Working title: Discharge and suspended sediment time series as controls on fine sediment ingress into gravel river beds

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Abstract

Fine sediment availability and channel hydraulics are two of the primary controls on the ingress of fine sediment into gravel river beds. A novel dataset consisting of fine sediment ingress measurements coupled with high-resolution turbidity and discharge time series, was analysed to investigate relations between ingress, discharge and turbidity. Discharge and turbidity demonstrated a weak association with each other, and their relations with fine sediment ingress were relatively weak. An alternative, but widely applied ‘redundancy’ approach was investigated that focused on key metrics, or facets, of the discharge and turbidity time series and their association with fine sediment ingress. Principal component analysis was used to distil the most important facets driving variation in the discharge and turbidity datasets and these were then used as independent variables in regression models with sediment ingress as the dependent variable. These models accounted for a larger amount of the statistical variation in sediment ingress over time than discharge and turbidity time series. Facets of the turbidity time series were found to be the most effective explanatory variables. The results suggest that this approach could be valuable and justify its application and testing across a range of river types in different hydrological and sedimentary settings. Application of this method could improve our generic understanding of what controls ingress at larger spatial and temporal scales and therefore complements process-based approaches, which is vital for the development of fine sediment management strategies.

Keywords: sedimentation, redundancy approach, principal component analysis, facets, management.

1. Introduction

Excessive sedimentation within aquatic ecosystems is a global concern and can have detrimental consequences for all aspects of lotic ecosystem health (Heppell et al., 2009; Relyea et al., 2012; Naden et al., 2016). The deleterious effects of fine sediment on biota are well documented and are predominantly associated with sediment deposition onto, and ingress into, the river bed (Kemp et al., 2011; Jones et al., 2012a, b; 2014). Effective management of fine sediment loading therefore requires understanding of the relations between deposition and ingress and their key drivers, including sediment supply and water discharge (Diplas and Parker, 1992) at scales that are relevant to catchment management.

Fine sediment deposition into a framework of gravel clasts involves a complex set of processes. Ingress rates are related to several factors including local hydraulics (Buffington and Montgomery, 1999), vertical and lateral interstitial exchange (Mathers and Wood, 2016), the relative size of the infiltrating and framework particles (Gibson et al., 2009), the concentration of suspended sediment and the settling flux (Brunke, 1999), and sediment transport capacity (Naden et al., 2016). Local hydraulic characteristics such as shear stress, flow velocity and Froude number have been associated with fine sediment accumulation, but studies often disagree regarding the gross influence of these hydraulic parameters (Petticrew et al., 2007). Beschta and Jackson (1979) found that the Froude number was positively associated with ingress, whilst Einstein (1968) and Carling (1984) found no relationship with flow parameters. It is possible that local hydraulic influences differ as a function of the dominant hydrological process. In low energy, slow-flowing waters, fine sediment ingress rates can be high because deposition rates are enhanced (Wood and Armitage, 1999), whereas in high-velocity areas sediment supply can be accentuated, enhancing the availability of fine sediment for subsequent infiltration (Frostick et al., 1984). As such, the availability of fines, as regulated by supply, transport capacity and, potentially biotic effects (e.g. Rice et al., 2016) may dominate the rate of infiltration irrespective of local hydraulics and framework size (Carling and McCahon, 1987; Sear, 1993).

Despite an enhanced understanding of the small-scale processes that control fine sediment infiltration (grains to patches; seconds to minutes) there is still no simple predictive model of fine sediment ingress than can be applied at large spatial and temporal scales. Moreover, despite a general understanding that both local hydraulics and sediment supply respond to hydrological processes that occur over longer, monthly-annual timescales, few studies have investigated the relations, over longer timescales, between variations in fine sediment ingress, suspended sediment concentrations and river discharge. This is unfortunate because there is a global need to set river management targets that maintain healthy rates of fine sediment delivery, deposition and transport (Collins et al., 2011) and gaining an understanding of the factors that influence fine sediment ingress on such time-scales is vital for developing relevant management strategies (e.g. Naden et al., 2016).

Both field and laboratory studies have identified fine sediment availability as a key determinant of ingress rates (Petts, 1984; Sear, 1993), with positive associations between suspended sediment concentration and ingress (Beschta and Jackson, 1979; Carling, 1984; Carling and McCahon, 1987). In general, fine sediment ingress rates are greatest during flood events when sediment transport rates are high and sediment is made available by scouring from pools and sub-armour deposits or is recruited to the channel via overland flow and other processes, including river bank collapse (Beschta et al., 1981; Sear, 1993; Petticrew et al., 2007). However, there is an apparent absence of studies which simultaneously investigate the relationship between flow, sediment supply and deposition to assess the potential explanatory power of different facets of these regimes (Wohl et al., 2015). Direct data on sediment transport and subsequent deposition is severely limited relative to river discharge and there is a need for more high resolution and long term suspended sediment data in order to characterise the magnitude, frequency, duration, timing and rate of change in suspended sediment levels (*sensu* Richter et al., 1996; Poff et al., 1997). Seeking greater understanding of the relations between the drivers and rates of fine sediment ingress over monthly-annual timescales is therefore valuable and consistent with Wohl et al.'s (2015) argument that the fine sediment regime can be managed through consideration of gross water and sediment balances.

In this regard, it is possible that ecohydrological approaches, which utilise a redundancy' methodology to associate key elements of hydrological time series with measurements of ecological health, may be useful (Richter et al., 1996; Olden and

Poff, 2003). The purpose of such research has been to determine the ecologically relevant components or 'facets' of discharge time series (duration, timing, frequency, magnitude, rate of change in flow events; Richter et al., 1996; 1997; Poff et al., 1997) that support ecologically healthy rivers, thereby facilitating the design of 'environmental flows' (Acreman and Ferguson, 2009; Wharfe et al., 2014; Mustonen et al., 2016). Natural variability in stream processes is vital in maintaining diverse and healthy systems (Arthington et al., 2006) and these facets, rather than single simplistic metrics of a dynamic time series, are more appropriate for setting management targets (Richter et al., 1997). Given the plethora of indices that can be obtained from time series data (Poff, 1996), researchers must select which and how many indices are relevant to use for modelling purposes, particularly when many are inter-correlated (Olden and Poff, 2003).

