Appraisal of a simple sampling device for collecting time-integrated fluvial suspended sediment samples

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Abstract Geochemical analysis of suspended sediment is a key requirement in nutrient and contaminant transfer studies, but the collection of fluvial suspended sediment samples is problematic due to the highly episodic nature of its transport. Traditional approaches involve the collection of instantaneous samples, but uncertainties regarding intra- and inter-storm variations in sediment-associated nutrient and contaminant concentrations introduce problems in establishing the total sediment-associated flux. This paper assesses the effectiveness of a simple, inexpensive, *in situ* sampler that collects a time-integrated sample of fluvial suspended sediment. The representativeness of the samples collected by the sampler was confirmed by comparing measurements of a range of geochemical properties of the sediment collected by the sampler with equivalent measurements undertaken on manual point samples collected during the period of sampler deployment. The potential for using the time-integrated sediment samples collected by the sampler is demonstrated by presenting an example of suspended sediment source fingerprinting.

INTRODUCTION

Recent years have seen a growing awareness of the important role of suspended sediment in the transport of nutrients and contaminants in fluvial systems (e.g. Horowitz, 1991; Walling *et al.*, 1997). Important advances have also been made in the use of suspended sediment properties as diagnostic signatures for fingerprinting suspended sediment sources (e.g. Walling *et al.*, 1993, 1999). Such studies frequently require the collection of a significant quantity (e.g. >10 g) of suspended sediment for geochemical analyses and this requirement can present problems, due to the highly episodic nature of suspended sediment transport. Traditional approaches to the collection of suspended sediment samples have commonly involved intensive manual sampling during storm events (cf. Collins *et al.*, 1997; Walling *et al.*, in press), and the deployment of automatic samplers (cf. Russell *et al.*, 1998). These traditional approaches suffer from three main problems. Firstly, their employment may be limited by manpower requirements in the case of manual sampling, or by cost in the case of automatic sampling equipment. Secondly, the small samples collected by most commercially available automatic samplers are unable to provide the substantial quantities of sediment frequently required for geochemical analyses. Finally, the suspended

sediment samples obtained will be representative of the time of sampling rather than longer periods. Intra-storm variations in the nutrient and contaminant concentrations associated with suspended sediment will frequently create problems in integrating the results of instantaneous measurements provided by automatic or manual samples in order to characterize the longer-term flux. Time-integrated samples afford a means of overcoming this problem. Time-integrated (composite) suspended sediment samples can be collected using automatic samplers which combine instantaneous samples on a flow proportional basis, but the resulting samples will not be truly time-integrated (cf. Kronvang *et al.*, 1997).

There is a need for a simple, inexpensive and reliable means of collecting time-integrated samples of fluvial suspended sediment for both quantifying sediment-associated nutrient and contaminant fluxes and for collecting representative samples for use in suspended sediment source fingerprinting studies. *In situ* samplers offer a potential solution, since they can be designed to continuously sample suspended sediment during the period of deployment and hence collect a time-integrated sample. However, there are few examples of *in situ* sediment samplers designed for deployment within fluvial systems and existing devices have been primarily designed for sand-sized material (e.g. Van Rijn & Gaweesh, 1992). This paper provides an appraisal of a simple sampling device that has been designed to be installed in the river channel to collect an *in situ* time-integrated sample of fluvial suspended sediment (<62.5 μm). The design and principle of operation of the sediment sampler is described fully in Phillips *et al.* (in press). Laboratory tests and field trials reported by these authors have confirmed its ability to collect statistically representative samples of fluvial suspended sediment, in terms of particle size composition.

This paper will focus on assessing the ability of the sediment sampler to provide geochemically representative samples, by comparing several geochemical properties of the time-integrated suspended sediment samples collected by the sediment sampler with those of instantaneous manual samples collected at times of significant sediment transport during the periods of sampler deployment. The potential for using samples collected by the sediment sampler in suspended sediment source fingerprinting studies is also demonstrated.

