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Using two contrasting methods with the same tracers to trace the main sediment source in a mountainous catchment

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Abstract: Assessing the contribution of sediments from different sources is essential to understand erosive processes and formulate further soil conservation strategies to address environmental problems. In this study, we combined the source fingerprinting approach with geochemistry, including comparison of potential sources, and distribution pattern of major elements, to estimate the different land-use relative contributions to streambed sediment in the Luowugou catchment (13.5 km^2) located on the Heishui River, the first branch of the Jinsha River, China. A total of 57 samples from stream bank, cropland, grassland, forest land, and sediments were collected, and then, 15 elements were analyzed for each sample. The fingerprinting results demonstrated that the stream bank (62.4%) had the greatest relative contribution to the bed sediment yield, while cropland, grassland, and forest land contributed 18.6%, 14.9%, and 4.1% to the bed sediments, respectively. In comparison to the fingerprinting method, even though the results upon geochemistry only provide a qualitative assessment, the ranking of sediment contributions based on geochemistry was consistent with the sediment fingerprinting ranking, that is, stream bank>cropland>grassland>forest land. Our findings suggest that the focal point for sediment control practices should be the stream bank rather than cropland in the region. Geochemistry can result in an important means in validating the fingerprinting results.

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Introduction

Soil erosion has been long recognized as a global issue of concern (Afshar et al. 2010; Bazshoushtari et al. 2016), especially in developing countries where economic development is superior to environmental protection (Jiang et al. 2015). Sediment redistribution caused by soil erosion exerts significant impact on the transport of nutrient and contaminants (organic and inorganic), reservoir siltation, streambed sediment clogging, flooding, decrease in water quality, loss of biodiversity (Collins et al. 2010; Gloski et al. 2019; Tiecher et al. 2018). Reliable information regarding sediment sources is vital to implementing targeted measures in response the sediment-related environmental problems.

The upper Yangtze River Basin is an important ecological shelter in China, in which the ecosystem is very fragile and susceptible to soil erosion due to deforestation, land reclamation, and other inappropriate land use (Pan et al. 2004; Long et al. 2006). Sediment induced by soil erosion is severe which poses great threats to the ecological environment and human living in the region, especially in the lower reaches of the Jinsha River (Jiang et al. 2015). The lower Jinsha River, bringing 2.37×10^8 t of the suspended sediment to the upper Yangtze River annually, contributing to ~51% of the sediment discharge at Pingshan station (Dai and Lu 2013). Meanwhile, many mega cascade reservoirs, such as Wudongde, Baihetan, Xiluodu, and Xiangjiaba, have been built or are under construction in the lower Jinsha River in recent years (Li et al. 2018). Yang et al. (2007) concluded that all reservoirs in the lower Jinsha River would probably trap 95% of sediment load (91% according to Hu et al. 2009) when such reservoirs were all put into full operation. The dynamics of soil erosion and deposition largely influences the multiple functions of reservoirs. For example, sediment delivery into river channels and reservoirs not only influences downstream flooding patterns and reservoir capacity due to deposition processes, but also results in major changes in the biotic and abiotic factors (Suif et al. 2016; Haregeweyn et al. 2017; Su et al. 2017). Thus, soil erosion and induced-sediment have become of greater concern to the government and the public, and there is an urgent need to assess the main sediment source to develop reasonable strategies to effectively control soil erosion and reduce sediment delivery in the Yangtze River.

Many previous studies mostly focused on the impact of human activities and climate change on the variations in the river's sediment supply in lower Jinsha River (Yang et al. 2002; Zhang et al. 2006; Yang et al. 2018). However, very few studies evaluated the sediment contributions, which primarily originate from gravitational erosion (e.g., debris flow and landslide) or sheet erosion (e.g., cropland, forestland, and grassland) in the region. Zhang et al. (1992) analyzed the potential sediment sources of the Jiangjiagou catchment located in lower Jinsha River using the ^{137}Cs technique and found that the fine sediments were dominated by gravitational erosion, for example, gully erosion, landslides, and bank collapse. In addition, Wen et al. (2000) determined that gravitational erosion contributed 54%-85% of the sediment yield Dam-control sediment in Longchuan River, a tributary of the lower Jinsha River. However, above mentioned studies have focused mainly on the sub-catchment on the right bank of the Jinsha River, where the topography is rolling and the river flows through a wide valley (Schmidt et al. 2019). In contrast, the topography of left bank of the Lower Jinsha River, characterized by a deep gorge inset into rolling topography, changes significantly within a catchment due to significant differences in elevation (Schmidt et al. 2019). Thus, the current studies result in insufficient comprehensive understanding of sediment sources in Lower Jinsha River, and the sediment sources dynamics located on the left bank of Lower Jinsha River need be recognized and studied.

The sediment fingerprinting approach has been widely used in many countries due to its potential to discriminate the potential sources of the sediment transported by river networks (Collins and Walling 2002; Koiter et al. 2013; Lamba et al. 2015; Walling 2013). Numerous tracers, such as fallout radionuclides (e.g., Ayoubi et al. 2013; Gheysari 2017), geochemical elements (e.g., Blake et al. 2012; Franz et al. 2014), biomarkers (Alewell et al. 2016), stable isotopes

(Mckinley et al. 2013), color (Martinez-Carreras et al. 2010), and plant pollen (Brown 1985), have been successfully used to characterize sediment sources and to quantify their relative contributions within a catchment or sub-catchment. Among all of these fingerprinting properties, geochemical tracers such as major elements and trace elements have been widely used as tracers since the late 1990s (Franz et al. 2013). For a specific setting, the contributions from stream banks, gullies, and sheet erosion can be fingerprinted directly based on differences in these tracers (Mukundan et al. 2010). However, the underlying assumption in the application of these geochemical tracers is that the tracer's properties are measurable, conservative (e.g., they do not change from source to sink or evolve in a predictable manner), and representative (Collins et al. 2010; Collins et al. 2017). These assumptions have been scrutinized and represent an area of much needed further research (Koiter et al. 2013; Collins et al. 2017). In addition, particle size and organic matter also significantly impacted the calculations of the contribution of different sediment sources (Motha et al. 2003; Pulley and Rowntree 2016). In response to the above described uncertainties, the calculation results for the sediment sources will be more comprehensive if we use additional measurements of the same tracer properties.

