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Soil erosion and sediment yield in the Indian arid zone

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Abstract High sediment yields are generated in the Indian arid zone due to erratic and torrential rainfall, sandy and eroded rocky drainage basins, and biotic activity. Sediment yield increases with increasing rainfall and drainage basin slope and its magnitude depends upon the nature of surface material. Sediment yield can be reduced by 65-94% through promotion of vegetation and construction of check dams in the drainage basin.

INTRODUCTION

In recent years, it has been confirmed that high sediment yields are associated with arid/semiarid, seasonal mediterranean, and tropical conditions (Walling & Webb, 1983). A compilation of sediment yields for meso scale drainage basins suggests that arid basins export 36 times more material than humid temperate and 21 times more than humid tropical equivalents (Reid & Frostick, 1987). Bare soil is highly susceptible to rainsplash and wash erosion, and arid zones produce record suspended sediment concentrations (Jones, 1981). The sediment not only causes water quality to deteriorate but also affects physical and biological conditions in the receiving systems. In the Indian arid zone, the storage capacity of small reservoirs (400 to 700 000 m^3) is reduced by 1.9 to 7.8% annually due to sediment deposition (Sharma & Joshi, 1982). The main features of erosion and sediment yield in the Indian arid zone are discussed here.

THE INDIAN ARID ZONE

Hydrologically, the arid zone in India (Fig. 1) consists of three main zones. Zone I covers 42 900 km^2 and receives major inputs of water from more humid regions, and supports extensive irrigated agriculture. This is a canal irrigated area and no significant sedimentation problems are encountered here. Zone II comprises sandy plains, interdune plains, sand dunes, eroded rocky/gravelly surfaces and isolated hillocks with a poorly developed or no stream network (148 600 km^2). It contains no integrated stream network in the conventional sense; rather, there is a system of repetitive micro-hydrology. The internal drainage basins generate high sediment yields under occasional and sporadic torrential rainfall. Zone III represents the sloping region with an integrated stream network (94 280 km^2). These are ephemeral channels which remain dry for 90% of the year. When runoff does occur as a direct response to torrential rainfall, flash floods result and large quantities of sediment are transported down the valleys. In this zone the infrequent nature of rainfall and runoff encourages intensive measurement programmes.

