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The behavioural characteristics of sediment properties and their implications for sediment fingerprinting as an approach for identifying sediment sources in river basins

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ABSTRACT

Sediment fingerprinting is a technique that is increasingly being used to improve the understanding of sediment dynamics within river basins. At present, one of the main limitations of the technique is the ability to link sediment back to their sources due to the non-conservative nature of many of the sediment properties. The processes that occur between the sediment source locations and the point of collection downstream are not well understood or quantified and currently represent a black-box in the sediment fingerprinting approach. The literature on sediment fingerprinting tends to assume that there is a direct connection between sources and sinks, while much of the broader environmental sedimentology literature identifies that numerous chemical, biological and physical transformations and alterations can occur as sediment moves through the landscape. The focus of this paper is on the processes that drive particle size and organic matter selectivity and biological, geochemical and physical transformations and how understanding these processes can be used to guide sampling protocols, fingerprint selection and data interpretation. The application of statistical approaches without consideration of how unique sediment fingerprints have developed and how robust they are within the environment is a major limitation of many recent studies. This review summarises the current information, identifies areas that need further investigation and provides recommendations for sediment fingerprinting that should be considered for adoption in future studies if the full potential and utility of the approach are to be realised.

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1. Introduction

Sediment fluxes within river basins are natural processes and are part of global erosional, weathering and biogeochemical cycles that are important for maintaining aquatic ecosystem health, resiliency and function (Owens, 2008). As a society, we are altering the landscape at an unprecedented scale for the purposes of urbanisation, agriculture, resource extraction, industry and recreation (Foley et al., 2005). These changes within the landscape are affecting sediment fluxes which in turn are resulting in the degradation of both the terrestrial and aquatic environments (Allan, 2004; Syvitski et al., 2005; Owens et al., 2010). Some land use practices result in unsustainable soil losses, where the rate of erosion is greater than the rate of soil production leading to a reduction in productivity. This is of particular concern within agricultural areas as there is limited new land suitable for sustained cultivation (Montgomery, 2007).

Both the quantity and quality of sediments can have an impact on the aquatic environment. Increases in sediment can reduce light penetration, act as a scouring agent and result in the sedimentation of the river bed. Sediment also acts as a vector for nutrients and a variety of contaminants including pathogens, industrial chemicals and metals, and plays an important role in the downstream conveyance of this material. Changes in the amount and composition of sediment can have an impact on the ecology of the aquatic ecosystem though the alteration or elimination of habitat, shifts in community composition and abundance, changes in the food web, increased mortality and a decrease in reproductive success (Henley et al., 2000; Palmer et al., 2000; Shaw and Richardson, 2001; Rabení et al., 2005; Harrison et al., 2007). In addition, increases in sediment delivery to the aquatic environment can also result in reduced reservoir capacity, a decline in drinking water quality, impairment of navigation, and impact recreational activities (Vörösmarty et al., 2003, 2010).

The impacts of sediment and associated nutrients and contaminants on water and aquatic habitat quality are well documented and represent a widespread problem facing many countries (Bilotta and Brazier, 2008; Horowitz, 2009). As the global population continues to increase, the pressures placed on our soil and water resources will also increase, and there is a need to design new resource management systems which can meet the growing demand for water, food, fibre and fuel, while safeguarding the environment. Good management of these resources requires a solid understanding of sediment dynamics, however, the often diffuse nature of sediment pollution makes obtaining reliable information as to the dominant sources of sediment and associate nutrients and contaminants within a river basin difficult (Smith et al., 2011b).

2. The sediment fingerprinting approach

Sediment tracing and sediment fingerprinting are terms that are often used interchangeably but can have different meanings and, therefore, it is important that a clear distinction be made. Sediment tracing in many instances refers to direct tracing or tracking of sediment in a downstream direction from its origins through the landscape with the assumption that the source of sediment is known. Specifically, the sources are identified using prior knowledge and the origins and behaviour of the tracers are generally well understood. Typically, the movement of the tracer and, by inference, the sediment is followed in a downslope or downstream direction. Sediment tracing studies often use artificially introduced tracers including foreign particles (e.g., fluorescent particles; Granger et al., 2011), rare earth elements (e.g., lanthanides; Polyakov and Nearing, 2004; Spencer et al., 2011) as well as fallout radionuclides (e.g., ^{137}Cs; Ritchie and McHenry, 1990; Wilson et al., 2012) to track the movement of sediment (for a review see Guzmán et al., 2013). In contrast, sediment fingerprinting generally refers to working in an upstream direction in an inferential manner to determine the source(s) of sediment, i.e., the contribution from a given source of sediment is unknown. The approach is based on the idea that one or more of the natural physical or biogeochemical properties of the sediment will reflect its source, and therefore can be used diagnostically to identify the origin(s) of the sediment. There is a wide range of natural soil and sediment properties that can be utilised as fingerprints and are related to three fundamental properties; nuclear properties, molecular identity and orbital electron properties (for a review, see Foster and Lees (2000) and Fig. 1). The unique sediment properties, which comprise the fingerprint, are measured in both the source and sediment samples and a statistical un-mixing model is subsequently used to estimate the contribution of sediment from each potential source (for an overview of the methodology and application of sediment fingerprinting, see Gellis and Walling (2011)). For the purposes of this review, the focus will be sediment fingerprinting as opposed to sediment tracing.

Sediment fingerprinting is a technique that has been used to investigate sediment dynamics at a variety of spatial scales ranging from individual field plots (<10 m^2) (e.g., Wilson et al., 2011) to large river basins (>100,000 km^2) (e.g., Wang et al., 2009), at temporal scales ranging from event-based (<24 h) (e.g., Martínez-Carreras et al., 2010b) to geological sediment records (>10,000 yr) (e.g., Yang et al., 2006), in environments ranging from forested (e.g., Smith et al., 2011a) to agriculture (e.g., Russell et al., 2001) to urban (e.g., Carter et al., 2003). It has been used to determine the provenance of sediment size classes from sand (250–355 μm) (e.g., Maher et al., 2009) to very fine-grained (<10 μm) sediment (e.g., Wilkinson et al., 2009). A search of the Web of Knowledge citation index (April 2013), using ("sediment") AND ("tracing" OR "fingerprinting") as topic keywords and excluding inappropriate subject categories (e.g., health sciences), returned over 450 entries that encompassed more than 150 different journals between 1990 and 2012. The increase in the number of publications per year over the past 22 years (Fig. 2) reflects the increased attention that these techniques are receiving as a tool to help understand sediment dynamics. Furthermore, the rapid uptake of the technique also reflects increasing concerns over water quality and its potential as a tool for river basin managers for improved decision-making in light of increasing policy and legislation (Owens and Xu, 2011). The large number and diversity of journal titles demonstrates that the technique is multidisciplinary, covering subject areas including