterranean soil erosion. The temperature and precipitation for base case 'Hol now' is that given for modern Lake Ioannina by Prentice *et al.* (1992) with our own estimate of potential evapotranspiration taken from a GIS cell appropriate to the region around Iannina. Base case Run 6 is the cool-wet winter/cool-dry summer scenario for glacial maximum times at Ioannina.

	J	F	M	A	M	J	J	A	S	O	N	D	μ
Hol now													
T (°C)	5	6	9.5	13	17	22	22.5	25	20	15.6	10	6.9	14.4
ppt (mm)	150	130	100	85	85	60	29	33	61	130	160	170	1193
R6 18 ka													
T (°C)	−1	0	3.5	10	17	22	22.5	25	20	15.6	7	0.9	11.9
ppt (mm)	170	150	120	105	65	40	9	13	41	110	180	190	1193

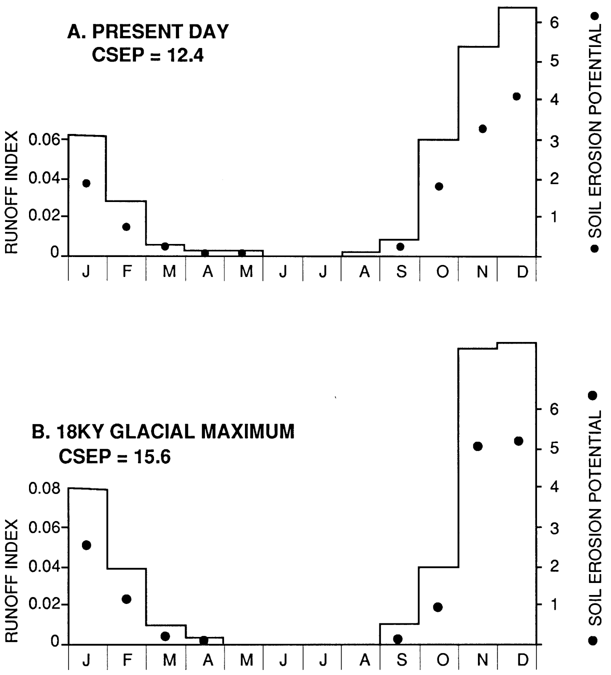

Fig. 6. Results of our CSEP experiments for present-day and glacial maximum Case 6 (cold wet winter, cool dry summer) scenarios (see Fig. 5, Tables 1 and 2). In the case of the current climate, vegetation equilibrium occurs after 299 years; for the 18 ka data after 319 years. The vegetation cover (not shown here) of each month under the 18 ka climate is lower than that of today. Total runoff was higher at 18 ka than today, with high winter runoff a major feature. In terms of monthly potential erosion levels there is a major difference between the two times, with higher levels of potential erosion in the cool wet winters of 18 ka. Overall the total annual erosion at 18 ka is higher, with a CSEP index of 15.6, compared with today's value of 12.4.

equilibrium has been reached in two of these cases. The vegetation cover of each month under the 18 ka climate is lower than that of today. Total runoff was higher at 18 ka than today, with increased winter runoff a major feature. In terms of monthly erosion levels there is a major difference in the distribution of erosion between the two times, with higher levels in the cool wet winters of the glacial maximum. Overall the annual erosion at 18 ka is higher, with a CSEP index of 15.6, compared with today's value of 12.4. Other CSEP runs (Table 1) using alternative climate cases from Prentice *et al.* (1992) (including our own new 5A, an arid cold winter/cool summer scenario) always yield lower CSEP indices than today's, sometimes very much lower. We conclude from our CSEP modelling that Mediterranean winter wet steppes were highly erodeable. This finds indirect support in the widespread pre-Holocene deposition (although this is very poorly dated) evident on many alluvial fans in the northern Mediterranean area (see Harvey, 1990, 1992; Leeder *et al.*, 1991; Nemec & Postma, 1993). Direct confirmation of our modelling must await rigorous late Pleistocene to Holocene sediment budget studies in the northern Mediterranean area. Climate change since 14 ka slowly re-established the Mediterranean woodland ecotype (Rossignol-Strick & Planchais, 1989), apparently stabilizing many alluvial fans and causing stream incision. Human forest clearance (and new *Pinus*-dominated growth) from Bronze Age times has caused sediment supply to increase once more in many areas (see papers in Bottema *et al.*, 1990; Lewin *et al.*, 1995), though again there is little accurate quantitative data other than that in Collier *et al.*, 1995). Some general trends predicted for sediment production and discharge in the late Pleistocene and Holocene of the northern Mediterranean are sketched in Fig. 7.