THE SEDIMENT SAMPLER

The design of the sediment sampler is illustrated in Fig. 1. The main body is made from commercially available polyvinylchloride (PVC) pipe (1 m × 98 mm (ID)) with an internal cross-sectional area of 7543 mm2. The cylinder ends are sealed by threaded end caps with internal "O-ring" seals. The inlet and outlet tubes are made of semi-rigid nylon pneumatic tubing (4 mm (ID) × 150 mm) with an internal cross-sectional area of 12.6 mm2. These tubes pass through holes drilled in the centres of the end caps, which are sealed with silicone sealant, and extend 20 mm into the body of the main cylinder. A polyethylene funnel placed over the inlet tube streamlines the body of the sampler and serves to minimize disruption to the ambient flow structure in the vicinity of the inlet tube aperture. Metal eyes are screwed into the front and rear of the upper surface of the main cylinder and these are used to secure the sampler to steel (Dexion) uprights inserted into the channel bed at the sampling site.

The sediment sampler operates *in situ*. The sampler is first filled with clean native water and it is then submerged in the channel, with the inlet tube orientated directly into the flow. The sampler is installed horizontally in the middle of the channel at approximately 0.6 of the mean water depth by securing it to the steel uprights. Once submerged, water continuously enters the inlet tube at a velocity proportional to the ambient flow velocity. Within the main cylinder of the sampler, the flow velocity is reduced by a factor in excess of 600, relative to the ambient flow. This reduced inflow velocity induces sedimentation of the suspended sediment particles as the water moves through the cylinder towards the outlet tube. The sediment sampler is not isokinetic as the inlet flow velocity is less than the ambient flow velocity. However, this is unlikely to influence the particle size distribution of the sediment retained by the sampler when the suspended sediment is predominantly silt- and clay-sized material (Phillips *et al.*, in press). Although theoretical calculations, based on the absolute particle size composition of the suspended sediment and estimates of settling velocities in relation to residence time of sediment within the sampler, indicate that the sediment sampler is unlikely to collect a representative sample of suspended sediment in terms of its particle size composition, the fact that most suspended sediment is transported as composite particles (cf. Droppo & Ongley, 1994) leads to greatly increased efficiency. Composite particles will settle more rapidly than discrete particles due to their larger size, thereby increasing the trapping efficiency of the sampler. Furthermore, the discrete particles comprising composite particles will frequently represent the range of absolute particles sizes in the suspended sediment, ensuring that very fine particles are collected by the sampler (cf. Walling & Woodward, 1993).

METHODS

The sediment samplers described above were deployed at two locations in a small (2.6 km²) lowland agricultural catchment located near Ashby-de-la-Zouch, Leicestershire, UK (cf. Hodgkinson & Withers, 1996) (Fig. 2). The suspended sediment load of the study streams comprised only fine-grained (<62.5 µm) material (Phillips *et al.*, in press). The sediment samplers were installed during October 1998 for the site at Lower Smisby and during December 1998 for the site at New
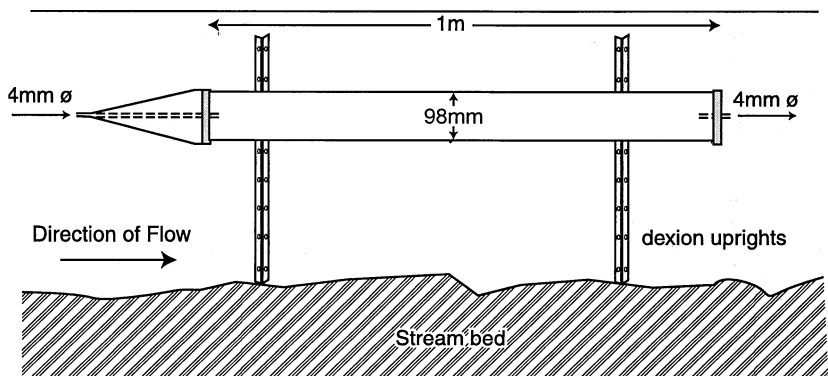

