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^{137}Cs Finger Printing Technique for Erosion and Sedimentation Studies

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Abstract: ^{137}Cs is an artificial radionuclide with a half -life of 30.2 years, which was released into the environment as a byproduct of atmospheric testing of nuclear weapons during the period of 1950s to 1970s with a peak deposition in 1963. ^{137}Cs fallout was strongly and rapidly adsorbed by soil particles when it deposited on the ground mostly with precipitation. Its following movements will associate with the adsorbed particles. ^{137}Cs tracing technique has been widely used in soil erosion and sedimentation studies since 1980s. This paper introduces the basis of the technique and shows several case studies of assessment of soil erosion rates, investigation of sediment sources and dating of reservoir deposits by using the technique in the Loess Plateau and the Upper Yangtze River Basin.

Keywords: ^{137}Cs; soil and sedimentation; the Loess Plateau; the Upper Yangtze River Basin

Introduction

Over the past 50 years, the potential for using ^{137}Cs radionuclide to study erosion and sedimentation has been drawn much attention in the world. The ^{137}Cs finger printing technique was first introduced to China in 1986 (Zhang et al. 1990) and it has been successfully used for assessment of soil erosion rates, for dating of sediment as well as for identifying sediment sources over the country (e.g. Zhang et al. 1990; Zhang et al. 1998; Yang et al. 1998; Yan et al. 2000; Li 2010). The basis of the ^{137}Cs techniques are introduced, then several case studies in the Loess Plateau as well as in the Upper Yangtze River Basin are shown in this paper.

1 The Basis of the ^{137}Cs Techniques

Caesium-137 (^{137}Cs) is a man-made fallout radionuclide with a half-life of 30.2 years that is present in the global environment, primarily as a result of the atmospheric testing of nuclear weapons in the late 1950s and early 1960s (Zapata 2002). ^{137}Cs aerosols produced by weapons testing were transferred into the stratosphere and the associated fallout was globally distributed. The temporal pattern of annual fallout was broadly similar across the globe and closely related to the intensity of weapons testing. Significant fallout was firstly recorded in the mid 1950s, maximum fallout occurred in the early 1960s, and fallout declined rapidly through the mid and late 1960s and early

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1970s as a result of the nuclear test ban treaty imposed in 1963. The ^{137}Cs deposition flux contributed by the Chernobyl disaster occurring in 1986 was limited in East Asia and much less than that in some parts of the Europe (Figure 1) (Japan Meteorological Agency 2001).

The deposition of ^{137}Cs from the atmosphere is primarily associated with precipitation. In most environments, ^{137}Cs reaching the land surface is rapidly adsorbed onto the fine fractions of the topsoil. Its subsequent redistribution, both within the soil profile and across the land surface, will be controlled by its interaction with land use practices, soil erosion, and sediment transport processes (Rogowski et al. 1970) (Figure 2). The ^{137}Cs technique is mainly used for assessment of soil erosion rates, for dating of sediment as well as for identifying sediment sources.

2 Assessment of Soil Erosion Rates

In uncultivated soil, the highest ^{137}Cs concentration occurs in the top horizon of 0-5 cm. It declines exponentially with depth and little ^{137}Cs is detected in the layer below 20 cm in depth and the ^{137}Cs inventory in soil at a site with neither soil loss nor gain is regarded as the local ^{137}Cs reference inventory (Figure 3a). In cultivated soil, ^{137}Cs will be mixed relatively uniformly within the ploughed layer by tillage. The ^{137}Cs inventory in soil at an eroded site is less than the local reference inventory (Figure 3b) and it is greater than the reference inventory at an accumulation site (Figure 3c) (Zhang et al. 1990).

