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A mixing model to incorporate uncertainty in sediment fingerprinting

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ABSTRACT

Information on sediment sources is required for effective sediment control strategies, to understand nutrient and pollutant transport, and for developing soil erosion models. Uncertainty associated with sediment fingerprinting mixing models is often substantial, but this uncertainty has not yet been fully incorporated in these models. The main objectives of this study are to apply geochemical fingerprints to determine relative contributions of sediment sources and to develop a Bayesian-mixing model that estimates probability distributions of source contributions to a mixture associated with multiple sources for assessing the uncertainty estimation in sediment fingerprinting in the Hiv catchment, Iran. In this analysis, 28 tracers were measured in 42 different sampling sites from three sediment sources (rangeland, orchard and stream bank) and 12 sediment samples from reservoir check dams. Discriminant analysis provided an important data reduction as it identified four tracers, i.e. B, C, Sr and Tl, that afforded more than 97% correct assignations in discriminating between the sediment sources in the study area. Using a stable isotope mixing model, the median contribution from rangeland, orchard and stream bank sources was 20.8%, 11.2% and 68%, respectively. Sediment source fingerprinting was used to explore the uncertainty in the contributions of sediment from the three sources. Uncertainty is considerable, as the range of probable values was wide: 2–24% for rangeland, 1–26% for orchards and 66–83% for stream banks respectively. While these results can be useful as a scientific basis of sediment management and selecting the soil erosion control methods for decision makers of natural resources they also show that it may not always be possible to identify sediment sources with great precision. Consequently, uncertainty needs to be accounted for when evaluating different management options.

1. Introduction

Accelerated soil erosion is a natural hazard which threatens the environment in many different ways, including soil and water degradation, environmental pollution, and sedimentation in dam reservoirs. For example, around 120 million hectares of land in Iran are affected by soil erosion with an estimated average annual soil loss rate of approximately 22.5 tons ha^{-1} $year^{-1}$ (Ahmadi, 1999). Arabkhedri et al. (2005) showed that sediment yield in drainage basins of Iran varied between 0.04 and 23.91 tons ha^{-1} $year^{-1}$. Jalalian et al. (1994) estimated mean annual soil loss rates and sediment yields for all of Iran to be approximately 25 and 7.5 tons ha^{-1} $year^{-1}$ respectively. Studies of dam reservoirs show that a significant amount of stream sediment accumulates in Iranian dam reservoirs: the accumulation rate is about 235 million cubic meters per year, and causes a loss of dam reservoir capacity of 1–2% per year (WRM, 2012). The magnitude of this problem is such that control measures are critical. However, to allocate resources to the most needed areas, it is necessary to identify sediment sources at a catchment scale.

The use of sediment fingerprinting is not limited to the identification of catchment areas that may need remedial measures: fingerprinting may also be of great help to increase our fundamental understanding of the processes and mechanisms that control sediment production and transport in various environments and at various temporal and spatial scales. Source fingerprinting techniques are being increasingly used in many different areas of the world (Collins and Walling, 2007; Minella et al., 2008; Nosrati et al., 2011; Walling and Collins, 2008). Fingerprinting techniques have been applied over a range of timescales, from immediate events (Kevin et al., 2008; Owens and Philip, 2008) to extended reconstructions involving sediment sinks such as floodplains (Owens et al., 1999), reservoirs and estuaries (Foster et al., 2007; Juracek and Ziegler, 2009; Kelley and Nater, 2000; Smith et al., 2009). While the number and diversity of fingerprinting studies have increased, relatively limited attention has been paid to the quality of the statistical models developed (Lees, 2007) and to the uncertainties associated with sediment allocation to different potential sources (Collins and Walling, 2002). It is important that methods for identifying and quantifying the contributions of individual sediment sources should

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provide an indication of the uncertainty associated with the result obtained: the latter allows taking better informed decisions on sediment and water management (Minella et al., 2008). The uncertainty assessment should therefore be incorporated into the fingerprinting approach (Martinez-Carreras et al., 2008), even though any uncertainty assessment will always be conditional on the possibilities considered and the assumptions made (Beven, 2007).

Several studies to date have considered uncertainty estimation when using the fingerprinting approach. Some recent sediment source studies applying mixing models used the spatial variability of source tracer properties to determine confidence limits of model estimates based on Monte-Carlo estimation approach (Collins and Walling, 2007; Collins et al., 2010; Krause et al., 2003; Motha et al., 2004; Smith and Dragovich, 2008; Wallbrink et al., 2003). The Monte-Carlo method computes output statistics (means, variances) by repeating simulations with random sampling of input variables and model parameters. The basic procedures are to define input distributions, sample randomly from the input distributions, run simulations with repeated samplings, and determine probability distribution for the output (Katz, 2002). Other approaches have adopted Bayesian uncertainty estimates (Fox and Papanicolaou, 2008; Small et al., 2002), which differ in their interpretation because contributions are presented as probability distributions (Moore and Semmens, 2008). Bayesian statistical methods quantify uncertainty by calculating probabilistic predictions. The procedure has three stages: (1) determination of the prior probability distribution for model parameters, (2) construction of a likelihood function for the statistical model, and (3) derivation of the posterior probability distribution for the parameters by using the Bayes rule to adjust the prior distribution based on the observed data (Bolstad, 2007). The Bayesian approach has shown advantages over un-mixing models solved with optimization because specifying prior knowledge for model parameters. Informative prior distributions for the source profiles help to focus the posterior distribution, and thus allow parameter estimation. The resulting posterior distribution thus gives an idea of the uncertainty associated with the source ascription.

