Hydrol. Earth Syst. Sci. Discuss., 7, 6677–6698, 2010
www.hydrol-earth-syst-sci-discuss.net/7/6677/2010/
doi:10.5194/hessd-7-6677-2010

Hydrology and Earth System Sciences Discussions

Application of quantitative composite fingerprinting technique to identify the main sediment sources in two small catchments of Iran

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Received: 27 June 2010 – Accepted: 8 July 2010 – Published: 2 September 2010

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Published by Copernicus Publications on behalf of the European Geosciences Union.

Abstract

The targeting of sediment management strategies is a key requirement in developing countries including Iran because of the limited resources available. These targeting is, however hampered by the lack of reliable information on catchment sediment sources. This paper reports the results of using a quantitative composite fingerprinting technique to estimate the relative importance of the primary potential sources within the Amrovan and Royan catchments in Semnan Province, Iran. Fifteen tracers were first selected for tracing and samples were analyzed in the laboratory for these parameters. Statistical methods were applied to the data including nonparametric Kruskal-Wallis test and Differentiation Function Analysis (DFA). For Amrovan catchment three parameters (N, Cr and Co) were found to be not significant in making the discrimination. The optimum fingerprint, comprising Oc, PH, Kaolinite and K was able to distinguish correctly 100% of the source material samples. For the Royan catchment, all of the 15 properties were able to distinguish between the six source types and the optimum fingerprint provided by stepwise DFA (Cholorite, XFD, N and C) correctly classifies 92.9% of the source material samples. The mean contributions from each sediment source obtained by multivariate mixing model varied at two catchments. For Amrovan catchment Upper Red formation is the main sediment sources as this sediment source approximately supplies 36% of the reservoir sediment whereas the dominant sediment source for the Royan catchment is from Karaj formation that supplies 33% of the reservoir sediments. Results indicate that the source fingerprinting approach appears to work well in the study catchments and to generate reliable results.

1 Introduction

The sediment transported by a river commonly represents a mixture of sediment derived from different locations and different sediment source types within the contributing catchments (Carter et al., 2003). An understanding of the nature and relative

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importance of the principle sediment sources within a catchment is needed to support the design and implementation of sediment control strategies in catchments (Collins et al., 2001). Resources could be effectively wasted if, for example, control strategies focused on reducing surface erosion, when most of the sediment transported through a river system was contributed by channel and gully erosion. Any attempt to identify the primary sediment sources within a catchment or river basin and to assess their relative contributions to the sediment load at the catchment outlet will face a number of important problems (Peart and Walling, 1988; Collins and Walling, 2004). Traditionally, for example, techniques employed have included field observations and mapping (Lao and Coote, 1993), the use of erosion pins (Lawler et al., 1997) and profilometers (Toy, 1983), terrestrial photogrammetry (Barker et al., 1997), soil erosion plots (Loughran, 1989) and remote sensing (Bryant and Gilvear, 1999; Vrieling, 2006) that are, however, frequently hampered by problems of spatial and temporal sampling, operational difficulties and the costs involved (Peart and Walling, 1988; Loughran, 1989; Loughran and Campbell, 1995; Collins and Walling, 2004). In response to the problems associated with conventional procedure for establishing the primary sediment sources within a catchment, the fingerprinting approach has been increasingly adopted as an alternative and more direct and reliable means of assembling such information. In particular, source fingerprinting techniques provide a relatively simple and cost-effective basis for assembling spatially and temporally integrated data for catchments of different scales (Collins and Walling, 2004; Walling, 2005; Collins et al., 2008). Fingerprinting technique is founded upon the link between the physical and geochemical properties of the sediment and those of its sources. If potential source materials can be distinguished on the basis of their fingerprints, the likely provenance of the sediment can be established using a comparison of the properties of the sediment with those of the individual potential sources (Walling et al., 2008). The application of this approach comprises two basic steps. These involve, first, the selection of diagnostic properties, which distinguish potential sediment sources, and secondly, a comparison of sediments and catchment source samples using these properties, in order to establish

