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Use of ^{137}Cs and ^{210}Pb$_{ex}$ measurements on deposits in a karst depression to study the erosional response of a small karst catchment in Southwest China to land-use change

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Abstract:

Karst depressions represent important sinks for sediment, and such sediment can provide a valuable record of the impact of environmental change on soil erosion rates. However, the sediment dynamics of karst depressions are not well understood. This contribution reports a study of the small catchment of a karst depression in Southwest China, with a drainage area of 0.054 km^2, aimed at using the sediment deposits in the depression to reconstruct the erosional response of the catchment to land-use change and, more particularly, the deforestation which took place in 1979. ^{137}Cs and ^{210}Pb$_{ex}$ are used as both chronometers and as tracers. Five cores, collected from the bottom of a depression, with an area of 2652 m^2, showed similar ^{137}Cs depth distributions, with a single ^{137}Cs peak, which was attributed to the 1979 deforestation. The ^{137}Cs activity associated with the peaks varied between 5.68 ± 0.64 and 9.19 ± 0.99 Bq kg^{-1}. The average depth of sediment deposition between 1979 and 2008 deduced from the depths of the 1979 ^{137}Cs peak was 74.1 cm. The existence of relatively high ^{210}Pb$_{ex}$ activity of 66.33 ± 8.44 Bq kg^{-1} in the upper section (0–16 cm) of the core analyzed for ^{210}Pb$_{ex}$ suggests that recent sedimentation has been very limited. Net erosion rates on the hillslopes contributing runoff and sediment t to the depression were estimated to be 5258 t km^{-2} year^{-1} from 1979 to 1990 and 256 t km^{-2} year^{-1} from 1991 to 2008, respectively. The high sediment yield in the first period was associated with the severe soil erosion triggered by the 1979 deforestation, which resulted from the changes in land ownership immediately after the Cultural Revolution. Soil erosion has been very limited since 1990 because the thin soils had been totally removed from many parts of the karst slopes and the soils remaining on the other parts of the slopes have been protected by terracing or vegetation rehabilitation. Copyright © 2012 John Wiley & Sons, Ltd.

KEY WORDS karst depression; sedimentation; ^{137}Cs; ^{210}Pb$_{ex}$; erosion; land-use change; deforestation

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INTRODUCTION

Southwest China is one of the three largest regions in the world where carbonate rocks (limestone) are widely exposed. Here, they cover an area of 54×10^4 km^2. Karst depressions are common landform features on the limestone plateau (Yuan, 1993). Reclaiming land for cultivation has destroyed most of the native evergreen forests, and deforestation has resulted in severe soil erosion in the region since the Ming dynasty (1368–1644) (Yuan, 1993). The serious land desertification caused by soil erosion has had an important impact on the local population and its livelihood and can trigger both social and economic problems on the limestone plateau, especially in the areas where pure carbonate rocks are widespread (Wang *et al.*, 2004). However, reliable information on the precise magnitude of these impacts is very limited, and classical investigation methods, such as runoff plots and hydrological monitoring stations, cannot provide reliable data on past impacts (Zhou and An, 2000).

The karst depression landforms in the region commonly represent closed depressions surrounded by steep hills and range in size from <1 ha to several hundred ha. There are generally one or more sinkholes at the bottom of the depression. The bottoms of some depressions are frequently inundated after heavy rainfall because storm runoff from the contributing catchment is unable to drain rapidly through the sinkholes. As a result, sediment mobilized from the surrounding slopes by erosion associated with the storm event and transported into the depressions by storm runoff is deposited there during heavy storms. Land-use change in a catchment impacts on the sedimentation rate in the depression and information on changing sedimentation rates can be deduced from the ^{137}Cs and ^{210}Pb$_{ex}$ depth distributions in the sediment deposits.

^{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 thermonuclear weapons during extending from the 1950s to the 1970s, with a maximum deposition rate in 1963. ^{137}Cs fallout occurred

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primarily in association with precipitation and was rapidly and strongly adsorbed by the fine particles in the surface soil, and its subsequent redistribution has been associated with the redistribution of soil and sediment by erosion and deposition. This fallout radionuclide has been widely used for assessment of soil erosion rates in a range of environments and for dating sediment deposits in lakes, reservoirs and floodplains in many areas of the world since the 1980s (Zapata, 2002; Walling *et al*., 1999; Ritchie *et al*., 2004; Zhang *et al*., 2007a, b;). ^{137}Cs has recently been used for assessing rates of soil loss on karst slopes and for dating sediment deposits in karst depressions in Southwest China (Bai *et al*., 2002; Zhang *et al*., 2007a, b; Wan *et al*., 1987, 1991 Zhang *et al*., 2010). Our studies have, however, indicated that the ^{137}Cs technique is unsuitable for assessments of rates of soil loss from karst slopes (Li *et al*., 2009; Yan *et al*., 2008; Zhang *et al*., 2010).

