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Ascribing soil erosion types for sediment yield using composite fingerprinting technique

Seyed Hamidreza Sadeghi[1], Saeed Najafi[2], Alireza Riyahi Bakhtiari[3] and Parviz Abdi[4]

[1]*Department of Watershed Management Engineering, Faculty of Natural Resources, Tarbiat Modares University, Noor, Iran*
sadeghi@modares.ac.ir

[2]*Watershed Management Engineering, Faculty of Natural Resources, Tarbiat Modares University, Noor, Iran*

[3]*Department of Environmental Sciences, Faculty of Natural Resource, Tarbiat Modares University, Noor, Iran*

[4]*Agriculture and Natural Resources Research Center, Zanjan, Zanjan Province, Iran*

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Abstract Soil erosion and eroded sediment are serious threats to sound land management. However, less attention has been given to quantifying the importance of different soil erosion features based on appropriate control measures that could be designated. Accordingly, this research was planned to quantify the contribution of potential sediment sources, i.e. sheet, rill and gully erosion, in Idelo watershed in Zanjan Province, Iran, using composite fingerprinting. Toward this aim, 16 geochemical and organic tracers were detected in sediment sources and sediment deposited at the outlet. The results of applying the composite fingerprinting technique, with a relative error of 16%, showed that sheet, rill and gully sources contributed 56%, 44% and 0%, respectively, to sediment yield. It was also apparent from the results that the composite fingerprinting approach could be successfully utilized to assess the provenance of sediment deposited at the main outlet of the study watershed by soil erosion type.

Key words composite fingerprinting; geochemical properties; sediment source discrimination; sediment yield; Idelo watershed, Iran

Attribution de types d'érosion des sols pour la production de sédiments en utilisant la technique des empreintes composites

Résumé L'érosion des sols et les sédiments érodés représentent de sérieuses menaces pour la bonne gestion des terres. Cependant, la quantification de l'importance des différentes caractéristiques de l'érosion des sols sur la base de mesures de contrôle appropriées qui pourraient être identifiées, a reçu une attention limitée. En conséquence, la présente recherche a eu pour objectif de quantifier la contribution des sources potentielles de sédiments, c'est-à-dire l'érosion en nappe, rigoles et ravines, dans le bassin versant de l'Idelo dans la province de Zanjan (Iran), à l'aide d'empreintes composites. A cette fin, 16 traceurs géochimiques et biologiques ont été détectés dans les sources de sédiments et les sédiments déposés à l'exutoire. Les résultats de l'application de la technique des empreintes composites, avec une erreur relative de 16%, ont montré que les sources de nappes, rigoles et ravines ont contribué respectivement à hauteur de 56%, 44% et 0%, au rendement sédimentaire. Les résultats ont également permis de comprendre que l'approche par empreintes composites pourrait être utilisée avec succès pour évaluer la provenance par type d'érosion des sols des sédiments déposés à l'exutoire principal du bassin versant d'étude.

Mots clés empreintes composites ; propriétés géochimiques ; discrimination de la source des sédiments ; rendement sédimentaire ; bassin de l'Idelo, Iran

INTRODUCTION

The provision of reliable information on the provenance of suspended sediment transported by rivers is important from a number of perspectives. Such information is needed: to establish watershed sediment budgets (Walling *et al.* 2008); to validate sediment yield models (Collins and Walling 2002); and to design plans to deal with the transport of nutrients, contaminants and damage to aquatic ecology, reservoir water storage capacity and water quality (Collins *et al*. 1997c, Juracek and Ziegler 2009). Perhaps more importantly, an understanding of the nature and relative importance of the principal sediment sources within a watershed is essential for the design of effective management strategies to achieve meaningful reductions in sediment loads and yields (Jenns *et al*. 2002, Collins and Walling 2004). Assembling detailed information on both the nature and relative importance of the primary sediment sources within a watershed represents a difficult task. Traditional direct monitoring techniques based on the use of erosion pins and troughs to estimate soil loss, a combination of pins and surveying to document channel bank contributions, or monitoring of sediment to compute the relative significance of sediment contributions from individual instrumented sub-basins to downstream suspended sediment loads, involve many operational problems and sampling constraints (Walling *et al*. 1993, Branski and Banasik 1996, Walling 2005, Collins and Walling 2007). Because of the problems associated with traditional methods for establishing the primary suspended sediment sources within a watershed, the fingerprinting technique, which offers an alternative approach, has been increasingly employed to identify sediment sources and avoids many of these problems. The problem is particularly complicated in developing countries like Iran where, due to financial constraints, many soil erosion control measures are not appropriately placed in the watershed area, because no prioritization has been made for sediment yield provenance.

