Temporal variation of suspended sediment properties

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ABSTRACT   Increasing awareness of the role of suspended sediment in the transport of nutrients and contaminants, of the significance of water-sediment interactions as an influence on river water quality and of the importance of sediment in nonpoint pollution, requires an improved understanding of spatial and temporal variations in suspended sediment properties. A study of suspended sediment yields in the basin of the River Exe, Devon, UK, undertaken by the authors, has attempted to provide information on the nature and extent of temporal variations in sediment geochemistry. Results from four measuring stations relating to major element composition, clay mineralogy and organic constituents are presented. Detailed patterns of storm-period variation in sediment properties are illustrated. The implication of these findings are reviewed.

INTRODUCTION

Increasing awareness of the role of suspended sediment in the transport of nutrients and contaminants (e.g. Shear & Watson, 1977; Allan, 1979), of the significance of water-sediment interactions as an influence on river water quality (e.g. Golterman, 1977; UNESCO, 1978), and of the importance of sediment in nonpoint pollution in general (e.g. USDA, 1976; Knisel, 1980) has introduced new perspectives and requirements into the study of erosion and sediment yield. Previously, attention focussed on the magnitude of suspended sediment loads and concentrations (e.g. ASCE, 1975), but information regarding those properties of the sediment which exert significant controls over sediment-associated transport and water-sediment interactions is now also required. A knowledge and understanding of the nature and extent of spatial and temporal variation of properties such as particle size, mineralogy, surface chemistry, chemical composition and organic matter content are essential to deal with these new perspectives.

Much less is known about the physical and chemical properties of suspended sediment than about the magnitude of concentrations and yields. A number of studies have evaluated spatial variations in sediment mineralogy and chemistry (e.g. Angino *et al.*, 1974; Gibbs, 1977; Rhoton *et al.*, 1979), but, with the exception of the work of Ongley *et al.* (1981), only limited attention has been given to temporal variations in sediment properties or geochemistry.

A priori reasoning would indicate that these properties could exhibit appreciable temporal variation at the annual, seasonal and storm-period level in response to temporal variations in the nature

and efficacy of erosion processes, the relative importance of particular sediment sources, the efficiency of delivery and conveyance processes and the operation of in-stream processes influencing sediment chemistry. A study of suspended sediment yields in the basin of the River Exe, Devon, UK, which has been undertaken by the authors since 1978, has attempted to provide information on the nature and extent of temporal variations in sediment geochemistry and some of the preliminary results are present in this paper.

THE STUDY BASINS

The results presented here relate to four sediment sampling stations within the basin of the River Exe (Table 1). They have been selected to be representative both of a range of drainage basin sizes and of the major terrain characteristics within the study area (cf. Walling, 1978). In particular, the two smaller basins of the Jackmoor Brook and River Dart provide a marked contrast between the former which drains a predominantly lowland area with widespread arable farming and the latter which drains an area of deeply dissected upland where permanent pasture predominates. Typical storm-period peak suspended sediment concentrations are of the order of 250 mg l^{-1} for the River Exe at Thorverton, 600 mg l^{-1} for the River Creedy at Cowley, 800 mg l^{-1} for the River Dart at Bickleigh and 1200 mg l^{-1} for the Jackmoor Brook.

TABLE 1   The study catchments

River	*Catchment area (km^2)*	*Estimated mean annual suspended sediment yield (t km^{-2} year^{-1})*
Exe at Thorverton	*601.0*	*25*
Creedy at Cowley	*262.0*	*50*
Dart at Bickleigh	*46.0*	*75*
Jackmoor Brook	*9.8*	*50*

FIELD AND LABORATORY TECHNIQUES

Suspended sediment sampling has been undertaken at all four measuring stations. Two approaches have been used for collecting samples of suspended sediment for laboratory analysis of sediment geochemistry. The first involved the collection of bulk (>100 l) storm water samples in polyethylene containers using a submersible pump suspended from a bridge. Sediment was separated from the samples by continuous-flow centrifugation in the laboratory. The sediment recovered was freeze-dried for storage prior to analysis. The centrifuge units have been shown to provide highly efficient recovery of suspended sediment >0.45 μm and the bulk samples typically provided between 30 and 250 g of sediment, depending on the ambient suspended sediment concentration. The second method made use

of the 400 ml water samples provided by automatic pumping samplers installed at the measuring stations on the two smaller streams. The sediment was recovered from these samples by sedimentation and decantation and was subsequently freeze-dried. Yields ranged between 0.1 and 1.0 g per bottle.

