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Research article

Use of spatially distributed time-integrated sediment sampling networks and distributed fine sediment modelling to inform catchment management

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ABSTRACT

Under the EU Water Framework Directive, suspended sediment is omitted from environmental quality standards and compliance targets. This omission is partly explained by difficulties in assessing the complex dose-response of ecological communities. But equally, it is hindered by a lack of spatially distributed estimates of suspended sediment variability across catchments. In this paper, we demonstrate the inability of traditional, discrete sampling campaigns for assessing exposure to fine sediment. Sampling frequencies based on Environmental Quality Standard protocols, whilst reflecting typical manual sampling constraints, are unable to determine the magnitude of sediment exposure with an acceptable level of precision. Deviations from actual concentrations range between −35 and +20% based on the interquartile range of simulations. As an alternative, we assess the value of low-cost, suspended sediment sampling networks for quantifying suspended sediment transfer (SST). In this study of the 362 km^2 upland Esk catchment we observe that spatial patterns of sediment flux are consistent over the two year monitoring period across a network of 17 monitoring sites. This enables the key contributing sub-catchments of Butter Beck (SST: 1141 t km^2 yr^{-1}) and Glaisdale Beck (SST: 841 t km^2 yr^{-1}) to be identified. The time-integrated samplers offer a feasible alternative to traditional infrequent and discrete sampling approaches for assessing spatio-temporal changes in contamination. In conjunction with a spatially distributed diffuse pollution model (SCIMAP), time-integrated sediment sampling is an effective means of identifying critical sediment source areas in the catchment, which can better inform sediment management strategies for pollution prevention and control.

1. Introduction

Fine sediment (<2 mm) is an essential, naturally occurring component of freshwater ecosystems, critical for habitat heterogeneity and ecosystem functioning (Owens and Collins, 2005). However when elevated levels persist, sediment sensitive species are affected and ecological degradation can occur (Collins et al., 2011). The negative impacts of fine sediment, as a diffuse pollutant, are widely acknowledged (cf. Bilotta and Brazier, 2008), and it is the sixth most common cause of water bodies failing to achieve good ecological status in England (Environment Agency, 2015). There is an implicit assumption within the EU Water Framework Directive (European Community, 2000) that fine sediment will be monitored by authorities in order to both effectively characterise the conveyance of adsorbed compounds and to establish whether sediment conditions contribute to 'good ecological status' (Collins and Anthony, 2008). However fine sediment itself is not one of the 33 priority physio-chemical substances and as such is not subject to Environmental Quality Standards and compliance targets (Crane and Babut, 2007). Indeed, following the repeal of the EU Freshwater Fish Directive (European Union, 2006) in 2013, which set a suspended sediment standard of 25 mg L^{-1}, there is still no accepted critical threshold of exposure. Such ambiguity has led to calls for fine sediment to have a more explicit profile in diffuse pollution policy (Collins and McGonigle, 2008).

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Although the omission of legally-binding suspended sediment standard(s) can, to an extent, be explained by complexities in the dose-response relationship between the composition and quantity of sediment, and the sensitivity of receiving ecological communities (e.g. Collins et al., 2011; Moss, 2008); this is exacerbated by the inability of authorities to obtain meaningful spatially distributed estimates of the variability in suspended sediment fluxes and its physical properties (Brils, 2008). These factors make it impractical for any theoretically sound, legally-binding, suspended sediment thresholds to be implemented given the operational protocols currently available to competent authorities.

Because current guidelines do not require an integrated assessment of fine sediment transport and its properties, routine sediment sampling strategies adopted by authorities involve sampling of accumulated sediment deposited on the channel bed. However, not only does this sampled material represent a historical pollution state, the presence of turbulent conditions, bioturbation, or low sedimentation rates, can result in the misrepresentation of the prevalent physical properties of fine sediment in the river system (Crane, 2003; Schubert et al., 2012). An alternative, and the most commonly adopted approach is sampling the typically fine, suspended particulate material directly from the water column (Greenwood et al., 2007; Madrid and Zayas, 2007). However, due to resource constraints and the complex temporal distribution of naturally transported fine sediment, these approaches are typically biased towards lower flows and concentrations (Carere et al., 2012; Johnes, 2007). These strategies rarely capture the state of the system when erosive processes, and connectivity across the catchment are most active (Ockenden et al., 2016; Perks et al., 2015), failing to reflect the nature of sediment-associated pollutant transport at appropriately high temporal and spatial scales (Eriksson et al., 2007; Horsburgh et al., 2010). As such, these monitoring campaigns are not robust or rigorous enough to provide realistic estimates of fluxes, or average pollutant concentrations (Etchells et al., 2005; Gray, 1999; Irvine et al., 2002). Investment in automated sampling systems can generate better estimates through flow-proportional, probability and stratified sampling methods (e.g. Braskerud, 2001; Thomas and Lewis, 1995), whilst surrogate technologies may generate meaningful high-resolution datasets (Collins et al., 2011; Owen et al., 2012). However, the application of such technology across catchments is currently unfeasible, or restricted, due to authorities seeking to reduce the cost of non-essential monitoring where possible (Skarbøvik et al., 2012). Whilst this is cause for concern, it does present an important opportunity to develop and test low-cost tools and technologies that are capable of capturing suspended sediment data at an appropriate scale for detecting changes in fine sediment dynamics, and at a resolution sufficient to inform specific catchment management strategies.