Principal component analysis, a well-established multivariate technique, enables several variables that are inter-correlated to be analysed for the degree of similarity they characterise and subsequently transformed into a number of uncorrelated axes (variables) called 'principal components' which represent linear combinations of the original variables (Abdi and Williams, 2010). By identifying a reduced set of indices that represent the degree of variability in the time series, annual river management targets can be identified using a comprehensive statistical characterisation of relevant regime characteristics (Richter et al., 1997). This is an explicitly empirical method that requires careful application to avoid rejecting variables that are important, but which are not principal drivers of statistical variability (Monk et al., 2007). The method has been widely used beyond its original applications with flow discharge time series; for example to establish associations between stream temperature variability and instream communities (Jackson et al., 2007; Olden and Naiman, 2010; White et al., 2017), to group relevant instream geomorphic parameters for hydrological and ecological models (Singh et al., 2009; Faller et al., 2016) and to identify geographical properties associated with landslide susceptibility (Komac, 2006). At the core of this paper is an application of this methodology to fine sediment ingress. It is motivated by a conviction that the design and implementation of strategies that aim to manage levels of fine sediment storage in rivers would benefit from a better understanding of how facets of flow and sediment regimes relate to ingress rates.

This paper utilises novel measurements of fine sediment ingress collected over several months. These data were used with time series of discharge and turbidity, where the latter is shown to be representative of fine sediment availability, to identify key drivers of sediment ingress using the ecohydrological 'redundancy' approach. This analysis reveals the exploratory power of facets of the discharge and turbidity regimes as predictors of fine sediment ingress into riverbeds and seeks to establish the potential of employing simple empirical models, at temporal and spatial scales relevant to catchment management, using variables that are easily collected in the field.

A two-stage approach was employed:

i) Classification of hydrological and turbidity time series into a small subset of indices that effectively characterise the dominant components (facets) of the series via a principal component analysis and redundancy reduction methodology (sensu Olden and Poff, 2003).

ii) Examination of the dominant facets of turbidity and discharge that influence sediment ingress using correlation matrices and the development of linear regression models using the principal component sample scores.

2. Material and Methods

2.1 Study Sites

Data was collected from two lowland rivers in Rutland, UK; the River Gwash (52˚38' N, 00˚44'W) and the River Chater (52˚37' N, 00˚ 44'W). At the sites where measurements were made, the rivers are broadly comparable in physical characteristics (channel size, water chemistry, altitude and geology). The two sites are only 2.6 km apart geographically and therefore experienced similar synoptic meteorology and hydrological regimes. Close to the catchment outlet, mean flow is 0.18 $m^3 s^{-1}$ and Q_{10} (90th percentile) flow is 0.449 $m^3 s^{-1}$ for the River Chater. For the river Gwash mean flow is 0.52 $m^3 s^{-1}$ and Q_{10} flow is 1.16 $m^3 s^{-1}$ (NRFA, 2017). Catchment geology is dominated by Jurassic mudstones and sandstones (British Geological Survey, 2008) with both field sites located adjacent to arable farmland. Surface and subsurface bed material consisted of mixed cobbles and gravel (Table 1). Invasive signal crayfish, *Pacifastacus leniusculus* (*Dana*), are present in high abundances in the River Gwash but historic routine sampling by the Environment

Agency of England and Wales and contemporary sampling during the study period by the author has not recorded any individuals in the River Chater. Previous work has suggested that signal crayfish are significant biogeomorphic agents capable of mobilising fine sediment (Harvey et al., 2014; Rice et al., 2014; 2016; Cooper et al., 2016) although this was not an explicit consideration in the research reported here.

2.2 Discharge data

Hydrological variability during the sampling period was analysed using data collected from local Environment Agency gauging stations on the River Chater (Fosters Bridge; 52°38' N, 00° 35' W) and River Gwash (Manton; 52°38'N, 00° 42' W) at 15-minute resolution. Discharge data ($m^3 s^{-1}$) were converted to hourly averages to facilitate the identification of marked differences in the series including known hydrological events (floods or low flows; Figure 1a). The majority of the study period consisted of baseflow conditions punctuated by flashy high flow events.

As the gauge sites were 2.9 km and 12.4 km downstream of the field sites on the River Gwash and River Chater respectively, discharge values at the gauge site were scaled based on the catchment drainage area of the sample site relative to the gauge location.

2.3 Turbidity data

Turbidity was monitored at a 5-minute resolution using two turbidity sensors: an Eureka 2 Manta sonde fitted with a self-wiping turbidity sensor (International Organisation for Standardisation (ISO) 7027; 0-3000 NTU, quoted error ± 1%) was deployed at Brooke on the R. Gwash and a Seametrics, Instrumentation Northwest Inc. (INW) self-wiping Turbo sensor (0-3000 NTU, quoted error ± 2%) was deployed at Ridlington on the R. Chater. Both sensors were independently calibrated before deployment using the same turbidity standards. They were mounted horizontally 0.1m above the river bed with the sensors approximately 0.3m from the left bank. Recording errors during the study were intermittent. Where single measurements were missing, they were interpolated using a local average of the previous and subsequent record. Where sections of data were in error or missing because of biofouling or data-logging problems, gaps were left in the time series. Datasets ran from 18th June 2015 to 24th September 2015 (98 days) with 12.0 and 18.1 days removed due to recording errors at Ridlington and Brooke, respectively (Figure 1b).

The continuous measurements of turbidity are used here as a surrogate of suspended mineral sediment concentration (SSC), and therefore of fine sediment availability for ingress. Turbidity is used as an independent variable because it is a measure of fine sediment availability that is easily and more readily measured then SSC, therefore representing a more widely available parameter. The use of turbidity as a surrogate for SSC should, however, be undertaken recognising that turbidity measurements are sensitive to the physical characteristics of suspended mineral sediments (colour, size, shape) and the presence of other suspended materials, including organic detritus (Bilotta and Brazier, 2008). To confirm the validity of the turbidity data as a representation of SSC, 93 and 206 water samples were collected from Ridlington and Brooke respectively, at baseflow through to storm flow conditions. Samples were collected using an ISCO 3700 automated water sampler fitted with a stage-activated trigger that drew water up from an inlet hose located immediately adjacent to the turbidity sensor. Samples were filtered using Whatman 0.7μm glass microfiber filters and analysed for percent organic matter and carbonate content through Loss-On-Ignition (LOI; Dean, 1974). The average organic component of samples was high at Brooke (21.5%, SD = 5.36%) and Ridlington (26.31%, SD = 7.77%) so SSC was calculated using only the mineral mass. The correlation between mineral SSC values and measured turbidity was significant ($r = 0.92$, $p < 0.001$) and demonstrated a strong linear fit ($R^2 = 0.86$; Figure S1). The continuous records of turbidity are therefore used as pragmatic surrogates for SSC and turbidity data (NTU) throughout the subsequent analysis.

