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Sediment provenance in the Shudu Lake basin, northwest Yunnan Province, China, as revealed by composite fingerprinting

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Abstract

Composite fingerprinting represents an effective method of reconstructing sediment-source changes in remote areas where long-term hydrological and sediment accretion records do not exist. A ca. 50-year record of sediment deposition was determined for a small catchment at Shudu, situated in northwest Yunnan Province, China. Woodland, pasture, shrubland and channel bank material are identified as the most likely sediment sources and this was confirmed using a composite sediment fingerprinting approach. Based on the findings of the fingerprinting technique, variations in the geochemical signature associated with lacustrine sediment deposits indicate that 49.2 % of the total catchment sediment yield over an approximate 50-year period originated from channel banks. In contrast, 19.2 % originated from pasture, 18.6 % originated from shrubland, and 13 % from woodland. The relative contributions of eroded sediment from both woodland and shrubland have generally remained stable over the period investigated, whereas the contribution of material from pasture has increased over recent decades. This is tentatively attributed to increased grazing pressure, which is probably due to increased stocking densities which have gradually exceeded the carrying capacity and regenerative capabilities of the available grassland.

Zusammenfassung

Composite-Fingerprinting stellt eine effektive Methode zur Rekonstruktion von Veränderungen in der Herkunft von Sedimenten in abgelegenen Gebieten dar, für die hydrologische und sedimentbezogene Langzeitaufzeichnungen nicht vorliegen. Für das kleine Einzugsgebiet des Shudu im Nordwesten der chinesischen Provinz Yunnan wurde für einen Zeitraum von ca. 50 Jahren die Sedimentation ermittelt. Wald, Weide, Buschland und Uferbänke wurden als wahrscheinliche Sedimentquellen identifiziert, was durch die Composite-Fingerprinting-Untersuchung der Sedimentproben bestätigt wurde. Auf der Grundlage der Ergebnisse aus der Fingerprinting-Untersuchung zeigen die Veränderungen der geochemischen Signatur in den Seesedimenten, dass 49,2 % der gesamten Sedimentfracht des Einzugsgebiets in dem 50-Jahre-Zeitraum aus Uferbänken stammt. Im Gegensatz dazu entstammen 19,2 % von Weideflächen, 18,6 % von Buschland und 13 % von den Waldflächen. Die relativen Anteile von Wald und Buschland an der gesamten Sedimentfracht sind dabei im Untersuchungszeitraum generell konstant geblieben, während der Beitrag der Weideflächen zur Sedimentfracht insgesamt in den letzten Jahrzehnten zugenommen hat. Dies kann vermutlich auf eine verstärkte Beweidung zurückgeführt werden, für die wiederum wahrscheinlich höhere Bestockungsdichten ursächlich sind, die allmählich die Tragfähigkeit und Erneuerungskapazität des zur Verfügung stehenden Graslandes überstiegen haben.

Keywords Yunnan Province, China; lake catchment; composite fingerprinting technique; sediment source

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1. Introduction

1.1 Soil erosion assessment

Concern over past and current levels of environmental degradation has intensified interest in soil erosion and suspended sediment delivery in lacustrine and fluvial catchment systems. A sustained loss of fine-sediment and sediment-associated nutrients and contaminants, particularly from agricultural areas, gradually reduces land capability and also results in diffuse pollution ultimately entering into both lentic and lotic systems. This can lead to severe environmental problems, due to the deleterious effect of these contaminants on the health of aquatic ecosystems (*Walling* and *Collins* 2008, *Russell* et al. 2001). Identifying potential sediment sources is of paramount importance, since it allows catchment managers to make informed decisions about land-management strategies for key areas that potentially pose the highest risk of erosion. The provision of such information is integral to the design of effective soil conservation measures as it allows managers to tailor particular erosion prevention strategies to more effectively target erosion 'hot-spots'. Identifying the main sediment conveyance routes within catchments, coupled with the implementation of effective soil conservation strategies, is currently viewed as one of the most effective ways of controlling soil erosion, and, by default, also minimising environmental degradation (*Walling* et al. 2006; *Walling* and *Collins* 2008).