Use of the former method was essential to obtain sufficient sediment for a large number of disparate laboratory analyses, and bulk water samples were collected from all sites over a wide range of flood conditions. The second method possessed the advantage of automatic sample collection at hourly intervals, but was restricted in its usefulness by the small quantities of sediment involved. These effectively restricted laboratory analysis to determinations of C and N content which were used for detailed studies of a number of storm runoff events.

Laboratory analysis of sediment samples involved standard laboratory procedures which included determination of major element concentrations by X-ray fluorescence (XRF), clay mineralogy by X-ray diffraction (XRD), C and N concentrations by pyrolysis/thermal conductivity, P by chemical fractionation/UV spectroscopy, and Fe by chemical fractionation/atomic absorption spectroscopy.

RESULTS

Background information on the modal mineralogy and the typical particle size composition of suspended sediment collected from the four sampling sites is presented in Tables 2 and 3. In terms of composition, the phyllosilicate, quartz, iron and organic matter components account for >99% of the total weight. Quartz is predominantly silt-sized and is rare in the clay (<2 µm) fraction.

TABLE 2   *Modal mineralogy of suspended sediment*

River	Phyllosilicate (%)			Quartz (%)	Iron oxides (%)	Organic matter (%)
	Mica	Others	Total			
Exe at Thorverton	30	16	46	35	5.6	14
Creedy at Cowley	23	20	43	42	5	10
Dart at Bickleigh	29	22	51	35	5.6	9
Jackmoor Brook	35	21	56	31	6	8

Major element composition

Limited data on the major element composition of five samples from each sampling station, representative of a wide range of flow conditions, are summarized in Table 4. The variability of Si, Al, Fe, Ti and K concentrations is low, reflecting overall uniformity in these sediment properties through time. This uniformity would be further emphasized if element concentrations were expressed in terms of the inorganic fraction of the sediment, since the analysis

TABLE 3   Mean particle size composition of suspended
sediment

River	Particle size distribution (%):*			
	<0.5 µm	0.5-2 µm	2-10 µm	10-62 µm
Exe at Thorverton	19	22	38	21
Creedy at Cowley	29	24	33	14
Dart at Bickleigh	26	19	31	24
Jackmoor Brook	54	26	15	5

* Particle size data relate to the chemically dispersed
mineral fraction.

includes a variable organic fraction.

In contrast, the concentrations of Ca, Mg and Mn exhibit much
greater temporal variation. In the case of Ca and Mg, a significant
portion of the element concentration is associated with exchangeable
cations rather than the mineral lattice and the temporal variation in
these values may be related to a varying equilibrium between the
sediment and solute phases as well as to variations in exchange
capacity. Mn levels have been shown by Ongley *et al.* (1981) to be
highly sensitive to bioaccumulation mechanisms, and the variability
in the concentration of this element may be tentatively linked to
variations in the magnitude and composition of the organic component.

TABLE 4   Major element composition of suspended sediment

River		Element (%):*							
		Fe	Mn	Ti	Ca[†]	K[†]	Si	Al	Mg[†]
Exe	$\bar{x}$[§]	3.61	0.20	0.46	0.25	2.14	24.74	7.62	2.25
	c.v.[¶]	7	21	5	35	6	3	7	33
Dart	$\bar{x}$	3.14	0.16	0.47	0.23	1.71	26.41	6.75	1.97
	c.v.	10	10	4	19	5	4	5	18
Creedy	$\bar{x}$	3.78	0.17	0.47	0.32	2.06	24.62	8.09	2.63
	c.v.	8	23	3	17	8	2	8	14
Jackmoor	$\bar{x}$	3.93	0.15	0.44	0.44	2.53	24.52	8.26	3.72
Brook	c.v.	10	35	10	13	11	6	14	12

* Concentration in % of freeze-dried suspended sediment.
† Includes exchangeable cations.
§ Mean.
¶ Coefficient of variation (%).