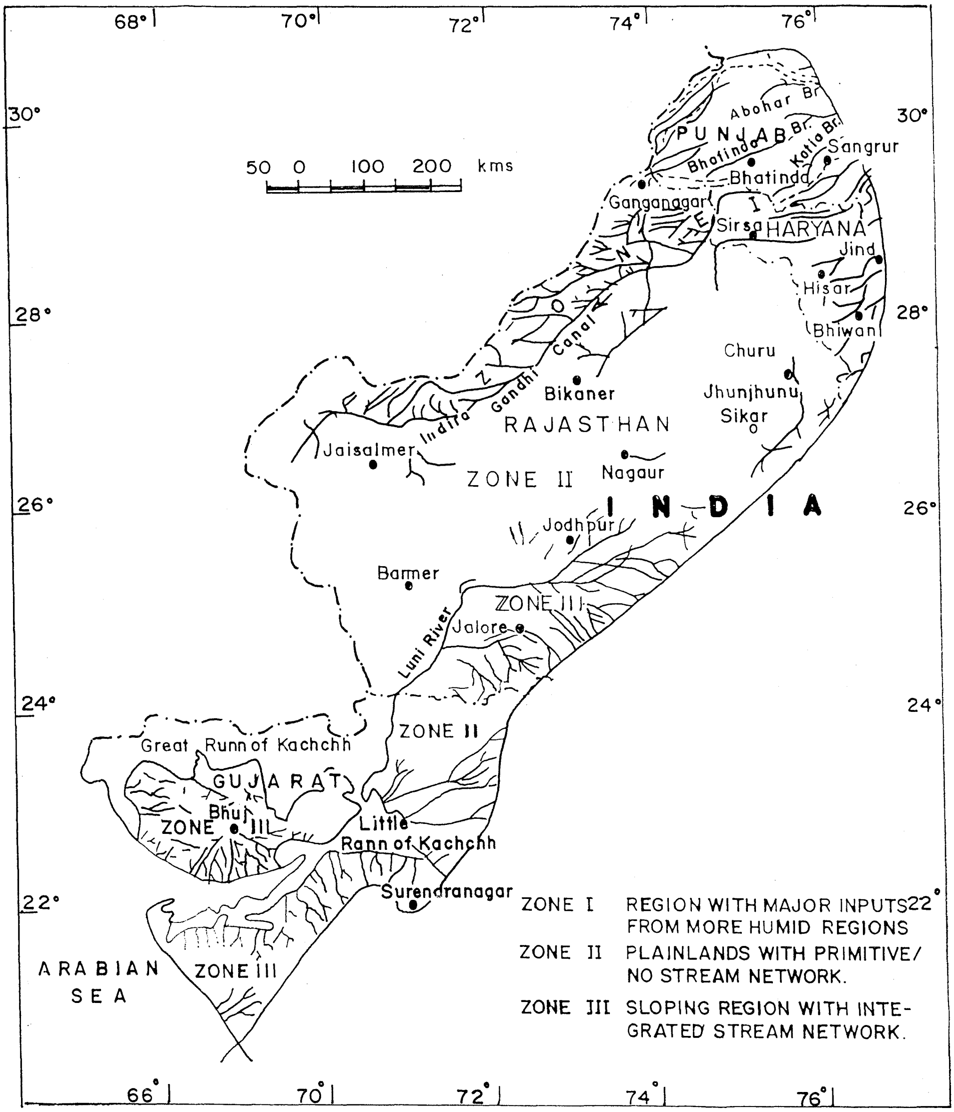

Fig. 1 Hydrological zones of the arid region of India.

HYDROLOGICAL DATA

In the zone of internal drainage (zone II), the sediment yields have been estimated through measurement of sediment accumulation in small reservoirs following the recommendation of McManus & Duck (1985), and Owens & Slaymaker (1992). One hundred small reservoirs were selected by stratified random sampling from a total of 1436 reservoirs occurring in the region. The distribution of the sample was adjusted to represent the majority of the physiographic environments, soil types, vegetation and rainfall conditions. In the sandy plain and dune complex environments, the deposited sediment mainly consists of fine to very fine sand, silt and clay, overlying wind blown loose sand. This layer is deposited during the summer when the reservoirs are dry and acts as a marker to identify the successive depositional cycles. The sediment deposited in the younger alluvial environment is composed of medium to fine sand and silt over which a thin layer of clay is deposited. The occasional presence of gravel in the deposits acts as a marker to identify the successive depositional cycles. A distinct layer of gravel mantled by medium to fine sand and silt is the characteristic depositional pattern in the older alluvial environment; and the proportion of clay is very small in these deposits. Equal amounts of fine sand, silt and clay are associated with the sediment deposits in the rocky/gravelly piedmonts. These sediments also contain stone chips. Sediment samples were obtained from fresh cuts in the beds during May-June 1993, when the reservoirs were dry. The annual average depth of deposition was calculated from 4 to 6 depth measurements in the bed of the reservoir between two successive marker layers. This value multiplied by the area of the reservoir provides an estimate of the total volume of sediment deposited each year. The annual specific sediment yield was obtained by dividing the total volume of sediment deposited per year by the drainage basin area. Measurements of drainage basin area and slope were taken from 1:50 000 scale topographic maps.

In the zone with an integrated stream network (zone III), information on the spatial variation of stream discharge and sediment yield has been obtained from 34 gauging stations which are located on various tributaries of the Luni River. Hourly stage heights were observed at each station during periods of flow and discharge has been calculated by the slope-area method, with values for the roughness coefficient of these sand bed channels taken from Vangani & Kalla (1985). The initial water sample is taken at the onset of flow, and subsequent samples are collected at irregular intervals and with significant changes in the discharge until the flow ceases. The samples were collected using a US DH-48 depth integrating suspended sediment wading type hand sampler, employing the equal transit rate method as recommended by Jones (1981) for arid regions. The samples thus collected were transported to the laboratory and subjected to standard concentration analysis by filtration and evaporation. The resulting data, together with recorded runoff rates, provided a reasonably accurate representation of the variation of sediment concentration during each flow event, as well as permitting the computation of sediment yield. These data were collected for 16 years over the period 1979-1994.

