Abstract

Delivery of fine sediment to fluvial systems is of considerable concern given the physical and ecological impacts of elevated levels in drainage networks. Although it is possible to measure the transfer of fine sediment at high-frequency using a range of surrogate and automated technologies, the demands for assessing sediment flux and sediment properties at multiple spatially distributed locations across catchments can often not be met using established sampling techniques. The Time-Integrated Mass-flux sampler (TIMs) has the potential to bridge this gap and further our understanding of fine sediment delivery in fluvial systems. However, these devices have undergone limited testing in the field. The aim of this paper is to provide a critical validation of TIMs as a technique for assessing fluvial fine sediment transfer. Fine sediment flux and sediment properties were assessed over two years with individual sampling periods of approximately 30 days. Underestimation of sediment flux ranged between 66 and 99% demonstrating that TIMs are unsuitable for assessing absolute sediment loads. However, assessment of relative efficiency showed that 6 out of 7 samplers produced statistically strong relationships with the reference sediment load (P<0.05). Aggregated data from all sites produced a highly significant relationship between reference and TIMs loads (R^2=0.80; P<0.001) demonstrating TIMs may be suitable for characterising patterns of suspended sediment transfer. Testing also illustrated a consistency in sediment properties between multiple samplers in the same channel cross-section. TIMs offer a useful means of assessing spatial and temporal patterns of fine sediment transfer across catchments where expensive monitoring frameworks cannot be commissioned.

1. Introduction

Although there is considerable knowledge of the impacts of changing land-use on the magnitude and timing of erosion within catchments, much less is known about the transfer dynamics of fine sediment (< 2mm) through the hydrological networks that drain these areas. This gap in understanding has led to calls for the development of frameworks that better characterise fluvial suspended sediment flux and more closely specify provenance of sediment at enhanced spatiotemporal resolutions (e.g. Owens and Collins, 2005; Wainwright *et al.*, 2011; Fryirs, 2012). Such monitoring frameworks would; a) enhance our understanding and prediction of the internal dynamics of the fluvial sediment system (Fryirs, 2012); b) permit better assessments of the magnitude and duration of aquatic organisms' exposure to detrimental levels of suspended sediment (Bilotta and Brazier, 2008); c) enhance our understanding of the effects of environmental and future climatic changes on sediment delivery; d) provide datasets suitable for evaluating models developed for the prediction of spatial variations in sediment transfer (Brazier, 2004) and; e) provide specific insight on the success of management practises and river restoration to ensure water quality guidelines are met and river habitats maintained.

Using traditional sampling frameworks, two parameters are required in order to assess the quantity of fluvial suspended sediment transfer, namely the instantaneous measurement of suspended sediment concentration (SSC) and river discharge. Discharge is relatively accessible in most drainage basins of developed countries. However, SSC data is somewhat more difficult to acquire given the current dearth of sediment monitoring schemes in the UK (Brazier, 2004). Where monitoring schemes do exist, their ability to achieve accurate suspended sediment flux data is largely dependent on two key issues. The first is the choice of method used to acquire the suspended sediment measurements, which itself can appreciably alter the representativeness of the concentration estimate (Gurnell *et al.*, 1992). The second issue, given the highly episodic nature of fine sediment transfer, is the sampling protocol adopted. Common sampling protocols for estimating the flux of fluvial suspended sediment involve the use of either automatic sampling protocols (Lewis, 1996; Lewis and Eads, 2008) or the deployment of turbidity probes providing high frequency surrogate measurements of in-stream SSCs (Pavanelli and Pagliarani, 2002; Pavelich, 2002). These methods have proved effective in producing load estimates (Walling and Webb, 1981; Phillips *et al.*, 1999; Minella *et al.*, 2007) and exploring the processes responsible for the delivery and transfer of sediment to and from the channel (Rovira and Batalla, 2006; Smith and Dragovich, 2009; Oeurng *et al.*, 2010). However, the spatial coverage and temporal duration of monitoring is constrained by the cost of establishing multiple monitoring sites (Collins and Walling, 2004), which can often lead to observations being restricted to catchment outlets.

An often secondary consideration of sampling frameworks is the ability to characterise the properties of the suspended sediment transported through the river networks (such as particle size and organic content). Such information is essential for understanding downstream transport of particles, chemical transport and for modelling and predicting the fate and effects of contaminants. Reliable information about the spatial and temporal variability of sediment properties also becomes particularly important when attempting to interpret such information for management purposes (Ongley, 1992). However, collecting representative data is often challenging given that even during individual events, fine sediment delivered to hydrological networks may be from multiple sources which become active temporarily (Keesstra *et al.*, 2009). This can lead to properties of suspended sediment being highly temporally variable (Grieve, 1984; Ongley, 1992) with even intensive sampling regimes potentially misrepresenting the properties of fine suspended sediment (Cuffney and Wallace, 1988).

