SCIENCE CHINA
Earth Sciences

• RESEARCH PAPER •

March 2011 Vol.54 No.3: 431–437
doi: 10.1007/s11430-010-4105-x

Application of a ^{137}Cs fingerprinting technique for interpreting responses of sediment deposition of a karst depression to deforestation in the Guizhou Plateau, China

ZHANG XinBao[1], BAI XiaoYong[1,3*] & LIU XiuMing[2]

[1] *Key Laboratory of Mountain Environment Evolvement and Regulation, Institute of Mountain Hazards and Environment, Chinese Academy of Sciences, Chengdu 610041, China;*
[2] *State Key Laboratory of Environmental Geochemistry, Institute of Geochemistry, Chinese Academy of Sciences, Guiyang 550002, China;*
[3] *Graduate School of Chinese Academy of Sciences, Beijing 100049, China*

Received February 23, 2010; accepted June 18, 2010; published online December 6, 2010

Deforestation to reclaim land often triggers severe soil erosion in the Guizhou Karst Plateau. ^{137}Cs dating of the deposited sediments in the karst depression bottom was used to estimate soil losses by surface erosion since deforestation started in 1979 on hillslopes in the Shirenzhai catchment, Puding County, Guizhou Province. The catchment has a drainage area of 0.054 km^2. The average ^{137}Cs contents of the top and peak layers in five cores of the depression bottom (with an area of 2652 m^2), collected in 2009, were 2.35 and 7.25 Bq kg^{-1}, respectively. The medium depths in the depression (which ranged between 84 cm and 113.5 cm with a mean value of 92.1 cm) showed the presence of sediments deposited in 1979. The total volume and weight of the deposited sediments since 1979 were estimated to be 1965 m^3 and 2496 t, respectively. The depression bottom can be treated as a temporary impoundment and its sediment trapping efficiency was estimated to be 0.7. The relevant average soil erosion rate on the hillslopes was 2315 t km^{-2} yr^{-1} since 1979. The mean ^{137}Cs inventory of the five cores was 7693 Bq m^{-2}, which was ~10 times the local reference inventory of 782 Bq m^{-2}. The total ^{137}Cs activity of the sediments in the bottom was 20.4×10^6 Bq, and the relevant ^{137}Cs inventory loss from the hillslopes was 358 Bq m^{-2} (since 1954), which accounted for 45.8% of the reference inventory. As soil erosion was not severe before and after the period of deforestation and following cultivation in 1979–1990, the erosion rates on the hillslopes could potentially reach 7000 t km^{-2} yr^{-1}.

^{137}Cs fingerprinting technique, karst depression, sediment deposition, deforestation, response

Citation: Zhang X B, Bai X Y, Liu X M. Application of a ^{137}Cs fingerprinting technique for interpreting responses of sediment deposition of a karst depression to deforestation in the Guizhou Plateau, China. Sci China Earth Sci, 2011, 54: 431–437, doi: 10.1007/s11430-010-4105-x

The Guizhou karst Plateau is a central area of exposed carbonate rock in Southwest China and one of the poorest regions in China [1]. Karst depressions are common landforms in the plateau [2]. Reclaiming land for cultivation has removed most of the indigenous evergreen forests and deforestation has brought about severe soil erosion in the plateau since the Qing dynasty (1636–1911) [3, 4]. Serious land desertification caused by soil erosion has important impacts on the local population and people's livelihoods, resulting in both social and economic problems in the plateau, particularly, in the areas where there are pure carbonate rock outcrops [5–7]. Soil erosion is minimal on the slopes under forest; however, erosion on the rocky slopes of severely degraded land is also minimal as the soils have largely already eroded [7, 8]. Further deforestation is likely to cause very severe soil erosion on the slopes, but data on erosion rates in this area is very limited.

For the karst depression landforms in the plateau, the

*Corresponding author (email: baixiaoyong@126.com)

closed depressions are mostly surrounded by steep hills and range in size from <1 ha to several hundred ha. There are commonly one or more sinkholes at the bottom of the depression. The bottoms of some depressions are frequently inundated with water after heavy rainfall because storm runoff from the contributing catchment is unable to drain rapidly through the sinkholes. As a result, sediment is mobilized from the surrounding slopes by erosion associated with the storm event, transported into the depression by storm runoff and deposited during heavy storms. Dating of the deposited sediments in the bottoms of such depressions can be used to estimate the rate of soil loss by surface erosion from the surrounding hillslopes in the catchment area. Classical investigation methods, such as runoff plots and hydrological monitoring stations, are difficult to use and to obtain reliable data from within a short timescale [9, 10] and hence we adopted the ^{137}Cs dating technique [11–28].

