The Role of Erosion and Sediment Transport in Nutrient and Contaminant Transfer (Proceedings of a symposium held at Waterloo, Canada, July 2000). IAHS Publ. no. 263, 2000.

Temporal and spatial patterns of suspended sediment yields for selected rivers in the eastern United States: implications for nutrient and contaminant transfer

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Abstract Spatial and temporal patterns of suspended sediment yields across the eastern United States are discussed and analysed. A database of 165 sites compiled from the US Geological Survey forms the basis for the investigation. There are magnitude differences in absolute yields across the region, with a general inverse relationship of increasing sediment yield with decreasing latitude. The temporal analysis is based on 11 rivers with at least 15 years of record, spanning six eastern United States. Results indicate an oscillation through the time-averaged series that spans the regional study area. These findings illustrate the sensitivity of the terrestrial environment to climatic variations, which has further implications for the conveyance of sediment-associated nutrients and contaminants. Maps of spatial patterns illustrate the non-stationarity of the yields across the regional setting, as relative highs vary from one year to the next.

INTRODUCTION

Knowledge of sediment yield patterns and the factors governing those patterns have important theoretical, socio-economic and environmental implications. Many researchers have estimated denudation using suspended sediment as their indicator of surface lowering (Dole & Stabler, 1909; Fournier, 1960; Ahnert, 1970; Stone & Saunderson, 1996). There has also been an increasing awareness of the significance of determining sediment loads of rivers for the purpose of assessing material transport to the world's oceans (Curtis *et al.*, 1973; Milliman & Meade, 1983), geochemical cycling (Walling & Webb, 1987) and the supply of material to coastal environments (Inman & Jenkins, 1999). Recent interest in the broader context of global environmental change promoted by the International Geosphere Biosphere Programme (IGBP) has also directed attention to the potential relationship between climate change and sediment fluxes (Walling, 1997). Impaired water quality in lakes and rivers, deterioration of municipal water supplies, and sedimentation of reservoirs and navigation channels are all socio-economic reasons for enhancing our understanding of fluvial sediment through time and space. Further underscoring the significance of understanding trends in sediment yields, are the environmental implications of increased sediment transport. Sediment plays a major role in water pollution at a global scale (Eckholm, 1976). Since most nutrients, chemical contaminants, and heavy metals in water bodies are carried on sediment particles (Allan, 1986), understanding the spatial and temporal context of fluvial suspended sediment yields at the regional scale has important environmental implications.

Spatial and temporal analyses of suspended sediment and nutrient loads in rivers may be conducted at various scales of investigation, from a particular stretch of river, to a drainage basin, a region, or even encompassing the entire globe. The present paper is a regional analysis of sediment yields. In order to assess the critical factors influencing changes in fluvial sediment yields through time and in space, and consequently, of nutrient transfer, a regional analysis of long-term data is appropriate. At a time when the Earth's atmosphere is increasingly being studied in a global context, it is crucial that the hydrosphere be studied and understood at a similar scale (Jenne, 1999).

STUDY AREA

The area under investigation spans the eastern United States (US) of Georgia, South Carolina, North Carolina, Virginia, Delaware, New Jersey, New York, Maryland, Maine, Massachusetts, Connecticut, and Pennsylvania. The eastern US can be divided into four major hydrographic regions (Fig. 1).

Mean annual precipitation is relatively continuous across the study area, with values typically varying between 1200 and 1600 mm year^{-1} (Lins *et al.*, 1990). Variations in the surficial hydrogeology span the study area, with depths of unconsolidated sediments tending to decrease with increasing latitude. In the New England states (Maine, New Hampshire, Massachusetts, Connecticut, Rhode Island, Vermont and New York), the surficial aquifer system consists primarily of glacial deposits. Depth of unconsolidated material ranges from approximately 3 to 330 m (USGS, 1995) in this region, but extends to depths as great as 1500 m along the southern coastal plain (USGS, 1996, 1997).

The region also has a history of intense human settlement and expansion. The population of the eastern United States has exploded, with stresses to the natural environment undoubtedly associated with that explosion. In 1900, for example, the population of Maryland and Pennsylvania was 1.2 and 6.3 million respectively. By 1990, those numbers had jumped from 1.2 to 4.8 and from 6.3 to 12, a four-fold increase in the population of Maryland, and an almost two-fold increase in the population of Pennsylvania.