Given the highlighted constraints of commonly adopted sampling frameworks, an alternative approach for bridging the previously identified research gaps may be through the placement of time-integrated sampling devices at key locations across catchments in order to collect representative samples of suspended sediment at low cost. Various time-integrated sampling devices have been designed and used for monitoring purposes, many of which share the basic characteristic of continuously capturing a sample of suspended sediment from the main flow of the river through principles of natural sedimentation. Samplers such as the IS3 (Scrudato *et al.*, 1988) were designed to capture a bulk sample of fine sediment with little consideration of the samplers ability to provide a sample which is representative of the transported material in terms of both mass and material properties (Scrudato *et al.*, 1988). The Time-Integrated Mass Flux sampler (TIMs) designed by Phillips *et al.* (2000) (Figure 1) was however developed to trap sediment to be used for the assessment of physical, geochemical and magnetic properties of transported material (e.g. Phillips *et al.*, 2000; Russell *et al.*, 2000). The device has subsequently been used in sediment source ascription studies (e.g. Fox and Papanicolaou, 2007; Collins *et al.*, 2010; Fukuyama *et al.*, 2010) and to assess sediment fluxes (e.g. Hatfield and Maher, 2008; Schindler Wildhaber *et al.*, 2012). If deployed appropriately, the device is subject to the full range of flow conditions over the sampling period, providing a continuous record of suspended sediment flux which may be representative of all events (Walling, 2005).

The operating principle of the TIMs is that water passes through the upstream inlet and into the expansion chamber where sudden expansion results in a significant reduction in velocity, encouraging sedimentation of fine particles within the sampler. The water continues to flow through and out via the outlet. The streamlined design minimises flow disruption, altering flow magnitude by no more than 20% whilst allowing the flow to exit unimpeded thereby minimising sampling bias which is often inevitable using other methods (Fox and Papanicolaou, 2007).

[Insert Figure 1]

Initial attempts to validate the TIMs as a representative means of collecting fine suspended sediment have had mixed success, with research being limited to laboratory experiments and short-term field experiments. In a laboratory experiment undertaken by Phillips *et al.*, (2000), capture rates of between 31 and 71% were obtained using very fine (< 2 μm), chemically dispersed fine sediment with inflow velocities of between 0.3 and 0.6 m s^{-1}, although the sampling efficiency was observed to decrease with increasing flow velocities. Russell *et al.*, (2000) also found that the sampler provided a means of collecting a geochemically representative sample of the ambient fine suspended sediment. More recently, a field study by Hatfield & Maher (2008) found significant correlations (R^2 of 0.89 and 0.97) between the maximum recorded discharge and the trapped mass recovered from the TIMs at two monitoring locations. A modified version of the sampler was also tested in an arctic fluvial environment (McDonald *et al.*, 2010). However, the reduction in sampler length from the standard 1000 mm to 228 mm, reduction of the sampler diameter from 100 mm to 63.5 mm and reduction of the inlet diameter from the standard 4 mm to 2 mm are likely to have undermined sampling efficiency (McDonald *et al.*, 2010). Despite the modifications, a weak linear relationship between actual and potential mass of sediment captured was observed (R^2 = 0.43) with the difference between the actual and potential capture success varying from 20% to 150%. Most recently, Schindler Wildhaber *et al.*, (2012) suggested that both TIMs and turbidity sensors are suitable for capturing large-scale spatial and temporal variations in SSCs or suspended sediment (SS) loads. They found the total weekly SS load from TIMs were significantly correlated with mean weakly SSCs, with spearman rank correlations of 0.8

(n = 212*)*, 0.2 (n = 204) and 0.7 (n = 204). However, on a weekly basis, the SS loads captured by six SS samplers per-site varied considerably with coefficients of variation between 12 and 100%, posing questions over their precision.

Despite their widespread use in arctic, temperate and tropical fluvial environments (Fox and Papanicolaou, 2007; Collins *et al.*, 2010; Fukuyama *et al.*, 2010; McDonald *et al.*, 2010), assessment of the validity of TIMs in long-term deployments has not yet been conducted. It is thus timely to explore the characteristics of this approach in more detail and to establish whether this technique is rigorous enough to characterise fine sediment flux and sediment properties more widely. This paper therefore aims to evaluate the suitability of the TIMs as a means of; a) characterising fine fluvial suspended sediment flux and; b) characterising the physical and mineral magnetic properties of the associated sediment. This will be achieved by directly comparing the estimated flux from the sediment sampler with reference sediment loads derived from high-frequency SSC and flow measurements in order to assess whether shifts in the magnitude of flux are detected, and; c) comparing the properties of sediment captured at multiple points within the same cross-section of flow to determine the consistency of the samplers.

