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Identifying trends in sediment discharge from alterations in upstream land use

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Abstract Environmental monitoring is a primary reason for collecting sediment data. One emphasis of this monitoring is identification of trends in suspended sediment discharge. A stochastic equation was used to generate time series of annual suspended sediment discharges using statistics from gaging stations with drainage areas between 1606 and 1 805 230 km^2. Annual sediment discharge was increased linearly to yield a given increase at the end of a fixed period and trend statistics were computed for each simulation series using Kendal's tau (at 0.05 significance level). A parameter was calculated from two factors that control trend detection time: (a) the magnitude of change in sediment discharge, and (b) the natural variability of sediment discharge. In this analysis the detection of a trend at most stations is well over 100 years for a 20% increase in sediment discharge. Further research is needed to assess the sensitivity of detecting trends at sediment stations.

INTRODUCTION

Fifty years ago, emphasis on monitoring sediment discharges was related to storage requirements and life expectancies of reservoirs. Since then the objectives for measuring sediment discharge have changed as environmental monitoring has become a primary motivation for the collection of sediment data. This change has shifted the focus of sediment data collection and analysis. For example, the identification of time trends in sediment discharge may signal changes in upstream land use or identify the success of environmental laws. The sediment gage monitors upstream changes in the basin and identification of trends at the gage justifies an examination to find upstream causes for sediment discharge change.

Identifying trends in sediment discharge is difficult because of inherent variability in the record. It is questionable whether a trend can be determined from a gage record and it is interesting to speculate on the magnitude of change in sediment discharge needed to detect a trend. This paper examines variability of annual sediment discharge at 24 daily sediment gages and the magnitude of change in sediment discharge needed to identify a trend in these annual values.

Only daily sediment stations are examined. These are stations at which sediment sampling is sufficient to interpolate between values and provide a daily sediment discharge assumed accurate. These daily values are summed to give an annual suspended sediment discharge used in this analysis. Periodic record (less than daily sampling) is not used to determine annual suspended sediment discharge because of the additional error associated with extrapolation methods. Determination of error from techniques used to extrapolate sediment discharges (Ferguson, 1986; Hanson & Bray, 1987; Osterkamp, 1977; Farr & Clarke, 1984; Kellerhals Engineering Services, 1985; Walling, 1977; Walling & Webb, 1981; 1988) and the incorporation of this error in trend detection is beyond the scope of this paper.

VARIABILITY OF SEDIMENT DISCHARGE

Identification of a land use change leads to a search for detectable trends in a sediment discharge record. The linkages are: (a) from change in sediment discharge derived from land use change, (b) to transfer (Walling, 1983; Ongley, 1987) of the sediment discharge downstream (sediment delivery), and (c) to detection of incremental change in sediment discharge at a downstream station. These linkages from upstream source to downstream measurement site are not direct and controls on these linkages are variable in space and time. Different sediment discharges result from land use change depending on timing and location of a disturbance. Distance between a disturbance and a gage may alter the magnitude of sediment discharge downstream.

A set of daily sediment stations in the United States operated by the US Geological Survey was selected in basins of 1606 to 1,805,230 km^2 (Table 1). Mean annual suspended sediment discharge (μ_Q) ranged from 0.087 to 118 million tonnes. Variability, as standard deviation (σ_Q), ranged from 0.052 to 70.6 million tonnes per year.

Variability in the annual series is apparent in a histogram of sediment discharges for the San Juan River at Bluff, UT (Fig. 1). The mean annual suspended sediment discharge is 16.4 million tonnes for the period used at this gaging station, but discharges range from 4.62 million tonnes in 1951 to 65.4 million tonnes in 1973. This variability is over an order of magnitude and yields a standard deviation for the annual series of 12.1 million tonnes. Sediment discharge in 1973 was almost double that of the next largest discharge. An important component of this variability is that most sediment discharge occurs during only a few days of the year. At the San Juan River gage in 1973, 31.2 million tonnes, or 48% of the total, was discharged in 4 days. Small changes in timing and distribution of precipitation in these 4 days could greatly affect the annual discharge.

