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A comparison on the accumulation characteristics of ^{7}Be and ^{137}Cs in lake sediments and surface soils in western Yunnan and central Guizhou, China

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Abstract

The uplifting of the Himalayas has resulted in the development of a three-tiered landform in Southern China, the Yunnan–Guizhou Plateau is the middle tier of this landform on the eastern slope of the Himalayas. Lake Hongfeng and Lake Baihua in central Guizhou are about 1000 km away from Lake Erhai in western Yunnan. Sediment cores were collected from Lakes Erhai and Lugu in west Yunnan and Lakes Hongfeng and Baihua in central Guizhou, along with 28 surface soil cores from the watersheds of these lakes. The accumulation characteristics of ^{7}Be and ^{137}Cs show that: (1) ^{137}Cs activities in the soil cores of central Guizhou were higher than that in the western Yunnan. The activities and maximum penetrative depth of ^{7}Be were similar for the two regions. The activity ratio of $^{7}Be/^{137}Cs$ in surface soil reached 100–1000 in western Yunnan, but only 10–100 for central Guizhou region. (2) ^{7}Be inventories in soil cores at most sampling sites of central Guizhou were low, reflecting severe soil erosion. ^{7}Be inventories in the soil cores of Lake Lugu watershed in summer–autumn were higher than that in Lake Hongfeng/Baihua watershed and also higher than that in Lake Erhai watershed. This could be related to high ^{7}Be precipitation in summer and altitude. (3) ^{7}Be inventories in sediment cores of Lake Erhai, Lake Lugu and Lake Baihua were 237 ± 73, 322 ± 19 and 783 ± 44 Bq m^{-2}, respectively. Based on activity values that were corrected to deposition, prior to 1986, ^{137}Cs inventories in these lakes were 519 ± 26, 937 ± 13 and 3704 ± 56 Bq m^{-2}, respectively. (4) Modeling indicated that ^{7}Be and ^{137}Cs accumulations in Lake Hongfeng and Lake Baihua were dominated by watershed erosion, and controlled by the retention factor in Lake Erhai and Lake Lugu, but the ^{137}Cs

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inventory ratios obtained in the sediment core and from direct atmospheric fallout were similar, and the ratios were smaller for ^{7}Be. (5) ^{7}Be inventories from direct atmospheric fallout in Lake Erhai, Lake Lugu and Lake Baihua were 0.07 ± 0.02, 0.29 ± 0.02 and 0.08 ± 0.01 Bq m^{-2}, respectively. Prior to 1986, ^{137}Cs inventories were 0.11 ± 0.01, 0.22 ± 0.01 and 0.37 ± 0.01 Bq m^{-2}, respectively, showing that ^{137}Cs deposition has a regional difference. This phenomenon may reflect that uplift of the Himalayas has a screening effect on the fallout of globally distributed atmospheric pollutants in western Yunnan, China.

Keywords: ^{137}Cs and ^{7}Be; Precipitation and accumulation; Lake sediments; Surface soils; Yunnan–Guizhou Plateau of China

1. Introduction

The uplifting of the Himalayas has resulted in the development of a three-tiered landform in Southern China, and produced variable effects on global and regional climate change and air pollutant diffusion. The Yunnan–Guizhou Plateau on the eastern slope of the Himalayas is located in the geologic transfer zone between the Tibetan–Yunnan fold belt and the Yangtze craton. The Yunnan–Guizhou Plateau has large altitude gradients and complex landforms with a subtropical climate influenced by both the southeastern (Pacific Ocean) and southwestern (Indian Ocean) monsoons. To understand the effects of the Himalayan uplift on recent environmental change in the Yunnan–Guizhou Plateau, it is important to comparatively study the distribution and accumulation of fallout radionuclides (^{7}Be and ^{137}Cs) in lake sediments and watershed surface soils throughout the Plateau.

Fallout radionuclides have a given input function and decay and have tracing value for geochemical processes in the environment on variable time scales (Wan, 1988). ^{7}Be, half-life of 53.3 days, is produced in the atmosphere as a spallation product of O and N nuclei by bombardment of cosmic rays. ^{7}Be can be rapidly delivered to sediment after being transported into lake waters (Krishnaswami and Lal, 1978), and has a mean residence time of 77 days (Robbins and Eadie, 1982; Wan et al., 1986, 1987). ^{7}Be can be used as a tracer for seasonal particle mixing and transport. ^{7}Be atmospheric deposition is related to precipitation (Schuler et al., 1991; Baskaran et al., 1993), therefore, ^{7}Be can trace aquatic particle movement (Santschi, 1986; Wan, 1988; Baskaran et al., 1997; Feng et al., 1999a,b). It is a good tracer for seasonal particle mixing and transport (Bai et al., 1996; Blake et al., 1999; Walling et al., 1999).

^{137}Cs has been produced by nuclear testing, and has a half-life of 30.2 years. Its flux to the earth's surface shows a dependence on nuclear testing density, region and latitude (Wan, 1988). Discrepancy between ^{137}Cs vertical distribution characteristics and depositional fluxes is probably caused by ^{137}Cs diffusion in early-diagenesis processes, but this does not affect the locations of the peaks (Wan, 1988). Sediment accumulation rates calculated by the 1963, 1975 and 1986 time markers, respectively, show good consistency. Using fallout ^{137}Cs as a geochemical tracer of soil erosion has yielded good results in the tracing rates of soil erosion (Brown et al. 1981; Ritchie and McHenry 1990; Walling and Quine, 1991; Walling and He, 1999; Ritchie and Rasmussen, 2000).

We explore the regional differences in the atmospheric pollutants in the eastern slope of the Himalayas here, based on the comparison of the accumulation of ^{7}Be and ^{137}Cs in sediments and soils.

2. Materials and methods

2.1. Study areas

Based on the authors' previous work, Lake Erhai and Lake Lugu in western Yunnan, and Lake Hongfeng and Lake Baihua in central Guizhou were selected as study areas in this paper (Bai and Wan, 1998, 1999; Wan, 1999; Xu et al., 1999).