2. Background and Methods

2.1 Study Area

This research was conducted in the River Esk and Upper River Derwent catchments, which drain the upland area of the North York Moors located in the North Yorkshire region of England (Figure 2). The Esk catchment, with an area of 362 km^2, is underlain by sandstone, siltstone and mudstone formations of the mid and lower Jurassic periods with rolling moorland dominating the upland landscape. Intensive agriculture is scarce with less than 1% of the area farmed for cereals although improved grassland is common in the lower catchment. The larger, 2048 km^2, Upper Derwent catchment is dominated by improved grassland and cereals with Ampthill clay and Kimmeridge clay geological formations of the late Jurassic dominating the geology. The climate of this region is cool temperate with a rainfall distribution that is complicated by a rain shadow effect produced by the high Pennines to the West. This results in only the highest points in the area receiving over 1000 mm yr^{-1} (Simmons, 2003). The Esk catchment in particular has long been home to one of the best salmonid fisheries in Northern England. However, siltation and excessive suspended sediment concentrations have been attributed to cause declines in the local populations of salmon, sea trout and brown trout in the area (Walling *et al.*, 2001). This prompted research to highlight areas responsible for the delivery of suspended sediment in the adjacent Esk and Upper Derwent catchments.

2.2 Sampling Design

In this study, 39 monitoring sites were established across the Esk and Upper Derwent catchments. These sites were equipped with one TIMs in order to capture the spatial and temporal variability of the sediment flux and properties of transported sediment (Figure 2). Of these sites, four were selected for validation purposes. At these sites, two TIMs were installed adjacent to gauging sites where river level/flow and turbidity were recorded (with the exception of Grosmont where only one sampler was installed) (Figure 2). These validation stations were designed to measure sediment flux which could then be compared with TIMs mass-flux estimates. The monitoring stations used for validation purposes in the Esk catchment are located at Grosmont and Danby on the River Esk and also on Glaisdale Beck. These locations have drainage areas of 286.6, 95.7 and 12.1 km^2 respectively. The second instrumented catchment is in the Rye sub-catchment of the Upper Derwent. This monitoring station is located on the River Rye, draining an area of 130.8 km^2 (Figure 2).

[Insert Figure 2]

2.3 Reference Load Determination

Turbidity measurements were made at 15-minute intervals using McVan Analite 395 nephelometers. For each monitoring site, a calibration between the Formazin calibrated turbidity (FTU) and SSC was established. These pairings were plotted and a linear regression model was adopted to best describe the fit between the variables. A condition set for each model was that the intercept had to pass through zero. This was chosen because in filtered, deionised water, there should be no particles available to scatter the incident beam and therefore the turbidity should be zero. Further to the development of the linear models, the uncertainty of the regression coefficients was evaluated. This was achieved using a bootstrap re-sampling method. This method randomly re-samples the dataset *n* times, replacing the original sample and providing detailed information about the characteristics of the population. A sufficient number of re-samples is 2000 (Trauth, 2010), although in some instances 100,000 samples have been used (Bilotta *et al.*, 2010). In this instance, *n* is set at

2000. Table 1 shows the uncertainty of the regression coefficients along with the number of calibration samples (*n*) and summary statistics. These calibrations are within the acceptable range of uncertainties for the given operating ranges, as set out by Gray *et al.* (2002).

[Insert Table 1]

River stage was also measured at 15-minute intervals at each of the sites where turbidity was monitored. Using this data in conjunction with velocity estimates derived using Manning's roughness coefficients, river discharge was estimated. Checks on the roughness coefficient at various discharges were made through salt-dilution gauging. Discharge estimates (Q_i) were used in conjunction with estimated SSCs (mg L^{-1}) (C_i) to estimate of the suspended sediment load (L) (Equation 1).

$$L = \int_{t_1}^{t_2} Q(t)C(t)dt \qquad \textbf{Equation 1}$$

Where L represents the load between t_1 and t_2, $Q(t)$ the discharge at time t and $C(t)$ the suspended sediment concentration at time t.

