Radiocesium Dating of Sediments from Lakes and Reservoirs of Different Hydrological Regimes

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Important information on the transport and deposition of anthropogenic substances in rivers and lakes can be assessed using sediment analyses. Dating is a necessary prerequisite to calculate fluxes, to account for varying sedimentation rates, and thus to allow comparison between different localities. For sediments not older than 40 years, ¹³⁷Cs dating has been successfully applied to natural and artificial lakes representing a wide range in waterresidence times and sediment-trapping characteristics. Sedimentation rates for the period 1986 to the time of coring (mid 1990s) vary as a function of distance to the inflowing rivers, between 0.5 and 2.5 cm yr^{-1} (0.13-1.0 g cm⁻² yr^{-1}) in Greifensee and between 1.4 and 3.5 cm yr⁻¹ (0.49-2.4 g cm⁻² yr⁻¹) in Lake Biel. In reservoirs located along the major Swiss rivers Aare and Rhine, sedimentation rates are in the same range from 1.8 cm yr⁻¹ (0.69 g cm⁻² yr^{-1}) in Augst (Rhine) to 3.4 cm hr^{-1} (1.8 g cm⁻² yr^{-1}) in Klingnau (Aare). Sedimentation rates from the period 1963— 1986 are in some cases significantly lower. The dating is based on the identification of radiocesium deposition maxima in sediment cores that are related to the global deposition of radiocesium during atmospheric nuclear weapons testing (maximum, 1963) and the accident of the Chernobyl nuclear reactor (April 1986). Additional markers confirm age determinations based on radiocesium. They are based on either known discharges of radioniclides by nuclear reactors or known maxima of anthropogenic organic substances such as detergent-derived chemicals. In cases where the Cs dating technique fails (e.g., in turbulent river sections with disturbed sedimentation), human activities can be used as time markers to estimate sedimentation rates, as documented for sediments from the Aare and Rhône rivers, where sedimentation rates between 1.7 (Niederried reservoir) and 13 cm yr⁻¹ (Chancy reservoir) were measured.

Introduction

Riverine transport represents an efficient process for dispersal of anthropogenic substances (1). A convenient way to evaluate the riverine transport for particle reactive substances is to sample and measure contaminant concentrations in sediments. The results obtained are used for toxicological impact assessment or radiological dose estimations. For regional comparisons, the time of sediment deposition must be known to calculate flux rates of associated pollutants.

Whereas reports of successful dating using the radionuclide 137 Cs are widespread for lake sediments (2–4), coastal sediments, and marsh sediments (5, 6), they are sparse for riverine sediments (7–9), despite their importance. For example, of the 81 nuclear reactors in operation in France, Germany, and Switzerland that discharge liquid waste into the aquatic system, only one is located upstream of a lake.

Aquatic systems, such as natural and anthropogenically influenced lakes or large and small riverine reservoirs, can be distinguished on the basis of water residence times, which vary from several years to less than an hour, and also on the basis of sedimentation rates. In natural lakes they vary from 0.005 to more than 1 cm yr $^{-1}$ and increase to 20 cm yr $^{-1}$ in reservoirs (8). Such sediment accumulation affects water quality and biological activity and causes loss of storage capacity and possibly turbine damage.

In this publication we summarize results from a radiocesium dating effort of sediments from sites in Switzerland ranging from lakes (Greifensee and Lake Biel) to riverine reservoirs built for hydroelectrical purposes. We will review the most critical aspects of sediment dating to illustrate the influence of catchment inputs and water-residence time and the impact of hydroelectric power plants. Focus will be on locations downstream of nuclear power plants in Switzerland (Figure 1). Included are both accumulation zones with relatively undisturbed sedimentation and hydrodynamically active zones with disturbed sedimentation. In the former, ¹³⁷Cs input maxima serve as time markers (*3*), and in the latter, other indicators result from engineering activities.

