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Recent lake sedimentation in the middle and lower Yangtze basin inferred from ^{137}Cs and ^{210}Pb measurements

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Abstract

The reduction of water storage capacity in the lakes of the Yangtze basin was an important factor for the disastrous 1998 flooding. This study attempted to quantify sedimentation and its role in the water storage reduction in the middle and lower reaches of the Yangtze basin using the radionuclide of caesium-137 (^{137}Cs) and lead-210 (^{210}Pb) as tracers. Sixteen cores were taken from eight lakes, including the two largest lakes in the region (Poyanghu and Dongtinghu). The two dating techniques were used in combination to quantify recent sediment accumulation rates and their changes over the last few decades. The ^{137}Cs and ^{210}Pb measurements indicated higher sedimentation rates for Dongtinghu which were consistent with observed severe reduction of water storage capacity. The inferred sedimentation rates for the remaining lakes were lower and did not reflect the perceived rate of severe soil erosion upstream or the substantial water storage reduction. The low sedimentation rates inferred for most lakes tentatively suggest that sediment deposition was not the primary reason for the observed reduction in water storage capacity. Nevertheless, a clear increasing trend in sedimentation rates has been documented for most of the studied lakes over the past few decades. Sedimentation and its role in water storage reduction require further study due to the many problems associated with its quantification such as the post-depositional redistribution of sediments and water exchanges between the Yangtze river and the studied lakes.

Keywords: Lake sedimentation; Flooding; ^{137}Cs; ^{210}Pb; The Yangtze basin

1. Introduction

The Yangtze is the third longest river in the world. Originating on the Tibet Plateau, the river carves its 6300 km route through the south-western mountains and meanders across southern China's vast, fertile plains into the East China Sea in Shanghai (Fig. 1). The Yangtze and its tributaries are vital transport routes, but they have also produced some of China's worst natural flood disasters such as in the year of 1933, 1954, 1991 and 1998. The 1998 floods, the worst in recent history in China, cost many lives and caused enormous economic loss. The disaster was accentuated by the reduction of flood storage capacity throughout the basin. For example, the lake of Poyanghu has reduced its surface area from 5000 km^2 in 1954 to 3900 km^2 in 1990, and the lake of Dongtinghu from 4300 km^2 in 1954 to 2600 km^2 in 1990 (Ping, 1998). As a result, Dongtinghu has reduced its water storage capacity from 29.3 billion m^3 in the 1950s to 17.8 billion m^3 in the 1990s (Ping, 1998). Previously designated flood-diversion areas in Jinjiang, Hubei province, are now farm and factory sites, making diversion impossible. Due to the considerable loss of water storage, water levels have risen and flooding occurs more frequently throughout the basin. Most of the hydrological stations along the middle reach of the Yangtze, for example, recorded higher water levels during the 1998 flooding than the historical highest level (Zong and Chen, 2000).

The reduction was probably due to agricultural reclamation around wetlands and sediment deposits in water bodies, such as lakes and river channels, resulting from severe soil erosion. However, it is not clear how much sedimentation has contributed to the reduction and information on recent sedimentation changes due to human activities is very limited for most of the lakes. The present study attempts to examine the storage reduction of the water bodies by quantifying sedimentation and its recent changes throughout the middle and lower reaches of the Yangtze basin using radionuclide of caesium-137 (^{137}Cs) and lead-210 (^{210}Pb) as

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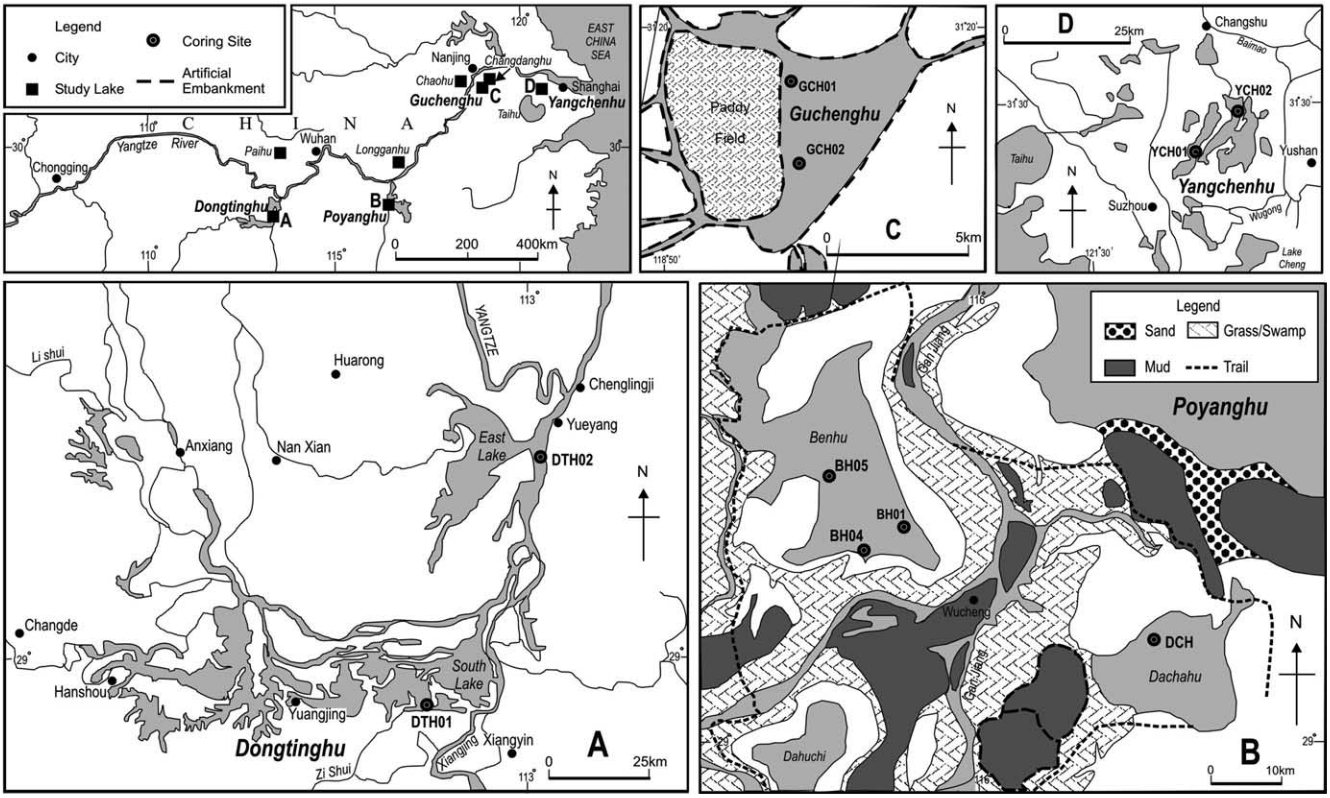

