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Use of ^{137}Cs and ^{210}Pb$_{ex}$ peaks produced by events in the catchment for dating sediments in the Jiulongdian Reservoir, Chuxiong, Yunnan Province, China

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Abstract A 393-cm long sediment core was collected from the Jiulongdian Reservoir in 2004. In addition to the expected 1963 ^{137}Cs peak at a depth of 231–237 cm, there was an unusual ^{137}Cs and ^{210}Pb$_{ex}$ peak at a depth of 15–21 cm. The ^{137}Cs and ^{210}Pb$_{ex}$ peak is related to a forest fire occurring in the spring of 1998 and can be used for sediment dating. The ^{210}Pb$_{ex}$ peak at a depth of 331–337 cm reflects the surface horizon of the original soil beneath the reservoir, which has been buried by the reservoir deposits since the reservoir was built in 1958. Based on the storage volume *vs* depth relationship for the reservoir, the amounts of sediment deposited during the periods 1959–1962, 1963–1997 and 1998–2003 were estimated to be 249.48 × 10^4 t, 262.78 × 10^4 t and 30.94 × 10^4 t, respectively. The corresponding specific sediment yields for the three periods are estimated to be 2421.2 t km^{-2} year^{-1}, 291.5 t km^{-2} year^{-1} and 200.2 t km^{-2}·year^{-1}, respectively. The highest specific sediment yields were associated with deforestation during the "Great Leap Forward" of 1958–1959. However, the severe erosion resulting from deforestation rapidly declined when the natural vegetation re-established itself after deforestation ceased.

Key words ^{137}Cs; ^{210}Pb$_{ex}$; reservoir; sediment core; forest fire; deforestation; soil erosion

INTRODUCTION

^{137}Cs and ^{210}Pb$_{ex}$ both originate as fallout from the atmosphere. ^{137}Cs is an artificial radionuclide, with a half-life of 30.1 years that was produced by nuclear bomb tests during the period extending from the 1950s to the Nuclear Test Ban Treaty of 1963. Peak fallout in the Northern Hemisphere occurred in 1963. Unlike ^{137}Cs, ^{210}Pb with a half-life of 22.3 years is a natural product of the ^{238}U decay series 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 soil and rock and upward diffusion of a small part of the ^{222}Rn, which is produced by ^{226}Ra decay introduces ^{210}Pb into the atmosphere. Its subsequent fallout provides an input of this radionuclide to surface soils. The fallout-derived ^{210}Pb is commonly termed unsupported or excess ^{210}Pb (^{210}Pb$_{ex}$), to distinguish it from the ^{210}Pb that is generated *in situ* by decay of ^{226}Ra and is in equilibrium with ^{226}Ra, which is termed supported ^{210}Pb (^{210}Pb$_{su}$) (Zapata, 2002).

Both ^{137}Cs and ^{210}Pb$_{ex}$ have been widely used for dating of lake and reservoir sediments (Ritchie *et al.*, 1973; Appleby, 1978, 2002; He & Walling, 1996; Walling *et al.*, 1999). To generate classic profiles in such sediments, the two radionuclides should originate primarily from direct deposition from the atmosphere to the water surface, and the catchment-derived contribution, associated with mobilization of sediment from the upstream catchment by erosion, should be very limited. Because ^{137}Cs deposition peaked in 1963 in the Northern Hemisphere, the peak in the ^{137}Cs depth profile can be dated to 1963 (Ritchie *et al.*, 1973; He & Walling, 1996; Walling *et al.*, 1999). Since ^{210}Pb$_{ex}$ fallout is continuous, the age of sediment at different depths can be estimated from the ^{210}Pb$_{ex}$ profile and the rate of decline of activity with depth (Appleby, 1978, 2002; Zapata, 2002). In many studies ^{137}Cs and ^{210}Pb$_{ex}$ depth profiles do not conform to the classic form due to variations in sedimentation rate through time, changes in radionuclide input due to changes in the catchment-derived component, or changes in the radionuclide content of the catchment-derived sediment input (Walling & He, 1992; Wallbrink, 1998, 2004; Wu *et al.*, 2001; Wan *et al.*, 2005; Wang *et al.*, 2008). If a ^{137}Cs or ^{210}Pb$_{ex}$ peak in the sediment profile is caused by a particular event, such as a forest fire, deforestation or a high magnitude rainfall event, it can also be used as a time marker for dating of the sediment (Zhang *et al.*, 2005, 2011).

