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The uncertainties associated with sediment fingerprinting suspended and recently deposited fluvial sediment in the Nene river basin

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ABSTRACT

The use of tracers within a sediment fingerprinting framework has become a commonly used technique for investigating the sources of fine sediment. However, uncertainties associated with tracer behaviour have been cited as major potential limitations to sediment fingerprinting methodologies. This paper aims to determine the differences between fingerprinting results derived using different groups of tracer properties and to determine the role of organic matter content, particle size, and within-source variability in tracer concentrations on the observed differences. A mean difference of 24.1% between the predicted contributions of sediment originating from channel banks was found when using different tracer groups. Mean differences between tracer group predictions were lower, at between 8% and 11%, when fingerprinting contributions from urban street dusts. Organic matter content and/or particle size showed little indication that they caused differences between tracer group predictions. The within-source variability in tracer concentrations and small contrasts between the tracer concentrations of different source groups were identified as probable causes of inherent uncertainty in the fingerprinting predictions. We determined that the ratio of the percentage difference between median tracer concentrations in the source groups and the average within-source tracer concentration coefficient of variation could indicate the likely uncertainty in model predictions prior to tracer use.

1. Introduction

The identification of the major sources of fine sediment in a catchment represents a key requirement for the application of targeted mitigation measures (Walling and Collins, 2008). Because the investigation of sediment inputs is time consuming when using conventional sediment source monitoring methods, such as erosion pins (Davis and Gregory, 1994) and surveys of erosion features (Werrity and Ferguson, 1980), sediment fingerprinting methodologies have gained widespread adoption in geomorphological research (Foster and Lees, 2000). The principle of sediment fingerprinting is based upon a comparison of the properties of fine sediment with those of the potential sediment sources present in a catchment. It relies on the ability of sources to be differentiated on the basis of their measured properties (tracers) and the assumption that properties of the sources reflect those of the sediment after its delivery to a river, floodplain, or lake (Collins et al., 1997a).

Over the last 2–3 decades, researchers have recognised the significant potential of sediment fingerprinting in a range of environments: e.g. lakes (Miller et al., 2005), floodplains (Collins et al., 1997b) recently deposited sediment on channel beds (Walling et al., 2006), and actively transported suspended sediment (Gruszowski et al., 2003). A wide variety of different tracers have also been employed in the published literature which include mineral magnetic signatures (Caitcheon, 1993), lithogenic radionuclides (Gruszowski et al., 2003), fallout radionuclides (Walling et al., 1999), geochemistry (Collins et al., 1997a), particle size, shape and colour (Krein et al., 2003) in addition to a range of organic tracers (Collins et al., 2010b).

It has been recognised that the use of multiple different tracer types in composite fingerprints is important for improving discrimination between sediment sources and for reducing the collinearity of the tracers used (Collins and Walling, 2002). Recent work by Collins et al. (2012, 2013a,b) have expanded upon this principle by fingerprinting a sediment sample using multiple different composite fingerprints of tracers derived by different statistical procedures to increase the robustness of fingerprinting outputs. Significant potential for uncertainty associated with tracer selection has been recognised in fingerprinting studies. For example Fu et al. (2006) showed that two different composite fingerprints using geochemical tracers predicted mean contributions from sediment sources differently by an average of 35%. Very little difference was found between the predictions of geochemical tracers and tracing using soil enzyme activity by Nosrati et al. (2011). However, it was shown in this latter study that, in individual samples, the root mean square differences could be up to 48%. Evrard et al. (2013)

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compared fingerprinting results derived using fallout radionuclide activity and geochemical signatures and diffuse reflectance infrared Fourier transform spectroscopy measurements; in one study catchment differences between predictions were as high as ~70% for some samples.

Many processes have been identified that could alter tracers and cause differences in sediment provenance predictions such as those described above. These include changes to the sediment particle size distribution during transport, with finer particles being carried further through a catchment than coarse particles (Walling et al., 2000). Particle size has been shown to be significantly correlated with concentrations of many different tracers, such as mineral magnetic signatures (Oldfield et al., 2009), fallout radionuclides (Ab Razak et al., 1996), and geochemical tracers (Mahler et al., 1998). Therefore, any changes in sediment particle size would also be expected to result in a change in tracer concentration and therefore a change in the sediment provenance prediction.

The organic fraction of sediment has been shown to often be carried farther in suspension through a catchment, primarily owing to its association with small particles and its lower density in comparison to the mineral fraction of sediments (Nadeu et al., 2011). In addition, the ingrowth of organic material can also occur within a river or lake or on a floodplain (Kansanen and Jaakkola, 1985). The impacts of organic enrichment or depletion have been shown to vary between different tracers. For example ca. 30% of unsupported Pb-210 (Pb-210_{un*}) activity was shown to be associated with organic matter in soils in a forested catchment by Wallbrink et al. (1997). Hirner et al. (1990) showed that the elements As, Ag, B, Cd, Co, Cu, Hg, Mn, Mo, Ni, Pb, Sb, V, and Zn were all enriched by up to three orders of magnitude within the organic fraction of sediments. However, mineral magnetic signatures are generally not associated with the organic fraction of sediment as organic matter is diamagnetic (Lees, 1999).

