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Fluvial Sediment Fingerprinting—Literature Review and Annotated Bibliography

Open-File Report 2014–1216

U.S. Department of the Interior
U.S. Geological Survey

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By Joyce E. Williamson, Adel E. Haj, Jr., John F. Stamm, Joshua F. Valder, and Vicki L. Prautzch

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SALLY JEWELL, Secretary

U.S. Geological Survey
Suzette M. Kimball, Acting Director

U.S. Geological Survey, Reston, Virginia: 2014

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Suggested citation:
Williamson, J.E., Haj, A.E., Jr., Stamm, J.F., Valder, J.F., and Prautzch, V.L., 2014, Fluvial sediment fingerprinting—Literature review and annotated bibliography: U.S. Geological Survey Open-File Report 2014–1216, 9 p., *http://dx.doi.org/10.3133/ofr20141216*.

ISSN: 2331-1258 (online)

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Conversion Factors

SI to Inch/Pound

Multiply	By	To obtain
	Length	
millimeter (mm)	0.03937	inch (in.)
	Area	
square kilometer (km^2)	0.3861	square mile (mi^2)

Abbreviations

®	registered trademark
ANOVA	analysis of variance
ASTER	Advanced Spaceborne Thermal Emission and Reflection Radiometer
TMDL	total maximum daily load
USGS	U.S. Geological Survey

Fluvial Sediment Fingerprinting—Literature Review and Annotated Bibliography

By Joyce E. Williamson, Adel E. Haj, Jr., John F. Stamm, Joshua F. Valder, and Vicki L. Prautzch

Abstract

The U.S. Geological Survey has evaluated and adopted various field methods for collecting real-time sediment and nutrient data. These methods have proven to be valuable representations of sediment and nutrient concentrations and loads but are not able to accurately identify specific source areas. Recently, more advanced data collection and analysis techniques have been evaluated that show promise in identifying specific source areas. Application of field methods could include studies of sources of fluvial sediment, otherwise referred to as sediment "fingerprinting." The identification of sediment is important, in part, because knowing the primary sediment source areas in watersheds ensures that best management practices are incorporated in areas that maximize reductions in sediment loadings. This report provides a literature review and annotated bibliography of existing methodologies applied in the field of fluvial sediment fingerprinting. This literature review provides a bibliography of publications where sediment fingerprinting methods have been used; however, this report is not assumed to provide an exhaustive listing. Selected publications were categorized by methodology with some additional summary information. The information contained in the summary may help researchers select methods better suited to their particular study or study area, and identify methods in need of more testing and application.

Introduction

Fluvial sediment (hereafter referred to as sediment) occurs naturally but is also one of the most common pollutants in rivers, streams, lakes, and reservoirs (U.S. Environmental Protection Agency, 1996). In general, sediment is the loose sand, clay, silt, and other soil that eventually settles to the bottom of a waterbody. Sediment entering a waterbody, particularly in excessive amounts, can degrade the quality of water for drinking and wildlife, increase the potential for flooding, harm the habitat for aquatic species, clog fish gills, increase the growth of harmful algae, and affect the navigational and recreational use (U.S. Environmental Protection Agency, 2012). The maximum amount of sediment (or another pollutant) that a waterbody can receive and still meet water-quality standards is the total maximum daily load (TMDL) (U.S. Environmental Protection Agency, 2012); however, this measure provides no information on the source(s) of sediment. Several different methods have been used to identify the source of sediment, referred to as sediment "fingerprinting." The identification of sediment is important, in part, because knowing the primary sediment source areas in watersheds ensures that best management practices are incorporated in areas that maximize reductions in sediment loadings. Methods used to determine the source of sediment can vary and are selected to help answer a particular question regarding a sediment concern such as best management practices to reduce sediment, habitat restoration, or studies of TMDLs. Sediment fingerprinting methods can be used to evaluate large-scale issues, such as the contributions of surface and subsurface sources of suspended sediment in a basin. In other situations, sediment fingerprinting methods can be used to identify local sources of sediment having a unique geochemical signature, such as uranium. Sediment fingerprinting methods commonly are used in combination with other quantitative methods such as statistically based models to quantify the likelihood of identified source areas. Other qualitative studies may include the use of aerial and satellite images to identify erosional landforms where areas of source sediments (such as gullied and rilled surfaces or eroding channel banks) are likely to occur.

