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Bed load as a component of sediment yield from a semiarid watershed of the northern Negev

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Abstract The installation of a fully automatic sediment monitoring station in an ephemeral channel allows the bed load and suspended sediment yields of a dryland stream to be assessed independently using measurements of bed load discharge and suspended sediment concentration obtained during flash floods. The suspended sediment yield of 433 t km^{-2} $year^{-1}$ is relatively high, even by global standards. The bed load yield (39 t km^{-2} $year^{-1}$) is also high but it represents, nevertheless, only 8% of the total sediment yield of 472 t km^{-2} $year^{-1}$. The balance between the bed load and suspended load reflects the specific environmental characteristics of the drainage basin. In particular, given that the floods are generated almost entirely by overland flow, the high suspended sediment yield indicates a substantial wash load that results from the plentiful supply of fine material on the sparsely vegetated slopes of the water catchment.

INTRODUCTION

Although sediment yield is defined as the total sediment load discharged from a watershed per unit time and area, the bed load component is usually ignored and sediment yield is equated with the outflow of suspended sediment. The exclusion of bed load from sediment yield studies reflects the huge time and effort required for direct measurement (Klingeman & Emmett, 1982) which, in part, can be attributed to the complications caused by the great spatial and temporal variability of bed load transport (Hubbell, 1987). The paucity of bed load yield measurements also reflects the historical development of stream-gauging techniques in humid-temperate environments such as the UK, where sediment yields are relatively low and, with the exception of mountainous

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and disturbed catchments, bed load constitutes a relatively small proportion of the total sediment load (Newson, 1981).

The relative importance of each component of catchment sediment yield depends, however, on the environmental setting, the nature and distribution of sediment sources, and the transport paths and processes by which sediment is delivered to the stream. For example, it is commonly believed that bed load is more significant in dryland streams than in those draining humid environments (Graf, 1988). However, because the difficulties of bed load measurement are exacerbated by the ephemeral nature of the flow regime, our understanding of the bed load dynamics of dryland rivers lags behind that of suspended sediment and, until recently, there were no measurements of bed load transport rates during flood conditions. Instead, estimates of bed load activity have largely been inferred from geomorphic reconstructions of recent floods using combinations of fan deposits, synthetic hydrographs, estimates of scour and fill, particle tracing studies and predictive formulae (Leopold *et al.*, 1966; Schick & Lekach, 1981, 1987, 1993; Hassan, 1990).

Automatic sampling can overcome many of the problems of undertaking bed load transport measurements in the ephemeral discharge regime. The installation of fully automatic sediment monitoring stations on Nahal Yatir and Nahal Eshtemoa, two ephemeral channels in the northern Negev Desert, Israel, has provided detailed insights into the sediment transport dynamics of dryland streams (Laronne & Reid, 1993; Laronne *et al.*, 1994; Reid & Laronne, 1995). In this paper, we use the 4 years of record currently available for Nahal Eshtemoa to derive the first estimates of catchment bed load yield from bed load transport rates measured during flash floods. These are compared with estimates of suspended sediment yield and placed in the global context of previously published results.

FIELD SITES AND METHODS

Nahal Eshtemoa is a fifth order gravel-bed ephemeral stream draining a basin of 119 km^2 on the southwestern flanks of the Hebron Hills in the northern Negev Desert, Israel. The bedrock of the drainage basin is late Cretaceous limestone, although there is a variable covering of Holocene loess that can be up to several metres thick. The loess mantle is deepest and most extensive over the gentler, lower slopes of the catchment. The loess thins upstream and rocky outcrops become more extensive. Here, the stream is incised into the limestone. Although the sparse vegetation of seasonal herbs and grasses is grazed by sheep and goats belonging to the local Bedouin who also grow wheat on the lower slopes, the drainage basin is reasonably undisturbed. The mean annual rainfall of 220-350 mm is seasonal, falling mainly between November and March.

