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INTRODUCTION

The fine sediment conundrum; quantifying, mitigating and managing the issues

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Abstract
Excess fine sediment is a global cause of lotic ecosystem degradation. Despite historic interest in identifying sediment sources and quantifying instream dynamics, tackling fine sediment problems remains a key challenge for river managers and a continued focus of international research. Accordingly, a national meeting of the British Hydrological Society brought together those working on fine sediment issues at the interface of hydrology, geomorphology, and ecology. The resulting collection of papers illustrates the range of research being undertaken in this interdisciplinary research arena, by academic researchers, environmental regulators, landowners, and consultants. More specifically, the contributions highlight key methodological advancements in the identification of fine sediment sources, discuss the complexities surrounding the accurate quantification of riverbed fine sediment content, demonstrate the potential utility of faunal traits as a biological monitoring tool, and recognize the need for improved mechanistic understanding of the functional responses of riverine organisms to excess fine sediment. Understanding and mitigating the effects of fine sediment pressures remains an important and multifaceted problem that requires interdisciplinary collaborative research to deliver novel and robust management tools and sustainable solutions.

KEYWORDS
ecology, management tools, sedimentation, sediment sources

1 | INTRODUCTION

The erosion, transport, and storage of fine sediment in riverine catchments are widely recognized to be a global cause of habitat and ecological degradation (Collins et al., 2011; Jones et al., 2012; Wharton, Mohajeri, & Righetti, 2017). Fine sediments are an essential component of healthy riverine functioning. However, sediment yields of many rivers currently exceed background levels due to changing land cover, land use, and management practices (Collins & Zhang, 2016; Farnsworth & Milliman, 2003; Foster et al., 2011; Owens et al., 2005). In addition, it is anticipated that fine sediment pressures will increase in the future due to climatically driven changes to rainfall and runoff regimes (Burt, Boardman, Foster, & Howden, 2016; Walling & Collins, 2016). Developing an improved understanding of fine sediment dynamics (i.e., key sources, pathways and exports, deposition, and ingress of fines into riverine substrates) and the associated implications for aquatic habitats and ecology is therefore essential for the development of effective intervention and management strategies. Such strategies should seek to combine both slope-based (e.g., on-farm) and morphological restoration in order to tackle both the sources and consequences of sediment mobilization. Slope-based interventions are commonly supported by agricultural policy including agri-environment schemes and also by management strategies funded by water companies in the form of payment for ecosystem services schemes. The increasing numbers of river restoration schemes being implemented as a result of widespread habitat degradation (Geist & Hawkins, 2016; Kail, Brabec, Poppe, & Januschke, 2015; Palmer et al., 2005) reflects the need for a twin-track approach to manage the degradation of aquatic ecosystems. In all instances, management must be considered in the context of catchment processes (Gurnell, Rinaldi, Belletti, et al., 2016; Gurnell, Rinaldi, Buijse, Brierley, & Piegay, 2016), with some interventions required to be catchment-wide whereas others may be targeted to the main areas of concern.

To explore and discuss ongoing challenges and uncertainties associated with improving the capacity to address the fine sediment "conundrum," a national meeting of the British Hydrological Society was held in 2016 at Loughborough University (UK). This meeting considered the fine sediment cascade in its broadest sense attracting a diverse and multidisciplinary group of attendees including hydrologists, geomorphologists, ecologists, environmental regulators, landowners, and consultants. This special issue stems from that meeting, and the papers herein reflect on three main themes (notwithstanding some inevitable overlap) associated with managing the fine sediment problem, namely, (a) characterizing the primary catchment sources of fine sediment inputs into riverine systems; (b) physical and biological approaches to the assessment of fine sediment pressures on aquatic ecosystems; and (c) evaluating the ecological consequences of excessive fine sediment using empirical and modelling approaches.

