

## **A study of scale effects on sediment transport modeling in arid regions**

**K. D. SHARMA**

*Central Arid Zone Research Institute, Jodhpur 342003, India*

**Abstract** Arid regions yield record suspended sediment; sediment concentrations increase from micro to macro scale due to high transmission losses in ephemeral channels. Based on studies conducted in arid regions of Argentina and India, the sediment transport is related to soil detachment at micro scale, whereas at macro scale a conceptual model predicts sediment transport with high accuracy. At meso scale, sediment transport is limited by the transport capacity of runoff. Appropriate models to predict sediment transport at patch to river-basin scale are derived and integrated through an equation based on transmission loss.

### **INTRODUCTION**

Large quantities of sediment are generated and transported in arid regions (Schick, 1970; Jones, 1981; Magfed, 1986; Reid & Frostick, 1987). Sediment degrades water quality and may carry adsorbed chemicals. Sediment deposition in the receiving systems reduces their capacity and requires costly dredging operations.

Areal heterogeneities in topography, soil properties, vegetation and land use (BAHC, 1993), which control the distribution of sediment sinks such as the toes of concave slopes, strips of vegetation, flood plains and impoundments within a drainage basin (Foster, 1982), occur as more or less direct differences in the subregional hydrological conditions and accordingly in rainwater infiltration, runoff behavior and sediment transport. Sediment from patches (homogeneous land surface areas) of different types (heterogeneous areas, river basins, etc.) is integrated in larger rivers and transported downstream towards the coastal zone. Inadequate work has been conducted on the linkages between micro-scale process-based descriptions and possible macro-scale parameterizations of drainage basins. This paper deals with the modeling of sediment transport at spatial and temporal scales and integration of processes across these scales in arid regions.

### **SEDIMENT TRANSPORT MODELING**

Sediment delivery is a result of net soil detachment and deposition within the basin. The continuity equation for sediment transport is (Lane *et al.*, 1992):

$$dQ_s/dX = D_f + D_i \quad (1)$$

where  $Q_s$  ( $\text{kg s}^{-1} \text{m}^{-1}$ ) is sediment transport rate;  $X$  (m) is downslope distance;  $D_f$  ( $\text{kg s}^{-1} \text{m}^{-2}$ ) is net flow-detachment rate; and  $D_i$  ( $\text{kg s}^{-1} \text{m}^{-2}$ ) is net rainfall-detachment rate. For calculation,  $D_f$  and  $D_i$  are computed on an areal basis; thus,  $Q_s$  is solved on a width basis. After computations, sediment transport is expressed as transport per unit area. The assumption of quasi-steady state allows deletion of time from equation (1).  $D_i$  is negligible because the transport capacity of rainsplash is low (Lu *et al.*, 1989).

The net flow-detachment rate is calculated for the case when hydraulic shear stress exceeds the critical shear stress of the soil and when sediment load is less than sediment transport capacity. For the case of flow detachment (Foster, 1982):

$$D_f = D_c (1 - Q_s/T_r) \quad (2)$$

where  $D_c$  ( $\text{kg s}^{-1} \text{m}^{-2}$ ) is detachment capacity by flow and  $T_r$  ( $\text{kg s}^{-1} \text{m}^{-1}$ ) is sediment transport capacity estimated by the Yalin equation (Yalin, 1963). When hydraulic shear stress exceeds critical shear stress for the soil, detachment capacity,  $D_c$ , is expressed as:

$$D_c = K_r (T_f - T_c) \quad (3)$$

where  $K_r$  ( $\text{s m}^{-1}$ ) is soil erodibility,  $T_f$  (Pa) is shear stress on the soil and  $T_c$  (Pa) is a flow-detachment threshold parameter or critical shear stress. Flow detachment is considered to be zero when shear is less than critical shear of the soil.

Combining equations (1) and (3), soil detachment and sediment transport can be modeled as:

$$dQ_s/dX = K_r (T_f - T_c) (1 - Q_s/T_r) \quad (4)$$

Equation (4) is solved using a Runge-Kutta numerical method.

