7Be distribution in surface soil of central Guizhou karst region and its erosion trace*

BAI Zhanguo (白占国), WAN Guojiang (万国江), WANG Changsheng (王长生),
WAN Xi (万曦), HUANG Ronggui (黄荣贵),
(State Key Laboratory of Environmental Geochemistry, Institute of Geochemistry, Chinese Academy of Sciences,
Guiyang 550002, China)

P. H. Santschi and M. Baskaran
(Department of Marine Sciences, Texas A & M University, Galveston, TX 77551, USA)

Received January 8, 1996

Abstract Soil erosion in karst region of south China is one of the major environmental problems. Beryllium-7, produced by energetic cosmic rays, has been used to trace the geochemical process of the soil erosion. The study has shown that 7Be activity profiles present a decreasing logarithmic pattern with soil depth. The maximum permeable depth of 7Be is 2—5 mm in different seasons and locations, which is deeper in autumn than in spring. On the contrary, its apparent activity on boundary soil is higher in spring than in autumn. The 7Be inventories in soil cores are higher in accumulative locations than in eroded one. Upper hills in the karst region are seriously eroded. Erosive intensity is higher in rainy periods than in dry ones. Influenced by the micromorphology and precipitation, the eroded particles accumulated in shallow basin after a short-distance transportation in winter and spring. However, in summer and autumn, they might be transported into drainage systems.

Keywords: surface soil erosion, 7Be tracing, central Guizhou karst region.

Soil erosion is one of the major environmental problems in the world. There are large areas of carbonate rocks with violent karstification in southwest China where surface soils are seriously eroded with the increasing trend of desertification landscape as a result of a long-term geological action and negative influence of mankind. In order to control soil erosion, it is necessary to reveal its erosive mechanism and particle transportation. Studies of soil erosion using fallout radionuclide cesium-137 have been conducted in recent 30 years. 137Cs (half-life=30.3a), whose flux to the earth’s surface depends on nuclear test, region and latitude, has good effects on tracing accumulation rate of soil erosion. Transportation rate of soil particles, however, has a seasonal dependence due to precipitation, and could not be traced by 137Cs.

Beryllium-7, with half-life=53.3d, produced in the atmosphere as a product of the spallation of oxygen and nitrogen nuclei by energetic cosmic rays, is suitable for the

* Project supported by the National Natural Science Foundation of China and National Science Foundation of USA.
purpose of tracing particle mixing and transportation of boundary sediments and soils. It is noticeable that studies of particle mixing in surface sediments of lakes and bays using \(^{7}\text{Be}\) have made much progress in recent years\(^{[6, 9]}\). But, very little is known about the distribution of beryllium-7 in soils.

In this paper, we present the results of \(^{7}\text{Be}\) distribution in the surface soil on six tablelands in watershed of Lake Hongfeng and on Hill Liangsuotun of An Shun, and discuss its significance for tracing soil erosion. Lake Hongfeng is the largest artificial lake in Guizhou Plateau which is a typical area with violent karstification and extensive calcareous soil or yellow soil. The sedimentation rate was studied by using \(^{20}\text{Pb}\) and \(^{137}\text{Cs}\), which provides comparative data for that of watershed erosion\(^{[4, 24]}\).

1 Sampling and methods

Soil cores are collected from the flat, uncultivated tablelands in the watershed of Lake Hongfeng (HF) and the Hill Liangsuotun (LS) in the end of spring (April 29) and end of autumn (November 23), 1994, respectively (fig. 1). Soil cores with the mass depth about 0.3—0.5 g·cm\(^{-2}\) within an area of 1.8×10\(^{3}\) cm\(^{2}\) were sectioned in 4 slices. Above the lake shore, sampling sites from HF-7 to HF-2 are corresponding to the tablelands from the first to the sixth (fig. 1). Characteristics of sampling sites are described in tables 1 and 2. Sampling area is underlying Triassic carbonate rocks. The six tablelands are relatively accumulated with thin yellow soil eroded from the above hills. But Hill Liangsuotun is bare landscape with discontinuous soils covered by little meadow in eroded karst shallow. All samples are freeze-dried and let to pass through a 0.15 mm sieve for measurements of \(^{7}\text{Be}\) activities. The whole sections were gamma-counted using an H-P Ge detector with high efficiency (50\%) and low background coupled to a multichannel analyzer (16384 Channels, Canberra, S-100). The counting efficiency was calibrated with standards formulated by Laboratory of Oceanographic and Environmental Research (LOER) of Texas A & M University at Galveston, the USA.

