Stochastic geomorphology – implications for monitoring and interpreting erosion and sediment yields in mountain drainage basins

LEE BENDA
Department of Geological Sciences, AJ-20, University of Washington, Seattle, Washington 98195, USA

Abstract Field measurements and a simulation model are used to analyze how interactions among sediment supply by mass wasting, channel network topology, and abrasion govern sediment routing and storage in a 200 km^2 basin in the Oregon Coast Range. Non-steady and non-uniform delivery of colluvium to channels creates (a) bed load waves at many scales and (b) pulses of suspended sediment, the frequency characteristics of which vary with network topology and drainage area. A Hurst effect in time series of bed and suspended loads indicates that low-frequency cycles of variability in sediment yield leads to large errors when extrapolating in time and space measurements obtained over short periods. Measurement times for characterizing sediment yield at a site extend from decades for small channels to centuries for large channels. In humid mountain environments, bed load, suspended load and channel environments are usefully characterized by frequency distributions.

INTRODUCTION

It is becoming increasingly important to interpret erosion and sediment yields accurately to understand the effects in small basins, often in mountainous terrain, of land uses such as forestry, grazing and mining, on the dependent parameters of water quality and aquatic habitat (Dunne, 1984). As sediment monitoring programs extend up drainage networks into small sub-basins (e.g. 10^1-10^2 km^2), closer to erosion sources, the potential for significant spatial and temporal variability in the measured variables increases. Recognizing this potential, pertinent questions to be addressed when beginning a monitoring program are (a) how are suspended and bed load transport and channel morphology affected by sediment supply (e.g. process, frequency, magnitude, spatial distribution and particle size); (b) how variable are sediment concentration and yield and how are they influenced by climatic fluctuations, spatial scale and network topology; and (c) can erosion, sediment yield or channel environment be adequately represented and monitored using a single value or condition? These questions are difficult because they involve temporal aspects of erosion and sediment routing, yet long time series of field data on erosion and sediment transport are generally unavailable in mountain basins. A field measurement program in the Oregon Coast Range is used with a simulation model to investigate time-variable aspects of erosion and sediment routing to address the above questions. Field observations indicate that simulation reliably represents sedimentation conditions in the Oregon Coast Range (Benda, 1988; 1990; Benda & Dunne, 1987).

EROSION IN THE OREGON COAST RANGE AND THE SIMULATION MODEL

The humid landscape of the central Oregon Coast Range is forested by Douglas fir (*Pseudotsuga menziesii*) and western hemlock (*Tsuga heterophylla*). This community, termed the western hemlock zone (Franklin & Dyrness, 1973), is a consequence of a mild mediterranean climate of rainy winters (2100 mm year^{-1}) and dry summers. Large, intense rainstorms periodically trigger shallow landslides in colluvium-filled bedrock hollows on steep hillslopes, and episodic and infrequent wildfires kill large areas of forest and reduce vegetative root strength, leading to landsliding. Shallow landslides often initiate debris flows that scour accumulated sediment from the floors of first and second order channels and deposit sediment into higher order channels (Benda & Dunne, 1987).

Field measurements define principal sediment routing pathways in the Oregon Coast Range, including shallow landslides in bedrock hollows, debris flow scour and fluvial transport in first and second order channels, bank erosion of debris flow fans and terraces and soil creep along hill sides (Dietrich & Dunne, 1978; Benda, 1988; Reneau & Dietrich, 1991). These sediment routing processes are simulated by a computer model for the 215 km^2 North Fork Smith River basin of the central Oregon Coast Range (Fig. 1). The mass flux of hillslope erosion (i) in the study basin is governed by a multivariate function written in general form as:

$(i) = f\{$bedrock and soil geometries, soil mechanical and hydrologic properties, root strength, soil accumulation rate and wildfire and rainfall characteristics$\}$ (1)