Net deposition is computed when sediment load,  $Q_s$ , is greater than sediment transport capacity,  $T_r$ . For the case of deposition (Foster, 1982):

$$D_f = (V_f/q) (T_r - Q_s) \quad (5)$$

where  $V_f$  ( $\text{m s}^{-1}$ ) is effective fall velocity for the sediment and  $q$  ( $\text{m}^2 \text{s}^{-1}$ ) is discharge per unit width. Combining equations (1) and (5), the deposition in and sediment transport from a drainage basin is:

$$dQ_s/dX = (V_f/q)(T_r - Q_s) \quad (6)$$

Equation (6) has a closed form solution of:

$$\ln(T_r - Q_s) = -(V_f/q)X + \ln C \quad (7)$$

where  $C$  ( $\text{kg s}^{-1} \text{m}^{-1}$ ) is a constant of integration equal to  $T_r - Q_s$  at  $X = 0$ .

The storage of channel sediment in drainage basins having significant channel elements has pronounced effect on sediment transport; therefore, sediment supply must be considered for sediment transport modeling in arid environments (Hadley, 1977; Reid & Frostick, 1987). As the flood flows traverse coarse, unsaturated sediment in the

ephemeral stream channels, the sediment transport capacity decreases progressively by transmission losses of streamflow, resulting in deposition of sediment (Walters, 1990; Sharma, 1992).

The sediment dynamics can be represented by a spatially-lumped continuity equation and a linear storage law. For a time interval  $\Delta t$  (s), these relations can be written as:

$$I_s(t) = Q'_s(t) + dS_s(t)/dt \quad (8)$$

and

$$S_s(t) = K_s(t)Q'_s(t) \quad (9)$$

where  $I_s(t)$  ( $\text{kg s}^{-1}$ ) is sediment input,  $Q'_s(t)$  ( $\text{kg s}^{-1}$ ) is sediment discharge,  $S_s(t)$  (kg) is sediment storage,  $K_s(t)$  (s) is a sediment storage coefficient, and  $t$  (s) is time since the beginning of sediment discharge. By successively routing through  $n$  identical reservoirs, Sharma *et al.* (1993) obtained a sediment impulse-response function as:

$$U_s(0,t) = [(ns - 1)^{ns}/t_p | (ns - 1)] [(t/t_p)\exp(-t/t_p)]^{(ns-1)} \quad (10)$$

where  $U_s(0,t)$  ( $\text{s}^{-1}$ ) is an ordinate of instantaneous unit sediment graph (IUSG) at time  $t$ ,  $ns$  is a dimensionless shape parameter and  $t_p$  (s) is time to peak sediment discharge. The IUSG convoluted with mobilized sediment generates the sediment graph at the drainage basin outlet.

## HYDROLOGIC DATA

Data source for the present study consists of (a) plot studies at micro scale (Vich *et al.*, 1983; Sharma, 1993) conducted during 1982-1992 in the Divisadero Largo basin in the Piedmont and Precordillera region of the Andes Mountains in the west of Mendoza (33.0-33.5°S; 68.8-69.1°W), Argentina, and (b) sediment transport studies at meso and macro scales conducted during 1979-1987 in the Luni River basin located within the Indian Arid Zone (Sharma *et al.*, 1993). The range of scales, which accounts for different categories of hydrological models, is as per Becker's (1992) classification.

Six field plots of 10 m<sup>2</sup> area were established in the Divisadero Largo basin in 1982. Soils are shallow and undeveloped medium to fine sands. Vegetation yields low shrubby pastures of 5-45% cover, depending on slope. The plots were equipped to record rainfall, runoff and sediment concentrations (Fernandez *et al.*, 1984). The area has a subtropical arid climate, is characterized by convective summer thunderstorms, and annual average precipitation is 201 mm, 77% of which is received during the summer months of October to March. The average annual temperature is 13°C.

The drainage basin areas in the Luni River basin range from 104 to 34 866 km<sup>2</sup>. Hourly sediment concentration was determined from samples collected using three to five US DH-48 depth-integrating suspended-sediment hand samplers, simultaneously, 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 practice of the US Geological Survey. 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.

