Journal of Environmental Management 194 (2017) 4–15

Contents lists available at ScienceDirect

Journal of Environmental Management

journal homepage: www.elsevier.com/locate/jenvman

Research article

Fingerprinting surficial sediment sources: Exploring some potential problems associated with the spatial variability of source material properties

Pengfei Du [a], Des E. Walling [b, *]

[a] International Research and Training Center on Erosion and Sedimentation (IRTCES), China Institute of Water Resources and Hydropower Research (IWHR), No. 20 Chegongzhuang Road West, Beijing, 100048, China
[b] Geography, College of Life and Environmental Sciences, University of Exeter, Exeter, EX4 4RJ, UK

A R T I C L E I N F O

Article history:
Received 29 February 2016
Received in revised form
25 May 2016
Accepted 26 May 2016
Available online 20 July 2016

Keywords:
Sediment source tracing
Fingerprinting
Spatial variability
Fingerprint properties
Property correlation
Soil redistribution rate

A B S T R A C T

Recent advances in sediment source tracing or fingerprinting procedures have focussed primarily on the use of novel sediment properties that are either easier to measure or provide improved source discrimination, or on improved procedures for representing and estimating the uncertainty associated with the final source apportionment results. Spatial variability of source properties has long been recognised as a potential problem for the approach, but there have been few attempts to explore the nature and magnitude of such variability and its wider implications for source fingerprinting investigations. This contribution addresses this issue with particular reference to surficial sediment sources. It reports the results of an investigation aimed at documenting the magnitude and nature of the spatial variability of the geochemical properties of surface soils within a single 7 ha cultivated field and exploring the implications of the findings for sediment source fingerprinting procedures. Samples of surface soil were collected from 52 points located within the field. Particular attention is directed to the extent of the spatial variability of 53 geochemical properties of the surface soil which could potentially be used as fingerprints, the importance of the influence of soil redistribution rate on the properties of the surface soil, provision of guidelines for selecting sampling points and the degree of correlation between different soil properties and its implications for the numerical procedures employed in sediment source fingerprinting studies. A novel aspect of the study is that caesium-137 (^{137}Cs) measurements were used to provide information on the magnitude and spatial pattern of the soil redistribution rate within the field, so that the influence of soil redistribution rate in causing systematic spatial variability of fingerprint properties could be further explored.

1. Introduction

Sediment source tracing techniques for fine fluvial sediment were first employed in the 1970s and over the ensuing 40 years they have been progressively developed and refined to take account of many potential problems (Walling, 2013). As a result of these developments and refinements, source tracing procedures have become progressively more complex, particularly in relation to the various approaches used to take account of and quantify the uncertainty associated with the final source ascription results. Perusal of the recent literature also indicates that there has been little standardisation of the approaches used and Smith et al. (2015) contend that a number of important challenges still remain to be addressed. As a result, it could be argued that source tracing techniques are still evolving and are essentially an evolving research tool, with further refinement and standardisation being required, if they are to become an accepted and reliable operational tool.

One problem that arguably merits greater attention in further developing sediment source fingerprinting procedures centres on the spatial variability of source material properties and the need to take this into account when characterizing the properties of individual potential sources. In early studies, this problem was addressed by assuming that the fingerprint properties of a given source could be represented by mean values for those properties

* Corresponding author.
E-mail addresses: dupf@iwhr.com (P. Du), d.e.walling@exeter.ac.uk (D.E. Walling).

http://dx.doi.org/10.1016/j.jenvman.2016.05.066
0301-4797/

and that collection of a sizeable number of samples using a spatially random sampling framework would provide a reliable estimate of the required mean values (Peart and Walling, 1986; Collins et al., 1998, 2001). This assumption had a clear physical basis, in that the suspended sediment sampled at the outlet of a catchment could be viewed as representing a mixture of sediment mobilised from a multitude of locations within the catchment. The coefficient of variation or a similar statistic provided an indication of the inherent variability of the individual properties of a given source. In some studies the median has been used as an alternative to the mean (e.g. Collins et al., 2010a; Smith and Blake, 2014). In order to increase the representativeness of the samples collected from individual locations, these were frequently composite samples comprising surficial material collected from numerous locations around the sampling point (e.g. Russell et al., 2001; Walling et al., 2008; Wilkinson et al., 2013), or from along a transect (e.g. Gellis and Noe, 2013). Sampling strategies have also frequently departed from a true spatially random sampling design by requiring that samples should be collected from active sediment sources, designated sources 'likely to erode' by Davis and Fox (2009), and source areas that are well connected to the stream network. This was seen as ensuring that the source material samples were representative of material that was likely to be mobilised by erosion and delivered to the stream channel and therefore directly comparable with the target samples. Such guidelines, whilst entirely logical, clearly introduce both additional considerations into the design of a sampling framework and a degree of subjectivity in locating sampling points. Other workers such as Koiter et al. (2013) explicitly rejected random sampling and used representative transects to target their sampling of surface sources.