Fig. 1. The middle and lower reaches of the Yangtze River showing the eight studied lakes, four of which, Dongtinghu (a), Poyanghu (b), Guchenghu (c) and Yangchenhu (d), are highlighted with the coring sites.

tracers. Caesium-137 has been used extensively as a tracer to reconstruct recent sedimentation rates (Ritchie and McHenry, 1990; He and Walling, 1995; Walling and He, 1997). The radionuclide has a half-life of 30.1 yr and has been redistributed globally as fallout since the onset of atmospheric nuclear weapons testing in the 1950s. Within the sediment horizons two clear dating markers, 1954 and 1963 (corresponding to the onset and the peak fallout of ^{137}Cs), can be identified at most depositional sites (Ritchie and McHenry, 1990). The ^{210}Pb, a natural radioactive isotope with a half-life of about 22 yr, has been used frequently for sediment dating over the time scale of last 100–150 yr. The two radionuclides can be combined to reduce the uncertainty in dating (Benninger et al., 1997).

The use of a rapid appraisal technique such as the ^{137}Cs and ^{210}Pb tracers for a systematic evaluation of sedimentation and its fluctuations is significant for understanding the control mechanism of the water storage reduction caused by sedimentation. This paper reports our study on the lakes along the middle and lower reaches of the Yangtze basin.

2. Study lakes

There are more than 600 lakes over 1 km^2 along the middle and lower reaches of the Yangtze basin, covering a total area of 18,400 km^2 (Wang and Dou, 1999). We examined eight lakes, including some of the major lakes in the Yangtze basin such as Poyanghu and Dongtinghu (Fig. 1). Summary information on water depth, lake area, catchment area and climate (rainfall and temperature) for the eight lakes, are summarized in Table 1. Poyanghu has an area of about 3900 km^2 and is presently the largest freshwater lake in China (Fig. 1b). It is fed by the Yangtze River in the north and receives water from a number of rivers in the south. Among these smaller rivers, the Ganjiang originates from the southern Jiangxi Province, one of the areas with most severe soil erosion in China. Dongtinghu used to be the largest lake in the Yangtze basin, but due to its severe reduction, it is now the second largest (Fig. 1a). The remaining lakes in the study are much smaller by comparison and four of them are located further down the Yangtze near Nanjing and Shanghai (Fig. 1). The eight lakes are severely impacted by land reclamation activity through construction of embankments or dykes.

3. Methods

3.1. Sample collection

Sixteen cores were taken from the eight lakes from 1992 to 1998 following the methods as introduced by Xiang (1998). The numbers of cores sampled from each lake are

Table 1
Basic information for the eight studied lakes

Names	Locations	Water depth (m)	Lake area (km^2)	Catchment area (km^2)	Rainfall (mm)	Temperature (°)
Dongtinghu	28°44′–29°35′N, 111°53′–113°05′E	6.39	2432.5	25.7×10^4	1305	16.6–17.0
Poyanghu	28°24′–29°46′N, 115°49′–116°46′E	5.10	2933	16.2×10^4	1570	16.5–17.8
Chaohu	31°25′–31°43′N, 117°16′–117°53′E	2.69	769.55	9258	995.7	16.1
Guchenghu	31°14′–31°18′N, 118°53′–118°57′E	1.56–6.5	24.5	248.0	1105.1	15.5
Yangchenhu	31°21′–31°30′N, 120°39′–120°51′E	1.4	119.0	–	–	–
Changdanghu	31°30′–31°40′N, 119°30′–119°40′E	1.10	89.0	–	1100	15.4
Longganhu	29°52′–30°05′N, 115°19′–116°17′E	3.78	316.2	5511.0	1291.3	16.6
Paihu	30°16′–30°19′N, 113°10′–113°16′E	1.5	12.4	260.3	1121.3	16.3

listed in Table 2. The coring locations in the four lakes: Dongtinghu, Poyanghu, Guchnghu and Yangchenhu, are highlighted in Fig. 1. The two cores taken from Dongtinghu cover two major parts of the lake—the East and South lakes (Fig. 1a). The four cores from Poyanghu are taken from the two smaller lakes located in the northwest corner of the lake (Fig. 1b). The two smaller lakes are joined to Poyanghu in the wet season but separated during the dry season. The cores were divided into different segments ranging from 0.5 to 4 cm depending on estimated sedimentation rates from field observations. In addition to the sediment cores, soil samples were collected to estimate baseline ^{137}Cs fallout for nearby Poyanghu and Yangchenhu. Soil samples for baseline fallout are normally taken from sites without obvious soil erosion or sediment deposition. It is difficult to find such ideal sites due to severe human disturbance close to the lakes, and eventually soil reference samples were taken from nearby paddy fields.

3.2. Radionuclides determination

Sediment and soil samples were air-dried, disaggregated, ground and sieved through a 2 mm mesh. ^{210}Pb was determined for all the sediment samples from the 16 cores, and ^{137}Cs for 10 out of the 16 cores using EG and G Ortec Gamma Spectrometry at the Institute of Limnology and Geography, Nanjing, China. ^{137}Cs was measured at 662 keV, while ^{210}Pb was determined via its gamma emission at 46.5 keV, and ^{226}Ra at 295 and 352 keV γ-rays emitted by its daughter isotope ^{214}Pb. Information on the

Table 2
^{137}Cs inventories and linear sedimentation rates since 1963 for the eight lakes

Lake	Sampling time	Baseline value of ^{137}Cs	Total ^{137}Cs (Bq m^{-2})	Linear sedimentation rates since 1963 (cm yr^{-1})
Dongtinghu	Oct. 1998	–	1535 (DTH01)	1.93
			1700 (DTH02)	0.78
Poyanghu	Mar. 1997	1714 ± 144	3453 (BH01)	0.62
			1596 (BH04)	0.24
			868 (BH05)	0.18
			828 (DCH)	0.10
Chaohu	Aug. 1997	–	–	0.14[a]
			–	0.20[a]
Guchenghu	May 1991	–	63 (GCH01)	0.23
			500 (GCH02)	0.13
Yangchenhu	May 1993	1661	161(YCH01)	0.28
			556 (YCH02)	0.27
Changdanghu	Sept. 1999	–	–	0.23[a]
			–	0.25[a]
Longganhu	Nov. 1993	–	–	0.05[a]
Paihu	Oct. 1994	–	–	0.55[a]

[a] The linear sedimentation rates are determined by ^{210}Pb.