Sediment fingerprinting is founded upon the link between the diagnostic properties of suspended sediment and those of its source material (Walling *et al*. 2006). To accomplish this, research has traditionally used single component signatures encompassing mineralogy (Klages and Hsieh 1975, Wood 1978), colour (Grimshaw and Lewin 1980, Carreras *et al*. 2010), mineral magnetic (Bonnet *et al*. 1989, Walden *et al*. 1997, Hatfield and Maher 2009, Wang *et al*. 2011), fallout radionuclides (Loughran *et al*. 1992, Walling and Woodward 1992, Olley *et al*. 1993, Wallbrink *et al*. 1998, Owens *et al*. 1999, Zapata 2003, Mabit *et al*. 2008, 2010, Shi *et al*. 2011, Yan *et al*. 2012, Benmansour *et al*. 2013) and organic matter (Santiago *et al*. 1992) properties. However, using single property or component signatures is likely to prove unrealistic and result in spurious linkages between source materials and sediment (Collins and Walling 2002), so most fingerprinting studies now employ composite fingerprints, which comprise a range of different diagnostic properties influenced by contrasting environmental controls, and thereby greatly improve the reliability of sediment source discrimination (Walling *et al*. 2006). Today composite fingerprints have been successfully employed by mixing models for source tracing and determining the relative importance of individual sediment source types in a number of different contexts (Walling and Woodward 1995, Russell *et al*. 2001, Motha 2003, Miller *et al*. 2005, Walling *et al*. 2006, Collins and Walling 2007, Minella *et al*. 2008, Collins *et al*. 2010a, 2010b).

Our review of the worldwide literature showed that previous studies mainly focused on determining the relative importance of different categories of potential sources, such as individual source types including surface soils from areas of different land use and channel banks (e.g. Walden *et al*. 1997, Russell *et al*. 2001), the spatial location of sediment sources according to tributary sub-watersheds (e.g. Collins *et al*. 1996, Walling *et al*. 1999, Shi *et al*. 2011, Benmansour *et al*. 2013) or geological zones (e.g. Walling and Woodward 1995, Collins *et al*. 1998, Yan *et al*. 2012). There is limited literature documenting the application of the fingerprinting approach to determine the contribution of the main erosion types, i.e. sheet, rill and gully erosion. This study to designate different soil erosion types from sediment deposited at the main outlet of the watershed using the fingerprinting technique was conducted for the Idelo watershed, one of the important sub-watersheds of the large Sefidrood basin in Iran, The aim was to: (1) determine which discriminative characteristics could differentiate the combination of different soil erosion types in the resulting sediment, and (2) to quantify the importance of different types of soil erosion in sediment from the study watershed.

MATERIAL AND METHODS

Study area

The Idelo watershed in Zanjan Province, Iran, (approx. 20 km^2) is underlain by Tertiary (red gypsiferouse marl) and Quaternary (old clastic and young alluvial deposits) rocks. The annual precipitation ranges from 250 to 300 mm of which 37%, 3%, 24% and 36% falls in spring, summer, autumn and winter, respectively. Altitude ranges from

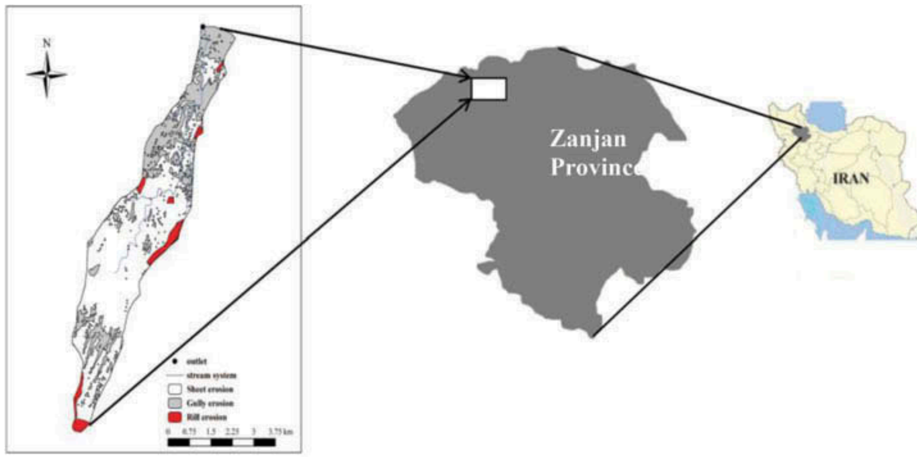

Fig. 1 Location of the study watershed.