Clay mineralogy

Information on the variability of the clay mineralogy of suspended
sediment from the four sites is presented in Table 5. Four major
clay mineral groups have been identified. Mica is the dominant group

TABLE 5   *Semi-quantitative clay mineralogy of suspended sediment*

River		Mica (%)	Mixed layer mica-vermiculite (%)	Kaolinite (%)	Chlorite (%)
Exe	$\bar{x}$	64.4	23.4	9.4	2.6
	c.v.	22	70	26	53
Dart	$\bar{x}$	52.3	35.7	7.3	4.7
	c.v.	33	55	14	42
Creedy	$\bar{x}$	54.4	30.0	13.1	2.4
	c.v.	24	56	28	71
Jackmoor Brook	$\bar{x}$	60.8	28.8	6.3	3.0
	c.v.	17	44	19	65

for all four rivers and the mixed layer mica-vermiculite component also forms an important group. Chlorite is present in small quantities although its thermal instability suggests that it probably represents a chloritized vermiculite rather than "true chlorite".

Overall this facet of sediment composition exhibits more variability than the major element composition. The chlorite and mixed layer vermiculite groups exhibit the greatest degree of variation. In the former case, this can be accounted for in terms of the relatively low amounts present and the fact that it is completely absent in certain cases. The variability of the mixed layer mica-vermiculite group is more significant in terms of overall sediment composition and may be related to the varying importance of particular sediment source areas within the drainage basin. This mineral group is a mica-transformation product and is dominant in some soils but almost absent from others.

Organic constituents

C, N and total-P concentrations have been used to evaluate the degree of variation of the organic fraction in the suspended sediment samples. Total-P has been included because of its proven close relationship with organic matter content in the study area. Fig.1 provides an indication of the degree of variation in the levels of these constituents by plotting the concentrations associated with samples collected during the 10 month period between September 1980 and June 1981, for three of the sampling sites.

Considerable scatter is evident for all three parameters at each of the sites, indicating that the organic matter content of suspended sediment can exhibit very significant temporal variation. Although there is some tendency for N and P levels to be at a minimum during the period December-March, the clear seasonal trends described by Ongley *et al.* (1981) for Wilton Creek are not evidenced by these rivers. Intra-storm variations in concentration dominate the pattern of variability. Although not depicted in Fig.1, values of the C/N ratio for individual sediment samples also demonstrate a similar degree of scatter, indicating that variations in C and N concentration are associated with both fluctuations in the absolute

RIVER DART   RIVER CREEDY   RIVER EXE

C%   N%   P mg kg⁻¹

Concentration

S O N D J F M A M J   S O N D J F M A M J   S O N D J F M A M J
1980   1981   1980   1981   1980   1981
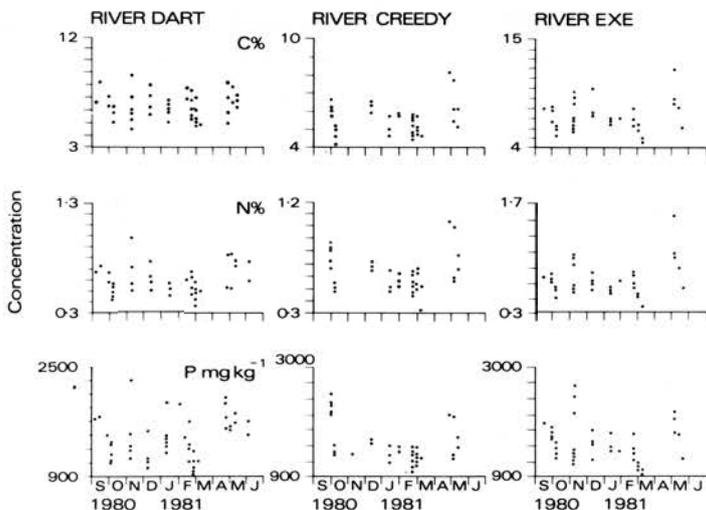
FIG.1   *The variation of C, N and total-P concentrations in suspended sediment samples collected during the period September 1980-June 1981.*

magnitude of the organic fraction and its composition.

