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Modelling soil erosion in arid zone drainage basins

K. D. SHARMA, R. P. DHIR
Central Arid Zone Research Institute, Jodhpur 342003, India
J. S. R. MURTHY
Indian Institute of Technology, Bombay 400076, India

Abstract Depending on the dominance of hydrological processes a closed form solution to the governing erosion equations under steady state conditions in the arid upland phase and a conceptual model of the instantaneous unit sediment graph in the ephemeral channel phase by routing the mobilized sediment through a series of linear reservoirs are developed. Combination of these two models reasonably approximates the sediment transport in the arid zone drainage basins. Sediment storage in the channel controls the sediment outflow from the drainage basins in the arid regions.

INTRODUCTION

The assessment and understanding of the soil erosion and sedimentation processes are essential components of the water resources assessment and an integral part of it, to control erosion particularly through sound land and water management techniques and to devise methods and design techniques to mitigate the harmful effects of sedimentation. Arid regions have a potential for generating and transporting large quantities of sediment (Schick, 1970; Magfed, 1986; Sharma *et al.*, 1992a) mainly due to the torrential rainfall (Bell, 1972), excessive weathering (Goudie & Wilkinson, 1977), almost total lack of natural protection against detachment of soil due to sparse vegetative cover (Pilgrim *et al.*, 1988), aeolian surficial deposits providing readily available material to be eroded by runoff (Jones, 1981), and increased biotic interference (FAO, 1973). In the present study, depending on the dominance of processes the arid zone drainage basin is conceptualized into an upland phase – where the runoff is only related to rainfall at the drainage basin viz. the hilly/mountainous region; and a channel phase – where the transmission losses play an important role; separate sediment transport models are developed for them and coupled to predict the sediment transport at the drainage basin outlet.

THEORY

Upland phase

Sediment movement downslope obeys the principle of continuity of mass expressed by (Nearing *et al.*, 1989):

$$\frac{\alpha O_s}{\alpha x} = D_F + R_{DT} \tag{1}$$

where O_s (kg s^{-1} m^{-1}) is mass transport rate per unit of width, x (m) is downslope distance, D_F (kg s^{-1} m^{-2}) is net rainfall detachment rate. The assumption of quasi-steady state allows deletion of time terms from the equation (1). Further, R_{DT} in negligible since the transport capacity of rain splash is very low. D_F in arid regions, where the initial potential load is always in excess of the transport capacity (Foster *et al.*, 1980; Sharma, 1992), has been estimated by a first order reaction model of the type

$$D_F = G(T_C - O_s) \tag{2}$$

where G (m^{-1}) is a first order reaction coefficient and T_c (kg s^{-1} m^{-1}) is transport capacity of runoff estimated from the modified Yalin equation which is capable of dealing with mixtures of particles of varying diameter and density (Foster, 1982).

Combining equations (1) and (2) the upland soil erosion model is derived as

$$\frac{\alpha O_s}{\alpha X} - GO_s - GT_c = O \tag{3}$$

Equation (3) is a linear nonhomogeneous ordinary differential equation which can be solved analytically as

$$\ln(T_c - O_s) = -GX + \ln C \tag{4}$$

where C (kg m^{-1} s^{-1}) is integration constant and is equal to $T_c - O_s$ at $X = O$. Conceptually, the outlet of upland basin may be considered as a gate which controls the amount of sediment leaving the basin. Steeper slopes at the outlet may result in higher sediment discharge rates because of greater soil detachment rates within the basin. When the slope at the outlet is reduced, large amounts of sediment may be deposited rapidly. Therefore, the conditions at the upland basin outlet could be used to calibrate T_c, with the expectation that the upland soil erosion model (equation (4)) would provide the greatest degree of accuracy at this critical location. The calibration options are (a) reference slope, (b) dual slope, and (c) average shear (Sharma *et al.* 1992b).