Field measurements

Bed load transport rates were obtained automatically at one minute intervals using five recording samplers aligned across the full width of the channel. The technique is identical to that used in an earlier study on the adjacent Nahal Yatir and is fully described by Laronne *et al.* (1992). In addition to the bed load measurements, suspended sediment concentrations were derived from samples obtained with a programmable pump sampler. The sampler inlet is located in the centre of the channel, 15 cm above the bed. Because the intake is fixed, the samples do not represent vertically and laterally integrated samples. However, the flow is always highly turbulent, so decreasing the vertical gradient of suspended sediment concentration. The samples represent a variety of flow conditions such as the initial flood bore and the rising and falling limbs of the flood waves.

Flow depth and water surface slope were both measured at one minute intervals using water level sensors. High flow velocities and rapid variations in stage precluded the use of current meters to establish a stage-discharge relationship. However, correction of surface velocities that were measured over a range of flows up to bankfull provides a credible rating curve ($r = 0.99$) which compares very well with Hey's (1979) flow resistance equation. The same difficulties of flow measurement mean that calculation of local shear stress has not been possible and so estimates of channel average shear stress are derived as

$$\tau = \rho g R S \tag{1}$$

where ρ is the density of the flow, g is the acceleration due to gravity, R is the hydraulic radius and S is the water-surface slope.

CATCHMENT HYDROLOGICAL RESPONSE

Since the inception of the study on Nahal Eshtemoa in January 1992, 19 flow events have been recorded. The annual average of 5.1 floods is consistent with an analysis of long-term hydrometeorlogical records for this region of the Negev by the Israel Hydrological Survey (Cohen & Ben-Zvi, 1979).

Several characteristics of the flood regime are illustrated by the stage hydrographs for the five events monitored during 1990-1991 on Nahal Yatir (Fig. 1(a)). Due to low infiltration capacity of the sparsely vegetated loess and reg-covered hillslopes, floods are generated by overland flow from quite moderate rainfall intensities. Consequently, the flood hydrographs are characterized by very steep rising limbs and many events (e.g. 8 January) commence as a flood bore travelling over a dry channel bed (Reid *et al.*, 1994). Flow events are generally multi-peaked, reflecting either the staggered contribution of tributary flow or variations in rainfall intensity. Recession limbs are also steep and flow duration ranges between 2 and 24 h.

Similar hydrographs are recorded for Nahal Eshtemoa. However, because of its larger catchment area, the magnitude, duration and general nature of the floods is more variable than those recorded in the Yatir. The longer record also demonstrates the high annual variability of runoff volumes characteristic of ephemeral flow regimes. Figure 1(b) shows the temporal distribution of flow events and flow volume over the study period. The number of flood events per season varies from two to six, annual runoff from 900 to 25 865 $m^3\ km^{-2}$ while the largest flood comprises 50% of the total 4 year runoff volume. The variability in annual flood discharge has obvious implications for the representativeness of the sediment yield estimates derived below.