Lake Erhai, the largest fault lake in the western Yunnan Plateau, is located in the north of Dali (100°5′ −17′ E, 25°35′ −58′ N). The surface of the lake is 1974 m above mean sea level, an area of 249.8 km^2 and a 2656 km^2 watershed. It has an average depth of 10.5 m, a maximum depth of 20.9 m, a volume of 2.88×10^9 m^3, a water residence time of 2.75 years and an annual water discharge of 8.13×10^8 m^3 (Wan et al., 1988). The Lake Erhai area has an average annual precipitation of 1060 mm, temperature of 15 °C, and potential evapotranspiration of 1970 mm. Lake Erhai lies in the eastern foot of the strongly uplifting Mt. Diancangshan. Its basin has an eroded geomorphic landscape with an asymmetric valley sharply incised by streams. The watershed of Lake Erhai is mainly underlain by sedimentary and metamorphic rocks, specifically carbonate and siliciclastic rocks and gneisses. Soil types are mainly Ultisols, Aquults and Fluvents. Forest coverage is 7%. Because of the influence of the carbonate bed rock and the subtropical monsoon, the lake water has the characteristics of (i) weak alkalinity (pH=8.0–8.5); (ii) low salinity; (iii) medium hardness (~8) as solutes in lake water are dominated by Ca^{2+}, Mg^{2+} and HCO_3^-, which represent more than 60% of the total equivalent anions and cations; (iv) ion concentrations $Ca^{2+}>Mg^{2+}>Na^{+}>K^{+}$, and $HCO_3^-\gg SO_4^{2-}>Cl^-$ (Wan et al., 1988).

Lake Lugu is located in Ninglang county in the western Yunnan Plateau (100°47′ E, 27°42′ N) with a mean lake water height of 2685 m above sea level. It has an average depth of 40.4 m, a maximum depth of 73.2 m, water area of 50.5 km^2, a watershed area of 171.4 km^2, a volume of 20.2×10^8 m^3, a water residence time of 18.5 years and an annual water discharge of 1.1×10^8 m^3 (Wan et al., 1988). The Lake Lugu area has an average annual precipitation of 926 mm, average annual temperature of 8 °C, and potential evapotranspiration of 1270 mm. It is a semi-closed deep fault lake in the Jinshajiang River drainage. Lake Lugu watershed is mainly made up of limestone, mud stone and sandstone. Soils mainly include Alfisols, Oxisols, Entisols and Mollisols. Forest coverage is 47.6%.

Lake Hongfeng, the largest artificial lake in central Guizhou, was built in 1960 near Guiyang, capital of Guizhou province (106°26′ E, 26°31′ N). It has a surface area of 32 km^2, a volume of 2.97×10^8 m^3, a drainage basin of 1551 km^2, a mean depth of 9.3 m, a maximum depth of about 50 m, water flux of 11.26×10^8 m^3 a^{-1}, a residence time of the water of 0.26 a, lake water height of 1233 m above sea level. It belongs to the drainage system of the Wujiang River, a tributary of the Yangtze River. Lake Hongfeng-Baihua watershed is mainly underlain by the Trias Limestone, with a well-developed karst landscape. The land is covered by Ultisols and Oxisols. Due to significant surface soil

erosion, a "rock desertification" landscape is in evidence. Hilltops are bare, thin soils remain in concave ditches and cracks and mountain slopes are covered with sparse grass and shrubs. Lake Baihua is another artificial lake 6 km downstream of Lake Hongfeng (Fig. 1).

Both western Yunnan and central Guizhou have a subtropical climate that is affected by the Southeast Monsoon (the Pacific Monsoon) and Southwest Monsoon (the Indian Monsoon). The climate is moderate with seasonal change. The annual average precipitations in western Yunnan and central Guizhou are 1000 and 1200 mm, respectively.

2.2. Sampling and analytical methods

A sediment core from Lake Hongfeng (HF880818-1, overlying water depth of 38 m) was collected in August 1988. Sediment cores of Lake Baihua (BH941003-2, overlying water depth of 20 m) and Lake Erhai (EH940713-3-2, overlying water depth of 16 m) and Lake Lugu (LG940706-2, overlying water depth of 60 m) were collected in October, 13 July and 6 July 1994, respectively, using the sediment collector described in Yuan et al. (1993). All the sediment cores were sampled from the deepest parts of the lakes. Cores were 26–90 cm long, surfaces of the cores were not disturbed and the interface water was clear. The cores were immediately sectioned at 0.5–1.0-cm intervals. All wet samples were weighed and freeze-dried. After weighing the dry samples were ground to pass a 0.15-mm sieve for analyses. The porosity and mass depth of each layer were calculated.

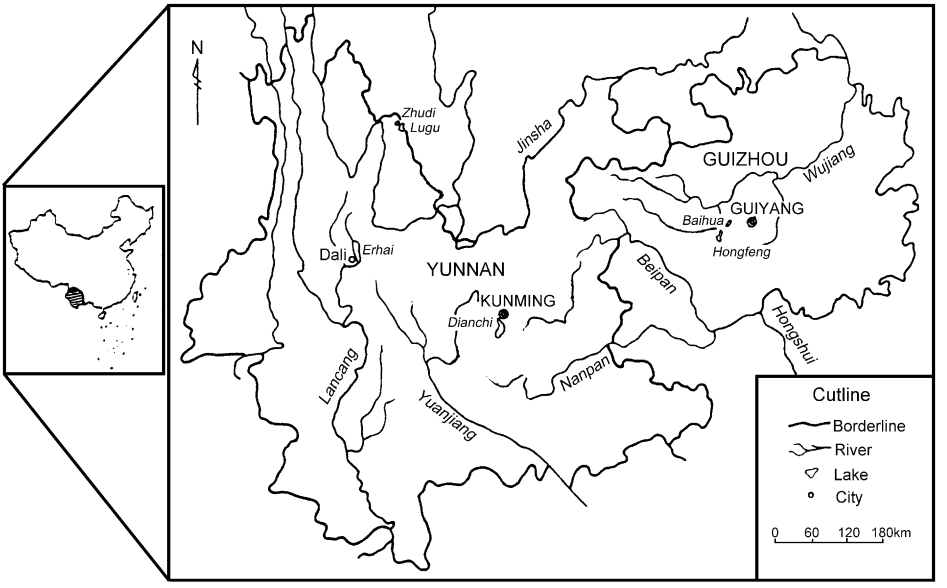


Fig. 1. Location of the studied areas.

Surface soil samples in Lake Hongfeng/Baihua watershed were collected before and after spring rains and in autumn of 1994 and spring of 1995. Soil cores in Lake Hongfeng watershed were collected at the Karst Experimental Station near the lake. The landform at the station is comprised of six terraces from up to down slope which were man-made in the early 1960s. HF-2 to HF-7 and site HF-1 were collected on the top of the mountain, with forest coverage. HF/pz was sampled on a bare red earth hill at the village Puzi. All terraces were depositional sites for detritus eroded mountain slopes. Samples LS-1, LS-2 and LS-3 were collected moving from the top to the foot of Mt. Liangsuotun.