1.2 Advances in measuring soil erosion

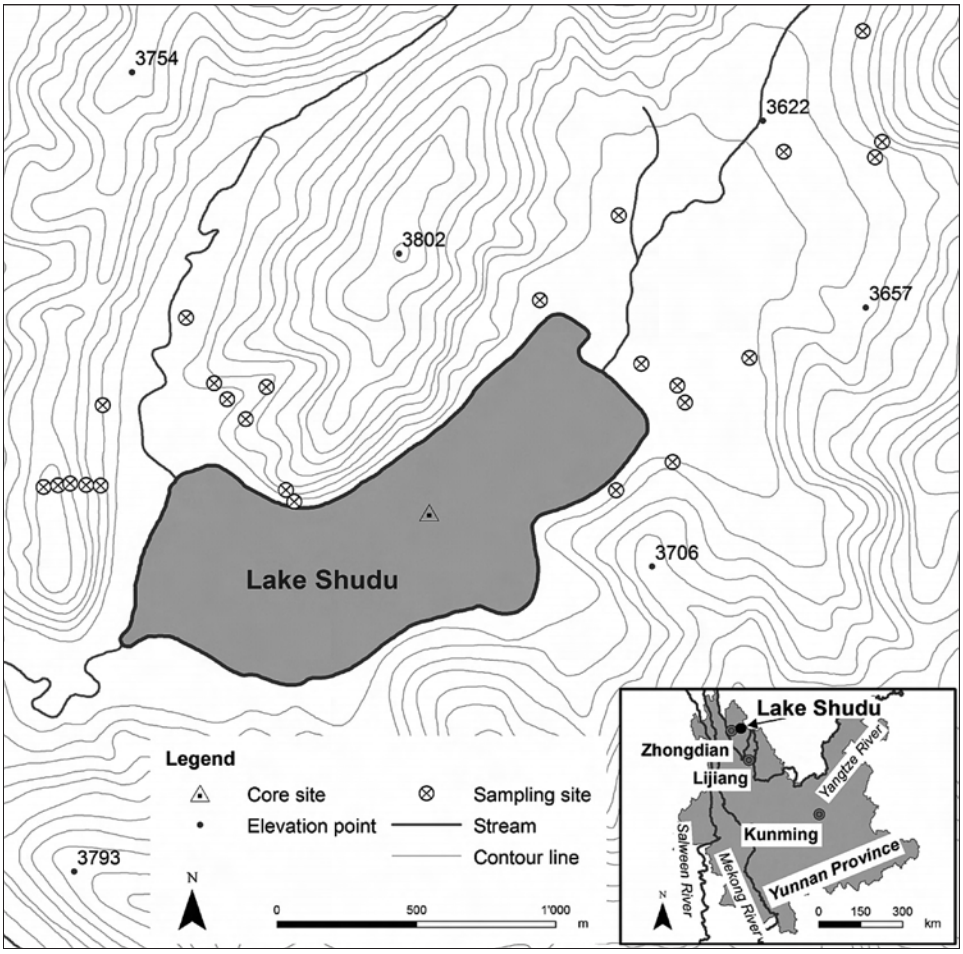
Obtaining reliable data on erosion rates at appropriate spatial and temporal scales has often been hampered, however, by an absence of historical records. Against this background, the development of indirect erosion measurement techniques has proven invaluable for estimating soil erosion in remote catchments where prolonged monitoring of hydrology and sediment-related characteristics is not possible. Indirect techniques include, among others, aerial photographic records, photogrammetry and remote sensing. Although these approaches are not new, recent technological improvements in data capture, digitisation and storage have increased the ease with which spatial and temporal dynamics of hydrological and sediment-related processes can be compiled at the catchment scale and beyond. Indeed, increased computing power has now facilitated the ease with which large data sets, often spanning many decades, can be analysed, queried and interrogated using just a personal computer (PC). One crucial limitation of these techniques, however, is the large spatial scale over which data is typically acquired (*Loughran* 1989, *Stroosnijder* 2005). Consequently, obtaining detailed information on sediment pathways at the hillslope scale and smaller is often not possible (*Walling* 1990, *Collins* and *Walling* 2004).

1.3 Sediment fingerprinting

In response to this limitation, a number of alternative indirect approaches have been developed which permit changes in sediment source to be retrospectively assessed over contemporary timescales (*Collins* et al. 1997b, *Collins* and *Walling* 2002, 2004; *Walling* et al. 2006). One such approach is through the use of sediment 'fingerprinting'. This technique has grown in popularity in recent years, due to its potential for estimating the provenance of suspended sediment and for ascribing sources of eroded material to particular land-use types (e.g. *Walling* and *Woodward* 1992; *Collins* et al. 1997a, 1997b). From a management perspective, the technique has increasingly become prominent when developing catchment management and sediment control strategies (*Walling* 2005, *Walling* et al. 1999, *Walling* and *Collins* 2008), where it is now frequently seen as a cheaper and altogether more convenient alternative to direct monitoring approaches.

Two fundamental assumptions underpin the sediment fingerprinting approach. The first is that the geochemical properties of potential sediment sources for any given catchment can be used to construct a composite 'fingerprint' which is unique to, and can distinguish between, different vegetation or land-use types. The second assumption is that the geochemical properties of suspended sediment (or floodplain and lacustrine deposits) can be compared against the fingerprint obtained from the source material, and thus provide an indication of source of the eroded sediment (*Walling* and *Woodward* 1992, *Collins* and *Walling* 2004). Analyses of the source material are undertaken to determine the geochemical characteristics and the results are then subjected to discriminant function analysis. This determines statistically which particular geochemical properties should be included in the fingerprint. A multivariate mixing model is then used to estimate which proportions of the eroded material originate from which particular land-use type (*He* and *Owens* 1995, *Walling* and *Woodward* 1992, *Collins* et al. 1997a, 1997b, 2010a, 2010b, 2012).

Fig. 1 Location of Lake Shudu catchment in Yunnan Province and location of the sampling sites



Where historical records of suspended sediment are incomplete or data sets are too short to be reliable, seasonal variations in flow regimes frequently alter the characteristics of the suspended sediment and can often compromise the representativeness of the available data (*Owens* et al. 1999). Given the likelihood of misinterpreting the available information, the physical and geochemical characteristics of lacustrine deposits offer an alternative means of reconstructing and interpreting environmental conditions over recent time periods (*Foster* and *Walling* 1994; *Foster* et al. 2005, 2007, 2008, *Rowntree* et al. 2008, *Boardman* and *Foster* 2011).

In China, records of surface runoff and suspended sediment characteristics are absent for many small drainage basins, particularly those in remote areas where logistical constraints, amplified by poor or only very rudimentary infrastructure, have prevented longer-term studies from being implemented. Given the prevalence and spatial distribution of small lake catchments throughout much of rural China, many of which are largely unmanaged, these systems offer a rich source of environmental information that, as yet, remains largely untapped. Information from these areas could provide a composite environmental record of their response to the influence of climatic and/or climate-driven land-use and associated hydrological changes (*Cook* and *Jones* 2012). In the absence of long-term records, however, the physical and geochemical characteristics of lacustrine deposits, particularly from unmanaged catchments, are of particular interest to geoscientists, since they offer a means of retrospectively studying their response to climate and land-use changes, and how these changes may influence surface hydrology and erosion rates in the future (*Zhang* et al. 1997). Against this backdrop, the physical and geochemical properties of lacustrine deposits were investigated in the Lake Shudu catchment in southwest China, in order to provide evidence of climatic/land-use driven changes in sediment source over the last 50 years.