UNSTEADY SEDIMENT SUPPLY AND BASIN ARCHITECTURE

Continental sedimentary basins such as rifts and foreland basins are frequently traversed by axial rivers. The axial river receives the cumulative water and sediment discharges that their tributary catchments provide. They are highly sensitive to variations in the relative amounts of water and sediment supplied by transverse catchment hillslopes (Bull, 1991; Blum, 1993). Yet computational architectural models for fluvial basin fills (Mackey & Bridge, 1995) assume an equilibrium between subsidence and sediment supplied (the false-bottomed flume analogue of Leeder *et al.*, 1996) and do not have the freedom to simulate channel aggradation or degradation in response to climatically induced changes in rates of sediment and water supply. The importance of these variables in controlling channel incision or aggradation is highlighted by Bull (1991) and Blum (1993). Plentiful supply of sediment from tributaries causes lateral fan growth and gives a 'choked' axial system that responds by frequent avulsions and aggradation. Such scenarios accompanied deglaciation in temperate and high latitudes during Quaternary times and we also infer they have characterized periods of changeover from tree-bearing to grass/scrub/steppe-bearing climates in Mediterranean and semiarid climates. If increased water discharge from tributaries to axial river is accompanied by reduced sediment input the result is likely to be incision and terrace formation. With sediment source areas stabilized under tree cover, depositional landforms in the basin must react. Fans develop widespread soil horizons surrounding incised channels whilst axial rivers adjust their planform and floodplains to changed sediment and water discharges.

Although we have stressed the role of major glacial to interglacial climatic changes in altering the balance of sediment and water discharges in rivers we stress that channels are sensitive to shorter term climatic fluctuations. The cases of the San Pedro, Paria and Gila rivers in the south-western USA (Burkham, 1972; Graf *et al.*, 1991; Hereford, 1993; Huckleberry, 1994) are instructive. Here the coincidence of the onset of channel degradation and widening with the onset of large winter floods above the base discharge suggests that seasonal distribution of floods controls the channel aggradation–degradation process. Winter floods due to frontal rains, although smaller