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sediment provenance (Walling et al., 2008). Existing research has provided valuable information on the range of properties that can be successfully employed to discriminate potential sediment sources in drainage basin. These have included mineralogy, and colour (Grimshaw and Lewin, 1980), mineral magnetism (Caitcheon, 1993), environmental radionuclides (Wallbrink and Murray, 1996), geogimical composition (Foster and Walling, 1994), Organic constiuence (Collins and Walling, 2002), acid extractable metals (Collins and Walling, 2002) and particle size (Stone and Saunderson, 1992). Such procedures have proved successful in distinguishing individual source types, such as surface soils beneath different land uses and subsoil/channel banks (Walden et al., 1997); the spatial location of sediment provenance, such as discrete geologies or sub-catchments (Collins et al., 1996, 1998); a combination of both (Collins et al., 1997a; Walling and Woodward, 1995); and in reconstructing recent changes in sediment provenance using sediment cores (Collins et al., 1997b; Owens et al., 2000). Due to the success of the fingerprinting approach in providing such data, in this paper investigated the application of a quantitative composite fingerprinting technique to establish the relative contribution of sediment sources to the reservoir sediment from the two catchments in Semnan Province, Iran.

2 Materials and methods

2.1 Study area

This area is located in Semnan Province of Iran.This catchment is including the two catchments: 1. Amrovan catchment: total area of the Amrovan catchment is 102.35 ha. The Altitudes range from 1795 m at the catchment outlet to 1925 m in the upstream areas and the catchment slope average is commonly 11.4%. The mean annual precipitation is 174 mm and occurs in winter and spring months generally. The geology is dominated by quaternary, Hezar-Dareh and Upper Red formations. All of the catchment area is covered by bush ranges. 2. Royan catchment: The catchment has a total

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area of 538.83 ha. The climate annual rainfall is 184 mm. Most of the rainfall occurs in winter and spring. The topography of the region mainly consists of highland parts up to 2000 m and the catchment slope average is commonly 23.95%. The geology is dominated by quaternary, Hezar-Dareh, Shemshak, Lar and Upper Red formations. All of the catchment area is covered by bush ranges. The selected reservoirs had been created by constructing earth embankments to harvest seasonal runoff.

2.2 SAMPLING

Field sampling involved the collection of representative samples of both main potential sediment sources identified within each study catchment and the sediments deposited in reservoir dam constructed in the outlet of catchments. Potential sediment sources were categorized surface soils from different geological formations and eroding gullies. 10 representative samples were collected from each primary sediment sources per catchments. These samples were collected using a stainless steel spade and care was taken to ensure that only material susceptible to erosion (the surface 0–2 cm) was collected. All source material samples were air-dried and subsequently dry-sieved to <63 µm to facilitate direct comparison with sediment samples (Walling et al., 2008). Sediment samples were collected from reservoir constructed in outlet of each catchment that was created by constructing earth embankments to harvest seasonal runoff. 10 undisturbed representative sediment samples were taken using a stainless steel spade per reservoir (near the dam axis, in the middle, side and at the inlet of the reservoir) all samples were subsequently air-dried prior to laboratory analysis. Oven-drying was avoided in order to prevent potential geochemical diagenesis under higher temperatures (Carter et al., 2003).

