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An investigation of source areas of sediment and sediment transport by overland flow along arid hillslopes

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ABSTRACT The paper presents a case study of sediment sources and sediment transport by overland flow along arid hillslopes. It is conducted at an experimental site which covers one half of a first order drainage basin extending on one side of the channel. The drained area is subdivided into 16 runoff and sediment plots, nine of which are equipped with automatic stage recorders and sediment samplers. Data obtained indicate that rain-showers are of short duration. Runoff and sediment generated at the upper part of slopes 60-70 m long usually fail to reach the slope base. Even at peak flow of high intensity rainstorms runoff velocities are unable to detach particles of the crusted topsoil. Sediment removed can be partially related to burrowing and digging activity of desert animals that provide disaggregated soil particles easy to remove by shallow low energy flows. The possible effects of the spatial and temporal variations in the biological activity on the sediment delivery from the slopes is discussed in detail.

Recherches sur les zones d'origine des sédiments et sur leur transport par écoulement en nappe à la surface du sol sur des versants de collines en zone aride

RESUME La communication traite des sources de sédiments et de leur transport par ruissellement, le long de versants arides. Le travail est effectué sur un site expérimental s'étendant sur la moitié d'un bassin versant du premier ordre. La superficie drainée est subdivisée en 16 parcelles. Neuf parcelles sont equipées d'appareil automatiques pour l'enregistrement du niveau d'eau et la collecte de sédiments en suspension. Les données obtenues indiquent que les averses qui provoquent le ruissellement sont de courte durée. Le ruissellement et les sédiments engendrés à la partie supérieure d'un versant ont très peu de chance d'atteindre la base de ces versants. Même lors d'averses intenses, les vitesses de ruissellement au débits de pointe sont incapables de provoquer l'érosion sur un sol encrouté. Les matériaux érodés et

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transportés semblent liés à l'activité d'animaux fouisseurs qui fournissent des aggrégats aisement transportés par des ruissellements a faible énergie. Les effets possibles des variations temporelles et spatiales de l'activité biologique sur l'érosion des versants édudiés sont analysés en détail.

INTRODUCTION

Studies dealing with effectiveness of climate in sediment removal from basins present contrasting data, leading to different conclusions (Langbein & Schumm, 1958; Fournier, 1960; Tabuteau, 1960; Corbel, 1964; Wilson, 1971). The problem was recently reviewed by Wolman & Gerson (1978) and by Walling and Kleo (1979), who conclude that "there is no clear evidence of the existence of higher sediment yields or increased variability in annual yields in arid than in more humid areas". However, on the basis of available data Walling & Kleo suggest that arid areas may differ from humid ones in terms of their sediment delivery ratio. Due to the assumed high frequency of localized intense convective rainstorms, runoff and sediment generated in one part of a large basin fail to reach the basin outlet due to infiltration losses in dry sandy channels, in braided channels or in alluvial fans. As such physiographic features are less developed in humid than in arid areas, the characteristic decrease in the sediment delivery ratio with increasing drainage area, observed in numerous studies (Piest *et al.*, 1975; Renfro, 1975; Livesey, 1975; Hadley & Shown, 1976; Schick, 1977), can be expected to be more pronounced in arid than in humid areas.

In the sediment delivery ratio the sediment yield at a given channel section is related to the gross erosion from all sources in the basin area above the point where sediment yield is estimated (Roehl, 1962; Renfro, 1975). Hillslopes, extending over 90-97% of the drainage basin area, represent one of the major sources of sediment. The relative abundance of soil loss data from hillslopes in humid and subhumid areas, together with soil loss equations developed for such areas (Musgrave, 1949; Gottschalk & Brune, 1966; Wischmeier & Smith, 1965; Beer *et al.*, 1966; Wischmeier, 1971) allow the inclusion of hillslope sediment delivery in the calculation of sediment delivery ratios. Although soil loss equations currently used have some inherent limitations (Meyer *et al.*, 1975; Piest *et al.*, 1975; Hudson, 1971; Williams, 1975; Osborn *et al.*, 1976) they provide at least some idea of the magnitude of hillslope sediment input into the channel system.

