# 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

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**Abstract** Soil erosion plays an important role in land desertification in the karst mountain areas of southwest China, but reliable data on rates of surface soil loss in the area are very limited. Hill-depressions are common landforms in the karst areas. The $^{137}$Cs technique was used to date the sediment deposits in six karst depressions, to estimate average rates of surface soil loss from their catchments. The estimates of soil loss rates obtained from this study evidenced considerable variability. A value of 1.0 t km$^{-2}$ year$^{-1}$ was obtained for a catchment under original dense karst forest, but the erosion rates ranged between 19.3 t km$^{-2}$ year$^{-1}$ and 48.7 t km$^{-2}$ year$^{-1}$ in four catchments under secondary forest or grasses, where the original forest cover had been removed in the Ming and Qing dynasties, several hundred years ago. The highest rate of 1643 t km$^{-2}$ year$^{-1}$ was obtained for a catchment underlain by clayey carbonate rocks, where the soil cover was thicker and more extensive than in the other catchments and extensive land reclamation for cultivation had occurred during the period 1979–1981, immediately after the Cultural Revolution.

**Key words** karst depression; accumulated sediment; dating; caesium-137; soil loss; erosion rates

## INTRODUCTION

Southwest China is one of the three largest regions of exposed carbonate rock (limestone) in the world, with an area of $54 \times 10^4$ km$^2$. Hill-depressions are common landforms in the karst mountain areas of this region (Yuan, 1993). Most of the karst areas in Southwest China are suffering from serious land desertification caused by soil erosion. Land desertification has important impacts on the local population and its livelihood, and can result in both social and economic problems, particularly in the areas of pure carbonate rocks (Wang *el al*., 2004). There is therefore an urgent need to obtain reliable information concerning contemporary soil erosion rates in these areas. However, reliable information on medium- and longer-term rates of soil loss in these areas is still very limited, and classical investigation methods, such as runoff plots and hydrological monitoring stations, cannot provide reliable data within a short timescale (Zhou *et al*., 2000). Attention has therefore turned to the potential for using caesium-137 ($^{137}$Cs) measurements to assemble information on rates of soil loss.

$^{137}$Cs is an artificial radionuclide with a half-life of 30.17 years, which was released into the environment as a result of the atmospheric testing of thermo-nuclear weapons during the period extending from the 1950s to the 1970s; the maximum deposition rate in the Northern Hemisphere was in 1963. The $^{137}$Cs fallout occurred 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 and its subsequent redistribution has been associated with the mobilization and transport of soil and sediment particles. $^{137}$Cs has been widely used in many areas of the world since the 1980s for assessment of soil erosion rates and for dating sediments in lakes, reservoirs and flood plains (e.g. Walling *et al*., 1999; Zapata, 2000; Ritchie *et al*., 2004; Zhang *et al*., 2007). $^{137}$Cs has been recently employed for assessing soil loss from karst slopes and for dating of sediment deposits in karst depressions in southwest China (Bai *et al*., 2002; Zhang *et al*., 2007; Wang *et al*., 2008). Studies by the authors have demonstrated that the $^{137}$Cs technique as traditionally applied 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 (Zhang *et al*., 2005; Bai *et al*., 2010). This paper reports the results of a preliminary attempt to use an alternative approach, involving the use of $^{137}$Cs to date sediment deposits in karst depressions and thereby estimate the volume of sediment accumulated in such depressions over a known period of time and thus the rate of soil loss from the contributing catchment. Closed depressions are very common landforms in the karst region of southwest China, which experiences a subtropical monsoon climate.

## THE STUDY SITES

For the hill peak-cluster depression landforms, the closed depressions are mostly surrounded by steep karst slopes and range in size from <1 ha to several hundred ha. There are commonly one or more sinkholes at the bottom of the depression (Fig. 1).