Study Area. To extend the Cs dating technique from large lakes with high water-residence times (e.g., Lake Constance, 13 year (10, 11)) to lakes and reservoirs with smaller waterresidence times, a range of aquatic systems with residence times up to 1 year has been chosen (Figure 1, Table 1). Waterresidence time represents a useful site parameter, because it provides information about the reaction time between reactive substances and particles in the system. Greifensee, the only natural lake in our series, has an average residence time of 420 days, and is characterized by two inflowing rivers with an average runoff of 1.6 and 1.1 m³/s (average 1980-1995). All other sites are located along the Aare, Rhine, and Rhône rivers, in the vicinity or downstream of the Swiss nuclear installations. Lake Wohlen and the reservoirs Niederried, Klingnau, Augst, and Chancy are all built for hydroelectrical purposes. Lake Biel has a strong anthropogenic influence since the rerouting of the Aare river, engineered at the end of the 19th century, which explains the relatively low water-residence time of 58 days. This rerouting drastically influenced the sediment delivery from the catchment. Catchment-derived particles (allochthonous particles) dominate rivers and standing waters with short water-residence times along the major rivers. Peak particle concentrations are in excess of 150 mg/L. The load of such particles in a river is related to runoff and is influenced by the type of catchment (erosion resistance of rocks and soils) and the presence of lakes and reservoirs located upstream and their particle removal efficiency. In addition, strongly changing hydraulic regimes, caused naturally by precipitation or as a consequence of higher demand for electric current, result in extreme heterogeneity of sediment deposition in the investigated reservoirs with a significant variability of the particle-bound radionuclide flux. This is particularly well demonstrated by the randomly changing flux of ²¹⁰Pb, making this method unsuitable for dating such sediments (12, 13).

In the main stream zone of smaller reservoirs or the free-flowing sections of rivers, sedimentation and erosion alternate

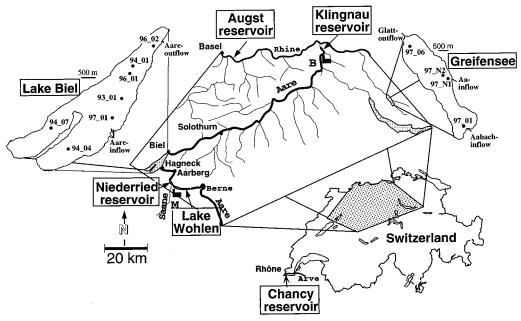


FIGURE 1. Map of Switzerland with major lakes and sediment core sampling sites. The enlarged map shows the Aare—Rhine river section between Berne and Basel, along which all cores, except the Greifensee cores (see upper right blowup) and the Rhône core (see lower insert), have been sampled. Positions of sediments taken in Lake Biel and Greifensee can be see in the respective blowups of the lakes. M and B stand for the nuclear power plants Muhleberg and Beznau.

TABLE 1. Geometric and Hydraulic Characterizations of Investigated Lakes and Reservoirs

	Greifensee	Lake Biel	Lake Wohlen	Augst reservoir	Klingnau reservoir	Niederried reservoir	Chancy reservoir
major river(s)	Aa, Aabach	Aare	Aare	Rhine	Aare	Aare	Rhône
surface area (km²)	8.45	39.3	2.7	0.61	0.85	0.78	0.25
estimated volume (km³)	0.15	1.2	0.022	0.0024	0.0034	0.002	0.0018
yearly averaged runoff (m³/s)	4.1	244	121	1048	314	121	341
water-residence time (days)	420	58	2.1	0.03	0.13	0.19	0.06

frequently. Whether or not the river bank is subject to erosion or accumulation depends mostly on changing runoff (14). With increasing size and depth of the reservoir, erosion may cease, in particular near the dam, as was the case for the sediment core sampled in Lake Wohlen during January 1994 near the dam at a depth of 12 m. Sediment resuspension and redeposition, in addition to bioturbation, are the only important processes disturbing regular, continued sedimentation (15). Undisturbed sediment cores can be found mostly in protected areas of smaller reservoirs, such as ox bows (Klingnau, sampled in 1-3 m depth in October 1994 and Augst reservoir, sampled in 5 m depth in May 1995). Where such zones of undisturbed sedimentation do not exist, ¹³⁷Cs maxima may not be found in the sedimentary record. Either sedimentation was lacking during this period or the layers were removed by subsequent erosion (Niederried and Chancy reservoirs, sampled in May 1996 and June 1997 in 1 m depth).