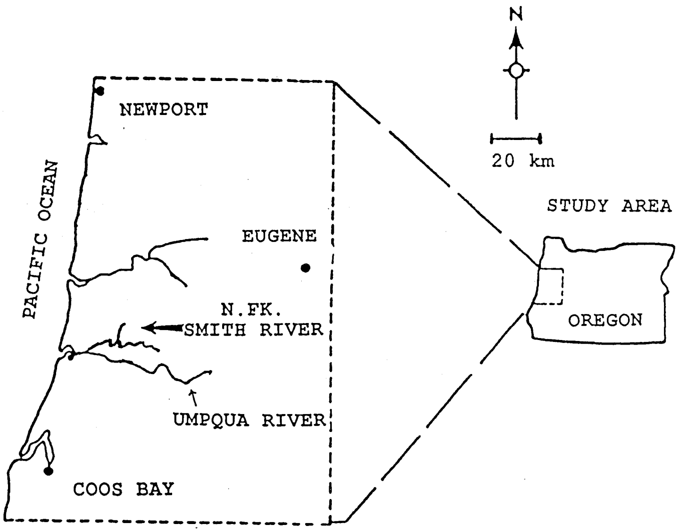

Fig. 1 Map of study area, showing North Fork Smith River in the central Oregon Coast Range, USA.

Erosion, (*i*), is highly stochastic in time and space because it is strongly influenced by rainfall and wildfires and by spatial and temporal variation in land forms, including gradient, convergence angles and depth of colluvial wedges in bedrock hollows; both help determine the probability of landsliding. Furthermore, the probability of landsliding at one time may be related to climate (i.e. timing and magnitude of fires and storms) of earlier decades and centuries (Benda, 1994).

The sediment transport continuity equation for total load in third and higher order channels is solved in the simulation model and in general form is:

$$Qs(x)_{inflow} - Qs(x)_{outflow} + (i) = \Delta S \qquad (2)$$

in which $Qs(x)_{inflow}$ is annual volume of bed load and suspended load (particles <0.25 mm) entering the channel reach of fixed length from upstream; $Qs(x)_{outflow}$ is annual volume of bed load and suspended load leaving the reach; (*i*) is annual volume of colluvium from hillslopes, including debris flow and fluvial sediment yield from first and second order channels along the length of the reach and ΔS is annual change in sediment storage volume in the reach (Benda, 1994).

EFFECT OF BASIN SIZE ON VARIABILITY OF SEDIMENT ROUTING

Model predictions for three channel segments with drainage areas of 3, 25 and 200 km^2 (third through sixth order) illustrate how basin size influences temporal variability of sediment routing. Total sediment yields in a third order channel of drainage area 3 km^2 for a 3000 year period of the latest Holocene are shown in Fig. 2. The long-term sediment yield in the channel is about 60 t km^{-2} year^{-1}, but the time series is characterized by periods of a few centuries that are sediment supply limited, when sediment yield is approximately 30 t km^{-2} year^{-1}. These long periods are punctuated by short periods when sediment supply is non-limited – a few decades when yields are greater than 150 t km^{-2} year^{-1} and individual years are above 300 t km^{-2} year^{-1}. During these periods landslides and debris flows deposit large volumes of sediment in the channel; thus, mean sediment yield does not usefully represent basin erosion and sediment routing in the channel segment.

High suspended sediment yield in the third order segment, generated during mining of stored colluvium, lasts only until the deposit is depleted, years to a couple of decades. In contrast, bed load from these deposits may remain in the channel network much longer and move downstream as waves with velocities of about 10^2 m year^{-1}). Bed load waves have finite durations, defined in terms of time or travel distance, because they attenuate downstream due to particle abrasion, channel widening and storage (Benda, 1994). Therefore, suspended load and bed load from the same deposit are routed out of phase.

Predictions of bed load to total load (*BL*/*TL*) in a fourth order channel of drainage area 25 km^2 are shown in Fig. 3. Although the average *BL*/*TL* is 0.25, annual values range between 0.1 and 0.6; hence, the long-term average is a poor representation of bed load, suspended load and total sediment yield.

