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The impact of particle size controls on stream turbidity measurement; some implications for suspended sediment yield estimation

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ABSTRACT River monitoring programmes frequently use turbidity measurements in order to provide continuous records of suspended sediment concentration. Four monitoring stations in Midland England were equipped with Partech S100, S1000 and SDM-10 optical turbidity meters. This paper presents estimates of sediment yield from the four stations based on field calibrations and examines problems of suspended sediment/ turbidity calibration over a wide range of suspended sediment concentrations.

INTRODUCTION

Hydrologists and geomorphologists are constantly seeking improved methods for the estimation of fluvial suspended sediment concentrations (SSC) in order to more accurately quantify suspended sediment loads (SSL) from drainage basins. However, the accuracy and precision of river SSC estimates are frequently compromised by inadequate sampling and analytical strategies (Webb, 1987). The most important source of error in SSC estimation derives from an inadequate sampling strategy. Most streams transport the majority of their sediment load during infrequent storm events (Hadley, *et al.* 1985). Regular but infrequent sampling can result in a gross underestimation of the sediment load, as well as for other fluvially transported constituents, particularly where rating curves are employed (Walling & Webb, 1981; Ferguson, 1987; Foster *et al.*, 1990). Given the impracticality of high frequency sampling, the alternative is to utilise in-situ sensors to indirectly monitor SSC which, according to Olive and Rieger (1988) may result in a more accurate data set despite the inherent problems involved in using such techniques.

Various devices have been used to monitor indirectly SSC, including ultrasonic and nuclear scattering gauges (Gippel, 1989). However, optical gauges are the most widely used since they are generally sensitive to a wide range of SSC and are relatively inexpensive. Although most suited to the concentration range of 0-1000 mg l^{-1}, higher concentrations can be measured, albeit with a decrease in sensitivity (Gippel, 1989). The use of continuously recording optical turbidity meters (OTM) is not new

(Fleming, 1969), yet considerable debate remains about the relationship between stream turbidity and SSC in order to provide accurate and precise estimates of SSL at an annual or more frequent level.

Turbidity is a function not only of SSC but also of particle size, shape and composition in addition to water colour. These variables do not necessarily vary in a predictable way with water or sediment discharge and consequently may introduce bias into the estimation of SSC.

This paper is concerned with the use of OTM to provide continous estimates of SSC at four Midland England monitoring sites under a range of land use and flow conditions (Table 1). Detailed site descriptions are to be found in Foster *et al.* (1985; 1986; 1990). Three sites were instrumented in the 1980s with Partech 7000 3RP MK II Suspended Solids Monitors with two types of dual path sensor (S100 and S1000). Due to high sediment concentrations recorded at the fourth gauging station, a Partech SDM-10 single gap sensor with a 0-5000 mg l^{-1} concentration range was used. Field data were logged on a Grant Instruments 'Squirrel' Data Logger and the data retrieved at weekly intervals by downloading into an Epson-HX portable computer.

TABLE 1 Site characteristics of the Seeswood and Merevale catchments.

Properties	Merevale	Seeswood
Grid Ref	SP300970	SP327905
Area above gauging stations (ha)		
M1	195.0	
M2	95.2	
S1		65.4
S2		161.0
Flow gauging		
M1 and M2	Compound 'V'notch weirs	
S1 and S2	Trapezoidal Flumes	
	Turbidity Probe	
M1 and M2	S100	
S1		SDM-10
S2		S1000
Max. Altitude (m)	175	160
Min. Altitude (m)	118	125
Relative Relief (m)	57	35