Methods

Sediment cores were taken between 1993 and 1997 using a gravity corer with an inner tube diameter of 59 mm. Completeness of sediment retrieval has been evaluated by measuring ⁷Be (half-life of 53 days) in the top few centimeters of sediment. Cores were sliced either in the field or in the laboratory into 0.4–2 cm sections depending on the anticipated sedimentation rate and the required resolution. Bulk densities were obtained on the basis of measured water content by weighing individual samples before and after freeze-drying and determination of sample volumes. Radionuclide activities were determined in Bq/kg (dry weight)

by γ spectroscopy (661.7 keV for 137 Cs, 30 year half-life; 604.7 and 795.5 keV for 134 Cs, 2 years; and 477.6 keV for 7 Be, 53 days) on high-purity Ge well detectors in bore-hole geometry. Geometry correction and calibration are based on standard solutions extending from 1 to 10 mL, according to sample masses, ranging between 0.5 and 10 gr dry weight.

Results and Discussion

Reservoirs with Water-Residence Times Larger 50 Days, Lake Biel and Greifensee. From the 11 sediment cores taken in Lake Biel and Greifensee (Figure 1) a detailed depth distribution profile of cesium radionuclides is depicted for core 9301 (Lake Biel) and GS9701 (Greifensee, Figure 2). The two lower maxima, both lacking 134Cs, are a consequence of atmospheric atomic bomb testing with a small maximum in global deposition during 1959 and a major maximum during 1963 (16). Age assignments to the ¹³⁷Cs maxima are based on known atmospheric deposition, the quick transfer from the water column to the sediment (17), and the efficient removal and transport of mobile radiocesium from the catchment to the lake after deposition (7). Lag times between the fallout time and deposition are, in most cases, about 6 months. The uppermost maximum, characterized by a coexistence of $^{134}\hat{\text{Cs}}$, was caused by the Chernobyl fallout in 1986 (18, 19). Sedimentation rates for Lake Biel determined for the periods 1963-1986 and 1986-1993 were 0.7 and 1.4 cm yr⁻¹, respectively (Table 2). For Greifensee, changes in sedimentation rate between the two periods are between 1.1 and 1.6 cm yr⁻¹ less significant. Assuming, for the core from Lake Biel, a constant sedimentation rate between the 1963

TABLE 2. Summary of Sedimentation Rates As Measured in Swiss Lakes and Reservoirs

		sedimentation rates (cm yr ⁻¹)		sediment accumula	ation rate (g cm ⁻² yr ⁻¹)
location/identification	reference to figure	1963-1986	1986—1993/97	1963—1986	1986—1993/97
Lake Biel					
93 1	2A	0.7	1.4	0.38	0.75
94 ⁻ 07	3D	0.74	1.4	0.28	0.49
94 04	3E	1.2	1.5	0.45	0.47
94 ⁻ 01	3F	nd	2.0	nd	0.69
96 ⁻ 01	3G	1.5	1.7	0.60	0.58
96 ⁻ 02	3H	nd	2.0	nd	0.75
97 ⁻ 01	31	nd	3.5	nd	2.4
Greifensee					
GS97 1	2B	1.1	1.6	0.60	0.66
GS97 ⁻ 6	3A	0.39	0.52	0.13	0.14
GS N2	3B	0.53	0.69	0.17	0.17
GS ⁻ N1	3C	nd	2.5	nd	1.01
Lake Wohlen					
WU94 03	4	1.8	2.3	0.8	1.0
Augst Reservoir					
ĀU95 01	5A	1.4	1.8	0.69	0.69
AU95 ⁻ 06	5B	1.3	1.8	0.62	0.73
Klingnau Res.					
9402	7A	nd	3.2	nd	1.5
9403	7B	nd	3.1	nd	1.2
9410	7C	nd	3.4	nd	1.8