## RESULTS AND DISCUSSION

At micro scale, the sediment transport model (equation (4)) was validated on seven discrete flow events. A comparison of observed and predicted sediment transport shows good agreement (Fig. 1). With a coefficient of determination,  $R^2$ , of 0.996 ( $P > 0.01$ ), the observed and predicted sediment transport can be regressed by:

$$Y = 1.208X - 0.022 \quad (11)$$

where  $Y$  ( $\text{kg m}^{-2}$ ) is predicted sediment transport and  $X$  ( $\text{kg m}^{-2}$ ) is observed sediment transport. For verification of the model, error in predicted sediment transport,  $E_s$ , was calculated by the equation:

$$E_s = |Q_s'' - Q_s|/Q_s \quad (12)$$

where  $Q_s''$  is predicted sediment transport and  $Q_s$  is observed sediment transport. The average  $E_s$  was 6.8%, the maximum was 16.5% and the minimum was 2.7%.

The other sediment transport models (equations (7) and (10)) gave lower values of  $R^2$  at micro scale. Also, equation (4) shows lower  $R^2$  values at the meso and macro scales (Table 1) and is valid at micro scale only for which sediment transport is limited by soil detachment. Further, the changes in vegetation, soil compaction and crusting are critical in determining the temporal variations in sediment transport at the micro scale.

Absolute values of sediment concentration for meso-scale drainage basins receiving runoff from limestone; phyllite, schist and shale/slate; gneiss and granite; and rhyolite terrains ranged from 0.2 to 13.0  $\text{g l}^{-1}$ , 0.4 to 29.0  $\text{g l}^{-1}$ , 0.2 to 18.0  $\text{g l}^{-1}$  and 5.7 to 28.9  $\text{g l}^{-1}$ , respectively. Nearly 90% of the sediment by weight has particle sizes ranging between 0.002 and 0.2 mm.

The sediment transport models (equations (4), (7), (10)) were tested for 10 meso-

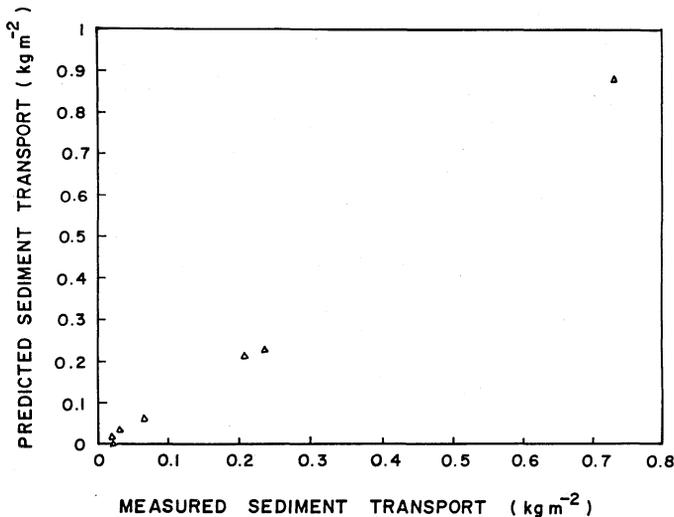
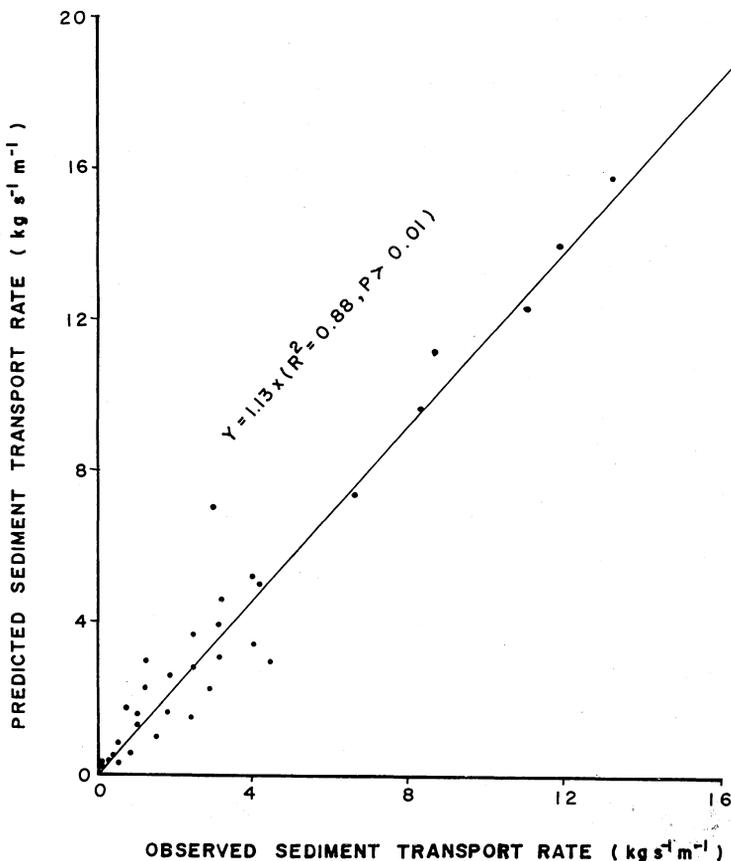