Unfortunately, existing soil loss equations cannot be used to estimate hillslope sediment delivery in arid areas where the soil cover is usually shallow and patchy, slopes often steep and rocky, and rainshowers of short duration. This lack of suitable soil loss equations together with the paucity of data on hill-slope erosion processes and rates, practically prevents any reasonable calculation of the sediment delivery ratio in arid basins. Where such ratios are provided, they are usually based on sediment data recorded at measuring stations located in the channel. Such a procedure may principally reflect the influence of channel properties rather than those of a whole basin. Considering that stream sediment loads may be bad indicators of hillslope erosion processes (Hadley & Schumm, 1961; Leopold *et al.*, 1966; Emmett, 1974; Trimble, 1975, 1976; Campbell, 1977), they provide a partial and very incomplete idea of the spatial variability in the sediment delivery ratio of arid basins. This is certainly the case in semiarid and arid areas where overland flow is more frequent than channel flow (Yair, 1972; Yair & Klein, 1973) and represents an essential stage in the very initiation and development of storm channel runoff.

The main objective of the present work is to provide an insight into the factors and processes controlling sediment removal from arid hillslopes. Special attention will be accorded to the identification of the sources of sediment and to the factors controlling the transport mechanism of suspended sediment along the slopes.

THE STUDY AREA

The study was conducted at the Sde Boqer experimental site (Yair *et al.*, 1978, 1980) in the northern Negev, Israel. Average annual rainfall is 93 mm with extreme values of 34 and 167 mm. The site covers 11 325 m^2. The drained area is limited to one half of a first order drainage basin extending on one side of the channel (Fig. 1). The site is subdivided into 16 runoff and erosion plots. Nine of them are equipped with water level recorders and automatic sediment samplers. Runoff water loaded with sediment is sampled during the flow at intervals of 2.5 or 5 min. The design of the plots (Fig. 1) allows for the study of spatial variation in runoff and sediment yield from the upper to the lower part of the experimental site, as well as along selected slopes, for both uniform and nonuniform lithologic units. A detailed description of the experimental design has been given in a previous paper (Yair *et al.*, 1980).

EROSION PROCESSES AND RATES

Two aspects of general interest were encountered in the study. The first relates to the detaching capacity of overland flow, as an erosive agent and the second refers to the spatial variability in sediment yield within the drained area.

The detaching capacity of overland flow, and therefore, sediment concentrations, can be expected to increase with a higher runoff rate. However, in numerous flow events recorded in the study area no correlation can be observed between sediment concentration and runoff rate or runoff yield (Fig. 2). The lack of a positive correlation is observed over a wide range of rainstorm intensities and durations (Yair *et al.*, 1980) including an extreme rainstorm with peak intensities of 1.6 mm during 1 min and 3.9 mm during 3 min (inset in Fig. 2). Such a systematic trend clearly indicates that runoff energy is not a predominant

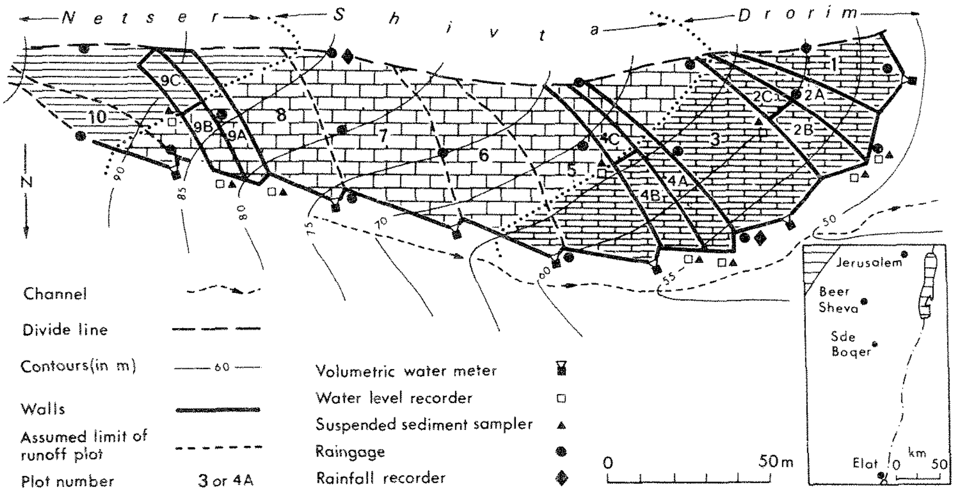

Fig. 1 Layout of the experimental site.