2.4 Fine sediment ingress

At each site, sediment traps were installed that measured the mass of fine sediment ingress over 14-day deployment periods. Each trap comprised a PVC cylinder (diameter 65 mm, height 200 mm) perforated with twelve horizontal holes (diameter 6 mm) to permit both horizontal and vertical exchange of flow and fine sediments (Mathers and Wood, 2016). All cylinders were filled with a prewashed gravel framework collected from each of the respective sample sites, truncated to exclude grains finer than 8 mm and enclosed in a net bag (7 mm aperture). Use of the local gravel framework negates the potential influence that differing framework matrices have on ingress rates (Petticrew et al., 2007). Cylinders were inserted into the river bed by placing the PVC cylinders onto a steel pipe (35 mm diameter) that was then driven into the bed sediments and subsequently moved from side to side until a sufficient sized hole was formed. Cylinders were inserted flush with the sediment surface to a depth of 200 mm (Figure 2). Cylinders were left in-situ for the entire sampling campaign, but every 14 days the gravel netting bag was removed and replaced with a bag of clean gravel, providing a constant record of sediment accumulation at a 14-day resolution. At the end of each 14-day sampling period, the net bag (containing the gravel clasts) was carefully lifted out and immediately placed in a plastic bag to be processed in the laboratory with any loss of fine sediment being minimal. Negligible fine sediment was observed diffusing into the water column during extraction with fine material being held in the interstitial spaces of the gravels. Sediment traps were installed from 18th June to 24th September 2015, providing a record of 98 days that consisted of seven 14-day sample sets (referred to as B1 – B7 for the Gwash site and R1 – R7 for the Chater site).

Three riffle sites were examined at Brooke and two at Ridlington (only one site was considered before 2nd July 2015). At each riffle, four cylinders were installed providing a total of 12 replicates at Brooke and eight at Ridlington (four until 2nd July - for the first three 14-day sample sets). Cylinders were evenly spaced across the riffle unit (head through to tail) because fine sediment accumulation can vary as a function of longitudinal hydraulic gradients (Mathers and Wood, 2016). In total, 105 and 57 samples were extracted from Brooke and Ridlington respectively (a total of three cylinders could not be retrieved at both sites during the campaign).

In the laboratory, the contents of the cylinder samples were passed through 4 and 2 mm sieves to remove the framework substrate and left to settle in a container. Fine sediment samples (< 2 mm) were oven dried at 60°C until a constant weight was recorded. Samples were gently disaggregated, passed through a sieve nest (1000 µm and 125 µm) and each fraction weighed to determine the grain size distribution in four grain size categories (total mass < 2000 µm,1000-2000 µm, 125-1000 µm; <125µm). These separate grain size fractions were examined because the rate of fine sediment ingress is inherently associated with site-specific size ratios of infiltrating particles to framework gravels (Frings et al., 2008). The total mass of material < 2000 µm collected in each 14-day sampling period for Brooke and Ridlington is shown in Figure 1c

2.5 Identification of time series facets via the redundancy approach

Spearman's rank correlation coefficients were calculated for hourly averaged flow and turbidity time series to establish whether there was any simple association between the two datasets. Preliminary analysis indicated that discharge values differed by site and so prior to subsequent analysis, flow data were scaled to Z-scores to enable comparison across sites. 23 turbidity and 14 flow indices (see Table 2 for definitions) were calculated for each 14-day sampling period at Ridlington and Brooke. Indices were based on four facets of the two regimes: (i) magnitude – the quantity measured at a sampling point at a given time including minimum and maximum; (ii) frequency – how often the time series moved above a given magnitude; (iii) duration – the period of time over a specific threshold; and (iv) rate of change – how quickly the time series changes from one magnitude to another (Richter et al., 1996; Poff et al., 1997). Previous applications of Richter's (1997) methodology have focussed on characterising hydrological series for the purpose of identifying ecohydrological associations over multiple years, so the most relevant indices were adapted for the shorter timeseries used here (Richter et al., 1997; Olden and Poff, 2003; Monk et al., 2007). In addition, a number of indices were calculated that aimed to characterise the potential effect of biotic diurnal bioturbation (by crayfish) on the turbidity series (cf Rice et al., 2014; 2016): average night turbidity – AVNt; average day turbidity – AVDt; difference in day – night turbidity – DDNt; and periodicity – PERt. Night was employed as a fixed time window (18:00-6:00; Rice et al., 2014).

Both hydrological and turbidity indices were analysed using principal component analysis (PCA) to identify redundant interrelated indices whilst retaining the major sources of statistical variation (Jolliffe, 1986). A series of PCAs were undertaken on turbidity and hydrological data in isolation and in combination using the 'prcomp' function in R version 3.2.2. PCAs were conducted to identify the dominant indices following the PCA redundancy reduction approach outlined by Olden and Poff (2003). Previous research employing this approach has typically utilized a maximum of six indices to sufficiently characterise the regimes (Monk et al., 2007; Belmar et al., 2013; Worrall et al., 2014) and consequently the six indices with the highest loadings on the first two principal component (PC) axes were identified for each set of variables (turbidity, hydrological and combined hydrological and turbidity).

Following Olden and Poff (2003), the number of indices selected from each axis was proportional to the variance explained by each PC relative to the others. For example, based on the turbidity data, the first PC explained 48.4% of the total 68.5% of the variance explained by the two significant components, resulting in four indices being selected from PC1 and two from PC2. Highly correlated variables, with Pearson's r values greater than 0.95, were considered redundant and removed to retain six indices that effectively characterised statistical variability whilst minimising collinearity (Monk et al., 2006).

2.6 Relationship between turbidity, discharge and fine sediment ingress

To examine the relationship between standardised discharge, turbidity and mass of ingress, Spearman's rank correlation matrices were constructed for all 37 indices and four ingress size categories. This enabled determination of the relative association of individual components of turbidity and discharge with sediment ingress. To assess the association of multiple facets of turbidity and discharge with ingress, the PC components (sample axis scores) resulting from the reduced set of variables in each dataset were used as independent variables to develop multiple linear regression models. In these models the dependent variables were mass of infiltrated sediment in each grain size fraction and the independent variables were PC components (axes scores). PC components with eigenvalues >1 were considered for inclusion in each model, and stepwise selection using the '*stepAIC*' function in the '*MASS*' package was used to select the best combination of variables (Venables and Ripley, 2002). As a result of the removal of highly correlated and redundant variables through PCA selection and the subsequent compartmentalisation of the data to reduce its dimensionality, overfitting of models was minimal. This approach generated models using (1) discharge PC components, (2) turbidity PC components or (3) discharge and turbidity PC components together, to predict each of the grain size mass fractions. This enabled an evaluation of the relative contribution to the explanatory power exerted by each driver (discharge or turbidity) independently and combined on the mass of sediment ingress by size fraction. To assess whether the turbidity or discharge regimes differed by site or time as a function of any facets of the series (e.g. magnitude and duration), a Generalised Linear Model (GLM) was fitted to the PC component scores using the '*glm*' function in the ‘*stats’* package with a Gaussian error distribution. All statistical tests were conducted in the R environment (R Development Core Team, 2017).

4. Results

4.1 Selection of turbidity and discharge variables

When PCA was employed to determine which turbidity and hydrological indices were most influential in characterising the dominant sources of variability, the percentage of variance explained ranged from 87.07% for the combined variables (turbidity and hydrology together) through to 98.18% for the reduced number of hydrological indices (Table 3). Turbidity indices demonstrated the greatest variability compared to hydrological indices, with less variance being explained on the first axis in both instances for the full and reduced number of indices.

