Spatiotemporal variability of sediment transport in arid regions

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Abstract Record suspended sediment concentrations are produced in the arid regions due to the torrential rainfall, weathered surfaces and biotic interference. Extreme variability of rainfall, the variable nature of surfaces in the drainage basin and channel storage of sediments cause high spatiotemporal variability of sediment transport in arid regions. A physically based sediment transport model in conjunction with satellite remote sensing and geographic information system is an appropriate tool for studying the spatiotemporal variability of sediment transport under arid conditions.

INTRODUCTION

In the arid regions, high intensity of the episodic rainfall (Bell, 1979; Branson *et al.*, 1981), presence of excessively weathered surface material (Goudie & Wilkinson, 1977), the sparse vegetation cover (Pilgrim *et al.*, 1987), erodible aeolian surficial deposits (Jones, 1981) and increased biotic interference (FAO, 1973; Sharma & Joshi, 1987) combine and produce record suspended sediment concentrations (Reid & Frostick, 1987). The process of sediment generation and resultant transport are related to high variability and seasonality of ephemeral stream flows (Magfed, 1986). As a result, sediment transport by such streams is quite variable both spatially (along various stream reaches) and temporally.

Sediment transport by water poses numerous problems connected with reservoir storage capacities, stream flow and channel morphology (Sharma *et al.*, 1984a). Many developing countries in the arid region are experiencing severe reservoir capacity depletion and short life of reservoirs constructed across small wadis and drainage channels for water supply (Jones, 1981). Therefore, the assessment and understanding of variability of sediment transport in the arid regions are essential to control soil erosion particularly through sound land and water management techniques and to devise methods and design techniques to mitigate the harmful effects of erosion and sedimentation. In the present study, an attempt in this direction has been made for the Indian and Argentinian arid zones.

THE INDIAN ARID ZONE

Sediment transport data were collected for a period of 9 years (1979-1987) from 10 arid upland basins with areas ranging between 104 and 1520 km^2 located within the Luni river basin in the Indian Arid Zone (Sharma *et al.*, 1992). Hourly sediment concentrations were determined from samples collected using US DH-48 depth integrating suspended sediment wading type hand samplers, employing the equal transit rate method as recommended by Jones (1981) for arid regions. Discharge measurements were by current meter and velocity area method, according to standard United States Geological Survey practice. The resulting data allowed a reasonably accurate representation of the variation in sediment concentration during each flow event, as well as the computation of suspended sediment discharge.

On average three to seven flow events occur in this region annually. The sediment concentration among different flow events varied between 0.2 and 453.6 g l^{-1}. Nearly 90% of the suspended sediment by weight have particle sizes ranging between 0.002 and 0.2 mm. For all the events, the highest sediment concentrations were observed during initial runoff. Concentrations decreased during the rising and recession stages of the flow. The initial high sediment concentration is attributed to the existence of a thin loose surface layer produced by weathering, drying and biotic interference in the drainage basins during the dry periods. Additional amounts of material may be provided by the splash erosion process during the time interval between the start of rainfall and that of runoff, before a protective layer of surface water detention is built up over the surface. Such a protective layer may well explain the decrease in sediment concentrations during the rising flow stage up to the peak discharge, and recession thereafter. It is also possible that beyond some critical value of transmission losses and flow velocity, part of the coarse sandy material transported is deposited, thus resulting in a rapid decrease in

Table 1 Drainage basin area *vs.* sediment yield (1979-1987).

Drainage basin	Area (km^2)	Mean runoff (mm)	Mean sediment yield (t km^{-2} $event^{-1}$)
Kori	104	24	968
Posalia	286	20	700
Auwa	351	19	540
Somesar	411	14	501
Rani	588	9	232
Sanderao	597	7	228
Pipar	631	7	212
Alniawas	950	5	172
Banjakuri	1449	5	52
Jasnagar	1520	4	43
Mean	689	11	365

sediment concentration values towards the end of the flow. Decrease in the absolute values of sediment concentrations during the subsequent events is due to the lesser availability of the loose material in the drainage basins after each preceding flow event (Sharma *et al.*, 1984a).