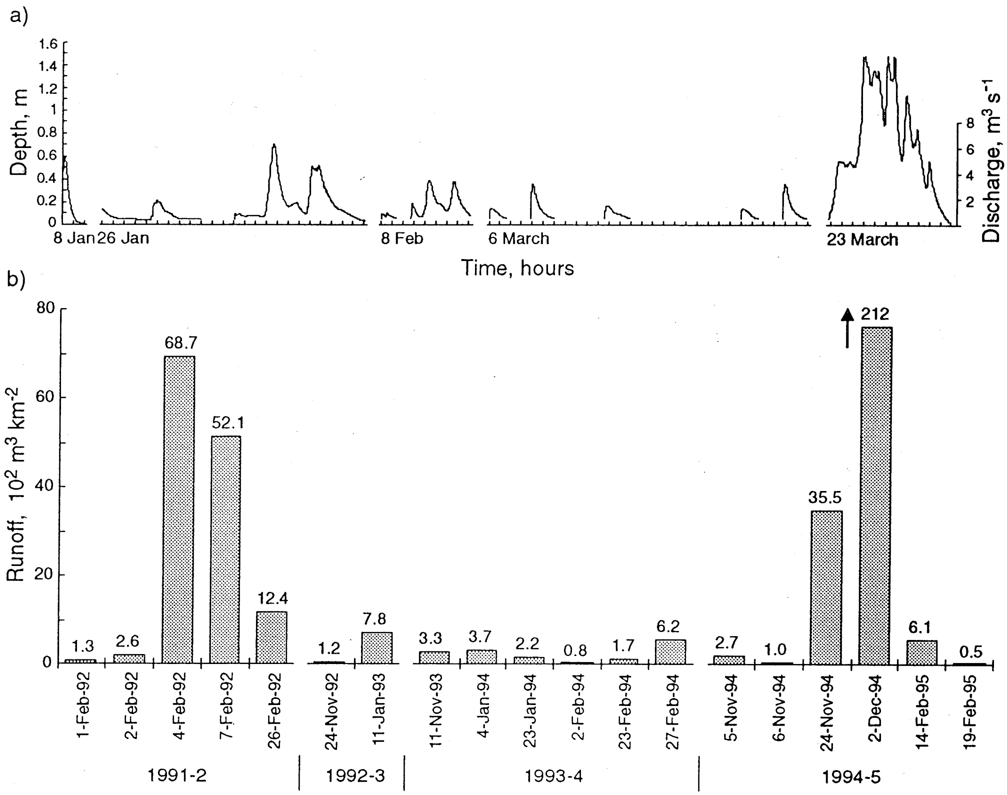

Fig. 1 Characteristics of the ephemeral flow regime as illustrated by the stage hydrographs of the five floods recorded during the 1990-1991 flood season in Nahal Yatir (a) and the temporal variation in flood events and flow volumes recorded during the study period at Nahal Eshtemoa (b). In (a), flow depths less than 0.05 m are not shown and discharges cannot be calculated reliably for overbank flows (>0.9 m).

CATCHMENT SEDIMENT YIELDS

Prediction of sediment yield components

Bed load and suspended sediment yields were derived by rating channel average bed load discharge (i_b) against channel average shear stress and suspended sediment concentrations (C) against discharge (Q) and applying the rating curve estimates of transport to the observed flow record. The bed load and suspended sediment rating curves are shown in Fig. 2(a)-(b). Unlike suspended sediment transport, bed load transport rates increase as a function of shear stress in excess of a threshold required for bed material entrainment (τ_c). The bed load record at Nahal Eshtemoa indicates that $\tau_c \approx 7$ N m^{-2}. Consequently, the rating curve in Fig. 2(a) is derived by ordinary least squares regression of bed load on excess shear stress ($\tau - 7$). Bed load transport rates are high, reaching 6.7 kg m^{-1} s^{-1} at discharges of about 9 m^3 s^{-1}, and the relationship is unusually well defined. These characteristics have been attributed to high excess shear