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In the study reported in this contribution it proved possible to make use of a ^{137}Cs and ^{210}Pb$_{ex}$ peak produced by a forest fire within the catchment in 1998, as well as the 1963 ^{137}Cs peak to develop a chronology for the sediment deposits in the Jiulongdian Reservoir, located near Chuxiong City, in Yunnan Province, China, and thereby to estimate the amounts of sediment deposited during the periods 1959–1962, 1963–1997 and 1998–2003 and the associated specific sediment yields from the catchment of the reservoir.

THE STUDY AREA

The Jiulongdian Reservoir is located on the upper reaches of the Zidianhe River (Lat. 75°14′30″N and Long. 101°40′48″E). The Zidianhe River is a tributary of the Longchuanjiang River in the Jinshajiang River basin (Fig. 1). The reservoir, which was built in the latter part of 1958, is impounded by an earth dam 38.5-m high and 265-m long. The reservoir has a surface area of 3.3 km^2 and a total storage capacity of 63 × 10^6 m^3, which includes a dead storage volume of 3.88 × 10^6 m^3 and a flood storage volume of 19.32 × 10^6 m^3. It has a catchment area of 257.6 km^2 and an upstream channel length of 42 km. The elevations of the former river channel at the dam site and of the river source at Moujiangpu Hill are 1871.5 m and 2812 m a.s.l., respectively, providing a relative relief of 940.5 m. The Zidianhe River basin, which is located in the Chuxiong Yi Autonomous Prefecture, in Yunnan Province, is characterized by the typical landforms of the Hilly Central Yunnan Plateau. The river valley is quite wide at the reservoir site, with a width of 600–700 m, but quickly narrows above the reservoir to a width of 20–100 m. The hillslopes on both sides of the valley are not very steep and the slopes mostly vary between 15° and 20°. The catchment is underlain by Mesozoic mudstones, siltstones and sandstones. “Purple soil” a weathering products of the Mesozoic rocks is predominant within the catchment, but alluvial soils and paddy soils are found in the valleys and yellow brown soils occur in the mountain zones where the elevation exceeds 2300 m. The catchment experiences a subtropical monsoon plateau climate, with an annual mean temperature of 15.6°C and a mean annual precipitation of ~864 mm, 86% of which occurs in the wet season from May to October. Prior to 1958, except for some limited paddy fields in the valleys and small areas of rainfed cultivated land on the slopes near the villages, the catchment supported a dense forest cover, comprising primarily natural subtropical evergreen forests, but also some secondary forests of Yunnanese Pine. During the period of the Great Leap Forward, 1958–1960, the forest cover in the catchment was largely destroyed; 80% of the forest was cut and harvested to make charcoal for iron and copper smelting. After that time, deforestation ceased and the natural vegetation cover regenerated quite rapidly due to the favourable climatic conditions and soils. Most of the secondary vegetation is Yunnanese Pine forest and the remainder is a cover of dense shrubs and grasses. Forest covered 58% of the catchment in 2004. In 2004 the population of the catchment was 9962, of which the Yi minority accounted for 20%. The farmed land in the catchment extended to 1022 ha, representing about 4% of the catchment. Of this land, ~60% was rainfed and ~40% was occupied by paddy fields. Field investigations in 2004 indicated that soil erosion was not severe in the catchment and that the main erosion types were sheet erosion on the slopes some limited bank erosion and mass movements in gullies.