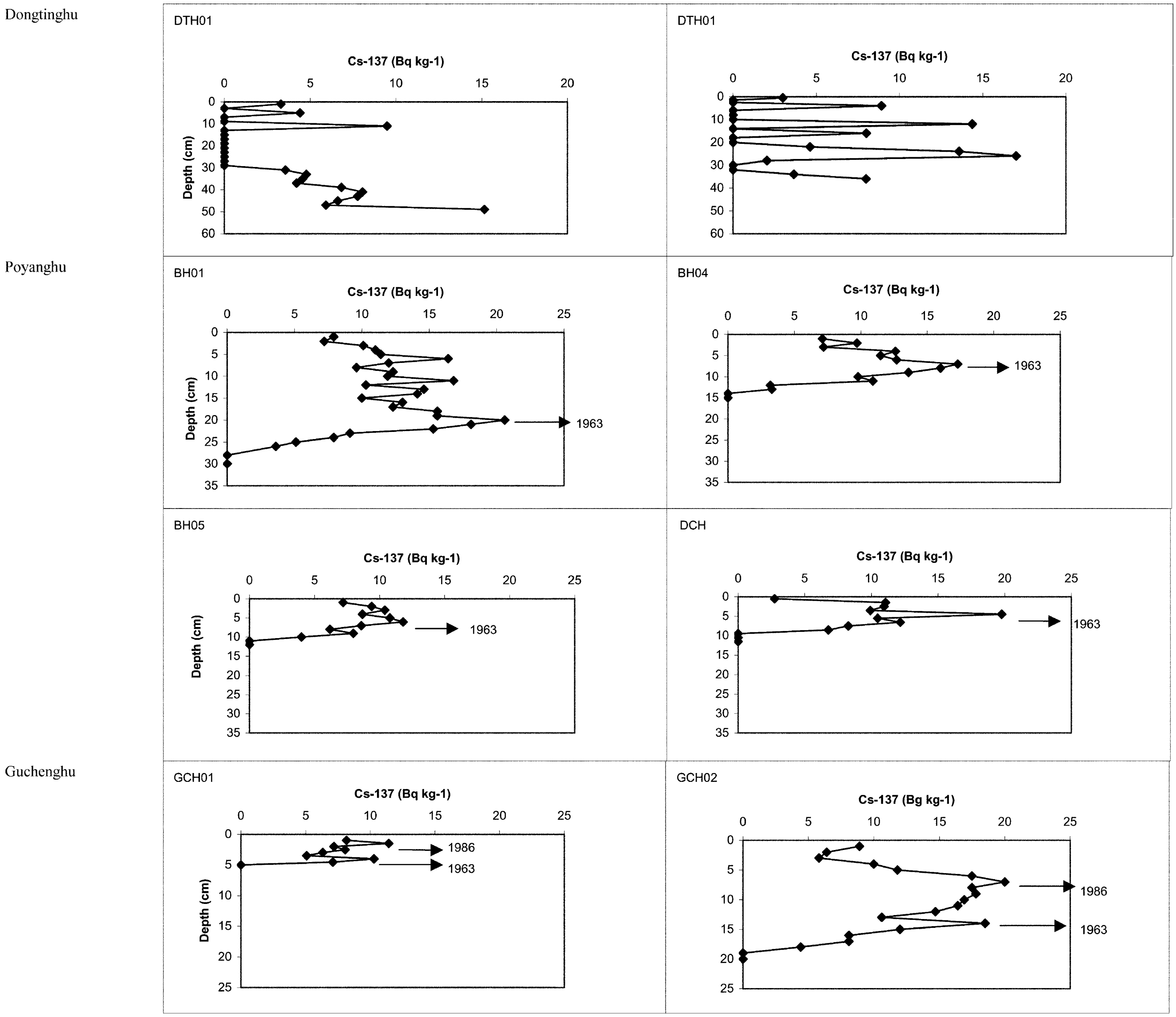

Fig. 2. ^{137}Cs concentration for the cores from the lake of Dongtinghu, Poyanghu and Guchenghu, in the Yangtze basin. Core names are indicated in the up-left corner.

ten cores with ^{137}Cs determination and the associated lakes can be found in Table 2.

4. Caesium-137 and Lead-210 profiles

4.1. Caesium-137 inventories

The total inventory of ^{137}Cs for the examined cores is considerably different, even for the cores from the same lake (Table 2). Among the lakes with ^{137}Cs measurements, the ^{137}Cs inventory is the highest in Poyanghu (the BH01) and the lowest in Guchenghu (the GCH01). The total inventories of the radionuclide can convey information about modern sedimentation processes (Benninger et al., 1997), by comparison with the amount of atmospheric input estimated from soil reference samples. The atmospheric fallout of ^{137}Cs is $1714 \pm 144\ \mathrm{Bq\,m^{-2}}$ for Poyanghu and $1661\ \mathrm{Bq\,m^{-2}}$ for Yangchenhu (Table 2). Atmospheric fallout is in general controlled by latitude and precipitation (Davis, 1963; Basher and Matthews, 1993). Higgitt et al. (2000) listed ^{137}Cs references for some locations in China. The reconstructed reference values for the two lakes fall in the range of Higgitt et al. (2000). The total ^{137}Cs inventory for the BH01 core from Poyanghu is higher than its reference value, suggesting enhanced deposition due to either sediment focusing or the major ^{137}Cs input from the drainage basin. ^{137}Cs inventories for the two cores from Dongtinghu and the BH04 from Poyanghu are close to the reference values. In contrast, ^{137}Cs for the rest of the cores are considerably smaller than the corresponding baseline values, suggesting significant post-depositional processes