Using the PCA selection procedure for the turbidity variables, three indices were identified that represented magnitude of turbidity (median, average night and average difference in day and night turbidity values), two that represented the duration of turbidity events (duration over 10 NTU and duration over 100 NTU) and one that characterised the rate of change in turbidity (number of rises in the turbidity series; Figure 3a). Within the subset of six hydrological variables identified, the majority represented magnitude of discharge (minimum, average and standard deviation of discharge), two characterised the duration of discharge events above or below a threshold (duration under 0.1 scores, and duration over 14 day average discharge)and one characterised the rate of change in the discharge regime (number of rises in discharge series; Figure 3b). When both environmental factors (turbidity and hydrology) were considered together, turbidity accounted for a larger proportion of variance with four dominant turbidity indices and two hydrological indices identified. Magnitude characteristics of the time series were the primary source of variability (median discharge, standard deviation in discharge, median turbidity, maximum turbidity and average turbidity) and the remaining two indices represented the duration of low magnitude events (duration under -0.1 discharge scores and duration under 10 NTU; Figure 3c).

4.2 Turbidity and discharge regimes characterisation

Examination of the sample sites on the ordination plots and via general linear regression of the first two PC axes scores, indicated that both sites were similar in character regardless of the presence of crayfish (Figure 3; $p > 0.05$ in both GLM models). Despite this, Ridlington exhibited greater variation in turbidity over time, with the majority of Brooke sites forming a cluster at the centre of the plot. Three turbidity series represent extreme outliers, with Ridlington sample set one (R1) being strongly associated with higher than average median turbidity, Ridlington set six (R6) by average night turbidity values and duration over 100 NTU and Brooke set one (B1) by difference in day and night turbidity. The dominant vectors of variation are associated with the duration of events over 10 NTU and difference in day versus night turbidity.

Discharge exhibited greater variability, with a wide spread of sites over time: the majority of sites were heavily loaded on PC1, which was associated with low flow conditions (Figure 3). Time periods in which baseflow conditions were dominant (e.g. B2, R1, R4, B4) plot to the right of the ordination and those with high flow events plot to the left (e.g. R6, R5, B3). When hydrological and turbidity variations were considered in combination, sites plotted consistently together (Figure 3c). The dominant vectors of variation were associated with low flow periods (duration under 0.1 discharge scores and standard deviation of discharge) with two outliers that were strongly influenced by turbidity (median turbidity –Ridlington set one, R1 and maximum turbidity – Ridlington set two, R2).

4.3 Discharge, turbidity and fine sediment ingress associations

Discharge and turbidity time series (hourly averaged data) yielded weak associations at both sites (Brooke $r_s = 0.040$; $p < 0.05$; Ridlington $r_s = 0.211$; $p <0.001$). However, moderate associations ($r_s > 0.5$) were apparent between some turbidity and discharge indices (Table 4). 16 out of 23 discharge variables were associated with the magnitude of the turbidity regime (i.e. maximum, minimum, range and standard deviation of turbidity) and 11 of these associations were significant ($p < 0.05$; Table 4). Of the remaining correlations, four were characterised by duration (three of which were significant), and two with frequency of turbidity events (both of which were significant). Duration of discharge was the main facets of the regime associated with turbidity events, with 14 discharge variables demonstrating moderate relations with turbidity (12 of which were significant), followed by magnitude of discharge (seven variables) and frequency of discharge events (two variables). The strongest correlation was between the duration over the 14-day average discharge (D14AVd) and the number of peaks over 100 NTU (NP100t; Table 4). Duration over the 14 day-averaged discharge (D14AVd) was most strongly associated with turbidity parameters.

In contrast, discharge and turbidity indices yielded weak associations with the mass of sediment that infiltrated into traps (Table 5). Only three turbidity indices and one discharge index had a moderate correlation ($r_s > 0.5$) with any of the different size fractions of deposited sediment. The strongest correlation was between duration of discharge over the 14-day average (D14AVd) and mass of fines in the size fraction 125-1000 µm ($r_s = 0.617$; $p \leq 0.05$). Grains in the size fraction 1000-2000 µm displayed the strongest correlation with turbidity, with three indices having moderate correlations, whilst total mass < 2000 µm was correlated with duration over 14 day average discharge (D14AVd ; Table 5).

Linear regression models developed for mass of deposited fines using the PC scores explained between 8.78% and 53.92% of the variance in the mass of ingress (Table 6). For grains 1000- 2000 µm, discharge was the most influential predictor with the model accounting for an additional 15.96% of the variance compared to turbidity alone or 9.56% for turbidity and hydrology combined. The duration and magnitude of high flow events were the most significant predictor variables ($p = 0.004$; Table 7).

The mass of sediment deposited in the range 125-1000 µm was strongly influenced by turbidity with the model accounting for 45% of variation, 10% greater than for discharge (Table 6). Both principal components were significant predictors with the duration and magnitude of turbidity values being the dominant explanatory factors (Table 7). The combination of discharge and turbidity parameters only accounted for an additional 0.9% of variation and the final model developed using PC components only characterised the turbidity series using PC1 and PC3 scores (Tables 6 & 7).

For grains <125 µm, mass of deposition was predominantly explained by turbidity, with the model accounting for 53.52% of variation, 32.42% more than the discharge model (Table 6). PC2 was the most significant predictor ($p = 0.005$) which characterised the magnitude of the turbidity regime (average conditions) and duration of low turbidity events. When total mass (<2000 µm) was considered, turbidity was the most influential factor (37.15%) and the magnitude and frequency of high turbidity events were the dominant predictors ($p = 0.047$; Tables 6 & 7). Similarly, the combined model (hydrological and turbidity) provided the best fit and PC components that characterised the average, maximum and duration of low turbidity elements of the regime were significant (Table 6). A summary of the multiple linear regression models and the interpretations of the PC loadings for each of the compartments are provided in Tables 6 and 7.

5. Discussion

This study investigated whether facets of discharge and turbidity time series can be used to predict fine sediment ingress measured at multiple locations over several months. It adopted a technique from ecohydrology, not previously applied to this problem and uses robust and widely applicable parameters that can be readily measured in the field. Discharge and turbidity have a relatively weak relationship with each other and with mass of fine sediment ingress when individual facets of the time series (e.g. magnitude or duration indices) are considered in isolation. In contrast, the application of a well-established ‘redundancy approach’ and principal component analysis enabled the fitting of multiple linear regression models, using combinations of time series facets, that accounted for a larger proportion of variation in the mass of fine sediment ingress. Turbidity, as a surrogate for suspended sediment availability, exerted a greater influence than discharge. These results indicate the potential of this method to be a useful tool for developing predictive models of fine sediment ingress at scales that are relevant to sediment management. Further testing and validation is required to evaluate the method’s applicability across different river types, flow and sediment regimes.

