Sediment Dynamics and the Hydromorphology of Fluvial Systems (Proceedings of a symposium held in Dundee, UK, July 2006). IAHS Publ. 306, 2006.

Dating of reservoir and pond deposits by the ^{137}Cs technique to assess sediment production in small catchments of the Hilly Sichuan basin and the Three Gorges Region, China

ZHANG XINBAO[1,2], QI YONGQING[1], HE XIUBIN[1], WEN ANBANG[1] & FU JIEXIONG[1]

1 *Institute of Mountain Hazards and Environment, Chinese Academy of Sciences, Chengdu 610041 China*
zxbao@imde.ac.cn

2 *State Key Laboratory of Loess and Quaternary Geology, Institute of Earth Environment, Chinese Academy of Sciences, Xi'an 710075, China*

Abstract There is a huge number of small reservoirs and ponds with quite high deposition rates in the Hilly Sichuan basin and Three Gorges Region, China. Ponds in four small catchments in Yanting and Nanchong of Sichuan Province and Kaixian of Chongqing were selected for this study. Incremental samples of sediment deposit profiles for ^{137}Cs dating were collected from the four ponds to estimate the volumes deposited since 1963. By analysis of the topographic characteristics and the ^{137}Cs depth distribution in rice fields it was concluded that no significant sediment accumulation occurs in the valley areas. The direct estimates of catchment erosion infer rates of 566–1869 t km^{-2} year^{-1}. The main factors accounting for the severe erosion of these regions are topography, soil erodibility and bedrock bedding conditions.

Key words ^{137}Cs; Hilly Sichuan basin; Three Gorges Region; sediment yield; small catchments

INTRODUCTION

The Hilly Sichuan basin and the Three Gorges Region are predominantly underlain by red Mesozoic sandstones and mudstones. Fertile purple soils are the weathering products of those rocks and are rich in mineral nutrients. Landforms are characterized by hills in the Hilly Sichuan basin and by medium-low mountains in the Three Gorges Region. The two regions have long cultivation histories, where both cropland ratios and population densities are quite high: 0.2–0.6 km^{-2} and 300–800 km^{-2}, respectively. Paddy fields are mostly distributed in valley areas, while the land is rainfed on slopes. Purple soils are prone to erosion and erosion rates on cultivated slopes are very high, and soil losses greater than 10 000 t km^{-2} year^{-1} have been observed from some runoff plots. At the end of the 1980s, the First State Soil Erosion Surveys, using remote sensing techniques, classified most areas as having erosion rates >5000 t km^{-2} year^{-1}. The extent of severe erosion was considered to have fallen by the Second Survey at the end of the 1990s (Ministry of Water Resources, China, 2002), but, in part due to the high soil losses and their proximity to the Three Gorges Reservoir, the two regions were selected as key soil conservation regions in China. Suspended sediment yields in rivers range mostly between 200 and 1000 t km^{-2} year^{-1} in the two regions, which is much lower than the soil erosion rates reported by the State Surveys. Therefore, low sediment delivery ratios are used to interpret the big differences between the high erosion rates and low sediment yields; for example, the sediment delivery ratios have been estimated to be about 0.1 in the Hilly Sichuan basin, though these figures have increasingly been questioned in recent studies (cf. Jing, 2002; Zhang, 1996; Zhang *et al*., 2004).

Reliable erosion rates are very important both for predicting future changes of the soil erosion situation in the two regions and for estimating the sediment flux into the Three Gorges Reservoir. It is impossible to provide reliable erosion rates using classical monitoring methods of runoff plots and hydrological stations with data for only a few years. However, there is a huge number of small reservoirs and ponds in the two regions, which are mainly used for irrigation and these can be regarded as "big sediment traps". The sediment yields of the catchments upstream can be estimated from the volumes of sediment deposited in these ponds, and by taking into account sediment storage within valley bottom sinks it is possible to infer erosion rates.