Channel phase

The channel storage of sediment in the arid ephemeral steams has greater effect on sediment transport and therefore, sediment supply has to be taken into account for sediment transport modelling in the arid environments (Hadley, 1977; Reid & Frostick, 1987). In fact, as the flood flows traverse coarse, unsaturated sediments in the ephemeral channels the sediment transport capacity reduced progressively by transmission losses of the flood flows resulting in deposition of sediment (Walters, 1990; Sharma, 1992).

Sediment transport in the channel can be represented by a spatially lumped continuity equation and a linear storage law. For time interval Δt (s), these can be written as

$$I_s(t) = O_s(t) + \frac{\mathrm{d}s_s(t)}{\mathrm{d}t} \tag{5}$$

and

$$S_s = K_s\, O_s^{'} \tag{6}$$

where I_s (kg s^{-1}) is sediment input, O_s' (kg s^{-1}) is sediment discharge, S_s (kg) is sediment storage, K_s (s) is sediment storage coefficient and t (s) is time since beginning of sediment discharge. For an instantaneous sediment inflow to the channel the outflow from the first linear reservoir is

$$O_s^{'}(t) = \frac{V_s}{K_s}\exp(-t/k_s) \tag{7}$$

where V_s (kg) is mobilized sediment. By successively routing through n reservoirs, the sediment outflow from nth reservoir is

$$O_s^{'}(t) = \frac{V_s}{K_s\sqrt{n_s}}\,(\frac{t}{t_p})^{n_s-1}\ \exp\,(-t/K_s) \tag{8}$$

where n_s is a dimensionless shape parameter and Γ is Gamma function. Differentiating equation (8) with respect to time and using the condition $\mathrm{d}O_s'/\mathrm{d}t = 0$ at $t = t\rho$ ($t\rho$ (s) is time to peak sediment discharge) one gets

$$t_p = (n_s - 1)K_s \tag{9}$$

On substituting the value of K_s ($K_s = t_p/(n_s - 1)$ from equation (9) to equation (8) the sediment impulse response becomes

$$U_s(O,t) = \frac{O_s^{'}(t)}{V_s} = \frac{n_{s-1}^{n_s}}{t_p\sqrt{n_s}}\left[(\frac{t}{t_p})\exp(-t/t_p)\right]^{n_s-1} \tag{10}$$

where U_s (0, t) (s^{-1}) is the ordinate of instantaneous unit sediment graph (IUSG) at time t. The IUSG convoluted with the mobilized sediment generates the sediment graph at the drainage basin outlet. V_s in the present study was calculated by a regression model.

$$V_s = a + b\,V_I + c\big[V_{up}(x,w) - V(x,w)\big] \tag{11}$$

where V_I (kg) is inflow sediment calculated from the area integration of upland sediment graph (equation 4); V_{up} (m^3) is inflow runoff volume, V (m^3) is outflow runoff volume both in a channel reach of length x (m) and average width W (m); and a, b and c are relationship parameters.

EVALUATION OF THE MODELS

The upland sediment transport model was tested for 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.*, 1992c). Basin complexity was accounted for by dividing the basin into three zones, namely, upper, middle and lower according to degree of steepness and the stream order (Sharma & Murthy, 1990). Values of G and C were determined by the least squares technique at each stage of the flow hydrograph viz. rising, peak and recession for 90, 68 and 76 events, respectively.