2.4 TIMs Load Estimation

Theoretical flow calculations indicate that the original design of the TIMs (after Phillips *et al.*, 2000) does not operate isokinetically under the full range of flow conditions in the operating environment despite claims to the contrary (e.g. Collins *et al.*, 2010). This is a result of hydraulic discontinuity occurring at velocities below 0.55 m s^{-1}, which may potentially bias the sample. It was therefore deemed appropriate to slightly modify the design to reduce this hydraulic discontinuity. A larger (8 mm diameter) inlet and outlet and a narrower (90 mm diameter) expansion chamber were used, producing fully-turbulent flow at velocities greater than 0.38 m s^{-1}whilst producing the necessary conditions for sedimentation to occur.

During deployment, the TIMs were attached to dexion uprights anchored to the river bed in the centre of a straight reach with the inlet positioned perpendicular to the direction of flow at 50% of the flow depth under base-flow conditions (approximately 10-15 cm above the bed). TIMs were left in-situ for approximately 30 days in order to capture a sufficient mass of sediment for subsequent analysis of the material. At the end of the sampling period the device was removed from the river and the fine sediment was collected in 5L containers. The samplers were rinsed, relocated and the samples taken to the laboratory for analysis. In the laboratory the samples were held in cold storage for 3 days to allow the sediment particles to settle. The supernatant was then siphoned from the container, ensuring material was not disturbed. Analysis showed that supernatant contained on average only 0.12% of the total mass of collected sediment. The remaining sediment was removed from the container and placed in an oven at 40°C until all remaining moisture had evaporated. The mass of sediment was then weighed.

With TIMs, the mass of material collected by the sampler does not represent a true load-weighted composite sample; rather it provides an at-a-point flux over the sampling interval. Therefore to provide a meaningful representation of suspended sediment load, this flux estimate must be multiplied by the cross-sectional area of flow at the time when the sediment was captured. This poses two issues; 1) SSCs have been shown to vary in the vertical and horizontal planes (Wass and Leeks, 1999) therefore it could be argued that any extrapolation from point measurement to cross-section should account for this. However, in well mixed and shallow streams such as those sampled in this research, single measurements at a point in the cross-section may still produce representative samples (Sheldon, 1994). 2) Unlike suspended sediment concentration samples which are usually discrete and accompanied with a paired flow measurement, the time-integrated mass collected must be scaled with the cross-sectional area of flow over the sampling period. In order to account for this, a scaling factor for each collection period was approximated by first sorting the instantaneous suspended sediment loads (over the entire collection period) and then producing a cumulative distribution of the values (Figure 3a). The discharge for the point at which 50% of the total suspended sediment load was transported was then selected as the scaling discharge value. By reversing the stage-discharge relation, it is possible to determine the river level for this point (Figure 3b). Finally, using data derived from detailed surveys, the cross-sectional area for the river could be calculated (Figure 3c) and then used as the scaling function for the sediment load estimates (Equation 2 a - b). This approach to scaling function development allows for the factor to be varied based on the sediment transfer dynamics during the monitoring period.

[Insert Figure 3]

2.5 Measurement of Sediment Properties

Following the drying process described previously, the sediment was gently disaggregated using a rubber bung and sub-sampled through a 2 mm sieve. Only coarse particulate organic material failed to pass through. The fine sediment was then ready for subsequent analysis. The particle-size distribution of the recovered sediment was determined for a representative sub-sample of between 0.3 and 0.5 g of material. Prior to analysis, the sample was twice treated with 20 ml of hydrogen peroxide to remove any organic material, followed by the addition of 2 ml of sodium hexametaphosphate to encourage deflocculation. The samples were then analysed using a Coulter laser granulometer (LS230). The magnetic properties of the sediment were determined using Bartington MS2 Magnetic Susceptibility System. Prior to measurement, the sample was ball milled in order to eliminate particle size effects (Dekkers, 1997). The organic and carbonate content was determined through mass loss following intense heating of the recovered material to 550 °C for 4 hours and 950°C for 2 hours respectively following recommendations by Heiri *et al.* (2001). Although this method is simple it has been shown to provide comparable precision and accuracy of other, more complex geochemical methods (Dean, 1974).

3. Results

3.1 Absolute Efficiency of TIMs

The first aspect of TIMs that is assessed is the efficiency with which fine sediment is captured. To achieve this, the reference load and TIMs load(s) have been calculated during the period from 21st September 2007 to 20th October 2009. Each data point for the reference and TIMs load(s) is the integration of the sediment load from the time of collection to the previous collection date. Figure 4 provides examples of the reference and TIMs load time-series for a) the Esk at Grosmont and; b) the Rye at Broadway Foot.

