

## Suspended sediment transport in flash floods of the semiarid northern Negev, Israel

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**Abstract** Our aim is to provide insight into various suspended sediment transport phenomena of upland ephemeral streams in a semiarid environment. Information about suspended sediment concentration is derived with the help of a programmable pump sampler and the continuous record of a turbidity sensor. Suspended sediment concentrations are high; the mean during six years of measurements was  $34\,000\text{ mg l}^{-1}$  and regression of suspended sediment concentration on water discharge takes the form  $SSC = 10^{4.41} Q^{0.42}$ . During individual flash floods, the suspended sediment–water discharge relation may be hysteretic (clockwise or counterclockwise) and/or monotonic. In spite of complicated intra-event behaviour, there is a good, deterministic ( $R^2 > 0.9$ ) relation between total suspended sediment yield and flood volume.

**Key words** flash flood; hysteretic response; suspended sediment yield

### INTRODUCTION

It has been shown that rating curves often do not adequately characterize suspended sediment transport in streams (Walling, 1977). The nature and disposition of source areas of erodible material and erosion and transport processes are controlled by several factors, such as: the seasonal distribution of rainfall and variation in the duration of preceding dry seasons (Walling & Webb, 1987; Batalla, 1994); the intensity and distribution of rain within a catchment (Graf, 1988; Williams, 1989); the antecedent moisture of catchment soils and channel banks (Wolman, 1959); seasonal variations in vegetation cover (Sharma, 1996); changes in vegetation cover as a function of human activity (Rozin & Shick, 1996; Poesen & Hooke, 1997; Reid, 2002); differences in travel distance from different source areas and the lag between water and sediment waves (Williams, 1989; Reid *et al.*, 1997; Bull, 1997); and changes in sediment source areas during a single hydrological season (Negev, 1969; William, 1989; Thorne, 1982). The objectives of the present study are to promote further understanding of suspended sediment behaviour during individual hydrological events and to propose a lumped event-based method of calculating sediment yield in ephemeral streams in semiarid, upland Mediterranean environments.

## STUDY AREA

The Eshtemoa basin is located in the northern Negev Desert, its headwaters draining the Hebron Hills of southern Judea (Fig. 1). The catchment is underlain by late Cretaceous limestones, dolomites, cherts and marls. During the Holocene, loess blanketed much of the landscape, but presently, a residual deposit—often reworked—is confined mainly to valley bottoms. Typical Mediterranean terra rossa soils and rendzinas develop on hillslopes and interfluvies and rock outcrops are ubiquitous. These thin or non-existent soils contrast with the loess and sandy loessial soils of the narrow valley bottomland.

Annual rainfall ranges from 220 mm at the catchment outlet to 350 mm in its headwaters. Rainfall usually occurs between November and March, with a monthly maximum in January. This annual rainfall is set against a potential evaporation of about 2000 mm. All flood events in the Eshtemoa are rain fed and discrete; on average, they occupy about seven days per year. Vegetation is sparse and can be sclerophytic or xerophytic, though winter rains encourage grasses to germinate, providing a thin sward over some parts of the basin. There are small Bedouin encampments throughout the catchment. Bedouins cultivate areas where the soil permits; they often use ancient stone bunds that were originally built across first-order streams to collect runoff and prevent soil erosion; they also use the longitudinal stream terraces for growing winter

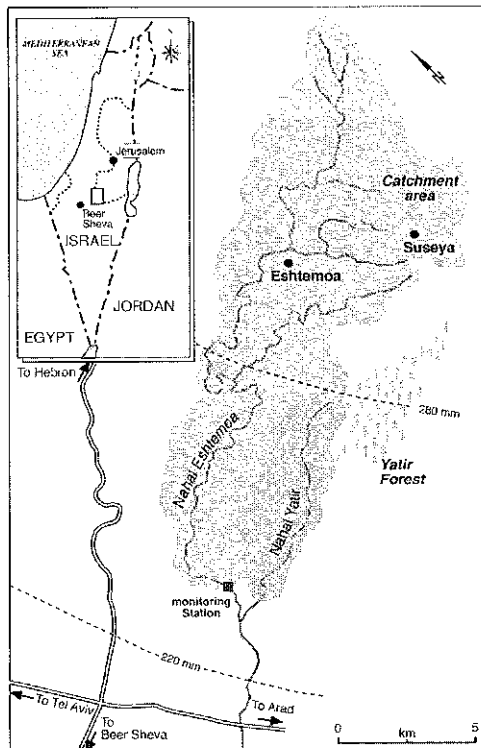


Fig 1. Location map of the Nahal Eshtemoa catchment. The pecked lines are isohyets of average annual rainfall.

wheat. The steeper hillslopes of the catchment are used for grazing, especially during winter and spring. As part of a landscape rehabilitation and soil conservation programme, the Israeli Land Development Authority has planted trees over an increasing fraction of the lower catchment—the part that lies within the 1948 Israeli border.