The reference slope, dual slope and average shear methods of calibrating G and C were evaluated using independent events for each stage of the hydrography (Table 1). For the rising stage the root mean squared difference was consistently the lowest with the reference slope method. This is because the desert streams convey the highest sediment concentration during the rising stage (Sharma *et al*, 1984) which may be attributed to the abundance of loose soil within the basin due to weathering and drying and the near constant soil surface condition produced by preceding wet and dry phases; and thus, the average conditions within the basin ie., the mean/reference slope controls the sediment transport rates. At the peak flow the flow conditions within the basin are at equilibrium i.e. $\mathrm{d}O/\mathrm{d}t \rightarrow 0$; where O ($\mathrm{m}^3\ \mathrm{s}^{-1}$) is discharge and t (s) is time; and the reduced slopes at the basin outlets result in the deposition of a significant proportion of the sediment eroded from the upstream area before it leaves the basin. Therefore, the dual slope method of calibration resulted in the least root mean squared difference. Finkner *et al.* (1989) also found the best agreement using the dual slope method of calibrating the sediment transport models. However, at recession the receding flow deposits sediment throughout the basin, since the actual flow velocity is reduced below the critical value. This results in a rapid decrease in the sediment concentration towards the end of the flow. Consequently the average shear stress has the least root mean squared difference, since it represents not only the basin slope but also the combination of slope and discharge and its cumulative effect at the outlet.

A comparison of observed and predicted sediment transport rates (Fig. 1) shows good agreement. Furthermore, when using the optimum calibration method, the maximum deviation between the observed and predicted sediment transport rates was always less than 10% (Table 1).

As a test to verify and validate the IUSG concept of sediment transport in the channel phase observed sediment graphs for four representative channels covering the

Table 1 Summary of statistical analysis of calibration methods for the upland soil erosion model.

Hydrograph stage	Calibration method	Sum of squares difference	Root mean squared (%)	Maximum deviation	No. of observations
Rising	Reference slope	3.46	0.20	6.1	84
	Dual slope	4.73	0.24	6.4	
	Average shear	5.75	0.26	15.0	
Peak	Reference slope	114.51	1.33	25.5	65
	Dual slope	41.68	0.80		
	Average shear	43.95	0.82		
Recession	Reference slope	3.73	0.23	31.2	70
	Dual slope	1.21	0.13	4.5	
	Average shear	1.03	0.12	3.9	

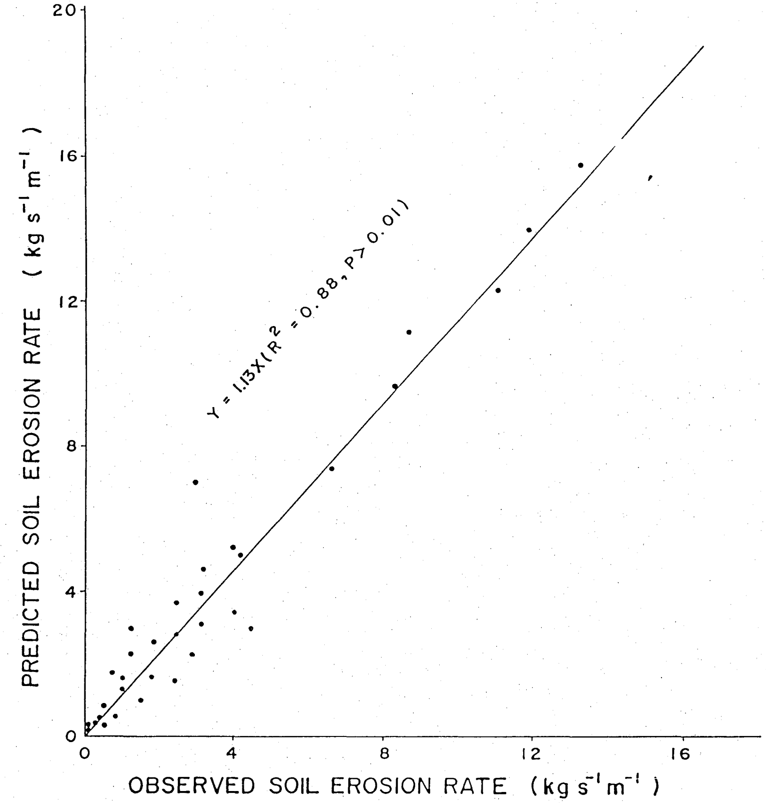

Fig. 1 Comparison of observed and predicted upland soil erosion rates.

Table 2 Time and shape parameters of the analysed storm events.