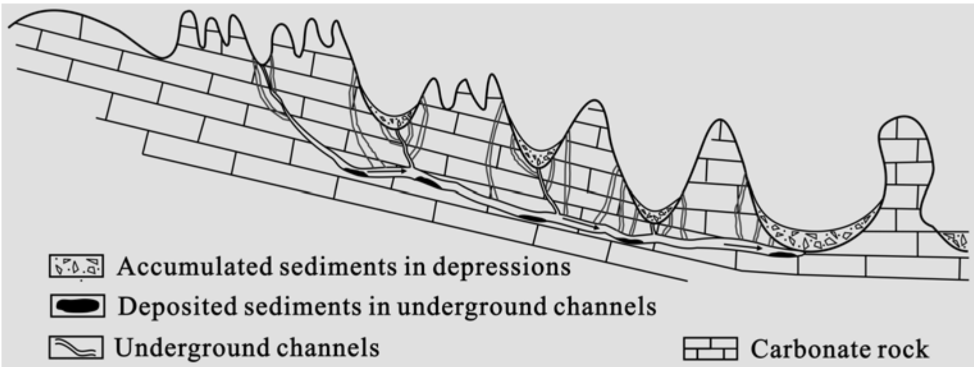


**Fig. 1** A schematic representation of typical hill peak-cluster depression landforms.

The bottoms of the 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 depression by storm runoff accumulates in the depressions during heavy storms. Several small karst catchments linked to depressions that were prone to inundation during heavy rainfall were selected for this study. Sampling was carried out in six karst depressions in 2007 and 2008. Three of the depressions are located in Puding County, Guizhou, two are in the Maolan Karst Forest Reserve, in Libo County, Guizhou, and the remaining depression is located in Huanjiang County, Guanxi, which is close to Libo County (Fig. 2).

The drainage areas of the catchments are less than 50 ha, and the depression bottoms cover areas ranging from 0.06 ha to 0.44 ha. The depression bottoms are very flat, while the slopes surrounding the depressions are very steep, and generally steeper than 30°in the study catchments (Table 1).

In the Shirenzhai depression catchment, which is underlain by clayey carbonate rocks, the slopes are mostly covered with thin rendzina soils. In the other five catchments, underlain by pure carbonate rocks, bare rocks are exposed on most of the slopes and the rendzina or yellow soils are found only in cracks and fissures within the rock outcrops. The original subtropical evergreen karst forest has been well preserved in the catchment of the Poge depression, which is located in the Molan National Karst Forest Park. However, in most areas, the original forest cover was removed several hundred years ago, and secondary forest or grasses are the dominant vegetation type in the other five catchments, where some of the gentler slopes may be cultivated (Table 1). In the case of the sampled depressions, at least two inundation events typically occur each year, with water detention times of >2 days for the event. The bottoms of the depressions were mostly cultivated, with maize ands beans representing the dominant crops.

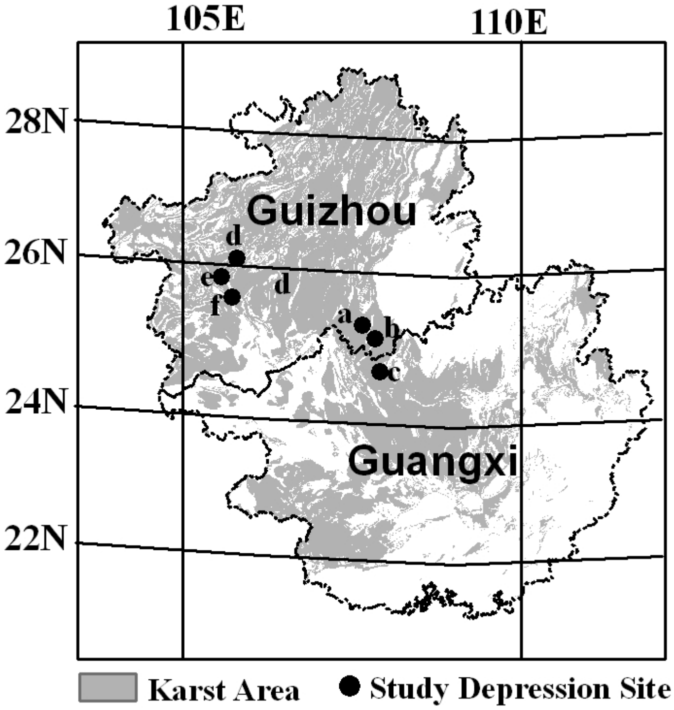


**Fig.2** The location of the study sites in the karst region of southwest China; a: Gongchengbei Depression; b: Poge Depression; c: Guzhou Depression; d: Maguan Depression; e: Zhongba Depression; and f :Shirenzhai Depression.