## MONITORING SITE AND METHODS

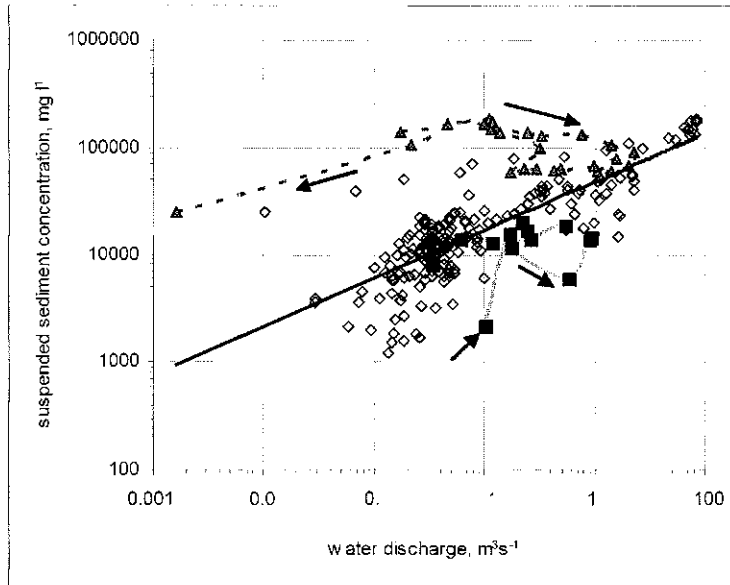
The monitoring station lies about halfway along a 250 m straight reach of the channel. The water catchment at the monitoring site is 112 km<sup>2</sup>; channel slope is 0.75%, channel width is 6.0 m and bankfull depth is 1.2 m.

Information about suspended sediment concentration has been derived in two ways. Water samples have been obtained using a programmed pump sampler containing 24 bottles. Sampling occurred at discrete intervals. The pump was programmed to sample in sympathy with the flashy character of floods in semi-desert regions (Reid *et al.*, 1997). To acquire a continuous record, we have used an *in situ* optical turbidimeter (Model 612 Single Beam Photometer with an AF10 Inline Sensor, Wedgewood Technology, California). Calibration was undertaken using local suspended material. Both the intake of the pump sampler and the sensing head of the turbidimeter lay close to the centre-line of the channel. Because they were fixed, the record does not integrate the flow vertically and laterally. However, occasional simultaneous manual sampling confirms that representation of the whole flow is good.

## RESULTS AND DISCUSSION

### Suspended sediment concentration vs discharge relation

A scattergraph of suspended sediment concentration vs water discharge in the Eshtemoa is presented in Fig. 2. Suspended sediment concentration varied from 1200 to 186 500 mg l<sup>-1</sup>, with a mean value of 34 000 mg l<sup>-1</sup>. The least-squares relation fitted to all the points in Fig. 2 is  $SSC = 10^{4.41} Q^{0.42}$ ,  $R^2 = 0.49$ ,  $\alpha = 0.05$ , where  $SSC$  is suspended sediment concentration [mg l<sup>-1</sup>] and  $Q$  is water discharge [m<sup>3</sup> s<sup>-1</sup>]. The relation has been adjusted for the statistical bias that is introduced by logarithmic transformation of the data. It is not unexpected that only 50% of the variance in suspended sediment concentration is “explained” by water discharge. In other words, it is not surprising that not only the hydraulic properties of the flow but also the supply of sediment in the river basin determine suspended sediment response. The triangular symbols in Fig. 2 relate to the event of 18 October 1998. This was the first flood of the season and resulted from a convective rain cell that moved up the basin from the monitoring station. Sediment concentration during this event was unusual, showing little dependence on discharge and a high dependence on supply that was governed by sub-catchment soil character, the concentration increasing with tributary inflows from loess-rich terrain and diluted by inflows from sub-catchments characterized more by regosols. The changes in sediment concentration with time, demonstrate that suspended sediment concentration is considerably higher in the flood bore than at similar discharge during flow recession. This flushing effect produces clockwise hysteresis in the relation between sediment concentration and water discharge.