Surface soil samples from the watersheds of Lakes Erhai, and Lugu were collected in the summer of 1994. Soil cores in the Lake Erhai watershed were collected on a mountain slope below 2100 m. The samples were EH-1, EH-2 and EH-3 from up-slope, middle and mountain foot, respectively. Soil samples in Lake Lugu watershed were collected from near the mountain slope (LG) and Zhudi (ZD), i.e., samples LG-1 to LG-4 are sited from the top to the foot of the slope which is situated on the SW bank of the Lake, near Luoshuicun. Specifically, LG-1 was located on a shallow plateau of the mountain (elevation 2800 m); LG-2 and LG-3 were sited on the middle and down slopes, respectively. LG-4 was on the bank of the lake; and LG/zs was collected from a mountain slope near Zuosuo situated on the eastern bank of Lake Lugu. ZD-1 and ZD-2 were sampled on a mountain slope and a depression at the mountain foot, respectively.

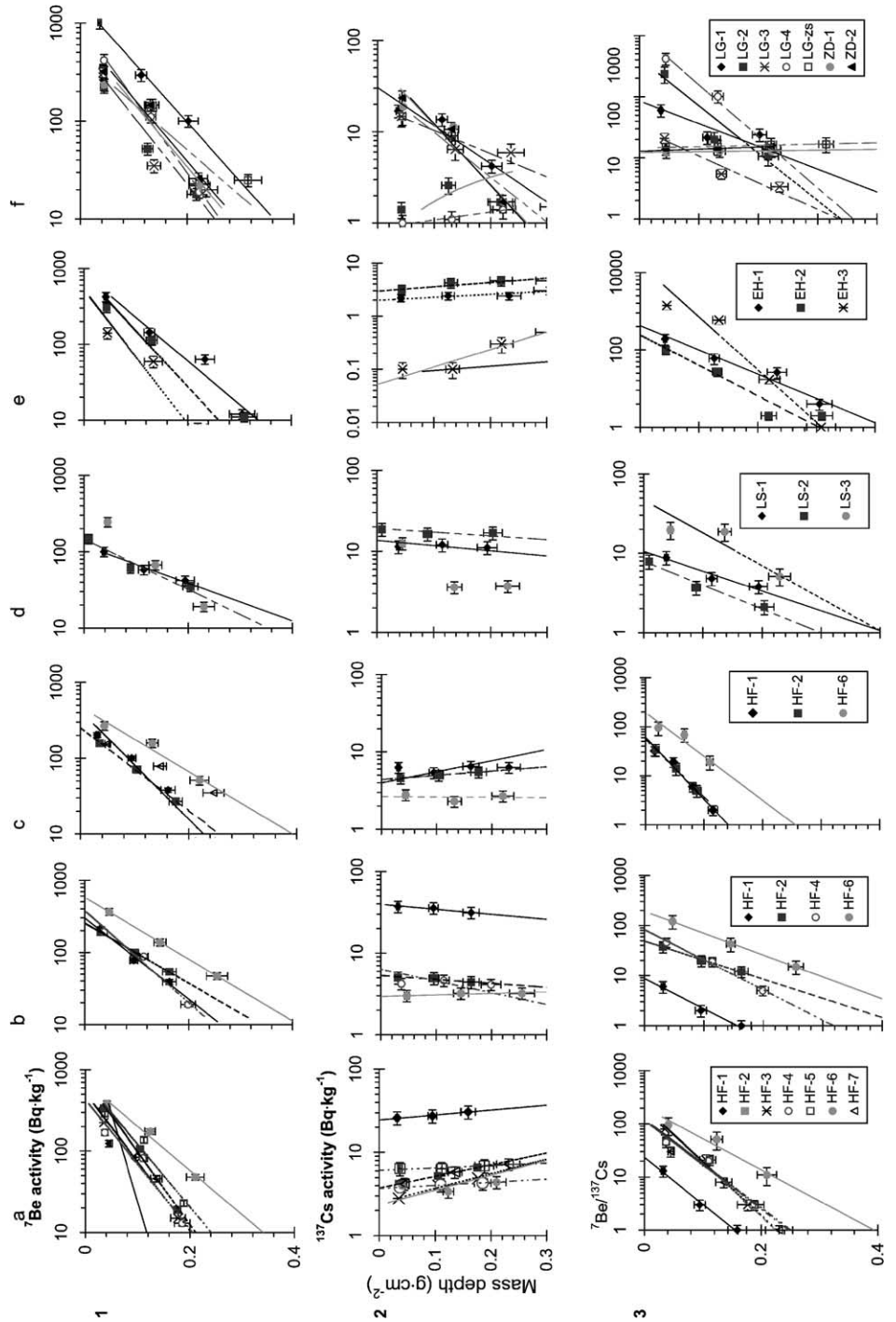
All sampling sites were uncultivated. Each soil core, with an area of 0.18 m^2, was sectioned into four to five slices and the sample weights were recorded. Samples were re-weighed after freeze-drying for calculation of the mass depth of each layer. The mass depth of the cores is about 0.3–0.5 g cm^{-2}, and amounts to 3–5 mm in situ. The samples were ground for analysis. Whole samples and standards were analyzed using an H-P Ge detector coupled to a multi-channel analyzer (Canberra, S-100) under the same geometric condition. ^{7}Be peak energy is 477 keV, and ^{137}Cs is at 661.6 keV. The counting efficiency was calibrated with standards provided by the Institute of Atomic Energy, Chinese Academy of Sciences, and these analytical data were compared to the results analyzed in the Laboratory of Oceanographic and Environmental Research (LOER) of Texas A&M University at Galveston, USA.

3. Results and discussion

3.1. Distribution characteristics of ^{7}Be and ^{137}Cs in surface soils

From Fig. 2-1, all 28 soil profiles show ^{7}Be activity as a logarithmic decrease with depth. This vertical profile distribution is directly related to ^{7}Be source, penetration and decay. From the boundary soil downward, ^{7}Be activities decrease gradually because of soil particle mixing and decay. At a mass depth of 0.3–0.5 g cm^{-2}, ^{7}Be activities are $\leqslant$10 Bq kg^{-1}. Fig. 2-1 shows the vertical profiles of ^{7}Be for three sampling events (before and after rain in spring, summer–autumn), respectively. They show that ^{7}Be has a similar vertical distribution, but the curves are much different in slopes and intercept.