Most of the reservoirs and ponds were constructed in the 1950s and 1960s and have no standard design. Therefore, sedimentation volumes estimated by bathymetric surveys and by comparison to the original contour maps is not reliable. ^{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 nuclear weapons. Most of the ^{137}Cs fallout was precipitated onto the Earth's surface in the 1950s to 1970s period. ^{137}Cs ions are rapidly and strongly adsorbed by fine particles in the surface horizons of the soil following deposition, and thereafter their fate is intimately linked to particulate matter and transport in sediment-associated form. Measurements of ^{137}Cs have been used for both estimating soil erosion rates and dating lake sediment sequences (Zapata, 2002). The highest ^{137}Cs precipitation flux occurred in 1963, since when it has rapidly decreased and little ^{137}Cs fallout is detected after 1970, except for that associated with the Chernobyl nuclear power station accident in 1986, though very little of this was precipitated in East Asia. ^{137}Cs has been widely used for dating of lake and reservoir deposits, and the peak ^{137}Cs concentration in the deposit profiles indicates the 1963 fallout maximum (Ritchie & McHenry, 1990; Edgington *et al*., 1991; Wan *et al*., 1991). Downward diffusion of 1963 ^{137}Cs peaks in deposit profiles may hinder dating efforts in lakes with very low deposition rates and additional problems can be experienced where the bed sediments are prone to disturbance by human activities or lake bottom currents and wave action. However, none of these issues were problematic in the study area. Sediment storage can be estimated from the deposit thickness and the deposition areas, which can be obtained by surveys, with estimates of sediment bulk density. In 2003–2004, a study of erosion and sedimentation in four small catchments was carried out in Yanting county and Nanchong City of the Hilly Sichuan basin, and in Kaixian County of the Three Gorges regions. The preliminary results of the study are reported in this paper.

STUDY AREAS

Geomorphologically, Nanchong belongs to the medium hill region of the Hilly Sichuan basin while Yanting is part of the medium-high hill region of the basin, and, Kaixian belongs to the parallel ridge-valley region with low mountains of the eastern basin (Fig. 1). The Wujia and Jiliu gullies have drainage areas of 0.22 and 0.09 km^2,

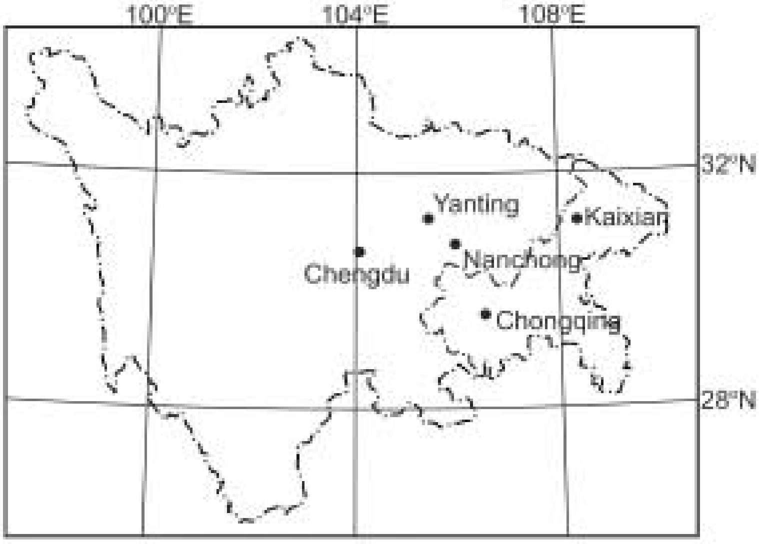

Fig. 1 A sketch map of the sampling locations.

respectively. The two catchments have similar physical geography and land-use conditions and elevations vary between 420 and 560 m with a relative relief of 140 m. The catchments are underlain by horizontally bedded mudstones, siltstones and sandstones of the Jurassic Penglaizhen Group. The landform typically comprises steep sandstone cliffs with slopes of 25–30° separated by gentle mudstone and siltstone terraces of <10°. The gentle terraces and the steep slopes account for one third and two thirds of the catchment area, respectively. The gentle terraces have been cultivated for centuries, whereas the steep slopes were originally covered by wild grasses but have gradually been afforested with cypress trees since the 1970s.