RESULTS AND DISCUSSION

As with the effective rainfall distribution, the largest number of events is found in the smallest sediment yield class of 0-100 t km^2; thus providing a positively skewed unimodal frequency distribution (Sharma *et al.*, 1994). Chang & Stow (1988) observed that catastrophic flood events caused the highest sediment loss from drainage basins in the arid zone. Thus, while sediment production occurs more generally in the drainage basin, significant sediment delivery is limited to major flood flows. The relationship between sediment yield and effective rainfall is depicted in Fig. 2.

Wide variations in the magnitude of annual sediment yield were observed among the various physiographic regions encountered in the Indian arid zone (Table 1). The older

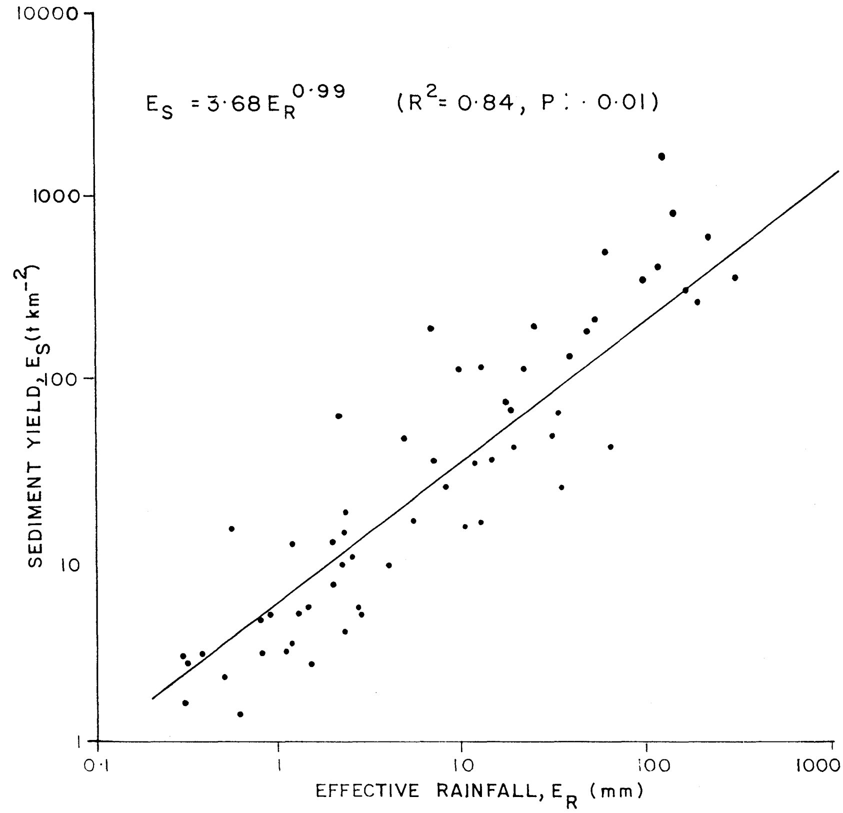

Fig. 2 Sediment yield as a function of effective rainfall.

alluvial plain has the highest sediment yield, while the younger alluvial plain has the lowest. The sediment yields from the rocky/gravelly piedmont, dune complex and sandy plain areas lie between these two extremes. Except for the higher sediment yields from the older alluvial plain and the rocky/gravelly piedmont, the annual sediment yields from the other physiographic regions are in agreement with the mean rates of 2.6, 4.0 and 4.6 m^3 ha^{-1} $year^{-1}$ reported from the arid regions of Australia, Tanzania and USA, respectively (Jones, 1981), under the similar rainfall conditions.

Sediment yield is also a function of basin lithology. together with the drainage basin slope, and the amount and intensity of rainfall. It can be seen from Fig. 3(a) that

Table 1 Annual sediment yields in the Indian arid zone.