Recent erosion rates can be derived from the ^{137}Cs inventory in eroded soil by using conversion models. The Mass Balance Model is often used for

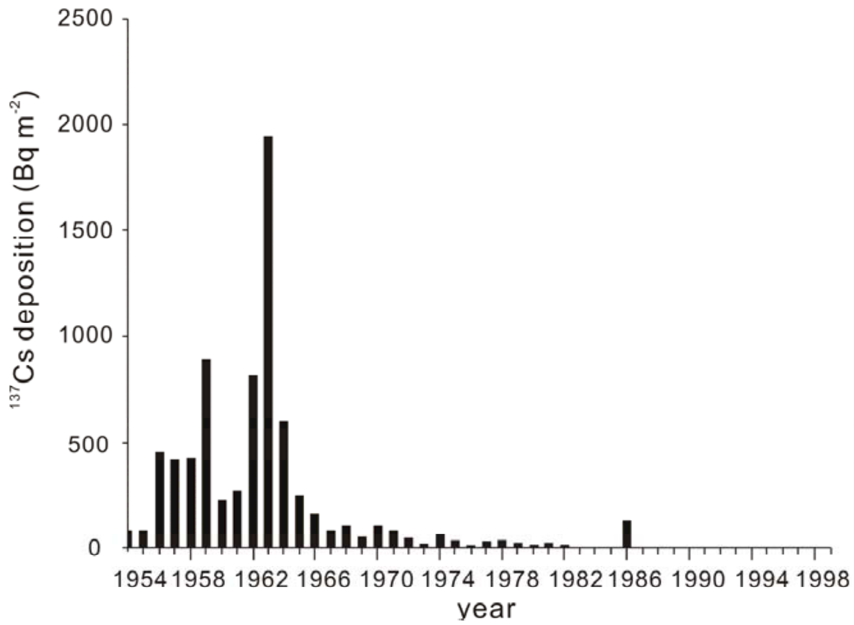

Figure 1 The annual ^{137}Cs deposition flux record for Tokyo, Japan

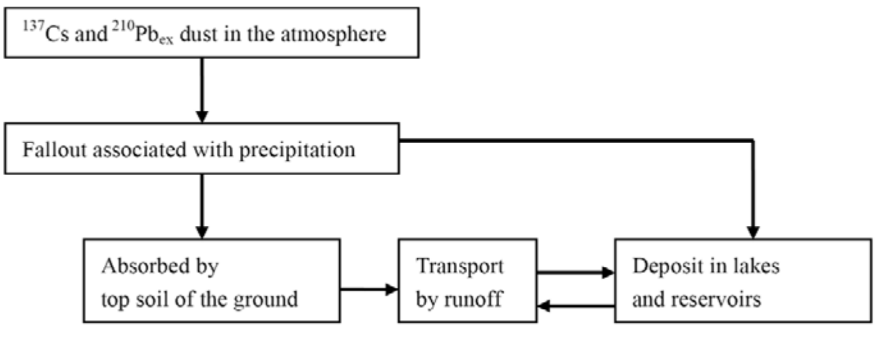

Figure 2 ^{137}Cs migration in the earth surface environment

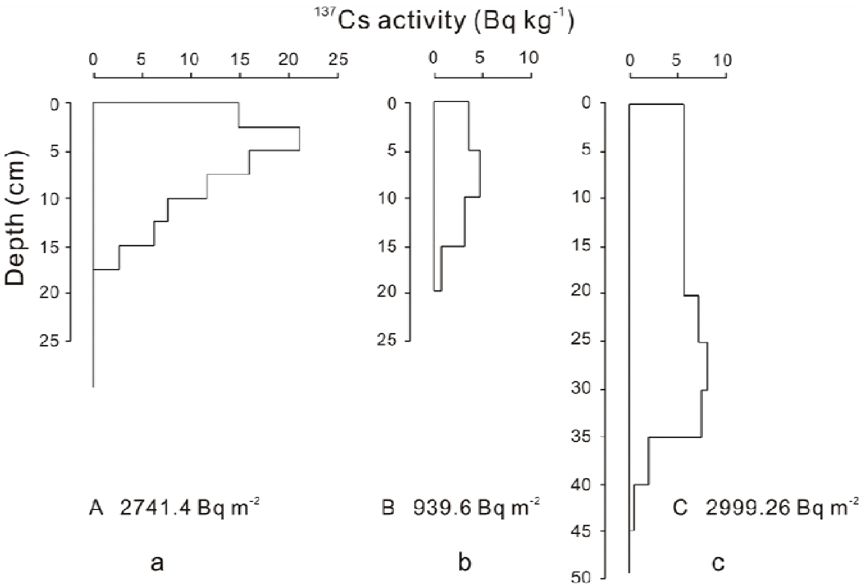

Figure 3 ^{137}Cs depth distribution in soils (a. Uneroded grass soil; b. eroded cultivated soil; c. Accumulated cultivated soil)

assessment of erosion rate on cultivated land and it is expressed as following:

$$A=A_O\,(1\text{-}h/H)^{n-1963} \qquad (1)$$

where A_O = the ^{137}Cs reference inventory (Bq/m^2); A = the ^{137}Cs inventory at an eroding point (Bq/m^2); h = the annual soil loss in depth (cm); H = plough depth(cm); n = the sampling year.

The Profile Shape Model is often used for assessment of erosion rates on uncultivated land and it is expressed as following:

$$A_x=A_O(1\text{-}e^{-x/h_O}) \qquad (2)$$

where x= mass depth from soil surface (kg/m^2); A_x=^{137}Cs inventory above depth x (Bq/m^2); h_O=coefficient describing profile shape (kg/m^2).