The primary functions of the reservoir are irrigation and water supply to Chuxiong City, the prefecture capital. In the Central Yunnan Plateau, water shortage is quite serious and water resources are very valuable. As much as possible of the water entering the reservoir is stored; in most years no water is discharged via the spillway. Enquiries made in 2004 indicated that any flow passing the dam was clear and carried little sediment. The reservoir was drained for maintenance in 1985, a very dry year, and in 2004. By 2004, the reservoir had silted to the dead water level of 1881 m with a maximum sediment depth of 9.5 m. The dead storage volume of 3.88 × 10^6 m^3 had therefore been filled by 2004. Assuming a bulk density of 1.4 t m^{-3} for the deposited sediments, the total mass of sediment deposited in the reservoir during the period 1959–2004 was estimated to be 543.2 × 10^4 t. This is equivalent to a mean annual deposition rate of 11.81 × 10^4 t year^{-1}.

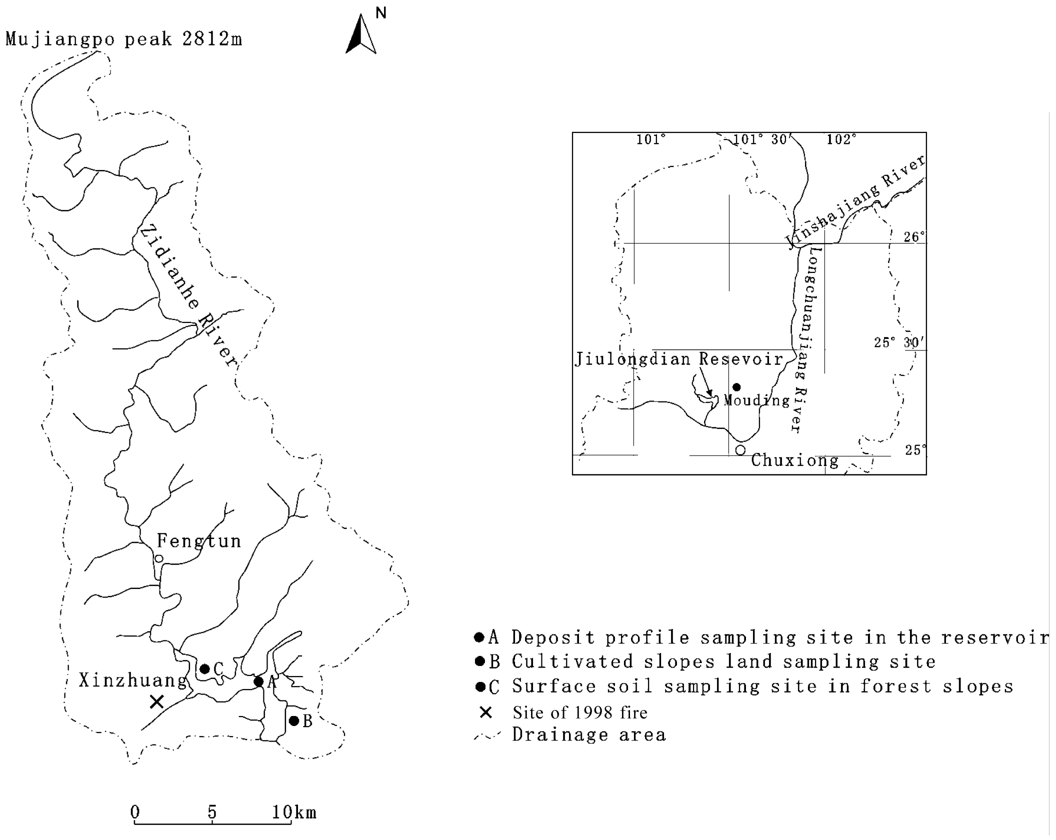

Fig. 1 A sketch map of the catchment of the Jiulongdian reservoir showing the sampling locations.