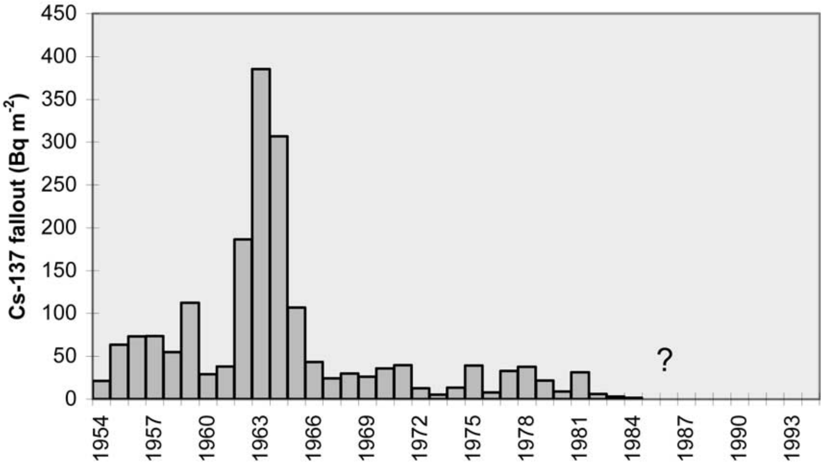

Fig. 3. Annual ^{137}Cs fallout between 1954 and 1984 for Changshou county in the Yangtze Three Gorges area reconstructed by Lu and Higgitt (2000). The Chernobyl fallout in 1986 is not clear.

occurred in these cores. This is particularly apparent for Guchenghu, assuming that its reference value is similar to the other two water bodies (given its similar latitude and precipitation, Table 1).

4.2. Caesium-137 profiles

The depth distributions of ^{137}Cs concentrations for some cores are shown in Fig. 2. The ^{137}Cs concentrations fluctuate throughout the profiles, particularly for the two cores from Dongtinghu. Most of the cores have one or more well-defined ^{137}Cs peaks, except for the cores from Dongtinghu. The input of ^{137}Cs into a lake consists of the atmospheric-derived and the catchment-derived contribution. Its profile is controlled by a number of processes such as the upward and/or downward diffusion of radionuclide in water, bioturbation of sediments and mixing of sediments by physical reworking (Stanners and Aston 1984; He et al., 1996). There are no reports on the atmospheric ^{137}Cs fallout in China. Lu and Higgitt (2000) constructed an annual fallout, as shown in Fig. 3, for the Yangtze Three Gorges using a model for predicting global distribution of ^{90}Sr fallout between 1954 and 1974 (Sarmiento and Gwinn, 1986) and the ^{137}Cs records in Tokyo (Hirose et al., 1987). The ^{137}Cs profiles for the BH01 from Poyanghu and the GCH02 from Guchenghu, reflect in general an atmospheric input history, e.g. the broad maximum at the lower part of each core is most likely associated with the peak fallout of ^{137}Cs in the mid-1960s from atmospheric nuclear weapons testing. The profiles for the cores from Dongtinghu are uncompleted (^{137}Cs is still high at the bottom of the profiles) and do not reflect an atmospheric input history. The ^{137}Cs profiles for the rest of the cores, which all have greatly reduced inventories, are not so apparent due to post-depositional processes. Post-depositional movements can spread ^{137}Cs over a large part of the profile and reduce the peak heights. However, most of those post-depositional movements will not change the position of the major ^{137}Cs horizon (Ritchie et al., 1975), except for diffusional movement.

If the post-depositional processes identified for some of the cores had no effect on the ^{137}Cs profile shape, then it is probable that the clear peak occurring close to the base of the profile was generated by peak fallout in 1963. This may or may not be the highest activity level in all the cores. The base of the profile can be assumed to represent ^{137}Cs onset in 1954, but possible downward diffusion must be taken into consideration. Caesium (Cs^+) is strongly absorbed by illite in aquatic environments although there is some desorption on time scales of weeks to months (Comans et al., 1991). Cs^+ is absorbed faster in a Ca^{2+} rich environment than in a K^+ rich environment (Callender and Robbins, 1993). The ^{137}Cs diffusion can be a problem due to water chemical properties in southern China where levels of K^+ are higher than Ca^{2+} in most water bodies (ESRS (Ecological Station of Red Soils), 1992).

4.3. Lead-210 profiles

The depth distributions of excess ^{210}Pb in the sediment profiles for several cores are shown in Fig. 4. Surficial excess ^{210}Pb activities are around 100 Bq kg^{-1} for most of the cores, except for the DTH01 from Dongtinghu and the BH05 from Poyanghu. In most shallow-water environments, excess ^{210}Pb is derived largely from the deposition of ^{210}Pb from the atmosphere, where it is produced by the decay of gaseous ^{222}Rn (Appleby and Oldfield, 1983). The general assumptions for ^{210}Pb application are homogeneity and steady-state conditions (Appleby and Oldfield, 1983). However, the conditions are rarely met in fluvial systems, where temporal, spatial, and textural patterns of deposition can change over small scales (Goodbred and Kuehl, 1998). This might be particularly true in China where human activity has a large impact on sedimentation. From the ^{210}Pb profiles it can be seen that the relationship between exponential ^{210}Pb and depth is non-linear for most of the cores.