5.1 The relative role of discharge and turbidity in controlling fine sediment ingress

When the individual regime facets (i.e. magnitude, duration, frequency) of turbidity and discharge time series were considered, there were no significant associations with the mass of infiltrated sediment. This indicates that, in isolation, individual flow or sediment availability parameters are likely to be weak predictors of sediment ingress. The lack of apparent correlation between suspended sediment availability and discharge also indicates that processes other than hydrological drivers may affect changes in turbidity concentrations, including, for example, biotic processes (Rice et al., 2012; Atkinson et al., 2017). Whatever the cause, temporal variations in suspended sediment transport are important and are driven independently of discharge.

In contrast, the application of linear regression using multiple facets of the discharge and turbidity regimes yielded improved associations, indicating that it is not a single element of discharge or turbidity that controls ingress, but a combination of multiple facets. This also clearly highlights the advantages of employing principal component analysis to distil time series datasets into a manageable number of unrelated variables and so avoid overfitting models. The construction of linear regression models using PC sample axis scores indicated that turbidity variables explained a greater proportion of the statistical variance in deposition than discharge variables. This suggests that the collection of high quality, turbidityntime series data should be a priority in order to corroborate and develop the findings of this study, perhaps for different flow conditions and different river typologies.

5.2 Individual grain size associations with discharge and turbidity

The strongest association in this study was between the ingress of grains <125 μm and turbidity, with the turbidity model accounting for 54 % of the variation (with only an additional 0.4 % explained when discharge indices were incorporated). The duration that turbidity was over 10 NTU was the most significant explanatory variable. Grains in this size fraction, once in suspension, can be transported long distances over extended time-periods because only low energy hydraulic conditions are needed to entrain them and keep them in suspension (Lambert and Walling, 1988). Consequently, as the amount of time with turbidity levels are above 10 NTU decreases, ingress of this size range may increase because fine sediment is available for deposition. Discharge had the weakest association with this size fraction (21 % variance explained) with rivers often acting as an effective conveyance system for silt sized particles, irrespective of hydraulic energy. Grains in the size fraction 125 -1000 μm were predominantly predicted by variables which characterised the magnitude of turbidity, with an explanatory power of 45%, and discharge indices provided little improvement (0.9 %) if incorporated.

The only grain size to be predominately associated with discharge was the size fraction 1000-2000 µm. The duration and magnitude of high discharge, accounted for 25 % of the variability in ingress rates compared to 9 % and 15 % for the turbidity and combined models, respectively. Grains in this size fraction are heavily reliant on sufficient hydraulic stress for entrainment and suspension. Turbidity is not an important driver because grains of this size are unlikely to remain in suspension and be available for deposition during long baseflow periods (Rathburn and Wohl, 2003).

5.3 Principal component analysis as a tool to upscale the temporal controls on fine sediment ingress

A significant gap in understanding and managing fine sediment ingress into river beds is the difficulty of scaling up fine-scale process understanding, partly because the key drivers are highly variable in space and time. Larger scale drivers, including discharge and sediment availability, vary on synoptic to annual timescales, and may provide an alternative means of modelling fine sediment deposition that is especially pertinent to management questions. However, investigation of relations at these larger scales has been limited by an absence of time series of sediment deposition and sediment availability (Gray and Gartner, 2009). Using turbidity as a surrogate for sediment concentration, longer, high-resolution datasets can now be routinely collected (Loperfido et al., 2010), albeit subject to appropriate local calibration and evaluation (Bilotta and Brazier, 2008).

Turbidity time series and gauged discharge data collected over a 14-week study period on two rivers were used in this study to gain a better understanding of how localised and temporal variations in discharge and turbidity influence the mass of sediment deposited in a clean gravel framework. The methodological approach employed highlights the potential value of undertaking principal component analysis to characterise the overall facets of discharge and turbidity regimes that influence fine sediment ingress and which can therefore inform large scale catchment sediment management practices. The approach is empirical, seeking site-specific relations between ingress, discharge and sediment availability. Its application and testing in additional field situations may yield wider generic understanding of important controls at these scales.

Despite the potential utility of the approach, it is important to exercise caution when employing data redundancy approaches, such as PCA, because they may reject variables of importance due to the assumption that statistically dominant sources of variability are the principal drivers of the association they are being used to describe (Monk et al., 2007). Nevertheless, as applied here, the approach enables characterisation of the key drivers of sediment ingress, improving our knowledge of the time series and, by inference, processes that are relevant to sediment loading at a scale appropriate for management strategies.

6. Conclusion

This study demonstrates, for the first time, that an adapted PCA-based data redundancy reduction method (sensu Olden and Poff, 2003) can effectively be used to identify the dominant facets of turbidity and discharge time series that influence the mass of fine sediment ingress into gravel river beds. The results from this study of two lowland rivers in England, indicate that discharge is weakly associated with ingress rates and that localised turbidity variations explain a greater amount of the variance in fine sediment deposition into clean gravels. In particular, the magnitude facet of the turbidity regime are important for the ingress of grains in the size fraction 125 – 1000 µm, whilst magnitude and the duration of turbidity events below 10 NTU are associated with grains in the size fraction <125 µm.

The study highlights the need for additional research that simultaneously monitors turbidity (or sediment concentrations), discharge and ingress rates during a range of flow conditions. It is widely acknowledged that discharge during extreme flow periods exerts a strong control over ingress rates (Frostick et al., 1984), but much less is known about deposition rates and the principal drivers of this process during baseflow conditions. Further understanding could be obtained by monitoring the gradients of vertical and lateral hydrological exchange as a function of discharge, as these exchanges exert a significant influence over ingress rates during baseflow (Pettricrew et al., 2007).