Pb-210 is a natural product of the ^{238}U decay series that is derived from the decay of gaseous ^{222}Rn (half-life, 3.8 days), the daughter of ^{226}Ra (half-life, 1622 years). ^{226}Ra exists naturally in most soils and rocks, and the ^{210}Pb in soils generated *in situ* by ^{226}Ra decay is designated supported ^{210}Pb. This supported ^{210}Pb will be in equilibrium with ^{226}Ra. However, upward diffusion of a small portion of the ^{222}Rn produced in the soils and rocks will introduce ^{210}Pb into the atmosphere, and its subsequent deposition as fallout provides an input to surface soils and sediments that will not be in equilibrium with its parent ^{226}Ra. This fallout-derived ^{210}Pb is commonly termed unsupported or excess ^{210}Pb ($^{210}Pb_{ex}$) to distinguish it from the ^{210}Pb produced *in situ* from the decay of ^{226}Ra. $^{210}Pb_{ex}$ has been widely used to establish the chronology of floodplain, lake, estuarine and marine sediments deposited during the past 100–150 years (Wan *et al*., 1987; Benoit and Rozan, 2001; Lu and Matsumoto, 2005; Du and Walling, 2012).

This paper reports the results of preliminary studies aimed at using ^{137}Cs and $^{210}Pb_{ex}$ to provide a chronology for sediment deposits in a karst depression located in Southwest China and thereby document the erosional response of its small catchment to land-use change.

STUDY AREA

The Shirenzhai catchment is located close to Chengjia Village, in Puding County, Guizhou Province. It represents the small catchment of a closed karst depression 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 bottom of the depression has an elevation of 1300 m. The catchment is underlain by limestone, with medium-thick bedding and a few thin shale layers. This forms part of the Triassic Guanling Group, which strikes NNW and dips to the SWW with a dip angle of approximately 25°. In the catchment, the consequent slopes of the two eastern hills are relatively gentle with a gradient of approximately 25°, while the steep slopes of

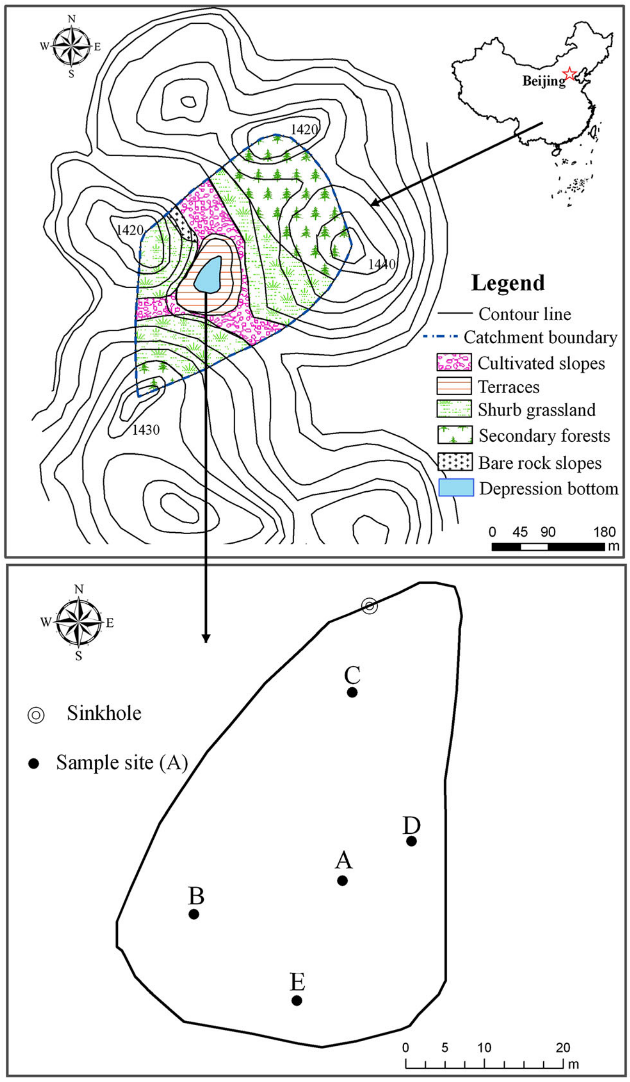

Figure 1. Present land use in the study catchment and the location of the coring sites