^{137}Cs is an artificial radionuclide with a half-life of 30.17 years, which was released into the environment as a result of atmospheric testing of thermo-nuclear weapons during the 1950s to the 1970s, with the maximum deposition rate occurring in the northern hemisphere in 1963. ^{137}Cs fallout occurs primarily in association with precipitation and the ^{137}Cs input to the land surface was strongly and rapidly adsorbed by fine particles in the surface horizons of the soil. The subsequent redistribution of ^{137}Cs has been associated with the mobilization and transport of soil and sediment particles. ^{137}Cs has been widely used since the 1980s' for assessment of soil erosion rates and for dating sediments in lakes, reservoirs and floodplains [10–28]. ^{137}Cs has been recently employed for assessing soil loss from karst slopes and for dating of sediment deposits in karst depressions in Southwest China [10, 17–21, 28]. Studies have demonstrated that the traditional ^{137}Cs technique is unsuitable for assessing soil erosion rates on karst slopes in Southwest China due to the discontinuous nature of the soil cover and the importance of cracks and fissures in controlling the spatial distribution of the soil [10]. However, the ^{137}Cs technique has been successfully used for dating the deposited sediments in karst depressions[1)]. This study reports our work on dating depression deposits using ^{137}Cs measurements to investigate erosion rates on hillslopes since their deforestation in 1979, in the Shirenzhai catchment, a small drainage basin in the Guizhou Karst Plateau of Southwest China.

1 Study area

The Shirenzhai catchment is near Chenjia Village, at approximately 26°13′10.03″N and 105°45′26.53″E, 8 km northeast of Puding, Guizhou Province, China. It is a small isolated karst hill-depression catchment and has a drainage area of 0.054 km^2 (Figure 1) The depression is surrounded by four hills. The hill top elevations vary between 1430 and 1470 m while the depression bottom has an elevation of 1300 m. The catchment is underlined by medium to thick limestone deposits, interrupted with a few thin shale layers, from the Triassic Guanling Group, which strikes NNW, dips to SWW and has a dip angle of about 25°. In the catchment, the slopes of the eastern two hills are relatively gentle with a gradient of about 25°, while the slopes of the western and southern hills are not consequent and have a gradient of >35°. From our survey, the flat depression bottom had a length of 68 m, an average width of 39 m and an area of 2652 m^2, which accounted for 4.9% of the catchment area. A sinkhole was located at the toe of the steep slope of the western hill having an exposed width of 0.8 m and a height of 0.7 m with its mouth being partly filled with sediment.

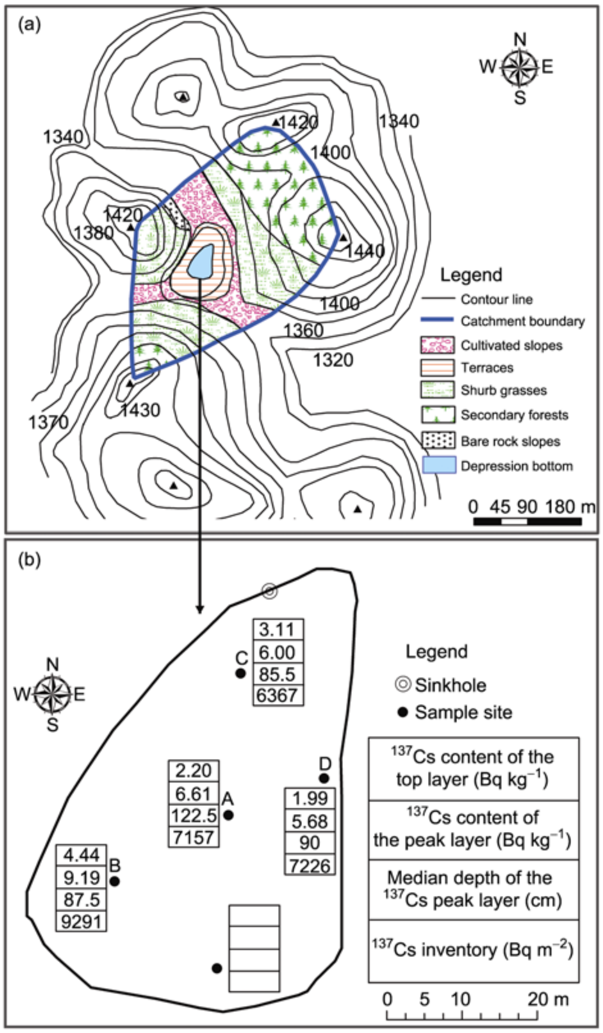

Figure 1 Present land use condition, the location of the cores sampled and ^{137}Cs characteristics of the cores in the Shirenzhai catchment. (a) Present land use conditions; (b) location of sampling cores and ^{137}Cs characteristics of the cores.