1281 m a.m.s.l. at the outlet, to 1699 m a.m.s.l. in the upstream areas, with steep slopes of 15–30%. Land use is divided between dry farming (51.2%) and rangeland (48.8%). A schematic view of the study watershed is shown in Fig. 1.

Fieldwork

The fieldwork included collection of source material samples from areas of different soil erosion types and sediment sampling at the valley outlet. Sampling involved the collection of representative samples of the main potential sediment sources within the watershed. Potential sediment sources were classified according to erosion type: sheet, rill and gully erosion. A total of 50 source material samples were collected, i.e. 20 sheet erosion samples and 15 representative samples each from the rill and gully erosion areas. The samples were taken from depths of 0–2 cm (Walling and Woodward 1995, Walling *et al*. 1999, Collins and Walling 2002, Collins *et al*. 2010a, 2010b, 2010c), 2–30 cm and >30 cm (Gruszowski *et al*. 2003) for sheet, rill and gully erosion, respectively. Furthermore, six samples were collected from deposited materials at the outlet of the watershed. Care was taken to ensure that only material likely to be mobilized by each particular erosion type was collected. Accordingly, rill and gully erosion sampling sections were limited to active erosion scars (Collins *et al*. 1997b, Juracek and Ziegler 2009). A range of locations was ultimately sampled within the watershed to represent areas with good connectivity to the watercourse system (Walling *et al*. 2006, Collins *et al*. 2010c, 2010d). All samples were collected using a stainless steel trowel that was regularly cleaned to avoid inter-sample contamination (Collins and Walling 2002). The entire samples were then sieved to separate sediments of size of ≤63 μm to ensure that all suspended sediments from either upland or channel bed materials could be considered.

Laboratory analysis

All samples were air dried, slowly disaggregated using a pestle and mortar, and dry sieved through a 63-μm mesh to ensure sample consistency. Laboratory analysis of materials included a range of potential fingerprint properties, including three property subsets, i.e. trace metals (Fe, Mn and Al), heavy metals (As, Cd, Co, Cr, Cu, Ni, Pb, Se, V and Zn), and organic and inorganic constituents (C, N and total P). Note that these groups of fingerprint properties were selected on the basis of the availability of analytical equipment used successfully in previous studies to discriminate sediment sources (Foster and Walling 1994, Collins *et al*. 1997a, Collins and Walling 2002, Wallbrink *et al*. 2003, Walling 2005). The concentrations of all metals were determined using Inductively Coupled Plasma Optical Emission spectrometry, VISTA-PRO model (ICP-OES), after direct and complete digestion with H_2SO_4, $HClO_4$, HNO_3 and HF acid (Marín *et al*. 2001, Balcerzak 2002, Hseu *et al*. 2002, Matusiewicz 2003). To assess the analytical capability of the proposed methodology, the accuracy of the total available elements was checked by including with each batch of 20 digested samples, one blank and Standard Reference Materials (SRM 2709) from the National Institute of Standards and Technology (NIST). Accordingly, the recovery rates were from 76% to 86% for the same methodology and equipment as applied for analysing the study elements in other studies. Total P was determined using UV-visible spectrophotometry after extraction with perchloric acid (Olsen and Dean 1965). Determination of organic C and N concentrations were undertaken using the Walkely-Black and Kjeldahl procedures (Walkely and Black 1934, Carter and Gregorich 2008).