Uncertainty in source apportionment results associated with spatial variability of source material properties and the need to use single values (e.g. the mean or median) to represent the properties of a given source in the mixing model employed for source apportionment has been addressed in a number of ways in recent studies. Researchers, including Collins et al. (2010a,b, 2012) and Wilkinson et al. (2013), have introduced weighting factors into the mixing model to take account of the degree of variability of the individual fingerprint properties that characterize a given source. Increased variability was seen as reducing the likely reliability of the mixing model output and the weighting was therefore inversely proportional to the variance of the source properties. Such a weighting factor will also reflect any variability introduced by the precision of the analytical methods used to measure the source properties, but it will commonly primarily reflect spatial variability in the property values. Gellis and Landwehr (2006) and Devereux et al. (2010) used a similar approach to derive an error term associated with the source ascription results.

Alternatives to the use of single (mean or median) property values to characterize the source fingerprint in the mixing model, aimed at taking account of the variability (primarily spatial) of source material properties, have also involved use of Monte Carlo techniques to provide multiple estimates of the mean or median property values, drawn from the statistical distributions of the raw data used to derive those values (e.g. Rowan et al., 2000; Motha et al., 2003; Krause et al., 2003; Collins and Walling, 2007; Collins et al., 2010a,b, 2012; Wilkinson et al., 2013). The frequency distributions of source apportionment results generated by the multiple iterations of the mixing model provide an effective means of defining the confidence limits of the final estimates of source contributions. A further development of this approach has recently been described by Laceby and Olley (2015). This incorporates the probability distributions of the fingerprint properties associated with the sampled source and target samples and of the proportional source contributions directly into the mixing model.

Although most work aimed at taking account of the spatial variability of source material properties has focussed on what can be seen as essentially random variation, a recent study reported by Wilkinson et al. (2015) has emphasised the need to also recognise the potential for systematic variation of fingerprint properties across a study area. In this context, they highlighted potential problems with the use of the fallout radionuclides ^{137}Cs and $^{210}Pb_{ex}$ as source fingerprints. The inventories and therefore the activities of both radionuclides found in surface source materials are likely to be influenced by spatial variation of annual precipitation across the catchment considered, since longer term fallout fluxes are commonly closely related to mean annual rainfall (e.g. Basher, 2000; Chappell et al., 2011; Schuller et al., 2004). Perhaps more importantly, Wilkinson et al. (2015) also emphasised the need to recognise that the ^{137}Cs and $^{210}Pb_{ex}$ activities of surface source material will be sensitive to the magnitude of the soil redistribution rate and more specifically the erosion rate. This relationship is fundamental to the use of these fallout radionuclides to estimate soil redistribution rates (Zapata, 2002; Walling et al., 2011). Most of the sediment mobilised from a surface source will originate from areas with higher erosion rates and this should be taken into account when assembling information on source material properties. As the erosion rate increases, the ^{137}Cs and $^{210}Pb_{ex}$ activity of the surface soil can be expected to reduce. The reduction in activity produced by a given erosion rate is likely to be much greater for an uncultivated soil than for a cultivated soil. This is because the former will be characterized by an exponential decline in activity with depth and most of the activity will be found within the upper ca. 15–20 cm of the soil. In contrast, the ^{137}Cs and $^{210}Pb_{ex}$ activity within a cultivated soil will be mixed fairly uniformly within the plough layer. Wilkinson et al. (2015) addressed this problem in their study of the 129 000 km^2 Burdekin catchment in Queensland, Australia by using the RUSLE soil loss model (Renard et al., 1997) to define three zones with different intensities of erosion and collecting representative surface source material samples from each of those zones. Each zone was characterized by probability distributions of ^{137}Cs and $^{210}Pb_{ex}$ activities, and these were combined to provide a single probability distribution for the surface source within the catchment or a given subcatchment, by weighting their contribution to the single distribution to reflect both the relative areas of the three zones and the relative magnitude of the erosion rates associated with the three zones. No explicit attention was given to the potential influence of erosion rate on the values of radionuclide activity associated with the source material samples collected within the zones.

Wilkinson et al. (2015) addressed the need to consider the relationship between erosion rate and fingerprint property values because they were using ^{137}Cs and $^{210}Pb_{ex}$ as fingerprint properties and the close relationship between the activities of these two fallout radionuclides and erosion rate is well recognised. The need to consider whether other fingerprint properties used to characterize surface sources might be influenced by the erosion rate as demonstrated by Du and Walling (2011) has to date received little attention. Equally, little information is available on other potential causes of systematic variation in source material properties that should be recognised when characterizing the properties of a surface source, particularly in larger catchments.

Notwithstanding existing recognition of the need to take account of the spatial variability of the properties of a given sediment source, there is arguably a need to direct further attention to the potential problems involved. This need is usefully demonstrated by several recent source tracing investigations undertaken in large river basins where the numbers of samples used to define the source material fingerprints were limited and it is not clear if the problems introduced by spatial variability of source material