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EDITORIAL

Sediment source fingerprinting: are we going in the right direction?

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1 Introduction and context

Over the last few decades, there has been a large growth in the number of publications that have used the sediment source fingerprinting (SSF) technique to identify the dominant sources of fine-grained sediment in a range of environments. Reviews by Walling (2005) and Collins et al. (2020) show that the number of journal publications has increased from < 5 each year in the 1970s to > 40 per year today. The recent paper by Evrard et al. (2022) suggests that now is a good time to assess where the technique lies in terms of its evolution and what developments are required for future improvement. This article contributes to this discussion.

As Walling (2005, 2013) and others have identified, the SSF technique was developed in the 1970s. Early studies focused on determining the sources of sediment transported in rivers (e.g., Klages and Hsieh 1975; Wall and Wilding 1976; Oldfield et al. 1979; Walling et al. 1979; Grimshaw and Lewin 1980). Initially, results were mainly qualitative, in the form of plots and simple comparisons, and used color, mineralogy, geochemical, and mineral magnetic properties of materials as fingerprints. Over time, the technique has (i) become more quantitative, using increasingly advanced statistical and modeling techniques; (ii) utilized new properties as fingerprints; and (iii) expanded to include new environments and applications. Useful reviews of the history and principles of the SSF technique are provided by Walling (2005, 2013), Haddadchi et al. (2013), Owens et al. (2016), and Collins et al. (2017, 2020).

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2 A shift in focus?

Sediment source fingerprinting was developed as a "tool" to help answer research questions about how landscapes function. Early applications were concerned with assessing erosion of the landscape, such as soil and channel bank erosion, especially in agricultural areas (e.g., Peart and Walling 1988; Walling and Woodward 1995; Collins et al. 1997). Additional applications included (i) determining the impacts of forest harvesting and wildfires on landscape erosion (e.g., Motha et al. 2003; Blake et al. 2006; Owens et al. 2012); (ii) assessing how urban development supplied additional sources of sediment (and contaminants) to aquatic systems (e.g., Charlesworth et al. 2000; Carter et al. 2003; Poleto et al. 2009); (iii) identifying sources in estuaries and coastal zones (e.g., Yu and Oldfield 1989; Gibbs 2008; Douglas et al. 2010); and (iv) reconstructing source changes over time using lake, floodplain, and estuarine sedimentary deposits (e.g., Dearing 1992; Foster et al. 1998; Owens et al. 1999). There is no doubt that these studies have greatly enhanced our understanding of earth surface processes and landscape evolution.

A second application addressed issues of watershed management. There is a vast literature that has discussed the problems associated with excessive soil erosion and with sediment and associated chemicals in aquatic systems (e.g., Montgomery 2007; Owens et al. 2005; Bilotta and Brazier 2008; Poesen 2018), i.e., the on-site and off-site consequences on landscape erosion. As such, the SSF technique provided an excellent means to assemble important information that could be used to develop advice to mitigate such problems. In other words, the SSF technique provided the scientific evidence to underpin management decision-making and policy development. In the earlier years of the technique, the attractiveness of SSF as a tool to the non-academic community (i.e., land owners, watershed managers and advisors, environmental regulators, policy developers) was that it was (i) conceptually simple and (ii) cost-effective. In terms of (i), the premise is that the properties of the problem sediment are compared to those of the potential sources and a link is established between the two types of materials. In the case of (ii), most of the properties used were easy to obtain in academic and commercial laboratories. For example, analysis of a soil or sediment sample for a suite of geochemical properties (> 30 elements) now typically costs in the range of US$10–$50. Thus, a study using 30 source samples (10 from three main source types) and 10 suspended samples might cost US$400–$2000. It was also cost-effective in that it did not require long-term monitoring of erosion and sediment transport dynamics; sampling and laboratory analysis could be done in a matter of months.

Over time, there has been a shift in the focus of many SSF studies. Numerous investigations are now concerned with "method development", which represents a natural progression of scientific inquiry for what is a relatively new technique. There are many excellent studies that have:

- examined the potential of new fingerprint properties, including compound-specific stable isotopes (CSSIs), eDNA, and spectral reflectance properties (e.g., Martinez-Carreras et al. 2010; Blake et al. 2012; Barthod et al. 2015; Evrard et al. 2019a; Reiffarth et al. 2019; Frankl et al. 2022);
- assessed ways to better sample and characterize sediment and source materials (e.g., Wilkinson et al. 2015; Du and Walling 2017; Boudreault et al. 2019; Haddadchi et al. 2019; Lake et al. 2022);
- developed protocols, statistical approaches, and numerical models that provide a more realistic and accurate estimate of source contributions and their uncertainties (e.g., Smith et al. 2018; Blake et al. 2018; Lizaga et al. 2020a; Upadhayay et al. 2020); and
- evaluated the accuracy and precision of the results derived from these models using artificial and virtual mixtures (e.g., Gasper et al. 2019; Batista et al. 2022).