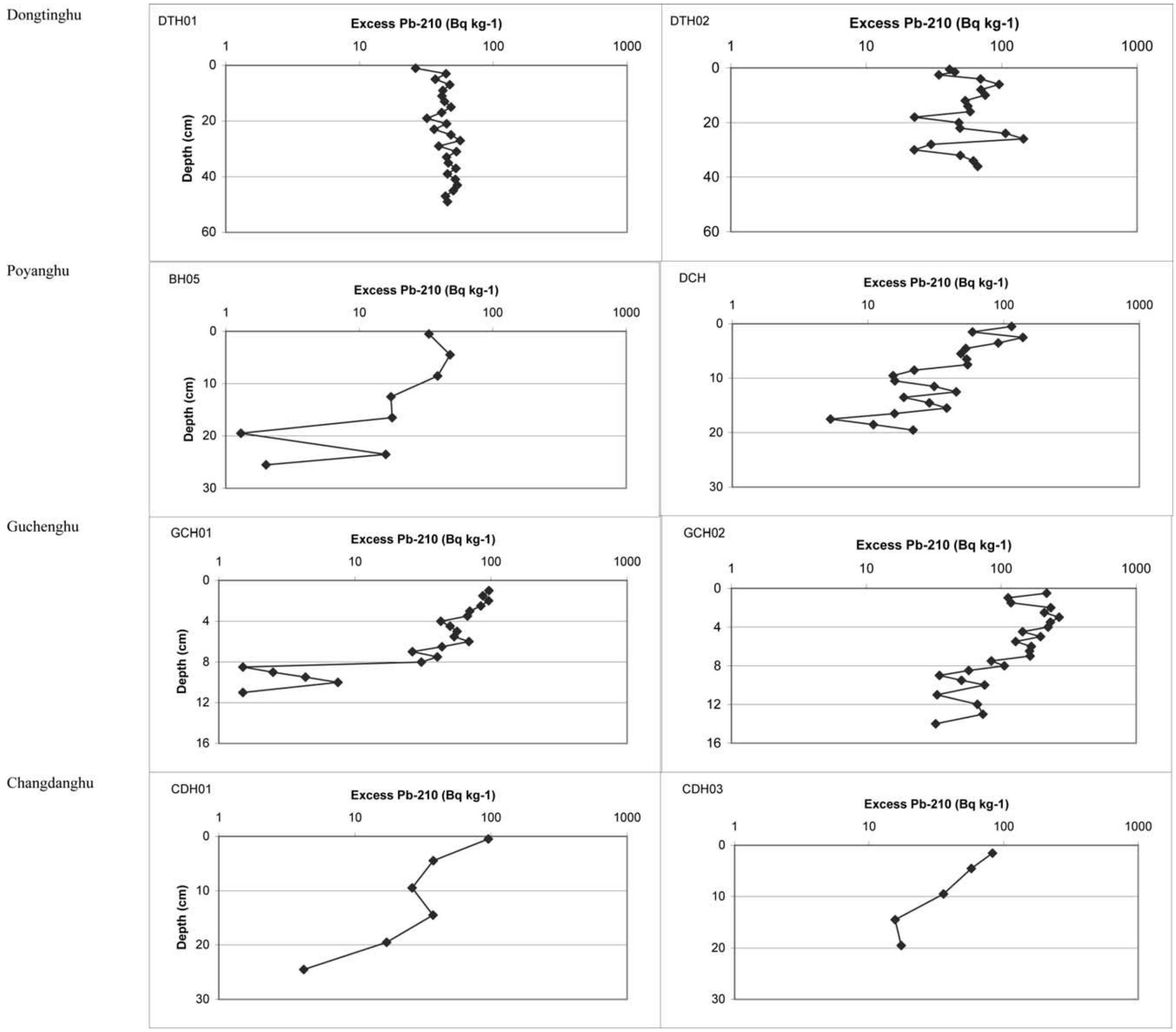

Fig. 4. ^{210}Pb activity for the cores taken from Dongtinghu, Poyanghu, Guchenghu and Changdanghu, in the Yangtze basin. Core names are indicated in the up-left corner.

Following the procedure tentatively outlined by Appleby and Oldfield (1983), the ^{210}Pb data were carefully evaluated. The CRS model (Constant Rate of ^{210}Pb Supply Model) was used to calculate chronologies, which assumes that there is a constant fallout of ^{210}Pb from the atmosphere to the lake waters, resulting in a constant supply rate of ^{210}Pb to the sediments irrespective of any variations which may have occurred in the sediment accumulation processes (Appleby and Oldfield, 1983).

The chronologies calculated by the ^{210}Pb are consistent with the ^{137}Cs dating markers in 1963 for some of the cores as represented by one of the cores from Guchenghu (Fig. 5a). The results are consistent with the study of Boyle et al. (1998). They find a good agreement between the ^{210}Pb dates and the peaks in bomb testing ^{137}Cs for the small lakes in the middle reach of the Yangtze. With the aid of the ^{210}Pb chronology, we can assign the ^{137}Cs peaks in the upper middle of the two cores from Guchenghu as fallout of the 1986 Chernobyl accident. The Chernobyl fallout corresponds to the fallout in the Yiwanshui Reservoir as described by Lu and Higgitt (2001). Wan et al. (1990) also identified the Chernobyl fallout in a reservoir in Guizhou in the Upper Yangtze. The evidence suggests that it is possible to identify Chernobyl fallout from sediment cores in the Yangtze basin. This provides one more dating markers, but leads to some difficulties with erosion quantification using ^{137}Cs as a tracer (Lu and Higgitt, 2000).

For some cores the ^{210}Pb chronologies are not consistent with the ^{137}Cs dating. For example, the ^{210}Pb calculations for the core BH05 from Poyanghu ascribe 1963 at a depth of around 10 cm, which is 4 cm further down the core compared to the ^{137}Cs dating (Fig. 5b). This is probably due to sediment

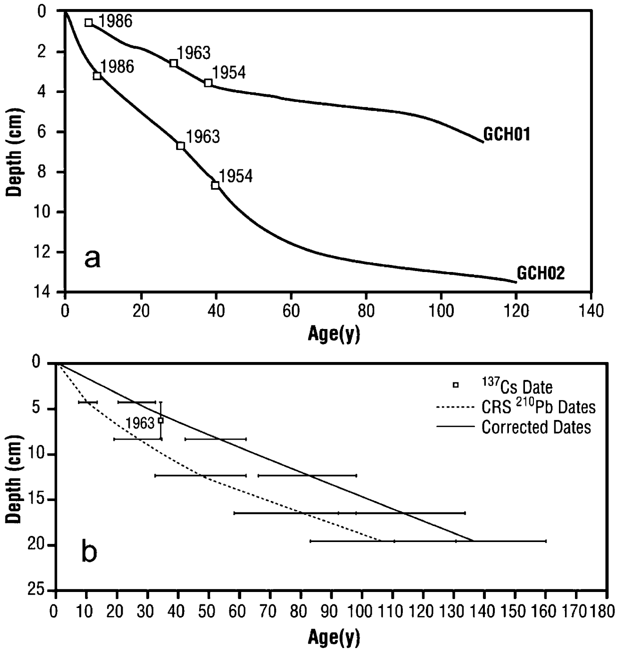

Fig. 5. Comparison between ^{137}Cs markers and ^{210}Pb chronologies: ^{137}Cs markers are consistent with ^{210}Pb chronology for Guchenhu (a) and not consistent for Poyanghu (b).

mixing and it may be necessary to fit the CRS model using an average ^{210}Pb value from the top mixing layer rather than the surficial value (Benninger et al., 1997). Alternatively, the ^{210}Pb chronologies can be corrected using the 1963 ^{137}Cs marker (Fig. 5b) and subsequent calculation of sediment accumulation rates for those cores is based on the corrected ^{210}Pb chronology (Xiang, 1998).