Spatial distribution of ^{137}Cs inventories on a cultivated hill slope (L = 88. 82 m, α= 11. 21°) in Ansai, The Loess Plateau (1992) is shown in Figure 4 (Zhang et al. 1998). At the top of the slope ^{137}Cs inventory was greater than 2000 Bq/m^2, which was slightly less than the reference inventory of 2540 Bq/m^2 and it indicated limited erosion occurring there. The inventory decreased as slope length increased and the lowest value was less than 700 Bq/m^2. At the toe of the slope, the inventory was greater than 2500 Bq/m^2 and it indicated accumulation occurring there. The mean value of ^{137}Cs inventories over the slope was 1106.3 Bq/m^2 (n=112), which was 43.53% of the ^{137}Cs reference inventory and the weighted mean value of erosion rates over the study slope was derived to be 4858. 6 t/ (km^2 ·a) by using Eq(1).

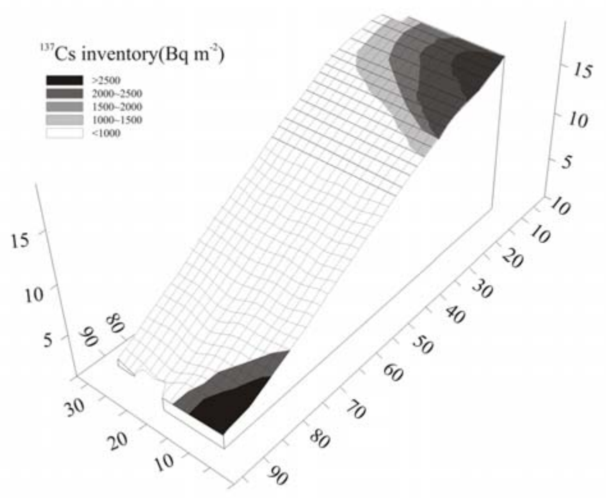

Figure 4 Spatial distribution of ^{137}Cs inventories on a cultivated hill slope in Ansai, NorthShaanxi, The Loess Plateau

^{137}Cs depth distributions in profile in two sloping terraces of purple soil (1991), near the Yanting Station, Yanting, Sichuan, are shown in Figure 5 (Zhang et al. 2003). Both terraces had a slope length of 60m and an average gradient of 6.2°. One of the terraces was divided into two short terraces. On either the long terrace or the two short terraces, ^{137}Cs inventory increased as the slope length increased, and the weighted mean values