Within the same drainage basin the sediment yield decreased from 5.1-183.3 to 0.3-6.4 km^{-2} $event^{-1}$ from the first to the last flow event of the season, respectively. This is due to the presence of greater amounts of loose material within the drainage basin at the onset of the first event of the wet season. The supply of this loose material decreases continuously with the subsequent events due to the shorter intervals that allow less biotic interference. Also, by increasing the drainage basin area from 104 to 1520 km^2 the sediment yield per event decreased from 968 to 43 t km^{-2} (Table 1). Jansson (1982) and Sharma *et al.* (1984b) attributed this to the high transmission losses of runoff in the drainage channels thereby resulting in the low transport capacity of the reduced runoff at the drainage basin outlet.

In the Indian arid zone, the largest number of events occur in the smallest class of 0-100 t km^{-2} $event^{-1}$ sediment yield group; thus having a positively skewed unimodal frequently distribution (Fig. 1). Figure 2 indicates that the catastrophic flood events caused the highest sediment loss from the arid upland basins. Thus, while the sediment production occurs in the drainage basin, significant sediment delivery is limited to the major flood flows – a characteristic of the arid regions (Chang & Stow, 1988; Sharma, 1992).

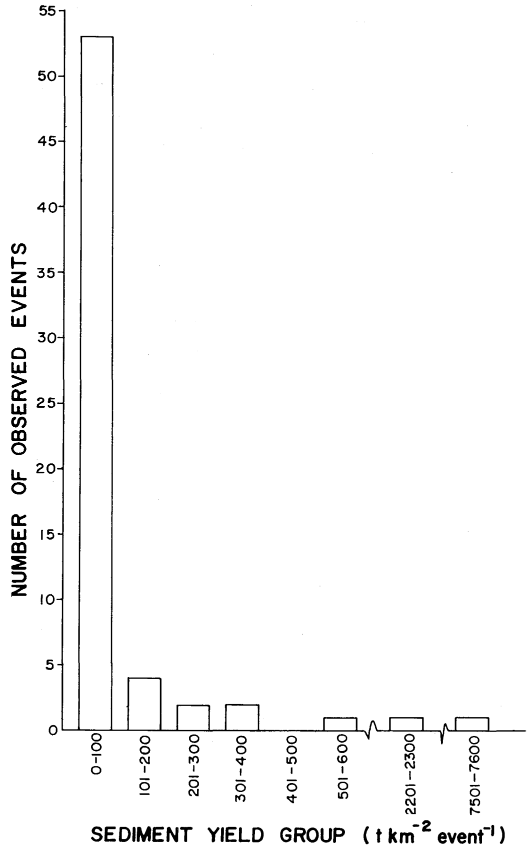

Fig. 1 Frequency distribution of sediment yield in Indian arid zone basins.

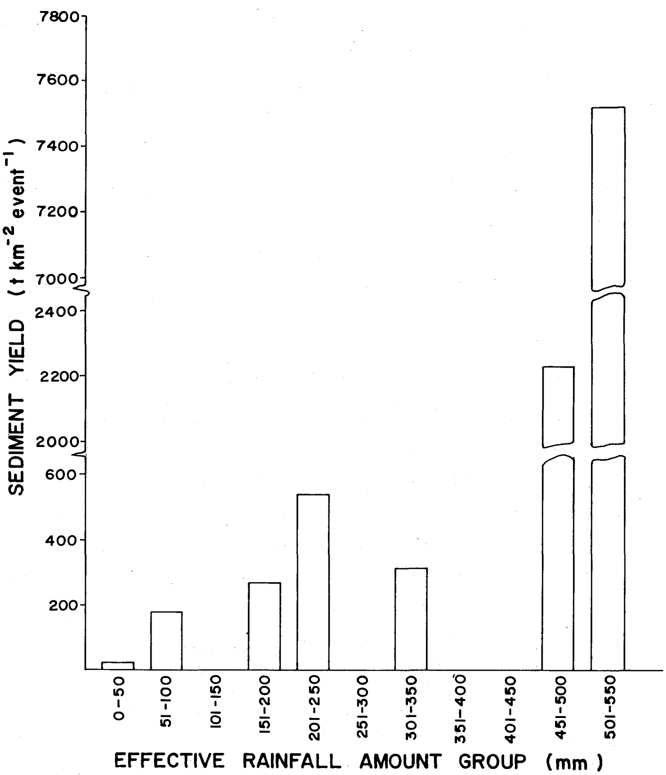

Fig. 2 Frequency distribution of sediment yield under observed effective rainfall classes, Indian arid zone basins.