[Insert Figure 4]

Through examination of the examples provided in Figure 4, it is clear that the TIMs loads are markedly smaller than the reference loads with a much more damped response. The level of underestimation is between 66.38 and 96.31% (Table 2). Nash Sutcliffe coefficients for each site are less than zero, ranging from between -0.444 and -0.9783 (Table 2). This highlights deviations from the 1:1 line and confirms that the TIMs are not an efficient indicator of total suspended sediment load and should not be used independently as a means of quantifying the absolute fluvial fine suspended sediment loads.

[Insert Table 2]

3.2 Relative Efficiency of the TIMs

Although TIMs are not able to measure the actual suspended sediment load, Figure 4 does demonstrate that TIMs sediment loads appear to show some synchronicity with trends in estimated discharge. Periods of sustained low flow e.g. February – June 2009 produce negligible load estimates, whereas periods containing individual or multiple moderate to high flow events produce the greatest sediment loads. Furthermore, peaks in the TIMs load estimates do correspond with peak reference sediment loads. Therefore, if the device is precise and underestimates the sediment load in a predictable and consistent manner, which is comparable (in terms of mass and properties) at multiple points in the river cross-section, there is potential for TIMs to be useful in characterising the patterns of suspended sediment transfer in fluvial systems. These assumptions were assessed in three ways:

1) Regression analysis of the relationship between the reference flux and TIMs flux estimates.
2) The coefficients of the regression equations between reference sediment load and duplicate TIMs A and TIMs B samplers were compared.
3) Mann–Whitney *U* test for differences in the properties collected by the paired TIMs A and B samplers.

Results of regression analysis between the reference and TIMs sediment loads are presented in Figure 5. The significance level of the relationship is also shown. Of note is that four of the seven relations are statistically significant at the 99% level, with two instances where the relationship is significant at the 95% level. Only one relation is not significant at the 95% level.

[Insert Figure 5]

The regression relationships between the reference sediment load and TIMs A/TIMs B at Broadway Foot are statistically significant at the 95% and 99% levels respectively. The slope coefficients of the regressions are 3.5% and 6.7% respectively which are not statistically similar. Clearly there is clearly inherent sampling bias between the samplers. Most notably, between 11th February and 18th March 2009 the reference sediment load is 1364 t however, TIMs A estimates a load of 29 t whilst TIMs B estimates a load of 114 t. This reduces the slope coefficient for sampler A. Given the dramatic underestimation of sampler A during this period it is feasible that the sampler became obstructed by debris, resulting in a blockage of the sampler intake. This is one of the limitations with using the sampler which cannot be easily predicted nor quantified (McDonald *et al.*, 2010). Both of the regression relationships between reference sediment load and TIMs A/TIMs B at Glaisdale Beck are statistically significant at the 95% and 99% levels respectively. The slope coefficients are 7.6% and 21.7% respectively which are again not statistically similar. At the Danby monitoring site the linear fit between reference sediment load and TIMs A is poor (R^2 = 0.16) and is not statistically significant at the 95% level, whereas sampler B is highly significant (R^2 = 0.63). The estimated slope for TIMs B is 8.6%.. At Grosmont, only one sampler was installed so therefore analysis is limited to assessing the efficiency of the sampler with reference to the reference load. In this case, the relationship is significant at the 99.9% level, with an R^2 of 0.78. The slope of the regression equation for this site is 8.9%. This analysis demonstrates that although the TIMs significantly underestimate the actual (or reference) sediment load, in 6 out of the 7 cases a statistically significant ($P < 0.05$) relation between the reference and TIMs loads was observed highlighting a relative efficiency of the sampler and showing that individual TIMs operate consistently over prolonged periods, underestimating the actual sediment load in a predictable manner with underestimation of between 60 and 99% for individual sampling periods.

However, the regression slopes of paired TIMs are not statistically similar, illustrating a varying magnitude of responses and sensitivity between the two samplers (Table 3). This suggests that although reference and TIMs loads may be highly correlated, within site variations act to bias the replicate estimates within the cross-section. This variability has also observed by Schindler Wildhaber *et al.,* (2012), highlighting the sensitivity of flux estimates to sampler positioning. The criteria for determining the sampler location should therefore, wherever possible, be consistent between sites.

[Insert Table 3]

Finally, through aggregation of these individual data sets, the TIMs load can be predicted from the reference load using the power law ($y = 0.056x^{0.9581}$), which produces an R^2 of 0.80 ($P < 0.001$). The *m* coefficient of 0.056 highlights the considerable degree of underestimation whereas the *b* coefficient of 0.9581 highlights a degree of linearity and consistency in response, with log y increasing by 0.96% with every 1% increase in log x units.