Fig.2 presents the graphical relationships between the three chemical parameters and discharge at the time of sampling for three of the measurement sites, in an attempt to decipher the marked intra-storm variation in the organic matter content of the sediment samples.   In all cases there is a clear inverse relationship between C, N and total-P concentration and discharge, indicating that the

RIVER DART   RIVER CREEDY   RIVER EXE

C%   N%   P mg kg⁻¹

Concentration
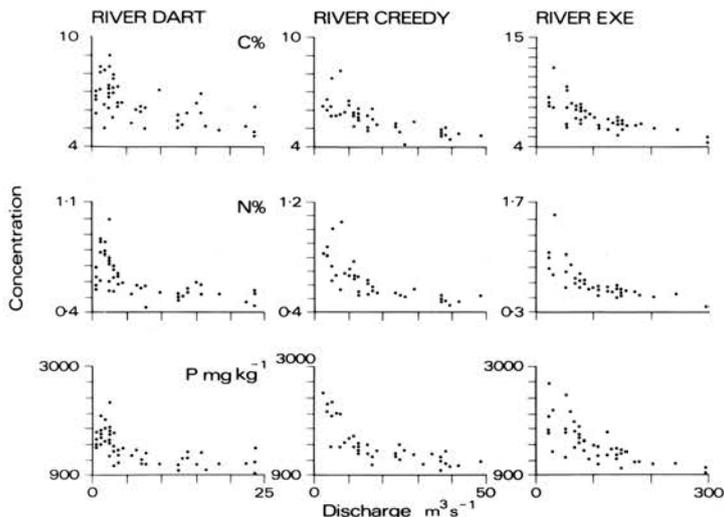
Discharge   m³s⁻¹

FIG.2   *Relationships between C, N and total-P concentrations and discharge at time of sampling, for suspended sediment collected from three of the measurement sites.*

organic matter content of suspended sediment declines at times of
high discharge. The trend of the graphical relationships suggests
a simple logarithmic function of the form:

$$\text{concentration} = aQ^{-b}$$

and the associated regression equations provide r^2 values between
0.42 (Dart P) and 0.76 (Creedy P).

In order to examine the extent to which the inverse trends
evidenced in Fig.2 reflect the influence of sediment concentration
rather than discharge (sediment concentration in itself positively
related to discharge), Fig.3 presents relationships between sediment
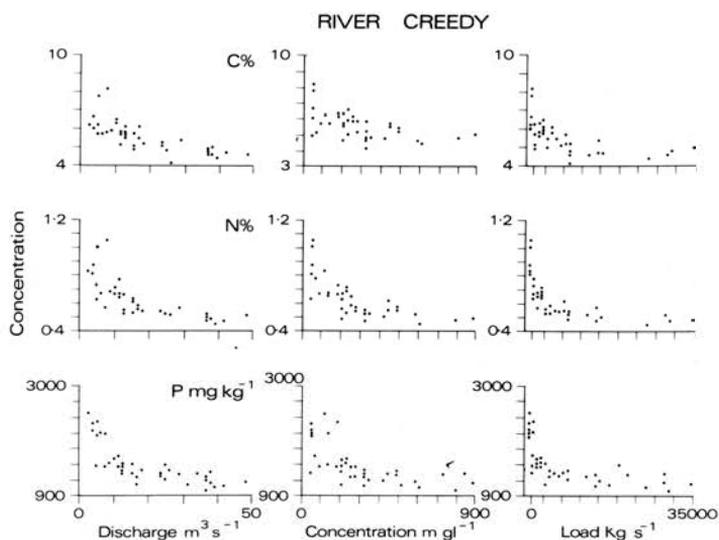
FIG.3 *Relationships between C, N and total-P*
concentrations and the discharge, suspended sediment
concentration and suspended sediment load at the time of
sampling, for suspended sediment collected from the River
Creedy.

chemistry and discharge, suspended sediment concentration and
suspended sediment load for the River Creedy. The correlation
coefficient between discharge and concentration (log data) for this
data set is 0.73. The lack of any clear distinction between the
degree of explanation afforded by the discharge and concentration
plots and the somewhat improved explanation associated with sediment
load (discharge x concentration) is confirmed by the r^2 values for
the equivalent logarithmic relationships. This in turn suggests that
discharge and concentration both exert independent inverse effects on
organic matter concentrations.