THE ARGENTINIAN ARID ZONE

Rainfall-runoff and sediment transport data were collected for a period of 12 years (1982-1993) in Divisadero Largo basin (5.47 km^2) located within the piedmont and precordillera areas of the Andes mountains in the west of Mendoza (33.0-33.5°S; 68.8-69.1°W), Argentina. The altitude ranges from 950 m in the east to 1450 m in the west. The area is intersected by steeply eroded gullies and rock outcrops. The soils are shallow, undeveloped and consist of medium to fine sand. The vegetation is comprised of low shrubby pastures ranging from 5 to 45% cover depending upon the steepness of the slope. The area lies in a subtropical arid climate and is characterized by convective summer thunderstorms. The annual average precipitation is 201 mm; 77% of which is received within the summer months of October to March. The average annual temperature is 13°C. The hydrological network comprised of 32 automatic raingauges and 2 stream gauging stations covering an area of about 600 km^2 within the region (Amorocho *et al.*, 1983) and the data were recorded through a telemetry network (Fernandez *et al.*, 1984).

The sediment transport has been estimated by a physically based soil erosion model (Sharma *et al.*, 1992):

$$\ln (T_c - Q_s) = -GX + \ln C \tag{1}$$

where T_c (kg s^{-1} m^{-1}) is flow transport capacity estimated by the Yalin equation (Yalin, 1963), Q_s (kg s^{-1} m^{-1}) is actual sediment transport, G (m^{-1}) is a first order reaction coefficient, X (m) is downslope distance, and C (kg s^{-1} m^{-1}) is a constant of integration and is equal to $T_c - Q_s$ at $X = 0$.

Equation (1) is amenable to the use of modern technologies such as satellite remote sensing and geographic information system (GIS) along with the limited ground truth for the sediment transport studies.

Spatiotemporal distribution of rainfall excess depths for each storm within the study basin was generated in digital map form using a one dimensional dynamic simulation model SWAMIN for each of the identified 26 hydrological response units (Sharma, 1993). The hydrological response unit has a unique combination of soil type, slope class, vegetation density, surface storage potential and rainfall distribution pattern. These were derived by means of a GIS package IDRISI (IDRISI, 1992) from the Thematic Mapper data, digital soil map and a digital terrain model. The rainfall excess map in combination with the soil particle characteristics and slope map generated the spatiotemporal distribution maps of soil erosion rate for the Divisadero Largo basin.

The sediment transport model (equation (1)) was validated on seven independent rainfall events for which the soil loss data were recorded. The coefficient of determination between the observed and predicted sediment transport was found to be 0.996 ($P > 0.01$) and the average relative error was 6.8%; the maximum was 16.5% and the minimum was only 2.7%. It was also observed that a surface protected by vegetation loses less sediments than a bare surface; for example at 1.0 kg s^{-2} m^{-1} shear stress acting on the surface the former loses 22 times less sediments than the latter. This result is available because of the capability of the physically based sediment transport model in conjunction with the GIS to predict the spatial variability of soil erosion within the drainage basin. As an example, a map showing the spatial variability of actual soil loss for storm 09 recorded on 22 November 1985 is depicted here (Fig. 3). This is useful in the identification of vulnerable areas within the drainage basin for the siting of needs based soil conservation measures and thus, in the reduction of overall cost of treating the entire basin, which is presently being done.

DISCUSSION

The arid regions are characterized by sporadic rainfall of high temporal and spatial variability. Sharon (1972), Jones (1981), Pilgrim *et al.* (1988) and Sharma (1992) observed spottiness and extreme variability of rainfall in the deserts. Uncertainties increase while estimating areal rainfall and still further when taking rainfall intensity into account. Because runoff depends on many variables other than rainfall its variability is considerably greater than that of rainfall (Sharma, 1992). Not enough is known about these variables in arid zone conditions and since resulting sediment transport data are few (Reid & Frostick, 1987) and fragmentary, the uncertainties are even greater. Also the role of extreme events due to their rare occurrence and relatively short duration, and the transitory hydrological and hydraulic regimes is not fully understood in the arid zones.