The Tianmawan Gully in Nanchong has a drainage area of 0.19 km^2 and elevations vary between 310 and 420 m with a relative relief of 110 m. The catchment is underlain by horizontally bedded mudstones and siltstones of the Jurassic Suining Group. The landform typically comprises dozens of small steep cliffs separated by short gentle terraces. The steep cliffs usually have heights of a few metres and are covered by wild grasses and scattered young cypress trees, while the gentle terraces with slopes of <10° and with lengths of 10–30 m are mostly rainfed areas. The Chunqiu Gully in Kaixian County has a drainage area of 0.58 km^2 and elevations of 190–400 m with a relative relief of 210 m. The catchment is underlain by mudstones and sandstones of the Jurassic Shaximiao Group with an inclination of about 30°. The landforms are characterized by rocky low mountains which are typical in the parallel ridge-valley region of the Eastern Sichuan basin. The catchment and the bed rock have the same orientation. As the catchment face has same direction as the bedrock dip, bedding slopes occupy most of the catchment. Soils are thin on the bedding slopes and some are bare. Part of the bedding slopes are rainfed areas and others are wild grass lands.

Purple soils dominate in the four study catchments, but important differences in erosion resistance depend upon parent lithology. Due to different proportions of sandstones, the purple soils of the Penglaizhen Group and the Suining Group have relatively high and low erosion resistances, respectively, while the resistance of the

Shaximiao Group is in between (He, 2003). As the catchment areas are less 1 km^2, the four small catchments have small valley areas and relatively high longitudinal channel gradients of 10–20%. The cropland ratio in the Tianmawan Gully is 0.45, while the ratio is 0.25 in each of the other three catchments. Annual precipitation is 1100 mm in Kaixian, 1010 mm in Nanchong and 826 mm in Yanting, 70% of which occurs in the wet season from June to September.

Each of the study catchments was impounded by an earth dam of 4–5 m height during the period 1949–1956, and storage volumes range between 1.5–5.1 × 10^4 m^3. The dams were made up of soil dug from the valley bottoms within the ponds. The four ponds have simple water delivery facilities of weirs or bottom culverts with intakes. The storage water in the ponds is used for irrigation in spring and summer. The two ponds in the Chunqiu and Jiliu gullies have no flood spill ditches, while the pond in the Wujia Gully has a ditch that is seldom used. The pond of the Tianmawan Gully has a flood spill ditch which was seldom used prior to 1981, but following reorganization of land management systems in that year it has been used to divert big floods with high sediment concentrations away from the pond.

SAMPLING AND MEASUREMENTS

Sediment profiles were collected in the four ponds in 2003–2004. The two ponds of the Wujia and Jiliu gullies in Yanting were drained out in the autumn of 2003 for construction of a new irrigation channel, so pits were dug out for sampling. Sediment samples of deposit profiles of 1.2 and 1.9 m depth were collected from the beds of the Wujia and Jiliu respectively. The Tianmawan and Chunqiu gullies were sampled by drilling a core with a diameter of 98 mm at the centre of the ponds, and a PVC pipe with a diameter of 100 mm was used to protect the core during the drilling. Due to the homogeneous composition of the deposited sediments over the profiles, it was impossible to identify flood couplets in the profiles and the profiles of the four ponds were sectioned at ~5 cm increments. It was noticed that a grey-green fine sand layer was present at a depth of 50–55 cm in the deposit profile of the Jiliu gully pond. By interviewing local farmers, it was ascertained that the layer resulted from road construction in 1984, in the course of which a grey-green sandstone layer in the bed-rock was exposed.

In the Tianmawan Gully, incremental samples of two soil profiles were collected to investigate accumulation conditions in the paddy fields dominating the valley bottom upstream of the pond. Evidence for deposition at the head of the ponds (deltaic deposits) was also measured by rods and tapes during the field work (see Table 1).

All sediment and soil samples were air-dried, disaggregated and passed through a 2-mm sieve prior to analysis of their ^{137}Cs activity by gamma spectrometry. Measurements of ^{137}Cs activity in samples were undertaken by gamma spectrometry, using a high resolution, low background, low energy, hyper-pure n-type germanium coaxial γ-ray LOAX HPGe detector. The samples with a weight of ≥380 g were placed on the detector and counted for ≥50 000 s, providing a precision of approximately ±6% at the 95% level of confidence for the gamma ray measurements (at 662 keV). Particle-size distributions of the sediment samples in the Jiliu Gully were analysed using a pipette method.

