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Research article

Ascribing soil erosion of hillslope components to river sediment yield

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A R T I C L E I N F O

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A B S T R A C T

In recent decades, soil erosion has increased in catchments of Iran. It is, therefore, necessary to understand soil erosion processes and sources in order to mitigate this problem. Geomorphic landforms play an important role in influencing water erosion. Therefore, ascribing hillslope components soil erosion to river sediment yield could be useful for soil and sediment management in order to decrease the off-site effects related to downstream sedimentation areas. The main objectives of this study were to apply radionuclide tracers and soil organic carbon to determine relative contributions of hillslope component sediment sources in two land use types (forest and crop field) by using a Bayesian-mixing model, as well as to estimate the uncertainty in sediment fingerprinting in a mountainous catchment of western Iran. In this analysis, ^{137}Cs, ^{40}K, ^{238}U, ^{226}Ra, ^{232}Th and soil organic carbon tracers were measured in 32 different sampling sites from four hillslope component sediment sources (summit, shoulder, backslope, and toeslope) in forested and crop fields along with six bed sediment samples at the downstream reach of the catchment. To quantify the sediment source proportions, the Bayesian mixing model was based on (1) primary sediment sources and (2) combined primary and secondary sediment sources. The results of both approaches indicated that erosion from crop field shoulder dominated the sources of river sediments. The estimated contribution of crop field shoulder for all river samples was 63.7% (32.4–79.8%) for primary sediment sources approach, and 67% (15.3%–81.7%) for the combined primary and secondary sources approach. The Bayesian mixing model, based on an optimum set of tracers, estimated that the highest contribution of soil erosion in crop field land use and shoulder-component landforms constituted the most important land-use factor. This technique could, therefore, be a useful tool for soil and sediment control management strategies.

1. Introduction

The problem of accelerated soil erosion in Iran has increased significantly over the last 50–60 years (Nosrati et al., 2011a). Accelerated soil erosion leads to on-site and off-site adverse agronomic, ecological, environmental, and economic effects. Not only does erosion reduce the quality of crop fields, but also the quality of forests, pastures, and rangelands (Blanco-Canqui and Lal, 2008). The main on-site effects involve the reduction in soil productivity, while the off-site effects are mostly due to the transportation of sediment and sediment-associated chemicals from the source into surface waters. The growing impact of soil erosion on water supply catchments of Iran necessitates a better understanding of the soil erosion process and sediment sources in order to apply effective conservation measures to mitigate this problem. Of particular concern for catchment managers and planners are the off-site impacts on water reservoirs. In part, this concern is related to sediment accumulation behind dams and in reservoirs. Identification of the catchment sediment sources is, therefore, a prerequisite for understanding sediment delivery processes as well as the sediment budget of a catchment to target effective mitigation measures.

From a geomorphologic viewpoint, the ground surface throughout Iran is composed of different landform elements. Hillslopes are the most common landform, consisting of many slope units (Huggett, 2007). A widely used system describing a hillslope has five slope units—summit, shoulder, backslope, footslope, and toeslope (Ruhe, 1960). Gravity and water transport material over and through hillslopes. Hillslope components are, therefore, potentially susceptible to surface and subsurface erosion processes. Hillslopes are places of much human activity, and their study has practical applications. Knowledge of erosion and sediments on slopes is important for planning agricultural, recreational, and other activities.

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Knowledge of soil loss rates from different sources is required to evaluate soil erosion models to assess the influence of erosion on the evolution of landforms, and to identify the watershed activities to minimize the off-site effects of erosion and sedimentation. Therefore, there is a strong need for techniques to establish an accurate sediment budget and predict catchment sediment yield in an efficient and cost-effective manner (Walling et al., 2003).

The concept of sediment fingerprinting refers to a field based measurement technique that apportions or unmixes eroded soils into multiple sources through the use of tracers (Collins et al., 1998). To determine the relative contribution of potential sediment sources to different land use, geology and erosion type sources can be discerned on the basis of appropriate tracers, which can then be compared with the same conservative tracers of in-stream sediment samples using mixing models. Sediment fingerprinting techniques in many different source types using different tracers are being increasingly used (Nosrati et al., 2011b, 2014; Olley et al., 2013; Schuller et al., 2013; Smith and Blake, 2014; Walling, 2013; Walling and Collins, 2008). However, limited attention has been paid to the ascribing of hillslope components to sediment yields in different land use types strategies.

Using the most common fallout radionuclides is being increasingly recognized as an effective method to fingerprint source tracing in sediments. Several successful studies have used environmental radionuclides in tracing sediment sources around the world (Alewell et al., 2014; Olley et al., 2013; Porto et al., 2005; Pulley et al., 2015; Schuller et al., 2013; Smith et al., 2016; Walling et al., 2003), but relatively little attention has been paid to the application of radionuclide fingerprints for tracing sediments in Iran. It is therefore worthwhile to investigate if, and to what extent, radionuclide fingerprints can be used as reliable tracers to quantify the relative contributions of the potential sources to the sediment yield. As far as we are aware, this hypothesis has not yet been tested. While the number and diversity of fingerprinting studies has increased, these models have not fully investigated the substantial uncertainty associated with sediment fingerprinting mixing. A recent sediment source study, applying a mixing model, used the variability of source tracer properties to determine the uncertainty based on Bayesian statistics (Nosrati et al., 2014).