5. Sedimentation

5.1. Sedimentation rates

A variety of methods have been developed to estimate sedimentation rates using ^{137}Cs techniques. This includes the most direct method using ^{137}Cs dating markers such as in 1954 or 1963 (Ritchie and McHenry, 1990; Allison et al., 1998), and modeling (Smith et al., 1987; Walling and He, 1997; Callender and Robbins, 1993). Either way it is necessary to take account of the potential post-depositional redistribution in the sediment profile and of the ^{137}Cs residence time. Goodbred and Kuehl (1998) examined the three methods: ^{137}Cs penetration depth (e.g. 1954) and excess ^{137}Cs and ^{137}Pb inventories, and found that the calculated accretion rates correlate well among the three methods. Considering ^{137}Cs diffusion, the study calculates linear sedimentation rates for post-1963 (Table 2). The linear sedimentation rates for the cores without ^{137}Cs measurements are averaged using ^{210}Pb dating.

The linear sedimentation rates for Dongtinghu are the highest being close to 2 cm yr^{-1} for the East lake (e.g. the DTH01). The estimated sedimentation rate for the East lake is consistent with a report that an average 100 million m^3 of sediment is deposited each year in Dongtinghu (Ping, 1998; Chen et al., 2001). The high sedimentation is also supported by field measurements in Dongtinghu after the 1998 Yangtze flooding. The average sediment thickness from the single flood event is around 20 cm with a maximum of 30 cm based on over 20 measurement sites. For Poyanghu, sedimentation rate is higher for the core BH01 (Table 2). The BH01 core was taken from the part of the lake which is controlled by the Ganjiang flowing from the southern Jiangxi Province (Fig. 1b), which is well known for its severe soil erosion in the catchment. The differences between sedimentation rates within the same lake demonstrate spatial variations, which are most likely due to variations in sediment inputs and in part post-depositional movement.

The linear sedimentation rates can directly indicate sedimentation but are not comparable between lakes because of the influence of catchment-lake surface area ratio (Fig. 6). Nevertheless, the remaining lakes have much lower linear sedimentation rates (<1 cm yr^{-1}). Boyle et al. (1998) examined seven lakes flanking the middle reach of the Yangtze and found that average sediment accumulation rates were in

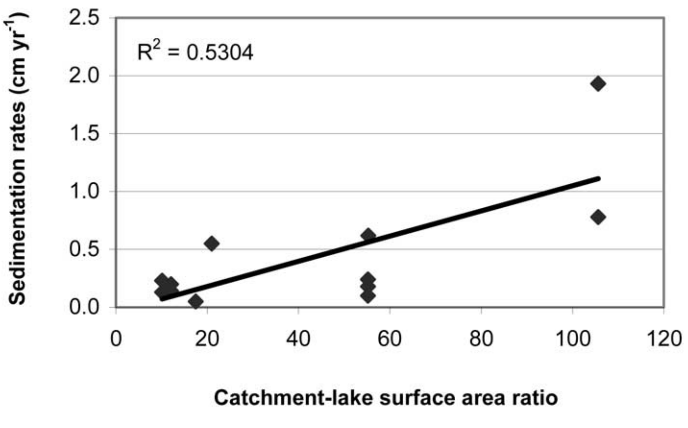

Fig. 6. Relationship between linear sedimentation rates and catchment-lake ratio for the studied lakes.

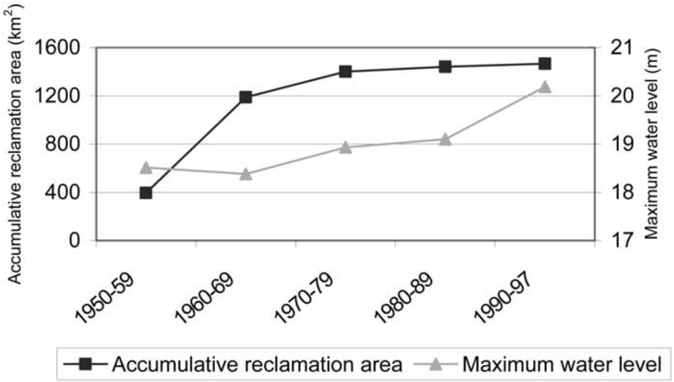

Fig. 7. Relationship between agricultural reclamation and water levels for Poyanghu (Xiang, unpublished data).

the range of 0.05–0.29 cm yr^{-1} assuming a bulk density of 1.0 g cm^{-3}. The low sedimentation may be caused by frequent water exchange between the lakes and the Yangtze. During the exchange process, part of the sediment is flushed into the main Yangtze River.

The reconstructed lower sedimentation rates for most of the lakes do not reflect the severe soil erosion upstream and the considerable reduction in water storage capacity. This suggests that other processes such as land reclamation around the lakes contribute to the severe loss of water storage capacity for these lakes. The relationship between land reclamation and maximum water levels around

