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Sediment sources in a small agricultural catchment: A composite fingerprinting approach based on the selection of potential sources

Huiping Zhou [a,*], Weina Chang [b], Longjiang Zhang [a]

[a] Nanjing Institute of Environmental Sciences, Ministry of Environmental Protection of People's Republic of China, 8 Jiangwangmiao Str., Nanjing 210042, China
[b] School of Geographic and Oceanographic Sciences, Nanjing University, 163 Xianlin Ave., Nanjing 210023, China

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ABSTRACT

Fingerprinting techniques have been widely used as a reasonable and reliable means for investigating sediment sources, especially in relatively large catchments in which there are significant differences in surface materials. However, the discrimination power of fingerprint properties for small catchments, in which the surface materials are relatively homogeneous and human interference is marked, may be affected by fragmentary or confused source information. Using fingerprinting techniques can be difficult, and there is still a need for further studies to verify the effectiveness of such techniques in these small catchments. A composite fingerprinting approach was used in this study to investigate the main sources of sediment output, as well as their relative contributions, from a small catchment (30 km^2) with high levels of farming and mining activities. The impact of the selection of different potential sediment sources on the derivation of composite fingerprints and its discrimination power were also investigated by comparing the results from different combinations of potential source types. The initial source types and several samples that could cause confusion were adjusted. These adjustments improved the discrimination power of the composite fingerprints. The results showed that the composite fingerprinting approach used in this study had a discriminatory efficiency of 89.2% for different sediment sources and that the model had a mean goodness of fit of 0.90. Cultivated lands were the main sediment source. The sediment contribution of the studied cultivated lands ranged from 39.9% to 87.8%, with a mean of 76.6%, for multiple deposited sediment samples. The mean contribution of woodlands was 21.7%. Overall, the sediment contribution from mining and road areas was relatively low. The selection of potential sources is an important factor in the application of fingerprinting techniques and warrants more attention in future studies, as is the case with other uncertainty factors.

1. Introduction

The dynamic change of river sediment transport can influence hydrologic regime in catchment. Increased suspended sediment concentrations can accelerate sedimentation and alter channel morphology. Sediment is also an important vector for the transport and transformation of nutrients, heavy metals and other organic or inorganic pollutants in a water body and thus has a substantial effect on the water quality and aquatic ecological environment in the lower reaches (Owens and Walling, 2002; Bilotta and Brazier, 2008; Bird et al., 2010; Song et al., 2011). Because non-point-source pollution in catchments has attracted worldwide attention in recent decades, sediment and sediment-associated pollutants, as well as their resulting human health risks, have also become foci of research on the control of water pollution in catchments (Yi et al., 2011; Doody et al., 2012; Falbo et al., 2013;).

Implementation of appropriate and specific management solutions to soil erosion and water pollution control require the information of the major sediment sources. Studies of sediment sources facilitate a better understanding of soil erosion and the characteristics of sediment transport and deposition in the catchment. Fingerprinting techniques, characterized as a “direct” approach, have been shown to represent a valuable and effective alternative for apportioning sediment sources. Sediment fingerprinting can be used to establish the relative importance of multiple sediment sources and has been widely used in recent sediment source apportionment studies (Collins et al., 1998, 2010a, 2012; Walling, 2005; D'Haen et al., 2013; Smith and Blake, 2014). The premise of the fingerprinting approach is that soils from different sources can be distinguished based on their material composition. Two basic steps are involved in the application of the fingerprinting approach. The first step involves the collection of soil samples from various potential sediment sources and the selection of fingerprint properties that can discriminate among different sources based on the comparison of the geochemical or geophysical properties of the soil samples. The second step involves comparisons of the correlations and differences between the fingerprint properties of the sediment samples and the soil samples from the potential sources; additionally, this step includes quantitative analyses of the relative contribution of each potential source to the sediment output.

* Corresponding author.
E-mail address: zhp@nies.org (H. Zhou).

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Earlier works of sediment fingerprinting employed a single fingerprint property. However, the discrimination power of a single fingerprint becomes inadequate when the spatial variability of the potential sediment sources and the sediment mobilization process are relatively complex (Collins et al., 1998). In contrast, a composite fingerprinting technique combines multiple fingerprint properties that can effectively discriminate among different sediment sources to form an optimum composite fingerprint. Such a composite technique serves as an integrated discrimination tool and is based on the statistical examination of large soil-properties datasets. Previous studies have shown that composite fingerprints markedly improve sediment source discrimination (Collins et al., 1998; Walling et al., 1999). A study of five catchments in the UK and Africa has shown that a composite fingerprint that consists of several properties from a specific property type can improve the results over those achieved by with a single fingerprint. However, the level of discrimination attained by such a composite fingerprint varied between different catchments (Collins and Walling, 2002). That study also demonstrated that an optimum composite fingerprint, comprising constituents selected from different groups of fingerprint properties, could consistently provide a robust means of discriminating sediment sources. The key aspect of the fingerprinting approach is to compare the contents of the fingerprint properties of the sediment and of the source soils. Many studies have investigated the factors that affect such comparisons. For example, several studies have considered the effects of particle size and organic matter content on the fingerprint properties of sediment and the source soils, and have incorporated correction factors into the mixing models (Collins et al., 1998; Russell et al., 2001). Collins et al. (2010a) also simultaneously considered the within-source variability of the fingerprint properties and the weighting of the discrimination power of each property in the composite fingerprint. However, some researchers (Walling et al., 1999; Russell et al., 2001; Smith and Blake, 2014) believe that (1) particle size and organic matter affect the content of each fingerprint property to different extents, (2) unified corrections to all of the properties may generate new errors, and (3) simultaneous corrections to the particle size and organic matter contents of the fingerprint properties may result in “over-correction”. With the continuous increase in applications of the fingerprinting approach, the optimization of the mixing models, the uncertainties of the sediment mobilization process and the analysis of the limitations of the fingerprinting approach have become foci of recent studies (Rowan et al., 2000; Koiter et al., 2013; Nosrati et al., 2014).