**Table 1** Depths and volumes of accumulated sediment in the sampled depressions and the resulting estimates of average rates of soil loss from their catchments.

| Depression / location | Sampling year | Precipitation (mm) | Depression bottom area/ catchment drainage area (ha) | Land use in catchment | Thickness (cm) /volume of accumulated sediment since 1963 ($m^{-3}$) | Avg. rate soil loss from catchment since 1963* (t $km^{-2}$ $year^{-1}$) |
|---|---|---|---|---|---|---|
| Gongchengbei /Libo,Guizhou | 2007 | 1753 | 0.06/15.4 | Fairly dense secondary forest and grasses. | 18/108 | 20.7 |
| Poge /Libo,Guizhou | 2007 | 1753 | 0.07/42.6 | Dense original forest. | 2/14 | 1.0 |
| Guzhou / Huanjiang,Guangxi | 2008 | 1638 | 0.44/41.8 | Dense forest on very steep karst upper slopes (>45°); ~33% of the steep lower slopes (25°–35°) are cultivated. | 16/704 | 48.7 |
| Zhongba /Puding,Guizhou | 2008 | 1397 | 0.40/36 | Fairly dense secondary forest. | 6/240 | 19.3 |
| Maguan /Puding,Guizhou | 2008 | 1397 | 0.44/45 | Fairly dense secondary forest , a few hectares of cultivated land. | 8/352 | 22.6 |
| Shirenzhai /Puding,Guizhou | 2008 | 1397 | 0.22/5.4 | Most land was reclaimed for cultivation in 1979–1981; secondary forests and grasses account for ~75% of the catchment and the rest is now cultivated. | 121/2662 | *1643 |

*Since 1979 for the Shirenzhai depression catchment.

## METHODS

One sediment profile was collected from each study depression in 2007 or 2008. In the Shirenzhai depression the depth incremental samples were collected using a 6.5-cm diameter core tube, using depth increments of about 10 cm and providing a total sampling depth of 156 cm. In the other five depressions, a pit was dug in order to expose the sediment profile. Depth incremental samples were then collected from the pit wall at intervals of 2–5 cm and the total sampling depths ranged between 40 and 60 cm. The topography of the sampled depression bottoms was surveyed using a theodolite.

All samples were air dried, disaggregated, passed through a 2-mm sieve and weighed prior to measurement of their $^{137}$Cs activity. The $^{137}$Cs activity of the <2 mm fraction of each sample was measured by gamma spectrometry using a hyperpure coaxial germanium detector and multi-channel analyser system. The samples had a weight of ≥250 g. Caesium-137 was detected at 662 keV and counting times were in excess of 33 000 s, providing a precision of approx. ±5% at the 90% level of confidence.

## RESULTS AND DISCUSSION

The $^{137}$Cs depth distributions documented for the six depressions are shown in Fig. 3. With the exception of the Shirenzhai depression, the $^{137}$Cs profiles associated with the depressions have similar shapes. In these profiles, $^{137}$Cs is generally evenly distributed within the upper part of the profile and below this the $^{137}$Cs activity decreases sharply with increasing depth. In most cases, this zone of rapidly decreasing $^{137}$Cs activity is less than 20 cm in depth. The average $^{137}$Cs activity of the sediment in the upper part of the profile characterized by relatively uniform $^{137}$Cs activity ranges between 4.8 and 7.8 Bq kg$^{-1}$ and the thickness of this layer varies between 18 and 40 cm. The relatively uniform $^{137}$Cs concentrations found in the upper part of the profile reflect the mixing within the plough layer caused by cultivation since the 1950s (Zhang *et al*., 2005). The tail of declining $^{137}$Cs activity beneath the upper layer characterized by relatively uniform $^{137}$Cs activity, reflects the slow downward diffusion and migration of radiocaesium that is characteristic of most $^{137}$Cs profiles reported for cultivated soils. The difference between the thickness of the upper layer with relatively uniform $^{137}$Cs activity and the plough depth (~16 cm) provides an estimate of the depth of sediment that has accumulated since the onset of $^{137}$Cs fallout. With the exception of the Poge depression, the $^{137}$Cs inventories associated with the sediment profiles from these depressions were greater than the local $^{137}$Cs reference inventory, providing further evidence of sediment accumulation. The $^{137}$Cs inventories associated with the sediment profiles documented for the Gongchengbei and Guzhou depressions were 1584 and 1611 Bq m$^{-2}$, respectively, whereas the local reference inventory in 2007 was 998 Bq m$^{-2}$. The $^{137}$Cs inventories for the Zhongba and Maguan depressions were >1772 and 1788 Bq m$^{-2}$, respectively, which were again in excess of the local $^{137}$Cs reference inventory in 2007 of 806 Bq m$^{-2}$ (He *et al*., 2009). The $^{137}$Cs inventory of 937 Bq m$^{-2}$ for the Poge depression, where the thickness of the upper layer (18 cm) was close to the plough depth (16 cm), was slightly less than the local $^{137}$Cs reference inventory of 997 Bq m$^{-2}$ (He *et al*., 2009.). By subtracting the plough depth from the total depth of the layer of uniform activity, and assuming that most of the $^{137}$Cs fallout was deposited in 1963 (Zhang *et al*., 1990), it is possible to estimate the depth of sediment deposited at the sampling site since 1963. An approximate estimate of the volume of sediment accumulated since 1963 can be derived as the product of this depth and the area occupied by the bottom of the depression that was subject to flooding. The depths of sediment accumulation and the associated volumes of sediment deposited during the period extending from 1963 to the time of sampling for the five depressions ranged from 2 to 18 cm and from 14 to 352 m$^3$, respectively (Table 1).