In particular, the geochemistry technique has been widely used to determine sediment sources and biogeochemical processes from natural archives, including fluvial sediment, loess (e.g., Hao et al. 2010; Ishtiaq and Rakesh 2013), aeolian deposits (Du et al. 2015), and fluvial plains (Zhang et al. 2016). The application of this proxy is based on the assumption that clear and intuitive conclusions can be obtained based on comprehensive research and mutual verification of multiple index parameters and discrimination diagrams (Zhang and Yue 2018). Accordingly, a wide range of geochemical analyses, for example, the comparison of the major and trace element compositions of different deposits (Ye et al. 2018), the distribution patterns (e.g., Zhang et al. 2016; Ishtiaq and Rakesh 2013), and the ratios of characteristic elements (Zhang et al. 2014), have been practiced in many studies that have used the tracer technique. Among these geochemical analyses, the comparison of the element compositions of different deposits and their element distribution patterns has been increasingly used to identify potential sources. For example, Ye et al. (2018) used both element and mineral composition comparisons to determine that the provenance of loess-like sediments was dominated by paleo-dammed lake sediments. Li et al. (2016) used geochemical compositions and the chemical index of alteration (CIA) value technique to determine the provenance of the Tajikistan Loess. Ishtiaq and Rakesh (2013) analyzed major, trace and, rare earth elements and determined the chemical composition, provenance, and intensity of paleo-weathering of the source rocks. Wu et al. (2013) collected riverbed and suspended sediments in the upper Yangtze River and analyzed the sources of the river and suspended sediments based on trace geochemistry. Above studies have been undertaken to examine sediment sources at a larger regional scale, but little is known about sediment sources at a smaller catchment or sub-catchment scale.

The Luowugou catchment, located on the lower Jinsha River is characterized by deep valleys and steep mountains, where sloping cultivated lands are widely distributed. Sever soil erosion caused by intensive tillage has led to land degradation in this region. In response to soil erosion, the primary conservation management practice is to divide longer slopes into shorter slopes separated by a ridge and converting gently sloping farmland into level terraces, which increases rainfall infiltration and reduces erosion (Zhang et al. 2008). For landscapes in which the topography changes significantly, the above agricultural practices are expected to change the connectivity to a stream network and exert a large influence on sediment transport and deposition from the cropland. Therefore, it is necessary to determine the impact of agricultural practices on sediment dynamics.

The objectives of this study were (1) to quantify the relative contribution of the potential sources (e.g., forest land, cropland, grassland, and stream banks); (2) to assess the effect of terraces on the sediment contributions within the catchment; and (3) to evaluate the reliability of the geochemistry technique to discriminate between eroded soil sources in a small catchment of the lower Jinsha River in southwestern China.

1 Study Area

The Luowugou catchment (27°21'53"-27°23'05" N and 102°33'44"-102°37'47" E) is a 13.5 km² headwater agricultural basin located in the central part of the Heishui River basin, a tributary of the Upper Yangtze River in Southwestern China (Figure 1). The topography of the region is mountainous, with deep valleys and steep slopes (altitude ranging from 1060 to 3040 m above sea level (a.s.l.); average slope of 15°) (Gao et al. 2017). A topographical map at a scale of 1:50,000 that reflects land use characteristics was digitized and corrected in combination with a field survey using ArcGIS 10.1 software, and the catchment surface is primarily covered by cropland (8.51 km², 63%), followed by forest land (3.78 km², 28%) and grassland (1.21 km², 9%) (Figure 1c, Figure 2). This region experiences a subtropical monsoon climate, with two distinct seasons: a summer monsoon (June to October) and a dry winter (November to May) (Zhou et al. 2011). The annual average precipitation is 1164 mm (minimum 1140 mm and maximum 1460 mm according to data from 1973 to