The vertical distribution of ^{137}Cs activity in soils differs from that of ^{7}Be. ^{137}Cs, a fallout radionuclide, is input to soils similar to ^{7}Be. However, because ^{137}Cs has a longer


a
b
c
d
e
f
1
2
3
^{7}Be activity (Bq·kg^{-1})
^{137}Cs activity (Bq·kg^{-1})
^{7}Be/^{137}Cs
Mass depth (g·cm^{-2})
HF-1
HF-2
HF-3
HF-4
HF-5
HF-6
HF-7
LS-1
LS-2
LS-3
EH-1
EH-2
EH-3
LG-1
LG-2
LG-3
LG-4
LG-zs
ZD-1
ZD-2

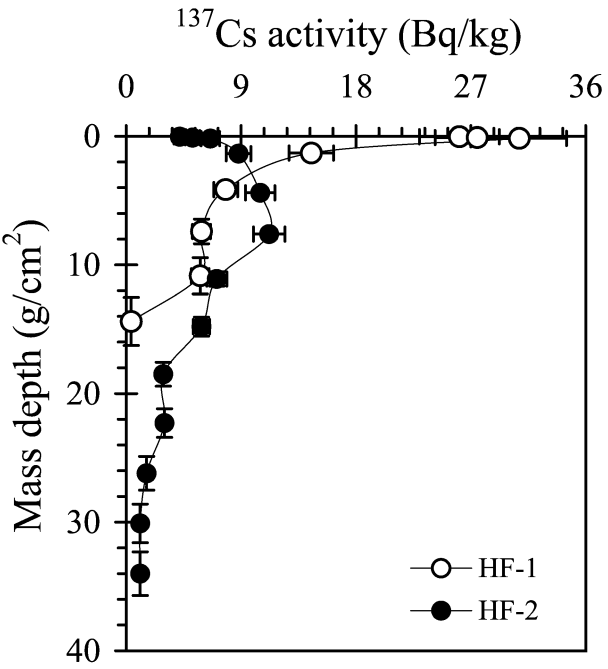


Fig. 3. ^{137}Cs vertical profiles in the soil cores at sites HF-1 and HF-2.

half-life (30.2 years) and it has time for penetration and mixing in soils. Fig. 3 shows the ^{137}Cs vertical profiles in cores at HF-1 and HF-2 to 40 cm. HF-1 is located in forests with undisturbed soils. ^{137}Cs activity at the topsoil is 26–31 Bq kg^{-1}, decreasing gradually with depth and reaches background level below 15 cm (mass depth 16 g cm^{-2}). ^{137}Cs activity in the topsoil was only 4–7 Bq kg^{-1}, increasing to 11 Bq kg^{-1} with soil depth and then decreases rapidly, at soil depth below 27 cm.

Since ^{7}Be only exists within a soil mass depth of 0.3–0.5 g cm^{-2}, a comparative discussion of ^{137}Cs and ^{7}Be could only be focused on surface soils. Fig. 2-2 shows that ^{137}Cs activities in soils of central Guizhou are higher than that in the western Yunnan. ^{137}Cs profiles of topsoil cores show that most curves trend near parallel, but some curves such as LS-1, LG-1, LG-3, LG/zs, ZD-1 and ZD-2 obviously decrease with soil depth (Fig. 2-2); whereas EH-3 appears to increase with soil depth (Fig. 2-2). These increases or decreases in ^{137}Cs activity result from the mixing and diffusion in soils, and erosion of the

Fig. 2. Vertical profiles of the activities of ^{7}Be and ^{137}Cs and their ratios in the surface soils of the Yunnan–Guizhou Plateau. First line: ^{7}Be profiles; second line: ^{137}Cs profiles; third line: the ratio of ^{7}Be/^{137}Cs, with: (a) sampling in Lake Hongfeng watershed in Spring (before rain) 1994; (b) sampling in Lake Hongfeng watershed in Autumn 1994; (c) sampling in Lake Hongfeng watershed in Spring (after rain) 1995; (d) sampling at Liangsuotun hill in Spring 1994; (e) sampling in Lake Erhai watershed in Summer 1995; (f) sampling in Lake Lugu watershed and its upstream Zhudi in Summer 1994.

topsoil or accumulation of low ^{137}Cs concentration soils. Fig. 2-3 shows that most vertical profiles of the activity ratio between ^{7}Be and ^{137}Cs ($^{7}Be/^{137}Cs$) tended to decrease in the soil cores. The $^{7}Be/^{137}Cs$ ratio in the topsoil reached 100–1000 in western Yunnan, but only 10–100 for the central Guizhou region. This suggests that ^{7}Be and ^{137}Cs have a regional difference in deposition and/or accumulation.

3.2. ^{7}Be and ^{137}Cs accumulation in soils

3.2.1. Vertical distribution model

The net input of fallout nuclides (F_{in}) in soils is controlled by atmospheric deposition ($F_{in(d)}$), and the input from eroded soil particles ($F_{in(a)}$), and the output with soil particle transport (or water flow) ($F_{out(e)}$). So, the net input of the fallout radionuclides in soils can be expressed as:

$$F_{in} = F_{in(d)} + F_{in(a)} - F_{out(e)} \tag{1}$$

The vertical distribution of radionuclides in soils is controlled by net input and penetrative mixing and radioactive decay. If the penetrative mixing is regarded as a diffusive process, the changes in radionuclides activity (c) with time (t) in a soil profile (z) have been described as (Robbins and Edgington, 1975):

$$\frac{\partial}{\partial Z}\left(D\frac{\partial}{\partial Z}\rho C\right) - P\left(\frac{\partial}{\partial Z}\rho C\right) - \lambda\rho C = \frac{\partial}{\partial t}\rho C \tag{2}$$

where D is the mixing coefficient ($cm^{-2}\ a^{-1}$), t is the mixing time (year), ρ is the soil density in situ ($g\ cm^{-2}$), P is the accumulation rate (+) or erosion rate (−) of soil particles ($g\ cm^{-2}\ a^{-1}$), and λ is the radioactive decay constant of ^{7}Be ($4.74\ a^{-1}$) and ^{137}Cs ($=0.023\ a^{-1}$).