2 Results and distribution of \(^{7}\text{Be}\) in surface soils

The analytical results of \(^{7}\text{Be}\) activities in the soil profiles are shown in tables 1 and 2. \(^{7}\text{Be}\) activities in the fourth layers of the selected sampling sites are less than 10 Bq·kg\(^{-1}\).

2.1 \(^{7}\text{Be}\) activity profiles present a logarithm decrease with respect to soil depth

As shown in tables 1 and 2, \(^{7}\text{Be}\) activities show a drastic decrease with respect to soil depth. Figs. 2 and 3 show exponential curves of \(^{7}\text{Be}\) activities vs. mass depth. Calculated from these exponential curve equations, the maximum penetrative depths of \(^{7}\text{Be}\) in undisturbed soil profiles are 0.16—0.41 g·cm\(^{-2}\), corresponding to the geometric depth of 2—5 mm \((\text{in situ})\), which agree with the results of \(^{7}\text{Be}\) activity measurements in the selected
2.2 $^7$Be penetrative depth in the surface soil shows deeper in autumn than in spring.

Beryllium-7 in the soil profiles is deeper in autumn than in spring at the same site, as in the example in Lake Hongfeng watershed (table 1). However, in the same season, the penetrative depth of $^7$Be varies at different sites which indicate the differences of surface soil erosion or accumulation.
Table 1 Activities of $^7$Be in surface soil of the six tablelands in Lake Hongfeng watershed$^a$

<table>
<thead>
<tr>
<th>Sample No.</th>
<th>Location</th>
<th>Sampling season$^b$</th>
<th>Mass depth /g · cm$^{-2}$</th>
<th>$^7$Be activity /Bq · kg$^{-1}$</th>
<th>$^7$Be inventory /Bq · m$^{-2}$</th>
<th>$^7$Be boundary apparent activity/Bq · kg$^{-1}$</th>
<th>$^7$Be penetrative mass depth/g · cm$^{-2}$</th>
<th>Accumulation or erosion rate/g · cm$^{-2} · a^{-1}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>HF-1</td>
<td>hill covered by yellow soil</td>
<td>Spring</td>
<td>0.063 ± 0.063</td>
<td>234 ± 11</td>
<td>906</td>
<td>0.16</td>
<td>-0.16</td>
<td>0.23</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Autumn</td>
<td>0.136 ± 0.206</td>
<td>39 ± 3</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>HF-2</td>
<td>sixth tableland</td>
<td>Spring</td>
<td>0.070 ± 0.140</td>
<td>105 ± 8</td>
<td>726</td>
<td>0.22</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td></td>
<td>with flat large area</td>
<td>Autumn</td>
<td>0.061 ± 0.131</td>
<td>99 ± 3</td>
<td>248</td>
<td>0.35</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td></td>
<td>covered by yellow soil</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>with grass</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>HF-3</td>
<td>fifth tableland, small area</td>
<td>Spring</td>
<td>0.069 ± 0.141</td>
<td>85 ± 4</td>
<td>494</td>
<td>0.20</td>
<td>0.02</td>
<td></td>
</tr>
<tr>
<td></td>
<td>slight lean, yellow soil</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>sparse grass</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>HF-4</td>
<td>fourth tableland</td>
<td>Spring</td>
<td>0.073 ± 0.147</td>
<td>82 ± 3</td>
<td>386</td>
<td>0.21</td>
<td>0.06</td>
<td></td>
</tr>
<tr>
<td></td>
<td>with small area, yellow soil</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>covered by thin grass</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>HF-5</td>
<td>third tableland, slight lean</td>
<td>Spring</td>
<td>0.073 ± 0.150</td>
<td>137 ± 5</td>
<td>645</td>
<td>0.25</td>
<td>0.08</td>
<td></td>
</tr>
<tr>
<td></td>
<td>lean, yellow soil with</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>sparse grass, spring</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>HF-6</td>
<td>second tableland</td>
<td>Spring</td>
<td>0.081 ± 0.166</td>
<td>174 ± 9</td>
<td>716</td>
<td>0.33</td>
<td>0.21</td>
<td></td>
</tr>
<tr>
<td></td>
<td>shallow basin, easy to</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>accumulate for soil particles</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

(to be continued on next page)
(continued)