2. The study catchment

Shudu catchment is located in the northwest of Yunnan Province, southwest China (27° 54’ 36” N, 99° 57' 02" E), lies at an average elevation of ca. 3,600 m asl., and covers an area equivalent to 13.7 km^2 (*Fig. 1*). Lake Shudu broadly lies at the centre of the drainage basin and has an average surface area of 1.16 km^2, which is equivalent to 8.5 % of the total catchment. The lake is fed by two small watercourses which drain the northern and eastern parts of the catchment. The west side of the lake is bounded by a moraine which has been dissected at its southerly end and now forms the lake outflow. The catchment geology is essentially uniform throughout and is dominated by Triassic mica schist, with very occasional limestone outcrops. Complete annual precipitation records for the region were obtained from a weather station located in nearby Zhongdiang for 11 years only, from a total period spanning 1963-1997. This was used to derive mean annual precipitation for the area which was estimated to be 461.4 mm per year (Tutiempo 2012). This should be treated with some caution, however, due to the limited data set from which it is derived, and because of the high within-sample variability (± 202.3 mm yr.$^{-1}$) for those 11 years. As mentioned above, no fluvial or sediment-related records are available for this catchment.

The eastern and southern parts of the catchment are characterised by a gentle relief with slopes typically ranging between 5 and 9 % (3-5°), with a maximum gradient of 14 % (8°). This contrasts with the western and northern parts of the basin where slopes of between 27 and 70 % (15-35°) are common.

Woodland, pasture and shrubland represent the three main vegetation types within the catchment (*Fig. 2*). Woodland is predominantly located in the southerly and extreme easterly parts of the catchment, whilst some smaller areas are also located directly to the north of the lake. In total, woodland accounts for 57.3 % (7.84 km^2) of the catchment area. Shrubland is located exclusively along the west/northwest boundary of the catchment and accounts for 8.7 % (1.19 km^2) of the total catchment area. Pasture lies immediately to the east of the lake

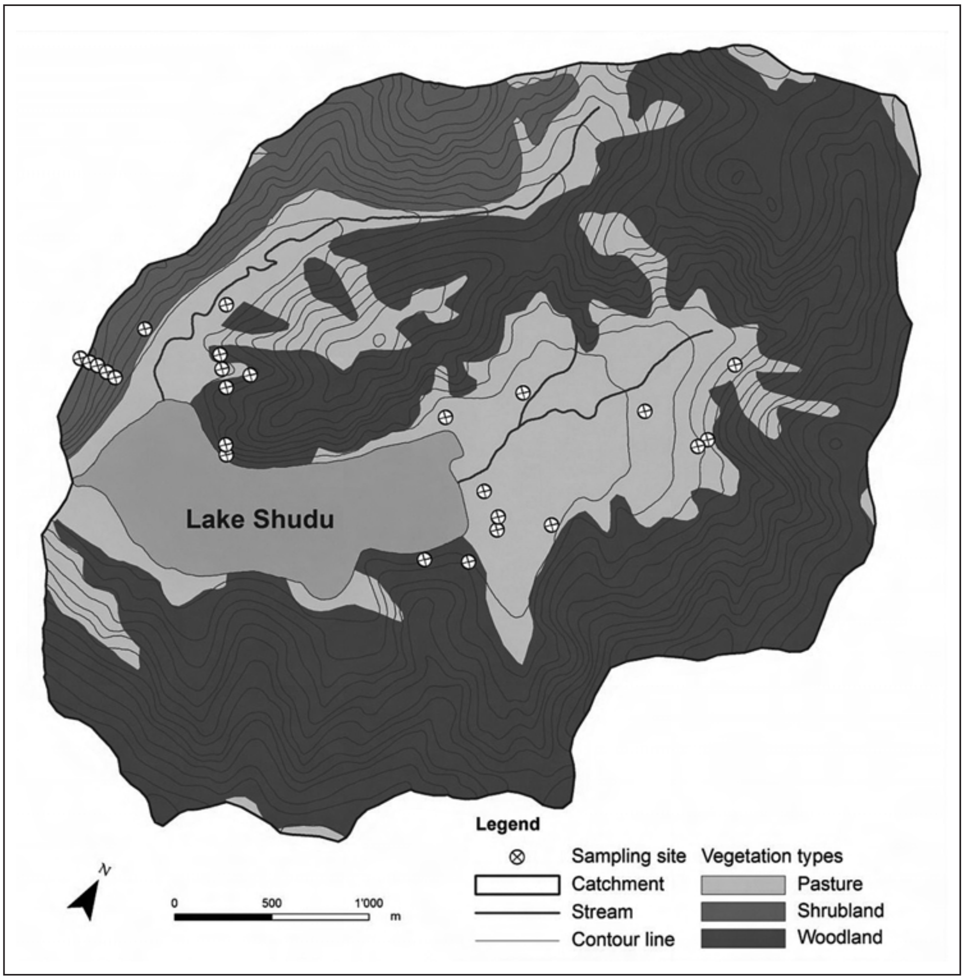


Fig. 2 Vegetation types in Lake Shudu catchment

Tab. 1 Wilks' lamda values and associated significance levels derived from the Kruskal-Wallis test undertaken on varying elements