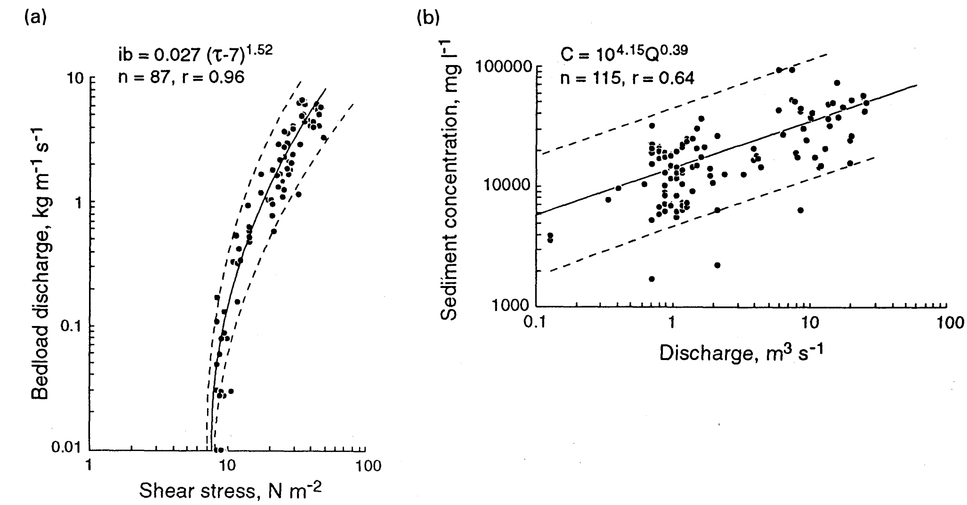

Fig. 2 Bed load (a) and suspended load (b) rating curves for Nahal Eshtemoa. The pecked lines represent the 95% confidence intervals of the regression lines. In both instances, the relations have been adjusted for the statistical bias introduced by the log-log transformation of the variables (Ferguson, 1986). *n* is the number of paired observations, *r* is the correlation coefficient.

stresses, the abundant supply of readily transportable sediment and to the absence of both a well-developed surface armour and other bed structures which are known to exert such strong controls on bed load transport in perennial systems (Laronne & Reid, 1993; Reid & Laronne, 1995).

Suspended sediment concentrations in Nahal Eshtemoa varied from 1688 to 92 535 mg l^{-1} with a mean value of 21 300 mg l^{-1}. These compare favourably with data from other semiarid catchments and, as might be expected, are higher than the concentrations of up to 1% measured in the Mediterranean coastal area of Israel (Negev, 1969) and much lower than the concentrations of 10-60% measured on Mount Sdom, a highly erodible salt diapir near the Dead Sea (Gerson, 1977). The relationship between suspended sediment concentration and stream discharge is shown in Fig. 2(b). Notwithstanding previous assertions about the simple response of dryland catchments (Reid & Frostick, 1987), the high degree of scatter is not unexpected given the widely documented complexities of suspended sediment dynamics. Of particular importance here may be spatial and temporal variations in sediment supply given the variable distribution of loess and runoff within the Eshtemoa basin. Suspended sediment concentrations are likely to be increased with tributary flows from loess rich sub-catchments and diluted by tributary flows from catchments with less extensive loess cover. However, the high coefficient and relatively low exponent of the least squares regression is characteristic of suspended sediment concentrations in semi-arid areas where the high concentrations are less sensitive to increases in discharge than is the case for streams draining humid-temperate regions (Frostick *et al.*, 1983).

Several potential sources of error arise in the estimation of sediment yields from sediment rating curves (Walling, 1977). Extrapolation of the stage-discharge curve to overbank flows is problematic as is the validity of the estimate of channel shear stress given by ρgRS as momentum is transferred between the high velocity channel flow and the lower velocity overbank flow. Furthermore, it is difficult to assess the importance of medium- and long-term temporal fluctuations in transport rate that may occur independently of the flow (Schick & Lekach, 1983). All these factors have to be taken into consideration when assessing the results.