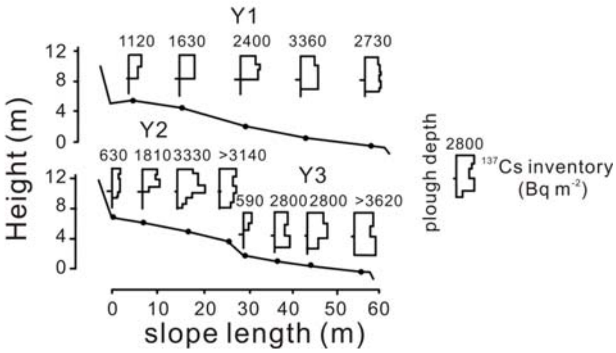

Figure 5 ^{137}Cs depth distributions in profile in two sloping terraces near the Yanting Station, Sichuan, China

were 2260 Bq/m² for the long terrace, 2230 Bq/m² for the upper short terrace and 2450 Bq/m² for the lower short terrace, respectively. The lower of the mean on the three terrace fields than the ^{137}Cs reference inventory of 2600 Bq/m² indicated that a certain amount of soil was removed from the fields by runoff and the net erosion rates were derived to be 1298 t/ (km² ·a) for the long terrace, 1421 t/ (km² ·a) for the upper short terrace, and 551 t/ (km² ·a) for the lower short terrace. It was noticed that the ^{137}Cs inventory always increased as slope length increased on the three terraces and ^{137}Cs inventories at the toe of the two short terraces, which were 3140 Bq/m² and 3620 Bq/m², were greater than the value of 2730 Bq/m² at the toe of the long terrace. These phenomena can't be singlely explained by water erosion mechanics, because water erosion rates increase as slope length increases. However, an idea of tillage erosion mechanics was thought out to interpret ^{137}Cs redistribution on cultivated slopes. ^{137}Cs redistribution is not only caused by water erosion but also by tillage on a cultivated slope, however, tillage only removes soil within a sloping field and doesn't remove soil out of the field, and has no influences on ^{137}Cs loss or gain for the whole filed. The erosion rate derived from the ^{137}Cs inventory at a point is integrated water-tillage erosion rate, which can't represent the water erosion rate at the point.

Variations of ^{137}Cs inventory on steep cultivated slopes of stony soil in Zenba, South Shaanxi, are shown in Figure 6 (Zhang et al. 1993). The sloping field had a length of 54 m and a gradient of 31°. ^{137}Cs inventory varies between 863.5-2784.6 Bq/m² with a weighted mean value of 1847.7 Bq/m², which accounts for 77.8% of the ^{137}Cs reference inventory of 2375 Bq/m². Unlike ^{137}Cs inventory variations downslope on the sloping terraces in Yanting, ^{137}Cs inventory decreased downslope in the upper part of the slope, then increased downslope in the lower part of the slope. The variation pattern of ^{137}Cs downslope on this sloping field was caused by integration of tillage erosion and water erosion. The average water erosion rate of the filed was derived to be 985 t/ (km² ·a). The value is lower than the rates on the gentle sloping terraces with a gradient of 6.2°, and it was suggested that the stony soil was more resistant to water erosion than purple soil.

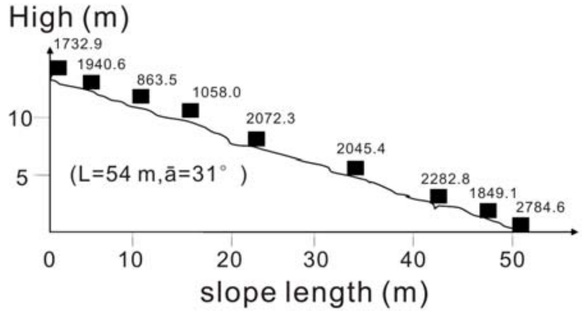

Figure 6 Variations of ^{137}Cs inventory (Bq/m²) on a steep cultivated slopes in Zenba, Shaanxi, China