The $^{137}$Cs depth distribution documented for the Shirenzhai depression has a different shape to those associated with the other depressions (Fig. 3). The $^{137}$Cs activity is not evenly distributed within the upper part of the profile and the peak $^{137}$Cs concentration of 8.80 ± 0.89 Bq kg$^{-1}$ is found in the layer at 96–106 cm depth. The $^{137}$Cs activity gradually decreases above this $^{137}$Cs peak and the activity in the upper 0–16 cm layer is 1.49 ± 0.23 Bq kg$^{-1}$. The $^{137}$Cs activity also decreases sharply below the $^{137}$Cs peak and little $^{137}$Cs is found below 123 cm. The $^{137}$Cs inventory associated with this profile is 6522 Bq m$^{-2}$, which is eight times greater than the local reference inventory. The greater depth to which $^{137}$Cs activity is found, and the greater $^{137}$Cs inventory for

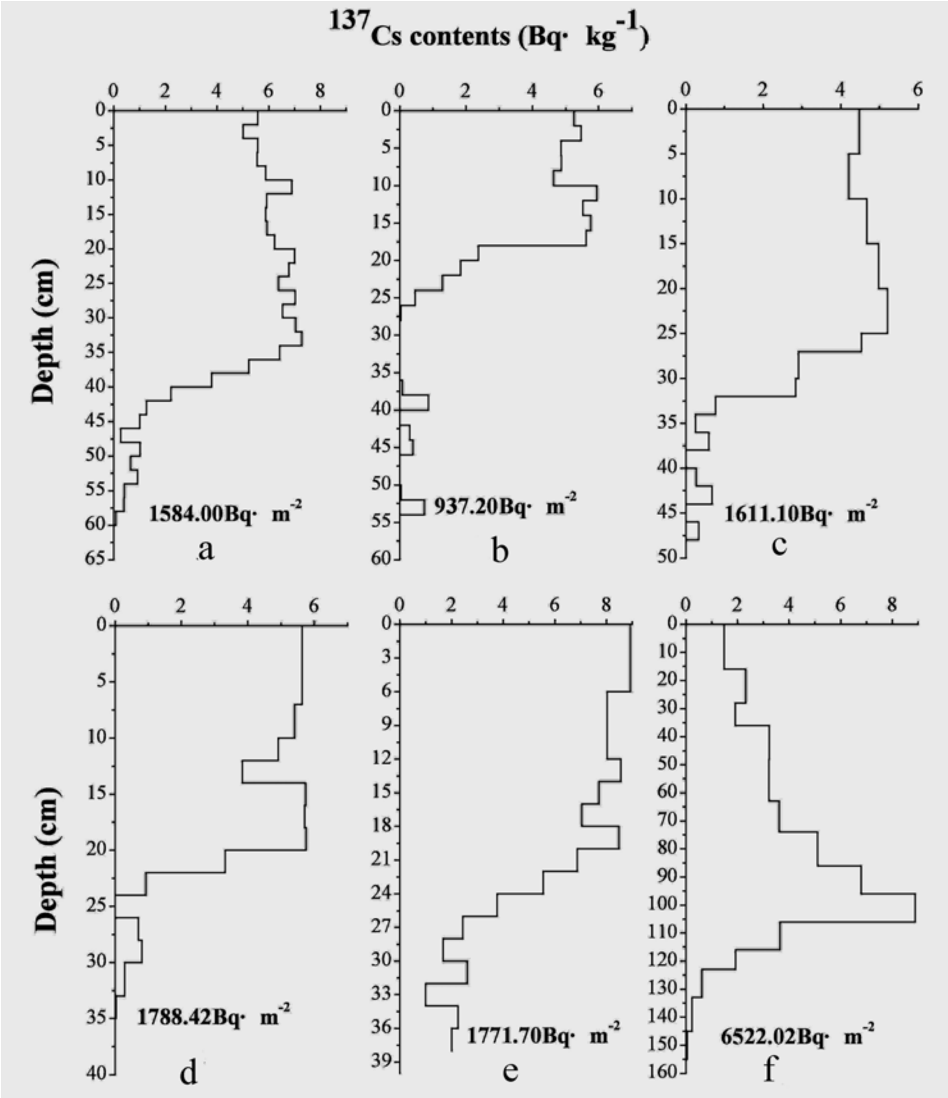


**Fig. 3** $^{137}$Cs depth distributions in sediments in the bottom of karst depressions: (a) Gongchengbei Depression; (b) Poge Depression; (c) Guzhou Depression; (d) Maguan Depression; (e) Zhongba Depression; and (f) Shirenzhai Depression.

the profile from the Shirenzhai depression reflect the different soil and land use conditions in the catchment draining to this depression. The Shirenzhai depression catchment is underlain by clayey carbonate rocks and the soil is both thicker and more extensively distributed throughout the catchment. Land ownership in rural areas, such as the study area, changed after the Cultural Revolution in China and farmers were given rights to clear their land for cultivation. Before 1979, the catchment of the Shirenzhai depression was mostly covered with secondary forest and shrub-grasses and only the relatively gentle slopes with a gradient of <20°, which accounted for only about 29% of the catchment area, were cultivated. During the period 1979–1981, most of the uncultivated land covered with secondary forest and shrub-grasses was cleared and reclaimed for cultivation. Since the 1990s, cultivation has gradually ceased, due to the low productivity of the poor soils and the migration of the farmers to the towns. A "natural" vegetation cover comprising trees, shrubs and grasses has re-established itself on the now-abandoned land.