2.3 Selecting fingerprint properties and laboratory analyses

Selection of fingerprint properties for use in the investigation was based on previous experience of source discrimination, as well as being constrained by available analytical facilities and the time available for analytical work. Because there is the potential

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problem that some tracer properties may be discharged from point sources to rivers in solution and subsequently sorb onto existing suspended sediment in the river (Owens and Walling, 2002), thereby elevating the property concentration of the sediment, it is necessary to exclude properties that show an elevated concentration in sediment relative to those for the various potential sources before the fingerprinting exercise is carried out. The 15 properties finally selected (see Table 2) comprised five groups of fingerprinting properties, including Organic constituents (C, N, P), base cations (Na, K, Ca, Mg), acid extractable metals (Cr, Co), clay minerals (Smaktite, Colorite, Illite, Kaolinite) and mineral magnetism (Xlf, Xfd). Both C and N were determined directly using a Carlo Erba Elemental Analyzer, and P was determined calorimetrically using UV Visible Spectrophotometry, after extraction with perchloric acid (Olsen and Dean, 1965). Ammonium acetate was used to extract Na, Mg, Ca and K (Qui and Zhu, 1993). Acid extractable metals were extracted using direct acid digestion (Allen, 1989). Clay minerals were determined using X-ray diffraction (Garrad and Hey, 1989) and Mineral magnetisms were determined using a Bartington meter and MS2B dual frequency sensor (Caitcheon, 1998).

2.4 Sediment source discrimination

The ability of the range of fingerprint properties employed in the study to discriminate between the potential sediment sources was tested statistically using the two-stage procedure proposed by Collins et al. (1997). In the first stage: the Kruskal–Wallis H-test was used as a basis for eliminating redundant fingerprint properties, by testing the ability of individual constituents to distinguish potential sediment sources in an unequivocal manner. In the second stage: multivariate stepwise Discriminate Function Analysis (DFA) was used to test the ability of the properties passing the Kruskal–Wallis H-test to classify all the source material samples from a given catchment into the correct categories and to identify the optimum (i.e. smallest) combination of properties, or composite fingerprint, for discriminating the source material samples from that catchment.

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2.5 Sediment source contribution

A multivariate mixing model, as described by Collins et al. (1997), was used to estimate the relative contribution of the potential sediment sources to the individual sediment samples collected from each designated catchment. This model assumes that the concentrations of the selected fingerprint properties in any given sample of sediment directly reflect the corresponding concentrations in the original source materials and the relative proportions of sediment contributed by those sources. An error assessment of the sediment mixing model results was also performed using the Mean Relative Error (MRE) statistic. This involves a comparison of the actual fingerprint property concentration measured in sediment sample with the corresponding values predicted by the model, based on the optimized percentage contribution from each source group. Walling and Collins (2000) suggest that relative errors <15% indicate that the mixing model provides an acceptable prediction of the fingerprint property concentrations associated with a sediment sample and therefore that the relative contributions of the potential sources estimated by the mixing model are likely to be reliable. Almost all of the mixing models met this criterion.

3 Results and discussion

3.1 Source type contribution in the Amrovan catchment

The Kruskal–Wallis test was used to assess the ability of tracer properties to discriminate between the four source types that occur in the Amrovan catchment, namely surface materials from quaternary, Hezar-Dareh and Upper Red formations and up surface materials from gully vales (Table 1). The majority of tracer parameters exhibit p-values well below the significance value of 0.05, indicating that they can strongly discriminate between the four source types. Three parameters (N, Cr and Co) were found to be not significant in making the discrimination, and were therefore removed

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at this stage. Multivariate stepwise discriminant function analysis (DFA) was subsequently used to identify the best composite fingerprint incorporating a number of these properties, and the results are shown in Table 2. Results indicate that the optimum multicomponent fingerprint, comprising C, P, Kaolinate and K was able to distinguish correctly 100% of the source material samples. This composite fingerprint includes tracer properties from several different.