FIELD AND LABORATORY CALIBRATION

The Partech OTM is calibrated using a suspension of known concentration. The S100 and S1000 probes were calibrated here using dilutions from a Formazin standard supplied by

the manufacturer and made up to 4000 Formazin Attenuation Units (FAU) in accordance with APHA procedures (APHA, 1975; Partech, 1980). The S100 and S1000 sensors were calibrated to 500 and 1000 FAU concentrations at full scale deflection respectively. In contrast, the single gap SDM-10 sensor was calibrated with a Fuller's Earth standard as recommended by Partech (1980), to give a full scale deflection of 5000 mg l^{-1}. The calibration curves for the S100 and S1000 sensors were non-linear; a feature reported in other studies using similar instruments (Finlayson, 1985). Nevertheless, repeated calibration of the probes produced insignificant differences in the form and quantitative nature of the relationship. At the low concentrations usually experienced at the M1 and M2 gauging stations, the relationship was approximately linear. In contrast to the twin sensor calibrations, the SDM-10 probe produced a simple linear calibration with the Fuller's Earth standard.

Calibration was also performed with suspended sediment samples retrieved by manual sampling and against storm-period sediment samples collected in Northants' Automatic Liquid vacuum samplers at 30 minute intervals. The former confirmed the non-linearity and insensitivity of the S1000 probe at concentrations in excess of 400 mg l^{-1} whereas the SDM-10 probe remained linear at concentrations exceeding 1500 mg l^{-1}. An example of the relationship between gravimetric and turbidity estimates of SSC for the S1000 probe at S1 (Figure 1) suggests that turbidity is a good surrogate measure of SSC, although slight deviations between turbidity and gravimetric estimates of SSC can be seen.

Where organic material forms a significant component of the suspended sediment load, turbidity often provides a poor measure of the minerogenic fraction. Although dissolved organic matter was present in the water at M1 and M2 (Foster & Grieve, 1982) this affected turbidity measurements by less than 1% and was therefore considered insignificant. Similarly, organic matter concentrations had no measurable effect on the S1000 turbidity calibration at S1. However, in addition to the high minerogenic component, organic turbidity at S2 recorded with the SDM-10 sensor was frequently associated with a-periodic organic discharges from farmyards, most of which were recorded at night. These turbidity pulses often occurred just before midnight and were usually not associated with a detectable increase in stream discharge or a rainfall event. The turbidity trace of Figure 2 illustrates such a series of events where an attempt is made to disaggregate organic turbidity from turbidity associated with storm events and sediment transport.

In addition to the high suspended sediment concentrations, water samples collected from site S2, particularly in the spring and summer, contained high concentrations of nitrate, phosphate and potassium (Foster & Dearing, 1987). These high nutrient levels gave rise to

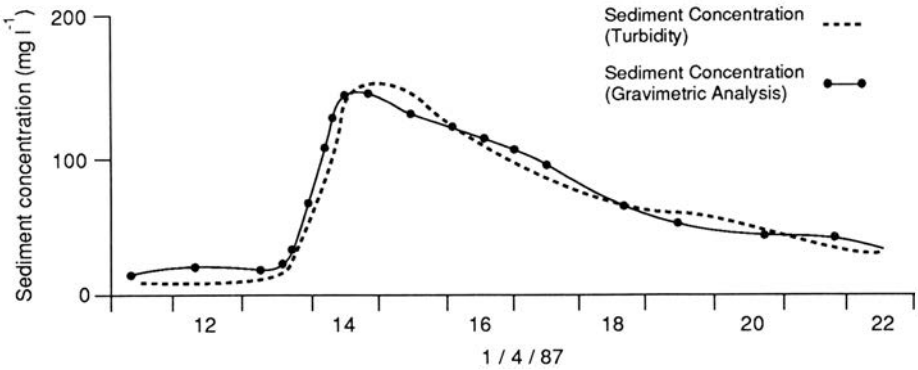

FIG. 1 Comparison of SSC estimates from manual sampling and turbidity meter for the S1000 sensor at gauging station S1.