Prior to 1979, the surface soils under undisturbed secondary forest and shrub-grasses would have been characterized by relatively high $^{137}$Cs activities, due to lack of disturbance and very low rates of soil loss. However, the $^{137}$Cs activity associated with sediment mobilized in the subsequent period could be expected to have decreased sharply, as a result of both disturbance and mixing of the soils by cultivation and the effect of erosion in progressively reducing the $^{137}$Cs inventory in the remaining soil. Therefore, the amounts of sediment delivered to the depression would have increased greatly after 1979 and the activity of that sediment would have progressively decreased. It is therefore suggested that the $^{137}$Cs peak clearly evident within the $^{137}$Cs profile represents the stable surface of the depression up until 1979, on which the bomb fallout associated with the preceding *c.*25 years would have accumulated, and that the portion of the profile above the peak (i.e. above 96–106 cm depth) represents the sediment deposited after 1979, when the catchment area was disturbed by the expansion of cultivation. The depth and volume of sediment accumulated during the period 1979 to 2008 are estimated to be 90 cm and 1980 m$^3$, respectively (Table 1).

In order to use the estimates of sediment accumulation in the karst depressions derived above to estimate rates of soil loss from the contributing catchments, it is necessary to take account of the trap efficiency of the depression basins. In this context, karst depressions, which are frequently inundated for a few days during heavy rain, can be treated as temporary reservoirs. 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 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 about 70%. However, because some of the temporarily stored water is lost by infiltration through the floor of the depression, rather than outflow via the sinkhole, the trap efficiency may be greater. A value of 70% for the trapping efficiency is therefore likely to be a minimum value. Because of the permeable nature of carbonate rocks, runoff indices are very low and inundation of the floors of the karst depressions is limited to a few large floods associated with heavy rainfall. The monitoring data available for runoff plots on karst slopes in the Chengqi Gully catchment in Puding County show that the runoff index ranges between 0.02% and 1.9%. Runoff is only detected when the daily rainfall exceeds 60 mm and the discharge rapidly increases as the daily rainfall exceeds 80 mm (Peng *et al*., 2008, 2009). Since the transport of sediment into the karst depressions is limited to a few major floods, rather than a large number of floods of very variable magnitude, it was judged acceptable to apply a constant trap efficiency of 70% to these systems.