Property groups (i.e. organic constituents, base cations and clay minerals) and confirms the need to use properties with different environmental controls in order to obtain a composite fingerprint that affords a high degree of discrimination (cf. Collins et al., 2002). The numerical mixing model was used to establish the relative contribution of each source to the individual sediment samples collected from the Atary catchment. The results are presented in Table 3. These estimates were obtained by averaging the results of the mixing model calculations for each sediment sample collected from the reservoir sediments. The mean contribution from the Upper-Red formation (36%) is most important, followed in descending order by the Hezar-Dareh formation (28%), gully erosion (21%) and quaternary units (15%). These results demonstrate that all parts of the catchment provide significant contributions to the sediment at the reservoir. Upper Red formation consists of evaporitic (haliferous and gypsiferous) marls. It is hilly and deprived of vegetation. The fact that this sediment source approximately supplies higher than 36% of the sediment while only occupying the small area (see Table 3) may reflect higher rates of erosion and sediment supply associated with the Upper Red formation. This finding is consistent with that obtained for another Iranian river (Hakim Khani et al., 2007). Hezar-Dareh formation consists of conglomerate with sandstone and little claystone, it has medium erodibility and the high contribution from this sediment source is probably duo to high surface areas of this geological formation and the close proximity of this source to the channel network. 21% sediment sources are derived from gully erosion and this sediment source is the third contribution. The less contribution of gully erosion than that Upper-Red and Hezar-Dareh formations is du to small area of catchment and therefore presence of undeveloped gullies in this

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catchment. Since gully erosion could be expected to be more important in larger catchments with well-developed gullies, whilst smaller catchments provide greater opportunity for a particular land use or geological formation to be dominant and to therefore dominate the source contribution (Carter et al., 2003). The relatively small contribution from the area of quaternary units is in accordance with the small area that these rocks occupy in the catchment (Collins, 1997), while the contribution from the other formations is larger than expected on the basis of their areal extent (see Table 3).

3.2 Source type contribution in the Royan catchment

The source materials collected from the Royan catchment were also classified into surface material from different geological formations (Upper Red, Karaj, Lar, Shemshak and quaternary) and material from gully erosion. The results of the Kruskal–Wallis test are shown in Table 4. All of the 16 properties provided a clear discrimination between the six source types. A multicomponent signature containing Cholorite, Xfd, N and C was selected as the optimum fingerprint capable of classifying 92.9% of the source material samples correctly (Table 5), and the addition of further tracer properties to the composite fingerprint does not increase the success of the classification. The fact that discriminate function analysis were not classified 100% of the samples correctly into the appropriate source groups indicate that there is some overlap between the samples collected to represent source groups. Table 6 examines the mean results of the mixing model calculations for the relative contribution from each sediment source to the reservoir sediment sampled at Royan catchment. The results presented in Table 6 indicate that Karaj formation represents the dominant sediment source in the Royan catchment (33%), but that both quaternary units and gully erosion also represent important sources (32% and 28%, respectively). This three sediment sources overall approximately supplies higher than 80% of the sediments. The increased importance of Karaj formation reflects the existence of large areas occupied by this geological formation (see Table 6) and location of this formation close proximity to the channel network. Quaternary units is located downstream and along the main drainage and its sediments enter the drainage directly and are not trapped in the way. The high contribution of sediment from gullies in the Royan catchment is firstly due to severe eroded gullies in the reaches of the catchment spatially downstream, where gullies are often big and secondly it also reflects the downstream location of the sampling sites, and thus the distal location of other sources, particularly Upper-Red and Lar formations, which are mainly located in upstream areas. Due to their distal location, the opportunity for conveyance losses is greater. There was insufficient sediment supplied by Shemshak, Upper-Red and Lar formations for their contribution to be detected by the mixing model. This reflects both the limited extent of these sources in the catchment and the lack of erosion from such sources. Looking in general at the results presented in Tables, Surface sources, as taken together, are the dominant source in both Amrovan and Royan catchments, accounting for 79 and 73% of the sediment yield, respectively.