1) Zhang X B, Bai X Y, Wen A B, et al. A preliminary investigation of the potential for using the ^{137}Cs technique to date sediment deposits in karst depressions and to estimate rates of soil loss from karst catchments in Southwest China. IAHS, in press.

The region experiences a subtropical highland climate has annual rainfall of 1397 mm, 665 mm of which occurs in the wet season from June to August.

In April 2009, apart from the cultivated depression bottom, the cultivated land, secondary forests and shrub-grasses on the hillslopes had similar areas. Half of the cultivated land on the slopes was on terraces, which were protected by stone banks and distributed around the depression, while the rest was sloping land with a gradient of <15° on the western, northern and southeastern pass areas. Secondary indigenous forests are found on the upper slopes of the two eastern hills and on the top of the southernmost hill. Shrubs mixed with grasses were present on the lower slopes of the two eastern hills and on the slopes of the western and southern hills. There are rendzina soils on the slopes, however, most of the slopes were very rocky and covered with discontinuous thin soils except for the cultivated land on the gentle pass areas where the soil thickness varied between 10 and 40 cm like the terraces where the soils were generally deeper than 40 cm. There was a small block of land containing rocky outcrops which had an area of about 1000 m^2 on the steep lower slopes of the western hill.

After interviewing the local farmers, it was determined that before 1979, the catchment was covered with secondary forest except the flat cultivated depression bottom and the terraces around the depression bottom. Except for the present forests on the upper slopes of the two eastern hills and the top of the southern hill, the forests were all cleared between 1979 and 1981 because the land ownership rules in rural areas changed after the Cultural Revolution in China and farmers were given the right to cut down trees. The gentle slopes of the pass areas and the lower slopes of the two eastern hills were reclaimed for agricultural use after deforestation, but the slopes of the western and the southern hills were too steep for cultivation and were allowed to revert to shrub-grass land. Consequently, severe erosion occurred and a large amount of agricultural soil was lost and transported into the depression bottom. The newly cultivated land on the lower slopes of the eastern hills was abandoned after a few years' cultivation and it became shrub-grass land until 1990. The 'reclaimed' agricultural land obtained from deforestation was cultivated and stone banks have been used to protect it against soil erosion since the mid 1980s. Before 1979, sedimentation was very limited in the depression bottom. However, fast sedimentation has occurred since deforestation. Farmers showed us two terrace banks of about 1m in height on the side of the depression bottom that had been buried by the deposited sediments and added that "sedimentation mostly occurred before 1990".

The eroded soils from the hillslopes, transported into the depression bottom by runoff are very fertile. Two seasons' crops of maize and oil rape can be grown on the depression bottom land. From the interviews of the local farmers, we found that the depression bottom was often waterlogged when heavy storms occurred and at least two flooding events typically occurred in a year, with water retention times of more than 2 days for each event. The flood waters, which are temporarily stored in the depression bottom, partly penetrate the soils through infiltration and partly flow into the underground river system through the sinkholes.

2 Sampling and measurements

In December 2007, a test core was drilled to obtain the depth distribution of ^{137}Cs in the sediments of the depression bottom. Systematic sampling took place during April, 2009, and five cores were drilled in the depression bottom to collect depth incremental samples using a 6.5 cm diameter tube corer. The depth increments were about 10 cm for core A, located at the centre of the depression bottom and the other four cores (B–E) were taken from the four sides of the basin (Figure 1). Nine surface soil samples (0–5 cm) were collected on the hillslopes, of which four were soils on the cultivated slopes and the other samples were soils from the forest and shrub-grass slopes.

All samples were air dried, passed through a 2 mm sieve and weighed prior to the measurement of ^{137}Cs activity. Each sample weighed ⩾250 g. The ^{137}Cs activity of the <2 mm fraction of each sample was measured by gamma spectrometry using a hyperpure coaxial germanium detector and multichannel analyzer system. ^{137}Cs was detected at 662 keV and counting times were in excess of 33000 s, providing a precision of approximately ±5% at the 90% level of confidence. The grain size distribution (for soil texture analysis) of the sediment samples were measured using a laser-diffraction apparatus for the <63 μm fractions and for the >63 μm, fraction sieving was employed.