the western and southern hills, which are not consequent, have a gradient of >35°. A survey undertaken for the study indicated that the flat depression bottom has a length of 68 m, an average width of 39 m and an area of 2652 m^2, which accounts for 4.9% of the catchment area. A sinkhole is located at the toe of the steep slope of the western hill. Its mouth is partly filled with sediment, and it has an exposed width of 80 cm and a height of 1.1 m. The region has a subtropical highland climate with a mean annual rainfall of 1397 mm, 65% of which occurs in the wet season, which extends from June to August.

Investigations undertaken in April, 2009, indicated that, in addition to the cultivated depression bottom, the areas of cultivated land, secondary forest and areas of shrub grassland on the hillslopes were of similar extent. Terraces accounted for 50% of the cultivated land on the slopes, and these are well constructed with stone banks and distributed around the depression. The remainder of the cultivated land on the slopes has a gradient of <15° in the western, northern and southeastern col areas. Areas of secondary forest were found on the upper slopes of the two eastern hills and at the top of the southern hill. Areas of shrub grassland were found

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primarily on the lower slopes of the two eastern hills and on the slopes of the western and southern hills. Where well-developed soils were found on the slopes, these were of the rendzina type. However, most of the slopes were very rocky and covered with discontinuous thin soils, except for the cultivated land in the more gently sloping col areas where the soils were continuous with a thickness varying between 10 and 40 cm. On the terraces, the soil thickness commonly reached 40 cm. There was a small area of bare rock with an area of approximately 1000 m^2 on the steep lower slopes of the western hill. Interviews with local farmers indicated that before 1979, continuously cultivated land was found only on the flat cultivated depression bottom and on the terraces around the depression bottom, with the remaining areas of the catchment supporting secondary forest and shrub grassland. However, some of the shrub grassland had been temporarily cultivated in the past. Except for the present forests on the upper slopes of the two eastern hills and at the top of the southern hill, the existing forests were all cleared in 1979, as a result of a change in land ownership in rural areas. After the Cultural Revolution in China, farmers were given rights to cut trees on their land. Part of the shrub grassland and the deforested land, including the gentle slopes of the col areas and the lower slopes of the two eastern hills, were reclaimed for cultivation, but the slopes of the western and southern hills were too steep for cultivation. As a result of these changes, severe erosion occurred on the slopes, and a large amount of soil was mobilized and transported into the depression bottom. Because the soils there were very thin and suffered from severe erosion, the newly cultivated land on the lower slopes of the eastern hills was abandoned after only a few years of cultivation, and by 1990 it had reverted to shrub grassland. Other land reclaimed for cultivation was protected from soil erosion by stone banks in the mid 1980s. Local farmers indicated that before 1979, there was visible evidence of sedimentation within the depression bottom, but this was of limited depth and extent. However, severe sedimentation occurred after the 1979 deforestation. The farmers identified two terrace banks approximately 1 m in height on the side of the depression bottom which had been buried by the deposited sediments since 1979 and indicated that most of the sedimentation occurred before 1990.

The soil developed on the sediment deposited in the bottom of the depression is very fertile. This permits the cultivation of double crops—maize and oil seed rape. The interviewed farmers reported that the bottom of the depression was, however, often waterlogged when heavy storms occurred. At least two inundation events with a water detention time of <2days typically occurred each year. The floodwater, which was temporarily stored on the bottom of the depression, dissipated partly by infiltration and partly by flowing into the sinkhole.

SAMPLING AND MEASUREMENTS

In December 2007, a core (A) was collected from the centre of the depression bottom (Zhang *et al.*, 2010). Additional four cores (B–E) were collected in April 2009, from locations near the four sides of the depression bottom (Figure 1). Depth incremental samples were obtained from these cores by using a 6.5-cm-diameter core tube and slicing the core into increments of approximately 10 cm. Core A was the deepest core and had a depth of 3.07 m, and the other four cores (B–E) varied between 1.29 and 2.20 m in depth. Nine surface soil samples (0–5 cm) were collected from the slopes of the catchment, with four samples being collected from the cultivated slopes and the rest from the areas of forest and shrub grassland.