The U.S. Geological Survey (USGS) has evaluated and adopted various field methods for collecting real-time sediment and nutrient data. These methods have proven to be valuable representations of sediment and nutrient concentrations and loads but are not able to accurately identify specific source areas. Recently, more advanced data collection and analysis techniques have been evaluated that show promise in identifying specific source areas. Application of field methods could include studies of sources of sediment. To aid researchers that may be unfamiliar with these methods and to provide a reference for studies that apply these methods, the USGS completed a literature review of sediment fingerprinting methods. The information provided by the literature review may help researchers select methods better suited to their particular study or study area, and identify methods in need of more testing and evaluation. The intent of this report is not to provide an exhaustive listing of publications, rather, it is hoped that readers will be able to use this literature review and bibliography as a valuable reference on this topic.

Purpose and Scope

The purpose of this report is to summarize selected methods for fluvial sediment fingerprinting by providing a literature review and annotated bibliography. The scope of this report includes the various methods for sediment fingerprinting organized into broad categories of methods. This literature review is designed to provide a bibliography for many of the publications where sediment fingerprinting methods have been used; however, it is not the intent of this report to provide an exhaustive listing but to offer the publications most relevant to studying fluvial sediment fingerprinting methods. For each category of methods, a detailed description and selected references are provided. In addition, the annotated bibliography provided in the appendix presents a broader listing of studies where various sediment fingerprinting methods have been applied. It is beyond the scope of this report to provide any interpretation as to the success or failure of the different fingerprinting methods, and it is left up to the reader to interpret the results of each of the techniques.

Sources of Bibliographic Information

Bibliographic information was obtained by completing a literature review and then vetting the list with other USGS scientists that have applied or had first-hand familiarity with these methods. This listing serves as a summary of methods available to date (2014). Not all references obtained were included in the literature review because several were duplicative and referred to previous publications in their respective descriptions of methods.

Overview of Fluvial Sediment Fingerprinting Methods

Several different methods have been used in investigations to determine the sources of fluvial sediments. Fluvial sediments are sediments in suspension that are transported by the turbulent flow of water. Fingerprinting methods seek to identify unique physical and chemical properties of fluvial sediments that can be matched with the properties of source material(s), namely surface sediments or subsurface sediments in the study area. Geochemical and physical fingerprints might include the following:

- Physical properties of sediment, such as size, color, and texture;
- Mineralogical and geochemical properties, such as the presence of unique clay mineralogies;
- Presence of rare earth elements;
- Presence of fallout and cosmogenic radionuclides;
- Stable isotope signatures, particularly of carbon and nitrogen isotopes;
- Mixing models, such as multivariate statistical models; and
- Other qualitative methods, such as erosion field studies and geomorphic analysis of aerial or satellite imagery.

Sediment fingerprinting studies commonly apply several methods in concert. Geochemical and physical characteristics can be quantitatively analyzed through models. These methods can use physical characteristics that might on their own not be considered a fingerprint, but unique groupings of characteristics may have the capability to provide a unique fingerprint.

Literature Review of Fluvial Sediment Fingerprinting

For each category, or method, of sediment fingerprinting presented in this report, a general description of the method, a summary of selected example studies, and references are provided. The references within a given category also may be included in other categories as they may present multiple methods of sediment fingerprinting.

Physical Properties of Fluvial Sediment

Physical properties of fluvial sediment typically used for sediment fingerprinting studies include coloring, grain size distribution, and organic content. These physical properties may be used in conjunction with other fingerprinting methods and with mixing models. Collins and others (1998a) used the physical property of silt grain-size fraction, in addition to trace metals, heavy metals, base cations, organic constituents found in the clay, and a multivariate mixing model to differentiate surface and subsurface sources.

Grimshaw and Lewin (1980) used physical properties of sediment color, size, and details of the relation between sediment and stream discharge to differentiate channel and nonchannel sediment sources. Horowitz (1991) provided an overview of several physical properties of sediment useful in sediment fingerprinting studies. Wallbrink and others (1998) determined sediment contributions from different land-use types using the sediment fraction less than 2 millimeters and applying a simple mixing model. Additional studies that used physical properties in conjunction with other fingerprinting methods for various applications include Collins and others (1997a, 1997b).

Mineralogical and Geochemical Properties

Fluvial sediment can inherit many of the mineralogical and geochemical properties of sediment sources. Commonly, fluvial and source sediments are analyzed using x-ray crystallography and x-ray diffraction to determine their mineralogical or geochemical fingerprint. Klages and Hsieh (1975) used x-ray crystallography with a focus on x-ray peaks dominated by quartz, silts, and smectite to establish a mineralogical fingerprint to infer the source of suspended solids to a river. Wall and Wilding (1976) determined that the presence of mica and carbonate were diagnostic for surficial sediment sources.