SUSPENDED SEDIMENT YIELDS

The original source of the daily suspended sediment load data was the US Geological Survey (USGS WATSTORE database). The data were acquired from Hydrosphere Data Products, Inc., Boulder, Colorado. The database included all streamgauging locations in the eastern United States, which were searched for the locations with suspended sediment load data that had been collected continuously for at least one full year. Absent from the data set were the states of Maine, New Hampshire,

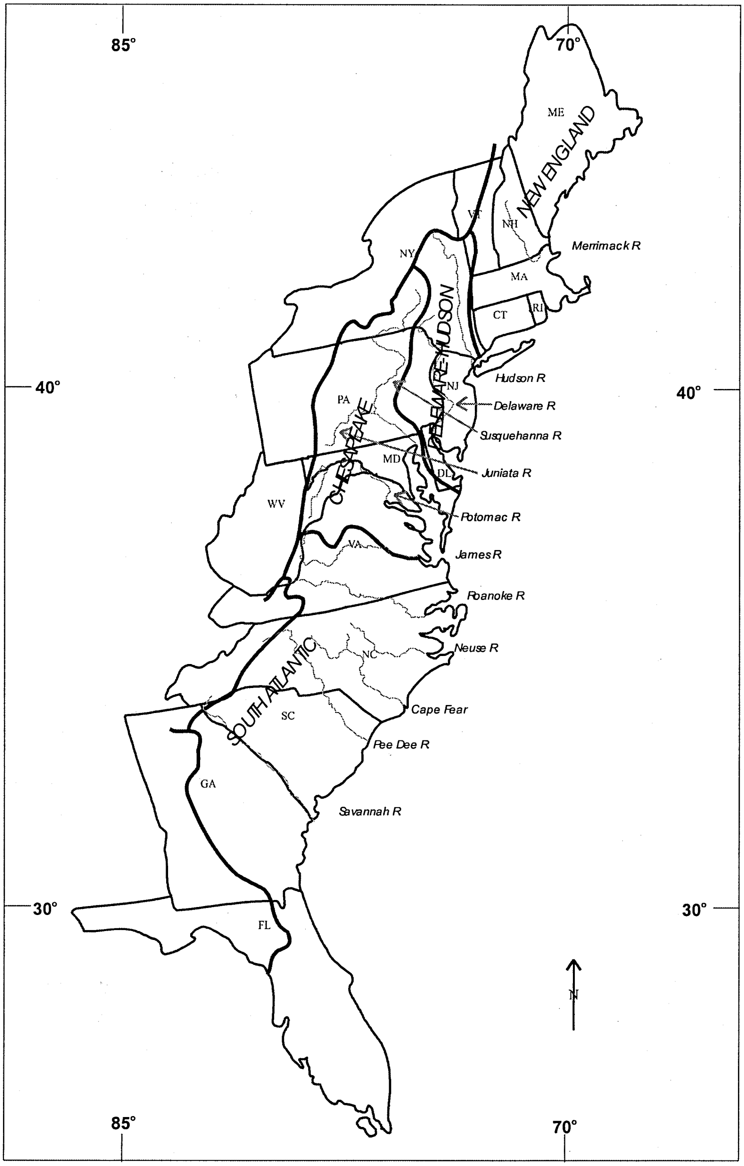

Fig. 1 The hydrography of the eastern United States: major drainage basins.

Vermont and Florida. Alternative sources of data were sought for these states. However the sediment load information has either not been collected (e.g. Florida), or is in limited supply (e.g. Maine). Many of the states had numerous gauging stations, but only a few (2.47%) collected or had collected sediment data. Figure 2 shows the locations of gauging stations with suspended sediment load data.

Intervals of record ranged from one to 42 years. Table 1 gives a breakdown of the number of sites and years of record (by state). Most stations have less than ten years of record, but some have more than 20 years. From the annual sediment load

Table 1 Available suspended sediment data for the eastern United States.