All samples were air-dried, disaggregated, sieved to < 2 mm and weighed before radiometric analysis. Both ^{137}Cs and $^{210}Pb_{ex}$ activities were measured on the samples representing core A, whereas only ^{137}Cs activities were measured on the samples from the other four cores and the soil samples. The ^{137}Cs and the $^{210}Pb_{ex}$ activities of the <2-mm fraction of the samples were measured by gamma-ray spectrometry, using a high-resolution, low-background, low-energy, hyper pure n-type germanium coaxial detector (EG and G ORTEC LOAX HPGe) coupled to an ORTEC amplifier and multichannel analyzer. Where both ^{137}Cs and $^{210}Pb_{ex}$ were measured, the samples (≥250 g in weight) were sealed in plastic pots (9.0 cm internal diameter and 6.5 cm high) for 21 days before assay to achieve equilibrium between ^{226}Ra and its daughter ^{214}Pb (half-life, 3.8 days). No resealing was required when only ^{137}Cs was measured. Where both radionuclides were measured, they were measured concurrently. Caesium-137 was detected at 662 keV. The total ^{210}Pb activities of the samples were obtained from 46.5 keV. ^{210}Pb peak and the ^{226}Ra activities were obtained from the 351.9-keV peak associated with ^{214}Pb, a short-lived daughter of ^{226}Ra. The $^{210}Pb_{ex}$ activities of the samples were calculated by subtracting the ^{226}Ra activity from the total ^{210}Pb activity. Counting times for the samples in core A, for which both ^{137}Cs and $^{210}Pb_{ex}$ activities were measured, exceeded 45 000 s, providing a precision of approximately ±10% at the 90% level of confidence. Counting times for the samples in the four cores (B–E), for which only ^{137}Cs activities were measured, exceeded 33 000 s, providing a precision of approximately ±5% at the 90% level of confidence. The grain-size distributions of the sediment samples in cores B–E were determined. The <0.063-mm fractions were analyzed using a laser-diffraction apparatus, whereas the >0.063-mm fractions were analyzed by sieving.

RESULTS AND DISCUSSION

The depth distribution of ^{137}Cs

The depth distribution of ^{137}Cs in the five cores is shown in Figure 2. The ^{137}Cs depth distributions of the five cores show very similar features. The ^{137}Cs peaks occur in the middle sections of the cores, and the ^{137}Cs concentrations decrease above and below the ^{137}Cs peak. The ^{137}Cs peak in core A, collected from the centre of the depression bottom, was at a depth of 96–106 cm, and the