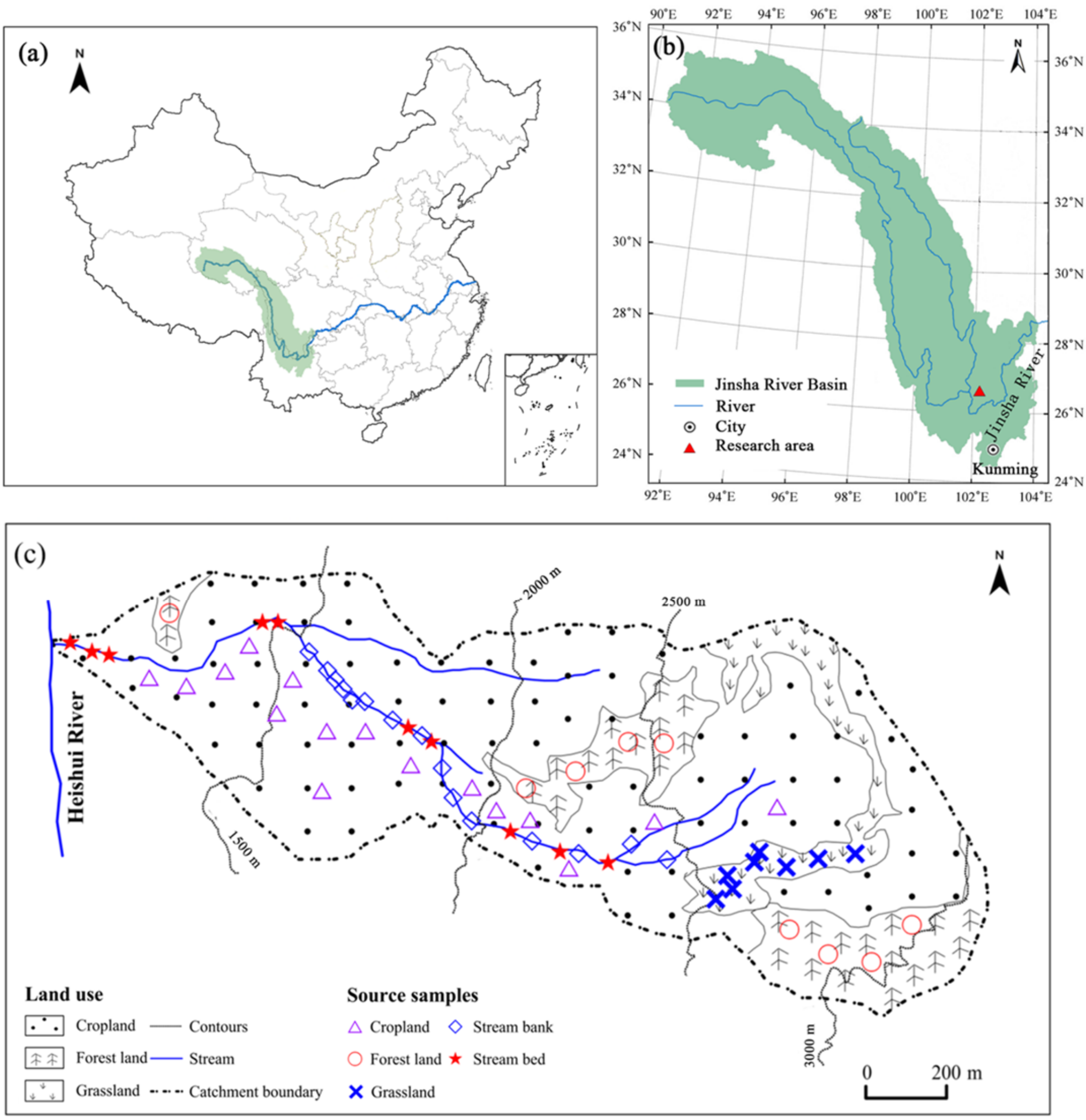

Figure 1 (a) and (b) Location of the Luowugou catchment on the upper Yangtze River, China; (c) Sediment sources and sediment mixtures samples sites.

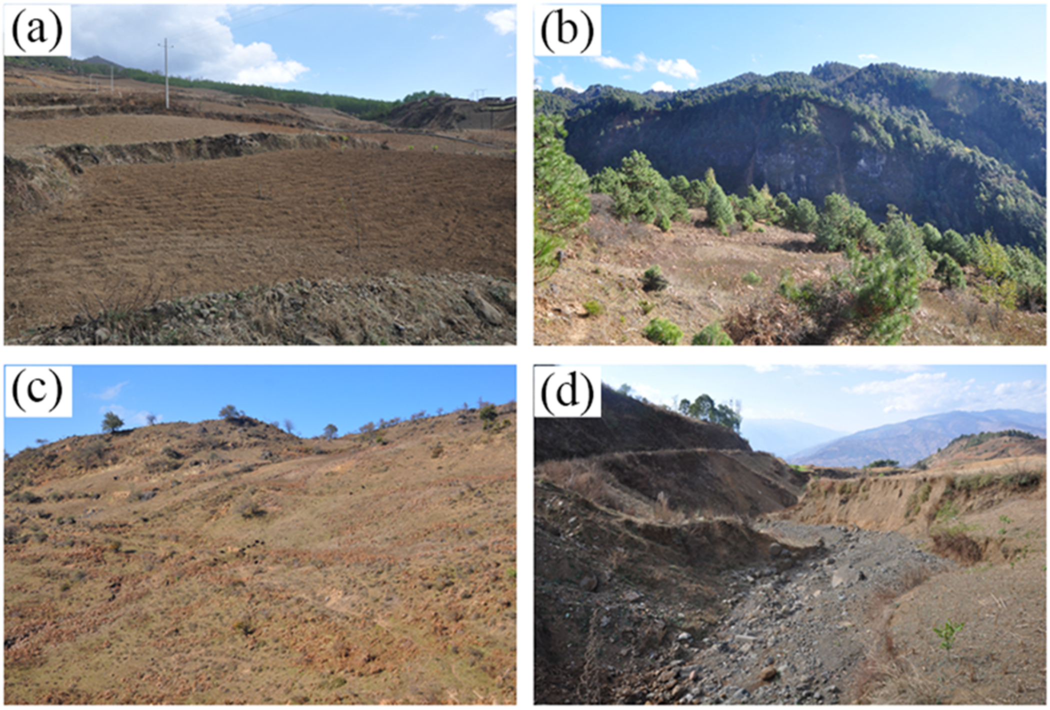

Figure 2 Classification of potential sediment sources: (a) cropland; (b) forest land; (c) grassland; (d) stream bank.

1982) (Puge County Annal 1992). Most precipitation (about 89%) occurs during the peak monsoon season, between May and September, but 11% of precipitation occurs between November and April (Zhou et al. 2011).

The catchment lithology is primarily dominated by the Emeishan basalts (Zhang et al. 2018). In the study area, the main soil types are classified as red soil (<2500 m) (Ultisols in US Taxonomy; Ferralisols in FAO taxonomy) and yellow-brown soil (>2500 m) (Alfisols in US Taxonomy; Luvisols in FAO taxonomy) (Soil Survey Staff 1999; FAO 2015). The surface soils are characterized by a higher gravel content (~61.8%) on cropland compared to forest land (~38.5%) based on dry sieve and weigh originated from 24 samples. To expedite soil and water conservation on the upper reaches of the Yangtze River, and to ensure the safe operation of the Hydropower stations, the Changzhi Project was carried out in the basin since 1989 (Long et al. 2006). A measure "Slope to terrace", converting the linear hillslopes to inconsecutive flat terraces, and in stream networks were implemented to reduce soil erosion in the catchment. For example, the local government and farmers changed the gently sloped cropland to terraced cropland, and numerous rocky ridges were built throughout the steep cropland in 2006. According to our field investigations, the types of gravity erosion are widely distributed in the main stream within this catchment, for example, small landslides and bank collapse, which may be responsible for much of the contribution of sediment (Figure 2d).