Assuming that ^{7}Be activities are constant at a given site in specific season, i.e., $(C/t)=0$; D, P and ρ remain constant:

$$Z = 0,\ C_{(z)} = C_0^* \tag{3}$$

$$Z = \infty,\ C_{(z)} = 0. \tag{4}$$

solving Eq. (2) and obtaining,

$$C_{(z)} = C_0^* e^{\alpha z} \tag{5}$$

where

$$\alpha = \frac{P - (P^2 + 4D\lambda)^{\frac{1}{2}}}{2D} \tag{6}$$

On a sampling site, assuming there is no erosion or accumulation of soil particles, and mixing penetration is dominant, i.e., $P=0$, we can obtain,

$$D = \frac{\lambda}{\alpha^2} \tag{7}$$

$$\alpha = -\left(\frac{\lambda}{D}\right)^{\frac{1}{2}} \tag{8}$$

$$C_{(z)} = C_0^* \mathrm{e}^{-Z\left(\frac{\lambda}{D}\right)^{\frac{1}{2}}} \tag{9}$$

In model (9), if Z is 0, the activity is defined as the apparent activity (C_0*). When radionuclide activity tends to zero, the soil depth is regarded as the maximum penetrative depth (Z).

3.2.2. ^{7}Be apparent activity, maximum penetrative depth and inventory in soil cores

On the basis of the above model, ^{7}Be apparent activity and maximum penetrative depth in the soils were calculated using the equation to imitate the curves from Fig. 2-1a–f. Results from the model are given in Table 1.

^{7}Be apparent activities in the 28 soil profiles varied greatly, ranging from 119 to 1584 Bq kg^{-1}. This variation was affected by surface soil erosion or accumulation and by penetration and mixing in the soils. Affected by seasonal change and precipitation, ^{7}Be apparent activities in the soil cores of the Hongfeng Karst Station were higher in the spring than in autumn, and larger in pre-rain than in the post-rain period of spring (Table 2). ^{7}Be maximum penetration depths in the undisturbed soils were 0.3–0.5 g cm^{-2} (analytical datum line$\geqslant$10 Bq kg^{-1}), corresponding to the ^{7}Be activity results of the fourth soil layers. ^{7}Be penetrative depths at the same sites of the Hongfeng Karst Station (HF-1, HF-2, HF-4 and HF-6) in the autumn were larger than in the spring (Fig. 2-1a). Furthermore, during the same spring, ^{7}Be maximum penetration depths in soils were obviously greater in the post-rain than in the pre-rain. ^{7}Be apparent activity and maximum penetrative depths in the soil of the western Yunnan were similar to the central Guizhou (Table 1).

3.2.3. ^{7}Be inventory in the soils of western Yunnan and central Guizhou

Data on ^{7}Be inventory in the soils of western Yunnan and central Guizhou are listed in Table 1.

Table 1 shows that the average ^{7}Be inventory in all the 28 soil profiles was 335 Bq m^{-2}, ranging from 154 to 1065 Bq m^{-2}. The mean ^{7}Be inventory at the 10 sampling sites in Lake Erhai and Lake Lugu watersheds in western Yunnan was 445 Bq m^{-2}, and 274 Bq m^{-2} at the 18 sites in Lake Hongfeng/Baihua watershed. ^{7}Be inventory in western Yunnan was higher than that in the central Guizhou, and a distinct difference appeared in the Lake Lugu watershed.

Precipitation in Lake Hongfeng watershed occurs from June to November, comprising 60–70% of the total annual precipitation. Therefore, ^{7}Be atmospheric flux and its inventory of soils in summer and autumn should be higher than in spring and winter. The seven sampling sites in the Lake Hongfeng watershed are within 1 km^2 area, ^{7}Be flux

Table 1
^{7}Be apparent activity and maximum penetrative depth and inventory in the soils

Area	Sampling no.	Apparent activity ($\times 10^3$ Bq kg^{-1})			Max. penetrative depth (cm)			Inventory (Bq m^{-2})		
		Spring (pre-rain)	Spring (post-rain)	Summer–autumn	Spring (pre-rain)	Spring (post-rain)	Summer–autumn	Spring (pre-rain)	Spring (post-rain)	Summer–autumn
Central Guizhou	HF-1	906	370	321	0.16	0.28	0.27	263 ± 7	217 ± 4	208 ± 5
	HF-2	726	251	248	0.22	0.26	0.35	321 ± 8	178 ± 4	224 ± 4
	HF-3	494			0.20			226 ± 8		
	HF-4	386		363	0.21		0.25	194 ± 5		229 ± 4
	HF-5	645			0.25			337 ± 8		
	HF-6	688	440	571	0.34	0.42	0.41	501 ± 13	419 ± 5	539 ± 7
	HF-7	249			0.24			159 ± 8		
	HF/pz		227			0.42			262 ± 5	
	LS-1	119			0.45			154 ± 11		
	LS-2	199			0.34			198 ± 11		
	LS-3	450			0.28			300 ± 17		
Western Yunnan	EH-1			788			0.33			541 ± 15
	EH-2			514			0.27			380 ± 15
	EH-3			466			0.20			184 ± 11
	LG-1			1584			0.36			1065 ± 2
	LG-2			560			0.24			341 ± 1
	LG-3			422			0.27			308 ± 1
	LG-4			947			0.26			480 ± 1
	LG/zs			486			0.30			361 ± 1
	ZD-1			539			0.30			359 ± 11
	ZD-2			685			0.30			430 ± 21

Table 2
Data on ^{7}Be and ^{137}Cs accumulation in Lake Erhai, Lake Lugu, Lake Hongfeng and Baihua sediment cores

Lake name	Core no.	^{7}Be		^{137}Cs				
		Penetrative depth (cm)	Inventory (Bq m^{-2})	Peak mass depth (g cm^{-2})	Accumulative rate (g cm^{-2} a^{-1})	Peak activity (Bq kg^{-1})	Total inventory (Bq m^{-2})	Pre-1986 inventory (Bq m^{-2})
Lake Erhai	EH940713-3-2	2	237 ± 73	1.455	0.047 ± 0.002	48.3 ± 2.7	590 ± 27	519 ± 26
Lake Lugu	LG940706-2	2	322 ± 19	1.354	0.045 ± 0.004	104.4 ± 4.5	1111 ± 13	937 ± 13
Lake Baihua	BH941003-2	2	783 ± 44					
Lake Hongfeng	HF880818-1			4.112	0.17 ± 0.01	252.6 ± 15.1	3713 ± 56	3704 ± 56

should be identical. Variation of ^{7}Be inventory at the different sites reflects changes in soil erosion or accumulation. ^{7}Be inventory was lower in the rainy season than in the dry season, which means that increasing precipitation intensity could raise the erosive rate. However, at the other sampling sites, the values are higher in autumn than in spring. This indicates that in the study of eroded or accumulative soil particles traced by beryllium-7, more attention should be paid to the comparison of ^{7}Be inventories at different sites in the same season than that in different seasons. These data show that ^{7}Be inventories in the soil cores at most sampling sites in central Guizhou were relatively low, which reflects serious soil erosion in the region. EH-1 is situated on a plain at the top of Mt. Diancangshan with dense forest and has little erosion. EH-2 and EH-3 were on the middle slope and foot, and slope with little vegetation, the soil erosion was serious, ^{7}Be inventories at the two sites were lower than EH-1.