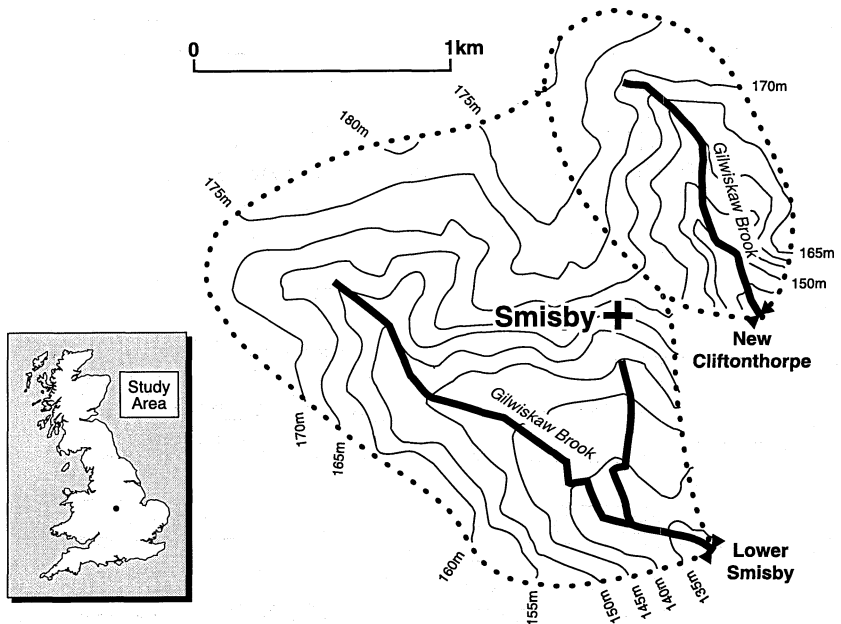**Fig. 1** Cross-section of the suspended sediment sampler.

Fig. 2 Location of the sampling sites in the Gilwiskaw catchment.

Cliftonthorpe. In addition, a sediment sampler was deployed for the duration of a single storm at New Cliftonthorpe in January 1999.

The properties of the time-integrated sediment samples have been compared with those of instantaneous manual samples collected from the same sites over the period of sampler deployment during storm events producing significant sediment transport (cf. Fig. 3). The instantaneous manual sampling involved collection of between 100 and 200 l of stream water. The sediment was recovered from the manual samples and from the samples obtained from the sediment samplers by continuous flow centrifugation and the sediment was subsequently freeze dried prior to analysis.

Analysis of the geochemical properties of the sediment focused on four groups of properties:

1. several basic sediment properties, namely, iron (Fe), organic-Fe (Fe_p), manganese (Mn), and total carbon (TC) content;
2. the concentrations of trace elements, including arsenic (As), lead (Pb) and zinc (Zn);
3. the activity of two environmental radionuclides, namely, caesium-137 (^{137}Cs) and unsupported lead-210 (^{210}Pb);
4. the sediment-associated total phosphorus (TP) and total nitrogen (TN) content.