The objective of this study was to test the use of radionuclides as sediment source fingerprints in order to estimate the relative contribution of hillslope components as potential sediment sources in a catchment from forest and cultivated land in Iran. The use of the ^{137}Cs was coupled with the use of additional environmental radionuclides, ^{40}K, ^{238}U, ^{226}Ra, ^{232}Th and also soil organic carbon as fingerprint properties. We hypothesize that the summit and shoulder hillslope components in forest and cultivation lands will be the primary sediment sources in Iranian water catchments. We further hypothesize that the backslope and toeslope of forest and cultivated lands will be a secondary source of sediments. To quantify the relative contribution of each of these sources to the sediment yield, the Bayesian-mixing model will be used based on these fingerprint properties.

2. Materials and methods

2.1. Study area

The study was conducted in the Nachi catchment as a sub-catchment of the Ghazalche Soo catchment, located near the town of Marivan in western Iran (46° 7′–46° 15′ E, 35° 34′–35° 43′ N) and is conterminous with the eastern border of Iraq. The drainage area of the Nachi catchment is 4.47 km^2 including 8.4 ha (1.9% of total area) of residential rural area, 184.4 ha (41.2% of total area) of forest (Quercus infectoria, Crataegus aronia, Pyrus spp, and Contoneaster vulgaris species) and 254.5 ha (56.9% of total area) of crop field (wheat and barley). The Nachi catchment topography is mountainous, with elevations ranging from 1340 to 2502 m above sea level in the upper most part of the catchment. The catchment's average slope gradient is 27%.

The catchment has variable lithological characteristics, with outcrops of lacustrine deposits with sand, marl, and loam soils as well as Anjiran limestone with a thinly bedded, slightly metamorphosed rock type. The soils within the catchment are mainly Typic Xerorthents and Typic Calcixerepts. Long-term (1992–2009) mean annual precipitation in the study area is ca. 940 mm.

2.2. Sampling and data collection

Sediment samples: river fine bed sediment samples that appeared to have been recently deposited were collected at each sampling site. These are referred to as drape sediment deposits (Olley et al., 2013). This approach has been used to characterize river sediment in the study area because of sampling difficulties during high flow conditions due to poor access and remoteness. In order to ensure the bed sediments were representative samples, composite samples, made up of 7 sub-samples, were collected over a length of approximately 20 m.

Sediment source samples: prior to sampling, field surveys were carried out to identify the potential sediment yield sources of the Nachi River. Surface erosion in the hillslope components of the forest and cultivated land was identified as the main sediment source within the catchment. Hillslope sediment source samples were collected from two major land-use types including natural forests and cultivated land, based on hillslope components and aspect. For each land-use type, at least one slope aspect, including southern, western, and eastern, was determined. A widely used system that has been described by Ruhe (1960) with five hillslope units including summit, shoulder, backslope, footslope, and toeslope were applied to differentiate hillslope components. In this study, one combined sample was collected from both footslope and toeslope hillslope components. Then, 32 soil samples in all were collected from eight hillslope sites (S1 to S8) with four different hillslope components (see Fig. 1). A composite sampling procedure is needed to reduce soil property variability due to processes such as micro-topography, especially in forest land uses. The spatial variability of measurements can be statistically overcome by measuring replicable independent samples from each landform unit, or simply combining them and then measuring the concentrations for a faster measurement with minimal cost (Zhang et al., 2015). Then, to reduce the variability of radionuclide concentration of each sampling site and to collect a representative sample, five sub-samples from 100 m^2 area were collected (size ~1000 g). To collect composed sub-samples from transects of landform components, zigzag or multiple design approaches were used. The samples of potential sediment sources were collected using a trowel to obtain a representative sample of the uppermost layer of the source material (0–5 cm). Further, 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.

The activity of ^{40}K, ^{238}U, ^{226}Ra, ^{232}Th and ^{137}Cs were simultaneously determined by high resolution gamma-ray spectrometry, using a gamma HPGe detector, ORTEC, USA, with an energy resolution of 1.8 keV at 1332 keV (^{60}Co) and a relative efficiency of 38.5% for line of ^{60}Co. The samples were sealed in containers with adhesive tape, labelled with the weight, and sent to the laboratory at Malek-ashtar University, Tehran, for analysis. The activity concentrations of ^{40}K, ^{238}U, and ^{137}Cs were derived directly from the measured intensity of the single 1460.8, 63.29 and 66.8 keV gamma-ray transitions, respectively. The direct determination of