State/province	Number of sites	< 10 years data	10–20 years data	> 20 years data	Max. period of record
Connecticut	7	7	0	0	1981–1990
Delaware	2	1	0	1	1948–1980
Georgia	13	13	0	0	1959–1963
Maine	2	2	0	0	1966–1972
Maryland	12	6	5	2	1959–1993
Massachusetts	2	2	0	0	1966–1972
New Jersey	15	12	2	1	1949–1982
New York	20	20	0	0	1954–1979
North Carolina	10	7	2	1	1951–1993
Pennsylvania	61	54	5	1	1951–1993
South Carolina	2	4	0	0	1966–1972
Virginia	19	16	0	3	1951–1993
Total	**165**	**144**	**14**	**9**	

Data used in this study can be broken down into a number of years of record. Although most sites have < 10 years of continuous, daily data, there are some which have a significantly long period of continuous record (1951–1993).

Table 2 Sediment yield for the individual states.

State/province	Sediment yield	Maximum yield	Minimum yield
Connecticut	20	30.6	9.3
Delaware	119.9	173	66.7
Georgia	62.3	152.9	1.5
Maryland	62.9	155.4	5.7
Massachusetts	13.8	18.4	9.2
New Jersey	18.8	58.3	2.2
New York	108.5	425.2	4.6
North Carolina	157.3	1017	17.5
Pennsylvania	114.4	1436.2	12
South Carolina	12.6	21.8	3.4
Virginia	327.9	3156.7	3.2
Eastern States	**96.7**	**3156.7**	**1.5**

Overall sediment yield, maximum and minimum yield averaged for the eastern United States in the study (t km^{-2} year^{-1}).

totals, time-averaged sediment yields were calculated (t km^{-2} year^{-1}) for each site. The sediment yield for each state, and the maximum and minimum yield within each state are shown in Table 2. Maximum yields ranged from 18.4 to 3156.7 t km^{-2} year^{-1} and minimum yields from 1.5 to 66.7 t km^{-2} year^{-1}. These values are orders of magnitude greater than estimates that had been calculated previously by the authors (Conrad & Saunderson, 1999).

SPATIAL ANALYSIS

Multiquadric surfaces were generated (Conrad & Saunderson, 1999) for portions of the eastern United States. In terms of visual smoothness, goodness of fit, flexibility

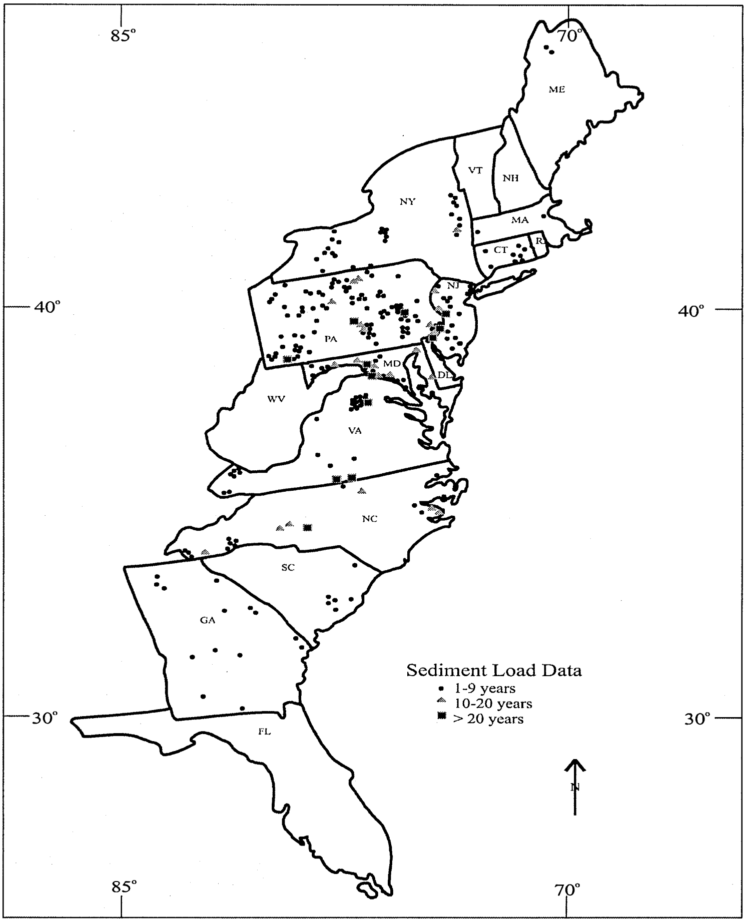

Fig. 2 Location of gauging stations in the eastern United States with 1–9 years, 10–20 years and >20 years of continuous sediment load data.