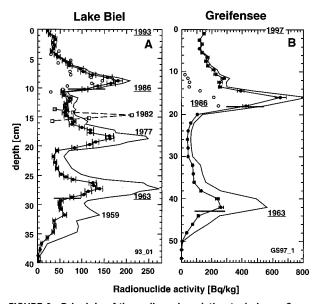


FIGURE 2. Principle of the radiocesium dating technique: Cores from Lake Biel (A) and Greifensee (B) archive the complete ¹³⁷Cs deposition history of the last 40 years (decay corrected to the day of sampling, filled circles with 2σ measurement errors). Using the peaks marked 1963 and 1986 and average sedimentation rates (Table 2), each individual sediment sample can be dated, and the radionuclide activities decay-corrected (continuous line). ¹³⁴Cs (open circles, decay-corrected to May 1, 1986) originates from deposition as a consequence of the Chernobyl accident. ⁶⁰Co in the core from Lake Biel (open squares, only peak area shown, decay-corrected to the date of deposition) was caused by higher discharges of the nuclear reactor MUhleberg in August 1982.

and 1986 markers, the additional ¹³⁷Cs maximum can be dated to the period of 1975–1977. This maximum was caused by higher discharges of the nearby Mühleberg nuclear reactor using low-quality fuel rods during 1976–1978.

Continued deposition of 137 Cs and the existence of smaller maxima are related to continued erosion of 137 Cs-carrying soil particles from the catchment area of both lakes (12).

Core 9301 (Lake Biel) can also be used to illustrate the applicability of other radionuclides as a dating tool. The

Mühleberg nuclear reactor discharges wastewater containing low activities of different radionuclides, in particular $^{60}\mathrm{Co}$, within the limits defined by the Swiss Federal Nuclear Safety Inspectorate (HSK). These discharges result in $^{60}\mathrm{Co}$ activities usually not surpassing 50 Bq/kg in sediments downstream of the reactor. The maximum of 209 Bq/kg (Figure 2; decay corrected to the date of deposition), dated to 1981 on the basis of $^{137}\mathrm{Cs}$, was actually due to higher discharges that were released in August of 1982.

Variability within the Lakes. In both Greifensee and Lake Biel, particle accumulation changes as a function of distance to the inflowing rivers (20–22) (Figure 1). The ¹³⁷Cs depth profiles of additional sediment cores illustrate this local variability (Figure 3). The sedimentation rates representing the periods 1963–1986 and 1986–1997 vary in Greifensee from 0.14 to 1 and from 0.5 to 2.5 cm yr⁻¹, respectively (Table 2). For Lake Biel a sedimentation rate of 3.5 cm yr⁻¹ was obtained for the late period near the Aaredelta (Figure 3I). In the deeper parts of the lake, sedimentation rates vary for the early and late periods between 0.7 and 1.5 and between 1.4 and 2.0 cm yr⁻¹ (Figure 3D–H, Table 2), respectively. Despite these local variations, all peaks can be reliably identified.

Core 97_N2 from Greifensee (Figure 3B) illustrates the application of independent time markers. The depth distribution of the fluorescent whitening agent (DSBP, (23)) indicates a first appearance at a depth of 14–15 cm (6 ng/g of dry sediment). On the basis of Cs dating, this corresponds to 1972–1974, corresponding well with the first production of the substance in 1972.

Depth Versus Mass Depth and the Conversion of Mass-Related Activities to Fluxes. In addition to depth-related sedimentation rates, it is possible to use mass depths (depth per year \times density) to allow for correction of density differences in individual cores and from different locations. The density increase with depth is related to greater compaction. From the surface to a depth of about 10 cm, densities generally increase by a factor of 2. Density differences between cores are related to the type of particles and the sample treatment. Cores, which were compressed during transport, have higher bulk densities and are characterized by lower apparent depth-related sedimentation rates. Cores 9301 and 9401 from Lake Biel provide a good

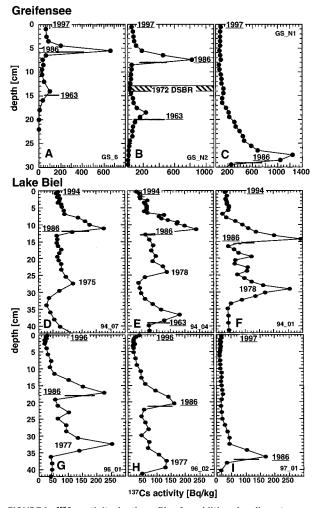


FIGURE 3. ¹³⁷Cs activity depth profiles for additional sediment cores from Greifensee (A, close to outlet; B, C close to delta) and Lake Biel (three deeper basins D, E, F, G) and from shallow sites near the Aare outflow, H, and within the Aare delta, I. The bar in Greifensee core 97_N2 (B) indicates the first appearance of the fluorescent whitening agent DSBP (1972, ref *23*).