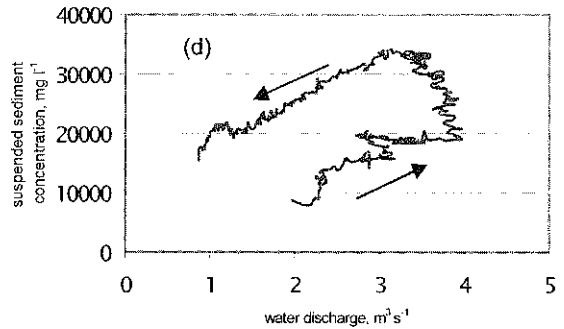
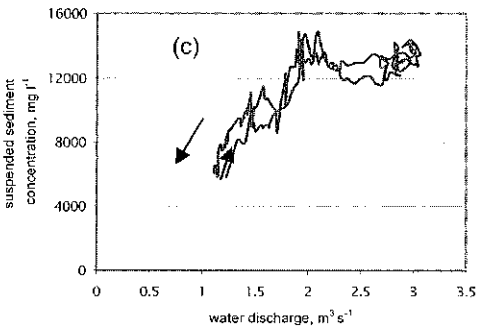
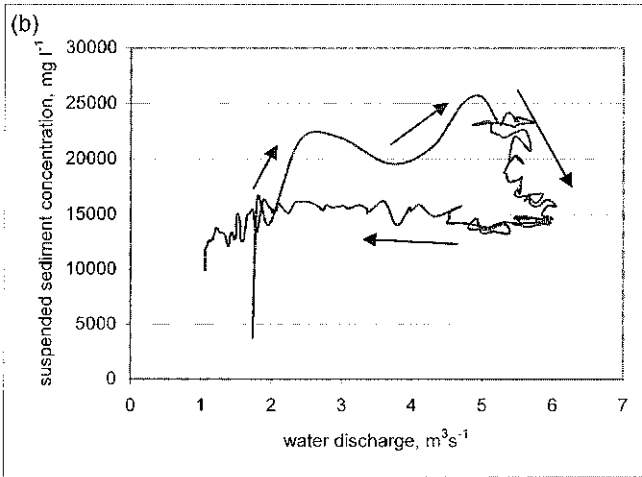
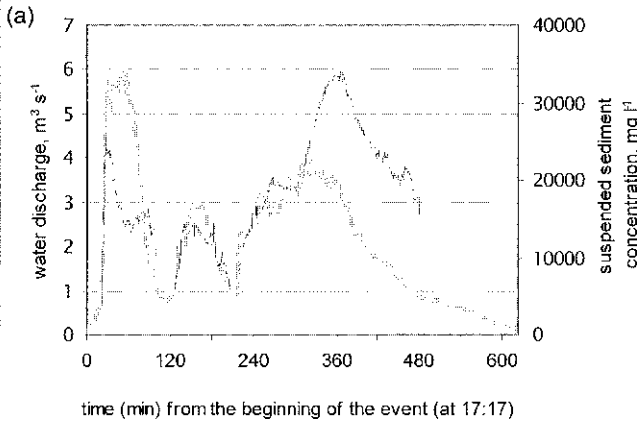


**Fig. 2** Suspended sediment concentration rated against discharge in the Nahal Eshtemoa. The straight black line is the least-squares relation fitted to all values presented in the graph. The filled triangles joined by a pecked line relate to the event of 18 October 1998, when suspended sediment concentration was highest in the flood bore and decreased during the rising stage of hydrograph. This enhances the clockwise hysteresis between rising and falling stage. The filled squares joined by a grey line relate to the event of 5 November 1994. Anticlockwise hysteresis between rising and falling limbs is evident in both of the two loops of this flood hydrograph.