and variable distribution of data, the multiquadric (MQ) method of analysis is an invaluable analytical technique (Franke, 1982). Hardy's (1971) MQ method was used to generate surfaces where $z = f(x, y)$, z being the scalar dependent variable and x, y the locational coordinates of z. Mapping the regional pattern of time-averaged yields (t km^{-2} year^{-1}) required, as a first step, solution of the following multiquadric equation:

$$\sum_{j=1}^{n} c_j \left[(x_i - x_j)^2 + (y_i - y_j)^2 \right]^{0.5} = z_i \tag{1}$$

where c_j is a column vector of coefficients representing the slopes of cones, the vertices of which are located at $[x, y]_{ij}$, and having known value z_i. Interpolation of any intermediate values for sediment yields (z_p) was then derived from the equation:

$$\sum_{j=1}^{n} c_j \left[(x_j - x_p)^2 + (y_j - y_p)^2 \right]^{0.5} = z_p \tag{2}$$

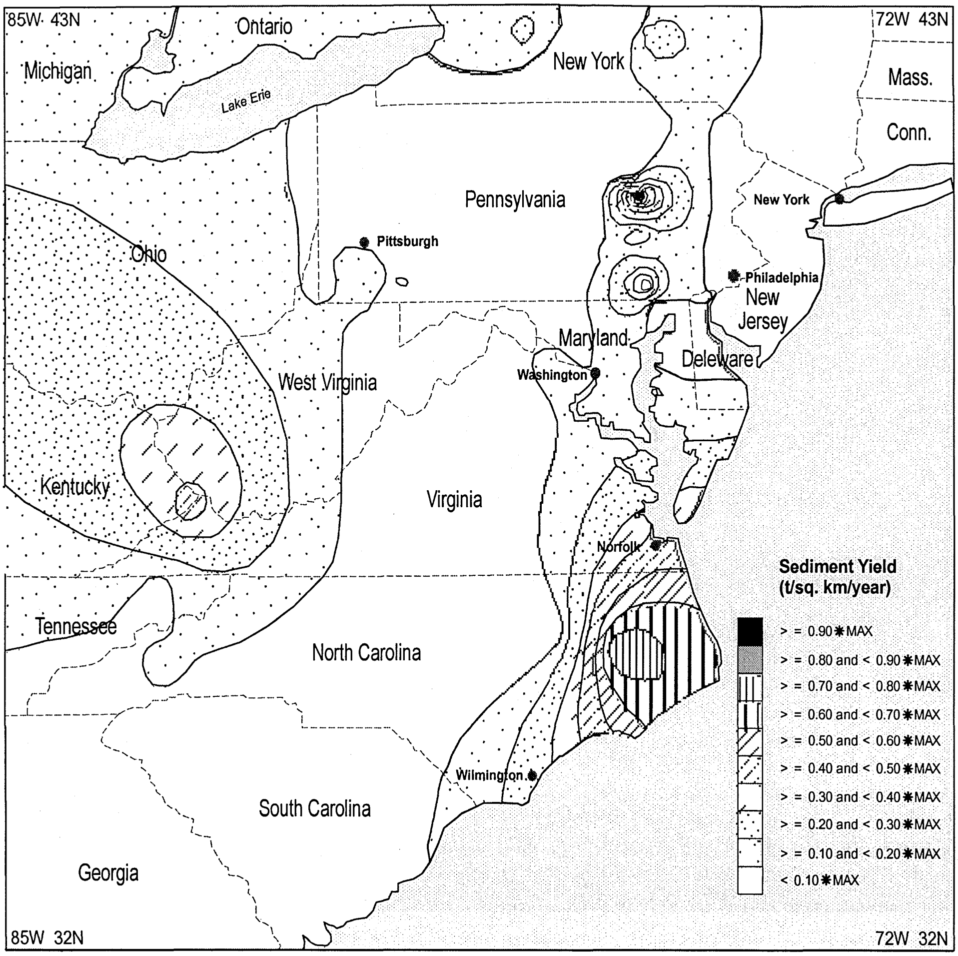

Fig. 3 Sediment yield patterns based on a sample of (79) records (max. 42-year record; max. yield: *c.* 900 t km^{-2} year^{-1}).

with the column vector c_j being the solution of a set of simultaneous, linear equations (Saunderson, 1994).