3 Identification of Sediment Sources

Finger printing techniques are often used to identify sediment source in a catchment and the relative contributions from various sources to the sediment can be derived from the concentrations of ^{137}Cs and other tracers in the source soils and the sediment by using the following Mixing Model:

$$\begin{cases} S_k = \sum_{i=1}^{n} S_{ki} b_i \,(k = 1 \cdots n-1) \\ \sum_{i=1}^{n} b_i = 1 \end{cases} \quad (3)$$

where, S_k = the concentration of k type of tracer in the sediment; $S_{k\,i}$ =the concentration of k type of tracer in i type of soil sources; b_i = relative contribution from i type of source soil.

In the Loess Plateau, the sediment contributed from the inter-gully area, where sheet and rill erosion on cultivated slopes is dominant, contains

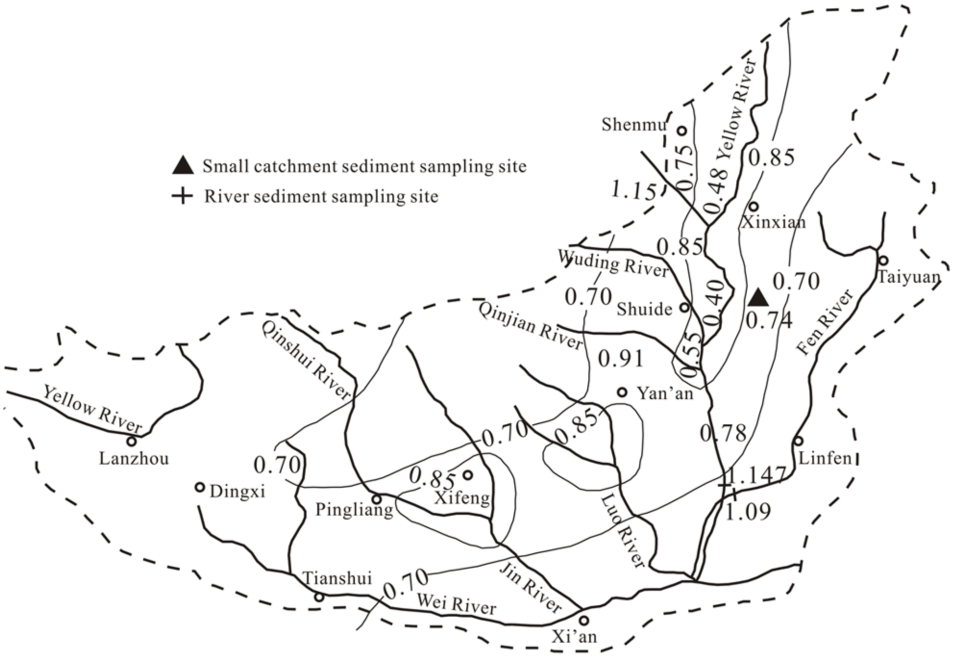

Figure 7 Variations of relative sediment contributions from the gully area in the Middle Reaches of Yellow River

considerable ^{137}Cs, while the sediment from the gully area, where gravitational erosion is dominant, contains little ^{137}Cs. The relative sediment contributions from the inter-gully area and the gully area can be easily derived from the ^{137}Cs contents in deposited sediment of sediment trapping reservoirs (or suspended sediments in rivers) and in cultivated soils in the inter-gully area (Wang et al. 2003). The average ^{137}Cs concentrations in the suspended sediments of the Yellow River and its main tributaries and in the deposited sediments in the sediment trapping reservoirs were 0.74 Bq/kg and 0.90 Bq/kg, respectively, which were much less than the average ^{137}Cs concentration of 3.41 Bq/kg in the cultivated soils of the inter-gully area (Zhang et al. 2006). No doubt, the sediment is mostly contributed from the gully area in the Loess Plateau. By comparison of the ^{137}Cs concentrations in the suspended sediments of flood runoffs at seven hydrological stations of the Yellow River and its main tributaries and in the deposited sediments of the sediment trapping reservoirs with the ^{137}Cs concentrations in the cultivated soils of the inter-gully area, the variation of the relative sediment contribution from the inter-gully area and from the gully area in the middle reaches of Yellow River was drawn up (Figure 7) (Jing 1997). the relative sediment contributions from the gully area ranged between 70%～85% in most of the middle reaches area, while it was greater than 85% in the Shanxi-Shaanxi Gorges area and less than 70% in the Fenhe-Weihe rivers Basin and in the stream source areas of the tributaries.