Yields of bed load and suspended load in a sixth order channel draining a basin of 200 km^2 are plotted in Fig. 4. The variability in sediment yields is much less than in

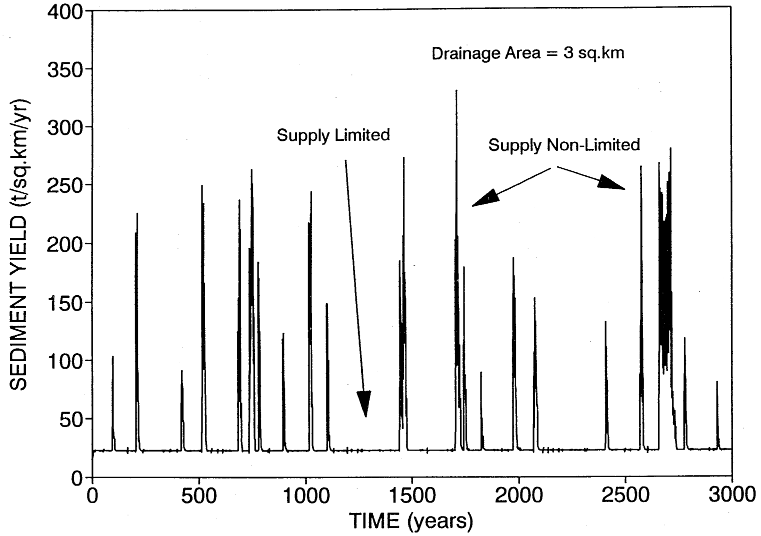

Fig. 2 Graph showing simulated total sediment yields for a 3000 year period of the latest Holocene for a channel segment with a drainage area of 3 km^2.

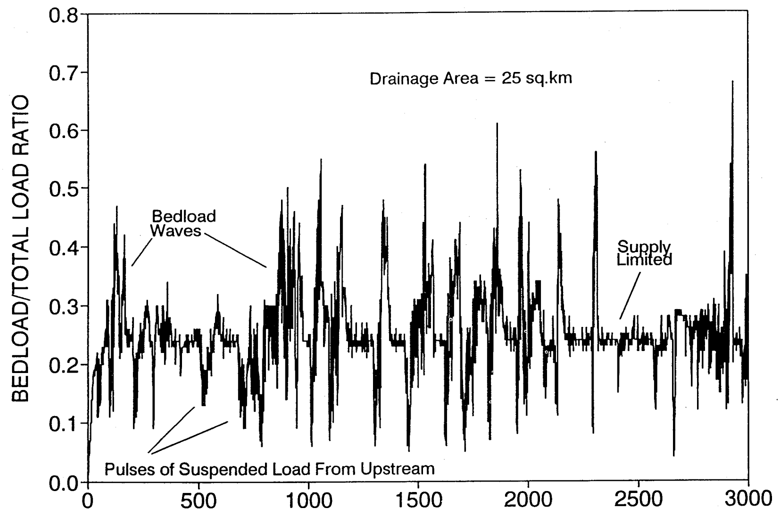

Fig. 3 Graph showing simulated ratios of bed load to total load (*BL*/*TL*) for a 3000 year period of the latest Holocene for a channel segment with a drainage area of 25 km^2. *BL*/*TL* of approximately 0.1 represents periods when pulses of suspended load generated from erosion upstream pass through the segment; *BL*/*TL* values of 0.4 to 0.6 correspond to bed load waves passing through the channel segment.

segments upstream, although variability around the long-term mean, approximately 70 t km^{-2} $year^{-1}$, is about 100%. Variation in bed load does not correspond closely with variation in suspended load because different particle sizes travel out of phase and