If radionuclide fluxes are identical, radionuclide inventory in soils depends on its activity and penetrative depth. Fig. 4 shows that ^{7}Be inventories are closely related to their apparent activity and maximum penetrative depth, i.e.,

When $C_0^* = (1141 \pm 300)\ e^{-4.24Z}$, ^{7}Be inventory in the soils is low, <230 Bq m^{-2};
When $C_0^* = (2139 \pm 450)\ e^{-5.24Z}$, ^{7}Be inventory in the soils is moderate, 230–400 Bq m^{-2};
When $C_0^* > (2139 \pm 450)\ e^{-5.24Z}$, ^{7}Be inventory in the soils is high, >400 Bq m^{-2}.

Based on the above levels of ^{7}Be inventories of the 18 soil cores in the central Guizhou, 11 belong to "low", 4 to "moderate" and 3 to "high"; but for 10 soil cores in the western Yunnan, 4 belongs to "high", 5 to "moderate" and 1 to "low". These also indicate that

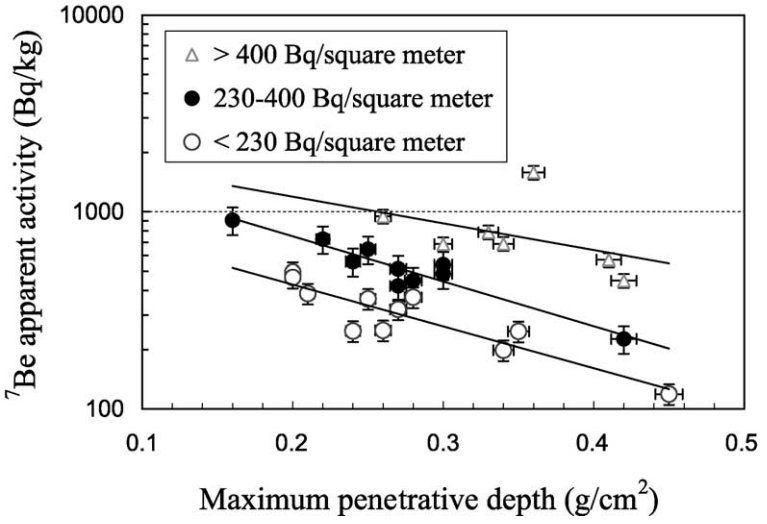


Fig. 4. Scattering distribution of the apparent activity and maximum penetrative depth of ^{7}Be in the soil cores of the Yunnan–Guizhou Plateau.

^{7}Be deposition and accumulation was different between the two regions. Seasonal differences in ^{7}Be deposition and accumulation show that ^{7}Be inventory in the soils of Lake Lugu watershed during the summer–autumn were higher than that in the Lake Hongfeng/Baihua basin. It also was higher than that in the Lake Erhai watershed.

3.3. ^{7}Be and ^{137}Cs accumulative characteristics in the sediment cores

3.3.1. ^{7}Be accumulation in sediment cores

^{7}Be was mainly distributed within the top 2 cm of sediments in these lakes, identical to other lakes and bayou (Wan et al., 1986, 1987). However, due to the difference in input source and action, ^{7}Be penetrative depth in soils differs from lake sediments (Bai and Wan, 1999). ^{7}Be inventories in the sediments of Lake Erhai, Lake Lugu and Lake Baihua were 237 ± 73, 322 ± 19 and 783 ± 44 Bq m^{-2}, respectively (Table 2).

Study on ^{7}Be geochemical speciation has shown that more than 79% of ^{7}Be was bound to the organic and the Fe–Mn fraction (Bai et al., 1997). The ^{7}Be average inventory of 10 soil cores in the watersheds of Lake Erhai and Lake Lugu is 445 Bq m^{-2} (184–1065 Bq m^{-2}), but only 274 Bq m^{-2} (154–539 Bq m^{-2}) for the 18 soil cores in Lake Hongfeng/Baihua watershed (Bai and Wan, 1999). ^{7}Be inventory was much higher in the lake sediment core of Baihua than in the soil cores of the catchment, indicating that ^{7}Be in soils could be transported into the lake sediment. However, ^{7}Be inventory in the sediment cores of Erhai and Lugu were less than that in the soils of their watersheds, suggesting little soil erosion in the basins of Lake Erhai and Lake Lugu.

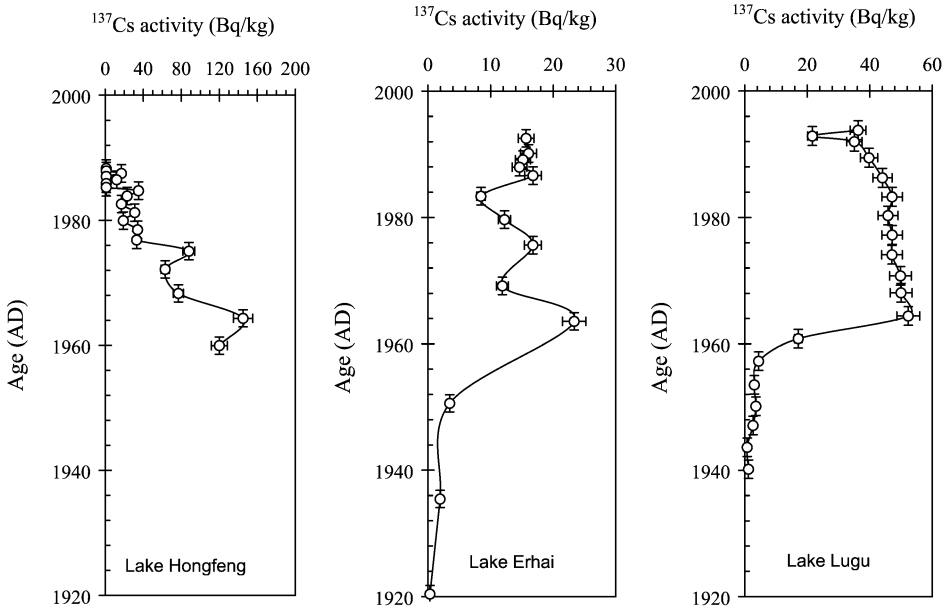


Fig. 5. Vertical distribution of ^{137}Cs in the sediments of Lake Erhai, Lake Lugu and Lake Hongfeng.