In view of its importance in ion exchange, adsorption and
complexing mechanism, these variations in the magnitude and
composition of the organic fraction of the suspended sediment must
be viewed as being of considerable significance to sediment-

associated transport and water-sediment interactions.

Storm-period variations in sediment geochemistry

Fig.4 introduces information on the detailed behaviour of C and N concentrations in suspended sediment during individual storm events, as a means of further elucidating the variation of these properties in response to changes in discharge and sediment concentration. The data obtained from analysis of the hourly samples provided by the automatic samplers on the River Dart and the Jackmoor Brook have been used to illustrate two events from each measuring station. The more limited data on total-P, inorganic-P and acid ammonium oxalate extractable Fe concentrations and magnetic susceptibility (χ) provided by bulk sediment samples collected during the events are also plotted.

Certain contrasts between the two rivers are immediately apparent, in that the River Dart exhibits higher levels of C, N, and P, and therefore a larger organic fraction, than the Jackmoor Brook. Taking the storm of 14-15 January 1981, which is depicted for both sites (Fig.4A, C), C and N concentrations and also the C/N ratio show a general decline during the event in each case. The range of variation shown by the River Dart is, however, almost double that evidenced by the Jackmoor Brook. More importantly, no simple relationship to the pattern of discharge or concentration variation is evident. In the Jackmoor Brook, the minimum levels and C and N occur near the end of the event and lag the hydrograph and sediment concentration peaks by 3 and 5 h respectively. There is more correspondence to the discharge peak in the case of the River Dart, but more short term fluctuation is apparent. In both cases the C/N ratios show considerable variation during the event, again stressing a change in the nature as well as the magnitude of the organic fraction. In the River Dart, the decline in the C/N ratio essentially occurs after the hydrograph peak whereas in the Jackmoor Brook it occurs throughout the event. This decline marks a change from C/N ratio values typical of soil humus towards lower values more typical of subsurface horizons.

In the case of total-P and inorganic-P, the data base is more restricted, but the patterns exhibited by both streams appear more closely related to discharge variations, and indicate an inverse relationship. Values of magnetic susceptibility, which have previously been shown to be a useful indicator of sediment provenance (Walling & Peart, 1980), and of Fe demonstrate a strong positive relationship with discharge in the River Dart but this tendency is much less evident in the Jackmoor Brook where in fact Fe exhibits a clear inverse relationship.