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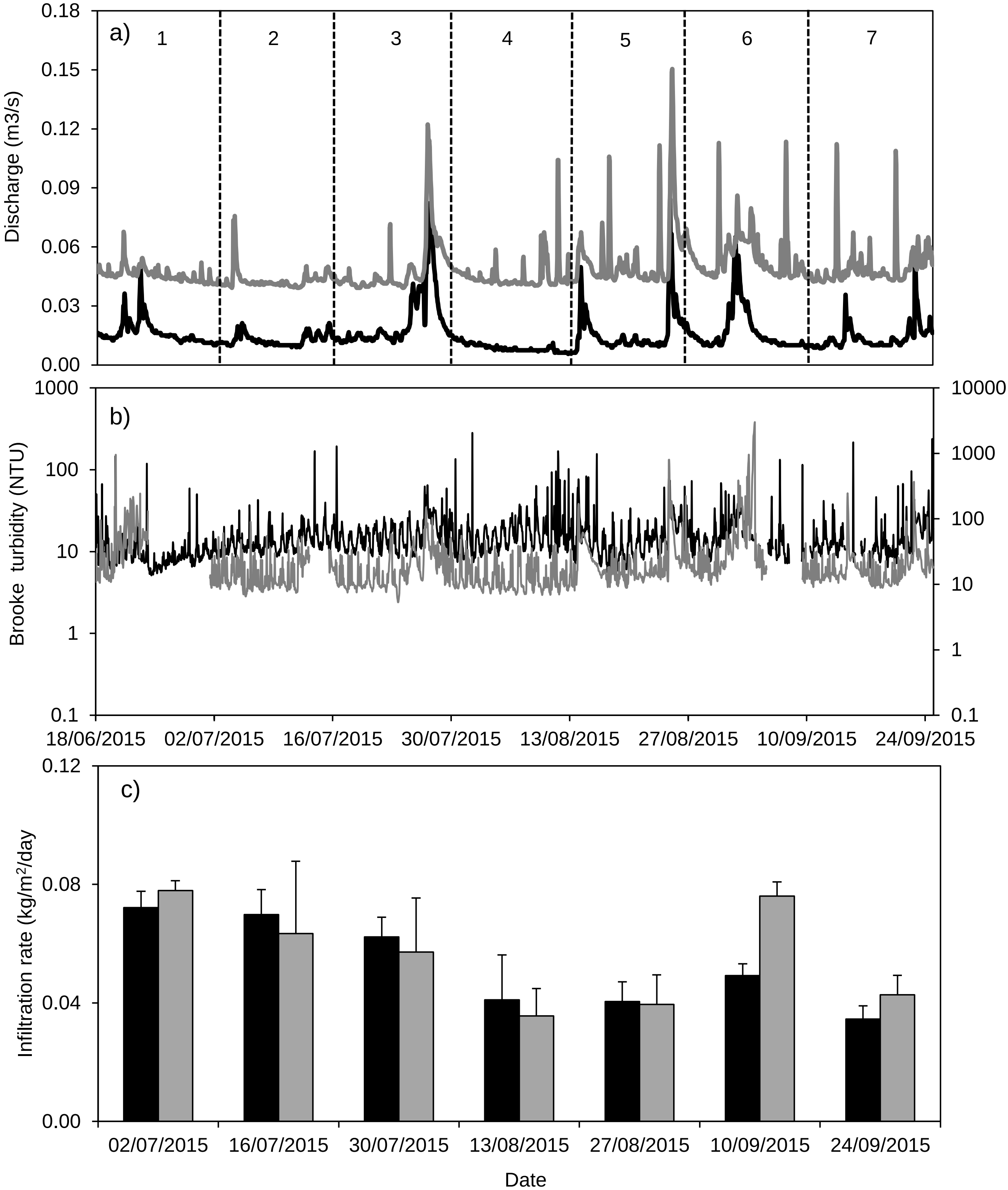

a)
1
2
3
4
5
6
7
Discharge (m3/s)
0.18
0.15
0.12
0.09
0.06
0.03
0.00
b)
Brooke turbidity (NTU)
Ridlington turbidity (NTU)
1000
100
10
1
0.1
10000
1000
100
10
1
0.1
18/06/2015
02/07/2015
16/07/2015
30/07/2015
13/08/2015
27/08/2015
10/09/2015
24/09/2015
c)
Infiltration rate (kg/m²/day
0.12
0.08
0.04
0.00
02/07/2015
16/07/2015
30/07/2015
13/08/2015
27/08/2015
10/09/2015
24/09/2015
Date

Figure 1.

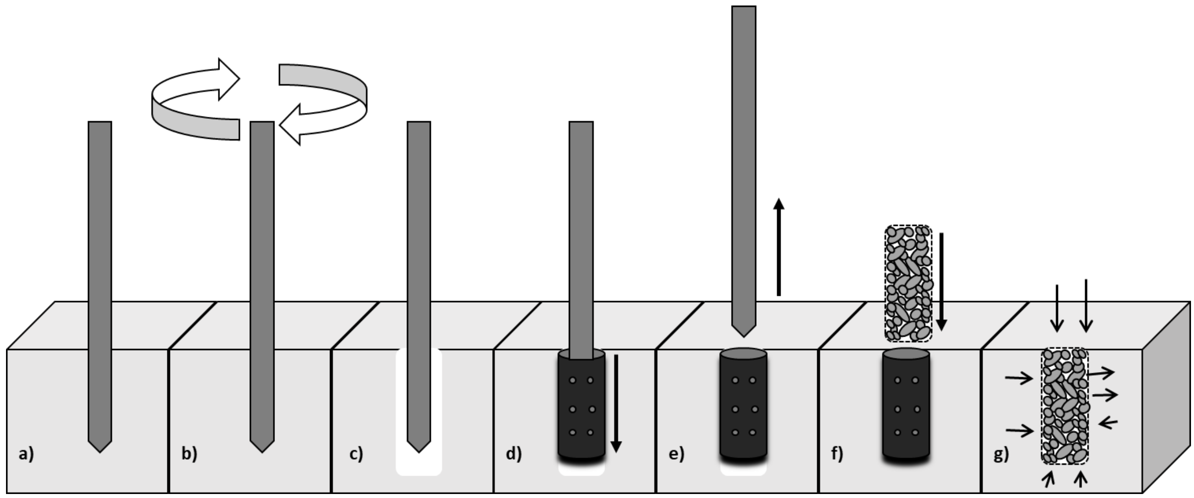
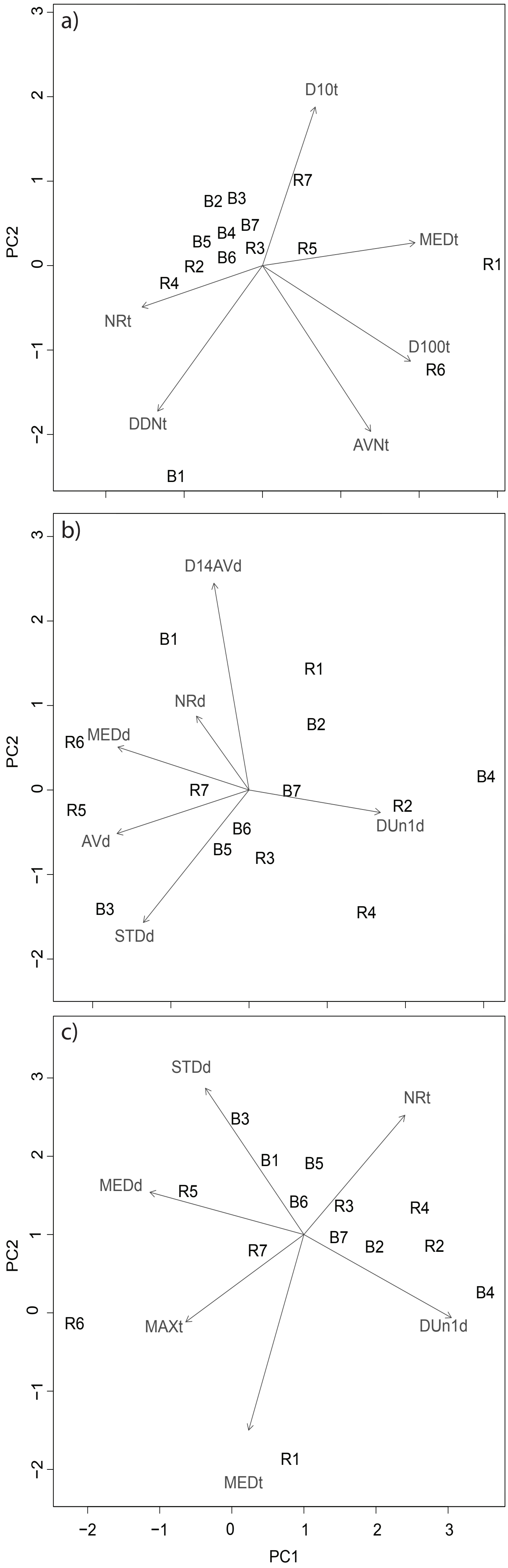