3.3.2. ^{137}Cs accumulative characteristics in sediment cores

There is a similar vertical distribution of ^{137}Cs in the sediment cores from Lake Erhai and Lake Hongfeng (Fig. 5). In the Lake Erhai sediment core, the peak of ^{137}Cs maximum accumulation was at a mass depth of 1.455 g cm^{-2} and the sub-peaks of accumulation were at mass depths of 0.370 and 0.888 g cm^{-2}. In the Lake Hongfeng sediment core, the peak of ^{137}Cs maximum accumulation was at a mass depth of 4.112 g cm^{-2} and the sub-peaks of accumulation were at mass depths of 2.286 g cm^{-2}. The ^{137}Cs peak of maximum accumulation occurred in 1964; the sub-peaks were related to the global fallout deposition in 1975 and the Chernobyl accident (1986).

The sediment dating using ^{137}Cs is identical to the result from ^{210}Pb, showing that there was a constant sedimentation in the past three decades. Although the ^{137}Cs vertical profile in Lake Lugu sediment core indicates that the top sediment has been mixed, its dating results are in agreement with ^{210}Pb (Wan, 1999; Xu et al., 1999). Although ^{137}Cs dating in the sediment cores of the three lakes in the two regions gives reliable sedimentation chrono-sequences, its activities in the corresponding layers of the three lake sediment cores show distinct differences. Corrected to deposition time, ^{137}Cs activity at the peak of the maximum accumulation in the sediment core of Lake Erhai is 48.3 ± 2.7 Bq kg^{-1} and 252.6 ± 15.1 Bq kg^{-1} in the sediment core of Lake Hongfeng. The peak of ^{137}Cs activity in Lake Lugu is 104.4 ± 4.5 Bq kg^{-1}, only 41% of that in Lake Hongfeng (Table 2).

Usually, if a radionuclide has stable deposition or erosion in a basin, the higher the sedimentation rate is, the lower the activity is in the corresponding layers. On the basis of the ^{137}Cs dating, the sedimentation rate of Lake Erhai (0.047 g cm^{-2} a^{-1}) remains stable in the past three decades. The 0.17 ± 0.01 g cm^{-2} a^{-1} rate in Lake Hongfeng is 3.6 times that in Lake Erhai. The fact that the sedimentation rate differs from the ^{137}Cs activity in the sediment reflects the variations of ^{137}Cs inventories among the lakes.

There is an apparent difference in the ^{137}Cs inventories in the sediment cores among Lake Erhai, Lake Lugu and Lake Hongfeng. Expressed by the data corrected to deposition time, ^{137}Cs inventories in the sediment cores from prior to 1986 among Lake Erhai, Lake Lugu and Lake Hongfeng are 519 ± 26, 937 ± 13 and 3704 ± 56 Bq m^{-2}, respectively. ^{137}Cs inventory in Lake Hongfeng is 7.1 times of that in Lake Erhai, and 4 times of that in Lake Lugu (Table 2). This suggests that ^{137}Cs accumulation in the lake sediment of western Yunnan is obviously lower than that in the central Guizhou area. Moreover, within the soil cores of HF-1 and HF-2 (Fig. 3), ^{137}Cs inventories were 1036 and 1843 Bq m^{-2}, respectively. However, ^{137}Cs inventories in the soils of Lake Erhai watershed were less than 1000 Bq m^{-2}.

3.3.3. Model analysis of ^{7}Be and ^{137}Cs in sedimentation

Accumulation of fallout radionuclides in lake sediments is controlled by direct precipitation, hydrogeologic conditions, and surface soil erosion. To understand the precipitation–accumulation characteristics of ^{137}Cs and ^{7}Be in western Yunnan and central Guizhou regions, a model analysis of sedimentation was made (Table 3). A model was constructed to distinguish radionuclide distribution relationship between direct atmospheric precipitation, basin erosion, and sedimentation (Wan and Santschi, 1987; Wan et al., 1987). The model is used in this study to calculate the ratio of accumulation

Table 3
Model simulation of accumulation–precipitation of ^{137}Cs and ^{7}Be in the lake sediments in western Yunnan and central Guizhou[a]

Nuclide	Lake name	λ_s (a^{-1})	τ_s (day)	f_r	F_e	f_r/f_e	$F=f_r+f_e=I_c/I_a$	I_c (Bq cm^{-2})	I_a (Bq cm^{-2})
^{137}Cs	Lake Erhai	0.18	2.05×10^{3}	0.32	0.17	1.9	0.49	0.052 ± 0.003	0.11 ± 0.01
	Lake Lugu	0.04	8.21×10^{3}	0.37	0.06	6.6	0.42	0.094 ± 0.001	0.22 ± 0.01
	Lake Hongfeng	0.73	5.01×10^{2}	0.19	0.81	0.2	1.00	0.370 ± 0.006	0.37 ± 0.01
^{7}Be	Lake Erhai	2.13	1.71×10^{2}	0.28	0.05	5.2	0.34	0.024 ± 0.007	0.07 ± 0.02
	Lake Lugu	0.53	6.86×10^{3}	0.09	0.02	5.3	0.11	0.032 ± 0.002	0.29 ± 0.02
	Lake Baihua	10.01	3.65×10^{1}	0.40	0.62	0.6	1.02	0.078 ± 0.004	0.08 ± 0.01

[a] In the model calculation, solid–liquid distribution coefficient K: ^{137}Cs: 4×10^{3} cm^{3} g^{-1}, cited from Robbins et al. (1977); ^{7}Be: 5×10^{4} cm^{3} g^{-1}, cited from Wan et al. (1987). λ_s is the first-order removal rate constant with respect to sedimentation (a^{-1}); τ_s is the residence time of the radionuclide in the lake with respect to sedimentation (=$1/\lambda_s$, day); f_r and f_e are the retention factor and erosion factor, respectively; I_a is the radionuclide inventory from direct atmospheric fallout (Bq cm^{-2}); I_c is the radionuclide inventory in sediment core (Bq cm^{-2}); $f=I_c/I_a$.

and precipitation of radionuclide in the lake sediments, then based on the measured inventories to determine the regional difference in direct atmospheric fallout.