<table>
<thead>
<tr>
<th>Sample No.</th>
<th>Location</th>
<th>Sampling season</th>
<th>Mass depth ( g \cdot cm^{-2} )</th>
<th>Be activity ( Bq \cdot kg^{-1} )</th>
<th>Be inventory ( Bq \cdot m^{-2} )</th>
<th>Be boundary apparent activity ( Bq \cdot kg^{-1} )</th>
<th>Be penetrative mass depth ( g \cdot cm^{-2} )</th>
<th>Accumulation or erosion rate ( g \cdot cm^{-2} \cdot a^{-1} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>HF-7</td>
<td>first tableland, flat. close to the lake, covered with eroded particles</td>
<td>Spring</td>
<td>( 0 - 0.089 )</td>
<td>124 ± 5</td>
<td></td>
<td></td>
<td>0.24</td>
<td>0.18</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>( 0.089 - 0.182 )</td>
<td>46 ± 3</td>
<td>158 ± 8</td>
<td>249</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>( 0.182 - 0.278 )</td>
<td>&lt;10</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

a) The errors are expressed as 1 standard deviation; b) sampling time: spring, on April 29, autumn, on Nov. 23, 1994; c) reported activities are decay corrected.

Table 2. Activities of \(^{7}Be\) in surface soil on the hill of Liang Suotun

<table>
<thead>
<tr>
<th>Sample No.</th>
<th>Location</th>
<th>Mass depth ( g \cdot cm^{-2} )</th>
<th>Be activity ( Bq \cdot kg^{-1} )</th>
<th>Be inventory ( Bq \cdot m^{-2} )</th>
<th>Be boundary apparent activity ( Bq \cdot kg^{-1} )</th>
<th>Be penetrative mass depth ( g \cdot cm^{-2} )</th>
<th>Accumulation or erosion rate ( g \cdot cm^{-2} \cdot a^{-1} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>LS-1</td>
<td>upper hill</td>
<td>940501</td>
<td>( 0 - 0.076 )</td>
<td>100 ± 10</td>
<td></td>
<td></td>
<td>0.36</td>
</tr>
<tr>
<td></td>
<td></td>
<td>( 0.076 - 0.154 )</td>
<td>58 ± 6</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>( 0.154 - 0.233 )</td>
<td>42 ± 7</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>( 0 - 0.081 )</td>
<td>147 ± 11</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>LS-2</td>
<td>middle hill</td>
<td>940501</td>
<td>( 0.081 - 0.160 )</td>
<td>61 ± 7</td>
<td>198 ± 11</td>
<td>198</td>
<td>0.28</td>
</tr>
<tr>
<td></td>
<td></td>
<td>( 0.160 - 0.248 )</td>
<td>35 ± 4</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>( 0 - 0.090 )</td>
<td>245 ± 17</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>LS-3</td>
<td>down hill</td>
<td>940501</td>
<td>( 0.090 - 0.183 )</td>
<td>67 ± 7</td>
<td>300 ± 17</td>
<td>453</td>
<td>0.24</td>
</tr>
<tr>
<td></td>
<td></td>
<td>( 0.183 - 0.277 )</td>
<td>19 ± 4</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

a) The errors are expressed as 1 standard deviation; reported activities are decay corrected to the sampling date.
2.3 $^7$Be apparent activities on boundary layers of the surface soils are higher in spring than in autumn

Calculated from the exponential curve equations, the apparent activities of $^7$Be vary with the sampling sites in Lake Hongfeng watershed. The values in spring range from 249 to 906 Bq kg$^{-1}$. However, corresponding to the same site, the apparent activities of $^7$Be decrease markedly in autumn, which can possibly be attributed to the seasonal change of soil erosion (table 1).

2.4 $^7$Be inventories are higher in accumulative locations than in erosional ones

As shown in tables 1 and 2, $^7$Be inventories at LS-1 and LS-2 are clearly much less than those at LS-3 (fig. 4), which are also less than those at the whole sampling sites in Lake Hongfeng watershed. Similarly, $^7$Be inventories at the second tableland in Lake
Hongfeng watershed are the highest either in spring or in autumn due to its shallow micromorphology (figure 5).

2.5 7Be inventories in the soil profiles change with both sampling sites and seasons

As the seven sampling sites in Lake Hongfeng watershed are within a scale of less than 1 km², the 7Be flux should be identical. Its inventories vary with the sampling sites in the same season, which would result from the precipitation pattern in this region (table 1). The rainfall in Lake Hongfeng watershed mainly takes place in summer and autumn (June—November), which makes 60%—70% of the total yearly precipitation. 7Be deposition to land surface is positively related to the amount of precipitation[20]. The flux is higher in rainy season than in dry one due to the atmospheric fallout of 7Be settled with precipitation, which should be higher in summer and autumn than in spring and winter, the same for 7Be inventories in soil profiles. However, 7Be inventories at some studied sites demonstrate lower values in rainy season than in dry one, which suggest the drastic soil erosion caused by intensive rainfall. At other sampling sites, the values are a little higher in autumn than in spring. Both cases indicate that, in the study of eroded and accumulative soil particles traced by beryllium-7, more attention should be paid to the comparison of 7Be inventories at different sites in the same season than that in different seasons.