Two radionuclide tracers of ^{137}Cs and $^{210}Pb_{ex}$ were used to investigate sediment sources in the Wujia Gully, a small catchment near the Yanting Station, Yanting, the Hilly Sichuan Basin in 2002 (Zhang et al. 2004). The catchment had a drainage area of 0.22 km^2, gentlely cultivated terraces and steep forest slopes accounted for 1/3 and 2/3 of the catchment area, respectively. The average ^{137}Cs and $^{210}Pb_{ex}$ concentrations in the surface soils of the gentle cultivated terraces, of the steep forest slopes and of the channel banks were 7.15 Bq/kg and 162.01 Bq/kg, 4.01 Bq/kg and 70.96 Bq/kg, and 0 Bq/kg and 15.12 Bq/kg, respectively. The average ^{137}Cs and $^{210}Pb_{ex}$ concentrations in the recent deposited sediments in the pond at the gully mouth were 3.06 Bq/kg and 72.66 Bq/kg, respectively. The relative sediment contributions from the steep forest slopes, the gentle cultivated terraces and channel banks were derived to be 18 %, 46 % and 36 %, respectively. Gentle cultivated terraces and channel banks were the first and the second important sediment sources in the catchment.

4 Dating of Sediment and Identification of Flood Couplets

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 and McHenry 1990; Wan et al. 1991). In small catchments in Loess Plateau, most of delivering sediments are produced by a few floods occurring in a year. For the deposited sediments in the trapping reservoirs, the flood couplets can be easily identified from the changes of ^{137}Cs concentration in profile, because the bottom layer of a flood couplet is coarse and has low ^{137}Cs concentration while the top layer is fine and has high ^{137}Cs concentration, and ^{137}Cs is prone to being adsorbed by fine particles and coarse sediment particles fall down faster than fine particles in the reservoir water body. In the profile of reservoir deposits in the Yuntaishan Gully of a small catchment in Ansai, Loess Plateau, 44 flood couplets were identified from variations of ^{137}Cs concentrations and clay contents (<0.002mm) in the profile (0–28.1 m) (Figure 8) (Zhang et al. 2006). By integrated analysis of reservoir construction and management history, variations of ^{137}Cs content over the profile, sediment yields of flood couplets and rainfall data during the period of 1958-1970, individual storms related to the flood couplets were identified. 44 floods with a total sediment yield of 2.36×10^4 m^3 occurred during the period of 1960-1970, and flood events for a year varied between 1 and 10 times. 7-10 flood events occurred during the wet period of 1961-1964 with very wet autumn, while only 1-2 events during the dry period of 1965-1969. The average annual specific sediment yield was 1.29×10^4 t/ (km^2·a) for the Yuntaishan Gully during the period of 1960-1970.

The 1963 ^{137}Cs peak is clear and easily identified in the deposit profiles of the four Ponds