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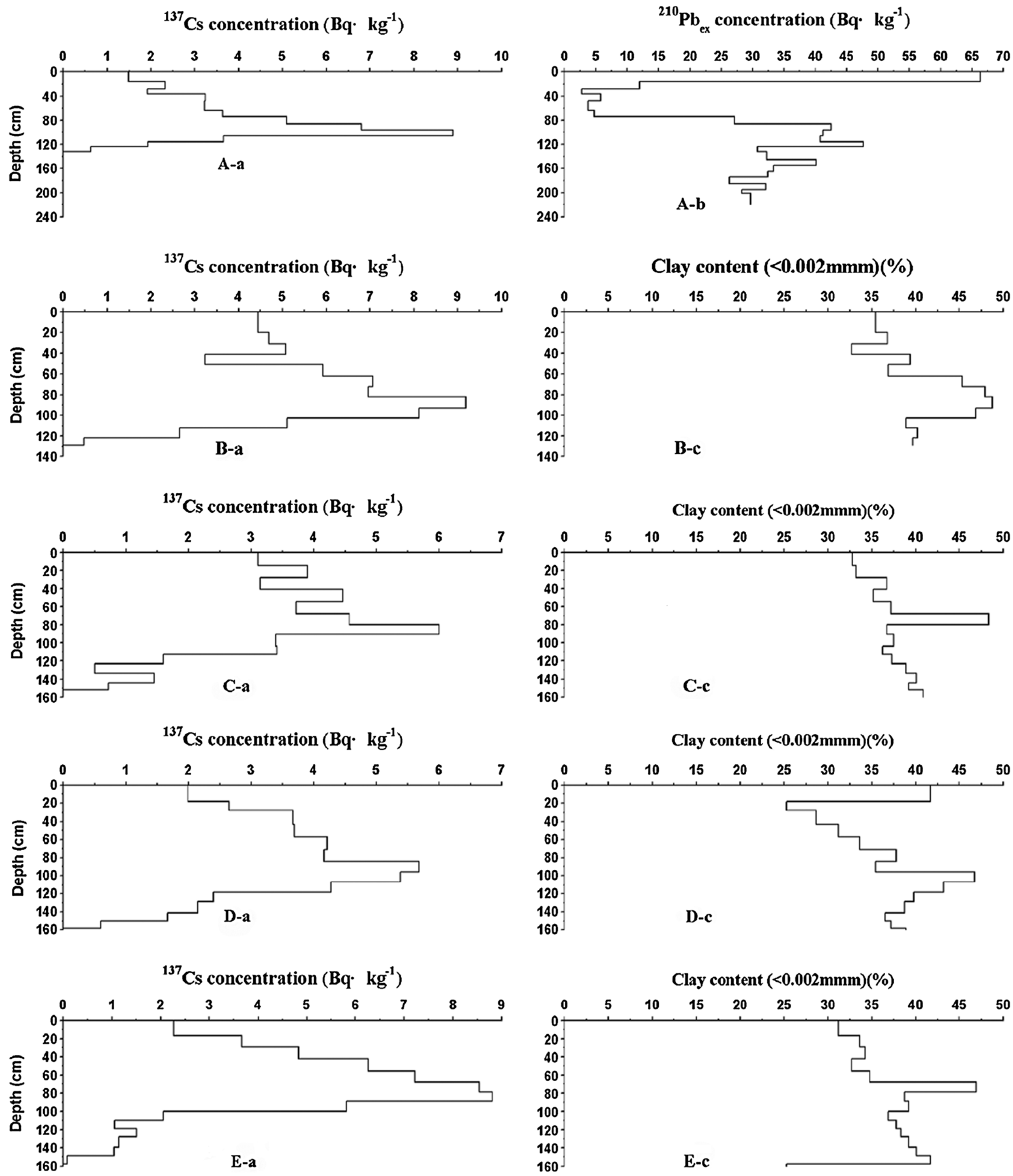

Figure 2. Depth distributions of ^{137}Cs and $^{210}Pb_{ex}$ activity and clay content (<0.002 mm) in the cores collected from the depression bottom

^{137}Cs activity in the section representing the peak is $8.89 \pm 0.~91$ Bq kg^{-1}.The ^{137}Cs peaks in the other four cores collected from near the sides of the depression bottom are not as deep as that in core A, and their midsection depths range between 84 and 94 cm. The greater depth of sedimentation above the ^{137}Cs peak in core A compared with the other four cores indicates that sedimentation in the depression focused on the centre of the depression. The ^{137}Cs activities associated with the ^{137}Cs peak layers in the four cores collected from near the sides of the depression vary between 5.68 ± 0.64 and 9.19 ± 0.99 Bq kg^{-1}, respectively. The ^{137}Cs concentrations of the top layers in the five cores vary between 1.49 ± 0.21 and 4.44 ± 0.53 Bq kg^{-1}, respectively.

The four cores have similar depth distributions of clay content (<0.002 mm), and the ^{137}Cs peaks are associated with the highest clay contents of >45% in each of the cores (Figure 2). In the sections of the cores above and below the ^{137}Cs peak, the clay content commonly varies between 25% and 40%. The rapid and marked changes in the clay content associated with the ^{137}Cs peak is interpreted as reflecting the occurrence of a sudden land-use change in the catchment, which resulted in these layers being deposited on the depression bottom. As reported earlier, local farmers indicated that the two terrace banks about 1 m high on the side of the depression bottom had been buried by the deposited sediment since the 1979 deforestation. The ^{137}Cs peaks associated with the 1979 deforestation period reflect the transfer of surface soil labelled with ^{137}Cs from the uncultivated soil in the areas of forest and shrub grassland on the slopes to the depression bottom. This sediment was finer than the