[Insert Figure 6]

3.3 Sediment Properties

Although TIMs have been highlighted as having potential to detect changes in the magnitude of suspended sediment flux, the large underestimation in the actual mass captured may lead to questions being posed as to whether the sampler can be used to appropriately capture the physical properties of fine sediment. This section addresses questions of sampler precision by comparing measurements between two samplers in the same cross-section of flow. The properties tested for differences are the median absolute particle size, magnetic susceptibility, organic and carbonate content. At each of the monitoring locations and for all the parameters tested apart from magnetic susceptibility at Danby, the results of the Mann–Whitney *U* test demonstrated no statistically significant differences ($P > 0.05$), suggesting that the median values measured over the entire monitoring period are indeed similar. This provides us with confidence that the sampler is consistent and precise in these environments. The summary statistics and results of the Mann–Whitney *U* test are provided in Table 4. Although all parameters are statistically similar, it is clear that the sediment quality indicators (i.e. magnetic susceptibility, organic and carbonate content) are most stable between samplers. The absolute deviation in median values between samplers is 0.02 (10^{-6} m^3 kg^{-1}) for magnetic susceptibility; 1.58% for organic content and; 0.17% for carbonate content. Conversely, the deviation for median grain size is more varied with median measurements between the samplers varying by 6.86, 2.84 and 29.31 μm. The magnitude of variation for particle size also appears to be influenced by the size of sediment transported, with greatest variation where the coarsest suspended sediment is found. These findings are entirely expected and could be hypothesised due to the particle size of transported material being affected by both in-channel hydraulics, sampler positioning and the properties of source material, whereas sediment quality descriptors may be affected to a lesser extent, with properties being relatively stable through the cross-section with a lesser impact of flow hydraulics.

[Insert Table 4]

4. Discussion: Potential use of TIMs in fine sediment studies

Results of laboratory experiments have previously shown that between 35% and 70% of fine suspended sediment particles are trapped by the sampler (Phillips *et al.*, 2000), with the potential for enhanced sampler efficiency in a natural setting due to the presence of composite particles and flocs acting to improve sedimentation rates within the sampler. This has led to their widespread deployment with the assumption that the material captured is representative of the ambient in terms of properties, and more increasingly, flux. This paper confirms that the samplers are capable of capturing suspended material with physical and mineral magnetic properties statistically similar to material sampled adjacently in the water column, highlighting a degree of precision in the sampler. This paper also demonstrates that TIMs grossly underestimate the total fine sediment flux but nevertheless, due to their comparable efficiency, may be useful in capturing spatial patterns and the temporal variability of flux across catchments.

The advantage of using these samplers in fluvial sediment studies can be illustrated using two examples. The first example is the generation of estimated specific sediment yields (t km^{-2} yr^{-1}) for TIMs monitoring sites across the Esk catchment (Figure 7). This would be extremely expensive to develop and maintain using established sampling protocols, whereas this inexpensive, time-integrated network allows some key information to be extracted. For example, the SSYs peak in the Esk catchment at the 8.84km^2 catchment scale, along with relatively high SSYs over the 8.84 – 15.56 km^2 range. This is consistent with previous research indicating that peak SSYs may vary within the range of 0.1 – 20 km^2 (Poesen *et al.*, 1996; Osterkamp and Toy, 1997; Chaplot and Poesen, 2012). Of particular note is the similarity of the patterns between the two hydrological years, providing some assurance of consistency in sampling operations. Furthermore, key sediment transfer 'hotspots' have been identified, namely at Butter Beck and Glaisdale Beck which have the largest and second largest SSYs for both years. This information is invaluable and can be used to inform the direction of mitigation measures and funding across the catchment (Warburton, 2007; Emery *et al.*, 2013).

[Insert Figure 7]

The second example provided utilises data which describes the physical properties of transported fine sediment across the Esk catchment. Figure 8 demonstrates how organic content can vary both spatially and temporally, something which may be missed through discrete sampling campaigns. Of the 374 time-integrated samples, 266 fall between 10 and 30% which Walling & Webb (1987) suggested to be typical of British rivers. Throughout the monitoring period there is a great deal of within site variability in the organic fraction of fine sediment, with a typical range in values of 20%. However, when specific sites are assessed, some interesting details can be extracted. For example, Butter Beck, which has the lowest proportion of particulate organic matter (POM) relative to the inorganic fraction, has been the focus of management activity in the last 10 years, with wooded debris being removed from the channel. This woody debris, which is rarely mobilised by flows, may not have provided much to the POM content of the river due to their slow breakdown rates (Webster *et al.*, 1999). However, these natural structures which provide stability and act to diversify flow may enhance the retention of POM (Bilby, 1981; Naiman, 1982) and produce a rich faunal habitat with a rich diversity of flora. With the removal of this material, it is feasible that in-stream production of organic matter has subsequently declined. The combination of these processes may therefore have acted to produce the relatively low POM content of the fine suspended sediment in this sub-catchment. Conversely, the high organic contents measured in the Murk Esk catchment (Beck Hole and West Beck), may be explained by the enhanced transfer of litter from the riparian zone (Madej, 2005) as these catchments are primarily overlain by shrub and coniferous forest.