Figure 3 was prepared with data from 79 stations. Lengths of record ranged from one to 42 years. Yields are as high as 900 t km^{-2} year^{-1} which are found in Pennsylvania, where tributaries to the Susquehanna River have large sediment yields. The pattern of suspended sediment yields prepared with five years of record (Fig. 4) shows largest yields associated with tributaries of the Potomac ($\sim$400 t km^{-2} year^{-1}) and in the western corner of Virginia, associated with Ohio River tributaries ($\sim$580 t km^{-2} year^{-1}). The area around Washington, DC also has five-year high sediment yield values. Figure 5 shows the results of mapping suspended sediment yields which have been averaged over a 10-year interval of record. This map depicts a smaller region since there are now fewer stations which have a continuous ten-year record. The region around Washington, DC still emerges as a high yield region on the 10-year record, with largest yields of up to $\sim$250 t km^{-2} year^{-1}.

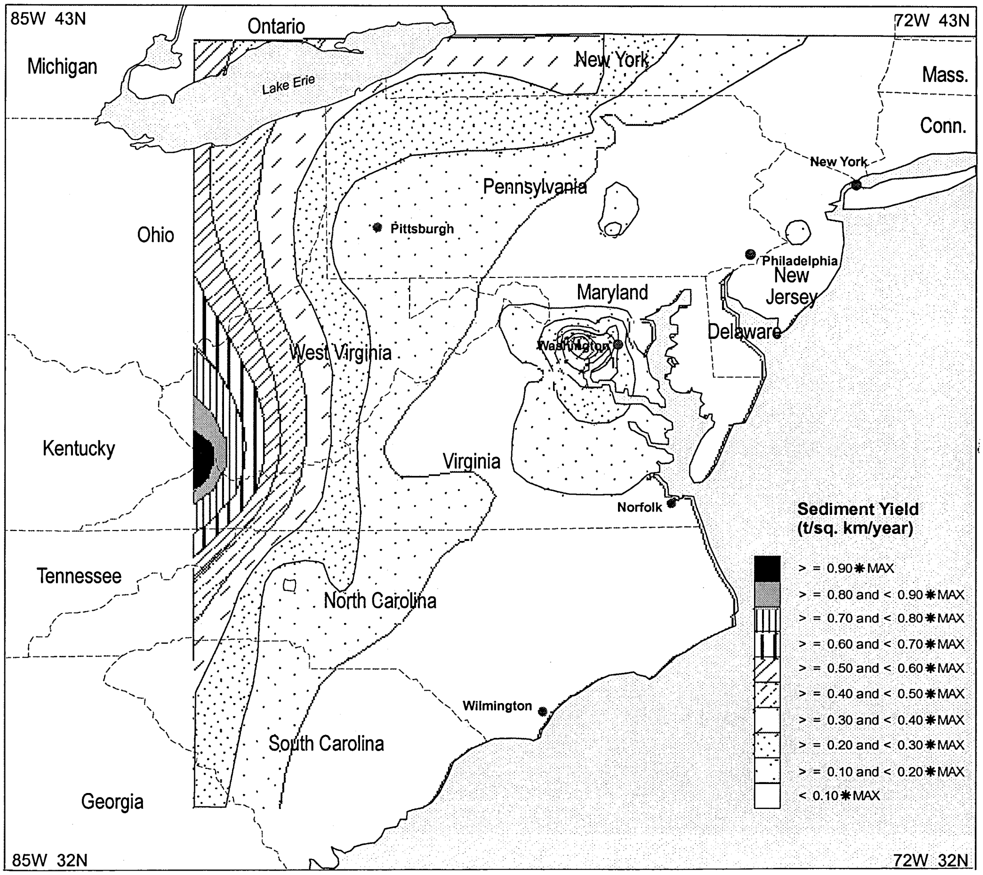

Fig. 4 Sediment yield patterns based on a five-year time average (max. yield: *c.* 580 t km^{-2} year^{-1}).