When applicable, unique mineralogical properties of sediment and tracer materials can be used, such as magnetism, to fingerprint, source, and monitor transport rates. Bunte (2010) used magnetic properties of a tracer in coarse bedload material to monitor movement of bed material. Bunte (2010) documented two sediment pulses that were associated with the daily peak streamflow and the daily falling limb of the stream hydrograph. Ergenzinger and Conrady (1982) presented a pioneering use of magnetic properties of cobbles to track movement. Using a detector on an aluminum frame installed above water surface, magnets were embedded in cobbles upstream and the transport rate was monitored as they passed the sensor. Motha and others (2003) combined the use of geochemical tracers and ratios for silicon dioxide, iron oxide, aluminum oxide, and radiometric tracers cesium-137 and lead-210, with a simple mixing model and found that unsealed roads were an important sediment source. Additional references for application of mineralogical and geochemical properties include Horowitz (1991), Oldfield and others (1979, 1985), Walden and others (1997), and Walling and others (1979).

Rare Earth Elements

Rare earth elements are given the name “rare” in that they are commonly disseminated, rather than concentrated in ore deposits (Haxel and others, 2002). Rare earth elements had previously been referred to as “earths,” which is an obsolete term for oxides that could not be smelted to extract metal. There are 17 rare earth elements, most notably lanthanum, praseodymium, samarium, galolinium, and cerium. Many are part of the lanthanides, which are elements with filled outer shells (5s, 5p) and incompletely filled inner shells (4f) (Peters and Raber, 2003). As such, the lanthanides do not fit into the normal sequence of elements in the periodic table and are listed separately.

Rare earth elements have been successfully used as tracers in sediment fingerprinting studies. Little research exists in this category but initial studies indicate that this technique can be used for a variety of soil types.

Kimoto and others (2006) tested the use of rare earth elements throughout a multi-year period in a small agricultural watershed and determined that although this method can be used to track sediment sources, some error was introduced by the depletion of elements and contamination from downslope areas. Polyakov and others (2010) applied this method to course-grained semiarid soils and determined that rare earth elements worked well as a tracer, although some limitations were discovered from underestimation of some boundary conditions, such as areas with stream incision.

Fallout and Cosmogenic Radionuclides

Fluvial sediment sources can be determined by the presence/absence of fallout or cosmogenic radionuclides. Fallout radionuclides cesium-137 and lead-210 were introduced into the environment from nuclear testing that began in the early 1950s and from nuclear accidents such as Chernobyl and Fukushima (U.S. Environmental Protection Agency, 2011). The cesium-137 and lead-210 tend to be concentrated in surficial deposits, and therefore can be used to characterize the importance of overland flow as a source of sediment in comparison to other processes that erode subsurface material (Zapata, 2003).

The presence or absence of fallout and cosmogenic radionuclides in a sediment sample indicates the approximate age (young or old) of the sediment, and can be used to distinguish whether the fluvial sediment originated from younger surficial material or older channel bank material. Laboratory analyses of fallout and cosmogenic radionuclides in samples from fluvial sediments, probable sediment sources, and streambed and streambank material can be analyzed with a mixing model to determine the likely contributions from sources necessary to generate the concentrations found in the fluvial sample.

Collins and others (1997c) presented laboratory analyses of source material and suspended sediment samples using many methods of fingerprinting including analysis of cesium-137 and lead-210. Collins and others (1997b) and Collins and Walling (2002) established supported guidelines for reliable composite fingerprinting. Mukundan and others (2009) and Mukundan and others (2010) found cesium-137 and nitrogen-15 (nitrogen isotope associated with fertilizer use) to be the best indicators of a surficial sediment source; results in these studies were interpreted using a mixing model. Harden and others (2011) used cesium-137 to identify historical flood sediment in caves and rock alcoves. Owens and others (2012) investigated potential changes in sediment sources caused by the effects of wildfire in a basin. For this study, Owens and others (2012) analyzed cesium-137 and lead-210 and interpreted results using an unmixing model to calculate relative source contributions to fluvial sediment samples. Results indicated that a stream whose watershed was subjected to wildfire had an increase in sediment from surface soil erosion from
0 to 8.5 percent plus or minus 2.5 percent as determined by the unmixing model.

Gellis and others (2009) used analyses of beryllium-10 and cesium-137 in conjunction with Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) satellite imagery (2000–05), 1:24,000-scale orthophotographs, and radiometric analyses of stable isotopes of carbon-13 and nitrogen-15 to determine if agricultural fields were the source of the silt- and clay-sized fluvial sediment. Results were interpreted using Kruskal-Wallis H-test (medians) and Tukey test (rank test) (Helsel and Hirsch, 2002). Additional references that describe the use of isotopes for sediment fingerprinting include He and Owens (1995), Mukundan and others (2010), Nagle and Ritchie (2004), Olley and others (1993), Peart and Walling (1988), Wallbrink and Murray (1993, 1996), Walling (2003, 2005), Walling and Woodward (1992, 1995), Wan and others (1987), and Zapata (2003).