2 | CATCHMENT SCALE EVALUATION OF SEDIMENT SOURCES

To manage increased fine sediment loading effectively requires reliable knowledge of the sources of such material at a catchment scale. Fine sediment is typically referred to as particles <2 mm in diameter, but it is important to note that predicting the effect of excess loadings on instream organisms is heavily dependent on a number of critical factors including, grain size distribution, chemical composition, duration of exposure, and concentration (Bilotta & Brazier, 2008). Available methods for investigating sediment sources can be divided into indirect and direct approaches (Collins & Walling, 2004). The most commonly applied direct method of identifying catchment sediment sources is the fingerprinting approach that quantifies the relative contributions of individual sediment sources to target sediment samples, including those collected in gravel beds or from the suspended load (Collins, Foster, et al., 2017; Owens et al., 2017). Potential sources of sediment and associated organic matter are identified and sampled, such as agricultural top soils, channel banks, damaged road verges, septic tanks, farmyard manures, and decaying instream vegetation. Representative samples of target sediment are also collected, including channel bed sediments, often via remobilisation (Duerdoth et al., 2015) or time-integrating methods (Phillips, Russell, & Walling, 2000). These samples are analysed in the laboratory for unique physical or biogeochemical properties known as tracers or "sediment fingerprints." By coupling the composition of source materials with channel sediments, the contribution of each source may be quantified at catchment scale. This approach is a valuable tool in the identification of priority source types and geographical areas for sediment management and mitigation programmes.

Four papers within this special issue illustrate and reflect on how sediment fingerprinting can be implemented in the management of sediment and associated organic matter using diverse case study examples. Zhang et al. (2017) present the findings of a study conducted in three tributaries of the River Itchen, in southern England, which successfully identifies the main sources of sediment-associated organic matter inputs. In all three subcatchments, the top three sources were found to be watercress farms, farmyard manures/slurries, and decaying instream vegetation, although the relative contributions and importance varied. These results highlight that sediment management strategies should be undertaken on a subcatchment specific basis to accommodate scale dependency and corresponding spatial variations in source contributions. Biddulph, Collins, Foster, and Holmes (2017) reflect on the perennial problem associated with the identification of diffuse sources of fine sediment across relevant spatial scales and the implications for on-farm management of the sediment problem. They highlight the need for sediment sources to be considered from individual farms through to the landscape scale in order to effectively partition the relevant contributions of individual sources. They advise coordinated farm-scale interventions taking due account of sediment source and corresponding erosion process domains to maximize management impacts at the landscape scale.

Collins, Zhang, et al. (2017) examined the provenance of fine sediment-associated organic matter and complimented this with sediment oxygen demand measurements. By utilizing the two methods simultaneously, it was possible to account for the key sources of sediment-associated organic matter that contributed to oxygen demand and therefore habitat and ecological degradation. Pulley, Van der Waal, Collins, Foster, and Rowntree (2017) discuss the importance of carefully defining source group classifications when using sediment fingerprinting. The classification of sources is often the least considered aspect of the methodology. Their methodology introduces an additional step that complements conventional decision-trees by enabling assessment of the environmental relevance of different source groupings.

In-channel sources of sediment, and in particular the role of tributary inputs, are considered by Marteau, Batalla, Vericat, and Gibbins (2017). Much of the research focussing on sediment delivery by tributaries has typically tended to consider coarse grain fractions in perennial rivers (Hooke, 2003; Rice, 2017; Rice, Greenwood, & Joyce, 2001). However, the authors illustrate that following a restoration project that reconnected an ephemeral river to the main stem, sediment yields increased by 65%. They highlight that even a small increase in catchment area, in this instance 1.2% of the catchment size, can result in significant alterations to fine sediment dynamics, particularly in sediment starved and regulated rivers. This also clearly highlights the importance of considering alternative sediment sources, which may have previously been overlooked in sediment dynamic models.

3 | PHYSICAL AND BIOLOGICAL APPROACHES TO THE APPRAISAL OF FINE SEDIMENT PRESSURES

Many of the deleterious effects of enhanced fine sediment levels on instream ecology are associated primarily with the deposited rather than suspended component because substrate characteristics exert an important control on habitat availability especially during the critical life stages of many organisms (Berry, Rubinstein, Melzian, & Hill, 2003; Culp, Wrona, & Davies, 1986; Jones et al., 2012). Consequently, the ability to quantify accurately the fine sediment content of a river bed is vital for assessing habitat status, checking compliance with recommended thresholds, and successfully implementing management strategies. Fine sediment pressures in river substrates can be measured using two primary means. First, the fine sediment content of riverbeds can be physically measured or estimated, and second, biological metrics derived from the sediment tolerance of a community of organisms can be used as a proxy to monitor deviation from reference conditions. Six papers within this special issue address the complexities surrounding the accurate quantification of fine sediment content in stream substrates.