The other pattern of hysteresis is counterclockwise, as seen, for example, in the behaviour of suspended sediment concentration during the event of 5 November 1994 (filled squares in Fig. 2). Both patterns add to the complex relation between sediment concentration and water discharge (Alexandrov *et al.*, 2003). Indeed, elsewhere in Israel, the suspended sediment concentration *vs* water discharge relation has been shown to be better defined by separation of the data into seasons and/or the rising and falling limbs of hydrographs (Negev, 1969).

### Intra-event changes in suspended sediment concentration

The variation in suspended sediment concentration cannot be explained always by invoking the flushing of sediments at the beginning of runoff and the dilution or exhaustion of sediment supply towards the end. Of importance appears to be the complex spatio-temporal interplay of the pattern of sediment supply—in part a function of the distribution of loess—and the pattern of rainfall-runoff, which reflects the peculiarities of a rainfall regime that involves, both discrete, wandering thunderstorms and ubiquitous frontal rainfalls. This can be illustrated by the unpredictable nature of suspended sediment behaviour during the event of 5 December 2001 (Fig. 3). Changes in suspended sediment concentration (black line) do not follow those of water discharge (grey line) for much of the flood. Also, the maximum values of suspended



**Fig. 3** (a) Hydrograph of water discharge (grey line) and continuous record of suspended sediment concentration (black line) for the event of 5 December 2001. (b) Suspended sediment concentration vs discharge for the first 120 min of the flood. There is clockwise hysteresis between rising and falling stage. (c) Suspended sediment concentration vs discharge for the second rise (120–220 min). Here there is a monotonic response. (d) Suspended sediment concentration vs discharge for the third rise (220–480 min). A wide counterclockwise hysteresis describes the relation.

sediment concentration do not occur during the first rise in the hydrograph (so eliminating the operation of a flushing effect), but occur during recession of the third and last rise in flow, probably reflecting a late contribution from a tributary catchment known to have many gullies in its loess-rich bottom-land. The behaviour of suspended sediment concentration during each of the three risings of the flood was different. So, during the first rise there were two major peaks in sediment concentration, but these were not matched by anything obvious in the hydrograph. Indeed, the second rise in the sedigraph was on the falling limb, possibly resulting from bank material falls or from the late input of a tributary, and the general response was clockwise hysteretic (Fig. 3(b)). Curiously, during the flow maximum there was dilution of the suspension. During the second rise, the relation between suspended sediment and discharge was monotonic (Fig. 3(c)) with two small deviations on the rising and falling stages. During the third rise, the lack of immediacy in sedigraph response has to reflect a temporary supply exhaustion which was then compensated by additions from an unidentified source that led to an increase in sediment concentration up to  $32\,000\text{ mg l}^{-1}$ , producing a counterclockwise response pattern (Fig. 3(d)).

### Suspended sediment yield

Suspended sediment yields for 20 events of different magnitude and frequency were calculated by interpolation, using the suspended sediment concentrations of individual samples, rather than a generalized rating curve. This provides a very good relation ( $R^2 > 0.9$ ) between event suspended sediment yield and event flood volume (Fig. 4). The comparative simplicity of the event-based relation encourages greater confidence in its use as a predictive tool for engineering purposes than can be gained from use of a rating curve that attempts to describe the scatter inherent in a set of individual samples (such as that of Fig. 2). So, if plans were laid to construct a dam on an ephemeral channel, the acquisition of a hydrometric database similar to that used to construct Fig. 4 would allow more accurate prediction of reservoir siltation rate than could be obtained using other methods.

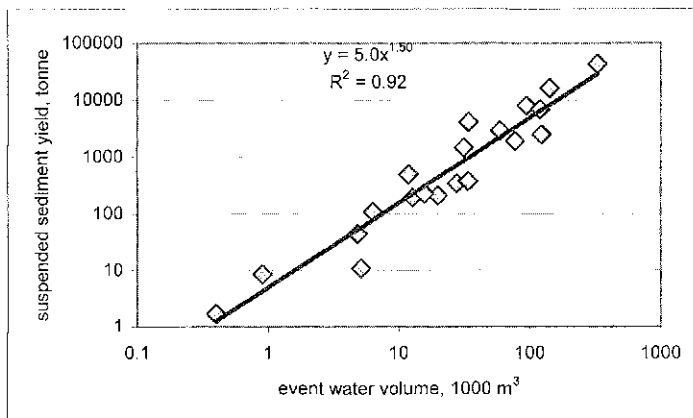


Fig. 4 Event suspended sediment yield vs event water volume.

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