Whilst monitoring for the protection of aquatic habitats is an important step-forward, there is also a need for current research to develop frameworks that better characterise spatial variability in fluvial suspended sediment flux and more closely specify provenance of sediment at enhanced spatio-temporal resolutions (Fryirs, 2012; Owens and Collins, 2005; Wainwright et al., 2011). Such frameworks will address the current dearth of knowledge about the impacts of land-use on the temporal discontinuity of fluvial suspended sediment transfer and facilitate appropriate catchment-scale management strategies through better understanding of the scale dependence of sediment yields (Jansson, 1988; Mills et al., 2008). This raises the important question of whether low-cost spatially distributed sampling networks can provide fine sediment data at a precision that can enhance understanding of how these dynamic fluvial systems operate.

The aim of this paper is to demonstrate how novel, low-cost time-integrated networks provide essential information about the exposure, quality and composition of suspended sediment in fluvial networks draining upland and piedmont zone catchments of significant size (10^1–10^2 km^2). We contend that programmes based upon infrequent sampling are often unsuitable, and whilst high-frequency traditional sampling and surrogate (turbidity) monitoring programmes are essential to meet critical regulatory commitments (e.g. discharges from wastewater treatment plants), lower cost, time-integrated suspended sediment sampling networks (e.g. Perks et al., 2014) may be used by competent authorities to assess spatio-temporal changes in contamination status across catchments. We demonstrate this through the presentation of: (i) the uncertainty in characterising the sediment transport regime through evidence gathered by a synthetic sampling programme logistically constrained to represent a typical environmental quality standards style assessment; (ii) data generated by a low-cost time-integrated network which is used to provide evidence of catchment-wide variations in suspended sediment flux; and (iii) an illustration of how distributed sampling networks and risk modelling can be used in conjunction to inform sediment management plans for the delivery of adequate pollution prevention and control.

2. Regional and catchment setting

This study takes place in the 362 km^2 River Esk catchment, located in the North Yorkshire region of Northern England, UK (Fig. 1). The climate is cool, temperate-maritime with annual average rainfall of less than 1000 mm. The catchment is underlain by sandstone, siltstone and mudstone formations of the mid and lower Jurassic periods with the River Esk originating as a group of upland springs at Esklets on Westerdale Moor at an altitude of 432 m above sea level. Several major tributaries of the Esk, orientated south-west to north-east, drain the upland plateau which is dominated by the largest area of heathland in England (Boon et al., 2015; Evans et al., 2014). Beyond the upland plateau, pasture and rough grazing dominate in the headwaters with some woodland and improved grassland prevalent in the middle and lower reaches of the Esk valley and along riparian river corridors (Fig. 1). The formerly glaciated Esk valley accommodates a meandering river that traverses the landscape for 42 km from West to East, before joining the North Sea at Whitby. Here, flow can approach 950 m^3 s^{-1} during extreme events. The Esk is one of only two nationally recognised Atlantic salmon *Salmo salar* rivers in Yorkshire, and it supports a regionally important sea trout *Salmo trutta* population. It is also one of only two rivers on the east coast of England to have known populations of the freshwater pearl mussel, *Margaritifera margaritifera* (Geist, 2005). This species is one of the most critically endangered bi-valves in the world, with siltation and excessive suspended sediment concentrations being attributed to causing their decline (Walling et al., 2001). This has led to local conservation and restoration efforts being undertaken by the competent authorities over the last 20 years (Arnold-Forster, 2002; Emery, 2010; Emery et al., 2013; Perks and Warburton, 2016).

3. Materials and methods

Field data presented herein were collected in the Esk catchment from a network of 17 spatially distributed monitoring sites (Perks et al., 2016d), with high temporal resolution turbidity monitoring at two primary locations (Perks et al., 2016b, c), over a two year period spanning the 2008 and 2009 hydrological years (Fig. 1). Results were compared with the SCIMAP spatially distributed modelling approach, which was developed to predict diffuse pollution risk across catchments (Reaney et al., 2011).