Statistical analysis

Before using the fingerprinting approach for discriminating sediment sources, all the data were checked for univariate and multivariate outliers. The criterion of the mean ±1 SD (standard deviation) was used to identify univariate outlier data, but given the nature of geochemical data, this rule could not deliver a relevant threshold estimate for the study variables. Therefore, the median ±3 Median Absolute Deviation (MAD) criterion was used (Hampel 1974, Rousseeuw and Croux 1993):

$$\text{MAD} = 1.482 \text{ Median } (|x_i - x_{\text{median}}|) \quad (1)$$

The multivariate outliers were also addressed using the squared Mahalanobis Distance measure (D^2) as a multivariate assessment of each observation across a set of variables. This method measures the distance of each observation in multidimensional space from the centroid of all observations, providing a single value for each observation, no matter how many variables are considered. For detection of outliers, the D^2 measure was divided by the degrees of freedom (df) equal to the number of variables involved (D^2/df); its distribution approximates a *t*-value. Given the nature of the statistical tests, it was suggested that a conservative level of significance (0.001) be used as the threshold value for detection as an outlier. So, observations having a value of $D^2/df > 2.5$ in samples of under 80 observations were designated as possible outliers (Tabachick and Fidell 2007, Hair 2010).

In addition, a sufficient number of samples per category was taken for use of multivariate Discriminant Function Analysis (DFA) so that the minimum ratio of sample size to the number of tracers was approximately five, and at least 15 to 20 observations per category were considered (Hair 2010). The two-stage statistical procedure proposed by Collins *et al*. (1997a) was employed to confirm the discrimination of the potential sediment sources in the watershed. In stage one, all fingerprint properties were tested for their ability to discriminate source types encompassing sheet, rill and gully erosion using the Kruskal-Wallis H-test and One-Way ANOVA. The One-Way ANOVA and Kruskal-Wallis H-test were used for normally and non-normally distributed data, respectively (Tabachick and Fidell 2007).

In the next step, DFA was employed to identify composite fingerprints likely to distinguish source types involving sheet, rill and gully erosion. Application of DFA was based on three assumptions, namely normality of independent variables, lack of collinearity among independent variables and equality of group covariance matrices that needed to be satisfied initially (Hair 2010). For the first assumption, we assessed the univariate and multivariate normality. The Kolmogrov-Smirnov test and normal probability plots were used for normality testing, recognizing that achieving univariate normality of individual variables will often suffice to reach multivariate normality as well, as DFA is robust to failures of normality if non normality (violation of the assumption) is caused by skewness in outlier data (Tabachick and Fidell 2007). For the collinearity, we used two criteria, i.e. correlation matrix and tolerance (TOL) or Variance Inflation Factor (VIF). The correlation matrix was used as the simplest means of distinguishing collinearity for the independent variables. Generally, a level of 0.9 and higher of correlation shows the first criterion of significant collinearity. But it does not ensure a lack of collinearity because multi-collinearity may occur due to the combined effect of two or more other independent variables. To overcome this issue, we used TOL and VIF (Tabachick and Fidell 2007, Hair 2010). Tolerance indicates that two or more independent variables are explained by the other variables and thus will not have high explanatory power in fingerprinting (Hair 2010). In other words, tolerance denotes the proportion of the variation in the independent variables not explained by the variables already in the function. A tolerance with 0 value means the independent variable under discussion is a complete linear combination of independent variables already in the function. Generally acceptable levels of TOL and VIF (VIF is the inverse of TOL) are up to 0.1 and below 10, respectively; violation of these thresholds indicates multicollinearity among variables (Hair 2010).

Finally, the equality of group covariance matrices was assessed with Box's M test. In this approach an attempt is made to find a nonsignificant probability level which indicates that there are no differences between the group covariance matrices. When the assumption is challenged, using group-specific covariance matrices instead of total covariance matrices can minimize this effect and a significant level is not regarded as too important (Hair 2010). Composite fingerprints were finally constructed using the criterion D^2 in the stepwise method (Hair 2010). According to this method, D^2 is used to select the variable that has a statistically significant difference across groups while maximizing D^2 between the other closest groups. In this manner, statistically significant variables are selected that maximize the discrimination between the most similar groups at each stage. This procedure continues as long as additional variables provide statistically significant discrimination beyond those differences already accounted for by the variables in the discriminant function.