Stable Isotopes of Carbon and Nitrogen

Stable isotopes of carbon and nitrogen can be used in sediment fingerprinting studies to differentiate surficial sediment sources based on land use, vegetation type, or anthropogenic activity. For example, analysis of stable carbon and nitrogen isotopes of the organic matter in a sediment sample can indicate if the sediment originated from either a forested or cropped land surface.

Fox (2009) used analysis of stable carbon and nitrogen isotopes to identify forested watersheds disturbed by surface coal mining as the sources of stream sediments. In situ suspended sediment traps were placed at the outlet of each watershed and were used to sample fine-grained sediments during storm events. Samples were analyzed to measure stable carbon and nitrogen isotope values, total organic content, and total nitrogen of sediment particulate organic matter. Sediment transport sources in disturbed and undisturbed watersheds were analyzed using a Monte Carlo mass balance unmixing approach. Statistically significant differences were found in all measured values. Results indicated that surface and subsurface sources could be differentiated using nitrogen isotope values and soil organic matter and that geogenic organic matter sources could be differentiated using carbon isotope values.

Methods used by Gellis and others (2009) included the use of stable isotopes for carbon and nitrogen, ASTER satellite imagery (2000–05), 1:24,000-scale orthophotographs, and radiometric analyses of beryllium-10 and cesium-137. Additional references for these methods include Fox and Papanicolaou (2007) and Mukundan and others (2010).

Mixing Models

A mixing model uses the principle components (including, mineralogical constituents, geochemical constituents, and color) of the sediment fingerprints for source areas in a basin to determine concentrations of the principle components in the fluvial sediments at downstream locations. Mixing models commonly are used in combination with other sediment fingerprinting and sediment sourcing techniques.

Collins and others (1997b) used a variety of potential fingerprint properties in combination with a mixing model. The model first applied the Mann-Whitney U-test (Helsel and Hirsch, 2002) to each individual parameter to verify its ability to discriminate between source categories. Next, a multivariate discriminant function analysis, with the minimization of Wilks' lambda, was used as a stepwise selection algorithm to identify the set of parameters (Ni, Co, K, total P, and N) that were capable of distinguishing source samples in each catchment. The goodness-of-fit was tested by comparing fingerprint properties measured in suspended sediments with property values predicted by the model.

Additional references for mixing models include Burns and others (2001), Christophersen and Hooper (1992), Collins and others (1996, 1997c, and 1998b), Collins and Walling (2002), He and Owens (1995), Owens and others (1999), Slattery and others (1995), Walling and Woodward (1995), Walling and others (1993, 1999), and Yu and Oldfield (1989).

Other Qualitative Methods

Other qualitative methods also have been used in sediment fingerprinting studies including erosion field studies and geomorphic analysis of aerial or satellite imagery. Gellis and Walling (2011) present a fine-grained sediment composite fingerprint by comparing physical and geochemical properties of fluvial sediments with potential sediment sources. This method was most effective when used for drainage basins greater than 300 square kilometers. Gellis and Walling (2011) used an unmixing model and sediment budget model that quantifies the importance of sources and sinks. Examples of sediment fingerprinting methods for Chesapeake Bay, New Mexico, southern England, and southern Zambia are included in Gellis and Walling (2011).

Kalin and others (2004) used a physically based, watershed-scale, surface-flow and erosion model that estimated sediment loads through prediction algorithms. This study included the identification of sediment generating regions within a watershed using geomorphologic information, rainfall data, and flow and sediment data. Statistical methods used by Kalin and others (2004) to interpret results included testing the equality of means with a Tukey's procedure, and an analysis of variance (ANOVA) test to ensure that the sample means are not all equal for a given confidence level. Additional references that describe other qualitative methods for sediment fingerprinting include Band (1983, 1985), Eriksson and others (2003), Haigh (1977), Morgan (1980), and Peart and Walling (1988).

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Appendix 1. Annotated Bibliography of Selected Reports and Articles on Fluvial Sediment Fingerprinting Research

An annotated bibliography for studies described in this report and additional studies associated with the sediment fingerprinting methods was compiled as a digital Microsoft® Excel spreadsheet (available at: *http://pubs.usgs.gov/of/2014/1216/Sediment_fingerprinting_references.xlsx*). The references included in the annotated bibliography were categorized by the primary fingerprinting method used in the associated research. The spreadsheet includes the reference, key words, and the type of method or methods used in the associated research.

Publishing support provided by:
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ISSN: 2331-1258 (online)
http://dx.doi.org/10.3133/ofr20141216