2 Methods

2.1 Sample collection

Samples, including surface soil, stream bank, and sediment, were collected between 2017 and 2018. The collection of representative samples of sediment source materials within the watershed is shown in Figure 1c. Total 39 samples were collected from eroding areas of uncultivated (stream bank, grassland, and forest land) and cultivated (cropland) land, these included 15 samples from bank areas, 16 from cropland, 8 from grassland, and 8 from forest land. All samples were collected by a non-metallic trowel, and care was taken to ensure that these samples were susceptible to erosion and delivery to stream. For each hillslope source sample, 8 sub-samples were collected from 0 to 5 cm in a 6 m× 6 m grid and were combined in the field to form a single composite sample. For each stream bank sample, 3 sub-samples were collected from top to bottom along the vertical direction of stream bank, and all stream bank samples sites were located on the obvious bank collapse point. All samples were always taken at sites sensitive to erosion and connected to the stream network.

Samples of fine sediment deposited on the stream bed were collected to apportion the relative contributions within catchment (Figure 1c). River bed fine-grained sediment was the target sediment collected in previous studies (Collins et al. 2017). In the fieldwork, we found that most sections in stream bed were on high vertical gradient, and most of stream bed was covered by smooth basement, resulting in rare sedimentation. On the contrary, the sedimentation was mainly distributed in gentle slope stream bed and down hole. Therefore, the collection of samples of fine sediment deposited on the stream bed depended on where the fine sediment deposits were located. The sampling points for fine sediment samples were collected from the top 2 cm located in the main stream outlet and at three sub-stream outlets. For each sediment sample, 4~5 sub-samples were collected from the adjacent position using a stainless steel spade. And each sample had a mass of ~300 g.

2.2 Laboratory analyses

All of the samples were air-dried for four weeks in the lab, disaggregated using a mortar and pestle, and dry sieved with a 63 μm sieve. Concentrations of Na, Mg, K, Ca, Ba, Ti, Mn, Cu, Zn, Cr, Co, Ni, S, and P were measured using ICP-MS (inductively coupled plasma mass spectroscopy) and ICP-AES (inductively coupled plasma atomic emission spectroscopy) based on elemental concentration. Samples for two means were digested in aqua regia at 95°C in a micro-processor digestion block for 2h. The results have an analytical error of <6% for all of the elements analyzed. The entire experiment was conducted at the physicochemical Laboratory at the Institute of Mountain hazards and Environment, Chinese Academy of Sciences.

2.3 Fingerprinting analysis procedure

2.3.1 Statistical analysis and tracer selection

A three-step statistical analysis was applied to identify optimal fingerprinting tracers with a maximum discriminatory potential suitable as an input for a multivariate mixing model (Yu and Rhoads 2018). The first consideration is the mass conservation from source to sink within the catchment. We verified the mass conservation based on calculations of the minimum and maximum values of both the source and the in-channel sediments. In general, if the minimum and maximum values of a tracer originated from potential sources were outside the source range, the tracer was removed (Yu and Rhoads 2018). In addition, significant discrimination from the four sources was identified based on the non-parametric Kruskal-Wallis H-test (Collins and Walling 2002). Fingerprinting tracers that did not pass the Kruskal-Wallis H-test (i.e., $p > 0.05$) were removed for the next input. Finally, a stepwise discrimination function analysis (DFA) was used to determine the combination of optimal fingerprinting tracers with the smallest Wilk's lambda from the remaining tracers, which provided the greatest discrimination between the potential sediment sources (Collins et al. 1998; Walling 2005). All the statistical analyses were performed through the IBM SPSS 21.0 software (Armonk, NY, USA).

2.3.2 Sediment source discrimination

A multivariate mixing model was used to determine the relative contributions to the fine-grained sediment on the riverbed from cropland, forest land, grassland, and stream bank (Collins et al. 2010). Relative source contributions from these potential sources to the fine-grained sediment of the riverbed were identified by minimizing the objective function value, that is, the sum of the squares of the weighted relative errors, as shown in Eq.(1);

$$R_{es} = \sum_{i=1}^{n} \left\{ \frac{C_{ssi} - (\sum_{s=1}^{m} P_s S_{si})}{C_{ssi}} \right\}^2 \quad (1)$$

where n is the number of fingerprinting properties; m is the number of sediment sources; C_{ssi} is the concentration of the fingerprinting property, i is the fine sediment sample; P_s is the relative percentage contribution from source group s; and S_{si} is the concentration of fingerprinting property (i)

in source group *s*. The multivariate mixing model used had only two boundary conditions: a) the contributions from potential sediment sources are non-negative, and b) the sum of the source contributions should be equal to 100% (Collins et al. 1997).

In addition, the goodness-of-fit (*GOF*) of the optimized mixing model was assessed by comparing the actual fingerprinting property concentration in the sediment samples with the corresponding values predicted by the optimized mixing model (Walling 2005; Collins et al. 2010). The calculated *GOF* (Eq. 2) provided a unique value for each sediment sample. An acceptable P_s value was reached when *GOF*>0.8 (Motha et al. 2003).

$$GOF = 1 - \left\{\frac{1}{n}\sum_{i=1}^{n}\frac{|C_{ssi} - \sum_{s=1}^{m} C_{si}P_s|}{C_{ssi}}\right\} \tag{2}$$

2.4 Geochemistry analysis procedure

Geochemistry was applied to validate the results of the fingerprinting technique. We determined the main sediment source based on the similarity for the elements in the sediment sources, including cropland, grassland, forest land, and stream bank. These similarities were identified by comparing the major and trace element compositions of the different deposits using comparison distribution patterns, which has been successfully used in many studies (e.g., Ye et al. 2018; Zhang et al. 2016; Ishtiaq and Rakesh 2013). In this study, the average value of every element within the different sediment sources and the channel bed sediment was calculated using geochemistry.