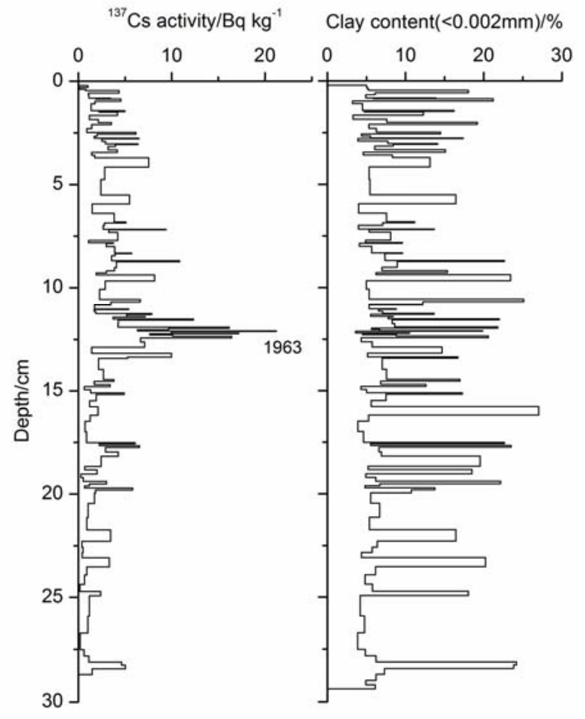

Figure 8 Variations of ^{137}Cs activities and clay contents (<0.002 mm) in the profile of deposits in the sediment trapping reservoir of the Yuntaishan Gully

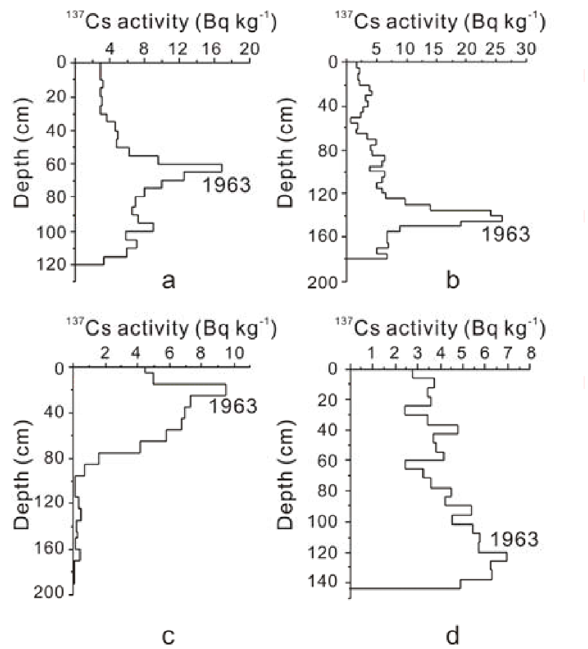

Figure 9 ^{137}Cs depth distributions in the pond deposits in the Hilly Sichuan Basin and the Three Gorges Area (a. Wujia gully, Yanting; b. Jiliu gully, Yanting; c. Tianma lake, Nancong; d. Chunqiu gully, Kaixian)

with a drainage area of <1.0 km^2 in Yanting, Nanchong of Sichuan and Kaixian of Chongqing (Figure 9) (Zhang et al. 2004). According to the depths of the deposited sediments since 1963, the specific sediment yields of the four catchments were estimated and the sediment delivery ratios assumed to be close to 1.0 for such small catchments. The highest yield was 1869 t/ (km^2·a) for the Chunqiu Gully in Kaixian of the paralleled ridge-valley area; 802 t/ (km^2·a) and 713 t/ (km^2·a) for the Wujia Gully and the Jiliu Gully in Yanting of the medium hill area; and 566 t/ (km^2·a) for the Tianmawan Gully in Nanchong of the lower hill area, respectively. Those values were much less than the soil erosion rates of 3000-5000 t/ (km^2·a) reported by the State Soil Erosion Surveys, using remote sensing techniques.

5 Conclusion

Several case studies in the Loess Plateau and the Upper Yangtze River Basin show that the ^{137}Cs technique has advantages of fast and reliable measurements and low costs, particularly suitable for assessing erosion rates, for identifying sediment sources as well as for dating of deposited sediments in ponds, lakes and reservoirs in the areas with little monitoring data and that the technique is able to solve some scientific problem, which is difficult to solve by classic monitoring techniques. Popularization and application of the technique are conductive to solve the shortage of information on soil erosion and sedimentation, such as erosion rates, sediment yields and sediment sources.

Acknowledgment

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