4 Conclusions

Statistically verified composite fingerprints of source materials and a multivariate mixing model have been used to identify the main sources of the reservoir sediment transported by the rivers of Amrovan and Royan catchments, Semnan Province, Iran. The results provide important information on the relative importance of the contributions from different geological formations and gullies to the reservoir sediments, which can be used to support model validation and the targeting of management and control strategies. In addition, the availability of information on sediment from different sources adds to existing understanding of the relative importance of surface and subsurface sources and of surface sources under different geological formation to sediment in similar catchments. The optimum composite fingerprint was selected by DFA comprising constituents selected from a number of the different groups of properties generally affords the most robust discrimination of the sediment sources within the study catchment. The optimum composite fingerprint identified for the Amrovan catchment (C, P, Kaolinite and K), correctly classifies 100% of the source material samples. For the

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Royan catchment, the optimum fingerprint provided by stepwise DFA (Cholorite, Xfd, N and C) correctly classifies 92.9% of the source material samples. If fingerprint properties used in combination (for example to construct a composite finerprint) the different types of property afford a more robust means of discriminating catchment sediment sources. (Walling et al., 1999; Collins et al. 1997, 1998, 2001, 2002). The contribution of each sediment source obtained by multivariate mixing model varied at two catchments. For Amrovan catchment Upper Red formation is the main sediment sources as this sediment source approximately supplies 36% of the reservoir sediment whereas the dominant sediment source For the Royan catchment is from Karaj formation that supplies 33% of the reservoir sediments. But that both quaternary units and gully erosion also represent important sources (32% and 28%, respectively). The mean (average for all properties within each composite fingerprint) relative errors for the mixing model calculations were typically around 10%, confirming that the relative contributions from the individual source types generated by the mixing model were meaningful. The clear discrimination between the potential source materials provided by the source fingerprint properties, the relatively high levels of correct classification demonstrated by the stepwise discriminate function analysis and the limited divergence between the observed and predicted values for the sediment properties associated with individual suspended sediment samples, demonstrated by the RME analysis, indicate that the source fingerprinting approach appears to work well in the study catchments and to generate reliable results. Most of the studies associated to fingerprinting technique were used the suspended sediment. However a further problem associated with the sediment sampling procedures commonly used in suspended sediment is the need to obtain the collect of large volumes of water to sufficient dry mass of sediment and to permit analysis of a wide range of fingerprinting properties (Walling, 2005) whereas reservoir sediment are free from these significant problems. There is clearly a need to provide guidance on the initial selection of fingerprint properties, in order to reduce the number of properties analyzed. The source fingerprinting approach relies heavily on the assumption of conservative behavior of the fingerprint properties during sediment

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mobilization and transport. This assumption is usually addressed by selecting fingerprint properties that are known to be conservative. However, further work is undoubtedly required to explore this problem further and to verify empirically the assumption of conservative behavior for a range of fingerprint properties. The study reported by Motha et al. (2002), which involved use of a rainfall simulator in the field, to simulate the mobilization of sediment from the land surface and permitted direct comparisons between the properties of the mobilized sediment and the in situ source material, provides one potential approach for addressing this issue.

Acknowledgements. The authors are thankful to the Government Offices of Iran, for providing the data, maps and reports for this work.

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Table 1. Results of applying the Kruskal–Wallis test to assess the ability of each tracer property to discriminate between surface materials from different sediment sources collected from the Amrovan catchment.

Tracer property	p-value	H-value
N	0.35	3.30
P	0.00*	75.15*
C	0.00*	26.67*
Ca	0.00*	14.99*
Cr	0.19	4.80
Co	0.06	7.41
Mg	0.00*	23.40*
K	0.00*	24.77*
Na	0.00*	18.65*
Smektite	0.00*	16.20*
Cholorite	0.00*	16.09*
Ilite	0.00*	16.35*
Kaolinite	0.01*	11.21*
Xlf	0.03*	9.28*
Xfd	0.00*	16.67*

* Significant at $p=0.05$.

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Table 2. Results of using stepwise discriminate function analysis to identify which combination of tracer properties provides the best composite fingerprint for discriminating source materials from the Amrovan catchment.