example (Table 2, Figures 2,3C). The former was transported before sampling, the latter sampled on-site. The depthrelated sedimentation rate between 1986 and 1993 for the transported core is 1.4 cm yr⁻¹, the mass depth related sedimentation 0.75 g cm⁻² yr⁻¹ (with a ratio of 2 between the two). For the core sampled on-site, rates were 2.0 cm yr⁻¹ and 0.69 g cm⁻² yr⁻¹, respectively (with a ratio of 2.9). The difference in ratio of the two rates illustrates the higher compaction of the transported core. Comparison of sedimentation rates of cores, which were treated differently, should therefore be based on mass depth, rather than depth. Changes in sediment accumulation rates should also be given in g cm⁻² yr⁻¹, particularly when comparing rates for different periods. In both Greifensee and Lake Biel sedimentation rates (in cm yr⁻¹) are higher for the period from 1986 to the mid 1990s than for the period 1963-1986. Based on mass accumulation rates, these differences become less significant. In Greifensee, rates vary between 0.13 and 0.60 g cm⁻² yr⁻¹ for the early period and between 0.14 and 0.66 for the late period; thus there is no significant difference. In Lake Biel, however the difference is significant between 0.28 and 0.60 g cm⁻² yr⁻¹ in the early period and between 0.49 and 0.75 g cm⁻² yr⁻¹ in the late period, possibly related to higher erosion rates in the catchment.

Reservoirs with Water-Residence Time Larger Than 1 day, Lake Wohlen. The sediment core has archived sedi-

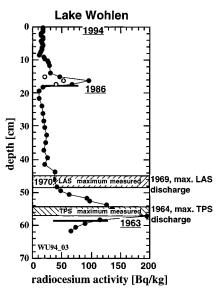


FIGURE 4. Radiocesium depth profile (137Cs, filled circles, corrected to the day of coring; 134Cs, open circles, corrected to May 1, 1986) in a sediment core from Lake Wohlen, with time markers based on the known events (atomic weapons testing, 1963; Chernobyl, 1986, for list of assumed constant sedimentation rates between events see Table 2). The maxima surfactant inputs (tetrapropylenebenzenesulfonate, TPS, (1964) and linear alkylbenyenesulfonate, LAS (1969), ref *24*) allow an independent evaluation of the radiocesium dating.

ments since 1960 (Figure 4). Depth-related sedimentation rates increased from 1.8 cm yr⁻¹ for the period 1963-1986 to 2.3 cm yr⁻¹ for the more recent period 1986-1994. Massrelated sedimentation rates increased from 0.8 to 1 g cm⁻² yr^{-1} , respectively (Table 2). While in Lake Biel (Figure 2) the peak representing the Chernobyl accident has a larger amplitude than the bomb peak, the bomb peak is higher in Lake Wohlen (Figure 4). Such a relative variation in the deposition of radionuclides is a characteristic of riverine systems, mostly related to changing runoff. As deposition of Chernobyl radionuclides occurred during spring when river runoff reaches the yearly maximum, water-residence times decreased, and the time for radionuclide adsorption and deposition of particles was shorter. In large lake systems, which are only to a small extent influenced by catchment processes, the deposition in the sediment can be linked to atmospheric deposition. In reservoir systems such as Lake Wohlen, which are mostly characterized by catchmentderived particles, the substance of interest here, 137Cs, originates only to a small extent from direct atmospheric deposition. The change in the concentration as a function of time (high during 1963, low in 1986, with similar atmospheric deposition for the site) precludes such reservoir sediments to serve as an estimation tool for atmospheric deposition.