Average annual sediment yield

Average sediment yields for Nahal Eshtemoa during the study period are shown in Table 1. For comparison, the sediment yields of Nahal Yael, a small stream located in the hyperarid southern Negev, are also shown (Schick & Lekach, 1993). Although the suspended sediment yield of 433 t km^{-2} $year^{-1}$ is relatively high by global standards (Jansson, 1988), this is not unexpected, given the semi-arid environment of Nahal Eshtemoa and the value is consistent with estimates of sediment yield derived from small agricultural and forested hillsides in the same geographical area (Laronne, 1990). However, the suspended sediment yield of Nahal Eshtemoa exceeds that from 10 of the 11 basins from the Mediterranean zone of Israel that were considered by Inbar (1992) and which yield 16-310 t km^{-2} $year^{-1}$. Inbar notes that these Israeli basins lie along the curve of Langbein & Schumm (1958) that describes the relationship between sediment yield and effective precipitation. The higher yield of Nahal Eshtemoa, which has a lower mean annual precipitation, is compatible with the increase in suspended sediment with decreasing rainfall predicted by the Langbein-Schumm curve for the sub-humid-semiarid transition. However, there is some doubt about the applicability of the curve to the Negev region further down the rainfall gradient towards hyperarid environments. Yair & Enzel (1987) found that basins within the Negev's 200 mm isohyet did not show an expected decrease in sediment yield with decreasing rainfall, although Schick & Lekach (1993) report lower suspended sediment yields for the hyperarid Nahal Yael (Table 1).

A small, but significant fraction of the Eshtemoa's total sediment yield is composed of bed load (Table 1). The bed load contribution of 17 250 t represents 8.3% of the total sediment yield of the study period and a mean annual bed load yield of 39 t km^{-2} $year^{-1}$. This is comparable with the oft-quoted but largely unsubstantiated proportion of up to 10% of the suspended sediment yield (e.g. Jansson, 1988). The bed load contribution is, however, much lower than the estimate of 68% for Nahal Yael (Table 1). The much higher bed load yield of Nahal Yael is likely to be a reflection of a high sediment delivery ratio resulting from the small size of the basin (0.5 km^2) and the strong

Table 1 Average bed load, suspended load and total sediment yields for Nahal Eshtemoa. The sediment yields of Nahal Yael are also shown for comparison (Schick & Lekach, 1993). The estimates of bed load and suspended sediment yield for Nahal Eshtemoa have 95% confidence intervals of +18% and −15% and +19% and −23%, respectively.

Stream	Drainage area (km^2)	Rainfall (mm)	Sediment yield (t km^{-2} $year^{-1}$)		
			Suspended	Bed load	Total
Nahal Eshtemoa	119	220-350	433	39	472
Nahal Yael	0.5	31	55	114	169

coupling between the debris-rich slopes and the channel system, all of which are in marked contrast with the loess-covered, less rugged limestone hills of the larger Eshtemoa catchment.

It is interesting to compare the bed load yields of Nahal Eshtemoa to those of humid environments where sediment transport rates are much lower. Although data are sparse, studies in catchments of 0.25-13 km^2 in the mountainous area of mid-Wales in the UK suggest bed load yields of 3-26 t km^{-2} $year^{-1}$ for undisturbed grassland catchments and 5-119 t km^{-2} $year^{-1}$ for forested catchments (Newson, 1981). The higher bed load yields for the forested catchments are a result of the ditched drainage which has exposed erosion-prone scree and colluvium beneath the top-soil. Ratios of bed load and suspended load in lowland rivers of the U.K lie in the range 0.02-0.1:1, although the situation may be reversed in upland rivers where ratios of 4:1 have been suggested by Lewin *et al.* (1974).

Annual variability of component sediment yields

The preceding discussion has not addressed the question of the inter- and intra-annual variability of sediment yield. As noted above, there is a marked variability in flood frequency, magnitude and duration during the study period (Fig. 1(b)) which will affect the yearly amounts of sediment transported out of the basin. Figure 3 presents the variation in sediment load on a flood-by-flood and annual basis, and shows the proportions of bed load and suspended load. Significant inter- and intra-annual variability in sediment transport is evident. Half of the study period (1992/1993-1993/1994) accounts for less than 3% of the total sediment load, whilst 56% is transported by the flood of 2 December 1994 and 85% by the three largest floods. The relative contributions of bed load and suspended load also varies between events. Thirty-seven percent of these failed to reach the threshold for bed load transport and carried only suspended sediment. In contrast, a maximum bed load contribution of 13% was recorded for the floods of 26 February 1992 and 11 January 1993.