2.5 Statistical analysis

All data processing and statistical analyses were carried out using Excel 2007 software and SPSS 21.0 statistical software. The LSD procedure and contrasts with a 0.05 probability level were performed to identify significant differences between stream bank sediment contribution and different land-use sediment contributions.

3 Results

3.1 Sediment fingerprinting analysis

3.1.1 Sediment source discrimination

In the Luowugou catchment, a total of 15 elements (Mn, P, Ca, K, Mg, Na, Ti, Ba, Ni, Pb, Cu, Cd, Zn, Co, and Cr) were available as potential fingerprint properties, as shown in Table 1. 14 (Mn, P, Ca, K, Mg, Na, Ti, Ba, Ni, Pb, Cu, Cd, Zn, and Cr) in 15 elements met the constraint that the mean of the sediment sample concentrations was within the

Table 1 Element concentrations in sediment sources and sediments, results of the Kruskal-Wallis H-test in Luowugou catchment

Element	Source samples			Sediment samples			Sediment mean inside[a]	Sediment samples inside[b]	*H-value*	*p-value*
	Mean	Min	Max	Mean	Min	Max				
Mn(g/kg)	1.54	1.31	1.72	1.67	0.67	6.27	P		30.906	0.000**
P(g/kg)	1.34	1.20	1.71	1.51	0.90	2.22	P	P	22.526	0.000**
Ca(g/kg)	15.52	15.57	24.33	7.49	1.32	24.52	P	P	28.132	0.000**
K(g/kg)	10.65	7.43	13.66	9.22	2.06	18.84	P	P	24.242	0.000**
Mg(g/kg)	16.31	5.77	23.84	10.60	2.52	28.31	P	P	34.856	0.000**
Na(g/kg)	6.77	1.56	11.64	4.51	0.86	13.12	P	P	18.552	0.002**
Ti(g/kg)	26.20	17.78	33.38	21.60	11.85	32.26	P	P	10.959	0.052
Ba(mg/kg)	220.81	100.28	323.03	187.52	1.66	455.3	P	P	14.717	0.012*
Ni(mg/kg)	90.00	72.50	105.31	86.83	54.85	169.69	P		11.232	0.047*
Pb(mg/kg)	13.21	9.51	24.37	20.27	7.54	38.14	P	P	25.280	0.000**
Cu(mg/kg)	221.02	180.24	263.25	205.78	86.68	334.76	P	P	17.398	0.004**
Cd(mg/kg)	0.37	0.26	0.50	0.42	0.14	0.92	P	P	22.971	0.000**
Zn(mg/kg)	169.41	136.52	200.79	145.4	103.44	193.5	P	P	13.982	0.016*
Co(mg/kg)	44.29	38.24	50.05	45.57	21.35	96.72			24.913	0.000**
Cr(mg/kg)	236.53	116.74	323.69	188.22	75.1	360.27	P	P	10.391	0.065

Notes: P indicates that element concentrations that passed each constraint for input to the fingerprint optimization procedure; * Significant at $p< 0.05$; ** Significant at $p<0.01$; [a] Mean sediment concentration within the range of the source category mean values; [b] All sediment sample concentrations were within the range of the source sample values.

range of the source's mean concentrations. In addition, 12 elements (P, Ca, K, Mg, Na, Ti, Ba, Pb, Cu, Cd, Zn, and Cr) met the constraint that all of the sediment samples were within the range of the source values. The results of the Kruskal-Wallis H test indicate that 10 elements (P, Ca, K, Mg, Na, Ba, Pb, Cu, Cd, and Zn) had a statistically significant difference between potential sediment sources. Finally, a total of 10 elements met the three constraints, and consequently, these 10 elements were analyzed using the stepwise discriminant function analysis (DFA).

In this case, a total of 4 tracers (Cd, Cu, P, and Mg) were selected by DFA as the optimal composite fingerprinting set, correctly distinguishing 85.1% of the samples that were used to represent each of the four source types (Table 2).

Table 2 Results of the stepwise discriminant function analysis (DFA) as indicated by the Wilks' lambda values

Step	FP	Wilks	Source (%)	Cumulative (%)
1	Cd	0.406	48.9	48.9
2	Cu	0.193	34.0	66.0
3	P	0.118	40.4	80.9
4	Mg	0.077	48.9	85.1

Notes: FP = Fingerprint property selected; WL=Wilks' lambda; STC=Source type samples classified correctly; CSTC=Cumulative % of source type samples correctly classified.

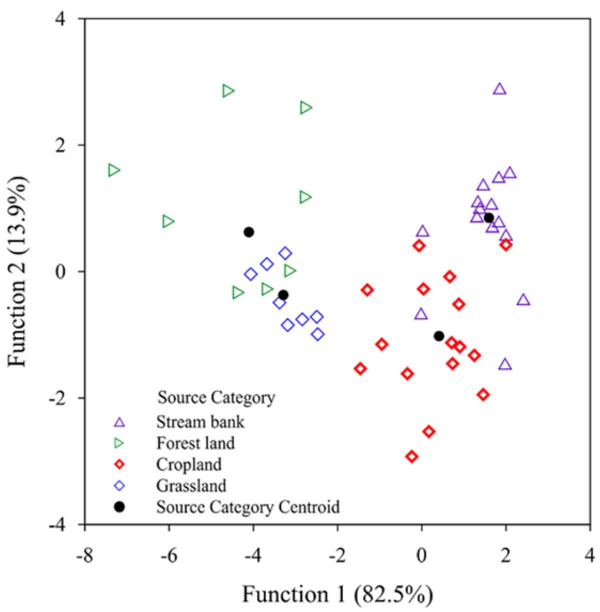

Figure 3 Discriminative power of the composite fingerprints used to distinguish between the sediment sources, that is, stream bank, forest land, cropland, and grassland.

However, the discriminatory power of the remaining 4 elements ranged from 34.0% to 48.9%, and no single tracer was able to correctly classify 100% of the source samples within the respective source groups. The final value of the Wilk's lambda value in the DFA was 0.077. Figure 3 shows the final stages of the stepwise selection when Cd, Cu, P, and Mg are included in the composite fingerprint. Though the first two DFA axes were significant and explained 82.5% and 13.9% of the total variance in sample group data, there is the partial for overlap between the source categories, such as between stream bank and cropland and between forest land and grassland.