In addition to ¹³⁷Cs, the depth distribution of the anionic surfactants LAS (linear alkylbenzenesulfonate) and TPS (tetrapropylenebenzenesulfonate) was measured (*24*). LAS was introduced in the mid 1960s as a substitute for the poorly biodegradable TPS. The maximum in TPS in the core of Lake Wohlen (Figure 4) was dated to 1964, using ¹³⁷Cs. This coincides well with peak production of 1963/64. The maximum discharge of LAS into the environment occurred during the late 1960s before the installation of sewage treatment plants. The highest LAS concentrations were found at a depth of 48 cm or 1970 according to the ¹³⁷Cs dating (Figure 4).

Reservoirs, with Water-Residence Times below 5 h, Augst Reservoir. In the Augst reservoir (Figure 1), sediment cores

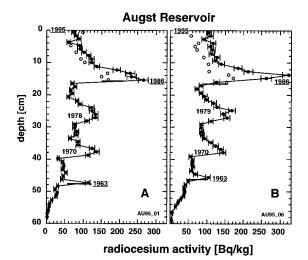


FIGURE 5. Comparison of two sediment cores taken close to each other in the Augst reservoir (A and B). The two additional peaks are related to higher discharges by the nuclear reactors Beznau in 1971 and Muhleberg in 1976—1978. For symbol assignments and decay corrections see Figure 4.

were taken in an oxbow, where relatively undisturbed sedimentation can be expected. To allow an estimation of the reproducibility of sediment core data, two cores were taken a few meters apart (Figure 5). The depth, amplitude, and form of all four peaks are almost identical in each core. The peaks indicated with 1963, 1976, and 1986 are those already found in Lake Biel. The fourth maximum, dated to 1970, reflects higher discharges by the nuclear power plant Beznau. Both discharges were radioecologically insignificant (25). Sedimentation rates slightly increased from 1963–1986 to 1986-1995 (1.3-1.8 cm yr⁻¹ or 0.62-0.73 g cm⁻² yr⁻¹, Table 2). The weak representation of the bomb maximum in the two cores illustrates again the possible pitfalls in dating riverine sediments. This lack of adequate representation of a major radioactive fall-out event in a sediment core could be related to inefficient transfer either from the water column to the sediment or by an erosive event.

The Augst sediments illustrate additional issues important for radiocesium dating. Sediment deposition in rivers can change seasonally or as a function of changing weather patterns. A significant temporary decrease in runoff might lead to enhanced deposition of smaller particles which adsorb Cesium more efficiently than large particles (e.g., clay (26)). This could lead to a ¹³⁷Cs maximum, which is not related to any event mentioned above. A soil erosion event in the river catchment, in particular removal of the top soil with the highest ¹³⁷Cs activity (27), can also yield a ¹³⁷Cs maximum. Grain-size information can be used as an indicator for enhanced clay deposition; organic carbon or nitrogen is an indicator for a higher soil particle flux. The nitrogen depth profile in Figure 6B shows a continuous diagenetic decrease from 0.35% to 0.2%. The lack of a correlation between N concentration (or organic C, not shown) and Cs activity makes erosion an unlikely cause for any of the four ¹³⁷Cs maxima. Likewise, the median grain-size distribution (Figure 6C) allows exclusion of grain-size variations as the cause for the four ¹³⁷Cs maxima. The insignificance of the local minima, corresponding to the lower two ¹³⁷Cs maxima, can be deduced by comparison with the low particle size in the upper 10 cm. The four peaks are thus not related to secondary processes, but indeed reflect higher fluxes of ¹³⁷Cs.

Klingnau Reservoir. The Klingnau reservoir, although similar to the Augst reservoir, has a larger exchange zone between the river section and the accumulation zone. The Klingnau reservoir illustrates the difference in sedimentation

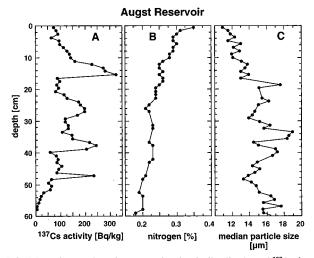


FIGURE 6. Comparison between the depth distribution of ¹³⁷Cs (A, filled circles, corrected to the date of deposition), nitrogen, and median particle sizes in core AU95_01 from the Augst reservoir.