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preexisting sediment in the depression bottom. The decline in ^{137}Cs activity above the peak reflects the progressive decline in the ^{137}Cs activity of the deposited soil. This in turn reflects the fact that the ^{137}Cs activity of soil eroded from both cultivated and uncultivated soil profiles would have progressively declined, as the remaining inventory declined. In the case of uncultivated soil, this decline is promoted by the exponential form of the ^{137}Cs depth distribution. With cultivated soils, the ^{137}Cs activity of the plough layer will progressively decline as soil is eroded from the surface and soil from beneath the original plough depth, containing little or no ^{137}Cs is incorporated into the plough layer (Zhang and Walling, 2005). The decline in ^{137}Cs activity below the peak layer reflects both the lower activity in the surface sediment of the depression bottom before the input of sediment related to the deforestation of 1979, which was characterized by higher activity and slow downward diffusion or migration of ^{137}Cs from the overlying high activity layer. The 1963 ^{137}Cs peak, which is widely used for dating lake, reservoir and floodplain sediments in the northern hemisphere (Wan *et al.*, 1987, 1991; Walling *et al.*, 1999), is not seen in the ^{137}Cs profiles for the depression sediments because the fallout input associated with the fallout peak of 1963 and adjacent years was mixed into the slowly accreting surface horizon of the cultivated depression bottom by tillage operations, and the total inventory associated with the bomb fallout and deposited sediment was substantially less than the major input of ^{137}Cs associated with the rapid erosion of surface soils from the catchment in 1979 and the deposition of the eroded sediment in the depression bottom.

The ^{137}Cs inventories of the five cores ranged between 6367 and 9291 Bq m^{-2}, whereas the local reference inventory was estimated to be 782 Bq m^{-2} in 2007 (He *et al.*, 2009). Taking account of the cultivation of the depression bottom and assuming a plough layer depth of 18 cm and a soil bulk density of 1.2 g cm^{-3}, it is unlikely that the input of bomb fallout to the depression bottom could have generated an activity greater than approximately 2.0 Bq kg^{-1} at the time of measurement. This is considerably less than the ^{137}Cs activities associated with the ^{137}Cs peak layers in the five cores, which range between 5.68 ± 0.64 and 9.19 ± 0.99 Bq kg^{-1}. The ^{137}Cs peaks observed in the five cores are therefore not related to the peak fallout in 1963. This conclusion is further substantiated by the fact that the ^{137}Cs inventories of the portions of the five cores below the peak layer range between 2370 and 3687 Bq m^{-2}(Table I). These values are much greater than the local reference inventory of 782 Bq m^{-2} and confirm that the ^{137}Cs peaks are likely to reflect sediment deposited after the main period of bomb fallout. Before 1979, the depression bottom would have received ^{137}Cs by both direct fallout and in association with sediment mobilized from the catchment slopes and deposited in the depression. Because deposition rates were relatively low before 1979, the total ^{137}Cs inventory of the depression bottom at this time would not have greatly exceeded the local reference inventory. The relatively high inventories now associated with the sediment profiles below the ^{137}Cs peaks reflect, in part, downward migration and diffusion of radiocaesium associated with the sediment deposited as a result of the increased erosion initiated in 1979.

The spatial distribution of ^{137}Cs

^{137}Cs activities associated with the ^{137}Cs peak and the upper sections of the five cores are variable. Core B collected near the toe of the steep shrub-grassland slope of the western hill has the highest ^{137}Cs activity (9.19 ±0.99 Bq kg^{-1}) in the peak layer. The ^{137}Cs activities of the peak sections in core A from the centre of the depression and in core E collected from near the toe of the steep shrub-grassland slope of the southern hill are also similarly high at 8.89 ± 0. 91 and 8.81 ± 0.96 Bq kg^{-1}, respectively. The ^{137}Cs activities associated with the peaks of the other two cores are 6.00 ± 0.68 Bq kg^{-1} (core C) and 5.68 ± 0.64 Bq kg^{-1} (core D). Considering the upper sections of the cores, core B has the highest ^{137}Cs surface activity (4.44 ± 0.53 Bq kg^{-1}). The lowest ^{137}Cs surface activities are associated with cores A and D collected near the toe of the lower part of the eastern hill (1.49 ± 0.20 Bq kg^{-1}.1.99 ± 0.28 Bq kg^{-1}), respectively.