The extraction of As, Fe, Mn, Pb, Zn involved direct acid digestion and Fe_p was extracted by potassium pyrophosphate (cf. Allen, 1989). These extract concentrations were measured using atomic absorption spectrophotometry (AAS). The TC and TN content was determined using a Carlo Erba NA 2500 CN analyser and TP was measured colorimetrically after perchloric acid digestion (Olsen & Sommers, 1982). Caesium-137 and ^{210}Pb activities were determined using a low background EG&G Ortec HPGe well-type detector.
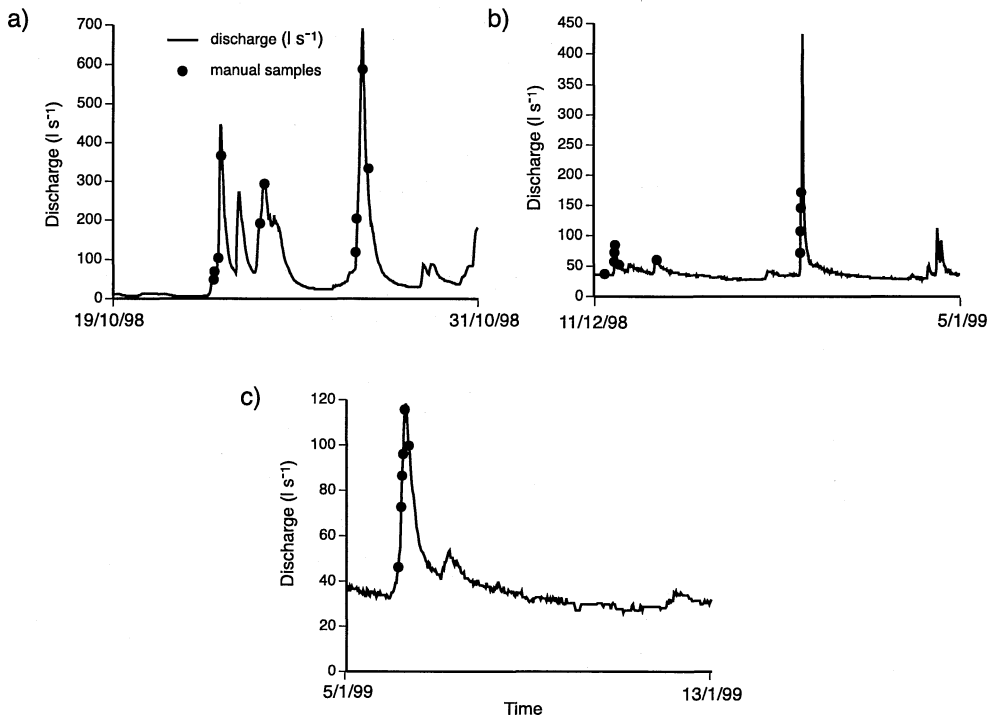
Fig. 3 Discharge records for the flume structures on the Gilwiskaw Brook for (a) the Lower Smisby site in October 1998, (b) the New Cliftonthorpe site in December 1998 and (c) the New Cliftonthorpe site in January 1999. Filled circles denote the times of collection of manual instantaneous suspended sediment samples.

RESULTS

In order to provide a rigorous assessment of the ability of the sediment sampler to collect a geochemically representative sample of the ambient suspended sediment flux, it is necessary to compare the concentration values for the individual sediment properties associated with the samples collected by the samplers with those for equivalent samples collected directly from the stream. However, it is difficult, if not impossible, to provide an equivalent time-integrated concentration value based on the samples collected directly from the stream. In this study, the concentration values obtained for the samples collected by the samplers were compared with the concentration-weighted mean concentrations of the same properties associated with the manual samples collected during the period of deployment of the sampler. The concentration-weighted mean concentration was calculated as:

$$\text{concentration-weighted mean concentration} = \frac{\sum_{i}^{n}(x_i \times y_i)}{\sum_{i}^{n} y_i} \tag{1}$$

where x is the concentration of the property in the manual sediment sample and y is the suspended sediment concentration (mg l^{-1}) at the time of sample collection. Direct