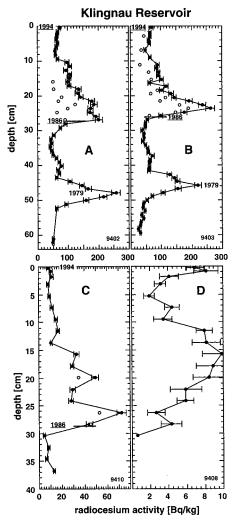


FIGURE 7. Klingnau reservoir cores taken from the accumulation zone (A and B), from the boundary between the accumulation and turbulent zones (C), and from the turbulent zone (D). For symbol assignments and decay corrections see Figure 4.

and dating between the two zones (Figure 7). Within the accumulation zone (Figure 7 A,B), sedimentation is relatively undisturbed. The Chernobyl peak (1986) and the Mühleberg reactor peak (1976–1978) are well represented. However,

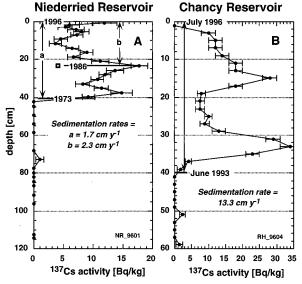


FIGURE 8. Cores from highly disturbed river sections from the Aare near Niederried (A) and the Rhône near Chancy (B). For symbol assignments and decay corrections see Figure 4. The open square in A indicates ⁶⁰Co (decay corrected to the day of coring), locally released to the atmosphere in 1986.

high sedimentation rates (>3 cm yr⁻¹, Table 2) and the difficulty in obtaining sediment cores longer than 60 cm explain the absence of the 1963 peak. Two sediment cores taken 5 m apart in the accumulation zone show similar depth, amplitude, and form of the 1976–1978 peak, but a different form of the Chernobyl maximum.

Assigning dates to ¹³⁷Cs maxima in cores taken within the river section (Figure 7C,D) is more difficult. Due to higher turbulence, fine particles play a minor role, which is reflected by lower ¹³⁷Cs activities. In the accumulation zone, ¹³⁷Cs maxima were above 200 Bq/kg, decreasing to less than 80 Bq/kg near the boundary (C) and less than 10 Bq/kg within the river zone (D). Chernobyl-¹³⁴Cs (2 years half-life vs 30 years for ¹³⁷Cs), which during deposition in 1986 had an activity half that of ¹³⁷Cs, reaches the detection limit, in samples, where the original activity was below about 25 Bq/kg. This precludes unambiguous age designation in the river zone.

Reservoirs with Water-Residence Times below 1.5 h. In smaller reservoirs without zones of undisturbed sedimentation, dating cannot be performed simply on the basis of radionuclide maxima. Such cases are represented by the Niederried (Figure 8A) and Chancy (Figure 8B) reservoirs. The ¹³⁷Cs maximum at 24 cm in the Niederried core (Figure 8A) may be related to the 1986 Chernobyl accident. Confirmation based on ⁶⁰Co is possible, which was locally released to the atmosphere by the Mühleberg reactor during 1986. A more significant feature is the sudden decrease of ¹³⁷Cs at a depth of 40 cm. This is caused by sediment dredging which was last carried out in 1972. On this basis it is possible to calculate a total sedimentation rate of 1.7 cm yr⁻¹ between 1972 and 1996, compared to $2.4 \,\mathrm{cm} \,\mathrm{yr}^{-1}$ for the period 1986– 1996. The dating of the sediment core taken in the Chancy reservoir (B) is impossible using event-related ¹³⁷Cs. A large part of the sediment is removed by weir openings, which usually occur every 2 years. The last weir opening, which was carried out in June of 1993, represents the only means for sediment dating. The sudden decrease in ¹³⁷Cs activity and low remaining activities below that depth allow correlation with the last weir opening and thus determination of an average sedimentation rate of 13.3 cm yr⁻¹.