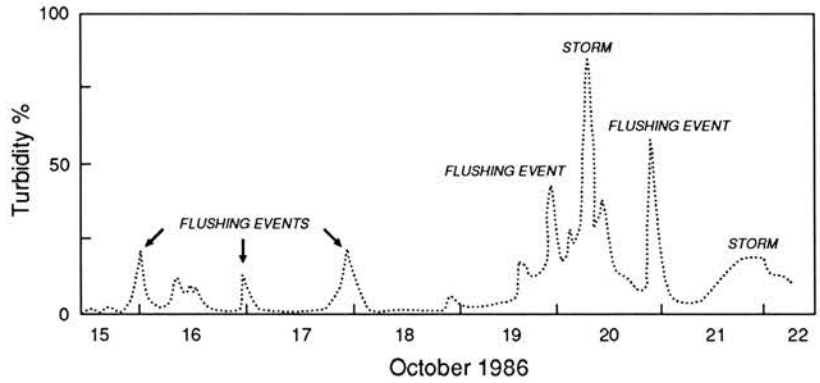

FIG. 2 A sample turbidity trace from gauging station S2 using the SDM-10 sensor. Turbidity is associated with organic 'flushing' and storm runoff events.

high rates of aquatic productivity which, at times, led to algal growths on the meter lenses. Attempts to overcome this problem by rinsing the lenses with weak sulphuric acid solutions and utilising an on-off light source, switched on just before measurement, failed to overcome these problems. Similar problems were not experienced with the twin gap sensor configuration of the S100 and S1000 probes at S1, M1 and M2.

SEDIMENT CONCENTRATION AND YIELD DATA

On the basis of field and laboratory calibration procedures outlined above and utilising gravimetric analysis, linear interpolation and cross correlation techniques to infill missing data at the various sites

(Grew, 1990), the continuous SSC record was sampled at two hourly intervals for a single years record at each station for further analysis, giving almost 4500 readings at each of the four gauging stations. Regression analysis of total data indicate very poor levels of explained variance which testifies to the strong hysteresis observed in many of the individual storm events (Table 2). Such poor statistical relationships clearly demonstrate the inadequacy of sediment discharge rating curves for estimating SSC at these four stations even with seasonally subdivided data sets. These results suggest that, despite some of the problems of field calibration and sensitivity, the continuous turbidity record offers the best opportunity to provide accurate and precise estimates of sediment yield.

TABLE 2 Regression and correlation analysis on suspended sediment data. From Foster *et al.* (1990).

	Total			Summer			Winter		
Site	a	b	r^2	a	b	r^2	a	b	r^2
S1	0.82	0.24	11.3	0.25	1.04	36.0	0.64	0.31	25.5
S2	0.91	0.58	23.0	0.28	1.13	37.6	1.08	0.50	25.1
M1	0.48	0.35	15.0	0.48	0.36	14.3	0.43	0.38	10.3
M2	0.46	0.38	25.8	0.46	0.51	40.9	0.52	0.29	8.0

a and b are from $Sc = 10a.Qb$
Sc = Sediment Concentration
r^2 = Coefficient of determination
All correlations significant at 99.9%
n = 4368 for total data set

By using the two hourly turbidity record with stream discharge data, annual SSLs for the four monitoring stations have been estimated (Table 3). Sediment yields range from a minimum of 6.4 t km^{-2} yr^{-1} at the M2 station to 68.9 t km^{-2} yr^{-1} at S2. The surprisingly low sediment yield recorded in the intensively cultivated S1 basin is a funtion of the presence of a riparian buffer zone minimising the input of suspended sediments from cultivated fields to the stream channel. The high sediment yield at S2 is a function of cattle poaching along the stream margins (Foster *et al.*, 1990).

TABLE 3 Sediment yield estimates from monitored catchments (t km^{-2} yr^{-1}).

Site	S1	S2	M1	M2
Sediment Yield	8.7	68.9	10.3	6.4

Although the field and laboratory calibrations appear to produce reliable and consistent results, it is well documented that the turbidity-sediment concentration relationship is, in part, a function of the particle size characteristics of the transported sediment (eg Ward, 1980; Gippel, 1989). Indeed, Yang and Hogg (1979) have described a method whereby particle size distributions can be determined from a measurement of turbidty at two different wavelengths. In consequence, a series of laboratory experiments have been undertaken in order to assess the performance of turbidity meters used in this investigation in relation to particle size. The results presented below relate to the performance of the twin gap S100 and S1000 probes only.