SEDIMENT SAMPLING AND ANALYSIS

A depth incremental sediment profile spanning a total depth of 3.93 m was collected from the centre of the reservoir bottom in April 2004, when the reservoir was drained for maintenance. The profile was collected from a point 2.1 km above the dam and 3.4 km below the entry of the Zidianhe River into the reservoir (Fig. 1). The upper part of the profile, 0–43 cm depth, was collected from the vertical side of an excavated pit, using depth increments of 5–6 cm. A thin charcoal layer, 2–3 mm thick, was observed at a depth of 21 cm. Conversations with the local farmers indicated that the charcoal layer resulted from a forest and shrub fire which occurred in 1998. The fire covered an area of 18 ha within the Xinzhuang Gully, which is located on the side of the reservoir, 1.9 km upstream of the sampling site. The lower part of the profile was sampled by collecting a 98 mm core which was subsequently sectioned into 6–7 cm increments. A total of 64 depth incremental samples were collected from the sediment profile. In addition, samples of surface soil of 0–5 cm depth were collected from sites on the side of the reservoir representative of the forest-shrub cover and cultivated land (Fig. 1). Four samples were collected from each site.

The total ^{210}Pb, ^{226}Ra and ^{137}Cs activities of the sediment and soil samples were measured in the radiometric laboratory of the Department of Geography at the University of Exeter, UK. The samples were air-dried, disaggregated and passed through a 2-mm sieve prior to being sent to the UK for measurement. The samples, which had a weight of ≥250 g, were placed in Marinelli beakers and sealed for 20 days prior to assay, in order to achieve equilibrium between ^{226}Ra and its daughter ^{214}Pb. Measurements of ^{210}Pb, ^{226}Ra and ^{137}Cs activity in the samples were undertaken by gamma spectrometry, using a high resolution, low background, low energy, n-type LOAX HPGe detector. The samples were counted for ≥50 000 s, providing a measurement precision of better than about ±10% at the 90% level of confidence. The ^{137}Cs concentrations were measured at 662 keV. The total ^{210}Pb activity of the samples was measured using the 46.5 keV gamma ray and the ^{226}Ra activity was measured using the 351.9 keV gamma ray from ^{214}Pb, a short-lived daughter of ^{226}Ra. Unsupported ^{210}Pb concentrations in the samples were calculated by subtracting the ^{226}Ra-supported ^{210}Pb concentration from the total ^{210}Pb concentration.

RESULTS AND DISCUSSION

The depth distributions of ^{137}Cs, ^{210}Pb$_{ex}$ and the proportion of fine particles (<0.002 mm) in the sediment profile are presented in Fig. 2. For the ^{137}Cs profile, there are two peaks, an upper peak of 10.90 ± 0.49 Bq kg^{-1} at 15–21 cm depth, and a lower peak of 4.26 ± 0.35 Bq kg^{-1} at a depth of 231–237 cm. If the upper peak is ignored, ^{137}Cs concentrations are characterized by a progressive decrease between the lower peak and the surface. Little ^{137}Cs is found below a depth of 250 cm. For the ^{210}Pb$_{ex}$ profile, there are also two peaks, an upper peak of 59.20 ± 3.4 Bq·kg^{-1} at the same depth as the upper ^{137}Cs peak, and a lower peak of 43.40 ± 6.4 Bq·kg^{-1} at a depth of 331–337 cm. Ignoring the two peaks, ^{210}Pb$_{ex}$ concentrations indicate a progressive decrease from 17.87 ± 1.17 Bq kg^{-1} at the surface (0–5 cm) to 2.94 ± 0.22 Bq kg^{-1} at a depth of 387–393 cm.

The fine particle (<0.002 mm) content of sediment from the profile varies between 8% and 59%. However, there is a clear distinction between sediment from above and below 83 cm depth. Above 83 cm, the fine particle content ranges between 21% and 59%, whereas below this depth the values fall into the range 8–21%.