Fig. 1 Measured vs predicted sediment transport at patch scale, Mendoza, Argentina.

**Table 1** Coefficient of determination for sediment transport models at micro to macro scales.

Equation	Spatial scales:		
	Micro	Meso	Macro
(4)	0.996	0.825	0.634
(7)	0.743	0.880	0.744
(10)	0.547	0.858	0.906

scale drainage basins of 104-996 km<sup>2</sup> area. The basin complexity was accounted for by dividing the basin into three zones: upper, middle and lower, according to degree of steepness and stream order (Sharma *et al.*, 1992). The calibration options for  $T_r$  were (a) reference slope, (b) dual slope, and (c) average shear. Values of the coefficients  $K_r$ ,  $V_r/q$ ,  $C$  and  $ns$  were determined by the least-squares technique. The sediment transport equation (7) gave the highest value of  $R^2$  for the meso-scale drainage basins (Table 1). A comparison of observed and predicted sediment transport rates (Fig. 2) shows good

**Fig. 2** Comparison of observed and predicted sediment transport at meso scale, Luni River basin, India.

agreement. Furthermore, when using the optimum calibration method, the maximum deviation between the observed and predicted sediment transport rates was only 6.4%.

Increase in the sediment concentration between 1.0 and 453.0 g l<sup>-1</sup> from the macro-scale drainage basins may be attributed to the cessation of smaller flows due to transmission losses. The losses resulted in a large amount of loose material available for transport by subsequent flows of greater magnitude. Sharma *et al.* (1984) observed that 50-70% of flow events, or 54-91% of runoff, failed to reach the outlet of the macro-scale drainage basins owing to transmission losses. This is contrary to the process in humid regions, where sediment concentration is further diluted with downstream increase in the discharge.

Figure 3 compares observed and predicted sediment graphs of four macro-scale drainage basins using the IUSG technique (equation (10)). The predicted sediment graphs appear to approximate actual storm sediment graphs (average  $R^2$  is 0.906; Table 1). This implies that in arid regions, sediment transport from macro-scale drainage basins depends on the availability of erodible material in dry channels that is hydraulically controlled.

Hydrologic response depends on a hierarchy of scales: patch to drainage basin to large river basin. The parameterization of hydrologic processes at any scale must integrate the description of heterogeneous hydrologic response that is manifested at smaller scale (Sivapalan, 1993). In arid regions sediment discharges from throughout a drainage basin, but most sediment delivery is limited to major flood flows (Chang & Stow, 1988). As spatial scale increases from micro to macro, increased transmission loss progressively reduces sediment transport capacity downstream, and the increased number and extent of sediment sinks govern the amount of sediment leaving a basin. The integration of sediment transport is based on transmission losses of runoff and is obtained through a regression model:

$$V_s = a + bV_i + c[V_{up}(X,W) - V(X,W)] \quad (13)$$

where  $V_s$  (kg) is mobilized sediment;  $V_i$  (kg) is inflow sediment;  $V_{up}$  (m<sup>3</sup>) is inflow runoff volume;  $V$  (m<sup>3</sup>) is outflow runoff volume – both over a length  $X$  (m) and average width  $W$  (m); and  $a$ ,  $b$  and  $c$  are relation parameters. Equation (13) links sediment transport from micro to meso to macro scale in arid regions and accounts for sediment supply at various scales.