THE INFLUENCE OF PARTICLE SIZE

The Partech S100 and S1000 sensors are dual path attenuance design instruments using a polychromatic tungsten light source combined with a cadmium sulphide detector. The light wavelength peak occurs at approximately 550 nm (Gippel, 1989). The sensitivity of these instruments was evaluated by examining the relationship between the meter reading and particle size and Formazin FAU and particle size for five particle size fractions.

In order to obtain fractionated suspended sediments over a limited particle size range, samples of instream sediments were obtained from the channel at S1. Samples were oven dried and ground and passed through a bank of sieves to 63 μm. The less than 63 μm fraction was subdivided by means of a decanting method based on the settling velocities provided by Stokes' Law (Allen, 1990). Particle specific gravity for the mixed material was derived from the method described by Avery and Bascomb (1982) and found to be an average of 2.58 g cm^{-3} from four replicate analyses. No attempt was made to examine particle specific gravity variations for the different particle size bands. The calculated settling velocities were intended to produce 5 particle size bands for turbidity calibration, <4 μm, 4-8 μm, 8-16 μm, 16-32 μm and 32-63 μm. Further details of the fractionation procedure are given by Millington (1990).

As a cross check on the particle size range obtained by this fractionation procedure, a Malvern Instruments model 2600 Diffraction Particle Sizer was used to produce particle size curves for each of the five samples. Three replicate samples were analysed for each of the particle size fractions produced by settling with excellent reproducibility. It was apparent from this analysis, however, that the intended particle size bands did not exactly coincide with those in the three finest fractions obtained by settling. The median sizes of the frequency distributions of each fraction were 3.87, 8.30, 15.75,

24.12 and 46.48 μm respectively. This may reflect, in part, the different principles by which particle size is determined using the two different methods (Allen, 1990).

Suspensions of the five subsamples were prepared in both natural stream water collected from the S1 basin and in dispersant (a 10% Calgon solution in distilled water) which permitted the effects of electrolyte chemistry on particle aggregation to be observed in addition to the effects of any natural colouration in the stream water samples. The stream water was filtered through Whatman No 3 and GFC filters to remove all material greater than 0.7 μm. The S100 and S1000 sensors were immersed in tandem in the calibration solutions in the laboratory. Samples were held in a rigid plastic container screened with a double thickness of heavy-gauge black polythene to prevent incident light reflecting onto the photosensitive cells.

The relationships between suspended sediment concentration and turbidity meter scale reading (%) for the S1000 and S100 sensors in both stream water and dispersant are non-linear for the three finest particle size bands for the S100 sensor and for the finest particle size band using the S1000 sensor. No significant difference in response is recorded between the sediments suspended in river water or dispersant. The maximum recordable concentration of finest sediment was less than 400 mg l^{-1} and 800 mg l^{-1} for the S100 and S1000 sensors respectively.

In order to define the relationship between particle size and turbidity, the specific turbidity parameter Ta/M is often used, where M is the concentration in mass per unit volume terms and Ta is the attenuance turbidity. Gippel (1989) has shown that Ta, measured by turbidity meter relative to a formazin standard, reduces to:

$$Ta = KaM \quad (1)$$

where Ka is an attenuance turbidity coefficient which is a function of particle shape, refractive index, size distribution and specific gravity. Since several unknown quantities are included in the value of Ka, estimates of Ta were obtained by relating the turbidity measurments made on the particle size fractions to the FAU concentration from the relationships of Table 4 based on a simple linear regresssion procedure where;

$$Ta = a + bM \quad (2)$$

and a and b are constants obtained by least squares. On the basis of the relationships defined in Table 4, it is apparent that sensitivity of the turbidity measurement declines rapidly with increasing particle size as indicated by the constant b which ranges over two orders of magnitude for an order of magnitude change in the meadian particle size. The sensitivity over the range of particle sizes measured can be redefined in terms of the

TABLE 4 Regression equations for the S100 and S1000 sensors against turbidity (FAU) for five particle size bands.