Step	Tracer property	Wilks' Lambda	Cumulative geology samples classified correctly (%)
1	C	0.162	66.70
2	P	0.063	91.70
3	Kaolinite	0.025	90.50
4	K	0.002	100

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Table 3. Mean contributions of each sediment sources to the sediment. Samples collected from the Amrovan catchment.

Sediment sources	Area (ha)	Contribution (%)
Quaternary units	7.79	15
Hezar-Dareh formation	65.23	28
Upper-Red formation	31.33	36
Gully erosion	31.71	21

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Table 4. Results of applying the Kruskal–Wallis test to assess the ability of each tracer property to discriminate between surface materials from different sediment sources collected from the Royan catchment.

Tracer property	p-value	H-value
N	0.00*	20.18*
P	0.00*	35.10*
C	0.00*	34.50*
Ca	0.00*	17.10*
Cr	0.03*	12.24*
Co	0.00*	16.77*
Mg	0.00*	36.86*
K	0.01*	15.80*
Na	0.00*	19.19*
Smektite	0.00*	22.77*
Cholorite	0.00*	23.81*
Ilite	0.00*	22.24*
Kaolinite	0.01*	15.0*
Xlf	0.00*	16.77*
Xfd	0.00*	33.05*

* Significant at $p=0.05$.

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Table 5. Results of using stepwise discriminate function analysis to identify which combination of tracer properties provides the best composite fingerprint for discriminating source materials from the Royan catchment.

Step	Tracer property	Wilks' Lambda	Cumulative geology samples classified correctly (%)
1	Cholorite	0.097	57.10
2	Xfd	0.049	75
3	N	0.024	82.10
4	C	0.004	92.90

Table 6. Mean contributions of each sediment sources to the sediment samples collected from the Royan catchment.

Sediment sources	Area (ha)	Contribution (%)
Quaternary units	154.58	32
Upper-Red formation	47.02	2
Karaj formation	233.65	33
Lar formation	47.72	1
Shemshak formation	59.48	5
Gully erosion	148.72	27

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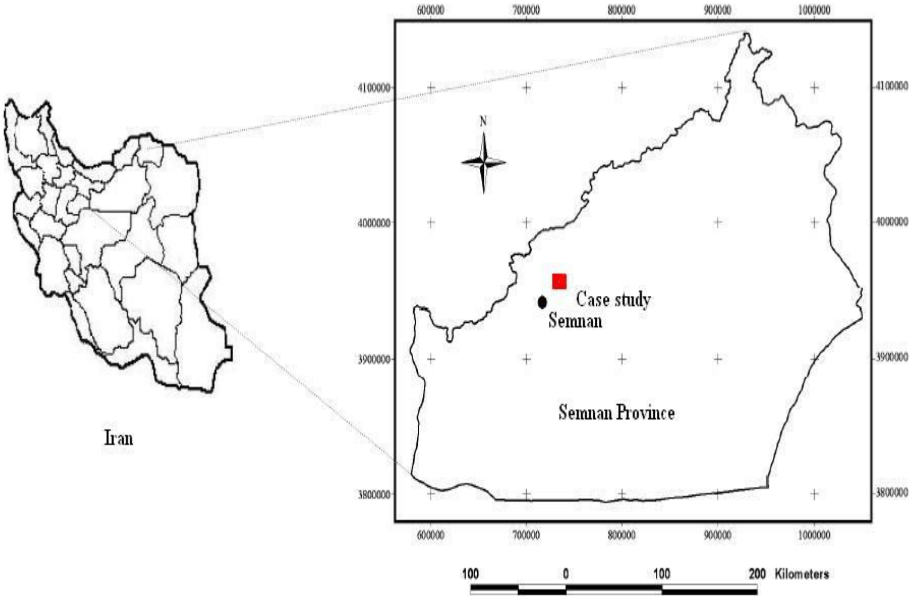

Fig. 1. Study area.

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