Parameter	Wilks' lambda	*P* value
Al	12.443	0.006
Ba	9.379	0.025
Be	8.908	0.031
Ca	16.13	0.001
Co	23.722	0.001
Cr	22.257	0.001
Cu	14.334	0.002
Fe	20.152	0.001
K	15.171	0.002
Mg	15.914	0.001
Mn	4.993	0.172
Na	20.145	0.001
Ni	20.327	0.001
P	7.349	0.062
Sr	17.943	0.001
Ti	20.672	0.001
V	12.822	0.005
X	13.625	0.003
ARM	9.158	0.027
IRM (1000)	12.756	0.005
S-ratio	11.897	0.008

Critical H-value = 6.12; $P < 0.05$

and represents the dominant vegetation type within this area. In addition, a narrow band also lies to the northeast part of the catchment and generally follows the route of the stream to form a floodplain. Other smaller fragments also lie immediately to the south and west of the lake's edge. In total, pasture accounts for the remaining 25.5 % (3.49 km^2) of the area. Shrubland and wooded areas in the west and north of the catchment were assumed to pose the greatest erosion risk, by virtue of the very steep slopes on which they are located.

3. Materials and methods

3.1 Field sampling

A strategy was designed to collect soil and sediment samples that were most representative of the type of material currently being transported to watercourses. Sampling was focused on particular landform features within the three vegetation types that exhibited visible evidence of erosion. These included gullies, channel banks and slippage scars. In addition, channel bank material was also collected at equidistant locations (approximately 200 m) along the length of both watercourses. Material from vegetated source areas was obtained at an average depth of ca. 200 mm below the soil surface, which generally corresponded with the base of the root zone. Channel bank material was obtained at a depth of ca. one metre below the soil surface and this corresponded with the observed zone of active erosion.

In total, 100 samples of source material were collected from locations throughout the catchment (*Fig. 2*), 46 of which were obtained from the channel banks, with the remainder collected equally from the three vegetation types identified above. In order to investigate temporal changes in catchment sediment dynamics, a short (i.e. approximately 200 mm) core was also recovered from the approximate central point of the lake (*Fig. 1*) using a simple gravity-corer (internal diameter 75 mm) for the purpose of reconstructing a depositional chronology of the lake sediment. Although attempting to construct a representative depositional chronology based on a single core inevitably places the accuracy of the obtained dates into doubt, this strategy, however, was unavoidable and was dictated by logistical constraints that placed strict limitations on the amount of sample material that could be transported out, due to the remoteness of the location and the very rudimentary infrastructure serving the region.

3.2 Laboratory analyses

For samples undergoing geochemical analysis, 0.5 g of material, weighed to within 0.0001 g, were prepared following an established protocol (Anon 2005) and analysed on either a Unicam 939 Flame Atomic Absorption Spectrometer (FAAS) for heavy metals, or an Inductively Coupled Plasma-Mass spectrometer (ICP-MS) for all other elements. The range of geochemical elements investigated included trace metals (Fe, Mn, Al, Be), heavy metals (Cu, Zn, Pb, Cr, Ni, Co, V), and base cations (Na, Mg, Ca, K). Sample preparation for heavy metal extraction involved using a nitric acid (HNO_3) and hydrochloric acid (HCl) digestion. Samples of both Certified Reference Materials (CRMs) and House Reference Materials (HRMs) were digested and simultaneously analysed to determine the relative extraction efficiencies. These were calculated at between 93-96 %. The resultant data were not corrected for recovery inefficiencies.

In order to obtain information on the physical characteristics of samples, absolute particle size composition and specific surface area (SSA) (expressed in $m^2\ g^{-1}$) was determined using a Malvern Mastersizer laser granulometer. Samples were subjected to an established pretreatment to decompose organic matter and to determine absolute size values of sample material. This involved adding 5 ml of hydrogen peroxide (H_2O_2), followed by 5 ml of sodium hexametaphosphate ($(NaPO_3)_6$) as a dispersing agent and then heating each sample to ca. 80°C for ca. 12 hours, or until a clear supernatant was obtained (*Collins* et al. 1997b; Anon. 2005).

A depositional chronology was established for the lake sediment using the fallout history of the anthropogenic gamma-emitting radionuclide ^{137}Cs ($t_{0.5}$ = 30.2 yrs.) (*Collins* et al. 1997a; *Foster* et al. 2005, 2007, 2008). The core was sectioned in 5 mm intervals and samples were prepared for radiometric assay following the established protocol reported by *Pennock* and *Appleby* (2002). Gamma assay was performed on a hyper-pure germanium (HPGe) coaxial detector (relative efficiency; 53.8 % for ^{60}Co: measured at 1,331 keV). The mean counting time for samples was in the region of 55,000 s which provided an error uncertainty of around < 10 % ($P < 0.05$). Upon compiling and presenting the radiometric data graphically, sediment horizons recording peak activities could then be readily identified and attributed depositional dates based on the global fallout history of ^{137}Cs.

4. Results and discussion

4.1 Composite fingerprinting

The results from the geochemical analyses indicated that some elements were strongly correlated with the depth of burial, and hence with the time of deposition. It was therefore necessary to exclude them from the fingerprint (*Walling* 2005). To differentiate between potential source types, it was also necessary to evaluate the ability of each element to discriminate between potential source areas. This was achieved using a two-stage statistical verification procedure, which resulted in multi-component signatures which were able to discriminate between different source types (*Collins* et al. 1998; *Walling* et al. 1999; *Carter* et al. 2003). The non-parametric Kruskal-Wallis H-test was used to determine which elements exhibited significant differences between source areas within the Shudu catchment. The results of the test are summarised in *Table 1*. The critical H-value for the catchment is 6.12 ($P < 0.05$). With the exception of two elements, Mn and P ($P > 0.05$), all other elements yielded H-values in excess of the corresponding critical value ($P < 0.05$). This provided evidence of their ability to discriminate between areas identified as potential sediment sources and indicated those elements that should be included to form a composite fingerprint.