## CONCLUSION

Sediment transport results from soil detachment and entrainment in response to rainfall and runoff in a drainage basin. In arid regions, basin complexity increases with area; a fundamental equation of soil detachment with a detailed spatial resolution significantly predicts the sediment transport from patches (micro scale), whereas at macro scale, due to high transmission losses of runoff in the sediment sinks, conceptual physically-based models are appropriate. At meso scale, sediment transport is limited by transport capacity, for which a deposition-based equation models the sediment transport with high accuracy. Through parameterization that links mobilized sediment with the sediment input in the system and transmission loss, sediment transport is integrated at various spatial scales.

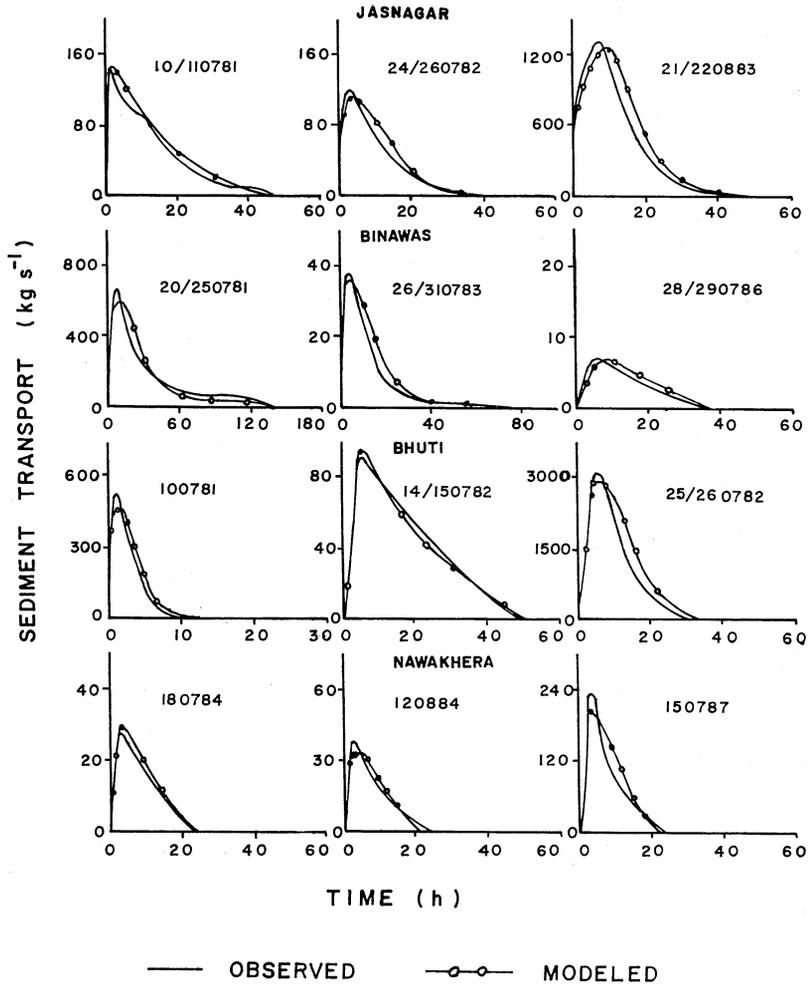


Fig. 3 Comparison of observed and predicted sediment graphs at macro scale for the range of flow, Luni River basin, India.

**Acknowledgement** Sediment transport data for the Argentina part of the study were provided by A. Vich.

## REFERENCES

- BAHC(1993) *Biospheric Aspects of the Hydrological Cycle – The Operational Plan*. The International Geosphere Biosphere Programme, Stockholm.
- Becker, A. (1992) Criteria for a hydrologically sound structuring of large scale land surface process models. In: *Advances in Theoretical Hydrology: A Tribute to James Dooge* (ed. by J. P. O'Kane), 97-111. European Geophysical Society Series on Hydrological Sciences, Elsevier, Amsterdam.
- Chang, H. H. & Stow, D. A. (1988) Sediment delivery in a coastal stream. *J. Hydrol.* **99**, 201-214.
- Fernandez, P. C., Roby, H. O., Fornero, L. A. & Maza, J. A. (1984) Telemetering hydrometeorological network in Mendoza, Argentina: one year of experiments and research. In: *Microprocessors in Operational Hydrology*, 81-90. WMO, Geneva.