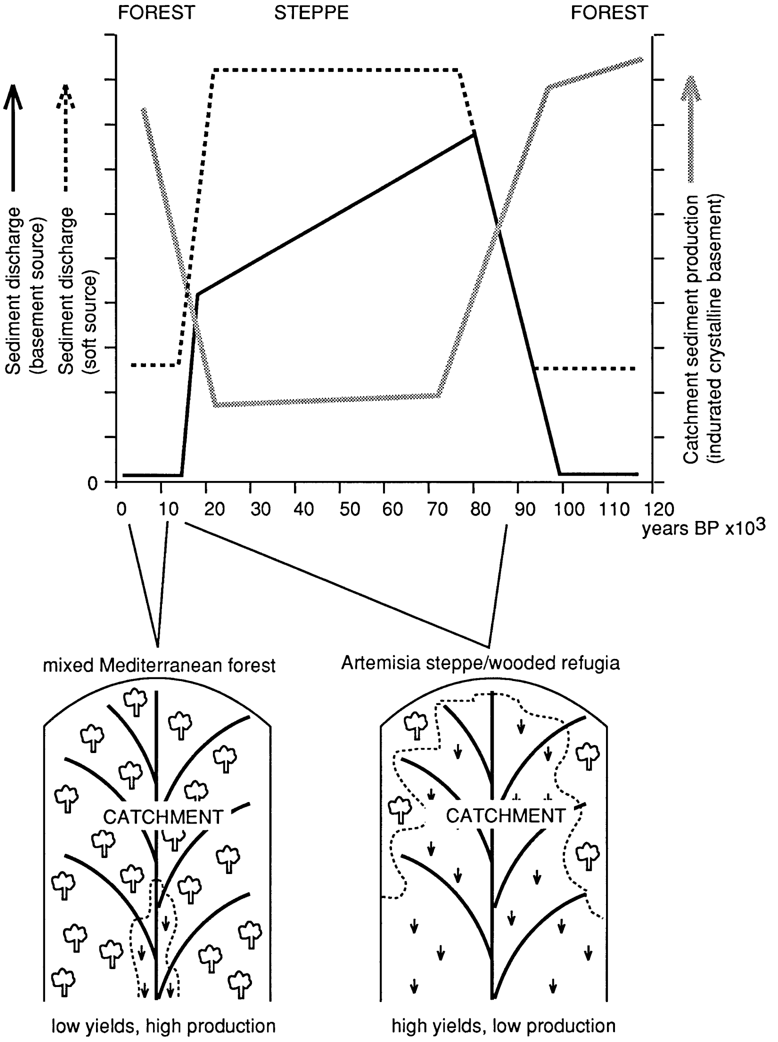

Fig. 7. Cartoon graph to show general trends in vegetation, sediment production (i.e. the rate of *in situ* production of soil from hard bedrock for weathering-limited transport conditions) and sediment discharge (for both weathering- and transport-limited conditions) across an eccentricity time band for Mediterranean climates. The graph is indicative only and unscaled, ignoring the changes that have undoubtedly occurred at precessional and tilt timeband frequencies. The effect of human alteration to the natural vegetation is not shown.

and less frequent than summer and fall floods, carry very little sediment and have a greater ability to erode the channel than do summer and fall floods due to storms. These latter may also be insufficient to increase the main channel's discharge so that accumulation of the introduced sediment results (Blum, 1993)

Turning briefly to marine and lake environments within sedimentary basins we return to the sediment

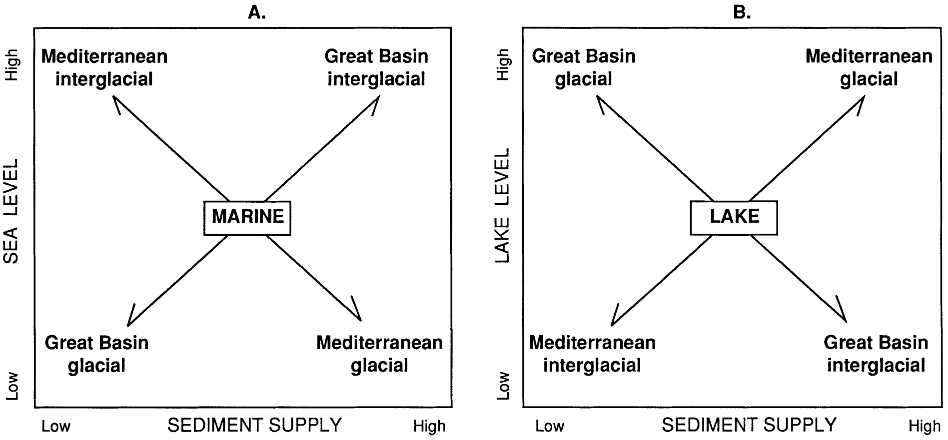

Fig. 8. Relative rates of sediment supply in relation to sea (A) and lake level (B) for Mediterranean and Great Basin Quaternary climatic regimes. For the marine scenario the Great Basin case is indicative and generalized, in the sense that much of the drainage here is internal – the response of the Colorado catchment and delta to climate change would be a direct and interesting test of our thesis.