3 Results and discussion

3.1 Depth distributions of ^{137}Cs and clay contents in the deposited sediments

The depth distribution of ^{137}Cs and the clay contents of the deposited sediments in the five cores collected in April 2009 are shown in Figure 2. In core A at the centre of the depression bottom, the maximum ^{137}Cs content was 6.61± 0.78 Bq kg^{-1}, occurring at a depth of 110–117 cm. The ^{137}Cs content of the top layer (0–12 cm) was 2.20±0.32 Bq kg^{-1} and little ^{137}Cs was detected below 184 cm. The other four cores had similar ^{137}Cs depth distribution to core A. The maximum ^{137}Cs content and the intermediate depths of the ^{137}Cs peak layers in the remaining cores were not as deep as core A, ranging between 129 cm and 171 cm and between 84 cm and 113.5 cm, respectively. ^{137}Cs contents of the top and peak layers ranged from 1.49±0.21 to 4.44±0.53 Bq kg^{-1}, and from 5.68±0.64 to 9.19±0.99 Bq kg^{-1}, respectively.

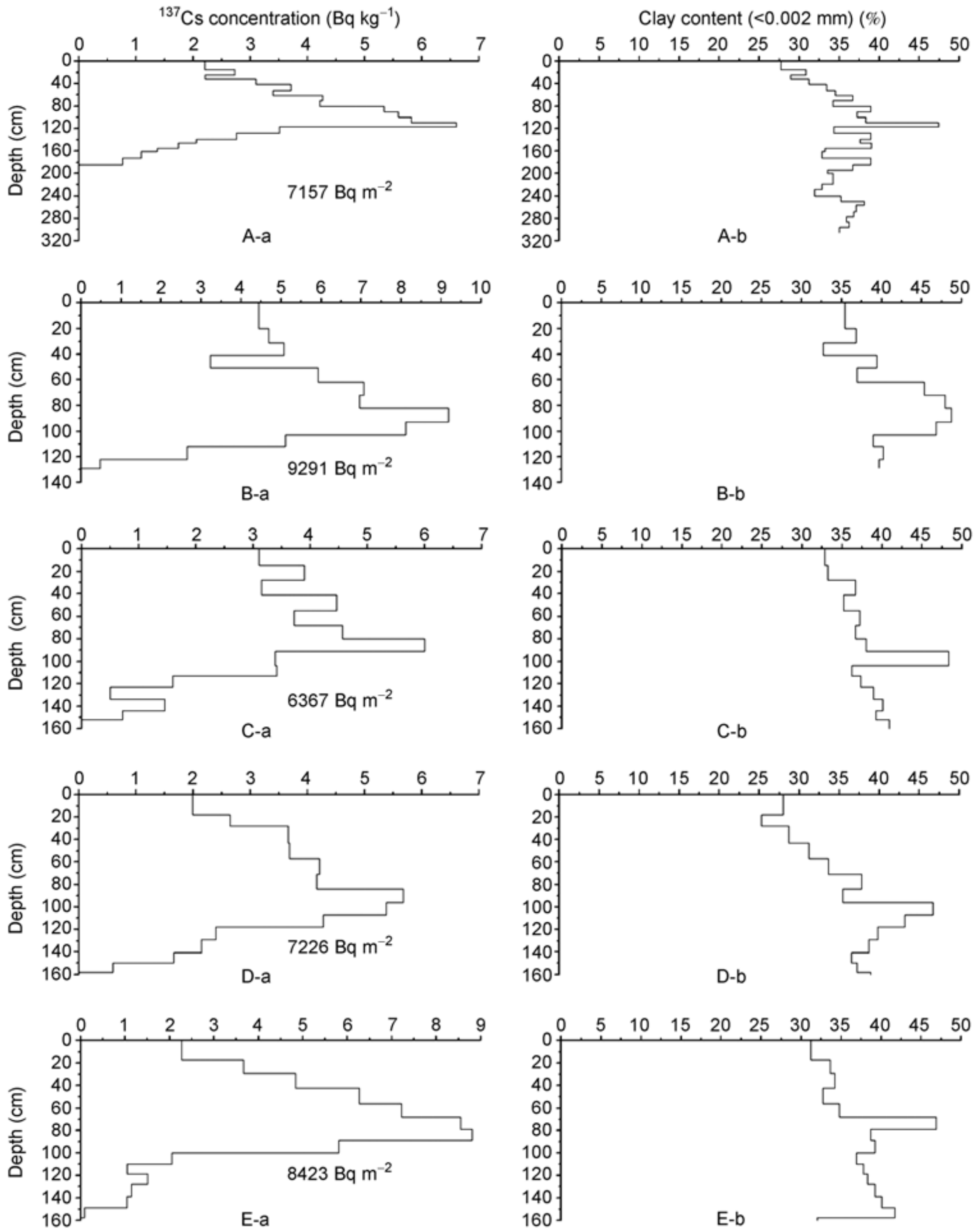

Figure 2 Depth distribution of ^{137}Cs and clay content (<0.002 mm) in the sediments of five cores at the bottom of the Shirenzhai depression.