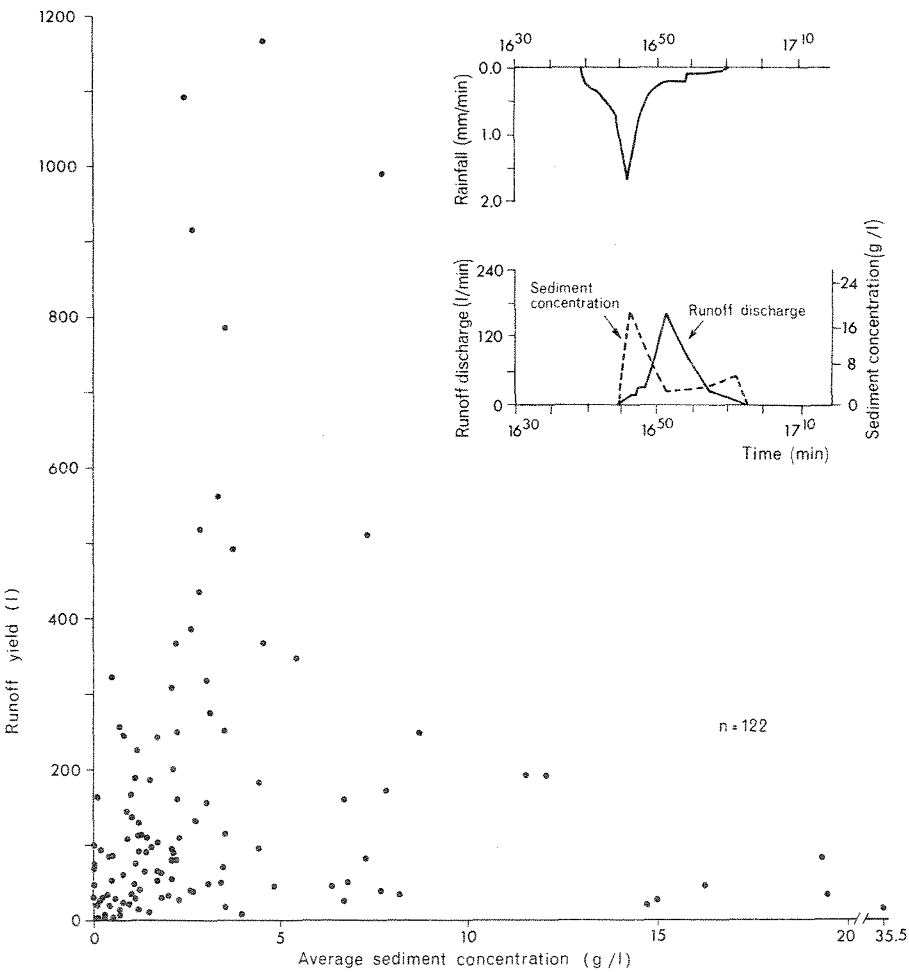

Fig. 2 The relationship between sediment concentration and runoff rate and yield.

factor in soil erosion processes in the study area. It also suggests the existence of two types of material within the drained area. One easy to remove by shallow, low velocity flows and the other highly resistant to erosion even at high energy flows.

The spatial distribution of sediment removal for a whole rainfall season is presented in Table 1. A similar distribution was obtained for each of the three flow events recorded in the season. Most of the sediment was removed during a rainstorm of 18 mm with a peak rainfall intensity of 1.7 mm in 3 min that occurred at the very beginning of the rainfall season (Yair, 1974).

Table 1 Rainfall year 1972-1973 – runoff and sediment data

Surface properties					Sediment and rainfall data		
Plot no.	Area (m^2)	% of total drained area	Slope length (m)	Slope angle (%)	Sediment removed (g per 100 m^2)	% of total sediment	% of total runoff
1	590	5.2	55	27	220	1.7	4.3
2	870	7.7	63	27.5	132	1.5	3.6
3	1830	16.2	68	28.5	169	4.0	9.1
4	1025	9.1	72	29	no data	no data	9.6
5	1230	10.9	72	29.5	235	3.7	13.5
6	1250	11.0	70	25	333	5.4	9.7
7	1520	13.4	70	24	2168	42.3	21.4
8	1050	9.3	63	26	1653	22.3	12.1
9	1440	12.7	75	17.5	928	17.2	12.8
10	510	4.5	76	11.5	302	2.0	3.9

The total amount of sediment removed from the drained area is estimated at 800 kg ha^{-1}. But sediment contribution from contiguous plots is strikingly nonuniform. Plots 7, 8 and 9, extending over 15.2%, 10.4% and 14.4% of the drained area, supplied respectively 42%, 22% and 17% of the sediment. The contribution by all other plots, which cover altogether 60% of the surface, amounted to 19% and varied for individual plots from 1.5 to 5.4%.