Physiographic region	Average sediment yield (m^3 ha^{-1} $year^{-1}$)	No. of observations
Sandy plain	3.4	36
Dune complex	4.8	18
Younger alluvial plain	2.7	30
Older alluvial plain	18.4	5
Rocky/gravelly piedmont	14.3	11

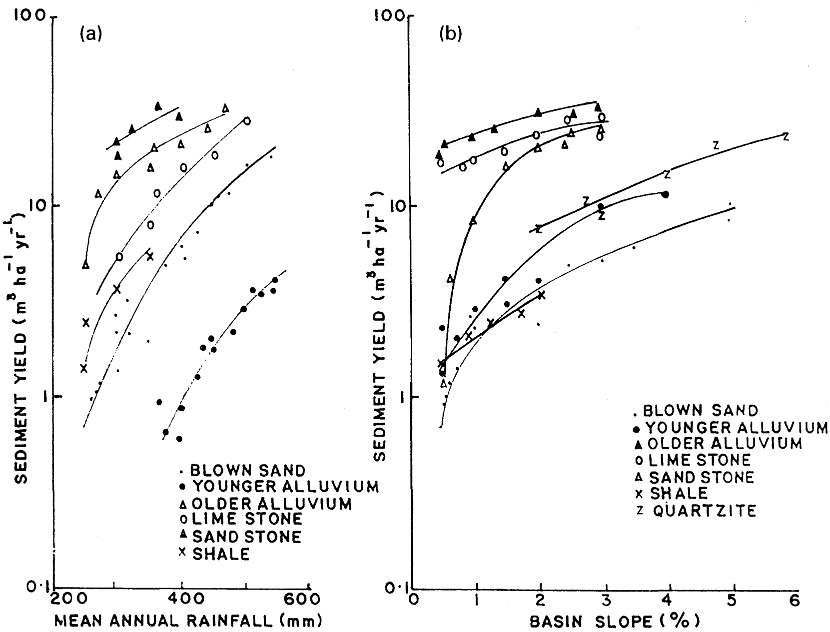

Fig. 3 Mean annual sediment yield as a function of (a) mean annual rainfall, and (b) drainage basin slope for the indicated lithologies.

sediment yields are highest from the sandstone drainage basins, (26.1 m^3 ha^{-1} $year^{-1}$) followed by the phyllite (22.7 m^3 ha^{-1} $year^{-1}$), older alluvium (14.8 m^3 ha^{-1} $year^{-1}$), limestone (12.0 m^3 ha^{-1} $year^{-1}$), quartzite (8.4 m^3 ha^{-1} $year^{-1}$), blown sand (5.8 m^3 ha^{-1} $year^{-1}$), shale (2.0 m^3 ha^{-1} $year^{-1}$) and the younger alluvium (1.5 m^3 ha^{-1} $year^{-1}$). However, this trend is slightly changed when the relationship between sediment yield and basin slope is plotted (Fig. 3(b)). In this case sediment yield follows the order: sandstone (25.9 m^3 ha^{-1} $year^{-1}$) > phyllite (22.7 m^3 ha^{-1} $year^{-1}$) > limestone (18.1 m^3 ha^{-1} $year^{-1}$) > older alluvium (14.9 m^3 ha^{-1} $year^{-1}$) > quartzite (14.2 m^3 ha^{-1} $year^{-1}$) > younger alluvium (4.4 m^3 ha^{-1} $year^{-1}$) > blown sand (4.1 m^3 ha^{-1} $year^{-1}$) > shale (2.5 m^3 ha^{-1} $year^{-1}$). For a single lithologic unit there is a general increase in sediment yield with both annual rainfall and drainage basin slope.

The variations of sediment yield with rainfall and drainage basin slope are due to the nature of the rock. The sandstone outcrops in this region are composed of medium to fine sand with intercalated beds of grit or gravels; these outcrops generate the highest sediment yield in comparison to shale which is more resistant, and in consequence loses the least sediment. The phyllite is composed of medium to coarse grains with uniform structure and loses less sediment than the sandstone. The limestone formations are fine, compact, hard and cherty with fractured and weathered upper layers and, thus, still produce less sediment than the quartzite which is medium to coarse grained.