Drainage basin	Date	Time parameters: Time to peak, t_p (h)	Storage coefficient K_s (h)	Shape parameter n_s
Jasnagar	100781	1.00	32	1.03
	240782	2.00	23	1.09
	220883	7.00	6	2.17
Binawas	200781	2.00	4	1.50
	260783	2.00	12	1.17
	280786	0.50	20	1.03
Bhuti	100781	1.80	10	1.18
	140782	0.83	17	1.05
	250782	4.50	6	1.75
Nawakhera	180784	2.00	19	1.11
	120884	1.83	16	1.11
	150787	2.00	13	1.15

Table 3 Parameter values of sediment mobilization model (equation 11).

Channel reach	a	b	c	R^2	Number of events
Alniawas-Jasnagar	1119	0.61	-0.0001	0.99**	9
Pipar-Binawas*	259	0.10	-20.5840	0.98**	5
Sanderao-Bhuti	-4998	1.29	-0.0011	0.96**	8
Posalia-Nawakhera	4294	-0.03	0.0001	0.95	15

* Disorganized, loosing stream
** $P > 0.01$

dominant lithologies encountered in the Luni basin were compared with the corresponding sediment graphs obtained form the model. For these drainage basins, the peak runoff rate and the maximum sediment transport rate coincides for the individual

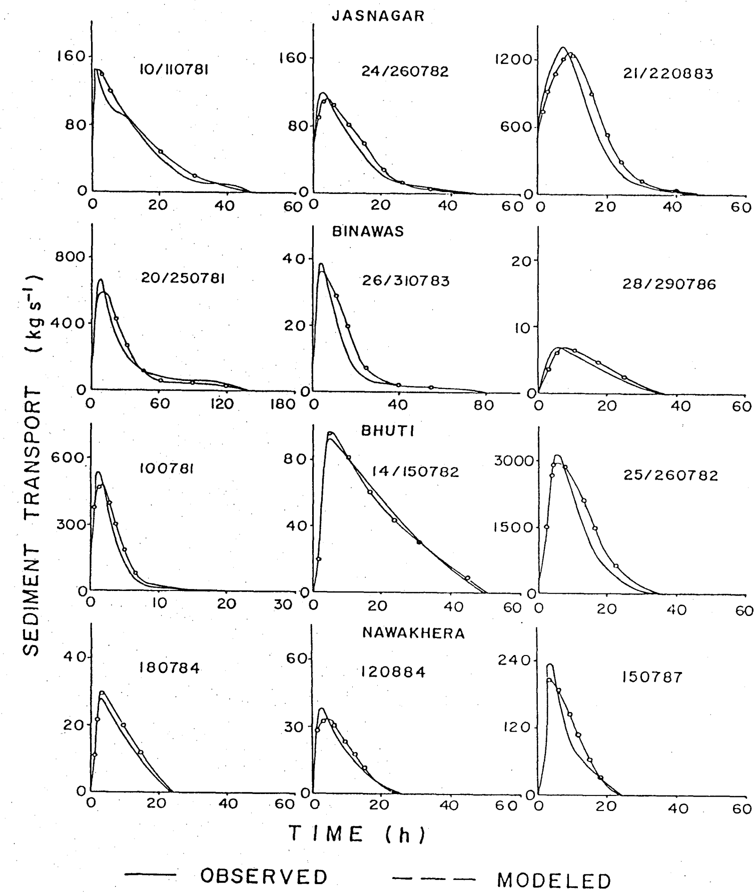

Fig. 2 Comparison of observed and predicted sediment graphs at the drainage basin outlet.

storms. The IUSG parameters t_p was taken from a regression model between the peak flow and time to peak at the drainage basin outlet and k_s was approximately considered as equivalent to the travel time of runoff crests in the main trunk of stream (Sharma, 1992). These parameters for the analysed events at the outlet sections of the study drainage basins are shown in Table 2. Parameter values of sediment mobilization model (equation (11)) are also given in Table 3.