Figure 2.



a)
D10t
R7
B2
B3
B7
B4
B5
MEDt
R3
R5
B6
R1
R2
R4
NRt
D100t
R6
DDNt
AVNt
B1
b)
D14AVd
B1
R1
NRd
B2
MEDd
R6
B4
R7
B7
R2
R5
DUn1d
B6
AVd
B5
R3
B3
R4
STDd
c)
STDd
NRt
B3
B1
B5
MEDd
R5
B6
R3
R4
B7
B2
R2
R7
B4
R6
MAXt
DUn1d
R1
MEDt
PC1
PC2
3
2
1
0
−1
−2

Table 1. Metrics of bed material grain size distributions, including fine sediment measures, for the study reaches

Grain size characteristic	Brooke	Ridlington
Surface [a]		
D_{16} (mm)	4.2	6.0
D_{50} (mm)	13.4	32.0
D_{84} (mm)	20.6	64.0
Mass < 4mm (%)	4.3	3.9
Subsurface [b]		
D_{16} (mm)	1.4	0.8
D_{50} (mm)	9.1	7.8
D_{84} (mm)	24.2	36.3
Mass < 2mm (%)	20.0	28.8

[a] based on 400 pebble count, 200 at two riffles per site (Wolman, 1954)

[b] based on four pooled McNeil samples from two riffles at each site, average sample weight 20.01 kg (McNeil and Ahnell, 1964)

Table 2. Summary of turbidity and flow indices calculated in this study.

Facet of the turbidity regime	Turbidity indices	Description	Facet of the discharge regime	Discharge indices	Description
Magnitude	MAXt	Maximum turbidity	Magnitude	MAXd	Maximum discharge
Magnitude	MINt	Minimum turbidity	Magnitude	MINd	Minimum discharge
Magnitude	RANt	Turbidity range	Magnitude	RANd	Discharge range
Magnitude	STDt	Standard deviation of turbidity	Magnitude	STDd	Standard deviation of discharge
Magnitude	AVt	14 day average turbidity value	Magnitude	AVd	14 day average discharge
Magnitude	MEDt	Median turbidity value	Magnitude	MEDd	Median discharge
Duration	D10t	Duration over 10 NTU	Duration	D1d	Duration over 0.1 (z standardised score)
Duration	D20t	Duration over 20 NTU	Duration	D2d	Duration over 0.2 (z standardised score)
Duration	D50t	Duration over 50 NTU	Duration	DUn1d	Duration under - 0.1 (z standardised score)
Duration	D100t	Duration over 100 NTU	Duration	DUn2d	Duration over - 0.2 (z standardised score)
Duration	DU10t	Duration under 10 NTU	Duration	D14AVd	Duration over 14 day average discharge
Duration	D14AVt	Duration over 14 day average turbidity value	Duration	DTAVd	Duration over total average discharge
Duration	DTAVt	Duration over total average turbidity value	Frequency	NPTAVd	Number of peaks over total average discharge
Rate of change	PERt	Periodicity	Rate of change	NRd	Number of rises in discharge series
Magnitude	AVNt	Average night turbidity value			
Magnitude	AVDt	Average day turbidity value			
Magnitude	DDNt	Average difference in day and night turbidity			
Frequency	NP20t	Number of peaks over 20 NTU			
Frequency	NP50t	Number of peaks over 50 NTU			
Frequency	NP100t	Number of peaks over 100 NTU			
Rate of change	NRt	Number of rises in turbidity series			

Table 3. Summary of the percentage variability explained on axes 1-4 for each of the six sets of variables

	Principal component (% variance explained)				**Total (%)**
	1	**2**	**3**	**4**	
All turbidity	48.39	20.06	11.47	7.15	87.07
Reduced turbidity	52.48	25.59	11.84	8.74	98.65
All hydrological	66.68	15.5	11.45	4.04	97.67
Reduced hydrological	55.41	19.87	16.30	6.60	98.18
Turbidity and hydrological combined	39.08	21.23	13.06	8.51	81.88
Reduced turbidity and hydrological	48.19	27.37	16.93	4.9	97.39

Table 4 . Spearman's rank correlations for all discharge (standardised) and turbidity indices (only those with a moderate correlation stronger than $r_s > 0.5$ are presented).

Discharge index	**Turbidity index**	**ρ value**
MINd	MAXt	0.546 *
MINd	RANt	0.546 *
MEDd	MAXt	0.596 *
MEDd	RANt	0.596 *
MEDd	AVt	0.595 *
MEDd	D100t	0.519
MEDd	STDt	0.522
NPTAVd	MINt	0.504
NPTAVd	NRt	-0.613
D14AVd	MAXt	0.709 ***
D14AVd	RANt	0.709 ***
D14AVd	AVt	0.630 *
D14AVd	D50t	0.570 **
D14AVd	D100t	0.720 *
D14AVd	AVNt	0.522
D14AVd	NP50t	0.541 *
D14AVd	NP100t	0.782 ***
D14AVd	STDt	0.674 *
D14AVd	D14AVt	-0.617 *
DUn1d	MAXt	-0.525
DUN2d	MAXt	-0.560 *
DUN2d	RANt	-0.560 *
DTAVd	AVt	0.530

* $p \leq 0.05$, ** $P \leq 0.01$, *** $p \leq 0.005$

Table 5. Spearman's rank correlations for discharge (standardised) and turbidity indices and ingress grain size characteristics (g; only those with a moderate correlation stronger than $r_s > 0.5$ are presented).