3.1.2 Sediment source apportionment

The multivariate sediment mixing model (Collins et al. 1997) was used to calculate the sediment contributions. For the geochemical tracers, the *GOF* of all of the samples ranged from 83.4% to 92.1%, indicating that the relative contributions from the individual source types generated by the mixing model were meaningful, with a *GOF* criterion of >80.0%. The mixing model's results demonstrated that the collected channel bed sediments were predominantly composed of stream bank sediment (Figure 4; Mean: 62.4%; range: 1.9%-84.4%), whereas cropland, forest land, and Grassland contributed 18.6%, 4.1%, and 14.9%, respectively, to the overall sediment supply.

3.2 Element geochemical analysis

The major (g/kg) and trace (mg/kg) element concentrations of the potential sources in the Luowugou catchment are presented in Table 3. These analyses reveal that the Ti content is significantly greater than the other 14 elements. Compared with the samples from the stream bank, forest land, cropland, and grassland, the sediment samples have a higher Ti, Mg, K, Na, and Ca contents and lower Zn, Cr, Pb, and Cd contents. Figure 5 compares the major and tracer element concentrations of the channel bed sediment and the possible sediment sources. A high degree of geochemical similarity between the channel bed sediment and stream bank sediment can be seen in Figure 5. The difference in the Mn, Ca, and Cd of the sediment and the grassland and forest land was significant. The sum of the distance between each element and the line y=x is presented in Table 4. The degree of the similarity of the elements is as follows: stream bank>cropland>forestland >grassland, suggesting that the stream bank is responsible for the majority of the channel bed fine sediment in the Luowugou catchment.

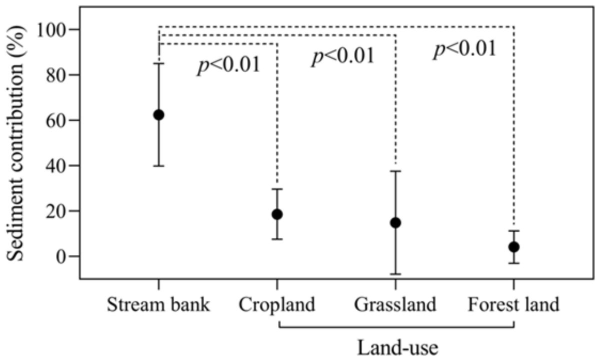

Figure 4 Box plot of the contributions of the sediment sources based on the division of land use in the Luowugou catchment.

Figure 6 shows the distribution of the major and trace elements in the channel bed fine-grained sediment and the possible sediment sources normalized to upper continental crust (UCC) (Taylor and McLennan 1985). In comparison with the UCC, the major and trace elements have the following characteristics: (1) the stream bank and sediment were slightly enriched in Mg, whereas the cropland, forest land, and grassland were depleted; (2) the Ti, Cr, P, Ni, Ba, and Cd contents of the sediment are similar to those of the possible sediment sources; (3) the most significant differences between the sediment and the possible sediment sources were the Mg, Na, and Ca contents. Additionally, the most significant difference was observed between the fine-grained channel bed sediment and the grassland sediment. There was no significant difference between the fine-grained channel bed sediment and the stream bank sediment, indicating that the stream bank sediment dominates the sediment, which is consistent with the above results (Figure 5, Table 4).

4 Discussion

Our results indicated that the stream bank is the dominant source of fine-grained sediment, followed by cropland and grassland (Table 4, Figures 4-6). The findings demonstrate sediment mitigation measures in this catchment should be targeted on stream bank using a series of measures,

Table 3 Major (g/kg) and trace (mg/kg) elements data for the samples of Luowugou catchment

Element		Stream bank (n=15)			Forestland (n=8)			Cropland (n=16)			Grassland (n=8)			Sediments (n=10)		
		Min	Max	Mean	Min	Max	Mean	Min	Max	Mean	Min	Max	Mean	Min	Max	Mean
Major	Ti	14.26	31.99	22.33	12.90	27.01	20.01	15.19	30.47	22.97	11.85	13.67	12.67	23.89	30.49	27.29
	Mg	6.16	28.31	16.55	2.84	5.58	4.00	6.03	18.35	11.22	3.46	4.85	4.04	15.69	22.81	19.13
	K	6.04	18.84	10.76	2.06	7.48	5.66	6.05	17.16	10.55	6.59	7.99	7.16	9.33	13.66	11.89
	Na	2.02	13.12	6.89	1.50	11.45	3.15	1.07	8.92	4.38	1.72	2.00	1.84	6.89	11.64	9.29
	Ca	1.98	24.52	12.95	1.47	3.00	2.20	1.41	24.38	8.01	1.41	2.02	1.68	16.60	24.33	19.95
	P	1.19	1.79	1.40	1.06	1.82	1.45	1.29	2.22	1.73	1.34	1.43	1.37	1.26	1.39	1.32
	Mn	1.12	6.27	2.42	0.67	1.06	0.88	0.93	2.24	1.65	0.75	0.97	0.87	1.46	1.61	1.53
Trace	Cu	128.31	326.58	229.38	97.76	241.87	175.19	113.60	292.64	222.14	86.68	113.97	98.62	188.71	242.66	219.42
	Zn	114.50	192.39	147.66	103.46	177.76	142.19	121.21	193.50	157.10	103.44	109.12	106.17	153.11	185.91	173.17
	Cr	75.10	353.35	209.35	94.81	360.27	182.21	125.32	316.25	194.90	134.71	167.95	154.42	203.10	298.29	242.05
	Ba	66.56	455.30	225.35	28.97	244.04	167.56	88.03	274.65	170.55	243.73	287.76	260.49	137.19	263.52	203.49
	Ni	55.66	169.69	96.56	54.85	147.52	85.31	70.17	116.03	86.73	58.23	73.90	65.90	72.50	95.85	86.70
	Co	26.93	96.72	57.32	21.35	38.71	29.78	24.35	75.72	50.72	21.66	27.86	24.67	39.48	45.91	42.99
	Pb	7.54	31.31	13.82	19.43	38.14	29.28	10.21	34.89	19.43	27.75	30.71	29.14	9.95	19.37	12.17
	Cd	0.20	0.57	0.37	0.45	0.92	0.69	0.29	0.58	0.41	0.40	0.54	0.48	0.30	0.41	0.36