Tab. 2 Summary of the output data from the Wilks' lambda test

Element	Wilks' lambda	Cumulative correction (%)
Ti	0.38	56.4
Cr	0.159	62.4
X	0.033	82.6
Cu	0.018	90.5
Fe	0.009	100

A multivariate discriminant function analysis was performed on the data in order to construct a composite fingerprint capable of correctly discriminating 100 % of the source material used to characterise the different source types. In this analysis, which follows the protocol reported by *Collins* et al. (1997b), a stepwise selection algorithm was used based on the minimisation of Wilks' lambda values. A lambda value of 1 indicates that all group means are equal and close to zero. This, in turn, indicates that the within-group variability is small compared against total variability. Low lambda values thus provide an indication of the efficiency with which individual elements are able to effectively discriminate material from different source types. Results from the Wilks' lambda test are summarised in *Table 2*.

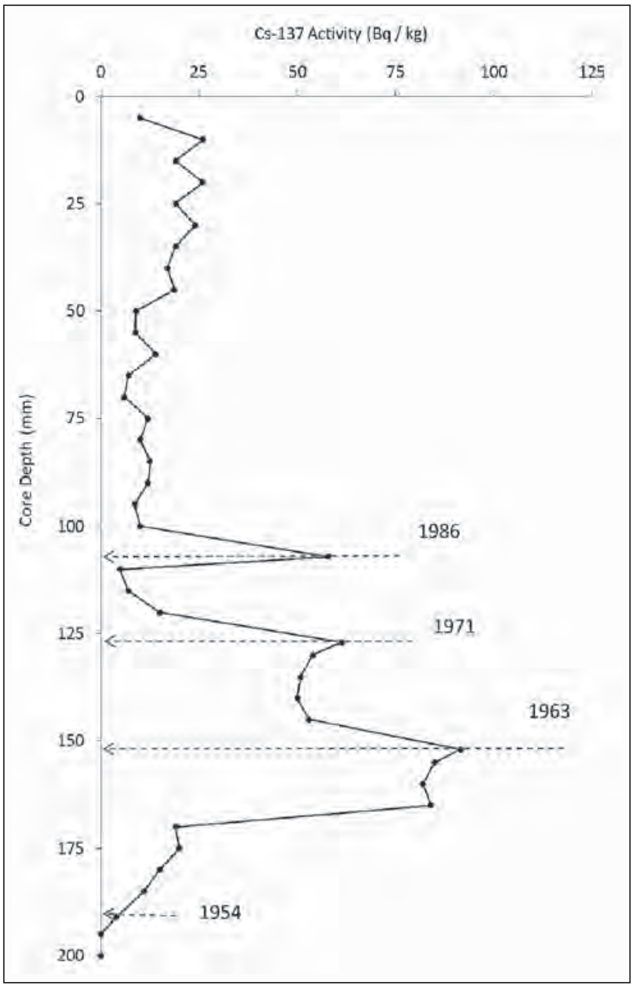


Fig. 3 Depositional fallout history of ^{137}Cs, as recorded in a short core of sediment obtained from Lake Shudu

4.2 Sediment source ascription

The relative proportions of lake-derived sediment originating from the four source areas were estimated using a multivariate mixing model (*Collins* et al. 1997a; *Walling* et al. 1999), which is described in the following Equation:

$$R_{es} = \sum_{i=1}^{n} \left(\frac{C_{ssi} - (C_{si} P_{si} Z_{gi})}{C_{ssi}} \right)^2$$

where R_{es} represents the relative proportion of lake-derived sediment originating from each of the four source types; C_{ssi} represents the relative concentration of each geochemical element in each sediment sample; C_{si} represents the mean geochemical concentration in each source area; P_{si} represents the relative proportion of sediment from each source area in individual samples; and Z_{gi} represents the particle size correction factor, expressed as the ratio of the mean SSA of lake-derived sediment divided by the mean SSA for each source area.

Suspended sediment is generally enriched in fine material when compared against source-area material and will thus frequently exhibit a higher concentration of certain elements than coarse-grained source material (*Walling* 2005). The influence of grain size composition between source material and suspended sediment was accounted for by restricting analyses to the < 63 µm fraction for all samples. However, in order to permit a direct comparison of the fingerprinting properties, a further correction for source and sample material was required. The SSA of sediment (expressed as $m^2\ g^{-1}$) closely reflects particle size distribution and associated geochemical concentrations (*Horowitz* 1995). A correction factor was used in this study based on the SSA of samples, in order to account for the differences in both source area and sample material. Using estimates of the particle diameter distribution, and assuming that all particles are spheroidal in shape, the output from the Malvern Master-Sizer software provided estimates of SSA values for sample material. The total surface area of each source sample was then divided by the percentage volume of a given sample with the same size fraction (Anon. 2005).

Specific surface area values for the four source types are listed in *Table 3*. Property concentrations derived from all source-area and sample material were corrected to a standardised SSA equivalent to 1 g cm^{-3}. A correction factor was obtained by calculating the SSA of lake sediment as a ratio of the mean SSA of reference material from each potential sediment source. The results of the particle size correction factor were then integrated into the optimised mixing model, which ensured that the source material concentrations were comparable with sample concentrations (*Collins* et al. 1998). No correction was made for differences in organic matter content or source material and sediment samples, due to the complex relationship that exists between organic matter content and the relative concentrations of the different elements.