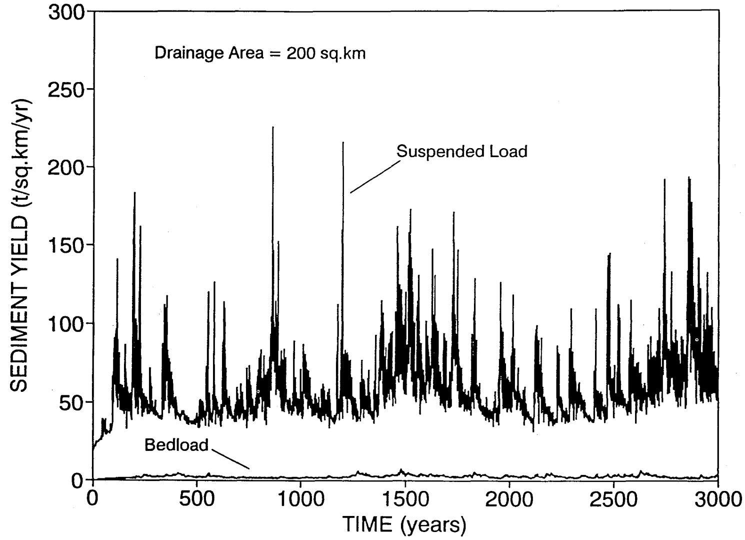

Fig. 4 Graph showing simulated bed load and suspended load yields for a 3000 year period of the latest Holocene for a channel segment with a drainage area of 200 km^2.

because suspended load from anywhere in the basin is additive at tributary confluences. Bed load, however, originates only in nearby upstream areas because of the attenuating effect of particle breakdown (i.e., bed load derived from mechanically weak rocks far upstream never reaches the sixth order segment).

The effect of drainage area on sediment routing is apparent by comparing Figs 2, 3 and 4. The channel below a 3 km^2 drainage area has sediment yields that vary by more than 10 fold at a frequency of one pulse every 150 years (Fig. 2), whereas for a 200 km^2 basin area, a higher frequency of variation in sediment routing, once every several years to a decade, occurs with a 2 to 3 fold range (Fig. 4). Although the time series of sediment yield for the 25 km^2 basin area is not shown, variation in sediment yield occurs at a frequency of 50 to 100 years and a 4 fold magnitude (Benda, 1994).

THE HURST EFFECT AND EXTRAPOLATION OF MEASUREMENTS

Commonly, erosion rates or sediment yields are estimated for short time periods, are extrapolated in time or space and then are used as standards to judge erosional behavior of a basin. Field data on erosion rates or sediment yields collected over periods of up to a couple of decades may not reveal significant variability, but low frequency cycles of variation may occur (Figs 2, 3 and 4), leading to error when extrapolating rates in time or space. This phenomenon, in hydrology, is the Hurst effect (Klemes, 1974; Kirkby, 1987); Kirkby (1987, p. 64) warns that "...estimates of long-term variability and the reliability of the sample mean as an estimate of the long-term mean are likely to be optimistic and ...direct extrapolations of the short-term mean may be seen to be of little value".

A value termed the Hurst coefficient is calculated by comparing the logarithm of the rescaled range, R_n/S_n, against the logarithm of the length of record, n, in which R_n is the sample range of cumulative departures from the mean and S_n is the standard deviation of the time series. Hurst (1950; 1957) found that in long geophysical records (i.e., 2000 year Nile River discharge records), $R_n/S_n \sim n^h$, in which h varied from 1 to 0.5 and typically was in the range 0.7 to 0.8, indicating low frequency cycles of variation. Statistical theory of stationary stochastic processes, however, requires that h equals 0.5 and, therefore, does not allow low frequency cycles. This discrepancy between theory and physically inexplicable h values of 0.7 and 0.8 in some data sets is termed the "Hurst Phenomenon" (Klemes, 1974). For mathematical formulations of the Hurst coefficient, see Hurst (1957), Klemes (1974) or Kirkby (1987).

Hurst coefficients for suspended load were calculated for four channel segments with drainage areas of 3, 25, 61 and 200 km^2 as a function of time series length (Benda, 1994). All of the channel segments exhibited Hurst effects with $0.8 < h < 0.7$ after at least several decades. Analysis of bed load and stored channel sediment for the segments showed similar Hurst coefficients. The origin of the Hurst effect in the simulation results is the episodic transfer of sediment from storage reservoirs of bedrock hollows, by landsliding, and first and second order channels, by debris flow, to third through sixth order channel storage reservoirs.