As the number of potential sources included in a mixing model increases, the uncertainty in the contribution of any one source also increases (in statistics, this phenomenon is referred to as the principle of parsimony—more parameters yield larger variance; Burnham and Anderson, 2002). Mixing models cannot deterministically solve mass-balance equations when the number of sources is different from the number of tracers + 1. A mixing model should be able to partition multiple sources, incorporate multiple sources of uncertainty and use prior information to solve the overdetermined mass-balance matrix. The use of Bayesian statistical techniques can account for all of these challenging aspects compared to the Monte-Carlo estimation approach. Thus successful applications of Bayesian-mixing models illustrate how these methods can be used as a standalone probabilistic tool to monitor watershed erosion processes (Fox and Papanicolaou, 2008). However, to our knowledge, there have been limited attempts to establish a formal means to incorporate such prior information into mixing model analyses. Thus, we see a pressing need for a mixing model that can partition multiple sources, incorporate uncertainty.

The implementation of measures to control excessive sediment production and sediment yield is important in controlling more sustainable land management practices in Iran. In order to achieve this effectively, the relative importance of various sediment sources (natural and anthropogenic) needs to be adequately understood. However, one also needs to quantify the uncertainty on such assessments to see if estimates are really meaningful. In a recent article Moore and Semmens (2008) outlined a Bayesian framework for incorporation of prior information and uncertainty into stable isotope mixing models in wildlife ecology. This mixing model allows the estimate of proportional contributions of different sources to a mixture. Therefore, the main objectives of this paper are to apply geochemical fingerprints to determine relative contributions of sediment sources and to demonstrate the efficacy of this uncertainty approach for assessing the uncertainty estimation in sediment fingerprinting.

2. Material and methods

2.1. Study area

Our study was conducted in the Hiv catchment (35°59′ to 36°07′ N and 50°36′ to 50°43′ E) which is part of the Hashtgerd Drainage Basin, in the Southern Alborz Mountains, 70 km Northwest of Tehran, Iran (Fig. 1). The drainage area of the Hiv catchment is 55 km^2 including 400 ha (7.3%) of orchards (walnut, almond and cherry trees), 128 ha (2.3% of total area) of residential rural area, 4322 ha (78.6% of total area) rangelands, and 650 ha (11.8% of total area) of rock outcrops. The Hiv catchment has a mountainous topography, with elevation ranging from 1280 m to 2720 m, and an average slope gradient of 27%. The soils within the catchment are mainly Typic Xerorthents and Typic Calcixerepts according to the soil taxonomy (Soil Survey Staff, 2010). A dispersed topsoil sample contains 16 to 84% sand, 9 to 57% silt, and 7 to 35% of clay. Long-term (1975–2003) mean annual precipitation in the study area is ca. 444.5 mm.

2.2. Sampling and data collection

Potential sediment sources were identified by examining the main land use types and soil erosion types within the study catchment, these being dominated by three main groups: rangelands, orchards and stream banks. Forty two representative samples were collected from these potential sources at different locations within the study catchment. The number of soil samples that were taken as well as their location was based on the statistical weighting of the area-percentage of each land use (rangelands and orchards) and stream bank erosion (sediment sources), considering the geological complexity.

The samples were collected using a trowel to obtain a representative sample of the uppermost layer of the source material (0–5 cm). In order to ensure that the source material samples were representative of the potential heterogeneity of the individual sources, composite samples, made up of 5 sub-samples, were collected over an area of approximately 100 m^2. For eroding stream banks a composite of 5 sub-samples was collected over a small stream bank area.

Sediment samples were collected from check dam reservoir deposits. In the study area concrete and cement check dams were built used in many small streams. Check dams reduce sediment and water transfer to rivers: in some cases these check dams prevent any runoff from reaching the lower lying plains during rainfall events. In total sediment samples were collected at 12 locations (Fig. 1). Sediment samples in reservoirs where deep water was present were collected using a 0.02 m^2 Petit-Ponar grab sampler: otherwise, a trowel was used. At each location 5–7 samples were taken, which were then mixed to obtain a composite sample.

In order to remove bias associated with grain-size effects, only the <63 μm soil and sediment fraction, obtained by dry sieving, was taken for tracer analysis (Fu et al., 2008). Organic carbon was removed by loss on ignition at 550 °C for 2 h. Total concentrations of Al, B, Ba, Be, Bi, Ca, Cd, Co, Cr, Cu, Fe, Ga, K, Li, Mg, Mn, Mo, Na, Ni, P, Pb, Se, Sr, Te, Tl and Zn were measured by ICP-OES (GBC Integra) based on ICP multi-element standard solution (Merck KGaA, Frankfurter, Germany) after digestion of 3 g of the soil samples with aqua regia (HCl–HNO_3; 3:1) for 2 h. In order to assess the validity of the analytical results, accuracy and precision were calculated. Precision is given at one relative standard deviation (RSD) and has been calculated on the basis of four replicates. Accuracy was determined as the percent recovery (%R) and is the relative difference from reference values. The results show that the %RSD of the analytical procedure was within 5.5%, while the precision was within 5% for all elements. Total N was determined by the Kjeldahl method (Rutherford et al., 2008) and the total organic C was