Source quantification

Finally, the fingerprint of the sediment deposited at the outlet was compared with that of the potential sources. This was achieved using a multivariate mixing model (Walling and Woodward 1995, Miller *et al*. 2005, Walling *et al*. 2006, Collins and Walling 2007, Minella *et al*. 2008, Collins *et al*. 2010a, 2010b):

$$C_i = \sum_{j=1}^{n} a_{ij} P_j \quad i = 1, \ldots, m\,; j = 1, \ldots, n \tag{2}$$

where C_i is the concentration of element i in the sediment sample; a_{ij} is the mean concentration of fingerprint property i in source j; P_j is the optimized percentage contribution from source s; m is the number of fingerprint properties comprising the optimum composite fingerprint and n is the number of sediment source type categories. The model seeks to satisfy the following constraints:

$$0 < P_j < 1 \tag{3}$$

$$\sum_{j=1}^{n} P_j = 1 \tag{4}$$

Since the model is over determined, it must be fitted iteratively by minimizing an objective function. Accordingly, the objective function was optimized by minimizing the sum of the squares of the deviations (R) of the predicted property concentrations from the measured values, to determine the relative contribution of each potential source. In many studies, two correction factors, the tracer-specific weighting and particle-size correction factors, have been used, but here, because of equipment constraints, the only form of correction possible was the sieving of both source and sediment samples through a 63-μm mesh. Equation (5) shows the objective function that was executed using the Solver function in Microsoft Excel (Walling *et al*. 2006):

$$R = \sum_{i=1}^{m} \left[\frac{C_i - \sum_{j=1}^{n} a_{ij} P_j}{C_i} \right]^2 \tag{5}$$

To provide an indication of the uncertainty associated with the mixing model, goodness-of-fit tests were also applied, due to their ease of application at the time of conducting the research, in which the fingerprint property concentrations measured in the sediment samples were compared with the corresponding values predicted by the model. It is now conventional for the modelling component of source fingerprinting studies to assess the stability of the average solutions by applying the Monte Carlo routine and genetic algorithms (Collins and Walling 2007, Collins *et al*. 2010b, 2010d).

RESULTS AND DISCUSSION

Based on the methodology explained above, 16 fingerprinting elements were measured in source areas (i.e. different erosion types) and sediment deposited at the main outlet of the watershed (Table 1). As seen in Table 1, the coefficient of variation (CV) ranges from 16.90% to 100.56% for Co and P, respectively. Many of the properties have positive skewness, which is due to mineralization or rare geochemical processes and contaminating human activities, as reported by Lalor and Zhang (2001) and Reimann *et al*. (2005). As there was no contaminating human activity in the study region, the skewed distribution can be attributed to the nature of geochemical data.

Applying the univariate outlier criterion showed that all data were within the threshold ranges. The results of applying the D^2/df criterion are given in Table 2. Only sample 46 was designated as an outlier, having a D^2/df value of 3.11 exceeding the critical value of 2.5 (Hair *et al.* 2010).

Table 1 Descriptive statistics of 16 fingerprinting elements in source material and sediment samples of the study watershed. All elements except OC (organic carbon, %) and N (%) are in μg g^{-1}. SD: standard deviation; CV: coefficient of variation.

Fingerprint property	Mean	Median	SD	CV (%)	Min	Max	Skewness
Source material							
Al	0.30	0.27	0.18	60.00	0.09	1.09	2.53
As	1.25	1.24	0.54	43.20	0.21	3.35	1.00
Cd	0.03	0.02	0.02	66.67	0.00	0.07	0.82
Co	10.00	9.77	1.69	16.90	7.03	14.62	0.22
Cr	30.67	31.80	7.34	23.93	17.67	48.12	0.28
Cu	21.32	20.22	5.77	27.06	13.25	39.15	0.94
Fe	1.02	0.97	0.46	45.10	0.26	2.15	−0.20
Mn	306.61	284.46	79.45	25.91	169.50	516.49	0.54
Ni	23.80	23.40	5.52	23.19	14.76	37.59	0.50
Pb	2.82	2.72	1.70	60.28	0.80	6.94	1.14
Se	1.01	1.09	0.44	43.56	0.22	1.50	−1.25
V	62.59	60.93	10.08	17.25	45.75	91.19	0.75
Zn	17.35	36.36	10.24	59.02	10.96	60.11	−0.20
P	7.13	6.20	7.14	100.56	0.00	36.12	1.75
OC	0.55	0.41	0.52	94.54	0.00	2.48	1.35
N	0.07	0.07	0.03	40.00	0.04	0.13	0.56
Sediment tracer values							
Al	0.31	0.32	0.14	45.62	0.08	0.47	−0.7
As	1.21	1.17	0.47	39.30	0.46	1.82	−0.4
Cd**	–	–	–	–	–	–	–
Co	11.60	12.77	3.25	28.00	5.29	13.95	−1.99
Cr	31.53	33.66	9.57	30.37	12.91	39.10	−1.95
Cu	27.35	30.59	7.47	27.30	13.35	32.58	−1.73
Fe	0.90	0.97	0.51	56.66	0.31	1.44	−0.27
Mn	395.88	429.12	116.00	29.30	170.85	493.49	−1.93
Ni	23.86	24.31	7.01	29.37	0.84	11.53	−0.88
Pb	3.09	3.07	0.56	18.13	2.42	3.80	0.19
Se**	–	–	–	–	–	–	–
V	71.19	78.29	21.05	29.56	32.43	88.78	−1.56
Zn	42.83	45.76	10.32	24.09	22.85	52.54	−1.88
P	7.42	2.73	12.24	164.95	0.00	31.50	2.08
OC	0.26	0.26	0.05	19.23	0.18	0.34	0.00
N	0.06	0.06	0.01	16.66	0.05	0.09	0.41