RESULTS AND DISCUSSION

The 1963 ^{137}Cs peak is clear and easily identified in the deposit profiles of the four ponds; the greatest ^{137}Cs peak depth (1.45 m) occurred in the pond of the Jiliu Gully and the shallowest (0.25 m) in the Tianmawan Gully (Fig. 2). The variations of clay content (<0.002 mm) with depth in the deposit profile of the Jiliu Gully pond show that the deposited sediments are very fine with an average clay content of 27% and the content has no significant changes over the profile (Fig. 2(a)–(d)).

The specific sediment yields for deposition in the ponds were estimated from the deposition volumes, the elapse time since construction, trap efficiency, sediment bulk density and catchment areas. The estimated specific yield is 1869 t km^{-2} year^{-1} for the Chunqiu Gully in Kaixian, and 802 and 713 t km^{-2} year^{-1} for the Wujia Gully and the Jiliu Gully in Yanting, respectively (Table 1). According to the depth of the 1984 grey-green fine sand layer in the profile, the estimated yield is 584 t km^{-2} year^{-1} since 1984, which is less than the value since 1963. The reduction of the specific sediment yield was probably caused by the forestation since the end of the 1970s in Yanting. Because most of the original valley floors in the three catchments are now flooded there is limited sediment storage potential elsewhere. The small gullies on slopes above the valleys are steep and the bedrock beds of the gullies display no sediment accumulation and thus it can be assumed that the sediment delivery ratio should be close to 1.0.

In the Tianmawan Gully, the new land made up by silting at the delta of the pond has been brought under cultivation as paddy fields; however, local farmers were unable to distinguish the new paddy fields from the old fields because the pond was built up a long time ago. Despite this, an estimated 1384 m^3 of sediment was deposited between 1963 and 1981, equating to a specific sediment yield of 566 t km^{-2} year^{-1}. Investigation of sediment deposition in small reservoirs and ponds in the Liuxi River catchment, in which the Tianmawan Gully is located, showed that the average specific sediment yield for deposition in small reservoirs and ponds is 762 t km^{-2} year^{-1}(Fu *et al.*, 2005). Most of valley areas above the pond in the Tianmawan Gully have not been submerged and have been cultivated as paddy fields for centuries. Two ^{137}Cs depth distribution profiles in the paddy fields of the valley above the pond show peak ^{137}Cs distribution depths of 25 and 28 cm, respectively, and the fallout is quite evenly distributed within the soil layers of the depths. These ^{137}Cs distributions are close to

Table 1 ^{137}Cs concentrations at different depths in deposit profiles and sediment deposition volumes.

Catchment	Sampling time	Deposit area (m^2)	Depth of the 1963 ^{137}Cs peak (cm)	Concentration of the 1963 ^{137}Cs peak (Bq kg^{-1})	^{137}Cs concentration of the top layer (Bq kg^{-1})	Sediment volume after 1963 (m^3)	Specific sediment yield* (t·km^{-2} year^{-1})
Wujia Gully, Yanting	2003.1	7349	60	16.86±0.98	2.92±0.24	4409	802
Jiliu Gully, Yanting	2003.5	1259	145	26.03±1.40	1.74±0.14	1826	713
Tianmawan Gully, Nanchong	2004.7	5534[a]	25	9.50±0.56	4.44±0.29	1384	566
Chunqiu Gully, Kaixian	2004.4	25400[b]	125	6.95±0.43	2.78±0.20	31750	1869

* Volume weight $\gamma = 1.4$ t·m^{-3}. [a] Water surface area. [b] Currently water surface area is 11 400 m^2.