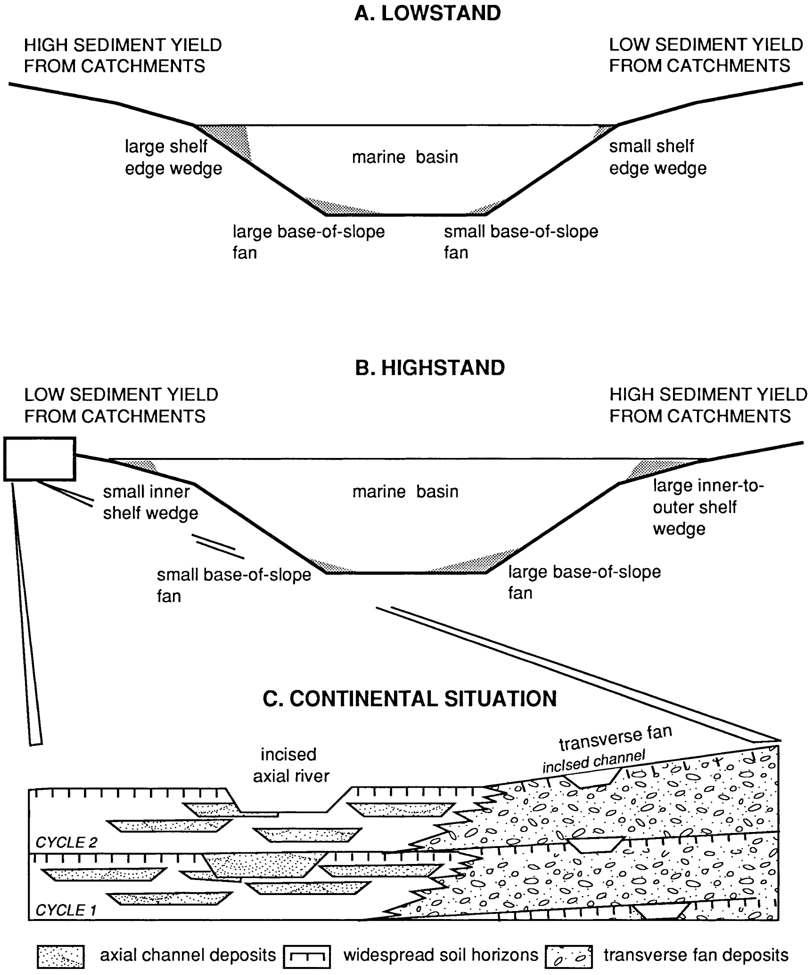

Fig. 9. Cartoons to illustrate effects of variations in sediment supply to the development of marine coarse-grained clastic wedges during lowstand (A) and highstand (B) conditions. The inset of (C) tries to show the development of fluviatile cycles in relation to climate change (in the spirit of Blum, 1993). These may occur independently of sea or lake level changes. Incision, fan retreat and soil formation are shown occurring during periods of low sediment supply from catchments to fans and axial rivers. Aggradation and fan growth (progradation) occur during periods of high sediment yield.

supply scenarios sketched out previously and summarized in Figs 8 and 9.

For catchments under Great Basin-type climates feeding marine environments we have seen that low sediment discharges occurred during full-glacial climate and hence at times of sea-level lowstand. Here the production of any incised valleys due to the gradient changes accompanying sea-level fall at the shelf–coastal break will be accentuated by lack of sediment availability. Although lowstand conditions enable shelf bypass and shelf erosion to occur, the lack of sediment availability from the hinterlands will limit the development of lowstand turbidite fans (Fig. 9). For lake environments the situation is different, with cool, wetter glacial maxima and lowered sediment yields coinciding with high lake levels due to a combination of increased runoff and/or decreased evaporation. We thus expect the development of upstream fluvial incision to coincide with the production of highstand deltas whose lack of sediment supply will cause low rates of highstand lake-margin delta progradation.

In Mediterranean environments, catchments are postulated to feed more sediment and water to marine and lake environments during glacial climates. Marine lowstands are thus likely to have coincided with aggradational conditions in river basins away from the influence of the shelf–coastal break. The high sediment supply will cause rapid lowstand progradation and the development of prominent submarine fans (Fig. 9). During highstands sediment supply is much reduced and river incision is likely to occur. Highstand deltas will migrate slowly seawards due to low sediment supply. For lakes, increased winter runoff during glacial times led to high lake levels at the same time as enhanced sediment supply.

CONCLUSIONS

We have briefly outlined major controls on sediment production rates, and have presented the results of CSEP experiments which indicate enhanced water and sediment supply from Mediterranean catchments during full-glacial times. The Mediterranean results are compared and contrasted with evidence for changing climate, vegetation and erosion for the Great Basin, western USA. Here, glacial times were characterized by reduced sediment supply due chiefly to altitudinal descent of arboreal vegetation, with evidence from lake levels indicating higher runoff and/or lower losses by evaporation. We explore the consequences of phase differences in sediment supply, sea and lake levels for the stratigraphy of sedimentary basins. Highstands and lowstands of sea or lake may be accompanied by greater or lesser sediment and water supply, as determined by the nature of the regional climate and the direction of the climatic change. Thus marine lowstands are not necessarily periods of great transfer of coarse clastic sediments to shelf wedges and deep water basinal fan environments.

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APPENDIX 1

CSEP

The Cumulative Seasonal Erosion Potential (CSEP) model was developed by Kirkby & Cox (1995) from a modified version of the Cumulative Erosion Potential model (CEP) of De Ploey *et al.* (1991). Full details of the CSEP are given in Kirkby & Cox (1995) and the outline given here is therefore brief, designed to acquaint basin researchers with the basics of the approach. The CEP was primarily a climatic index of the erosive potential of annual rainfall and the way in which the rainfall was distributed. The CSEP extended the CEP allowing seasonality to be incorporated and included a soil–vegetation component based on the earlier seasonal erosion model of Kirkby & Neale (1987). Figure 10 indicates the logical flow of the CSEP model.