A FREQUENCY APPROACH TO CHARACTERIZING SEDIMENT YIELD AND CHANNEL STATE

Where channels of a drainage network receive episodic waves of bed load and pulses of suspended load from colluvium, sediment transport rates estimated during short periods may not be adequate for understanding the natural erosion regime or for establishing regulatory standards. As an alternative approach in dynamic mountainous environments, frequency distributions may be used to characterize and understand better basin erosion rates and channel environments or states. To illustrate, frequency distributions of suspended load and channel sediment for two channels draining areas of 25 and 200 km^2 are shown in Figs 5 and 6. The form of the frequency distribution of suspended sediment varies according to drainage area (Fig. 5); the frequency distribution evolves from approximately exponential to lognormal as drainage area increases. Similarly, Fig. 6 shows that the most probable channel condition (in approximately 90% of years) for the 200 km^2 basin is sediment supply limited (i.e., bedrock floored or sediment depths less than 0.4 m) because of high particle attrition in the mechanically weak sandstone of the Oregon Coast Range. The frequency distribution of bed material in the 25 km^2 basin (Fig. 6) predicts that a supply-limited environment will continue to dominate, but with a 30% probability of aggradation (i.e., from bed load waves and episodic landslides). Changes in channel morphology or channel state that correspond to changes in channel stored sediment also can be represented by frequency distributions (Benda, 1994).

MONITORING AND INTERPRETING EROSION AND SEDIMENT YIELDS IN MOUNTAIN ENVIRONMENTS

Simulation results of this paper pertain specifically to the physical environment of the

Oregon Coast Range. Aspects of the analysis indicate, however, that mass wasting, network topology and particle abrasion that modulate sediment routing and storage may apply to other humid mountain landscapes, including those in which mass wasting is from large, continuously active features such as earth flows (Swanston, 1981) and where the episodic effects are due to influences such as earthquakes (Hara & Yazawa, 1987). Implications of the simulation analyses for monitoring and interpreting erosion and sediment yield in mountain basins include:

(a) Short-term sampling of sediment transport should not be extrapolated far in time or across a large spatial scale to characterize basin erosion regimes, either natural or imposed, because of the potential for large temporal and spatial variability. Both

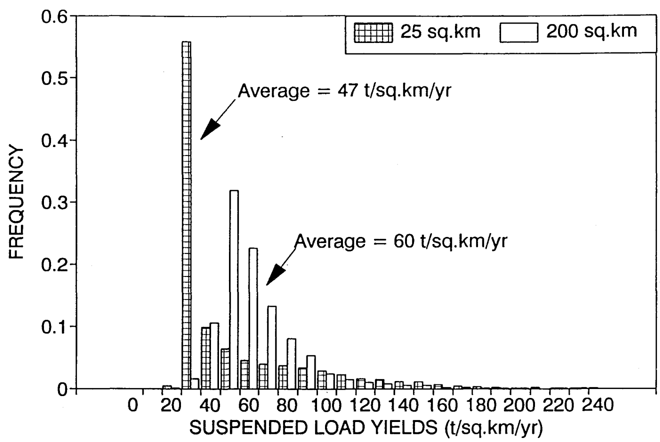

Fig. 5 Graph showing two frequency distributions of suspended sediment yield (obtained from simulated 3000 year time series) for channel segments with drainage areas of 25 and 200 km^2.

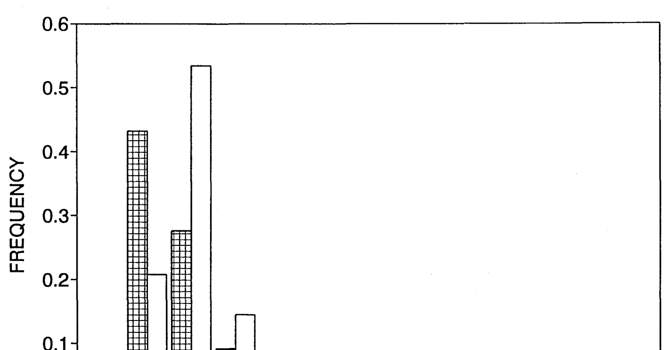

Fig. 6 Graph showing two frequency distributions of channel stored sediment (obtained from simulated 3000 year time series) for channel segments with drainage areas of 25 and 200 km^2.

temporal and spatial variability in sediment routing should increase with decreasing basin size.