Evidence of inter-storm contrasts in the behaviour of the individual sediment properties is afforded by Fig.4B, D which provide examples of a contrasting storm event for both measuring stations. The storm of 23 February 1981 on the Jackmoor Brook shows little evidence of the clear decline in C and N shown by Fig.4A and the N concentrations demonstrate a small overall increase. Similarly, there is evidence of an increase rather than a decrease, in C and N levels during the storm of 2 June 1981 on the River Dart. Clearly, the patterns of inter- and intra-storm variation in these measures
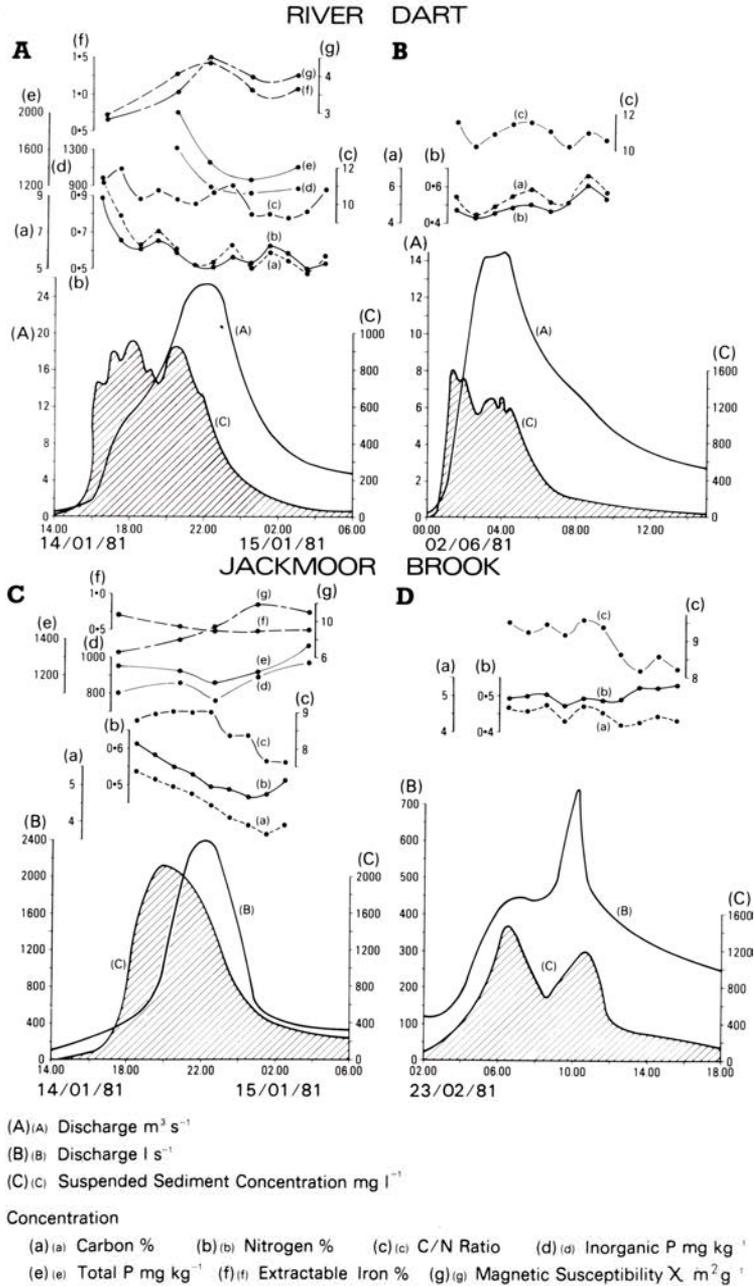
FIG.4   *The variation of selected geochemical properties of suspended sediment during storm runoff events on the River Dart and the Jackmoor Brook. (Extractable Fe refers to the acid ammonium oxalate value).*

of sediment geochemistry are extremely complex and more work is required to provide an effective explanation of the trends observed.

IMPLICATIONS

The aim of this paper has been to demonstrate the potential nature and extent of temporal variations in sediment geochemistry, and explanation of the patterns described lies outside the scope of this contribution. The results presented indicate that, whereas certain suspended sediment properties such as Si, Al, Fe, Ti and K concentrations may remain relatively constant over a range of hydrological conditions, others, particularly those associated with the organic fraction, may exhibit considerable variation. Because of their importance in the sediment association of nutrients and contaminants and in water quality interactions, temporal variations in these properties merit further investigation and analysis.

Sampling programmes aimed at documenting the behaviour of sediment properties or related parameters must take account of the considerable intra-storm variation which may occur and must not restrict sampling to flood peaks. Similarly, attempts to obtain reliable estimates of sediment-associated nutrient and contaminant flux will clearly necessitate intensive sampling programmes, in order to represent the detailed pattern of variation of sediment geochemistry, as well as of the sediment load (cf. Walling & Webb, 1981). Relationships between sediment properties and discharge and concentration, such as those reported in this study, may, however, provide a meaningful basis for extrapolation. Furthermore, the development of improved understanding and explanation of variations in sediment geochemistry may also shed further light on the nature of the erosion and sediment conveyance processes that operate in a drainage basin.

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