Acknowledgments

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Literature Cited

- Beurskens, J. E. M.; Mol, G. A. J.; Barreveld, H. L.; van Munster, B.; Winkels, H. J. *Environ. Toxicol. Chem.* **1993**, *12*, 1549–1566.
- (2) Wieland, E.; Santschi, P. H.; Höhener, P.; Sturm, M. Geochim. Cosmochim. Acta 1993, 57, 2959–2979.
- Ritchie, J. C.; McHenry, J. R. J. Environ. Qual. 1990, 19, 215– 233.
- (4) Jüttner, I.; Henkelmann, B.; Schramm, K.-W.; Steinberg, C. E. W.; Winkler, R.; Kettrup, A. Environ. Sci. Technol. 1997, 31, 806–812.
- (5) Albrecht, A.; Beer, J. Radioprotection 1997, 32, 277-285.
- Callaway, J. C.; DeLaune, R. D.; Patrick, W. H. J. Limnol. Oceanogr. 1996, 41, 444–450.
- (7) Ritchie, J. C.; McHenry, J. R.; Gill, A. C. Limnol. Oceanogr. 1973, 18, 254–263.
- (8) Van Metre, P. C.; Callender, E.; Fuller, C. C. Environ. Sci. Technol. 1997, 31, 2339–2344.
- Rostan, J. C.; Juget, J.; Brun, A. M. Sci. Total Environ. 1997, 193, 251–262
- (10) Robbins, J. A.; Lindner, G.; Pfeiffer, W.; Kleiner, J.; Stabel, H. H.; Frenzel, P. Geochim. Cosmochim. Acta 1992, 56, 2339–2361.
- (11) Dominik, J.; Mangini, A.; Mueller, G. Sedimentology 1981, 28, 653–677.
- (12) Albrecht, A. Aquat. Sci. in press.
- (13) Bierman, P. R.; Albrecht, A.; Bothner, M.; Brown, E. T.; Gray, L. B.; Turpin, L. In *Isotope Tracers in Catchment Hydrology*, McDonnell, J. J., Kendall, C., Eds.; Elsevier: New York, 1998.
- (14) Miller, M. C.; McCave, I. N.; Komar, P. D. Sedimentology 1977, 24, 507–527.
- (15) Bloesch, J. Mar. Freshwater Res. 1995, 46, 295-304.
- (16) Aarkrog, A. J. Environ. Radioact. 1988, 6, 151-162.
- (17) Santschi, P. H.; Bollhalder, S.; Zingg, S.; Lück, A.; Farrenkothen, K. Environ. Sci. Technol. 1990, 24, 519–527.
- (18) Devell, L.; Tovedal, H.; Bergström, U.; Appelgren, A.; Chryssler, J.; Andersson, L. Nature 1986, 321, 192–193.
- (19) Cambray, R. S.; Cawse, P. A.; Garland, J. A.; Gibson, J. A. B.; Johnson, P.; Lewis, G. N. J.; Newton, D.; Salmon, L.; Wade, B. O. Nucl. Energy (Br. Nucl. Energy Soc.) 1987, 26, 77-101.
- (20) Wright, R. F.; Matter, A.; Schweingruber, M.; Siegenthaler, U. Schweiz. Z. Hydrol. 1980, 42, 101–126.
- (21) Weiss, H. P. Eclogae Geol. Helv. 1979, 72, 407-424.
- (22) Wan, G. J.; Santschi, P. H.; Sturm, M.; Farrenkothen, K.; Lück, A.; Werth, E.; Schuler, C. Chem. Geol. 1987, 63, 181–196.
- (23) Stoll, J.-M. A.; Poiger, T. F.; Lotter, A. F.; Sturm, M.; Giger, W. In Molecular markers in environmental geochemistry; Eganhouse, R. P., Ed.; American Chemical Society Symposium Series 671; American Chemical Society: Washington, 1997; pp 231–241.
- (24) Reiser, R.; Toljander, H.; Albrecht, A.; Giger, W. In Molecular markers in environmental geochemistry; Eganhouse, R. P., Ed.; American Chemical Society Symposium Series 671; American Chemical Society: Washington, 1997; pp 196–212.
- (25) Albrecht, A.; Beer, J.; Bollhalder, S.; Lück, A.; Stengel, C.; Sturm, M.; Weidmann, Y. EAWAG Jahresbericht 1995 1996, 4–9.
- (26) Comans, R. N. J.; Hockley, D. E. Geochim. Cosmochim. Acta 1992, 56, 1157–1164.
- (27) Wallbrink, P. J.; Murray, A. S. Hydrological Processes 1993, 7, 297–304.

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