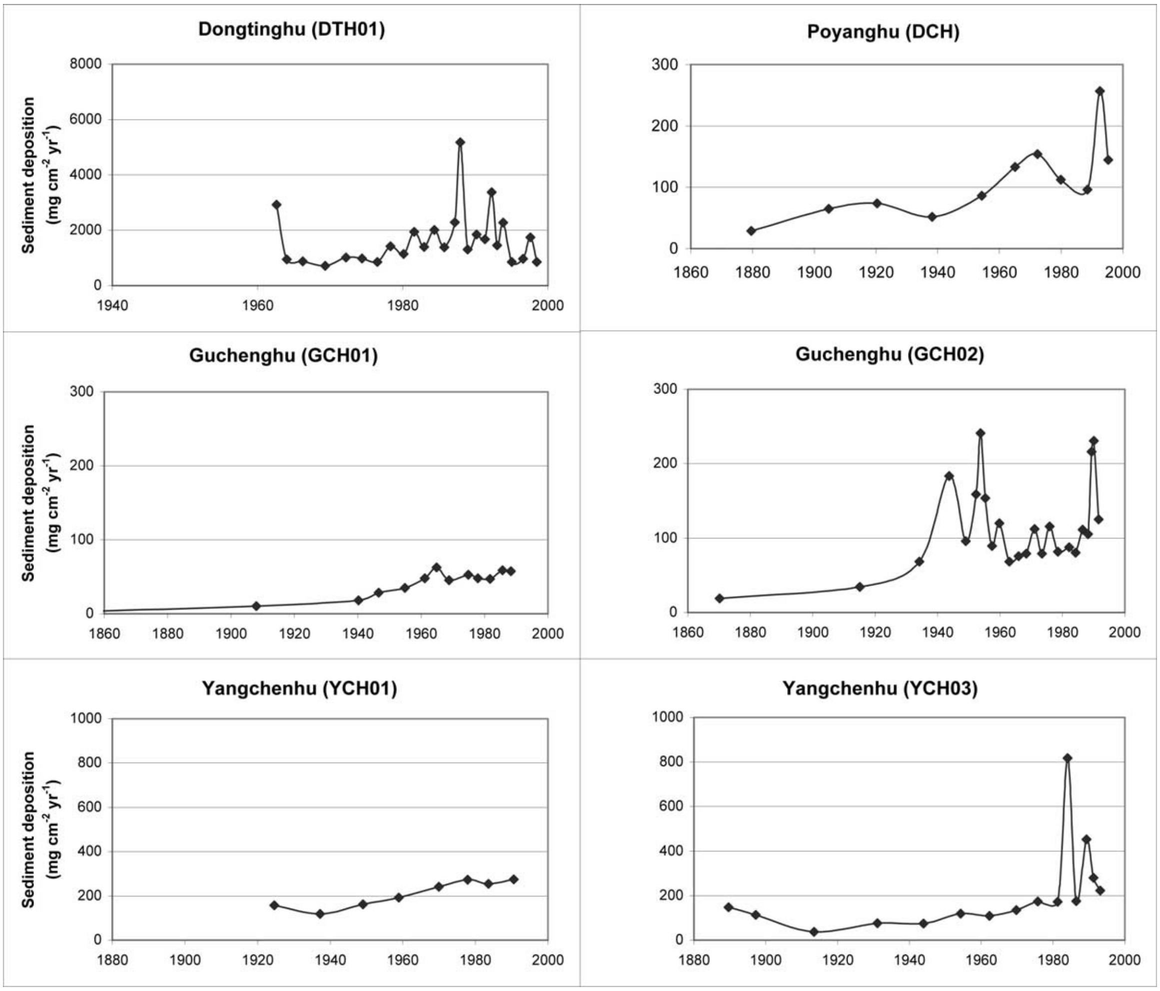

Fig. 8. Sedimentation rate changes inferred from ^{210}Pb chronologies for the cores taken from Dongtinghu, Poyanghu, Guchenghu and Yangchenhu, in the Yangtze basin.

Poyanghu is shown in Fig. 7. A detailed explanation on the impact of reclamation on the water levels requires more information, but it clearly indicates that the maximum water levels have steadily increased with increase of accumulated reclamation area over the past 50 yr. Therefore, the radical prevention of floods requires to reduce sediment deposition and control agricultural reclamation rather than to rely on the reinforcement of dykes and embankments.

5.2. Sedimentation changes

Using ^{210}Pb, it is possible to reconstruct sedimentation dynamics over the last 100 yr. The reconstructed sedimentation rates based on the ^{210}Pb chronologies for some of the lakes are depicted in Fig. 8. Sedimentation rates have significantly increased since the 1950s for most of the lakes. This may reflect increased soil erosion in the upstream catchment due to deforestation and the extension of agricultural land as reported by Lu and Higgitt (1998). Profound changes in land use, including widespread deforestation and extension of agricultural land, have been superimposed during the past 40 yr in China, especially during the great leap forward from 1958 to 1961. As a result, forest cover in China has been significantly reduced and soil erosion-affected areas increased. For example, the area affected by soil erosion in the Jiangsu Province, where the three lakes (Guchenghu, Changdanghu and Yangchenhu) are located, increased from 1850 km^2 in 1957 to 6100 km^2 in the 1980s (Yang and Shi, 1994). The significant increase in sedimentation rates along the middle and lower reaches of the Yangzte basin is consistent with the increased soil erosion areas. However, the significant increase in the reconstructed sedimentation rates contradicts the report by Boyle et al. (1998) who found that six out of seven lakes examined in the middle reach of the Yangtze showed little clear evidence of recent accumulation rate changes. Identifying the role of human activity in changing sedimentation rates is affected by the high degree of year-to-year variability in runoff and sediment transport. Some dramatic changes in sedimentation rate correspond to floods. For example, the two peaks for the GCH02 from Guchenghu reflect the floods in 1954 and 1991, respectively.

6. Summary and conclusions

This study attempts to use the ^{137}Cs and ^{210}Pb techniques to quantify recent sedimentation rates for eight lakes in the middle and lower reaches of the Yangtze basin. The profiles of the ^{137}Cs activity for most of the cores were similar to atmospheric fallout, although they fluctuated throughout the sediment profiles. The total inventories for some of the cores were much lower than atmospheric fallout, suggesting significant post-depositional movements. For most of the cores, the 1963 marker could be picked out from the ^{137}Cs profiles, but a few well-defined peaks were difficult to identify without the aid of the ^{210}Pb chronology. The ^{210}Pb chronology was calculated by employing a CRS model (Constant Rate of ^{210}Pb Supply Model) due to non-steady input of ^{210}Pb, and corrected by the 1963 ^{137}Cs marker when the chronology and the 1963 ^{137}Cs marker were not consistent with each other.

Sedimentation rates were subsequently estimated using the ^{137}Cs marker in 1963 and the ^{210}Pb chronologies. The reconstructed linear sedimentation rates were very high for Dongtinghu, but were, in general, low (<1 cm yr^{-1}) for the rest of the studied lakes. This is mainly because part of the sediment is flushed into the main Yangtze via the water exchange between the lakes and the Yangtze River. The reconstructed low sedimentation rates for most of the studied lakes suggest that sedimentation is not the primary reason for severe reduction in water storage capacity. Nevertheless, most of the cores with the ^{210}Pb measurements showed an increase in sedimentation rates since the 1950s.