3 Diffusion model of 7Be in the surface soil profiles

7Be distribution in the surface soil profiles depends on its deposition (fallout, eroded output or accumulative input), permeable mixing and radioactive decay. If 7Be permeable mixing in surface soil profiles is regarded as a diffusive process, the changes of 7Be activity (C) with time (t) within the vertical depth of soil profiles (Z) have been described as

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

(1)
where $D$ is the mixing coefficient (cm$^2 \cdot$ a$^{-1}$), $t$, mixing time (a), $\rho$, soil density in situ (g$\cdot$cm$^{-3}$), $P$, accumulation rate ($+$) or erosion rate ($-$) of soil particles (g$\cdot$cm$^{-2}$ $\cdot$ a$^{-1}$), and $\lambda$, radioactive decay constant of $^{7}$Be (4.74 a$^{-1}$).

Assume that $^{7}$Be activities are constant at a given site in specific season, i.e. $\frac{\partial C}{\partial t}$ = 0; $D$, $P$ and $\rho$ in contrast with time and depth remain constant with boundary conditions:

$$Z=0, \ C_{z=0}=C_0;$$
$$Z=\infty, \ C_{z=\infty}=0.$$

Solving eq. (1), we obtain

$$C_{z=0}=C_0 \cdot e^{\alpha z},$$

where

$$\alpha = \frac{P-(P^2+4D\lambda)^{1/2}}{2D}. \quad (3)$$

If there is no erosion or accumulation of soil particles but the mixing penetration is dominant, i.e. $P=0$, we can obtain

$$D = \frac{\lambda}{\alpha^2}, \quad (4)$$
$$\alpha = - \left( \frac{\lambda}{D} \right)^{1/2}, \quad (5)$$
$$C_{z=0}=C_0 \cdot e^{-\frac{z}{P}} \cdot \left( \frac{P}{\rho} \right)^{1/2}. \quad (6)$$

The following equation can be obtained from eq. (3): 

$$P = D\alpha - \frac{\lambda}{\alpha}. \quad (7)$$

In model (7), $P>0$ indicates the accumulation of soil particles; $P<0$, erosion of soil particles.

4 Discussion

HF-2 is located on the sixth tableland which is the largest platform with higher position in Lake Hongfeng watershed resulting in little input or output of soil particles compared to other sampling sites.

Assuming that the erosion at HF-2 is relatively corresponding to its accumulation, which means that $^{7}$Be vertical distribution in the soil profile is dominated by penetrative mixing, calculated from eq. (4), $^{7}$Be mixing coefficient in soil profile at HF-2 are $D_{spring}=1.21 \times 10^{-2}$ cm$^2 \cdot$ a$^{-1}$ and $D_{summer}=5.68 \times 10^{-2}$ cm$^2 \cdot$ a$^{-1}$, respectively. These show that $^{7}$Be
penetrability in autumn is approximately five times that in spring.

Assuming that the vertical structure of the studied soils in Lake Hongfeng watershed is similar, regarding HF-2 as a criterion, $P$ values calculated from eq. (7) at the sampling sites in different seasons indicate the relative erosion or accumulation rates of soil particles (table 1). The calculated rates are the comparative values of different sites based on the level of HF-2 in the same season. Comparing apparent soil erosion occurring at HF-2 in autumn with that in spring, the calculated rates in table 1 in autumn should be modified to negative direction (erosion). This will be further studied.

Based on $^{7}\text{Be}$ distribution in the soil profiles and the calculation from the model, the criteria of "accumulation or erosion rate" and "$^{7}\text{Be}$ inventory" can be adopted to describe the physical erosion of soil particles in the same season. Calculated values from the model are the synthetic criteria of both $^{7}\text{Be}$ penetrative depth in soil profiles and its apparent activities at top soil with confinement of constant $^{7}\text{Be}$ fallout within a given area in the same season and similar $^{7}\text{Be}$ penetrative mixing in soil profiles. Therefore, the calculated values can be used to compare the intensity of erosion or accumulation at different sites in the same season.

$^{7}\text{Be}$ inventories in the soil profiles are dependent on both its seasonal fallout and budget of accumulation or erosion, which can be regarded as both modifying criterion for the calculated values and qualitative distinction for erosion or accumulation.