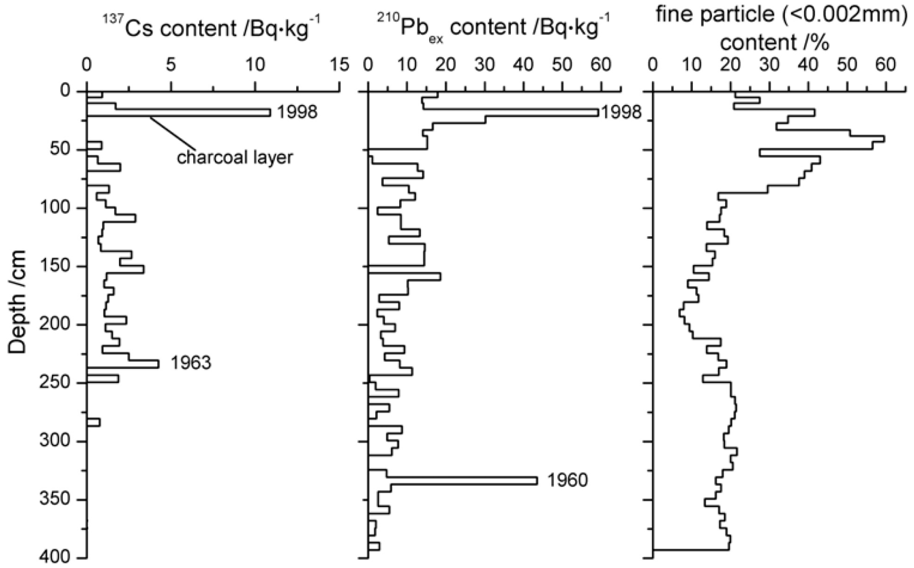

Fig. 2 Depth distributions of ^{137}Cs, ^{210}Pb$_{ex}$ and fine particle (<0.002mm) concentrations in the sediment profile collected from the reservoir.

The four samples of surface soil collected from the site with a cover of forest and shrub had a mean ^{137}Cs concentration of 6.77 ± 0.43 Bq kg^{-1} with the individual values ranging between 4.78 ± 0.33 and 9.35 ± 0.54 Bq·kg^{-1}. The mean ^{210}Pb$_{ex}$ concentration of these samples was 52.73 ± 3.05 Bq kg^{-1} with a range 35.33 ± 2.24 to 68.69 ± 3.94 Bq kg^{-1}. The four samples of cultivated soil had a mean ^{137}Cs concentration of 2.28 ± 0.25 Bq kg^{-1}, with a range 1.98 ± 0.20 to 2.64 ± 0.29 Bq kg^{-1}, and a mean ^{210}Pb$_{ex}$ concentration of 17.73 ± 1.04 Bq kg^{-1}, and range 11.37 ± 0.62 to 27.24 ± 1.67 Bq kg^{-1}. The ^{137}Cs reference inventory determined for the nearby Qingfeng Gully catchment, close to the Zidianhe River, in 1997 was 919.6 Bq·m^{-2}. When corrected for radioactive decay to 2004, this gives a value of 783.1 Bq m^{-2}.

The reservoir commenced operation in late 1958 and the lower ^{137}Cs peak 231–237 cm depth has been attributed to the 1963 fallout peak. The charcoal layer associated with the upper ^{137}Cs and ^{210}Pb$_{ex}$ peak indicates that this reflects the fire that occurred in 1998 on the side of the reservoir close to the site of the sediment profile. ^{137}Cs and ^{210}Pb$_{ex}$ activities are typically enhanced in the surface horizons of the undisturbed forest-shrub soils and the activity declines rapidly with depth, with little activity present below a depth of 15 cm. The forest-shrub soils in the area of the fire lost their vegetation cover and became bare and highly susceptible to soil erosion after the fire. Increased surface erosion, particularly sheet erosion, within this area as a result of the fire is likely to have contributed sediment with an increased ^{137}Cs and ^{210}Pb$_{ex}$ concentration to the profile site. The lower ^{210}Pb$_{ex}$ peak of 43.40 ± 6.4 Bq kg^{-1} at a depth of 331–337 cm is suggested to represent the surface horizon of the original soil in the valley bottom buried by the deposited sediment. The close similarity of the fine particle content of the buried soil and the overlying reservoir sediment reflects the presence of alluvial sediment on the original valley floor.