DISCUSSION OF RESULTS

The analysis of runoff yields recorded at the plots and of their surface properties, such as area, slope length and gradient, show that these factors can hardly account for spatial non-uniformity in the delivery of sediment. This nonuniformity may be explained by the spatial variability in the availability of sediment over the study area. Detailed field observations drew attention to intense burrowing and digging activity by desert animals such as isopods (*Hemilepistus reaumuri*) and porcupines (*Hystrix indica*). Burrowing isopods produce small pellets (Fig. 3) which disintegrate easily under the impact of raindrops. Digging by porcupines (Fig. 4), seeking bulbs for nourishment, breaks up the soil crust which, due to its mechanical strength

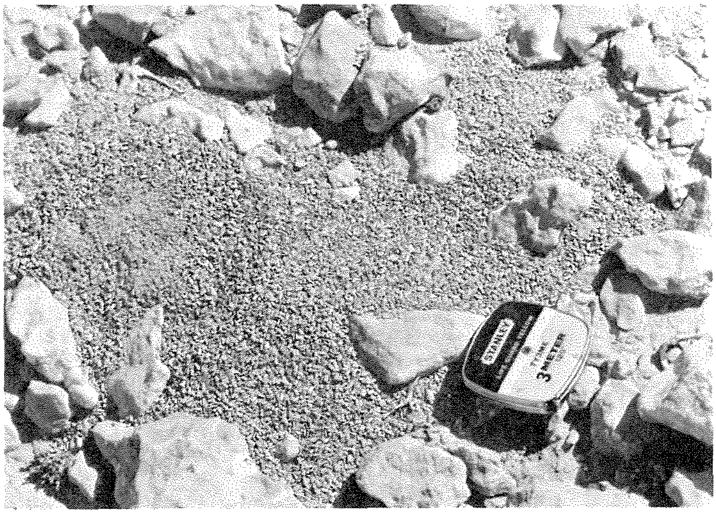

Fig. 3 A mound of isopod pellets.

Fig. 4 Digging activity of porcupines.

and cover of soil lichens and mosses, inhibits soil erosion. Thus fine soil particles with loose small aggregates are made available for transport by shallow low energy flows.

Following these observations a grid system was constructed over the entire study area. Measurements of the amounts of easily erodible soil produced through biological activity were made once a year. As most of the biological activity takes place in summer the surveys were conducted in September, at the end of the summer season and before the beginning of a new rainfall year.

The spatial distribution of the activity of porcupines and isopods for the period 1973-1979 is presented in Fig. 5. A similar distribution was obtained for each of the surveyed years. The amounts of easily erodible soil provided are far from being negligible. They are of the same order of magnitude as the amounts removed from the site during a single rainy season (Table 1; Fig. 5). However the spatial distribution of the biological activity is strikingly nonuniform. Very intense activity prevails in the central part of the experimental site where a massive limestone unit, the Shivta formation, outcrops (Fig. 1). Relatively limited activity takes place at the lower part of the site, where a colluvial soil caps the thinly bedded limestone of the Drorim formation, and at the upper part of the site where a shallow and patchy soil developed on the Netser formation. The nonuniform distribution described above is fully explained by the spatial variability in the soil moisture regime (Yair & Danin, 1980) which under the restrictive arid climatic conditions prevailing in the area, strongly controls the activity and distribution of animals and plants.