The five cores had a similar depth distribution for clay content (<0.002 mm) with the ^{137}Cs peak layer having the highest clay content. In Core A, the clay content was 47.4% in the ^{137}Cs peak layer of 110–117 cm. Below the depth of 117 cm, it varied between 31.4% and 38.9% except for the high clay contents of 46.7% and 48.9% in the two bottom layers. The clay content of Core A decreased from 38.3% in the layer above the ^{137}Cs peak layer to 27.7% in the top layer.

The changes in clay content below and above the ^{137}Cs peak layer indicated that a large land use change in the catchment occurred when eroded soils were deposited in the depression bottom, as described by the farmers. The ^{137}Cs peak layer would have been deposited during the deforestation period of 1979–1981, because ^{137}Cs was concentrated in the surface horizons of the soils from the forest and shrub-grass slopes, which were finer (<2 mm fraction) than the horizons below. It was evident that the decrease in ^{137}Cs content from the peak layer of the soil profile upward was a result of the ^{137}Cs contents in the eroded soils of both uncultivated and cultivated areas decreasing with time [25].

The decline in ^{137}Cs content below the peak layer could be caused by either the changes in the ^{137}Cs contents in the delivering sediments with time or from migration of ^{137}Cs downward in the sediments because of diffusion or infiltration with water. The ^{137}Cs peak concentration in 1963, which is widely used for dating of lake, reservoir and floodplain sediments in the northern hemisphere, did not appear in the sediments of the depression. The reason for this observation was probably because the ^{137}Cs precipitation inventory on the ground of the depression bottom in 1963 was not significant when comparing with the ^{137}Cs inventory of the deposited sediments of the eroded surface soils from the hillslopes in the catchment during the period of 1979–1981, and the thin layer of sediments deposited during the period of 1963–1979 being mixed with the plough layer

3.2 ^{137}Cs spatial distributions of the deposited sediments in the depression bottom

^{137}Cs inventories and ^{137}Cs contents of the top and ^{137}Cs peak layers and the depths of ^{137}Cs peak layer in the five cores are shown in Figure 1(b). Core A at the centre had the greatest depth for the ^{137}Cs peak layer, but the ^{137}Cs inventory and ^{137}Cs contents of the top and ^{137}Cs peak layers were not the highest at 7158 Bq m^{-2}, 2.20±0.32 Bq kg^{-1} and 6.61± 0.78 Bq kg^{-1}, respectively. Core B near the toe of the steep shrub-grass slopes of the western hill had the highest ^{137}Cs inventory, with ^{137}Cs contents of the top and ^{137}Cs peak layers,being 9291 Bq m^{-2}, 4.44±0.53 and 9.19±0.99 Bq kg^{-1}, respectively, although the depth of the ^{137}Cs peak layer was only 87.5 cm, 26 cm less than the depth in Core A. Core E near the toe of the steep shrub-grass slopes of the southern hill had the second highest ^{137}Cs inventory of 8423 Bq m^{-2} and the ^{137}Cs content of peak layer was 8.81±0.96 Bq kg^{-1}. Core C, on the uphill slopes of which were mainly from the moderately cultivated northern pass and the relatively gentle forest slopes of the eastern hills, had the lowest ^{137}Cs inventory of 6367 Bq m^{-2} and ^{137}Cs contents of the top and ^{137}Cs peak layers were quite low, 3.11±0.39 and 6.00±0.68 Bq kg^{-1}, respectively. Core D near the relatively gentle shrub-grass slopes of the lower part of the eastern hill had a ^{137}Cs inventory of 7225 Bq m^{-2}, which was close to Core A. Also, Core D had the lowest ^{137}Cs contents of the top and ^{137}Cs peak layers, 1.99±0.2 and 5.68±0.64 Bq kg^{-1}, respectively, which were slightly lower than the values of Core A.

The ^{137}Cs contents of the surface soils on the forest and shrub-grass slopes, which varied between 3.33±0.43 and 9.48±1.04 Bq kg^{-1} with a mean value of 5.75 Bq kg^{-1} (n=5), were significantly higher than the ^{137}Cs contents of the surface soils on the cultivated slopes, which varied between 0.85±0.23 and 1.78±0.26 Bq kg^{-1} with a mean value of 1.34 Bq kg^{-1} (n=4). Comparing the ^{137}Cs characteristics in the sediments of the five cores with the ^{137}Cs contents of the two types of source soils, it was evident that the ^{137}Cs contents of the sediments in those cores were closely correlated to the land type of the nearby slopes although the deposited sediments were also redistributed by tillage. The sediments of Core B and E, near the toe of the steep shrub-grass slopes of the western and southern hills, respectively, had high ^{137}Cs contents and inventories, because those slopes were too steep to be cultivated after 1979 and as a result, surface soils rich in ^{137}Cs were not disturbed. The sediments of Cores C and D, near the toe of the relatively gentle northern pass and the lower slopes of the eastern hills, respectively, had low ^{137}Cs contents and inventories, because those slopes were reclaimed for cultivation and the soils were disturbed; therefore, the surface soils rich in ^{137}Cs were mixed with the subsurface soils containing little ^{137}Cs. The sediments in core A at the centre of the depression were likely to be mainly from the lower part of the slopes of the eastern hills because the ^{137}Cs inventories and ^{137}Cs contents of the top and ^{137}Cs peak layer were similar to Core D.