4.3 Using lake sediments to reconstruct a chronology of sediment-source changes

Variations in the geochemical properties of lacustrine sediment deposits have been successfully used in previous investigations to reconstruct catchment-scale infor-

Tab. 3 Mean SSA and % coefficient of variation values for the four source types and for the lacustrine sediment

Source type	Mean SSA ($m^2 g^{-1}$)	Coefficient of variation (%)
Woodland	1.12	23.52
Pasture	0.86	18.36
Shrubland	0.95	32.05
Channel bank	0.82	23.46
Lacustrine sediment	1.18	28.42

mation on sediment-source changes over contemporary timescales (i.e. 50-100 yrs.; e.g. *Collins* 1997a; *Foster* et al. 2007, 2008). Relative changes in sediment source have frequently been placed into a temporal perspective using the dateable fallout history of the anthropogenic radionuclide ^{137}Cs. As described earlier, a number of maxima are readily identifiable in lake deposits in western China and these can be used to construct a depositional history since 1954, when its distribution was assumed to be global and generally homogeneously distributed. The vertical distribution profile of ^{137}Cs in the sediment core recovered from Lake Shudu is shown in *Figure 3*. The presence of three notable ^{137}Cs peaks generally agrees with vertical distribution profiles of cores taken from small lacustrine systems elsewhere in southwest China (e.g. *Wan* 1998, *Yan* et al. 2002, Chen et al. 2009).

4.4 Reconstructing sediment accretion rates

The core from Lake Shudu was ca. 200 mm in length, which was sufficient to capture the entire ^{137}Cs fallout inventory. The largest maximum, measuring an equivalent of 91.6 Bq kg^{-1}, was recorded at a depth of 152 mm and is duly attributed to the year 1963 when atmospheric testing of high-yielding thermonuclear weapons peaked (*Ritchie* and *McHenry* 1990, *Walling* and *Quine* 1990). Despite a worldwide treaty being signed that same year effectively banning further atmospheric tests, a second ^{137}Cs peak can be identified in lake deposits around many parts of southwest China. This is due to China, a non-signatory of the treaty, continuing with an intensive programme of atmospheric trials at a test site located ca. 1,600 km north of Lake Shudu (*Ritchie* and *McHenry* 1990, *Wan* 1998, *Yan* et al. 2002, *Simon* et al. 2006, *Chen* et al. 2009). The second largest maximum, which measured an equivalent of 61.3 Bq kg^{-1}, was recorded at a depth of 127 mm and is attributed to the year 1971 when fallout from these Chinese tests reportedly peaked (*Ritchie* and *McHenry* 1990, *Wan* 1998, *Yan* et al. 2002, *Chen* et al. 2009). At 57.9 Bq kg^{-1}, the third and smallest identifiable ^{137}Cs maximum was recorded at a depth of 107 mm and is attributed to the 1986 Chernobyl nuclear

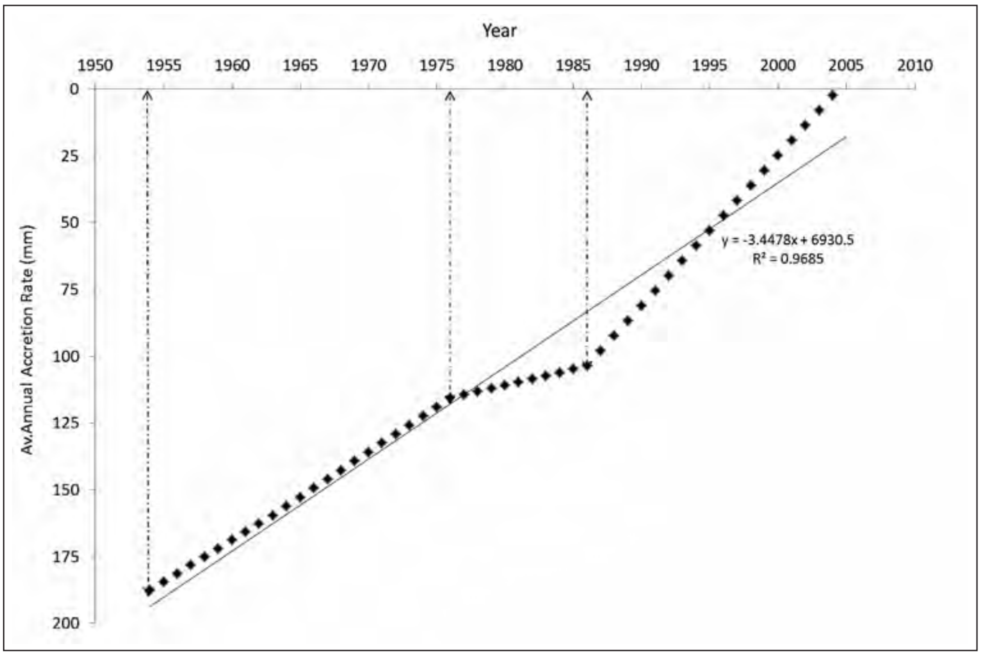
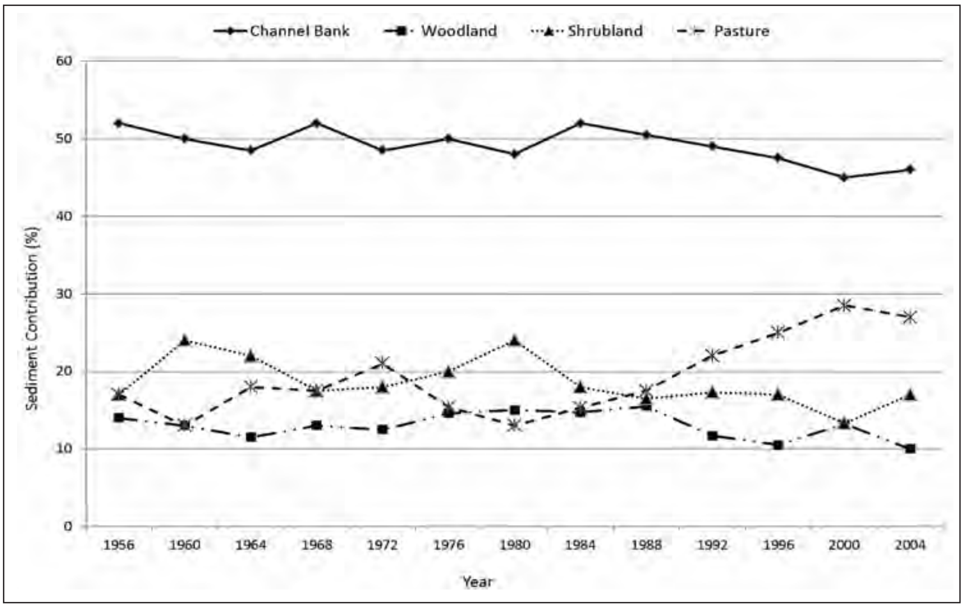