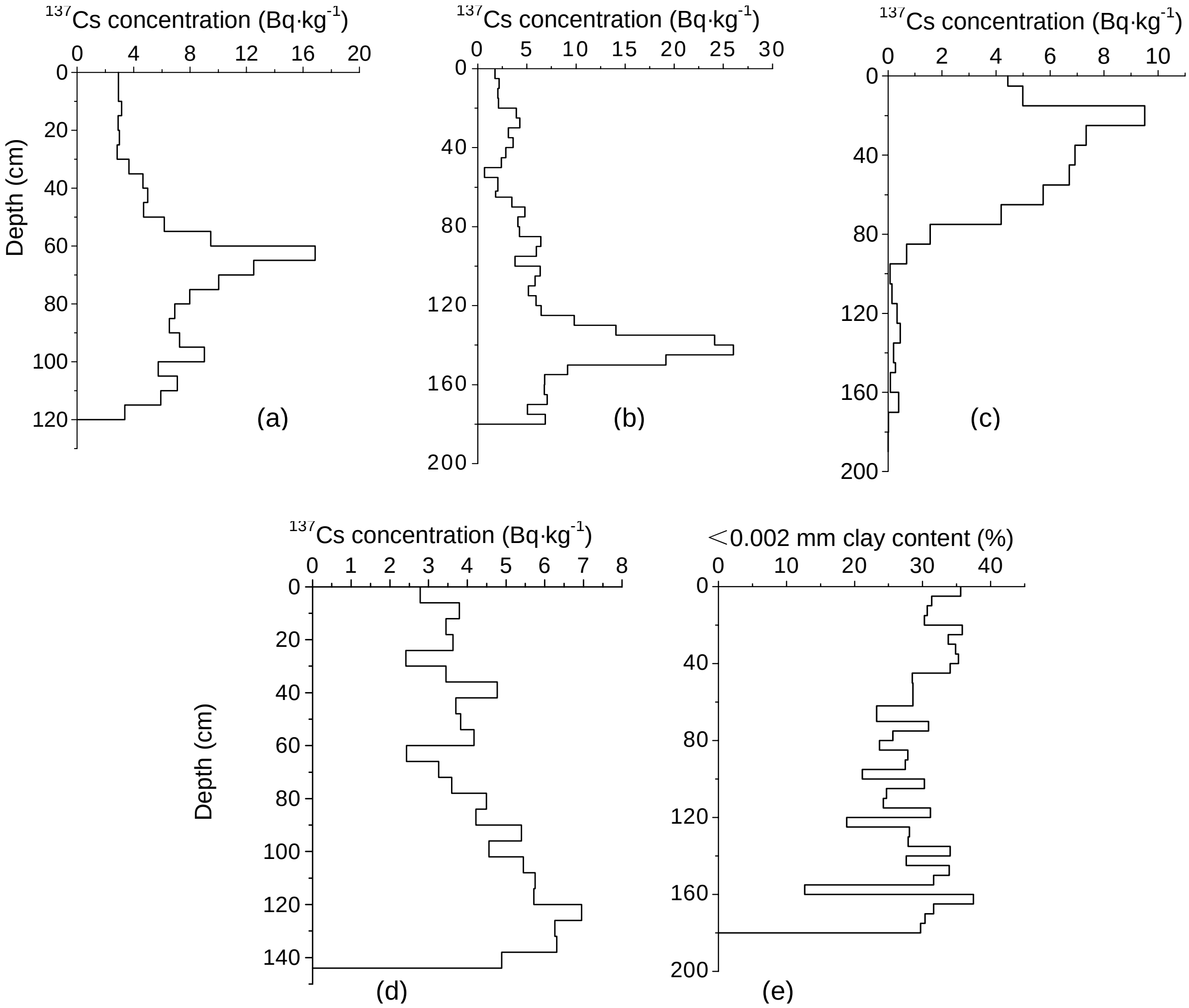

Fig. 2 Depth distributions of ^{137}Cs and clay content of the deposit profiles in the ponds: (a) Wujia Gully, (b) Jiliu Gully, (c) Tianmawan Gully, (d) Chunqiu Gully, (e) particle size distribution of the Jiliu Gully.

the plough depth of 25 cm in the paddy field, and provide no evidence of significant sediment accumulation to support the idea that sedimentation is widespread in the valley areas of the Medium Hilly Regions, such as in Nanchong. On the basis of this limited evidence, it is tentatively concluded that the sediment delivery ratios of such catchments are likely to be close to 1.0 and thus average erosion rates are between 1000 and 1500 t km^{-2} year^{-1} in the two regions.

The two ponds of the Jiliu and Wujia gullies in Yanting have the highest ^{137}Cs peak concentrations in the deposit profiles, which are 26.03 ± 1.40 and 16.86 ± 0.98 Bq kg^{-1}, respectively. The concentrations are 9.50 ± 0.56 and 6.95 ± 0.43 Bq kg^{-1} for the ponds of the Tianmawan Gully and Chunqiu Gully, respectively. The high ^{137}Cs peak concentrations in the deposit profiles of the two ponds in Yanting are probably due to the lithology of the Penglaizhen Group, which is dominated by sandstone. Bare sandstone cliffs are widely distributed in the two catchments and the limited soil cover suggests that much of the ^{137}Cs fallout would have been transported into the ponds in solution (runoff).