comparison of the resulting concentration values for the sampler and the manual samples is, however, complicated by four potential sources of error. Firstly, it is necessary to take account of the precision of the laboratory measurements involved. The precision of the measurements for each determinand was estimated by undertaking 10 replicate measurements on one of the manual suspended sediment samples. Secondly, intra- and inter- storm variability in the concentrations of the individual determinands and the precise timing of sample collection, which is biased towards periods with high suspended sediment concentrations (>100 mg l^{-1}) and may not be representative of periods with lower concentration, will inevitably influence the value obtained for the concentration-weighted mean concentration. Thirdly, the time-integrated values of concentration obtained for the sampler should ideally be compared with a mean value for the instantaneous samples weighted according to both concentration and flow velocity, since the latter will influence the intake velocity of the sampler. Finally, interactions between the sediment retained in the sampler and the water passing through the sampler may occur during the period of deployment. However, no consistent trend of overestimation or underestimation was evident for the concentrations of the individual determinands associated with the sediment collected by the sampler during the three periods of deployment. This suggests that exchange between the deposited sediment and water passing through the sampler is of limited importance in this instance.

Values of the percentage difference between the concentration value associated with the sediment collected by the sampler and the concentration-weighted mean

Table 1 A comparison of the difference between the concentration values for the sediment collected by the sampler and the concentration-weighted mean concentration of the manual point samples collected during the period of deployment of the sampler, expressed as a percentage of the weighted mean concentration, with the laboratory precision for the individual determinands expressed as the 95% confidence interval.

Property	Mean geochemical concentration of sediment collected by the sampler	95% confidence interval for analytical results (±%)	Deviation of sediment concentration collected by the sampler from the concentration weighted mean value calculated from the manual samples (%):					
			Lower Smisby Oct. 1998		New Cliftonthorpe Dec. 1999		New Cliftonthorpe Jan. 1999	
Fe	24 037.2	7.43	−7.36	(1.99)	−3.05	(1.96)	−5.96	(5.31)
Mn	537.5	5.63	−1.74	(2.96)	−3.78	(2.95)	9.50*	(2.68)
Fe$_p$	2 430.5	4.34	−0.04	(3.81)	−4.23	(3.90)	3.31	(10.11)
TC	58 652.0	2.18	−1.26	(4.67)	3.50*	(2.60)	−1.96	(3.40)
As	16.2	14.20	−12.26	(2.33)	−1.14	(2.78)	−13.66	(9.73)
Pb	85.4	10.24	−2.31	(3.41)	10.81*	(3.88)	8.65	(6.95)
Zn	206.8	7.30	−6.79	(2.29)	7.30	(2.61)	−2.04	(2.57)
^{137}Cs	15.1	12.35	8.46	(3.57)	6.23	(2.04)	−0.68	(6.88)
^{210}Pb	30.4	18.36	−15.03	(11.60)	−19.65	(27.71)	−26.72*	(12.65)
TP	1 403.0	5.49	−3.02	(7.13)	−3.93	(2.61)	0.61	(2.96)
TN	4 963.8	5.30	−11.93*	(4.93)	6.81*	(2.08)	−10.01*	(4.93)

Cases where the value for the sediment collected by the sampler is lower than the concentration-weighted mean concentration for the manual samples are shown as negative values.
Asterisks (*) indicate instances where the difference is greater than the laboratory precision.
The values in parentheses are the 95% confidence limits for the concentration-weighted mean concentrations based on the weighted standard error of the mean, expressed as a percentage.
Mean concentrations of the sediment collected by the sampler are expressed as µg g^{-1} except for ^{137}Cs and ^{210}Pb which are expressed as mBq g^{-1}.

concentration for the manual samples are presented in Table 1. To evaluate the uncertainties outlined above, the magnitude of this difference can be compared with the 95% confidence interval around the laboratory measurements listed in the second column of Table 1. For most determinands, the difference between the concentration values for the sediment collected by the sampler and the values derived from the manual samples is less than the 95% confidence interval associated with the laboratory measurements. This suggests that the sediment collected by the sampler provides a representative sample of the ambient suspended sediment flux. In some cases the difference between the two values exceeds the 95% confidence interval associated with the measurement precision. In these cases the potential uncertainty associated with the estimation of the concentration-weighted mean concentration can be taken into account by considering the 95% confidence limits around the weighted mean value, derived using the weighted standard error of the mean, expressed as a percentage. These values are shown in parentheses in Table 1. When this additional source of uncertainty is taken into account, almost all of the differences between the concentration values for the sediment collected by the sampler and the weighted mean values for the manual samples can be discounted as non-significant.