TEMPORAL ANALYSIS

To investigate changes in the sediment loads through time, time series of all stations with at least 15 years of continuous record were produced. Smoothing of the data was conducted by applying a moving average on the annual data values. Since a common trend in the eleven plots was not observed, nor could trend lines be plotted for any of the graphs, smoothing of the data was conducted in an effort to observe any common fluctuations (by increasing the graphical clarity). An interval of seven years was selected for two reasons. First, it neither entirely removed the signal in the data nor continued to make it too "noisy" to observe the trend. Second, a length of seven years has also been successfully used for other hydrological applications (McCuen & Snyder, 1986).

Figure 6 illustrates the results of the 7-year moving averages of the raw sediment load data for representative sites from four states. The line on the individual graphs is the smoothed trend and the scattered points on the graphs are the raw data points. In Fig. 6, Brandywine Creek, Delaware (DE) has a twofold sediment load increase from 1968 to 1973, with a general pattern of higher loads in the late 1950s–early

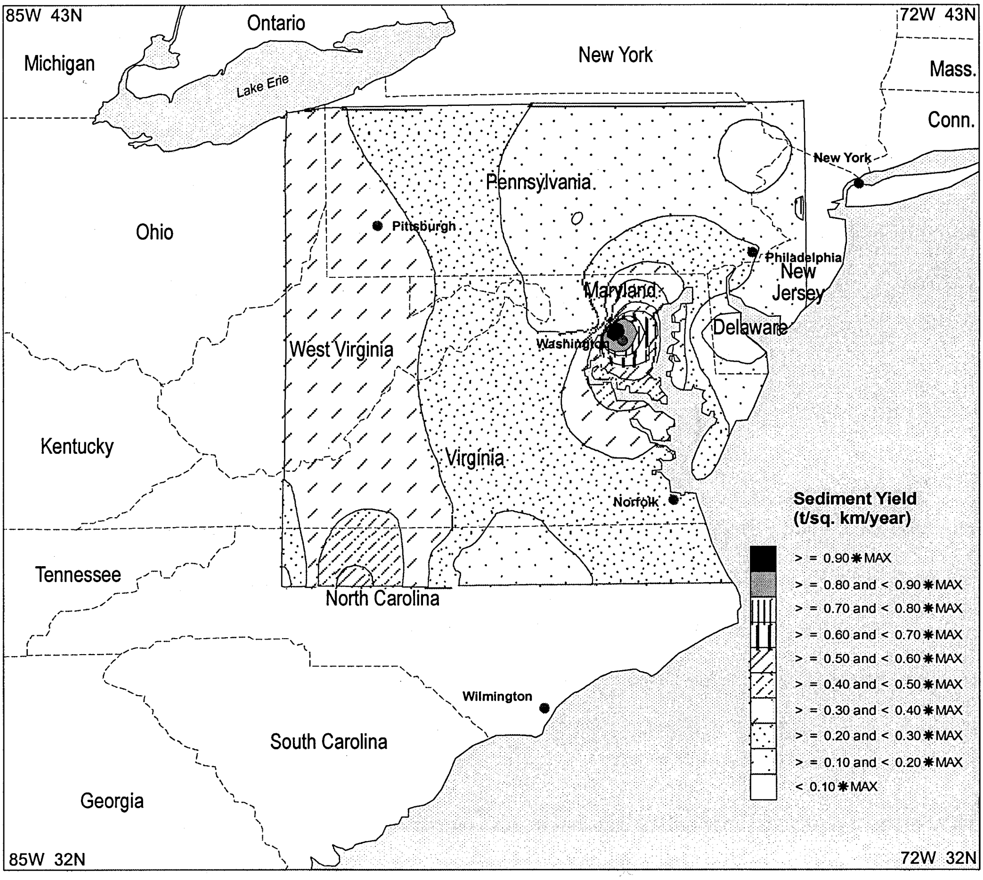

Fig. 5 Sediment yield patterns based on a 10-year time average (max. yield: *c.* 250 t km^{-2} year^{-1}).

1960s, a subsequent decline in yields through 1968, followed by higher yields again through the early 1970s. The Rappahanock River, Pennsylvania also has a marked oscillation with a low between 1965 and 1970 and peak around 1975 with a subsequent drop. The Yadkin River, North Carolina exhibits a similar oscillation. Finally, the Delaware River, New Jersey shows a falling limb from 1950 to a low around 1965, followed by a rising limb towards 1975, with another drop around 1980.