These studies and developments have greatly helped the SSF technique provide more rigorous and robust apportionment results and have increased its reputation within academia, in part, demonstrated by the growth of studies published in high-ranking journals. That said, the SSF community does need to be aware of the fact that too much method development can lead to a divergence of approaches and a lack of standardization. Perhaps more importantly, it can be argued that a change in focus to method development has resulted in a departure from the original objectives of the technique, namely, (i) improving our understanding of landscape evolution; and (ii) addressing the needs of watershed managers and regulators in terms of sediment-related problems.

3 Addressing Earth's urgent environmental problems

Numerous reports and publications have identified a series of global-scale environmental crises—including the climate change emergency and concerns associated with food and water security—and identified that the scientific community needs to address these challenges (e.g., McLaughlin and Kinzelbach 2015; Wheater and Gober 2015; Owens 2020a; Ripple et al. 2020). As such, the SSF technique offers great potential in answering a range of important questions that include (i) evaluating multiple stressors on sediment sources and sediment dynamics in large and/or complex landscapes and watersheds (e.g., Gateuille et al. 2019); (ii) assessing the degree and rate by which landscapes are responding to global environmental changes like climate change and land use change (e.g., Wynants et al. 2021); and (iii) determining whether management and remediation actions are effective (e.g., Evrard et al. 2019b). In this context, the power of the SSF technique is likely to be greatly increased when it is combined with other lines of evidence, such as sediment flux monitoring, sediment budget investigations, remote sensing, landscape modeling, and incorporation of indigenous and community knowledge (e.g., Dambroz et al. 2022). Thus, it is recommended that SSF should be part of a larger framework of research which involves a transdisciplinary approach to science and its utilization (Owens 2020b).

Evrard et al. (2022) also advocate the need for forward-thinking, broader-scale projects that look to identify regional environmental patterns. In other words, a move away from applications in yet another watershed or landscape—unless it is in environmental settings where existing data are not available (e.g., Gholami et al. 2017; Navas et al. 2020; Sellier et al. 2020)—to applications that provide a mechanistic understanding of earth surface processes and determine landscape-scale patterns of responses to change.

4 Addressing the utilization of findings

In many respects, the SSF technique has not been utilized by watershed managers and regulators as much as hoped. Many publications justify the research that they describe in the context of its application to help managers and regulators to solve problems. But in reality, the up-take of the technique has not met its potential, which suggests that there may be a disconnect. There are several reasons for this disconnect between the academic and practical applications of SSF. One relates to the departure from the original attractiveness of the SSF technique; its conceptual simplicity and its cost-effectiveness compared to alternatives.

The technique is now more advanced than its earlier incarnations, which has likely made it less appealing to those who wish to use it as an operational tool (Mukundan et al. 2012) and not a research tool or an intellectual exercise (i.e., method development). There are several ways forward. One is to allow the use of simple versions of the tool, and not be fixed upon the use of the most recent, state-of-the-art version. As others have recently advocated (e.g., Evrard et al. 2022; Pulley and Collins 2022), sometimes simple bi-plots of property values of source materials and sediments can be enough to provide the information needed for decision-making. Indeed, often watershed managers and regulators are looking for the rank order of the "main" sediment sources (e.g., topsoil erosion vs channel banks; agricultural land vs forested land) so as to make a decision and do not require accurate percent contributions. However, it should be recognized that quantitative scientific evidence is sometimes needed to leverage the incentive and funding required to implement management actions.

Another development is to provide ways that users can input the required data and obtain outputs without themselves having to perform complicated statistics and modeling. Thus, several recent modeling tools have been developed to enable this, many of which are open-access and with a user-friendly interface (e.g., Gorman Sanisaca et al. 2017; Pulley and Collins 2018; Lizaga et al. 2020b).

An important issue lies with knowledge transfer. It is likely that the information being generated from many SSF studies is not reaching those that need the information for management decision-making and policy development (Collins et al. 2020). There are several ways to address the issue of lack of communication. As Slob et al. (2008), Evrard et al. (2022), and others have advocated, one way is to engage stakeholders and end-users in the project development and application process. This will help the project to meet its objectives and generate the information required by end-users. Another is to have bi-directional knowledge exchange identified as a key objective of the project. This is a subtle, yet important, distinction from knowledge transfer in a single direction from researcher to end-user.

5 Concluding comments

The comments above are not meant to discourage researchers from further developing and improving the SSF technique. Indeed, such advancements are required to increase its value and will ultimately enhance its reputation. Recent reviews and position articles by Koiter et al. (2013), Laceby et al. (2017), Collins et al. (2020), Evrard et al. (2022), and others provide excellent guidance on what developments and considerations are required. However, it is important to recognize that we should not ignore the fact that the SSF technique is ultimately a tool that should be used to (i) answer fundamental questions about how landscapes, and especially modified landscapes, function in a changing world and (ii) provide local communities, managers, and regulators with the information that they require to make decisions and develop policy. The request comes amid warnings (e.g., IPBES 2018; IPCC 2022) that society needs to act quickly to address the global environmental crises that we are facing.

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