### 4.1 Erosion occurring on upper slope of the hill and accumulation on the foot

As shown in table 2 and fig. 4, $^{7}\text{Be}$ inventories at LS-1, LS-2 and LS-3 are $(154\pm11)$, $(198\pm11)$ and $(300\pm17)$ Bq $\cdot$ m$^{-2}$, respectively. $^{7}\text{Be}$ inventory at LS-1 makes 78% of LS-2, which means that intensive erosion on the upper slope takes place. However, $^{7}\text{Be}$ inventory at LS-3 is two times that of LS-1, which suggests that the eroded particles accumulate on the hillfoot.

Although HF-1 is covered by forest, slight erosion exists either in spring or in autumn. The eroded soil particles enrich on all the tablelands eroded soil particles after a short-distance transportation (in spring). The second tableland (HF-6), a shallow basin, is a favorable circumstance for the enrichment of the eroded soil particles. The accumulation rate at HF-6 in spring reaches 0.21 g $\cdot$ cm$^{-2}$ $\cdot$ a$^{-1}$, which is higher than the sedimentation rate in Lake Hongfeng$^{[4,30]}$.

In addition, table 1 and fig. 5 show that $^{7}\text{Be}$ inventories at HF-1 are $(263\pm7)$ (in spring) and $(208\pm5)$ Bq $\cdot$ m$^{-2}$ (in autumn), respectively, which are approximately 50% and 40% of those on the second tableland (HF-6) in the same season.

These studies have shown that intensive soil erosion occurs on the hill slopes and accumulates in relatively lower places after a short transportation due to micromorphology.
4.2 More intensive erosion and longer distance transportation of soil particles occurring in rainy season than in dry one.

Table 1 shows that in spring the eroded soil particles accumulate on all sampling sites except HF-1. The accumulation rates vary with the sampling sites due to micromorphology and precipitation. Besides the highest accumulation rate (0.21 g \cdot cm^{-2} \cdot a^{-1}) on the second tableland, the rate on the first tableland close to Lake Hongfeng shore is relatively high. Slight accumulation on the third, fourth and fifth tablelands also exists. However, in autumn, soil erosion occurs not only on the hill slope covered with forest (HF-1) but also on other tablelands, even on the second tableland (HF-6).

These results indicate that erosive intensity of soil particles is higher in summer-autumn (rainy season) than in winter-spring (dry season). Correspondingly, soil particles are transported for a longer distance or into the drainage systems in rainy period.

5 Conclusion

Beryllium-7, a short-life radionuclide produced by cosmic rays, is a very useful tracer for geochemical process of seasonal transportation of particles. Meticulous sampling from surface soils in the central Guizhou karst region have been taken in this paper, showing:

(1) $^7$Be activities in soil profiles show a logarithmic decrease with respect to depth within a maximum value of 5 mm (in situ). $^7$Be penetrability in autumn is about 5 times that in spring at the same site.

(2) $^7$Be inventories in soil cores on upper hills are half of that on the hillfeet, which suggests that eroded particles from upper hills accumulate in shallow locations after a short-distance transportation.

(3) $^7$Be inventories in soil profiles depend on both its fallout from atmosphere and erosion, which could only be used for qualitative analysis of erosion and accumulation of soil particles rather than for quantitative index.

(4) $^7$Be distribution in soil profiles depends on its deposition (fallout, eroded output or accumulative input), permeable mixing and radioactive decay. Results calculated from the model have demonstrated that soil erosion on the vegetated hills takes place in all seasons. All the tablelands are deposited by soil particles in spring. Accumulation rate on the first or second tableland is about 0.2 g \cdot cm^{-2} \cdot a^{-1}. The others are less than 0.1 cm^{-2} \cdot a^{-1}. However, soil erosion occurs on all the tablelands in autumn, and eroded particles are transported into drainage systems.

In our work $^7$Be geochemical species in surface soils will be studied soon to confirm its tracing values for soil erosion; new experiment schemes will be put forward to modify the accumulation or erosion rate in different seasons; seasonal changes of $^7$Be fallout will be
investigated, which may reflect seasonal changes of atmosphere influenced by cosmic rays, and might help further reveal the influences of the solar-earth relations on the global environment systems.

References

18. Wan, G. J., Santschi, P. H., Sturm, M. et al., Natural \(^{210}\)Pb, \(^{7}\)Be and fallout \((^{137}\)Cs, \(^{239,240}\)Pu, \(^{232}\)Sr) radionuclides as geochemical tracers of sedimentation in Greifensee, Switzerland, *Chemical Geology*, 1987, 63: 181.