Median Particle size (μm)	Dispersant a	b	r^2	Stream water a	b	r^2
S100 Monitor						
3.87	1.749	1.298	99.9	4.341	1.408	100.0
8.30	-14.940	0.605	99.4	-9.741	0.597	99.3
15.75	-6.198	0.276	100.0	-5.390	0.306	99.7
24.12	0.939	0.098	99.8	-0.916	0.112	98.5
46.48	3.053	0.049	99.5	4.765	0.057	99.9
S1000 Monitor						
3.87	13.380	1.243	99.8	-3.387	1.442	99.9
8.30	-12.590	0.611	99.8	-13.210	0.568	99.8
15.75	-6.198	0.276	100.0	-1.252	0.281	100.0
24.12	-3.848	0.092	99.8	-5.182	0.114	99.5
46.48	-1.582	0.052	98.4	-3.699	0.066	98.8

specific turbidity parameter Ta/M where Ta is calculated from the regression equations of Table 4 using the combined dispersant/stream water relationships given in Figure 4. The form of the relationship for the S100 and S1000 probes is logarithmic with;

$$Ta = 9.375Md_{50} - 1.346 \quad R^2 = 98.0\% \quad (S100) \quad (3)$$

and

$$Ta = 8.599Md_{50} - 1.313 \quad R^2 = 97.7\ \% \quad (S1000) \quad (4)$$

The two turbidity probes produce remakably similar exponent values with statistically insignificant differences between the two gradients.

Turbidity, as measured by the Partech S100 and S1000 probes, is highly sensitive to particle size when fractionated sediments are utilised to produce a calibration. The implications of such a fractionation can be illustrated by utilising the differnt calibrations produced with the S1000 probe on the sediment yield estimates at S1 given in Table 3. Recomputing the sediment concentration and load data for just 3 of the particle size specific curves (3.87, 8.3 and 15.75 μm Md_{50}) produces sediment yield estimates of between 16.99 and 78.65 t km^{-2} yr^{-1} in comparison with the field calibrated estimate of 8.7 t km^{-2} yr^{-1}.