A comparison between the spatial distribution of the easily

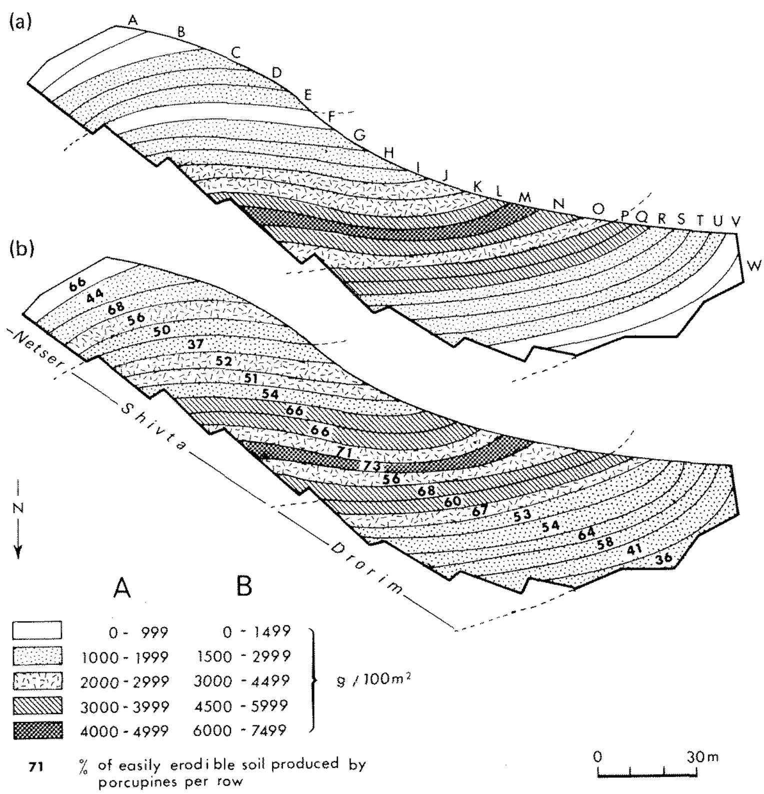

Fig. 5 Spatial distribution of the biological activity. (a) Average annual amount of low energy erodible soil produced by porcupines (1973-1977). (b) Average annual amount of low energy erodible soil produced by porcupines and isopods altogether.

erodible soil and the pattern of soil erosion as indicated in Table 1 suggests an explanation for the accelerated erosion in plots 7-9. The whole of plot 7 and the lower part of plots 8 and 9 extend over the massive limestone of the Shivta formation (Fig. 1). Therefore very high densities of biotic sediment are found at the lower part of these plots and especially in plot 7. It thus appears that the proximity of the sediment source to the slope base combined with the high frequency and magnitude of overland flow events that characterize the extensive rock outcrops of the massive limestone (Yair *et al.*, 1978, 1980) can account for the high sediment delivery at plots 7 to 9. It is worthwhile noting that the efficiency of sediment removal, for a geological time scale, along slopes carved from top to base in the massive limestone is indicated by the fact that no colluvium developed at the base of these slopes, and the adjoining channel is rocky and devoid of alluvium.

The spatial distribution of the biological activity may also explain the low sediment delivery of plots 1, 2 and 10 where the amounts of easily erodible soil are relatively reduced. This is not however the case for plots 3-6. Here the upper parts of the plots, extending over the massive limestone, display high to very high amounts of easily erodible soil (Fig. 5). These amounts are not expressed in the sediment delivery figures which are very low compared with those obtained for plots 7-9 (Table 1). This apparent contradiction is explained when the rainfall-runoff relationship prevailing in the study area is considered. Data obtained (Yair *et al.*, 1978, 1980), indicate that even under extreme rainfall conditions high runoff yields generated at the upper rocky part of the slopes have little chance of reaching the slope base. The process is explained by two main factors: (a) high infiltration losses into the lower, colluvial, part of the slope; (b) short duration of rainshowers. Under such conditions the proximity of the sediment source to the slope base becomes a crucial factor in sediment delivery, even within the rainfall covered area.

EXTRAPOLATION OF RESULTS TO LARGER ARID AREAS

From the above results it clearly appears that three major factors control slope sediment delivery in the study area. The first is the supply of easily erodible soil due to biological activity. The second is the proximity of the sediment source to the sediment measuring station and the third is the duration of rainshowers. The first and last factors are of general interest and merit further attention.

Duration of rainshowers

Any attempt to route storm runoff and sediment through a drainage basin must take into consideration rainstorm duration. A rainstorm is usually defined as a wet spell which may last a day or more. The time interval between two consecutive wet spells being at least one day with no rain. The above definition of a rainstorm certainly suits humid areas and channel runoff analysis. It may not be appropriate for arid areas where most rainstorms last less than a day. Furthermore, analysis of rainfall data collected in the northern Negev (Yair *et al.*, 1978, 1980) indicates that large storms lasting several hours, a day, or more than a day, actually consist of several separate short showers each having depths of a few millimetres. Such short showers generate separate short runoff events, causing runoff and sediment movement along the slopes to be discontinuous in time and space.