This study demonstrates that the combination of ^{137}Cs and ^{210}Pb dating techniques is useful in quantifying sedimentation in the Yangzte basin, but the seasonal hydrological regimes of water exchange with the Yangtze River for the lakes raise concerns about the applicability of such techniques. Determination of sedimentation rates from these lakes is further complicated by the post-depositional redistribution of sediments. The role of sedimentation in the water storage reduction in the Yangtze basin needs further attention.

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References

Appleby, P.G., Oldfield, F., 1983. The assessment of ^{210}Pb data from sites varying sediment accumulation rates. Hydrobiologia 103, 29–35.

Allison, M.A., Kuehl, S.A., Martin, T.C., Hassan, A., 1998. Importance of flood-plain sedimentation for river sediment budgets and terrigenous input to the oceans: insights from the Brahmaputra–Jamuna River. Geology 26, 175–178.

Basher, L.R., Matthews, K.M., 1993. Relationship between ^{137}Cs in some undisturbed New Zealand soils and rainfall. Australian Journal of Soil Research 31, 655–663.

Benninger, L.K., Suayah, I.B., Stanley, D.J., 1997. Manzala lagoon, Nile delta, Egypt: modern sediment accumulation based on radioactive tracers. Environmental Geology 34 (2/3), 183–193.

Boyle, J.F., Rose, N.L., Bennion, H., Yang, H., Appleby, P.G., 1998. Environmental impacts in the Jianghan Plain: evidence from lake sediments. Water, Air, and Soil Pollution 112, 21–40.

Callender, E., Robbins, J.A., 1993. Transport and accumulation of radionuclides and stable elements in a Missouri River reservoir. Water Resources Research 29 (6), 1787–1804.

Chen, Z., Li, J.F., Shen, H.T., Wang, Z.H., 2001. Yangtze River of China: historical analysis of discharge variability and sediment flux. Geomorphology 41 (2–3), 77–91.

Comans, R.N.J., Haller, M., Depreter, P., 1991. Sorption of cesium on illite: nonequilibrium behaviour and reversibility. Geochimica Et Cosmochimica Acta 55 (2), 433–440.

Davis, J.J., 1963. Cesium and its relationship to potassium in ecology. In: Klement, A.E. (Ed.). Radioecology. Reinhold, New York, pp. 539–556.

ESRS (Ecological Station of Red Soils), 1992. Research on Red Soil Ecosystem, vol. 1. Science Press, Beijing in Chinese.

Goodbred, S.L., Kuehl, S.A., 1998. Floodplain processes in the Bengal Basin and the storage of Ganges–Brahmaputra river sediment: an accretion study using ^{137}Cs and ^{210}Pb chronology. Sediment Geology 121, 239–258.

He, Q.P., Walling, D.E., 1995. Rates of overbank sedimentation on the floodplains of British lowland rivers documented using fallout ^{137}Cs. Geografiska Annaler 78A (4), 223–234.

He, Q.P., Walling, D.E., Owens, P.N., 1996. Interpreting the ^{137}Cs profiles observed in several small lakes and reservoirs in southern England. Chemical Geology 129, 115–131.

Higgitt, D.L., Lu, X.X., Pu, L.J., 2000. Soil erosion assessment using ^{137}Cs: examples from contrasting environments in southern China. In: Foster, I.D.L. (Ed.). Tracers in Geomorphology. Wiley, Chichester, pp. 165–182.

Hirose, K., Aoyama, M., Katsuragi, Y., Sugimura, Y., 1987. Annual deposition of ^{90}Sr^{137}Cs and ^{239,240}Pu from the 1961–1980 nuclear explosions: a simple model. Journal of the Meterological Society of Japan 65 (2), 259–277.

Lu, X.X., Higgitt, D.L., 1998. Recent changes of sediment yield in the Upper Yangtze, China. Environmental Management 22, 697–709.

Lu, X.X., Higgiit, D.L., 2000. Estimating erosion rates on sloping agricultural land in the Yangtze Three Gorges, China, from caesium-137 measurements. Catena 39, 33–51.

Lu, X.X., Higgitt, D.L., 2001. Sediment delivery to the Three Gorges Reservoir: 2, local response. Geomorphology 41, 143–156.

Ping, S., 1998. Re-thinking of the flood disaster in the summer. Chinese Science News-Overseas Edition September, 25 in Chinese.

Ritchie, J.C., Hawks, P.H., McHenry, J.R., 1975. Deposition rates in valleys determined using fallout cesium-137. Geological Society of America Bulletin 86, 1128–1130.

Ritchie, J.C., McHenry, J.R., 1990. Application of radioactive caesium-137 for measuring soil erosion and sediment accumulation rates and patterns: a review. Journal of Environmental Quality 19, 215–233.

Sarmiento, J.L., Gwinn, E., 1986. Strontium 90 fallout prediction. Journal Geophysical Research 91, 7631–7646.

Smith, J.N., Ellis, K.M., Nelson, D.M., 1987. Time-dependent modelling of fallout radionuclide transport in a drainage basin: significance of 'slow' erosional and 'fast' hydrological components. Chemical Geology 63, 157–180.

Stanners, A.A., Aston, S.R., 1984. The use of reprocessing effluent radionuclides in the geochronology of recent sediment. In: Robbins, J.A. (Guest-Ed.), Geochronology of Recent Deposits. Chemical Geology, vol. 44, pp. 19–32.

Walling, D.E., He, Q., 1997. Use of fallout Cs-137 in investigations of overbank sediment deposition on river floodplains. Catena 29, 263–282.

Wan, G.J., Lin, W.Z., Huang, G.R., Cheng, Z.L., 1990. Caesium-137 dating and erosion tracing in Hongfeng Lake. Science Bulletin 19, 1487–1490 in Chinese.

Wang, S.M., Dou, H.S., 1999. Chinese Lakes. Science Press, Beijing in Chinese.

Xiang, L., 1998. Dating sediment on several lakes inferred from radionuclide profiles. Journal of Environmental Sciences 10, 56–63.

Yang, Y.S., Shi, D.M., 1994. Soil erosion in the Three Gorges Area. Southeastern University Press, Nanjing in Chinese.

Zong, Y.Q., Chen, X.Q., 2000. The 1998 flood on the Yangtze, China. Natural Hazards 22, 165–184.