Note: **elements were not detected in sediment samples.

The results of applying appropriate ANOVA and Kruskal-Wallis tests are given in Table 3, which shows that, out of the 16 study elements, just Fe, Zn, Se and Ni, with *p* values below 5%, were capable of discriminating erosion types as a source of sediment. This result basically agrees with those of Collins *et al*. (1997a, 1997b), Owens *et al*. (1999), Collins and Walling (2002), Walling (2005), and Collins and Walling (2007).

Table 4 presents the final results of the DFA for the study watershed. The optimum composite fingerprints selected by DFA, Fe, Zn and Cr, could correctly distinguish only 64% of the source type samples, a result which agrees with that reported by Owens *et al*. (1999). This may highlight the importance of fallout radionuclides such as caesium-137 (Cs^{137}), excess lead-210 (Pb^{210}) and beryllium-7 (Be^7) for application of other elements or increasing the level of distinction of the erosion type (Bonnet *et al*. 1989, Walling and Woodward 1992, Walling 2005). According to Tables 2 and 3, unlike the findings of previous studies (e.g. Collins *et al*. 1997c, Collins and Walling 2002), the organic matter and total P properties could not discriminate between the source materials. This may reflect the low percentage of vegetation cover due to which no significant differences could be found in concentrations of C, N and total P as a function of soil profile depth expected to correspond to different erosion processes.

The contribution from each sediment source is represented in Fig. 2. Clearly the highest mean contribution is provided by sheet erosion (56%), whereas no contribution has been recorded for gully erosion (0%).

To provide an indication of the uncertainty associated with the mixing model, goodness-of-fit tests

Table 2 Results of applying the multivariate outlier criterion of ration of squared Mahalanobis Distance measure (D^2) to degrees of freedom (df) for outlier designation.

Sample	D^2	D^2/df	Sample	D^2	D^2/df
1	13.16	1.01	29	12.40	0.95
2	8.15	0.63	30	15.69	1.21
3	6.65	0.50	31	5.01	0.38
4	7.14	0.55	32	13.24	1.02
5	18.81	1.45	33	10.51	0.81
6	19.44	1.50	34	10.27	0.79
7	9.06	0.70	35	7.43	0.57
8	8.61	0.66	36	7.24	0.56
9	9.50	0.73	37	9.42	0.72
10	9.89	0.76	38	9.52	0.73
11	12.82	0.99	39	9.20	0.71
12	6.80	0.52	40	4.66	0.36
13	5.79	0.44	41	5.20	0.40
14	5.61	0.43	42	22.30	1.71
15	29.16	2.24	43	11.89	0.91
16	23.53	1.81	44	11.39	0.88
17	5.13	0.39	45	5.75	0.44
18	6.98	0.53	46	40.44	3.11
19	18.31	1.40	47	6.86	0.52
20	25.18	1.93	48	7.62	0.58
21	24.81	1.91	49	10.34	0.79
22	17.28	1.33	50	14.71	1.13
23	11.46	0.88	51	8.62	0.66
24	8.36	0.64	52	7.25	0.56
25	22.74	1.75	53	16.59	1.27
26	9.66	0.74	54	25.11	1.93
27	10.28	0.79	55	13.80	1.06
28	31.87	2.45	56	6.29	0.48

Table 3 Results of One-Way ANOVA and Kruskal-Wallis H-test application to the source type fingerprint properties datasets.