Apart from the rainfall, the practical impossibility of knowing in sufficient detail the surface characteristics of the basin slopes, material, depth to impermeable rock or water,

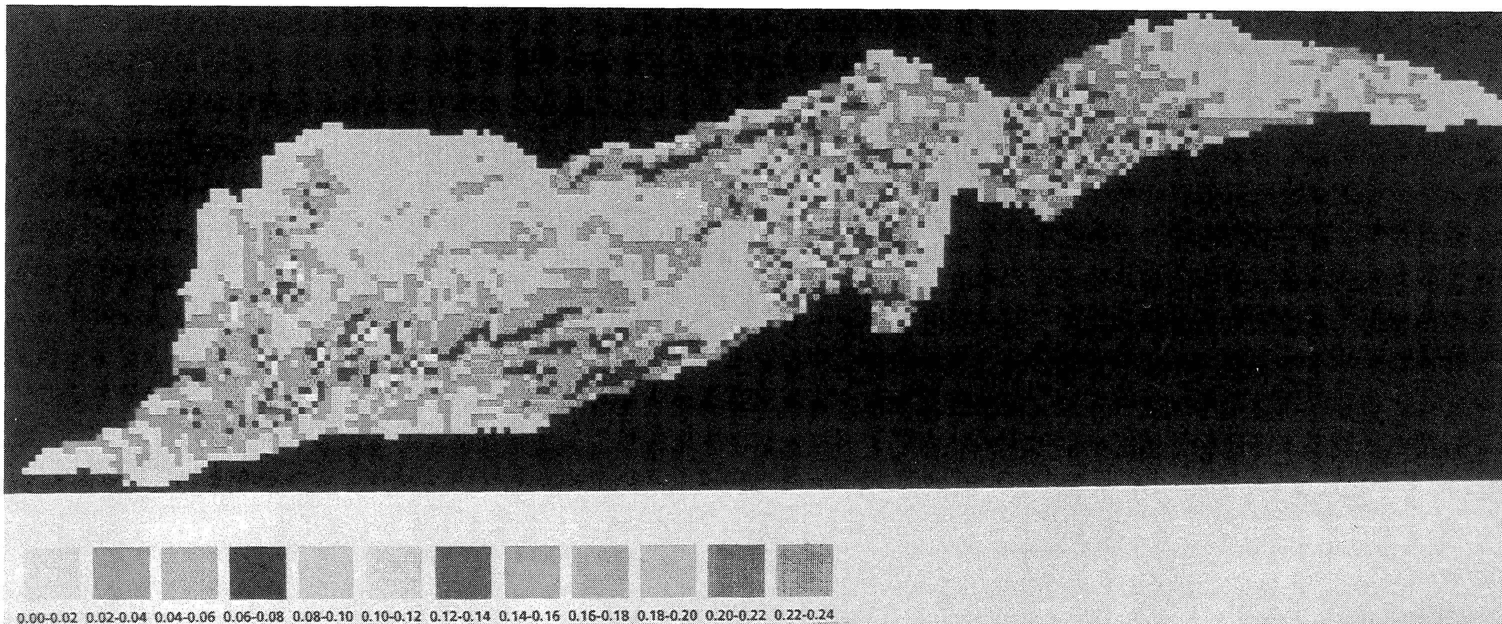

Fig. 3 Spatial variability of soil erosion (kg m^{-2}), 22 November 1985, Divisadero Largo basin, Argentina.

vegetational cover, biotic interference, etc. also adds to the variability of sediment transport in the arid regions (Fig. 3). The presence of sources and sinks in a drainage basin controls the amount of sediments leaving the basin, and thus affects the sediment delivery ratio. Foster (1982) identified the agricultural lands, construction sites, cuts and embankments, disturbed forest lands, surface mines and badlands as sources, and toes of concave slopes, strips of vegetation, flood plains and impoundments as sinks. In the arid zone streams, channel storage of sediment usually has greater effect on sediment transport than channel storage of water on flood discharge (Hadley, 1977; Sharma *et al.*, 1993). As a result the spatiotemporal variation in sediment transport and yield is manifested as channel storage/depletion of sediment associated with stream channel changes.

CONCLUSION

In arid conditions the mere existence of flow is exceptional and the common thing is its extreme flashiness and its extreme degree of variability which is manifested in the spatiotemporal variability of sediment transport. A physically based soil erosion model in combination with the satellite remote sensing and geographic information system predicts the variability of sediment transport within a desirable accuracy. The resulting information is useful for identifying and evaluating the extent of erosion and sedimentation and for recommending need based control measures.

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