Fig. 4 Depositional history of the anthropogenic fallout radionuclide ^{137}Cs used to provide estimates of depth-age relationships for a core of lacustrine sediment from Lake Shudu and to reconstruct average annual accretion rates for the period 1954-2005

Fig. 5 Results of the mixing model analysis to determine recent changes in sediment source from each of the potential source areas in the Shudu catchment



reactor accident (*Wan* 1998, *Yan* et al. 2002, *Chen* et al. 2009). From the profile shown in *Figure 3*, a fourth date of 1954 is also tentatively attributed to a depth of ca. 190 mm, corresponding to the year when ^{137}Cs was distributed globally and accumulated in sufficient quantities that it became easily measurable in most soils around the world (*Ritchie* and *McHenry* 1990).

- Age-depth relationships were derived by interpolating ^{137}Cs peaks, which enabled the depth of sediment deposited in the lake to be determined. Dates were then ascribed to the three peaks. These, combined with the 1954 date when ^{137}Cs was first detected in measurable quantities, were calculated and divided between each time period in order to derive average annual accretion rates. Dry bulk density values obtained for individual samples ranged from ~ 1.1 to 1.3 g cm^{-3} and there was no correlation between depth and bulk density ($P > 0.05$). The effect of sediment compaction due to overlying material, and to variations in pore space and water content, were thus considered negligible on such a shallow core.

- Average annual accretion rates were estimated at 3.11 mm $yr.^{-1}$ for the period 1954-1963, 3.38 mm $yr.^{-1}$ for the period 1963-1971, 1.2 mm $yr.^{-1}$ for the period 1971-1986, and 5.6 mm $yr.^{-1}$ for the period 1986-2005. Average annual accretion rates for each respective time period are presented cumulatively for the 1954-2005 period (*Fig. 4*). A linear regression function was fitted to the data set ($R^2 = 0.97$) and this highlights three distinct phases where accretion rates differ markedly. For the period 1954-1976, the rate of accretion generally follows the trend predicted by the regression function. For a 10-year period from 1976 to 1986, however, the rate of accretion diminishes markedly, but thereafter increases sharply from 1986 onwards.

- A mixing model was used to estimate changes in sediment source for the previous ca. 50-year period, the results of which are shown in *Figure 5*. *Table 4* also summarises varying descriptive information relating to the relative contribution of sediment from each source area over the previous 50-year period. Included within this information is an error value for each source area which is used to quantify the within-sample variability of each data set and thus provides an indication of relative stability of each source area.

- The average contributions of sediment from the four source areas over the 50-year period were estimated at 49.2 % from channel banks, 19.2 % from pasture, 18.6 % from shrubland and 13 % from woodland. Erosion from channel banks represented a major sediment source throughout the 50-year period, with minimum and maximum contributions ranging from 45-52 %. The relative contribution peaked on two separate occasions, at depths corresponding to 187 and 147 mm in the lake deposits, which equate to the years 1956 and 1968, respectively. The minimum 45 % input was recorded at a depth of 20 mm in the lake deposits, which equates to a date of ca. 2002. Despite the sharp increase in

Tab. 4 Descriptive data summarising the relative percentage contributions of sediment from the four source areas

	Channel bank	Woodland	Shrubland	Pasture
Av. (%)	49.2	13.0	18.6	19.2
Min. (%)	45	10	13.3	13
Max. (%)	52	15.5	24	28.5
Range (%)	7	5.5	10.7	15.5
+ - Error (%)	7.1	21.1	28.8	40.3

annual accretion rates recorded from 1986 onwards (*Fig. 4*), paradoxically, the relative contribution of material from channel banks gradually decreased over this latter period.

- Despite the generally high values, the ± error value of 7.1 % (*Tab. 4*) represents the lowest of the four source areas and infers that the contribution of sediment, although consistently high throughout the 50-year period, has generally remained relatively stable.