- Foster, G. R. (1982) Modelling the erosion process. In: *Hydrologic Modelling of Small Watersheds* (ed. by C. T. Haan, H. P. Johnson & D. L. Brakensiek), 297-360. American Society of Agricultural Engineers, St Joseph, Missouri, USA.
- Hadley, R. F. (1977) Some concepts of erosional processes and sediment yield in a semi-arid environment. In: *Erosion: Research Techniques, Erodibility, and Sediment Delivery* (ed. by T. J. Toy), 73-81. Geo Books, Norwich, UK.
- Jones, K. R. (1981) *Arid Zone Hydrology*. FAO, Rome.
- Lane, L. J., Renard, K. G., Foster, G. R. & Laflen, J. M. (1992) Development and application of modern soil erosion prediction technology – the USDA experience. *Austral. J. Soil Res.* **30**, 893-912.
- Lu, J. Y., Cassol, E. A. & Moldenhauer, W. C. (1989) Sediment transport relationships for sand and silt loam soils. *Trans. Am. Soc. Agric. Engrs* **32**, 1923-1931.
- Magfed, Y. A. (1986) *Assessment of Water Resources in Arid and Semi-Arid Regions*. UNEP, Kenya.
- Reid, I. & Frostick, C. E. (1987) Flow dynamics and suspended sediment properties in arid zone flash floods. *Hydrol. Processes* **1**, 239-252.
- Schick, A. P. (1970) Desert floods. In: *Results on Representative and Experimental Basins* (Proc. Wellington Symp., 1970), 478-493. IAHS Publ. no. 96.
- Sharma, K. D. (1992) Runoff and sediment transport in an arid zone drainage basin. PhD Thesis, Indian Institute of Technology, Bombay.
- Sharma, K. D. (1993) Distributed numerical modelling of runoff and soil erosion using Thematic Mapper data and GIS. *Technical Report, DLO – The Winand Staring Centre for Integrated Land, Soil, and Water Research, Wageningen*.
- Sharma, K. D., Vangani, N. S. & Choudhary, J. S. (1984) Sediment transport characteristics of the desert streams in India. *J. Hydrol.* **67**, 261-272.
- Sharma, K. D., Dhir, R. P. & Murthy, J. S. R. (1992) Modelling sediment transport in arid upland basins in India. In: *Erosion, Debris Flows and Environment in Mountain Regions* (ed. by D. E. Walling, T. R. Davies & B. Hasholt) (Proc. Chengdu Symp., July 1992), 169-176. IAHS Publ. no. 209.
- Sharma, K. D., Dhir, R. P. & Murthy, J. S. R. (1993) Modelling soil erosion in arid zone drainage basins. In: *Sediment Problems: Strategies for Monitoring, Prediction and Control* (ed. by R. F. Hadley & T. Mizuyama) (Proc. Yokohama Symp., July 1993), 269-276. IAHS Publ. no. 217.
- Sivapalan, M. (1993) Linking hydrologic parameterizations across a range of scales: hillslope to catchment to region. In: *Exchange Processes at the Land Surface for a Range of Space and Time Scales* (ed. by H.-J. Bolle, R. A. Feddes & J. D. Kalma) (Proc. Yokohama Symp., July 1993), 115-123. IAHS Publ. no. 212.
- Vich, A., Pedrani, A. & Martinez Carretero, E. E. (1983) Simulador de lluvias y parcela de erosion e influencia de la vegetacion. In: *Proc. XI Congreso Nacional del Agua* (Cordoba, Argentina).
- Walters, M. O. (1990) Transmission losses in arid regions. *J. Hydraul. Div. ASCE* **116**, 2-10.
- Yalin, M. S. (1963) An expression for bed load transportation. *J. Hydraul. Div. ASCE* **89**, 221-250.