Several observations can be made based on the graphs in Fig. 6:

- there is an almost universal low around 1967,
- the data do not illustrate a random pattern,
- the data are non-stationary,
- the data may be illustrating a decadal cyclicity, however a long enough time series does not allow this to be conclusively determined.

The observed trends may be attributed to climatic oscillations. The episodicity of the sediment fluxes in such disparate locations can not be attributed to human impacts, and geological and physiographic influences on sediment loads are relatively

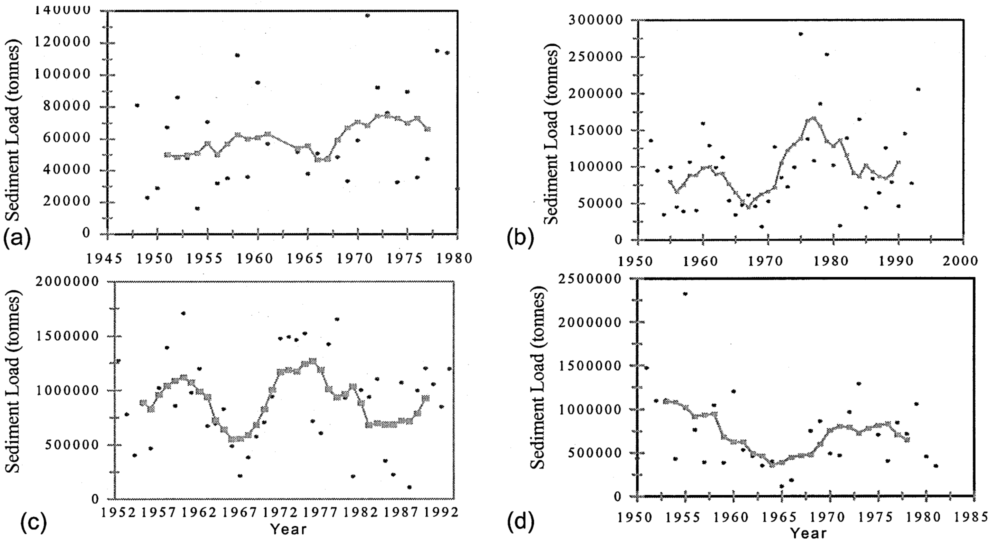

Fig. 6 Seven-year moving averages of suspended sediment load for (a) Brandywine Creek, Delaware; (b) Rappahanock River, Virginia; (c) Yadkin River, North Carolina; and (d) Delaware River, New Jersey. The line on the graph is the moving average and the remaining data points are the annual loads (tonnage of sediment) from which the smoothed data were derived.

constant in the decadal time span. Regardless of the magnitude of sediment loads (e.g. 140 × 10^3 t $year^{-1}$ at Brandywine Creek, Delaware *vs* 2.5 × 10^6 t $year^{-1}$ at the Delaware River), the pattern can be seen. Inman & Jenkins (1999) have noted a similar trend, which they refer to as episodicity of sediment flux, in small Californian rivers. This leads one to believe that the driving force of sediment flux in the time series is climatological, with sediment loads in wet years being upwards of two-fold what they would be in dry years.

DISCUSSION

Analysis of spatial variation indicates that sediment yields are non-stationary, as shown by maxima that shift geographically over time. At best, an individual map of sediment yield patterns provides us with a "snapshot" of the conditions which existed at that point in time (e.g. stations which were in operation, meteorological conditions, land use). Spatial patterns of sediment yields are influenced by human land uses and magnitude of disturbance, as well as the erodibility and availability of sediment. However, the common trends in the time series, regardless of the *magnitude* of the sediment loads, point to the importance of the driving forces in the temporal context: precipitation and, consequently, discharge. Other attributing factors, such as land use, and availability of erodible material, for example, will influence the magnitude of material transported. However, the trends through time are not anthropogenic in nature, but rather are driven by larger-scale climatological conditions. Flux of suspended sediment will also entrain soil organic material and associated agricultural chemicals, including pesticides and fertilizers (Inman & Jenkins, 1999). Agricultural soil brought to the Atlantic coast by rivers draining the eastern United States during wetter periods will consequently result in higher nutrient concentrations, which may have deleterious effects on coastal ecosystems.

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