SIMULATION OF TRENDS IN SEDIMENT DISCHARGE

A stochastic equation generated multiple time series of annual suspended sediment discharge. Examination of measured suspended sediment discharges for stations listed in Table 1 indicated that the variable could be characterized by a lognormal distribution. Given the mean (μ_Q) and respective standard deviation (σ_Q) of annual sediment discharges (Table 1), the mean of the logarithms of the annual sediment discharge (μ_y) is (Aitchison & Brown, 1981):

Table 1 Annual suspended sediment discharge of selected daily sediment stations in the United States.

River	Station, state	Drainage area (km^2)	Period record (years)	Annual suspended sediment discharge (millions of tonnes)	
				Mean	Standard deviation
Potomac	Point of Rocks, MD	24 996	1961-1992	1.03	0.781
Rappahannock	Remington, VA	1606	1952-1992	0.087	0.052
Yadkin	Yadkin College, NC	5905	1952-1992	0.823	0.377
Pearl	Bogalusa, LA	17 024	1968-1974, 1980-1992	1.27	0.785
Muskingum	McConnelsville, OH	19 223	1979-1989	1.01	0.390
Little Miami	Milford, OH	3116	1980-1987	0.398	0.107
Green	Munfordville, KY	4333	1952-1989	0.454	0.200
Mississippi	Anoka, MN	49 469	1976-1985	0.265	0.150
Mississippi	Winona, MN	153 328	1976-1985	0.761	0.285
Mississippi	McGregor, IA	174 825	1976-1989, 1991	1.80	0.858
Mississippi	St Louis, MO	1 805 230	1949-1992	118.	70.6
Missouri	Landusky, MT	106 156	1972-1991	7.60	6.96
Tongue	Miles City, MT	13 932	1978-1985	0.218	0.259
Bad	Ft Pierre, SD	8047	1972-1992	1.50	1.22
White	Acoma, SD	26 418	1972-1976, 1982-1992	6.25	3.92
Brazos	Richmond, TX	116 568	1967-1986	9.48	7.54
Grande	Otowi Bridge, NM	37 037	1956-1989,1992	1.80	1.23
Colorado	Cisco, UT	62 419	1948-1984	8.37	4.93
Animas	Farmington, NM	3522	1952-1989, 1992	0.586	0.375
San Juan	Bluff, UT	59 570	1943-1980*	16.4	12.1
Santa Ana	Santa Ana, CA	4403	1968-1987	0.934	2.49
Santa Clara	Montalvo, CA	4128	1968-1981, 1985	6.11	12.9
San Joaquin	Vernalis, CA	35 058	1960-1990, 1992	0.266	0.200
Russian	Guerneville, CA	3465	1968-1984	1.27	0.903

* Data before 1943 not used.

$$\mu_y = \ln\left[\frac{\mu_Q^2}{\sqrt{\mu_Q^2 + \sigma_Q^2}}\right] \tag{1}$$

and the variance of the logarithms of the annual sediment discharge (σ_y^2) is:

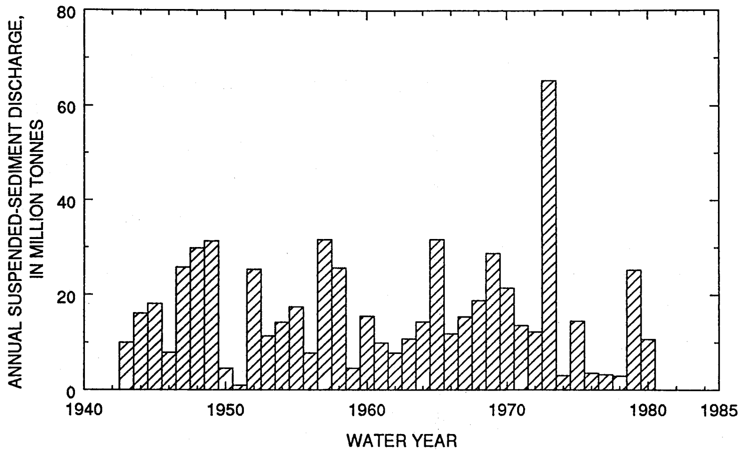

Fig. 1 Annual suspended sediment discharge of the San Juan River at Bluff, Utah, for the period 1943 through 1980.