3.3 Estimation of sediment deposition amount, sediment trapping efficiency and soil erosion rates since 1979

The karst depression bottom land was often cultivated and the deposited sediments mixed into the plough layer by ploughing as described earlier. The ^{137}Cs depth distribution at a deposition site should be greater than the depth of the plough layer. Therefore, the deposited depth since 1979 should be the difference between the ^{137}Cs peak and plough layer depth. The mean depth of the ^{137}Cs peak layers in the five cores was 92.1 cm. By subtracting the plough depth of 18cm from the depth of the ^{137}Cs peak layer, the total deposition depth since start of the deforestation in 1979 was 74.1 cm and the average sedimentation rate was 2.47 cm yr^{-1} over the depression bottom for last 30 years. The total deposited sediment volume and weight were 1965 m^3 and 2496 t (γ = 1.27 g cm^{-3}), respectively, for last 30 years.

Sediment trapping efficiencies in the karst depressions prone to being inundated were discussed in the authors' recent paper[1)]. Such depressions can be treated as temporary impoundments. Ward et al. [29] developed the DEPOSITS model for predicting the sediment trapping efficiency of small temporary impoundments, based on the plug flow concept. This model assumes a positive relationship between sediment trapping efficiency and runoff retention time. The plug flow concept can be also be applied to temporarily inundated karst depressions and assuming an average inundation duration of 2 days, the trap efficiency of the inundated depressions can be estimated to be ca.0.7 (Figure 3). However, because some of the temporarily stored water is lost by penetration into the ground of the depression bottom through infiltration, rather than outflow via the sinkhole, the trap efficiency may be greater. A value of 0.7 for the trapping efficiency is therefore likely to be a minimum value [29]. Since the transport of sediment into the karst depressions is limited to a few major floods, rather than a large number of floods of variable magnitude, it is acceptable to apply a constant trap efficiency of 0.70 to the studied karst depression. The close correlation of the ^{137}Cs in the sediments of the depression bottom to the soils on the

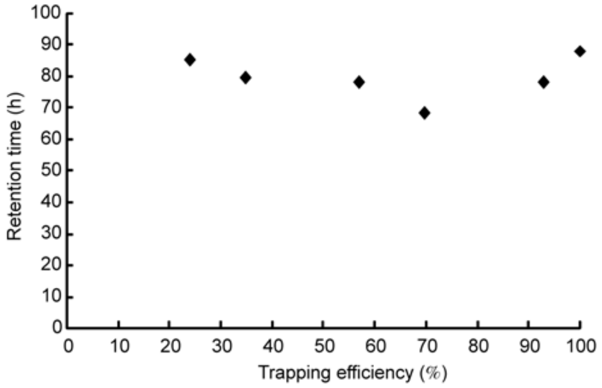

Figure 3 Relationships between flood detention times and sediment trapping efficiencies in the Callahan Reservoir, USA (re-drawn from Table 2 of ref. [29]).

nearby slopes indicated that the delivered sediments from the hillslopes were mostly deposited in the nearby bottom area and these observations strongly supported the high trapping efficiency.