Grain size	**Index**	**ρ value**
Total mass < 2000 µm	D14AVd	0.566 *
1000 - 2000 µm	NP100t	0.592 *
1000 - 2000 µm	AVNt	0.560 *
1000 - 2000 µm	D100t	0.531
1000 - 2000 µm	D14AVd	0.617 *

* $p \leq 0.05$, ** $P \leq 0.01$, *** $p \leq 0.005$

Table 6. Summary of multiple linear regression models fitted to ingress rates using PC scores from turbidity, discharge and turbidity + discharge datasets (reduced). * p ≤ 0.05, ** P ≤ 0.01, *** p ≤ 0.005.

Datasets	Predictor	Adjusted R^2	F	Model p value	Variable p value	
Total mass <2000 µm						
Turbidity	PC1 + PC2	37.15	4.48	0.03 *	PC1 0.047	PC2 0.053
Discharge	PC2	30.03	6.58	0.03 *		
Turbidity + Discharge	PC1 + PC3	32.39	4.11	0.05 *	PC1 0.0394	PC3 0.125
1000- 2000 µm						
Turbidity	PC1	8.78	2.25	0.16		
Discharge	PC2	24.74	5.27	0.04 *		
Turbidity + Discharge	PC2	15.18	3.33	0.15		
125 – 1000 µm						
Turbidity	PC1 + PC2	45.00	6.31	0.02 *	PC1 0.020	PC2 0.043
Discharge	PC1 + PC2	35.00	4.58	0.03 *	PC1 0.106	PC2 0.032
Turbidity + Discharge	PC1 + PC3	45.90	6.52	0.01 *	PC1 0.107	PC3 0.150
<125µm						
Turbidity	PC1 + PC2	53.52	8.49	0.01 *	PC1 0.056	PC2 0.005
Discharge	PC2	20.90	4.43	0.06		
Turbidity + Discharge	PC1 + PC3	53.92	8.61	0.01 *	PC1 0.020	PC3 0.010

Table 7. Principal component loadings for the variables within the principle components analysis.

Dataset	PC1		PC2		PC3	
	Variable loadings	**Interpretation**	**Variable loadings**	**Interpretation**	**Variable loadings**	**Interpretation**
Turbidity	MEDt (0.52), D100t (0.51), NRt (-0.41)	Magnitude, duration and frequency of turbidity events (high)	D10t (0.56), AVNt (-0.50), DDNt (-0.51)	Duration of low turbidity events and absolute value of average turbidity conditions		
Discharge	MEDd (-0.47), DUn1d (0.47), AVd (-0.47)	Duration of low discharge events and average discharge	D14AVd (0.71), STDd (-0.55), NRd (0.33)	Duration above average discharge conditions and magnitude of discharge		
Turbidity & discharge	AVt (-0.55), MAXt (-0.51)	Average and extreme turbidity conditions	STDd (0.62), DUn1d (-0.57), MEDt (-0.44)	Magnitude of discharge and turbidity, duration of low discharge conditions	DU10t (-0.66)	Duration under low turbidity threshold

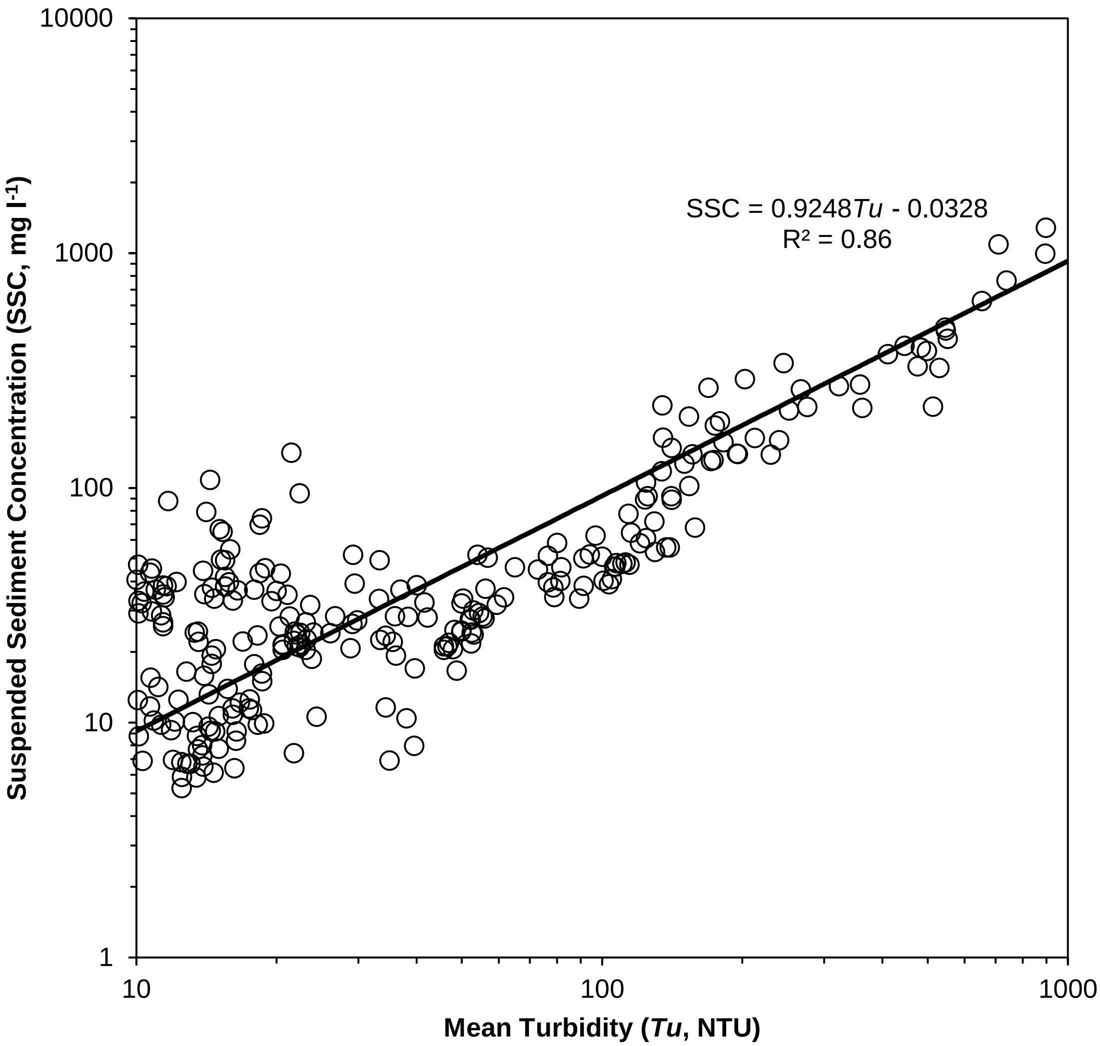


Figure S1. Relation between measure turbidity and concurrently suspended sediment concentrations from Brooke and Ridlington field sites (n = 299).