Seasonality in the POM content across the catchment is also observed, with peak organic content occurring during the summer months. This is consistent with research by Ankers et al. (2003) who found that transfer of organic material peaked during summer and early autumn. This temporal cycling may be due to the production of autochthonous material from phytoplankton production (Hedges *et al.*, 2000) or potentially from allochthonous sources such as litter inputs corresponding to maximum vegetative growth (Wetzel *et al.*, 1977).

[Insert Figure 8]

These examples demonstrate ways in which these sampling devices are capable of meeting the calls by researchers, agencies and managers for the development of sampling protocols capable of capturing the properties of transported material and understanding the delivery of fine sediment at enhanced spatial and temporal resolutions without the costs associated with generating the desired physical data required by established sampling protocols. This brings to the fore questions as to whether approximate and proxy data, which can be easily collected at a large number of sites, may be best able to meet researchers and practitioners' requirements as opposed to the current practice of highly detailed data at few sites, or whether a combination of the two approaches would be appropriate. Ultimately, a decision based on the project requirements must be made as to whether the benefits of collecting exact data from a small number of sites out-weighs the loss of information which could be gathered through establishing many sites producing approximate measurements (Ongley, 1992). For example, in situations where highly accurate information about fine sediment dynamics is required, the TIMs sampling protocol is deemed to be unsuitable. However, where there is little data available on the spatial and temporal variability of fine sediment fluxes and properties, this novel sampling protocol may provide a means of identifying areas in the catchment where more targeted monitoring resources may be of benefit, or highlight areas which may respond favourably to mitigation projects. Such data is vital to help to begin understanding spatial variations of sediment flux across catchments, especially in headwater areas which often receive little attention.

5. Further Research

A key finding of this work is that there is a considerable discrepancy between the results of sampler capture efficiency obtained through laboratory validation work and those obtained during this extensive field monitoring campaign. The low capture rates observed relative to the ambient transfer during validation in the field should therefore be further examined under a range of hydraulic conditions. Original laboratory research demonstrated a highly significant log-linear relationship between ambient flow and inlet flow within the range 15.4 – 58.5 cm s^{-1}. However, outside of this range, turbulent flow structures prohibited the measurement of representative flow velocities with turbulence resulting in a significant decrease in inlet velocity (Phillips *et al.*, 2000). Further research should therefore seek to assess the relationship between the ambient and intake velocities in conditions where the ambient velocity is greater than 0.5 m s^{-1}. Understanding of these relationships is important for two key reasons; 1) if during the course of a sediment transfer event, the changing effects of velocity and topographical forcing act to enhance the turbulence signature, the intake velocity may be significantly reduced leading an unpredictable sampling rate and to representativeness being questioned and; 2) non-isokinetic sampling will act to preferentially trap coarser suspended sediment within the sampler, biasing any sample. The trapped samples will therefore not be representative of the ambient particle size (McDonald *et al.*, 2010). This uncertainty in the continual sampling efficiency induces uncertainty in our descriptions of the properties of sediment being transported which could pose issues with using the TIMs as a means of collecting suspended material for source apportionment studies. This is especially important in locations where catchment erosion and fine sediment delivery to channels is complex with dynamic, multiple sources during the course of an event (Keesstra *et al.*, 2009).

6. **Conclusions**

Time integrated Mass-flux samplers (TIMs) were deployed in two adjacent catchments in the North York Moors National Park (North Yorkshire, UK) to assess the extent to which the samplers were successful in estimating suspended sediment flux over a two year monitoring period. Having shown that the TIMs significantly underestimated the actual (or reference) sediment load by between 96.31% and 66.38%, their relative efficiency was assessed. It was determined that in 6 out of the 7 cases a statistically strong (P < 0.05) relation between the reference and TIMs loads was observed. Aggregation of the data from all sites resulted in the observation of a highly significant relationship between TIMs and reference loads ($y = 0.056x^{0.9581}$) with an R^2 of 0.80 (P < 0.001). This showed that TIMs can potentially operate consistently over prolonged periods, underestimating the actual sediment load in a manner which is consistent with the magnitude change of the ambient flux. Furthermore, at all locations and for all sediment properties analysed (with the exception of magnetic susceptibility at one location), samples collected at multiple points in the channel cross-section were statistically similar demonstrating a useful degree of precision. Although the TIMs were initially developed for deployment in fine-grained lowland rivers, they also offer the potential to characterise the flux and properties of fine suspended sediment in upland rivers. Given requirements of spatially distributed and temporally integrated datasets describing the properties and magnitude of fine sediment transport, this device offers an additional sampling protocol for the assessment of flux at a range of locations in a catchment which may otherwise been unfeasible. However, this must only be done where the magnitude of under-estimation can be quantified and the response of the TIMs samplers is consistent with the overall estimated fine sediment flux. Further field investigations are required to assess the relationship between the ambient and sampler intake velocity in turbulent conditions to determine the conditions where the sampler operate flow proportionally.