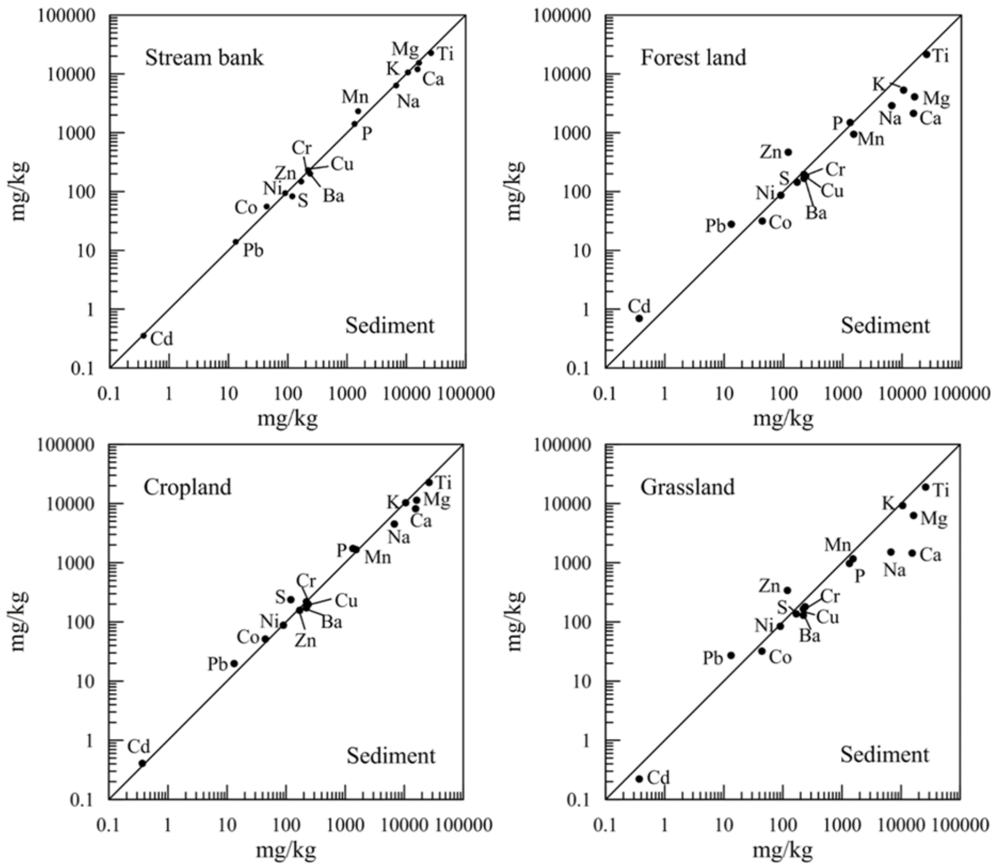

Figure 5 Comparison of the element concentrations of the Luowugou catchment sediments with the possible source region sediments.

Table 4 Element contents distance of sediments and the possible sediments sources in Luowugou catchment

Element	Stream bank	Forest land	Cropland	Grassland
Ti	2431.25	3292.59	2464.15	9566.57
Mg	633.67	8665.27	3468.16	8680.01
Ca	2522.57	9457.38	5185.08	9786.27
K	22.05	3776.07	189.46	2468.22
Na	295.89	2751.39	1609.28	3483.58
Mn	541.56	426.05	80.88	471.35
P	46.77	99.05	278.99	21.59
Cr	25.17	37.85	26.97	58.06
Cu	6.3	18.3	0.96	86.55
Ba	0.24	37.65	34.68	28.06
Zn	15.32	17.45	9.39	44.72
S	26.21	245.22	83.6	263.68
Ni	2.81	2.41	1.71	17.04
Co	7.79	8.91	4.75	13.87
Pb	0.56	10.35	4.53	11.27
Cd	0.01	0.23	0.03	0.08
Sum	6578.17	28846.18	13442.6	35000.89

such as in-channel restorations, channel reconfiguration, and bank stabilization, which can reduce the supply of sediments to the river and ensure the safety of the lower reservoir.

Gravitational erosion such as bank erosion, which is the main sediment contribution at a catchment scale, has been reported worldwide (e.g., Collins et al. 2010; Kessler et al. 2012; Cashman et al. 2018; Risse et al. 2010). Zhang et al. (1992) and Wen et al. (2000) analyzed the ^{137}Cs content and concluded that gully erosion and gravitational erosion were the main sediment contribution for the upper reaches of Yangtze River. A similar result was received in our study. The stream bank contributed about 62.4% of the sediment to the catchment. Although sloping cropland was widely distributed around the catchment, a series of agricultural practices effectively reduced soil erosion and sediment delivery. The Central Government of China has initiated “Ecological reconstruction of the Upper Yangtze River Basin” and enacted an afforestation/reforestation bill, that is, converting sloping farmland to terraces to mitigate serious soil erosion (Zhang et al. 2008). In the studied catchment, local farmers divided long slopes into short slopes, and converted gently sloping farmland into level terraces, which resulted in the reduction of sheet and rill erosion as well as runoff (Zhang et al. 2008). Most of the eroded soil from the upland terraces is transferred to the irrigated lowland terraces through sheet runoff and is deposited on the irrigated terraces. Such agricultural patterns could reduce the connectivity of stream networks, leading to the low contribution of sediment from croplands. However, our results are not consistent with the suggestion of some studies that sloping cropland is the primary sediment source for the upper reaches of the Yangtze River (Guo et al. 2014). This discrepancy may be related to the fact that there is a significant change in soil erosion in the different agricultural stages. Before the implementation of ecological projects, the region faced severe soil erosion with an erosion modulus of 6300 t/km^2 since many croplands were cultivated on steep slopes (Li et al. 2003). Since 1989, a series of agricultural practices including converting sloping farmland into terraces and sheet drainage have been implemented in many areas along the lower Jinsha River (Liu and Zhao 2004), which effectively reduced sediment erosion and changed the primary sediment source.