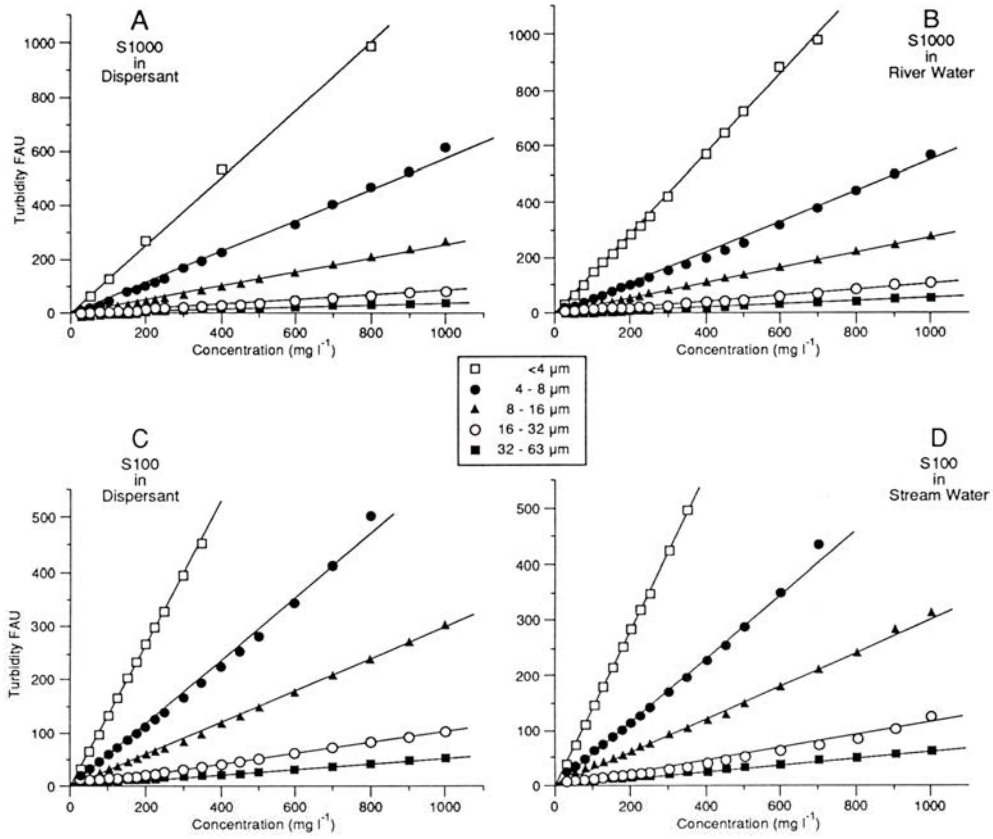

FIG. 3 Particle size/FAU turbidity relationships for five particle size fractions measured on the S100 and S1000 sensors in dispersant and river water.

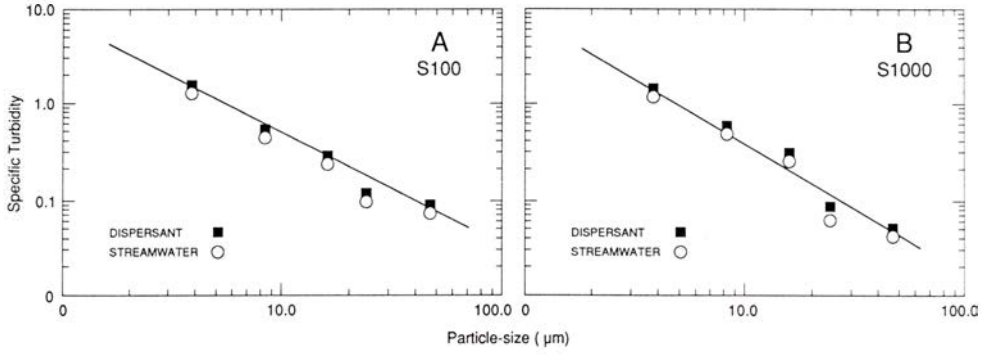

FIG. 4 Specific turbidity/particle size relationships for the S100 and S1000 turbidity probes.

DISCUSSION

It has been shown that nutrient rich rivers and rivers containing significant organic turbidity complicates the quantitative calibration of turbidity with inorganic suspended sediment concentration. It has also been shown that the response curves are particularly sensitive to particle size variations with the S100 and S1000 probes exceeding 100% turbidity at concentrations of 350 and 700 mg l^{-1} respectively for the sub 4 μm material in stream water. Results suggest that attenuance is a function of the cross sectional area of the particle size in suspension. Assuming a constant density of particles, and ignoring interference effects at high concentrations, attenuance will increase as a direct ratio of particle volume to cross sectional area.

The effects of particle size produced by laboratory simulation merely indicates the potential sensitivity of turbidity measurements. However, no account is taken in these experiments of the differences between effective and ultimate size and of the spatial and temporal variations in particle size. Ongley *et al.* (1981) and Peart and Walling (1982), for example, identified significant seasonal changes in particle size with changes in source areas as the most likely explanation of the differences recorded. Furthermore, there seems to be no consistent change in particle size with discharge for many UK rivers (Walling & Moorehead, 1987). Insufficient data were available from the Midland monitoring stations to define storm-period particle size variations but the effect clearly requires further consideration on turbidity meter estimates of sediment concentration.

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