Additional uncertainties have been shown to be associated with different mathematical unmixing models used to apportion sediment sources. An example of this was shown in a recent study by Haddadchi et al. (2013) who demonstrated that differently programmed unmixing models could produce provenance predictions up to 33% different when models used local optimisation and 95% different with global optimisation. The categorisation of tracer concentrations of the sediment source groups is a key difference between unmixing modelling approaches, therefore the sensitivity of modelling to small changes in source tracer concentrations is an additional potential source of uncertainty. The ability of tracers to adequately categorise and differentiate between sediment source groups is a fundamental requirement of sediment fingerprinting methodologies. Small et al. (2002) showed that the uncertainty associated with the calculation of contributory coefficients increased when the within source group tracer concentration coefficient of variation increased and when fewer samples were used to categorise each source group.

The paper was structured to fulfil the following objectives relating to the current uncertainties associated with sediment fingerprinting:

- To determine the difference between fallout radionuclide, lithogenic radionuclide, geochemical, and mineral magnetic fingerprint predictions when fingerprinting suspended sediment and recently deposited overbank and channel bed sediment.
- To determine the potential effects of particle size distribution and organic content of the sediment on the difference between the tracer group fingerprinting predictions.
- To gain an indication of the uncertainty associated with variability of sediment source tracer concentrations on a sediment fingerprinting investigation.

2. Study catchment

The study was undertaken in the Nene basin in the east Midlands, UK (Fig. 1). Sampling was conducted in the middle to upper Nene basin upstream of Ditchford with a total catchment area of 1060 km^2. The average annual rainfall for the previous 140 years is 638 mm, and the maximum elevation is 226 m Above Ordnance Datum (AOD). The catchment lithology is primarily Jurassic marine sedimentary deposits, Quaternary sand and gravel, and glacial diamicton. Land utilisation in the catchment is 56% cultivated, 22% pasture, and 9% urban (Morton et al., 2011); and extensive flood defences follow the course of the rivers main channel.

3. Materials and methods

3.1. Field sampling

Suspended sediment is frequently used in fingerprinting investigations (Collins et al., 2010b). For this study a total of eight time-integrated suspended sediment traps were deployed in the locations shown in Fig. 1. The sediment traps were constructed from a PVC pipe 1 m in length and 98 mm in diameter following the design of Phillips et al. (2000). A funnel with a 4 mm aperture was fixed to one end of the trap and a 4 mm hole was drilled in the other end to allow flow through the trap. The increase in diameter from the 4 mm inlet hole to the 98 mm internal diameter of the pipe results in a reduction in flow velocity and the deposition of suspended sediment within the trap. Sediment traps of this design have been shown to effectively provide a suspended sediment sample under a range of flow conditions and to effectively trap a sufficiently representative range of particle sizes for fine sediment investigation (Russell et al., 2001). A single sediment trap was installed at each sampling location, and the traps were secured to dexion uprights using cable ties at ~0.6 of the mean water depth during the period of drought when the traps were initially installed. Each trap was emptied on a monthly basis between October 2011 and March 2013 into 10 l plastic containers and returned to the laboratory for analysis.

Analyses of extreme events suggest that a single flood event has the potential to exceed the normal annual geomorphic activity (erosion) in a catchment (Gonzalez-Hidalgo et al., 2013). Therefore, a sample of sediment analysed during this period has the potential to be representative of sediment originating from a large spatial area of the catchment. In this study samples of sediment deposited overbank were collected from 17 locations after four high flow events in April 2012, July 2012, October 2012, and November 2012 once high water levels had receded to below bankfull level. Sediment was washed from riparian vegetation as described by Walling et al. (1997). The primary vegetation selected was common comfrey (*Symphytum officinale*) and common nettle (*Urtica dioica*). The vegetation was washed with native river water into a 5 l plastic container, and the resultant water and sediment was transported to the laboratory for analysis in 1 l Nalgene bottles.

Channel beds represent an important store of recently deposited fine sediment in river catchments. Not only is the degradation of channel bed habitats by fine sediment considered an important ecological issue (Collins et al., 2010b), but the stored sediment often represents a source of easily mobilised sediment ready to be transported when flows increase (Walling and Amos, 1999). The method developed by Lambert and Walling (1988) was used to obtain a sample of sediment stored on the bed of the Nene's tributaries. A total of seven sites (Fig. 1) were sampled on a quarterly basis from the period June 2011 to September 2012. A cylinder with a surface area of ca. 0.2 m^2 was pushed into the river bed creating a seal between the cylinder and river bed, and the depth of water within the cylinder was recorded. The river bed within the cylinder was then disturbed to a depth of 5 cm using a wooden pole for a period of 1 min and two 0.5 l subsamples were immediately taken from the water within the cylinder. Three repetitions were performed within a ca. 30 m reach of river at each sampling location to provide a sufficient quantity of sediment for laboratory analysis.