Based on the positions of the upper ^{137}Cs and ^{210}Pb$_{ex}$ peaks associated with the 1998 fire, the lower ^{137}Cs peak, which reflects the peak bomb fallout in 1963, and the lower ^{210}Pb$_{ex}$ peak, which represents the former surface of the valley floor, it is possible to divide the sediment profile into three distinct units representing specific periods. These are as follows: 0–21 cm, 1998–2003; 21–237 cm, 1963–1997; and 237–337 cm, 1959–1962. A relationship between reservoir storage volume and water depth, was provided by the Water Resources Bureau of the Chuxiong Prefecture. This was based on a topographic survey of the reservoir site undertaken in the 1950s. This relationship was used to estimate the mass of sediment deposited, the sedimentation rate and the specific sediment yield for the three periods (Table 1). Since these estimates are based on the chronology established for a single core, they involve a number of uncertainties. However, they are judged to provide meaningful estimates of the values involved and particularly of the relative magnitude of the values for the individual periods.

Table 1 Mass of sediment deposited*, sedimentation rates and specific sediment yields for the three periods.

Period	Depth (cm)	Mass of sediment deposited (10^4 t)	Sedimentation rate (10^4 t year^{-1})	Specific sediment yield (t km^{-2}·year^{-1})
1998–2003	0–21	30.94	5.16	200.2
1963–1997	21–237	262.78	7.51	291.5
1959–1962	237–337	249.48	62.37	2420.9
Mean value			12.07	468.3

* Assuming a bulk density for the reservoir sediment of 1.4 t m^{-3}.

The highest sedimentation rate of 62.37 × 10^4 t year^{-1}, and the associated highest specific sediment yield of 2420.9 t km^{-2}·year^{-1}, relate to the period 1959–1962. This period was not excessively wet and the annual precipitation varied between 695 and 1152 mm, with a mean value of 843 mm, which was close to the mean annual precipitation of 864 mm for the period 1958–2003 (Fig. 3). The high sedimentation rate for the period 1959–1962 can be attributed to the severe soil erosion triggered by the large-scale deforestation in the catchment during the Great Leap Forward. However, dam construction might itself also cause some soil erosion on the construction site and probably contributed to the reservoir sedimentation in this period. Because of the favourable climatic and soil conditions, the natural vegetation rapidly regenerated after the deforestation ceased. Consequently, soil erosion in the catchment rapidly declined and the specific sediment yield fell from an average of 2420.9 t km^{-2}·year^{-1} in the period 1959–1962 to an average of 291.5 t km^{-2}·year^{-1} in the period 1963–1997, and then to an average of 200.2 t km^{-2}·year^{-1} in the period 1998–2003.

The proportion of fine particles in the deposited sediment is mostly less than 20% in the lower part of the profile, below 193 cm depth, which is dated to *c.* 1968. However, the proportion of fines shows a general increase towards the upper part of profile above 193 cm depth, and the highest proportion of fines reaches 59%. The coarser sediment in the lower part of the profile is seen as reflecting the severe soil erosion caused by deforestation during the period of the Great Leap Forward, and it is suggested that the subsequent upward fining of the sediment in the upper part of the profile is related to the progressive reduction of soil erosion due to the regeneration of the natural vegetation after deforestation ceased.