CONCLUSIONS

There is a huge number of small reservoirs and ponds in the Hilly Sichuan basin and the Three Gorges Region. Due to high deposition rates, the 1963 ^{137}Cs fallout peak is easily identified in profiles obtained from the bed sediments of reservoirs in the two regions. ^{137}Cs dating, combined with morphological surveys, permitted sediment storage volumes to be determined and this provided the basis for estimating specific sediment yields and average erosion rates. This study shows that the highest specific sediment yields for deposition in the ponds is 1869 t km^{-2} year^{-1} for the Chunqiu Gully in Kaixian, and 802 and 713 t km^{-2} year^{-1} for the Wujia Gully and the Jiliu Gully in Yanting, respectively. For the Tianmawan Gully in Nanchong, the yield is 566 t km^{-2} year^{-1}.

The catchment areas for these systems are <1 km^2, and all have relatively high longitudinal channel gradients and feature limited valley storage areas. The small gullies on slopes above the valleys are steep and the bedrock beds of the gullies indicate no sediment accumulation occurring there. The ^{137}Cs profiles in the paddy field of Tianmawan Gully confirmed there is no severe sediment accumulation in these areas. In the absence of upstream storage losses it is reasonable to use the specific sediment yields to infer soil erosion rates, indicating generalized soil erosion rates of 2000 t km^{-2} year^{1} for Kaixian, 1200 t km^{-2} year^{-1} for Nanchong and 1000 t km^{-2} year^{-1} for Yanting. The main factors influencing erosion severity in the regions are topography, soil erodibility, and bedrock bedding conditions.

Acknowledgements This study was supported by, Chinese Academy of Sciences (Grant nos KZCX-SW3 422 and 330), MST (Grant nos 2003CB415202), NNSF (90502002) and International Atomic Energy Agency (12322/RO).

REFERENCES

Edgington, D. N., Klump, J. V., Robbins, J. A., Kusner, Y. S., Pampura, V. D. & Sandimirov, I. V. (1991) Sedimentation rates, residence times, and radionuclide inventories in Lake Baikal from ^{137}Cs and ^{210}Pb in sediment cores. *Nature* **350**, 601–604.

Fu, J., He, X., Wen, A., Qi, Y. & Zhang, X. (2005) Sediment yields of small catchments in Hilly Sichuan basin calculated by pond and reservoir deposits: a case study in the Liuxi River basin of Nanchong City. *Bull. Soil Water Conserv.* **25**(4), 50–53.

He, Y. (2003) *Purple Soils in China* (vol. 2). Science Press, Beijing, China.

Jing, K. (2002) A preliminary study on sediment delivery ratios in the Upper Yangtze River basin. *J. Sed. Res.* **47**(2), 53–59.

Ministry of Water Resources of China (2002) *Announcement on Soil and Water Losses in China*. MWR, Beijing, China.

Ritchie, J. C. & McHenry, J. R. (1990) Application of radioactive fallout cesium-137 for measuring soil erosion and sediment accumulation rates and patterns: a review. *J. Environ. Qual.* **19**, 215–233.

Wan, G., Lin, W., Huang, R. & Cheng, Z. (1991) Dating characteristics and erosion traces of ^{137}Cs vertical profiles in Lake Hongfeng sediments. *Chinese Sci. Bull.* **36**, 674–677.

Zapata, F. (2002) *Handbook for the Assessment of Soil Erosion and Sedimentation Using Environmental Radionuclides*. Kluwer Academic Publisher, Dordrecht, The Netherlands.

Zhang, X. (1996) Thinking on soil erosion control in the Upper Yangtze River basin. *Sci. Tech. Inf. of Soil and Water Conserv.* **4**, 7–9.

Zhang, X., He, X., Wen, A., Walling, D. E., Feng, M. & Zou, X. (2004) Sediment source identification by using ^{137}Cs and ^{210}Pb radionuclides in a small catchment of the Hilly Sichuan basin, China. *Chinese Sci. Bull.* **49**, 1953–1957.