DISCUSSION

The key advantage of a time-integrated suspended sediment sampler is the ability to obtain a representative sample of the suspended sediment flux during the period of deployment, without the need for extrapolation or interpolation of data obtained from point samples. The potential for using such time-integrated samples can be usefully illustrated by considering a sediment source fingerprinting application. Table 2 presents the results of applying a quantitative composite fingerprinting procedure and a multivariate mixing model to the 10 manual sediment samples and the sediment collected by the sampler from New Cliftonthorpe during December 1998, following the approach outlined in Collins *et al.* (1997). In this case, the source ascription procedure employed differentiated only channel bank material and surface-derived material as potential sources. The composite fingerprint was derived using a selection of the measured suspended sediment properties and included As, Fe, Fe_p, Pb, Zn, TC, TP and ^{137}Cs. The resulting composite fingerprint was capable of correctly differentiating 100% of the sediment samples used to characterize potential sediment sources in the upstream catchment. Application of the mixing model to the time-integrated

Table 2 Source type ascription based on the manual suspended sediment samples and the sediment sample collected by the sampler from the New Cliftonthorpe sampling site during December 1998.

Date/time	Surface (%)	Channel bank (%)	Date/time	Surface (%)	Channel bank (%)
12.12.98/05:10	78.8	21.2	25.12.98/14:25	79.1	20.9
12.12.98/21:30	65.2	34.8	25.12.98/14:55	85.5	14.5
12.12.98/22:10	88.2	11.7	25.12.98/15:10	86.8	13.2
12.12.98/23:00	95.0	5.0	25.12.98/15:25	91.8	8.2
13.12.98/05:20	87.9	12.1	Weighted mean	85.6	14.4
15.12.98/00:15	84.5	15.5	Sampler sediment	85.2	14.8

sediment sample indicated that during the period of deployment, 85% of the suspended sediment load was derived from surface soils and 15% from channel banks. The results for the manual individual sediment samples indicate that the contributions from surface sources and channel banks to the suspended sediment flux at the time of sampling varied from 65 to 95% and from 5 to 35%, respectively. In order to represent the source contribution values associated with the individual manual samples by a single value which may be compared with the time-integrated value provided by the sediment sample collected from the sampler, the load-weighted average contribution value has been calculated for the period of sampler deployment. This calculation was based on the instantaneous values of discharge and suspended sediment concentration at the time of sample collection. The value obtained shows very close agreement with the equivalent value obtained for the sediment collected by the sampler, and further emphasizes the potential value of the sampler in sediment source fingerprinting studies.

CONCLUSIONS

The simple *in situ* suspended sediment sampler described has been shown to collect a representative time-integrated sample of fluvial suspended sediment, based on measurements of a range of sediment-associated determinands. These results further support the findings of Phillips *et al.* (in press) which demonstrated that the particle size characteristics of the sediment provided by the sampler were statistically representative of the ambient suspended sediment. The potential to collect a time-integrated sediment sample offers considerable potential in documenting nutrient and contaminant fluxes and in sediment fingerprinting studies. The time-integrated sample provided by the sediment sampler is representative of the total suspended sediment flux and avoids the need for expensive flow and suspended sediment concentration monitoring equipment which is necessary to interpret the results obtained from instantaneous manual samples in terms of variations in the sediment flux.

The sediment sampler should, however, not be viewed as an alternative to collecting point samples, but rather as a complement. It is advisable to test the performance of the sampler at sites where it is installed, especially in highly contaminated systems where sediment–water interactions and chemical transformations of the sediment-associated properties could occur. Furthermore, the sampler is unlikely to retain a sufficient mass of sediment to permit sampling on an intra-storm basis, although samples could be collected from deployments encompassing individual storms.

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