- Despite the slight decrease in material originating from channel banks over recent decades, the overall results highlight their importance as a major contributor of sediment in the Shudu catchment. Field observations of riverbank degradation, made at the time of sampling, support this general conclusion. Possible reasons for the high rates of erosion may relate to the coarse glacio-fluvial material of which channel banks are composed. A lack of fine material would provide poor cohesion and low structural integrity. The nature of the material would thus render them highly erodible and particularly susceptible to the effects of poaching by livestock, which were prevalent in the catchment, presumably whilst gaining access to the streams in order to obtain drinking water. Once the surface vegetation has been trampled and the soil is exposed, the structural integrity of the channel banks would be quickly compromised, and areas subjected to excessive poaching would almost certainly become a focal-point of accelerated erosion. Despite the fact that channel banks are generally on flatter land, their susceptibility to poaching and erosion may explain why these particular landform features within this particular catchment continued to represent the predominant sediment source throughout the last half-century. Repeated poaching of channel banks as livestock congregate along riparian zones, presumably in a quest to gain access to drinking water, would quickly reduce the integrity of the channel banks and render poached areas vulnerable to erosion, most of which would probably occur during the snowmelt season when river levels are highest.

Although woodland occupies > 57 % of the total catchment area, it generally represents the lowest sediment contributor of the four source areas, with amounts ranging from 10 to 15.5 %. These low values, along with the small data range, would suggest that woodland areas have been relatively stable throughout the previous 50-year period. However, the ± error value of 21.1 % (*Tab. 4*) infers that woodland soils are vulnerable to disturbance. A likely cause of the fluctuating sedimentation rates may relate to clear-fell logging practices which were also observed at the time of sampling. Cycles of clear-fell logging would presumably be followed by periods of forest regrowth and increasing vegetation cover, thereby increasing the overall stability of the soil surface in such areas.

Occupying ~ 8 % of the total catchment area and with an average input of 18.6 %, shrubland represents the third smallest contributor of sediment. The minimum value of 13.3 % was recorded at a depth of 30 mm in the lake core, which corresponds with the year 2000. Two maxima, both measuring 24 %, were recorded at depths of 175 mm and 116 mm, which correspond with the years 1960 and 1980, respectively. Despite occupying only a relatively small proportion of the total catchment area, the ± error value of 28.8 % represents the third highest of the four source areas, indicating the vulnerability of the underlying soil to disturbance. Given the high elevation (3,750 m asl.) and mountainous terrain on which scrubland is located (i.e. 27-70 %), natural cycles of mass wasting and solifluction of material, initiated by freeze-thaw cycles, soil heave and nivation processes, are assumed to represent the dominant agents of erosion (*Brunsden* 1979, *Caviezel* et al. 2010). The very steep slopes within this part of the catchment would likely further exacerbate any downslope movement of material.

Although woodland covers the largest area within the catchment, its status, along with shrubland, as relatively low contributors of sediment is attributed to the dense vegetation cover that protects the underlying soil against erosion, particularly by processes inherent to alpine environments, such as frost heave, solifluction and mass wasting of seasonally thawed surface material. Furthermore, despite the fact that both vegetation types are located on relatively steep slopes, the low average annual precipitation for the region would imply that incidences of erosion by surface runoff are probably limited to the snowmelt season only. In addition, an altogether more fundamental reason for their comparatively low erosion rates is that neither vegetation type is vulnerable to trampling and overgrazing, since neither is a viable food source for bovine livestock.

With an average input of 18.2 % and occupying ~ 25 % of the catchment area, pasture represented the second highest contributor of sediment. The minimum input of 13 % was recorded at a depth of 174 mm, which corresponds with the year 1960. This contrasts with the maximum contribution of 28.5 %, recorded at a depth of 30 mm, which corresponds with the year 2000. Sediment inputs increased notably from 1980 onwards and this trend was generally mirrored, albeit commencing slightly later, by a gradual decrease in eroded material from channel banks. Possible reasons for the steady increase over recent decades may relate to increasing livestock densities, leading to the grassland soils becoming degraded. This is attributed to overgrazing and excessive livestock trampling. Moreover, both processes are believed to have facilitated the development of extensive and complex gully systems which were almost exclusively found within grassland areas. Drawing from field notes written at the time of sampling, many gully systems exhibited evidence of recent erosion, with many having developed into landform features reminiscent of 'badland' topography. At 40.3 %, pasture recorded the largest ± error value, indicating its sensitivity to disturbance, particularly by activities such as overgrazing as it represents the predominant food source of herbivorous animals (*Mwendera* and *Saleem* 1997). The relatively low annual precipitation for this region would imply that the erosion of soil from pasture by hydrological processes is limited. Given the potential dearth of incidences where surface runoff occurs, aeolian processes may thus even play a role in the mobilisation of surface material.

5. Conclusion

A geochemical fingerprint was compiled for four main sediment-source areas in the small and largely unmanaged Shudu Lake catchment situated in the northwest of Yunnan Province in southwest China. The aim of the investigation was to determine the influence of climate and/or land-use changes over the previous ca. 50-year period and to assess how these changes may have influenced surface hydrology and erosion rates. Within the constraints and limitations of the experimental techniques employed, the results indicate that 49.2% of lake-derived sediment originated from channel banks, 19.2% originated from pasture, 18.6% originated from woodland and 13% originated from shrubland. During the 50-year period, the relative contributions of material from woodland and shrubland both remained relatively stable. By contrast, sediment from channel banks consistently represented approximately half of the total lake deposits. Reasons for this are thought to be predominantly related to the coarse and highly erodible material which channel banks are composed of. In addition, the erodibility of the banks may be exacerbated by the effect of poaching as livestock gain access to the streams in order to obtain drinking water. With regard to pasture, the relative contribution of material fluctuates throughout the early part of the 50-year history and may reflect changes in livestock numbers within the catchment. The steady rise in sediment contribution beginning around 1980 onwards infers that pasture was becoming increasingly degraded. Reasons for this are attributed to increased land-use pressure, principally caused by overgrazing and trampling and are attributed to greater numbers of livestock than the catchment can support.

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