One-Way ANOVA			Kruskal-Wallis H-test	
Study element	F-value	P-value	H-value	*p* value
Al	–	–	0.79	0.67
As	0.82	0.45	–	–
Cd	0.23	0.79	–	–
Co	0.70	0.50	–	–
Cr	2.00	0.14	–	–
Cu	0.09	0.91	–	–
Fe	4.20	0.02*	–	–
Mn	0.80	0.45	–	–
Ni	3.10	0.05*	–	–
Pb	0.04	0.96	–	–
Se	9.80	0.04*	–	–
V	0.15	0.86	–	–
Zn	4.60	0.01*	–	–
P	–	–	0.17	0.84
OC	–	–	1.00	0.37
N	–	–	0.23	0.80

Note: *Represents statistically significant at the 5% confidence level.

Table 4 Final results of the stepwise Discriminant Function Analysis (DFA) for the Idelo watershed, Iran.

Step	Fingerprint property	Wilks' Lambda	Mahalanobis distance, D	Cumulative % of source type samples classified correctly
1	Fe	0.848	0.218	54
2	Zn	0.728	0.304	54
3	Cr	0.615	1.061	64

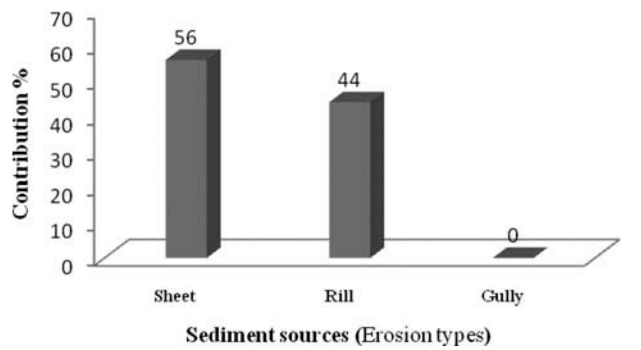

Fig. 2 Mean mixing model estimates for the relative sediment contributions from each source type to the suspended sediment sampled at the outlet of the study watershed.

comparing the fingerprint property concentrations measured in the sediment samples with the corresponding values predicted by the model, based on the optimized contributions from the individual source types to those samples, indicated a typical relative error of ±16%. This level of uncertainty confirms that the optimized mixing model provides an acceptable prediction of the fingerprint property concentrations associated with sediment samples and lies within ranges reported by Walling *et al.* (2006), Minella *et al.* (2008) and Collins *et al.* (2010c). High inputs from sheet erosion are consistent with susceptible soil; fine grained particles, poor vegetation and a large area promote relatively high sediment yields. This is supported by Walling and Webb (1996), Walden *et al.* (1997), Walling *et al.* (1999), Russell *et al.* (2001) and Walling *et al.* (2006). Although rill erosion covers only 5.07% of the watershed area, its contribution to sediment yield (44%) is relatively high. Enhanced sediment generation by rills is associated with the extension of rill erosion in steep areas; furthermore, they are well connected to the drainage system because of soluble materials in soils facilitating extensive piping phenomena.

The spatial distribution of different soil erosion types also affects their contribution to the sediment yield at the outlet, as emphasized by Sadeghi and Mahdavi (2004) for a watershed in Iran. Based on the field evidence and visual evaluations, it seems that the watershed is relatively stable regarding soil erosion, and just initial forms of soil erosion contribute to sediment yield. There is no contribution from gully erosion, which reflects the successful performance of different check dams (e.g. gabion and wire meshed), which effectively obstruct the transport of eroded material. The large proportion of coarse materials at depths >30 cm and the need for high flows to be able to transport such material, may be further reasons for the negligible contribution of gully erosion to sediment reaching the main outlet of the watershed.

CONCLUSION

This study aimed to test of the extent to which the composite fingerprinting approach can be successfully utilized to assess the source type provenance of sediment transported through the Idelo watershed. Several geochemical and organic tracers were recognized in source sediment and sediment transported to the main outlet. Field sampling was conducted and laboratory analyses carried out to quantitatively determine the selected tracers. Statistical procedures and assessments were adopted to quantify the relative contribution of each potential source in sediment delivered to the watershed outlet. The results show that surface soils eroded by sheet and rill erosion are the only sediment source in the watershed. The results also show the necessity for use of further fingerprinting elements, such as radionuclide tracers to improve the analyses. Extended research and field measurement are required to improve the understanding of erosion and deposition, and lead to the design of holistic policies for soil erosion and sediment control.

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