Previous studies have generally focused on relatively large catchments because (1) the spatial heterogeneities of geological units, soils and land use types are relatively high at a large scale, (2) different sources may have significantly different sediment properties, and (3) the application of fingerprinting technique can produce relatively good results (Collins and Walling, 2002; Cater et al., 2003; Collins et al., 2010a). In contrast, the surface materials in a small catchment tend to be relatively homogeneous. A successful application of a fingerprinting technique then requires greater numbers of discriminable fingerprint properties. However, properties meeting these requirements are rather difficult to identify and acquire. Moreover, relatively few studies have focused on small catchments. For example, Russell et al. (2001) attempted to discriminate the suspended sediment sources in two small catchments (areas of 1.5 and 3.6 km^2) in the UK. Smith et al. (2011) investigated a forested upland catchment in Australia with an area of only 1.36 km^2. Most studies classify potential sediment sources based on the land use or special terrains or landscapes, which primarily include cultivated land, pastureland (grassland), woodland and collapsed river banks. Several studies have focused on urban areas (Cater et al., 2003; Franz et al., 2014) and damaged roads (Collins et al., 2010b). Lin et al. (2012) conducted a sediment source apportionment study in the collapsing gully erosion region in Fujian, China and quantified the relative contributions of different soil layers of the collapsing gully section to the sediment output.

Two assumptions of the fingerprinting approach are that (1) the potential sediment sources are known and the components of the sediment only originate from these sources, and (2) the contribution from each source is greater than zero and the sum of the proportions of the contributions is unity. However, when using the fingerprinting approach, the determination of potential sources is subjective, and it is uncertain whether the selected potential sources are all actual contributors to final sediment output. In particular, complex and interlaced sediment source types or improper sampling times and locations can lead to confusing source information, which may affect the selection of fingerprint properties and reduce the power of source discrimination (Martìnez-Carreras et al., 2010; D'Haen et al., 2013). Therefore, it is necessary to further analyze the reasonableness of the selection and classification of potential sediment sources.

Representative sediment source fingerprinting studies that have been carried out in China have mainly concentrated on the region in the upper reaches of the Yangtze River, the Three Gorges Reservoir region, the Loess Plateau, and the collapsing gully region in Fujian. Because these regions have relatively large sediment discharges and complex or varied geological conditions, the use of single-fingerprint (Wen et al., 2000; Wang, 2002; Jia and Wei, 2009) or composite-fingerprint methods (Yang and Xu, 2010; Lin et al., 2012; Guo et al., 2014) in studying sediment sources has several advantages. However, these studies have not thoroughly investigated improvements of the fingerprinting approach or discussed the uncertainty issues. No similar studies have investigated the apportionment of sediment sources in small catchments in eastern China, which have relatively small sediment discharges and are disproportionately influenced by human activity. Therefore, it is necessary to further verify the feasibility of sediment source fingerprinting in such small catchments for clarity or strengthen the related issues. In addition, sediment source apportionment is conducive to studies of the control of non-point source pollution in this region. This study focused on a small catchment in the upper reaches of the Jiuxiang River in Nanjing, Jiangsu Province, eastern China. The main objectives of this study are (1) to explore the feasibility of the use of a composite fingerprinting technique to discriminate sediment sources in small agricultural catchments that are significantly affected by human factors, and (2) to discuss the selection of potential sediment sources and its impact on source discrimination.

2. Study area

Located in the eastern suburbs of Nanjing (118°52′–119°1′E, 32°1′–32°10′N), the catchment of the Jiuxiang River is approximately 18 km long from south to north and 5.7 km wide from east to west, and has a total area of 106.2 km^2 (Fig. 1). The topography of the catchment is characterized by mounds and hills in the south and plains along the river in the north, where the maximum elevation is about 340 m and the elevations of plains are generally 10–25 m. A sub-catchment with an area of 30 km^2, which is located in the upper reaches of the Jiuxiang River, was selected as the study area (Fig. 1 and Fig. 2). The land use types in the study area include cultivated land, woodland, land that is used for mining, roads and rural residential areas (Fig. 3). It is likely that human effects, such as the development of mineral resources in Qinglong Mountain in the upper reaches and the agricultural activities in the middle and lower reaches, play a role in sediment production in this area. In particular, long-term agricultural production has caused significant disturbances to the surface, and the non-point source pollution originating from this sub-catchment has also generated risks to the aquatic environment in the lower reaches (Hu et al., 2012). A main road that traverses the study area was the target of a road extension project in 2010. Since then, subgrade construction, with a substantial transport of large amounts of soil and rocks along the road, has resulted in significant sediment loss.