One physical method for measuring fine sediment deposition rates involves the installation of traps that collect fine sediment infiltrating into the river bed over a known time period. Harper et al. (2017) employed two different designs of such traps; one which permits vertical exchange and one which permits both vertical and lateral exchange. Their results corroborate a number of previous studies that demonstrate the importance of lateral transport for the accumulation and retention of fine sediment (Casas-Mulet, Alfredsen, McCluskey, & Stewardson, 2017; Mathers & Wood, 2016; Petticrew, Krein, & Walling, 2007). However, the authors also raise questions about the accuracy of traps and the physical processes that they measure.

Physical sampling techniques can, however, be labour and time intensive, and as such, many monitoring agencies (and increasingly researchers) employ rapid assessment methods. One such method is the visual assessment of substrate composition that involves an individual estimating the percentage cover of different particle sizes at a given site. Although such methods can be effective (e.g., Buffington & Montgomery, 1999), they can be associated with a high degree of operator subjectivity. Turley et al. (2017) present a novel, image-based technique that seeks to overcome operator subjectivity thereby providing non-destructive, rapid, and less subjective estimates of surface sediment cover.

Given the widely documented effects that excess fine sediment deposition has on a range of aquatic organisms, from fish through to macroinvertebrates and diatoms (Jones, Duerdoth, Collins, Naden, & Sear, 2014; Kemp, Sear, Collins, Naden, & Jones, 2011; Wood & Armitage, 1997), biomonitoring techniques, which use biota to track changes in the aquatic environment (Friberg et al., 2011), are increasingly being used to monitor fine sediment content. Based on quantified relationships between taxa abundances and benthic substrate composition, the extent of fine sediment stress on an ecosystem can be determined. A number of biological indices that relate the structural responses of macroinvertebrates to fine sedimentation have been proposed (e.g., Murphy et al., 2015; Relyea, Minshall, & Danehy, 2000; Turley et al., 2016). Extence, Chadd, England, and Naura (2017) evaluate one such biological index, the proportion of sediment sensitive invertebrates. They demonstrate its potential application as a national screening and catchment management tool in the identification of priority areas for sediment management practices and for post-management appraisals.

There is, however, a growing body of biomonitoring research that is focused on the use of biological traits, including life history, behaviour, and morphology characteristics, in environmental assessments. Trait-based approaches may be more widely applicable because they overcome the intrinsic problem with composition-based indices that are limited to the biogeographic region in which they were developed (Zuellig & Schmidt, 2012). Despite the high potential of trait-based indices as a tool for diagnosing fine sediment pressures, further research is required to improve their robustness. Two papers in this special issue call for an improved mechanistic understanding of macroinvertebrate functional responses to sedimentation (Murphy et al., 2017; Wilkes, Mckenzie, Murphy, & Chadd, 2017). In the first paper, Murphy et al. (2017) test the association of trait responses to fine sediment stress at national scale across England and Wales. They find limited evidence to support 18 predictions made in previous studies by Descloux, Datry, and Usseglio-Polatera (2014) and Mondy and Usseglio-Polatera (2013), but they do identify a number of traits that exhibit consistent patterns in relation to sediment stress. Wilkes et al. (2017) test the mechanistic basis of biological indices against species traits. The authors report a poor fit of two fine sediment indices against species traits. When only traits reported to respond to fine sediment based on available literature were included in the model, the fit was reduced further. Further refinement of the trait database is therefore required to enable trait-based approaches to be embedded into statutory monitoring and research projects.

Identifying and quantifying relationships between fine sediment loading and ecological responses are often confounded because the physical controls of hydrology and geomorphology vary in time and space (Bond & Downes, 2003; Evans & Wilcox, 2014; Gurnell, Rinaldi, Buijse, et al., 2016). River regulation and land use changes are two of the most common catchment disturbances globally and may occur independently or concurrently, which makes it difficult to isolate which process is responsible for ecological degradation (Jones, Growns, Arnold, McCall, & Bowes, 2015; Wood & Armitage, 1999; Wood, Armitage, Hill, Mathers, & Millett, 2016). Bradley et al., (2017) present a hydro-ecological model which, when used in combination with flow indicators and other local environmental information, can identify target areas where flow and fine sediment pressures need to be managed independently or in combination. Application of such coupled approaches will increase the ability of regulatory agencies to make effective management decisions by avoiding consideration of a single stressor in isolation.