(b) Single values of sediment transport, such as means, or single channel states measured over short periods may not be sufficiently representative for establishing performance standards or thresholds because time-invariant standards may not be met under natural conditions.

(c) Monitoring changes of substrate size, pool geometry, channel storage, etc. in channels and flood plains are best linked to hillslope processes and land use and are more useful than is monitoring in-stream sediment transport to assess basins.

(d) In recognition of implications (a), (b) and (c), a field-based analysis of erosion, sediment storage and sediment routing (i.e., sediment budget) might be used to supplant or augment in-stream sediment monitoring.

(e) Frequency distributions of sediment yield or channel morphology may be useful in determining whether land use has caused landscape shifts in those distributions having important ecological ramifications.

Acknowledgement This research was funded by the US Forest Service, Pacific Northwest Research Stations in Corvallis, Oregon, Seattle, Washington and Juneau, Arkansas. J. K. Agee assisted in the development of the wildfire model and J. Gabrielson coded the computer simulation model. I would like to thank Thomas Dunne for reviewing this manuscript. All errors are the responsibility of the author.

REFERENCES

Bende, L. (1988) Debris flows in the Oregon Coast Range. Unpublished MS Thesis, Dept Geol. Sci., Univ. Washington, Seattle, Washington.

Benda, L. (1990) The influence of debris flows on channels and valley floors of the Oregon Coast Range, USA. *Earth Surf. Processes & Landforms* **15**, 457-466.

Benda, L. (1994) Stochastic geomorphology in a humid mountain landscape. Unpublished PhD dissertation, Dept Geol. Sci., Univ. Washington, Seattle, Washington.

Benda, L. & Dunne, T. (1987) Sediment routing by debris flows. In: *Erosion and Sedimentation in the Pacific Rim* (ed. by R. L. Beschta, T. Blinn, G. E. Grant, G. G. Ice & F. J. Swanson) (Proc. Corvallis Symp., August 1987). IAHS Publ. no. 165.

Dietrich, W. E. & Dunne, T. (1978) Sediment budget for a small catchment in mountainous terrain. *Z. Geomorphol.* Suppl. Bd. **29**, 191-206.

Dunne, T. (1984) The prediction of erosion in forests. Keynote address at Symp. *Effects of Forest Land Use on Erosion and Slope Stability*. East-West Center, Univ. Hawaii, Honolulu.

Franklin, J. F. & Dyrness, C. T. (1973) Natural vegetation of Oregon and Washington. *USDA For. Serv. Gen. Tech. Rep.* PNW-8.

Hara, Y. & Yazawa, A. (1987) Ontake landslide of September 14, 1984, in Japan. In: *Erosion and Sedimentation in the Pacific Rim* (ed. by R. L. Beschta, T. Blinn, G. E. Grant, G. G. Ice & F. J. Swanson) (Proc. Corvallis Symp., August 1987). IAHS Publ. no. 165.

Hurst, H. E. (1950) Long-term storage capacity of reservoirs. *Proc. ASCE* **76**, 11.

Hurst, H. E. (1957) A suggested statistical model of some time series which occur in nature. *Nature* **180**, 494.

Kirkby, M. J. (1987) The Hurst effect and its implications for extrapolating process rates. *Earth Surf. Processes & Landforms* **12**, 57-67.

Klemes, V. (1974) The Hurst phenomenon: a puzzle? *Wat. Resour. Res.* **10**, 675-688.

Reneau, S. L. & Dietrich, W. E. (1991) Erosion rates in the southern Oregon Coast Range: evidence for an equilibrium between hillslope erosion and sediment yield. *Earth Surf. Processes & Landforms* **16**, 307-322.

Swanston, D. N. (1981) Creep and earthflow erosion from undisturbed and management impacted slopes in the Coast and Cascade Ranges of the Pacific Northwest, USA. In: *Erosion and Sediment Transport in Pacific Rim Steeplands* (ed. by R. H. Timothy *et al.*) (Proc. Christchurch Symp., January 1981), 76-95. IAHS Publ. no. 132.