Fig. 2 depicts the comparison of the observed and predicted sediment graphs at the drainage basin outlet. The sediment graphs generated by the IUSG technique are noted to be good approximation to the actual storm sediment graphs (coefficient of determination for the hourly sediment transport rates between the observed and modelled curves vary form 0.898 to 0.955; $p > 0.01$). This implies that in the arid zone drainage basins the sediment transport is dependent on the availability of erodible material in the channel which is hydraulically controlled.

CONCLUSION

Different hydrological processes dominate in the upland and channel phases of the arid zone drainage basins. Combination of a physically based model of sediment transport in the upland phase and instantaneous unit sediment graph model in the channel phase shows a close agreement between the computed and observed sediment transport rates at the outlets to the drainage basins. By means of this simple approach, in which a limited number of parameters are involved, a reasonable accuracy is attained that satisfies practical requirements in the arid region.

In the arid environment the sediment supply has to be taken into account for the soil erosion/sediment transport studies.

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REFERENCES

Bell, F. C. (1972) Precipitation. In: *Arid Land Ecosystems* (ed. by D. W. Goodall & R. A. Perry), 373-392. Cambridge University Press, London.

FAO (1973) *Man's Influence on the Hydrological Cycle.* FAO, Rome.

Finkner, S. C., Nearing, M. A., Foster, G. R. & Gilley, J. E. (1989) A simplified equation for modelling sediment transport capacity. *Trans. Am. Soc. Agric. Engrs* **32**, 1545-1550.

Foster, G. R. (1982) Modelling the Erosion Process. In: *Hydrologic Modelling for Small Watersheds* (ed. C. T. Hann, H. P. Johnson & D. L. Brakensiek), 297-360. American Society of Agricultural Engineers, St Joseph, Michigan, USA.

Foster, G. R., Lane, L. J., Nowlin, J. D., Laflen, J. M. & Young, R. A. (1980) A model to estimate sediment yield from field sized areas. In: CREAMS – *A field scale model for Chemicals, Runoff and Erosion from Agricultural Management Systems.* (ed. by W. Knisel), 34-64. USDA, Conservation Research Report No. 26, Beltsville.

Goudie, A. & Wilkinson, J. (1977) *The Warm Desert Environment.* Cambridge University Press, London.

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.

Jones, K. R. (1981) *Arid Zone Hydrology*. FAO, Rome

Magfed, Y. A. (1986) *Assessment of Water Resources in Arid and Semi Arid Regions*. UNEP, Kenya.

Nearing, M. A., Foster, G. R., Lane, L. J. & Finkner, S. C. (1989) A process based soil erosion model for USDA – Water erosion prediction project technology. *Trans. Am. Soc. Agric. Engrs* **32**, 1587-1593.

Pilgrim, D. H., Chapman, T. C. & Doran, D. G. (1988) Problems of rainfall-runoff modelling in arid and semi arid regions. *Hydrol. Sci. J.* **33**, 379-400.

Reid, I. & Frostick, L. 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 Symposium), 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, India.

Sharma, K. D. & Murthy, J. S. R. (1990) A physically based deterministic model of sediment transport form arid upland basins. In: *Water Erosion, Sediment Transport and Resource Conservation* (Proc. Dehradun Symposium), **42**.

Sharma, K. D., Vangani, N. S. & Choudhari, 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. (1992a) Modelling suspended sediment flow in arid upland basins. *J. Hydrol.* **37**.

Sharma, K. D., Dhir, R. P. & Murthy, J. S. R. (1992b) 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 Symposium, July 1992), 169-176. IAHS Publ no. 209.

Sharma, K. D., Murthy, J. S. R. & Dhir, R. P. (1992c) Streamflow routing in the Indian arid zone. *Hydrol. Processes* (in press).

Walters, M. O. (1990) Transmission losses in arid region. *J. Hydraul. Div. ASCE* **116**, 129-138.