$$\sigma_y^2 = \ln\left[\frac{\sigma_Q^2}{\mu_Q^2} + 1\right] \tag{2}$$

The mean annual sediment discharge was increased linearly each year so that a given percent increase was obtained at the end of a fixed period of years. It was assumed that annual values are independent and as the mean increases, variance increases by the same percent as the mean in order to keep the coefficient of variation ($C_v = \sigma_Q/\mu_Q$) constant. With C_v held constant, σ_y^2 will stay the same, and the mean (μ_y) with the introduction of the trend can be recomputed by:

$$\mu_y = \ln(\mu_Q) - \tfrac{1}{2}\sigma_y^2 \tag{3}$$

and the natural logarithm of the annual sediment discharge (Y_i) is generated by:

$$Y_i = \mu_y + Z\sigma_y \tag{4}$$

where Z is the standard normal deviate with a mean of zero and a variance of one (Press *et al.*, 1986). Equation (4) was used to generate multiple time series of annual sediment discharge for the gaging stations in Table 1.

Simulations of 20-year periods were generated for each gage (Table 1). Linear change in mean annual sediment discharge was specified to cause a desired percent change in mean annual discharge after 20 years. This linear change was used to represent alteration in land use that changes annual sediment discharge by the given percent over the 20-year period. Trend statistics were computed for each year of the simulations. The slope of the trend in the annual sediment discharge was calculated from estimates of Kendall's slope (Hirsch *et al.*, 1982), and the significance of the trend was determined with Kendall's tau statistic (Press *et al.*, 1986). The percentage of the 100 simulations that showed a significant trend at a significance level of 0.05 was determined.

DISCUSSION

Comparisons between the changes in mean annual sediment discharge and percent years with significant trends were made for each gage (Table 1). As examples, two stations that bracket most of the range of variability (Table 1) are shown in Fig. 2. Trends introduced to the sediment record on the San Juan River generally are undetected. Even if sediment discharge is doubled over 20 years, only 17% of the 20-year simulations have a detectable upward trend at the 0.05 significance level. The station on the Little Miami River has the lowest coefficient of variation among stations listed in Table 1; for it, 82% of the 20-year time series simulations show a significant upward trend when sediment discharge is doubled. Even in this case of lower natural variability, however, a 20% increase in mean annual sediment discharge over a 20-year period results in a trend detection of only 12%. This small detection level suggests the identification of a 20% increase in the mean sediment discharge (0.478 million tonnes) is unlikely. Results for most stations listed in Table 1 would plot between the two examples given in Fig. 2, suggesting that the high variability of annual sediment discharge makes detection of trends difficult.

To generalize the simulated data set, an indicator of the likelihood of detecting a change in sediment discharge was arbitrarily defined as years necessary to detect a significant trend (at the 0.05 level) in 50% of the simulations. In addition, a parameter was calculated that combines the two factors that control detection time of a trend: (a) magnitude of change in sediment discharge ($\Delta_{\mu Q}$) and (b) natural variability of sediment discharge at a station as indexed by the standard deviation of sediment discharge of the time series (σ_Q). This ratio is termed the signal-to-noise ratio, ρ, (McCabe & Wolock, 1991) and can be formalized as:

$$\rho = \frac{\Delta_{\mu_Q}}{\sigma_Q} \quad (5)$$

Using the signal-to-noise ratio and the detection time provides a way to compare

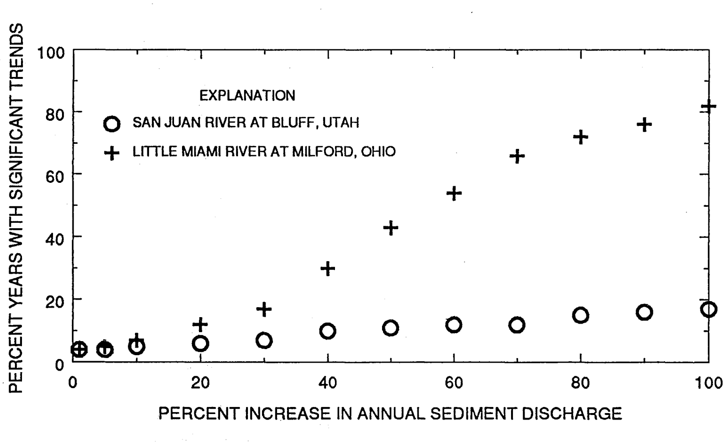

Fig. 2 Percent of simulations with statistically significant trends in sediment discharge (at the 0.05 significance level) due to increases in mean annual sediment discharge over a 20-year period for two daily suspended sediment gaging stations.

stations in Table 1 and include various percent changes in sediment discharge through time. In general, if the signal-to-noise ratio is large, the detection time is short (Fig. 3). Conversely, detecting trends in less than 20 years is difficult if the signal-to-noise ratio is less than 2.5.

To have a detection time of about 20 years for an increasing trend in sediment discharge at San Juan River station, ρ would be about 2.5 (Fig. 3). This suggests the mean annual suspended sediment discharge would have to increase from the current 16.4 to over 46 million tonnes, or almost a three-fold increase. An incremental change in suspended sediment discharge of 20%, or 3.28 million tonnes per year, yields a ρ of less than 0.3 and a detection time of over 100 years (Fig. 3).

If sediment discharge is doubled at the station on the Little Miami River, ρ is 3.7 and detection time is less than 10 years (Fig. 3). A 20% increase in the mean annual sediment discharge results in ρ equal to 0.75 and yields a detection time of over 70 years (Fig. 3). This signal-to-noise ratio for a 20% increase in sediment discharge for the Little Miami River is the highest value for any station listed in Table 1. For a 20% increase, other stations in Table 1 yield signal-to-noise ratios between 0.075 and 0.53, suggesting that detection times would be well over 100 years.

The annual variability of suspended sediment discharge at daily sediment stations with medium to large drainage areas was examined. Variability in the annual series is high and trends in sediment discharge due to change in land use may be difficult to identify. Simulated annual series of suspended sediment discharge suggests that, at the gaging stations investigated, trends may not be detected for incremental changes in sediment discharge of 20% or less. A signal-to-noise ratio is proposed as a method to assess the sensitivity of the sediment station to detect trends.

Further investigation is needed to test the sensitivity of gaging stations and to refine a signal-to-noise index to determine the sensitivity of particular gaging stations to identifying trends. It may be more constructive to couple gaging station measurements with routine assessments of upstream channels and erosion to identify trends. Such upstream assessments may provide information on changes in sediment storage and delivery, and of other physical factors important to the linkages between upstream perturbation and downstream measurement.

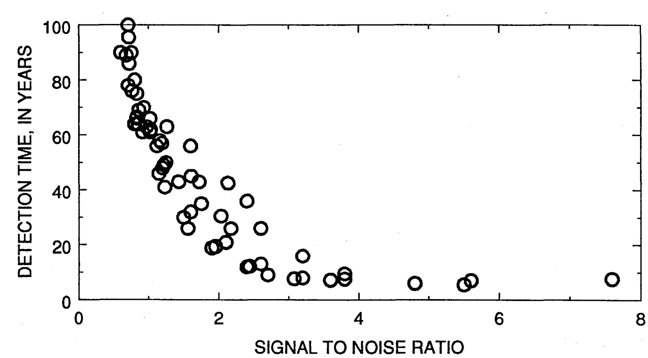

Fig. 3 Relation between signal-to-noise ratio and trend detection time. The signal-to-noise ratio is the change in mean annual sediment discharge over a fixed time period divided by the standard deviation of the measured annual sediment discharge. The detection time is the time necessary for 50% of the simulations to have a statistically significant trend in mean annual sediment discharge at the 0.05 significance level.

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