Recent rates of soil loss from the catchments draining to the six karst depressions investigated here were estimated from the volumes of sediment accumulated in the depressions, assuming a trap efficiency of 70% (Table 1). With the exception of the forested catchment of the Poges depression and the recently deforested catchment of the Shirenzhai depression, which are characterized by relatively low (1 t km$^{-2}$ year$^{-1}$) and high (1643 t km$^{-2}$ year$^{-1}$) rates of soil loss, respectively, the erosion rates for the catchments were estimated to fall into the range 20–50 t km$^{-2}$ year$^{-1}$. These values are consistent with the erosion rates of 0.69–32.49 t km$^{-2}$ year$^{-1}$, reported for six runoff plots on karst slopes in the Chengqi catchment, in Puding County, where lithological and land-use conditions are similar to those of the four depression catchments. This consistency provides independent evidence that the rates of soil loss derived by dating the accumulated sediments in the karst depressions are meaningful.

Of the five catchments underlain by pure carbonate rocks, the catchment of the Poge depression had the lowest erosion rate of 1.0 t km$^{-2}$ year$^{-1}$ and the rates for the remaining catchments ranged between 19.3 and 48.7 t km$^{-2}$ year$^{-1}$. It is suggested that soil erosion is very limited in the catchments where the original dense karst forest survives and that erosion rates are also relatively low in the catchments where the original dense karst forest was removed in the Ming and Qing dynasties several hundred years ago, because the surface soils in these catchments were severely eroded during the historical deforestation and there is now little soil left to be eroded. In contrast, in the catchment of the Shirenzhai depression, which is underlain by clayey carbonate rocks, the clearing and reclamation of vegetated areas for cultivation after the Cultural Revolution triggered severe soil erosion. The average rate of soil loss for the period extending from 1979 to the present is estimated to be 1643 t km$^{-2}$ year$^{-1}$, and it is likely that erosion rates were even higher during the years immediately after 1979 and have declined towards the present.

## CONCLUSIONS

The results presented above must be seen as preliminary, particularly since the estimates of soil loss are based on a single value for the depth of sediment deposition associated with each of the depressions. Although the floors of the depressions are relatively flat, some variation of the depth of sediment deposited must be expected. Similarly, use of a constant value of trap efficiency for the inundated depressions takes no account of possible temporal and spatial variability of the trap efficiency of the depressions. However, a number of important conclusions can be drawn from the current study using of $^{137}Cs$ to estimate rates of sediment accumulation in karst depressions in southwest China and associated rates of soil loss from the contributing catchments. These are:

(1) Caesium-137 measurements possess considerable potential for dating the sediment accumulated in karst depressions and for estimating recent rates of soil loss from small catchments in the karst region of southwest China.

(2) Karst depressions prone to inundation by flood water during heavy storms are generally suitable for the application of this approach. In the study area, the trap efficiency of such depressions was estimated to be at least 70%, where there were generally two flood events per year and the inundation times were in excess of 2 days per event.

(3) For the catchments underlain by pure carbonate rocks, rates of soil loss are relatively low. In the catchment under original dense karst forest the rate of soil loss was only 1.0 t $km^{-2}$ $year^{-1}$. In the other four catchments, where the original forest cover had been removed in the Ming and Qing dynasties, rates of soil loss ranged between 19.3 t and 48.7 t $km^{-2}$ $year^{-1}$. These values are also relatively low and reflect the fact that severe erosion occurred after the historical deforestation and little soil now remains to be eroded. In the catchment of the Shirenzhai depression, which is underlain by clayey carbonate rocks, the clearing and reclamation of the land for cultivation after the Cultural Revolution resulted in severe soil loss, with an average rate of 1643 t $km^{-2}$ $year^{-1}$ since 1979.

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