When sediment yields are plotted against the runoff generated in during individual events (Fig. 4), a general increase in sediment yield with runoff can be seen. The higher runoff is associated with greater kinetic energy for erosion and transport of the eroded sediment. There are striking differences between the various events however, in the rate at which sediment yield increases with runoff. This is due to the presence of greater

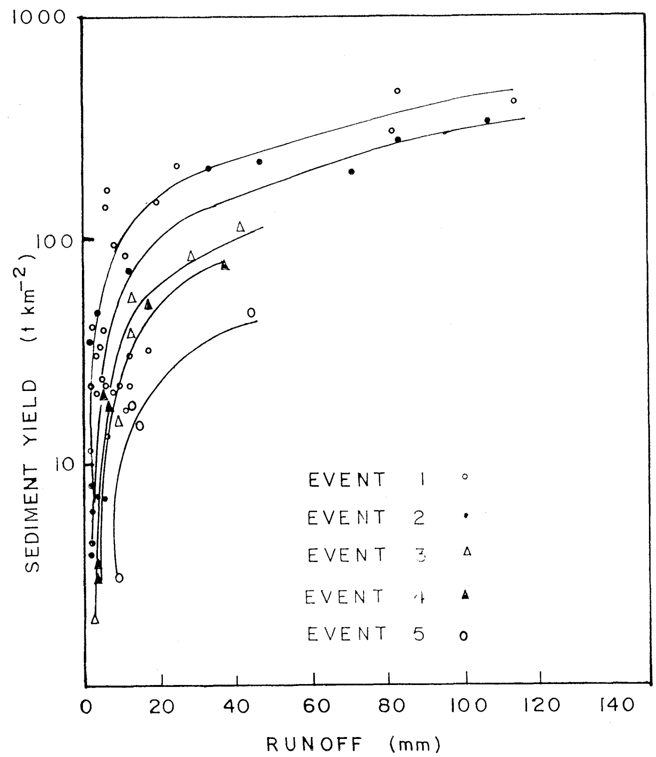

Fig. 4 The relationship between sediment yield and runoff for a sequences of storm events.

amounts of readily transported loose material in the drainage basin at the onset of the first event of the wet season. The supply of this loose material decreases progressively during a sequence of storm events, due to shorter intervals that allow less biotic activity.

Reducing sediment yield

Government sponsored large scale soil conservation programmes and watershed management strategies, involving the promotion of vegetation on the slopes within the drainage basins and engineering measures such as check dams, have caused significant

Table 2 The effect of vegetation cover on sediment yield.

Physiographic region	Estimated vegetation cover (%)	Sediment yield (m^3 ha^{-1} $year^{-1}$):	
		Without vegetation	With vegetation
Sandy plain	4	3.6	0.6
Dune complex	3	2.3	0.8
Younger alluvial plain	6	8.9	0.5
Older alluvial plain	3	5.2	1.2

reductions in sediment yield throughout the Indian arid zone. The qualitative effects of plant cover in reducing sediment yield through deposition of sediment in the drainage basin, due to increase resistance to flow and reduction in flow velocity are well known (Rodda, 1976; Morgan, 1981). It can be seen from Table 2, that sediment yield was reduced by between 65 and 94% in different physiographic regions by preserving vegetation on the slopes within the drainage basins. The reduction in sediment yield shows a positive correlation with the vegetation cover, which varies between 3 and 6%. Elwell (1981) observed that sediment yield decreased exponentially with increasing vegetation cover. The reduction in sediment yield was only between 33 and 60% for the coarser fractions (>0.05 mm) in similar physiographic and rainfall zones. Thus, the sediment generated is finer in the drainage basins with good vegetation cover.

From the drainage basins influenced by biotic activity, check dams reduced the diment yield by 71% from the older alluvium and shale formations under similar rainfall and drainage basin characteristics (Table 3). This reduction is due to the deposition of the coarser fractions within the impoundments as a result of the reduction in the flow velocity in passing through the check dam.

Table 3 The effect of check dams on sediment yield.

Physiographic region	Sediment yield (m^3 ha^{-1} $year^{-1}$):	
	Without check dams	With check dams
Older alluvial plain	16.6	4.8
Rocky/gravelly piedmont	4.2	1.2

CONCLUSION

Sandy and eroded drainage basins situated in regions characterized by occasional and sporadic torrential rainfall generate high sediment yields. Coarse to medium grained, loose and less compact formations generate more sediment with increasing rainfall and drainage basin slope than the fine grained, hard and compact formations. Promoting vegetation and construction of check dams are some of the measures recommended for controlling soil erosion and for reducing the sediment yield from arid zone drainage basins.

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