The ^{137}Cs activities measured in the surface soils of the slopes currently under forest and shrub grassland vary between 3.33 ± 0.43 and 9.48 ± 1.04 Bq kg^{-1}, respectively, with a mean value of 5.75 Bq kg^{-1}(n = 5). The values are significantly higher than the ^{137}Cs activities found in the surface soils on the cultivated slopes, which vary 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). When the ^{137}Cs activities measured in the five cores are compared with those found in the source soils, a close link between the ^{137}Cs activity in the cores and the land use of the adjacent slopes is apparent, although the sediment deposited on the depression bottom would have been mixed and redistributed by tillage. The sediment in cores B and E collected near the toes of the steep shrub-grassland slopes of the western and southern hills are characterized by relatively high ^{137}Cs activities, in both the ^{137}Cs peak and the surface layer, because those slopes were too steep to be cultivated after 1979 and the surface soils rich in ^{137}Cs were eroded. The sediments of cores C and D,

Table I. The ^{137}Cs inventories associated with the sediment cores collected from the depression

	Core A	Core B	Core C	Core D	Core E
Total inventory (Bq m^{-2})	6552.02	9291.40	6366.94	7225.63	8423.24
Sun inventory below the peak layer (Bq m^{-2})	2369.96	3654.28	2842.57	3686.87	3430.79

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collected near the toes of the relatively gentle northern col area and the lower slopes of eastern hills, respectively, are characterized by lower ^{137}Cs activities and inventories because those slopes were reclaimed for cultivation and the soils were disturbed and mixed during cultivation. In this case, the surface soil rich in ^{137}Cs was mixed with the subsurface soil containing little ^{137}Cs by cultivation, and the resulting mixed soil mobilized by erosion was characterized by a lower ^{137}Cs activity. The source of the sediment contained in core A collected from the centre of the depression would seem to have been more variable. It would seem that sediment associated with the sections around the peak were mainly derived from the southern hill and therefore characterized by higher ^{137}Cs activity. However, the lower ^{137}Cs activities found in the surface layers are more similar to those associated with core D, and this sediment is more likely to have originated from the eastern hill. Overall, however, there is a close link between the ^{137}Cs activities of the sediment deposited in the depression bottom and that of the surface soil on the adjacent slopes, indicating that the sediment delivered from the hillslopes was mostly deposited in the adjacent area of the depression bottom.

The depth distribution of $^{210}Pb_{ex}$

The depth distribution of $^{210}Pb_{ex}$ in core A is shown in Figure 2. The 0- to 16-cm section has the highest $^{210}Pb_{ex}$ activity of 66.33 ± 8.44 Bq kg^{-1}. The $^{210}Pb_{ex}$ activity is also relatively high in the middle section of the core (86–123 cm), where activities range between 42.46 ± 6.13 and 47.61 ± 7.39 Bq kg^{-1}. This section broadly coincides with the ^{137}Cs peak at 96–106 cm depth. $^{210}Pb_{ex}$ activities are relatively low in the intervening zone (16–86 cm) and are less than 10 Bq kg^{-1} in the layer between the depths of 28 and 74 cm. $^{210}Pb_{ex}$ activities show a general decrease with increasing depth below 123 cm.

$^{210}Pb_{ex}$ is a natural fallout radionuclide, and fallout inputs must be seen as occurring essentially continuously to the surface of both the depression and hillslopes. The surface layer of the receiving surface can be expected to be characterized by a relatively high $^{210}Pb_{ex}$ activity due to accumulation of the fresh fallout. However, the activity of this surface layer can be reduced by cultivation, which mixes the soil within the plough layer, and by deposition of sediment mobilized from adjacent areas, unless the deposited sediment has a high $^{210}Pb_{ex}$ activity. The existence of a relatively high $^{210}Pb_{ex}$ activity in the upper 0- to 16-cm section, which approximately coincides with the 18 cm deep plough layer, suggests that recent sedimentation has been very limited and that the $^{210}Pb_{ex}$ inventory found in this section was contributed primarily by direct fallout to the surface of the depression. The sections with high $^{210}Pb_{ex}$ activity found in the middle part of the profile at a depth of 86–123 cm are likely to reflect the deposition of sediment containing relatively high $^{210}Pb_{ex}$ activity eroded from the areas of forest and shrub grassland on the slopes of the catchment in 1979 and shortly after, in a similar way to the ^{137}Cs peak. Because the soils of these areas were initially uncultivated, the soil mobilized from the immediate surface by erosion would contain high $^{210}Pb_{ex}$ activity. The relatively high $^{210}Pb_{ex}$ activity associated with the section of the core below 123 cm and the ^{137}Cs peak is interpreted as reflecting the accumulation of $^{210}Pb_{ex}$ fallout on the cultivated surface of the depression, during a period of limited sedimentation