The extreme variability in the discharge regime of ephemeral streams makes the evaluation of sediment yields in semi-arid environments especially problematic, particularly with respect to their representativeness of longer term patterns (Mundorff, 1964; Walling & Kleo, 1979). For example, exclusion of the 2 December 1994 event would reduce the total sediment yield by more than half. Although this event was one of three overbank flows recorded during the study period, it was unusual in its duration, lasting nearly four days. The flow was maintained at or above three-quarters bankfull for approximately 27 h, a period which, in itself, exceeds the total flow duration of many of the other recorded floods.

CONCLUSIONS

Measurements of bed load discharge that were obtained during flash floods have enabled the first process-based estimate of bed load yield to be derived for an ephemeral stream. Over the duration of the study, the bed load contribution of 17 250 t represents a mean annual bed load yield of 39 t km^{-2} $year^{-1}$. Although bed load contributed up to 13% of

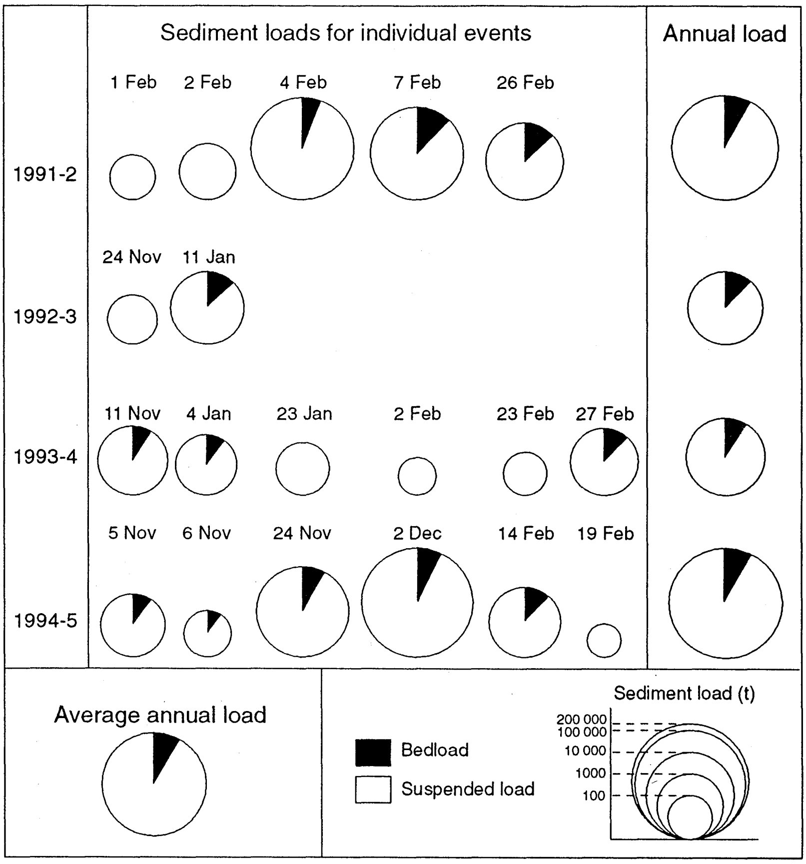

Fig. 3 Flood-by-flood and annual variation in total sediment loads showing the proportion of bed load and suspended load. Note the logarithmic scale.

the sediment load during individual events, on average it constitutes only 8% of the total sediment yield of 472 t km^{-2} year^{-1}. This balance of the two components of sediment yield reflects the particular characteristics of the drainage basin and its environmental setting. Bed load flux is high by global standards, but so is that of suspended sediment. The study also highlights the extreme inter- and intra-annual variability of sediment transport which make the evaluation of sediment yields for semi-arid areas especially problematic, particularly with regard to their representativeness of longer term patterns.

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