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Tables from main Text

	Regression Equation	Range in SSC (mg L^{-1})	Coefficient of Determination (R^2)	Lower & upper limit of coefficient (95%)	Uncertainty (95%)
Glaisdale (*n* = 58)	y = 1.1298*x*	1.65 – 1266.20	*0.92*	0.9762 - 1.2058	22.96%
Danby (*n* = 282)	y = 1.2413*x*	0.87 – 628.86	*0.91*	1.1377 - 1.3426	20.49%
Grosmont (*n* = 305)	y = 0.9078*x*	0.37 – 572.6	*0.94*	0.8471 - 0.9582	11.11%
Broadway Foot (*n* = 134)	y = 0.8134*x*	1.23 – 321.44	*0.92*	0.7380 - 0.9304	19.24%

Table 1: Summary statistics of the site specific field calibrations of turbidity probes. Relationships that are significant at the 99.9% level are italicised.

	Reference Load (t)	TIMs Load (as % of reference load)	Nash-Sutcliffe Coefficient
Danby A	10101	5.40	-0.9783
Danby B	10101	6.35	-0.8513
Glaisdale A	806	33.62	-0.6950
Glaisdale B	578*	13.94	-0.4850
Grosmont	18667	6.66	-0.4861
Broadway Foot A	4429	3.69	-0.5308
Broadway Foot B	4429	5.77	-0.4444

Table 2: Comparisons between the reference and TIMs derived sediment loads alongside the Nash-Sutcliffe coefficient. * Where the reference load varies between the two sites, due to the TIMs becoming dislodged and lost to the river, resulting in missing period(s) in the sampling.

	Intercept (T and *P* values)		Slope (T and *P* values)	
Broadway Foot A vs. B	0.5	0.62	-2.34	*0.03*
Danby A vs. B	1.45	0.16	2.37	*0.02*
Glaisdale A vs. B	1.2	0.24	-2.03	*0.05*

Table 3: Results of t-tests on intercept and slope coefficients for each of the monitoring stations. Statistically significant results of the two-tailed test are italicised.

	Danby A [MAD]	Danby B [MAD]	*n*	*U*	*P*
Median Absolute Particle Size (µm)	21.95 [26.57]	15.09 [31.51]	34	185.5	0.0800
X_{lf} (10^{-6} m^3 kg^{-1})	0.16 [0.03]	0.18 [0.03]	20	27	*0.0445*
Organic Content (%)	9.10 [2.94]	10.68 [2.76]	40	155	0.1143
Carbonate Content (%)	0.86 [0.34]	1.02 [0.28]	22	47	0.1967

	Glaisdale A [MAD]	Glaisdale B [MAD]	*n*	*U*	*P*
Median Absolute Particle Size (µm)	8.87 [12.35]	11.71 [24.84]	34	149	0.4452
X_{lf} (10^{-6} m^3 kg^{-1})	0.18 [0.02]	0.16 [0.02]	16	37	0.3227
Organic Content (%)	9.88 [2.37]	10.08 [2.77]	32	129	0.4925
Carbonate Content (%)	1.15 [0.31]	1.32 [0.22]	20	50	0.5151

	Broadway Foot A [MAD]	Broadway Foot B [MAD]	*n*	*U*	*P*
Median Absolute Particle Size (µm)	19.72 [15.08]	49.03 [51.47]	18	23	0.0667
X_{lf} (10^{-6} m^3 kg^{-1})	0.14 [0.03]	0.14 [0.05]	14	26	0.4508
Organic Content (%)	13.24 [4.39]	13.26 [8.82]	16	31	0.5608
Carbonate Content (%)	1.12 [0.32]	1.05 [0.27]	16	35	0.3992

Table 4: Median monthly values and median absolute deviation (MAD) of sediment properties along with results of the Mann–Whitney *U* test. The *P* value is italicised where differences are significant at the $P < 0.05$ level