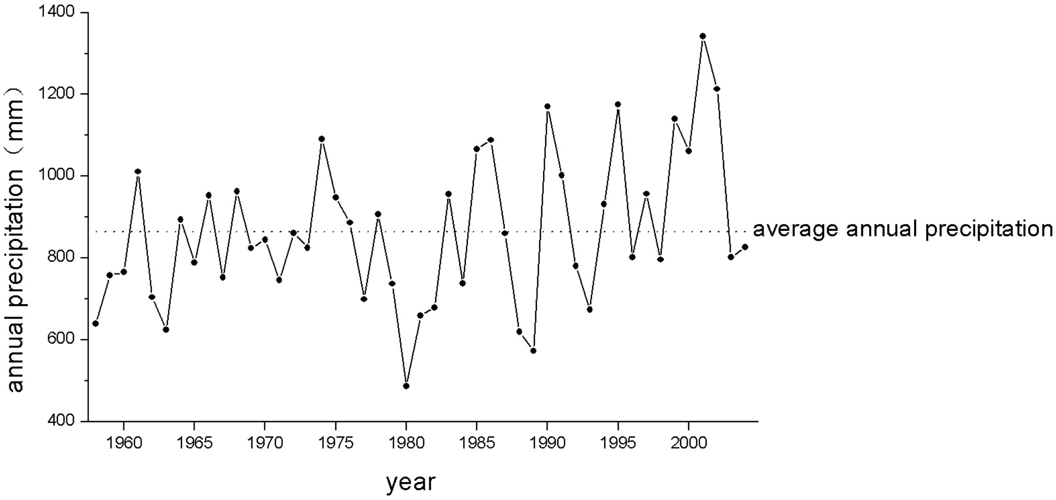

Fig. 3 Variation of annual precipitation at Chuxiong from 1958 to 2004.

Sediment mobilized from the surface soils on slopes with a forest or shrub cover or under cultivation, where sheet and rill erosions are predominant, are likely to contain relatively high levels of ^{137}Cs, while sediment, mobilized from subsurface sources by bank erosion, gully erosion and mass movements, etc., can be expected to contain little ^{137}Cs. An indication of the relative importance of the sediment contribution from surface soils with a forest and shrub cover and cultivated soils can be obtained by comparing the ^{137}Cs concentrations associated with recently deposited sediments with those of the surface soils. The ^{137}Cs concentration in the surface layer (0–5 cm) of the sediment profile was 0.92 ± 0.17 Bq kg^{-1}, which was only 19% of the mean ^{137}Cs concentration of the surface soil with a forest-shrub cover and 40% of the mean value for cultivated soils. This suggests that, at present, the dominant source of the reservoir sediment is subsurface material, which contains little ^{137}Cs, mobilized by bank erosion, mass movements and gully erosion. However, the high ^{137}Cs concentration of 10.90 ± 0.49 Bq kg^{-1} associated with the upper ^{137}Cs peak caused by the 1998 fire indicates that the sediment was contributed primarily from the surface horizons of the forest-shrub soils, which were characterized by high ^{137}Cs concentrations. The ^{210}Pb$_{ex}$ concentration of the sediment in the upper layer (0–5 cm) of the sediment profile was 17.87 ± 1.17 Bq kg^{-1}. This is 33.9% of the mean concentration in the forest-shrub soils and close to the value of 17.73 ± 1.04 Bq kg^{-1} found in the cultivated soils. The reduced contrast between the concentration in the sediments relative to those in surface soils evident for ^{210}Pb$_{ex}$, when compared with ^{137}Cs, can be accounted for by the fact that the ^{210}Pb$_{ex}$ content of the reservoir sediment reflects both the ^{210}Pb$_{ex}$ content of the mobilized soil delivered to the reservoir, as well as fallout to the reservoir surface which is subsequently adsorbed by the sediment. There is currently no fresh ^{137}Cs fallout. For this reason ^{210}Pb$_{ex}$ is not a good source fingerprint.

CONCLUSIONS

1 ^{137}Cs and ^{210}Pb$_{ex}$ peaks in reservoir or lake sediment profiles produced by particular events in the catchment can provide good time markers for establishing the chronology for deposited sediment. The ^{137}Cs and ^{210}Pb$_{ex}$ peak at a depth of 15–21 cm in the study reservoir was associated with the 1998 fire in an adjacent area of the catchment and has been successfully used for dating of the sediment profile.

2 The highest specific sediment yield of 2420.9 t km^{-2}·year^{-1} estimated for the period 1959–1962 was related to the severe soil erosion triggered by large-scale deforestation in the catchment during the period of the Great Leap Forward (1958–1960). When deforestation ceased, the natural vegetation regenerated quite quickly as a result of the favourable climatic and soil

conditions and the specific sediment yield declined to 200.2 t $km^{-2}\cdot year^{-1}$ by the period 1998–2003.

3 By comparing the ^{137}Cs activity of the surface layer of the sediment in the reservoir with that of potential source materials in the catchment, it has been shown that the sediment deposited recently in the reservoir was derived primarily from subsurface sources containing little ^{137}Cs, by bank erosion, gully erosion and mass movements, etc.

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