The model analysis has shown that ^{7}Be accumulation in the sediments of Lake Erhai and Lake Lugu was affected by atmospheric precipitation. However, in Lake Baihua, the erosion factors' influence on ^{7}Be accumulation is larger than that from precipitation, the influence factor ratio of the precipitation/erosion is only 0.6. The inventory ratios of that obtained in sediment core to that from direct atmospheric fallout in Lake Erhai and Lugu were only 0.34 and 0.11, respectively; but it was 1.02 in Lake Hongfeng. ^{7}Be inventories from direct atmospheric fallout in Lakes Erhai, Lugu and Baihua were 0.07 ± 0.02, 0.29 ± 0.02 and 0.08 ± 0.01 Bq cm^{-2}, respectively. This means that ^{7}Be atmospheric fluxes in the watersheds of Lake Erhai and Lake Hongfeng/Baihua were similar, but Lake Lugu basin was higher.

^{137}Cs accumulation in Lake Hongfeng was dominated by erosion, being 4.3 times the retention. ^{137}Cs accumulations in Lakes Erhai and Lugu were controlled by direct atmospheric fallout. The retention factors were 1.9 and 6.6 times of the erosion factors in Lake Erhai and Lake Hongfeng, respectively. However, the inventory ratios of that obtained in the sediment cores to that from direct atmospheric fallout in Lake Erhai and Lake Lugu by model calculation were similar, they were 0.49 and 0.42, respectively. This suggests that the difference in the measured accumulation of ^{137}Cs in the lakes mainly resulted from the regional difference in atmospheric precipitation. The inventory ratios (I_c/I_a) in Lake Hongfeng were two times of that in Lake Erhai and Lake Lugu, reflecting the important impact from erosion. ^{137}Cs inventories of direct atmospheric fallout in the Lake Erhai, Lake Lugu and Lake Hongfeng regions before 1986 were 0.11 ± 0.01, 0.22 ± 0.01 and 0.37 ± 0.01 Bq cm^{-2}, respectively. They show that ^{137}Cs inventories from direct atmospheric fallout in the western Yunnan are much lower than that in the central Guizhou region. ^{137}Cs from direct atmospheric fallout in the Lugu watershed is higher than that in the Lake Erhai watershed.

3.4. Regional differences in the ^{7}Be and ^{137}Cs atmospheric precipitation

^{7}Be fallout distribution and accumulation characteristics could be affected by latitude and altitude. In a given region, ^{7}Be from atmospheric flux is mainly affected by precipitation (Baskaran et al., 1993), its maximum value appears in summer, and could be several times that of winter and spring (Schuler et al., 1991). All sediment cores in this study were collected in summer and autumn. So, the higher inventory of ^{7}Be could have originated from direct atmospheric fallout. In the Lake Lugu region, this would mainly be the result of increased precipitation during sampling.

^{137}Cs flux to the earth's surface depends on the intensity of nuclear testing, region and latitude. ^{137}Cs vertical profiles in the sediment cores of these lakes correspond to the global fallout chrono-sequences. Therefore, the difference in ^{137}Cs from direct atmospheric fallout between west Yunnan and central Guizhou could not be explained by the nuclear test intensity. Since the variation in rain is just 20% between the two regions, ^{137}Cs atmospheric fallout should be close. Consequently, the reason for less ^{137}Cs fallout in west Yunnan than that in central Guizhou could only be explained by regional fallout differences. This difference is identical to the global fallout of the ^{137}Cs inventories reported by UNSCEAR (United Nations, 1969) and Agudo (1998).

4. Summary and conclusion

From the accumulation and distribution characteristics of ^{7}Be and ^{137}Cs in the sediments and soils in western Yunnan and central Guizhou, the following were found.

(1) The activity ratios of $^{7}Be/^{137}Cs$ in the topsoil reached 100–1000 in western Yunnan, but only 10–100 for the central Guizhou region, suggesting that the two radionuclides have a regional difference in deposition.

(2) The apparent activities and maximum penetrative depth of ^{7}Be in the soils of the two regions were similar, indicating that the two regions have similar erosion and ^{7}Be transportation with surface soil movement.

(3) There was a difference in the ^{7}Be fallout and accumulation between the two regions. ^{7}Be inventories in the soil cores in the Lake Lugu watershed in the summer and autumn were higher than that in Lake Hongfeng/Baihua watershed and also higher than that in Lake Erhai watershed. This was probably related to high precipitation in summer.

(4) ^{7}Be inventories in the sediment cores of Lake Erhai and Lake Lugu were 237 ± 73 and 322 ± 19 Bq m^{-2}, respectively, corresponding with the ^{7}Be inventories in the surface soils of their basins. ^{7}Be inventory in the sediment of Lake Baihua was 783 ± 44 Bq m^{-2}, which was higher than the average value in the soil cores, showing that watershed erosion had an influence on the accumulation of ^{7}Be in the sediments.

(5) On the basis of the activity values that were corrected to deposition, prior to 1986, ^{137}Cs inventories in Lakes Erhai, Lugu and Hongfeng were 519 ± 26, 937 ± 13 and 3704 ± 56 Bq m^{-2}, respectively. These show that the accumulated amount of ^{137}Cs in the lake sediments in western Yunnan was distinctly lower than that in central Guizhou.

(6) The model simulation indicated that ^{7}Be and ^{137}Cs accumulations in Lakes Hongfeng and Baihua were dominated by watershed erosion. But in Lakes Erhai and

Lugu, it was mainly controlled by atmospheric precipitation. The proportion of the influence factors from retention and erosion was similar, with a similar ratio for ^{137}Cs and a lower ratio for ^{7}Be. ^{7}Be inventories from direct atmospheric fallout in lakes Erhai, Lugu and Hongfeng regions were 0.07 ± 0.02, 0.29 ± 0.02 and 0.08 ± 0.01 Bq m^{-2}, respectively. But for ^{137}Cs prior to 1986, these were 0.11 ± 0.01, 0.22 ± 0.01 and 0.37 ± 0.01 Bq m^{-2}, respectively. ^{137}Cs is regarded as a global diffusion pollutant, the regional variations in the ^{137}Cs inventories from direct atmospheric fallout in the western Yunnan and central Guizhou regions reflect a screening effect of west wind airflow during transport. It is inferred that the uplifting Himalayas serve as a barrier to the fallout of global atmospheric pollutants in the western Yunnan–Guizhou plateau.

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