Erosional response to land-use change

The mean depth of the ^{137}Cs peak in the five cores is 92.1 cm. By subtracting the plough depth of 18 cm from the depth of the ^{137}Cs peak layer, the mean total deposition depth since the start of deforestation in 1979 can be estimated to be 74.1 cm, which is equivalent to an annual mean sedimentation rate of 2.47 cm year^{-1} within the depression bottom for the past 30 years. The total volume and mass of sediment deposited within the depression bottom during 1979–2008 were estimated to be 1967 m^3 and 2498 t ($\gamma = 1.27$ g cm^{-3}), respectively. Interviews with local farmers indicated that most of the sedimentation occurred before 1990 and that the thickness of the post 1990 deposits was only approximately 5 cm. The average deposition rate during 1991–2008 was therefore estimated to be 0.28 cm year^{-1}, providing an average deposition rate of 5.76 cm year^{-1} during period of 1979–1990.

The sediment trapping efficiency of inundated karst depressions has been discussed by the authors in a recent paper (Zhang *et al.*, 2010). Such depressions can be treated as temporary impoundments. Ward *et al.* (1981) 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 detention time. The plug flow concept can also be applied to temporarily inundated karst depressions. Assuming an average inundation duration of 2 days, the trap efficiency of the inundated depressions can be estimated to be approximately 0.7. However, because some of the temporarily stored water will be lost through infiltration through the floor of the depression, rather than by direct outflow via the sinkhole, the true trap efficiency may be higher. A value of 0.7 for the trap efficiency of the depression is therefore likely to be a minimum value. Because the transport of sediment into the karst depressions is restricted to a few major flood events, rather than a large number of floods of very variable magnitude, it is considered acceptable to apply a constant trap efficiency of 0.7 to the depression studied. The close correlation between the ^{137}Cs activity of sediment deposits on the depression bottom and that of soils on the adjacent slopes suggests that the sediment delivered to the depression by runoff from the hillslopes was mostly deposited in the adjacent bottom area, thus providing further evidence of a the high trap efficiency.

Taking the estimate of the total amount of sediment deposited in the depression bottom during 1979–2008 of 1967 m^3 and combining this with an estimated trap efficiency of 0.7, the total volume of sediment delivered

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from the hillslopes can be estimated to be 2810 m^3. This is equivalent to a specific erosion rate from the hillslopes of 2255 t km^{-2} $year^{-1}$ for the period 1979–2008. Assuming, as indicated above, that deposition post 1990 was very limited and only accounted for 5 cm of sediment, the mean net erosion rate from the slopes contributing to the depression for the period 1991–2008 is estimated to be 256 t km^{-2} $year^{-1}$. The mean net erosion rate for the period 1979–1990, which was induced by the 1979 deforestation immediately after the Cultural Revolution, is estimated to be 5258 t km^{-2} $year^{-1}$. Within the period 1979–1990, the mean net erosion rate is likely to have been considerably greater than the mean for the overall period in the years immediately following the deforestation. Equally, the erosion rate is likely to have evidenced a substantial decline during the 11-year period after 1979 to a value much lower than the mean for the overall period and closer to the value for the period 1991–2008. Assuming that the net erosion rate before 1979 was of a similar magnitude to that documented for the period 1991–2008 or probably lower, due to the limited area under cultivation before 1990, it seems likely that the net erosion during immediately after deforestation increased by about two orders of magnitude when compared with the preceding conditions.

CONCLUSIONS

The present study has demonstrated the potential for using ^{137}Cs and $^{210}Pb_{ex}$ measurements on cores collected from deposits in a karst depression to study the erosional responses of the catchment of the depression to land-use change. The five cores collected from the depression have similar ^{137}Cs depth distributions, with a single peak that was attributed to the 1979 deforestation. The existence of relatively high $^{210}Pb_{ex}$ activity of 66.33 ± 8.44 Bq kg^{-1} in the upper section of the core analyzed for $^{210}Pb_{ex}$ suggests that recent sedimentation has been very limited. The mean net erosion rates on the hillslopes contributing runoff and sediment to the depression were estimated to be 5258 t km^{-2} $year^{-1}$ from 1979 to 1990 and 256 t km^{-2} $year^{-1}$ from 1991 to 2008, respectively. Although the precise trend is uncertain, it is likely that net erosion rates within the period 1979 to 1990 would have declined from a maximum during the years immediately after deforestation to a lower value at the end of the period. It therefore seems likely that the net erosion during immediately after deforestation in 1979 increased by about two orders of magnitude when compared with the preceding conditions.

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