In order to obtain a statistical insight into the frequency of occurrence of rainshowers of a given duration, rainfall data recorded at seven stations located in the arid and semiarid parts of Israel were selected. The stations have average annual rainfalls of between 20 and 460 mm. From rainfall charts individual rainshowers were classified according to their duration in minutes. For the purpose of the study a rainshower is defined as a rain period during which rain is continuous; the minimum time interval between two consecutive rainshowers being 3 min. The results of the study are presented in Fig. 6. It clearly appears that the frequency of occurrence of any given rainshower duration increases linearly with increasing annual rainfall depth. For example: a rainshower that lasted 40 min

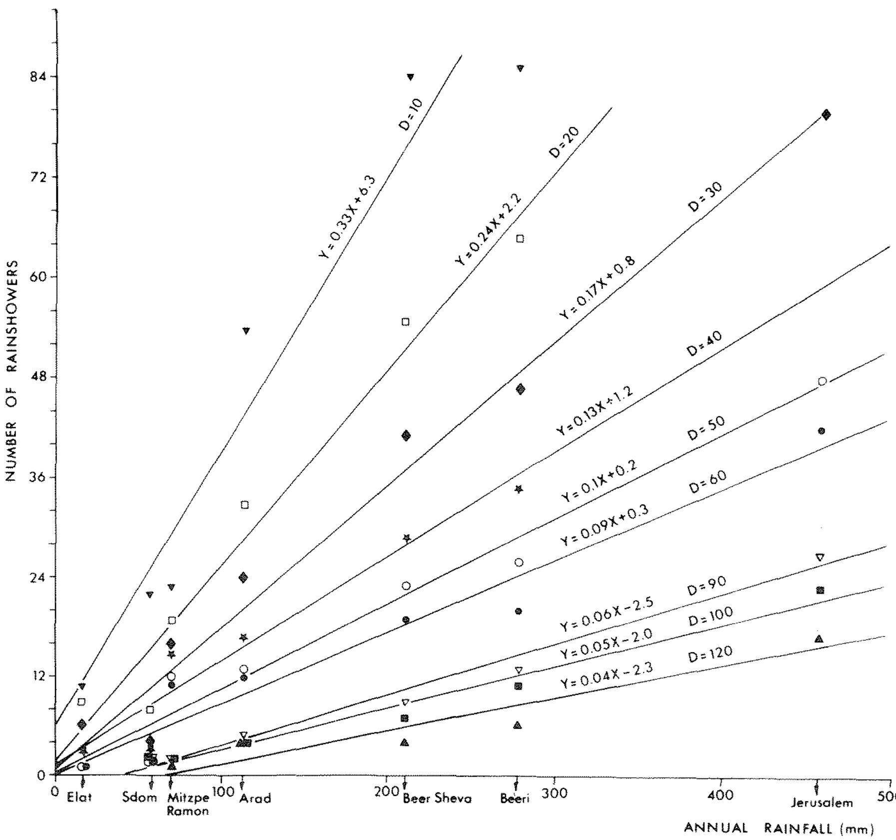

Fig. 6 The relationship between the frequency of occurrence of rainshowers of a given duration (D) and annual rainfall amount (1970-1971).

happened twice at Elat (20 mm); 15 times at Arad (115 mm); 27 times at Beer Sheva (210 mm) and 58 times at Jerusalem (460 mm). Furthermore, rainshowers of long duration, over 90 min, were not recorded at the driest stations but did occur several times at the relatively wet stations. Data presented above should be considered as preliminary as they refer to a single rainfall year when the rainfall amount recorded was close, at most stations, to the long term average annual rainfall. The study is being continued so as to cover a period of 10-20 years and to analyse in addition the frequency of rainshowers according to their intensity and amount.

The hydrological and geomorphological significance of the data obtained is that despite the low threshold rainfall depth needed to generate runoff in arid and semiarid areas, discontinuity in runoff and sediment is likely to occur in the vast majority of the events. The discontinuity phenomenon increases with increasing aridity. Where spatial variations in the infiltration capacities exist runoff may be discontinuous over distances of tens of metres even within the rainfall covered area (Yair *et al.*, 1980).

The biological factor

The biological activity is not restricted to the study area. Its importance, at a regional scale, was recently studied in the northern Negev (Yair & Rutin, 1981). Six plots having the same lithology and azimuthal direction and with average annual rainfall between 65 and 310 mm were selected. Data obtained show an increase in the production of easily erodible soil with increasing average annual rainfall amount. The result is explained by the combined effect of two factors: (a) increase in the density of the biological activity per unit area; (b) increase in the number of active animal species. Only porcupines are active at 65 mm of annual rainfall. They are joined by isopods at 90-100 mm of annual rainfall and by moles at 250 mm. Furthermore, the effect of the biological activity on sediment yield was reported in several recent studies conducted under various climatic conditions outside the arid zone (Imeson, 1976; Roose, 1976; Dunne, 1979).