4 | ECOLOGICAL EFFECTS OF FINE SEDIMENTATION

Improved understanding of the negative effects of excess fine sediment on ecosystem functioning remains an area where fundamental research is still required. Despite the wealth of literature and historic interest in the ecological consequences of sedimentation, many of the fundamental processes surrounding the effects remain unstudied. The implications of fine sediment deposition on salmonid embryos have been widely studied, partly because of their high economic value (Sear et al., 2016; Suttle, Power, Levine, & McNeely, 2004). In this collection, Sear et al. (2017) present a study in which they model Sediment Intrusion and Dissolved Oxygen and quantify the implications for dissolved oxygen supply to salmonid redds. They indicate that high sediment-associated consumption rates reduce dissolved oxygen concentrations within redds but that the mass of fine sediment was the most important controlling factor. Higher quantities of fine sediment result in elevated sediment oxygen demand but also physically block substratum pores causing a more dramatic decline in dissolved oxygen concentrations. Béjar, Gibbins, Vericat, and Batalla (2017) conclude the special issue by presenting a study that investigates the impact of suspended sediment on macroinvertebrate drift. The authors found that significant increases in suspended sediment concentrations were sufficient to trigger changes in drift behaviour, with some taxa demonstrating an increase in drift propensity whereas others displayed a reduction. It is clear that further research is required in this area to understand the mechanisms underlying these behavioural adaptations.

5 | FUTURE DIRECTIONS

The 13 papers in this special issue demonstrate the complex suite of issues that surround the management of excess fine sediment in aquatic habitats and the diversity of approaches used to inform characterization and intervention. Ultimately, effective management of rivers requires a multiscaled approach in which several disciplines combine to tackle the overarching problem. From this special issue, it is clear that research is required to further improve source fingerprinting procedures and to appraise the potential importance of additional sources of fine sediment that may become more important in the future, such as ephemeral streams (Acuña, Hunter, & Ruhí, 2017). Despite significant advances in sediment fingerprinting methods, there is a clear need to take account of the scale dependency of source apportionment data and to implement coordinated intervention strategies that target cumulative source contributions at the landscape scale and not just localised problems. This requirement would be facilitated by developing comprehensive and transparent assessment methods that enable both landowners and advisors to fully understand the science of fine sediment dynamics and impacts. This would enable greater engagement and process understanding and thereby facilitate better implementation of management practices and subsequent appraisals of their effectiveness.

Fundamental problems still exist in the quantification of fine sediment content in river substrates. Many of the methods employed are subject to operator and methodological errors and/or are time and labour intensive. As such, further work is required that objectively tests current methods to fully resolve their accuracy relative to resource implications (e.g., Duerdoth et al., 2015). Biological metrics provide an opportunity to monitor the health of lotic ecosystems effectively, but a deeper understanding of the mechanisms that link taxon responses to fine sediment pressure is required. This is particularly evident in the trait literature where results lack consistency. Experimental research is required that investigates and documents specific responses of organisms to fine sediment (*sensu* Beermann et al., 2018; Mathers, Millett, Robertson, Stubbington, & Wood, 2014; Vadher, Stubbington, & Wood, 2015) and which is subsequently corroborated via broad-scale field studies. There is also a growing body of work focused on the impacts that organisms have on fine sediment dynamics (e.g., Gurnell, 2014; Rice, Johnson, Mathers, Reeds, & Extence, 2016), recognizing the two-way interactions and feedbacks between the biotic and abiotic components of river systems and the potential importance of these processes for comprehensive management solutions. Finally, and linked to the effective monitoring of lotic systems, further research is required to improve understanding of the individual processes and components of fine sediment dynamics that cause shifts in biota behaviour and survival. Pinpointing the most influential factors such as organic matter content and associated oxygen demand, sediment size, or sediment quality will enable management practices to be implemented effectively whilst minimizing time and monetary costs.

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