Taking the trapping efficiency of 0.7 for the study depression, the total soil loss from the hillslopes was estimated to be 3566 t for the last 30 years, which is 118.9 t on an annual basis, and the specific erosion rate for the hillslopes was 2315 t km^{-2} yr^{-1}. The mean ^{137}Cs inventory of the five cores was 7693 Bq m^{-2}, which was ~10 times that of the local reference inventory of 782 Bq m^{-2} 2). The total ^{137}Cs activity of the sediments in the depression bottom was derived to be 20.4×10^{6} Bq from the mean ^{137}Cs inventory of sediments and the area of the karst depression bottom, 90.1% (18.3×10^{6} Bq) of which came from the soils on the hillslopes. The average ^{137}Cs contribution to the deposited sediments from the hillslopes was estimated to be 358 Bq m^{-2}, accounting for 45.8% of the reference inventory since nuclear weapon testing began in 1954. If ^{137}Cs was evenly distributed in surface soils, the deposited sediments during the period of 1954–2009 were equal to 48.6% of the surface soils on the hillslopes. Taking the plough depth of 12 cm on the cultivated slopes as the thickness of the surface soils containing ^{137}Cs, the average thickness of the lost soils, which were deposited in the depression bottom, was 5.8 cm; obtained using the proportional model [24]. Taking 0.7 as the sediment trapping efficiency, the average thickness of the total lost soils on the hill slopes was 7.85 cm and the relevant average erosion rate was 1570 t km^{-2} yr^{-1} for last 55 yr. Since the erosion rates were very limited on the hillslopes in the catchment before 1979, the average rate of 1570 t km^{-2} yr^{-1} for last 55 years agreed with the rate of 2315 t km^{-2} yr^{-1} for last 30 years, which was derived from the average depth of ^{137}Cs peak layers in the depression bottom. According to the recent erosion rates obtained from the monitoring runoff plot data in the Chengqi catchment [8, 9] and the study of depression sediment using ^{137}Cs dating techniques in several small catchments in Puding County [10], the average erosion rate was probably less than 100 t km^{-2} yr^{-1} in the Shirenzhai catchment since 1990 and the rate probably reached to 6000 t km^{-2} yr^{-1}or more during the period of 1979–1990.

4 Conclusions

This study has demonstrated the potential of ^{137}Cs dating of depression sediments to estimate soil losses by surface erosion from the hill slopes in a small karst catchment. The total volume and weight of sediments deposited in the depression bottom since deforestation in 1979 were 1965 m^{3} and 2496 t respectively, being derived from the average depths of the ^{137}Cs peak layers of 92.1 cm in five cores taken from the bottom of a depression, in the Shirenzai catchment. The depression bottom can be treated as a temporary impoundment and its sediment trapping efficiency was estimated to be 0.7; therefore, the relevant average soil erosion rate on the hillslopes has been 2315 t km^{-2} yr^{-1} since 1979. The close correlation of the ^{137}Cs contents of the sediments in the cores of soils on the nearby slopes indicated that the delivering sediments from runoff from the hillslopes were mostly deposited in the nearby depression bottom area. The mean ^{137}Cs inventory of the five cores was 7693 Bq m^{-2}, (which was ~10 times of the local reference inventory of 782 Bq m^{-2}). The total ^{137}Cs activity of the sediments in the bottom was 20.4×10^{6} Bq, and the relevant ^{137}Cs inventory loss from the hillslopes was 358 Bq m^{-2} since 1954, which accounted for 45.8% of the reference inventory. As soil erosion was not severe before and after the period of deforestation and following cultivation in 1979–1990, the erosion rates on the hillslopes in the Shirenzai catchment probably reached to 7000 t km^{-2} yr^{-1} during this period.

This work was supported by National Basic Research Program of China (Grant No. 2006CB403200), National Natural Science Foundation of China (Grant No. 41001162), Knowledge Innovation Project of the Chinese Academy of Sciences (Grant No. KZCX2-YW-306), National Key Technology R&D Program (Grant Nos. 2006BAC01A09 and 2008BAD98B07), and Provincial Governor Foundation of Guizhou (Grant No. 2010-95), Opening Fund of State Key Laboratory of Environmental Geochemistry (Grant No. SKLEG9008).

1 Wang S J, Li R L, Sun C X. How types of carbonate rock assemblages constrain the distribution of karst rocky decertified land in Guizhou Province, PR China: Phenomena and mechanisms. Land Degrad Dev, 2004, 15: 123–131
2 Yuan D X. Chinese Karst (in Chinese). Beijing: Geological Press, 1993. 1–25

2) He Y B, Yan D C, Zeng Y, et al. Three case studies on ^{137}Cs reference in inventories. Nuclear Tech, in press