In order to complete the analysis of the biological factor in the study area the temporal variations in biotic sediment production were considered. This production can be expected to be related to the size of the active isopod population and to the extent of foraging activity by porcupines. These two factors are far from being constant over time, varying in fact tremendously from one year to the next (Yair & Schahak, unpublished manuscript). Figure 7 presents the annual fluctuations in isopod population and Fig. 8 illustrates the annual variation in the activity of porcupines over a period of five consecutive years. Although a period of 5 years may be too short to characterize temporal variations in the biological activity, data obtained so far lead to three main points: (a) annual changes in biotic sediment production may be very rapid; (b) temporal changes seem to bear a cyclic form; (c) the cycle of activity of porcupines seems to differ from that of isopods. The temporal variation in

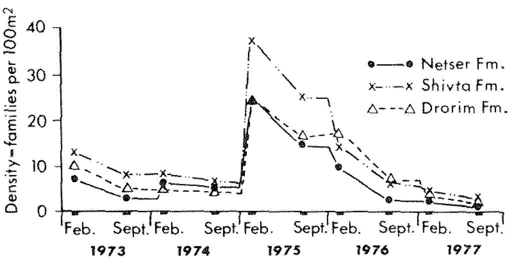

Fig. 7 Annual fluctuations in the density of isopod families, 1973-1977.

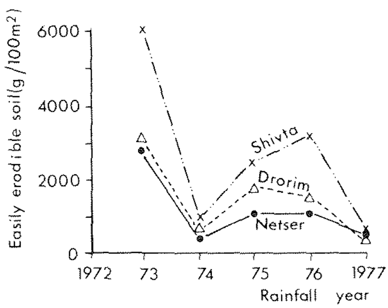

Fig. 8 Annual variation in the amounts of easily erodible soil produced by porcupines, 1973-1977.

the production of biotic sediment is far from being understood. It does not appear to be related to the fluctuations in the annual rainfall amounts (Yair & Schahak, unpublished manuscript) and may mainly be controlled by purely biological factors.

The introduction of biological elements into the field of soil erosion highly complicates the study of erosion processes. The following implications derived from the Sde Boqer study merit a special mention. Most of the digging and burrowing activity of porcupines and isopods takes place during the dry summer season. When the following rainfall season starts the crusted soil is covered by variable amounts of disaggregated soil. Under such conditions, the sediment yield for a given rainfall season may depend on the rate of biological activity during the preceding dry season. Furthermore, as the biological activity seems to bear a complex cyclic form, the sediment delivery from the area may also bear a cyclic form, at least partially, related to the cycles of production of biotic sediment. Needless to say a biological cyclic approach to the problem of soil erosion completely differs from the purely physical approach as expressed by the various soil loss equations.

CONCLUSIONS

The study of hillslope erosion processes at the Sde Boqer experimental site suggests that sediment delivery from arid slopes 60-70 m long is principally controlled by the combined effect of the short durations of individual rainshowers and the activity of burrowing animals.

(a) Due to the short duration of rainshowers the depth of overland flow is very shallow. Considering the high roughness of the stony environment flow velocities are low. Data obtained indicate that even during rainstorms of extreme intensity, velocities at peak flow are below the threshold value needed to detach particles from the crusted soil. These velocities are high enough to detach and transport disaggregated soil particles provided by the digging and burrowing activity of desert animals. Biotic sediment may therefore account for most of the sediment delivered by the slopes in the study area. As the biological activity is not influenced by slope gradient and slope length no correlation is found between the sediment yield and latter variables. This result is in agreement with previous findings (Yair & Klein, 1973; Shanan, 1975; Shanan & Schick, 1980) indicating that runoff generation over arid slopes is negatively correlated with slope angle.

(b) Due to the combined effect of short duration rainshowers and low flow velocities, runoff and sediment generated at the upper part of slopes will fail to reach the slope base in the vast majority of rainstorm events. This process is enhanced where a colluvial cover enhances infiltration losses in the downslope direction. Under such conditions the proximity of the sediment source to the slope base becomes an important factor in slope sediment delivery.

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