In contrast, the stream bank was major source of sediment (Figure 4; Mean: 62.4%; range: 1.9%-84.4%) input to the stream network. The high contribution of the stream bank to the sediment can probably be attributed to the gravity and wetness. In general, rainfall events could lead to slope instability and collapse since the shear stress of the flowing water is greater than the soil shear strength (Rodrigues et al. 2018). In addition, the instability induced by erosion, landslides, and collapse may prevent the growth of vegetation (Rodrigues et al. 2018). Although some soil-conservation programs have been implemented in this catchment, only a check dam located in the main channel was built in 2012, failing to mitigate serious stream bank erosion. Grassland was calculated to be the third largest source of sediment, with a contribution of 14.85% to the sediment. Many studies have demonstrated that grasslands could significantly reduce splash erosion caused by the kinetic energy of rainfall on surface soil (Ludwig et al. 2005; Fu et al. 2009), and biological soil crusts (Moore and Singer 1990) and plant roots reduce erosion due to the improvement of the soil's physical properties (Valentin et al. 2005). Similarly, forest land had only a small contribution to the sediment, indicating that forest management strategies are also effective in reducing soil erosion. As has been determined by other studies, forest land does not represent a significant sediment source and only contributes a small amount of sediment (Walling et al. 1999; Collins et al. 2010).

Many studies have shown that the number of tracers, the effect of particle size, and the organic matter content can cause uncertainty and exert a strong influence on many of the tracers used in fingerprinting (Motha et al. 2003; Pulley and Rowntree 2016; Collins et al. 2017). Correction factors are used in many cases as the geochemical concentrations of soil and sediment samples have been shown to be strongly correlated with both particle size distribution and organic matter content (Horowitz 1991). Although we have ignored the impact of uncertainty on our sediment contribution calculations, the application of geochemistry provides the same results, suggesting that geochemistry is an effective tool in validating and assessing sediment contributions on the catchment scale.

However, there are two constraints on the geochemistry method compared with the fingerprinting method. First, the geochemistry of a catchment only can provide a qualitative assessment of sediment

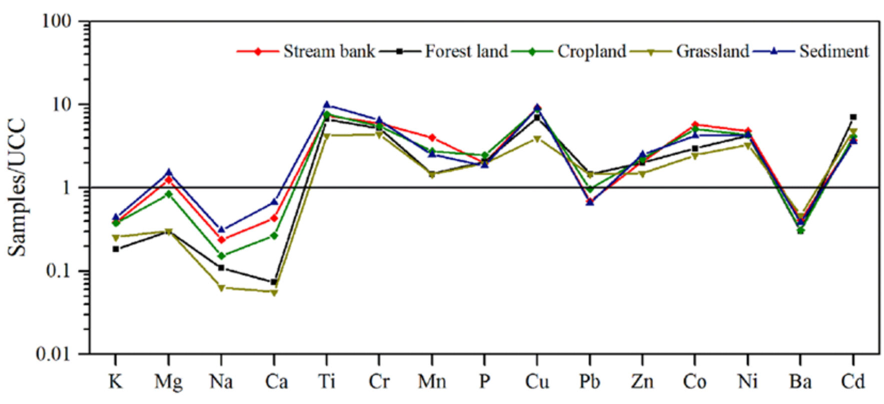

Figure 6 Upper continental crust normalized curves of the elements (UCC) in the different sediment sources and the sediments of the Luowugou catchment.

contributions, but it cannot provide a quantitative contribution. Secondly, many studies have shown that many elements in soils can change their activity due to the duration of weathering and specific climate conditions (Robinson and Johnsson 1997; Wronkiewicz and Condie 1987). Thus, we can divide the elements into active elements (Ca, Na, and K) and inert elements (Ti, Si, and Al) (Nesbitt et al. 1997; Zhang and Yue 2018). In large catchments, the sediments are more likely to be deposited and transformed during the transportation process, and they may be controlled by catchment processes such as denudation, transportation, deposition, and diagenesis (Bhatia and Crook 1986; Rollinson 1995). The above factors may have a large impact on element concentrations. In contrast to the traditional fingerprinting technique, there are simple steps that do not take into account the statistical analysis and computing methods, which have been widely used in many studies (e.g., Collins et al. 1996, 1998; Chen et al. 2016; Collins and Walling 2007). Additionally, the application of this approach ignores certain procedural steps, such as tracer conservation, tracer corrections, weighting, and statistical operations (Collins et al. 2017) that are included in the fingerprinting method.

Our results demonstrate that the main sediment source has significantly changed due to a series of soil-conservation programs, and thus, in this region, additional conservation measures should be taken on the stream bank rather than on cropland. In addition, our study concludes that the geochemistry represented by the distribution patterns and comparisons of major and trace elements has the potential to qualitatively discriminate between the contributions of individual sediment sources, which provides an alternative method to validate the reliability of fingerprinting results based on the same elements.

5 Conclusion

Sediment source contributions were evaluated for the Luowugou catchment in the lower Jinsha River, Southwest China, and two methods were used to identify sediment sources: the fingerprinting technique and geochemistry. This sediment fingerprinting study demonstrated that stream bank was unambiguously the main source sediment to the Luowugou catchment, and that conservation measures should be targeted on the stream bank rather than on the cropland. The results were consistent with those of geochemistry, suggesting that the sediment fingerprinting technique can be used to trace the sediment sources. Moreover, geochemistry has the potential to qualitatively discriminate between a wide range of different types of sediment sources, such as stream bank, cropland, grassland, and forest land.

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