3 Han Z Q. Exploitation of Guizhou Province during the Yongzheng Reign-Period and its effect on the rock-desertification in this area (in Chinese). J Fudan Univ (Soc Sci Ed), 2006, 120: 120–127
4 Han Z Q. The Institutional Reform and Its Effect of Guizhou Administrative Region in Early Qing Dynasty (1644–1735) (in Chinese). Shanghai: Shanghai People's Publishing House, 2008. 93–107
5 Wang S J, Liu Q M, Zhang D F. Karst rock desertification in southwestern China: Geomorphology, land use, impact and rehabilitation. Land Degrad Dev, 2004, 15: 115–121
6 Wang S J, Zhang D F, Li R L. Mechanism of rocky desertification in the karst mountain areas of Guizhou Province, Southwest China. Int Rev Environ Strat, 2002, 3: 123–135
7 Yuan D X. Rock desertification in the subtropical karst of south China. Z Geomorph NF, 1997, 108: 81–90
8 Peng T, Wang S j, Zhang X B. Results of preliminary monitoring of surface runoff coefficients for karst slopes (in Chinese). Earth Environ, 2008, 36: 152–157
9 Peng T, Yang T, Wang S J. Monitoring results of soil loss in karst slopes (in Chinese). Earth Environ, 2009, 37: 126–130
10 Bai X Y, Zhang X B, Chen H. Using ^{137}Cs fingerprint technique to estimate sediment deposition and erosion rates from Yongkang depression in karst region of Southwest China. Land Degrad Dev, 2010, 21: 1–6
11 Bai Z G, Wan G J, Huang R G. A comparison on the accumulation characteristics of ^{7}Be and ^{137}Cs in lake sediments and surface soils in western Yunnan and central Guizhou, China. Catena, 2002, 49: 253–270
12 Cao H, Yang H, Zhao Q G. Soil erosion and nutrients loss on the typical slope in hilly region of Taihu Basin. J Lake Sci, 2002, 14: 242–246
13 Li R Y, Yang H, Tang X Y. Distribution of ^{137}Cs and organic carbon in particle size fractions in an alumi-haplic acrisol of Southern China. Soil Sci, 2004, 169: 374–384
14 Ritchie J C, Finney V L, Oster K J. Sediment deposition in the flood plain of Stemple Creek Watershed, northern California. Geomorphology, 2004, 61: 347–360
15 Tang X Y, Yang H, Du M Y. Soil redistribution investigations by combined use of soil ^{137}Cs and selected chemical properties. Soil Sci Plant Nutr, 2003, 49: 557–566
16 Walling D E, Owens P M, Leeks G J L. Rates of contemporary overbank sedimentation and sediment storage on the floodplains of the main channel systems of the Yorkshire Ouse and River Tweed, UK. Hydrol Proc, 1999, 13: 993–1009
17 Wan G J, Bai Z G, Qing J. Geochemical records in recent sediments of Lake Erhai: Implications for environmental changes in a low latitude-high altitude lake in southwest China. J Asian Earth Sci, 2003, 21: 489–502
18 Wan G J, Bai Z G, Wang H R. Geochemical records of carbon in recent sediments of Erhai Lake, China: Implication of effects of the Himalayas uplift on global environmental changes. Chin Sci Bull, 1999, 44(Suppl): 123–124
19 Wan G J, Huang R G, Pu Y. Screening effect of the diffusive boundary layer in sediments of Lake Aha in the suburbs of Guiyang City, Guizhou Province. Chin J Geochem, 1997, 16: 347–352
20 Wan G J, Lin W Z, Huang R G. Dating characteristics and erosion traces of ^{137}Cs vertical profiles in Lake Hongfeng sedements. Chin Sci Bull, 1991, 36: 674–677
21 Wan G J, Santschi P H, Strum M. Natural (^{210}Pb, ^{7}Be) and fallout (^{137}Cs, ^{239,240}Pu, ^{90}Sr) radionuclides as geochemical tracers of sedimentation in Greifensee, Switzerland. Chem Geol, 1987, 63: 181–196
22 Wang H, Huo Y, Zeng L. A 42-yr soil erosion record inferred from mineral magnetism of reservoir sediments in a small carbonate-rock catchment, Guizhou Plateau, southwest China. J Paleolimnol, 2008, 40: 206–214
23 Yang H, Du M, Chang Q. Quantitative model of soil erosion rates using ^{137}Cs for uncultivated soil. Soil Sci, 1998, 163: 248–257
24 Zapata F. Handbook for the Assessment of Soil Erosion and Sedimentation Using Environmental Radionuclides. Boston: Kluwer Academic Publisher, 2002. 1–13
25 Zhang X B, Walling D E. Characterizing land surface erosion from Cesium-137 profiles in lake and reservoir sediments. J Environ Qual, 2005, 34: 514–523
26 Zhang X B, Higgitt D L, Walling D E. A preliminary assessment of potential for using Cesium-137 to estimate rates of soil erosion in the Loess Plateau of China. Hydrolog Sci, 1990, 35: 243–252
27 Zhang X B, Wen Z M, Feng M Y, et al. Application of ^{137}Cs fingerprinting technique to interpreting sediment production records from reservoir deposits in a small catchment of the Hilly Loess Plateau, China. Sci China Ser D-Earth Sci, 2007, 50: 254–260
28 Zhang Z W, Fu W L, Zhang H. Study on Soil erosion of different degrees in karst region by using cesium-137 technique (in Chinese). J Mt Sci, 2007, 25: 302–308
29 Ward A D, Rausch D L, Haan C T, et al. A verification study on a reservoir sediment deposition model. Am Soc Agric Eng, 1981, 24: 340–346