The model consists of a set of state variables developed at the global scale and which produce good erosion potential forecasts. Where data are available these state variables can be locally tuned to produce a more accurate picture. Input to the model is in the form of climate data at a resolution of 0.5° × 0.5° (≈ 50 km × 50 km) (Leeman & Cramer, 1991) and consists of mean monthly temperature, precipitation and cloud cover. Data on number of rain days are also valuable where available. Potential evapotranspiration is calculated from the input climatic data using the Priestley & Taylor (1972) equation.

Ecosystem

Using the monthly climate figures, and daily rainfall distributions fitted to an exponential form, vegetation and soil cover is 'grown' to equilibrium at each point on the globe. A vegetation growth model begins by calculating the climatically supportable gross primary productivity (GPP) at a point. This is calculated as being directly proportional to actual evaporation, established from Potential Evapotranspiration (PET) values based on the ratios of rainfall to PET as well as the magnitude of PET. Having established GPP, losses due to plant respiration and leaf fall are established. Leaf fall is simulated in a two-stage process. Firstly, where GPP is less than the respiration rate an accelerated leaf fall rate is initiated, analogous to a deciduous response, as the plant reacts to bring itself back to a positive productivity level. A positive value is re-established within about two model months. Second a natural death rate is calculated and the combined leaf fall from these two processes is added to the soil organic biomass with the rate of decomposition of this biomass being treated as an exponential functional of temperature:

$$\beta = \beta_0 \exp(\gamma T) \qquad (1)$$

where β is the rate of decomposition at temperature T (°C) and β_0 is the rate at 0 °C. Having established GPP and plant losses the net primary productivity (NPP) is calculated following standard International Biological Programme methodologies (Newbould, 1967; Milner & Hughes, 1968) which underlie the entire vegetation growth model.

The vegetation and soil are allowed to develop until vegetation equilibrium is achieved. Equilibrium is presently defined as existing when the monthly levels of vegetation and soil are replicated year on year. It is for this equilibrium condition that the erosion potential values are calculated, although the model may also be used in a transient mode.

Erosion

Overland flow generation is controlled by a soil water storage threshold. This threshold is controlled by the equilibrium vegetation–soil complex in four ways:

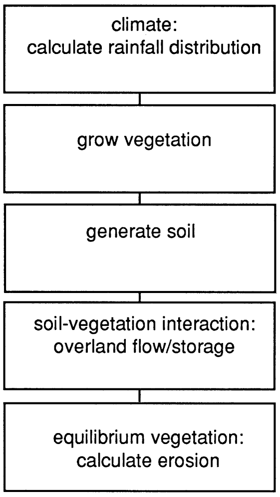

Fig. 10. Flow diagram for the CSEP model.

1 The soil organic matter acts as a dynamic store of soil water.
2 Above ground biomass intercepts and evaporates raindrops from leaf surfaces modifying ground and local water balances.
3 A large, but less dynamic, soil water store is provided by the degree of mineral soil present.
4 By reducing raindrop impact on the soil, the vegetation cover also prevents soil crusting which further modifies the threshold value.

Until the soil storage threshold has been reached (based on the interaction between the above ground input and the subsurface store drainage) overland flow will not occur. Once it does occur it is assumed that a proportion of the excess generates overland flow, and the resulting discharge will accumulate linearly downslope. The sediment yield resulting from this discharge is modelled as a power law with exponent 2:

$$S = q^2\Lambda = k[(r-h)a]^2\Lambda \qquad (2)$$

where: S = sediment transport, q = water discharge, Λ = hillslope gradient, k = erodibility coefficient, r = single rainfall event, h = soil moisture storage threshold and a = area drained per unit flow width. Equation (2) is combined with a standard mass balance equation.

The CSEP is written as the nonspatial part of Eq. 2:

$$\mathrm{CSEP} = \Sigma\,(r-h)^2 \qquad (3)$$

where the summation is over the distribution of daily rainfalls for each month. With N_0 and r_0 as empirical parameters of the rainfall distribution for a given month and R as the total monthly precipitation, the annual CSEP is obtained by summing over each month of the year:

$$\mathrm{CSEP} = 2N_0 r_0^2 \exp(-h/r_0) = 2r_0 R \exp(-h/r_0). \qquad (4)$$

A full derivation of eqn 4 is given in Kirkby & Cox (1995). The value of the CSEP obtained is the relative erosion potential based on the integrated effects of climate and the developing vegetation–soil system at the centre of the grid cell.