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ORIGINAL PAPER

Depositional rates and dating techniques of modern deposits in the Brno reservoir (Czech Republic) during the last 70 years

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Abstract Facies analysis, magnetic susceptibility, and analysis of grain size, TOC content and isotopes (^{137}Cs, ^{210}Pb, ^{226}Ra, ^{228}Ra, and ^{238}U concentrations) were used to determine the history of the modern deposits of the Brno reservoir. The sedimentary succession can be subdivided into two main units. The lower unit is formed predominantly by medium- to coarse-grained silty sands and is interpreted as a fluvial succession deposited before the Svratka River was dammed. The upper unit consists of brownish planar laminated silts and rarely of clayey or sandy silts and is interpreted as a product of the reservoir deposition. The concentrations of ^{238}U reflect the history of uranium mining in the upper part of the Svratka River catchment. As a consequence, ^{210}Pb radionuclide concentrations cannot be used for establishing a sediment chronology. Concentrations of ^{137}Cs show two marked peaks, the upper of which is attributed to the Chernobyl reactor accident in 1986, and the lower one is attributed to the maximum rate of atomic weapons testing in 1963. From these peaks, mean depositional rates of 3.2 cm year^{-1} for the time period of 1986–2007 and of 3.4 cm year^{-1} between 1963 and 1986 are calculated. Based on the known age of the reservoir, which was constructed in 1939, we can also calculate mean depositional rate for the time period of 1939–1963, which is 3.1 cm year^{-1}.

Keywords Reservoir deposits · Radiometric dating · Depositional rate · Hydrological changes · Human impact

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Introduction

Artificial lakes and reservoirs are known to act as effective traps for fluvial material and may represent a continuous record of deposition of modern sediments. Reservoir deposits can be used for the evaluation of climatic conditions, contamination history of the area and past environmental changes caused by both natural and artificial events (Foster and Walling 1994; Shotbolt et al. 2005; Yeloff et al. 2005; Bennett and Rhoton 2007). The sediments deposited in reservoirs can, thus, represent a valuable archive that can be used to reveal the erosion history of watersheds.

The depositional rate of reservoir sediments is influenced by various factors (Kashiwaya et al. 1997; Bell 1998; Brothers et al. 2008; Wren and Davidson 2008; Begy et al. 2009) and reflects processes taking place both in the source and depositional area. Modern deposits can be dated by several methods (Walker 2006). Sediment geochronologies based on the radionuclides ^{137}Cs and ^{210}Pb have been established for marine, lacustrine and intertidal environments (Koide et al. 1971; Robbins and Edgington 1975; Smith and Walton 1980; Lynch et al. 1989; Callaway et al. 1996; Håkanson 2007; Appleby 2008; Sikorski and Bluszcz 2008; Begy et al. 2009) and applied to study historical trends of contaminant emissions at industrial sites, effects of single events, e.g. a storm surge or flood, and local palaeoclimatic conditions (Ritchie et al. 1973; French et al. 1994; Callaway et al. 1996; Kirchner and Ehlers 1998; Barra et al. 2001; Oldfield et al. 2003; Lüder et al. 2006; Bennett and Rhoton 2007; Di Gregorio et al. 2007; Begy et al. 2009). The combined use of ^{210}Pb and ^{137}Cs for estimating sediment ages has been strongly recommended because information available from these tracer nuclides complements each other (Kirchner and Ehlers 1998), and validation of the ^{210}Pb-based geochronology by other time markers is essential (Anderson et al. 1987; Reinikainen et al. 1997; Smith 2001).

The present study focuses on the following: (1) depositional rate determination of the Brno reservoir deposits during the last 70 years, (2) definition of a geochronology of the reservoir deposits using ^{137}Cs, ^{210}Pb and other ^{238}U decay-chain radionuclides, and **(3)** identification of the role of hydrological processes in the sedimentary record of this particular reservoir.

Study area

The Brno reservoir was constructed on the Svratka River during the period of 1936–1939 and was completely filled for the first time by the summer flood in 1940. The reservoir has the characteristic geometry of the relatively long and narrow basin due to artificial flooding of the incised river valley. The flooded valley is relatively broad close to the reservoir dam, whereas distally it narrows rapidly with rather steep walls. The maximum depth of the artificial lake is 19 m and its length is $\sim$10 km. The total volume of retained water can reach a maximum of 18.4 million m^3, but the constant reservoir storage volume is calculated at 7.6 million m^3, with a maximum areal extent of approximately 2.59 km^2 (unpublished Povodí Moravy data, Vlček 1984). The reservoir was constructed for several purposes including stabilisation of the Svratka River discharge, reduction of the flood effect, electricity production, to act as a water source, and for recreational and commercial activities. The Svratka River is the only important tributary into the reservoir. The other tributaries are small and mostly ephemeral streams. The dominant role of the Svratka River for the fluvial and sediment flux of the dam is demonstrated by the following data: the reservoir catchment area is 1,575 km^2, and the Svratka River catchment area above the studied reservoir is more than 1,490 km^2. The average annual flow rate below the dam is 8.03 m^3 s^{-1}, and the average discharge of the Svratka River is approximately 8.00 m^3 s^{-1}.

Granodiorites and diorites of the Brno batholith (Cadomian; Neoproterozoic in age) constitute the major part of the reservoir bedrock. The areal extent of younger deposits (Permian, Neogene and Quaternary in age) along the reservoir margins is limited (Müller and Novák 2000). Input of rock debris from the steep walls is mainly the result of subaerial gravitational flows. Moreover, several transverse erosive short valleys are cut into the walls of the reservoir. Wind-generated currents and breaking waves are responsible for erosion of Quaternary loess and colluvial deposits in the central part of the reservoir, for cliff retreat and for redistribution of the material into the basin.

Methods

Our sediment sampling strategy was directed by the reservoir morphometry, distributions of deposits and position of the accumulation zone (Shotbolt et al. 2005). The complex bathymetry of the reservoir has caused complicated sediment distribution patterns. Therefore, the coring site of the core BP-4 was located in the upper part of the Brno reservoir (Fig. 1) where high trap efficiency potential is presumed. This was also confirmed by field screening (Franců et al.

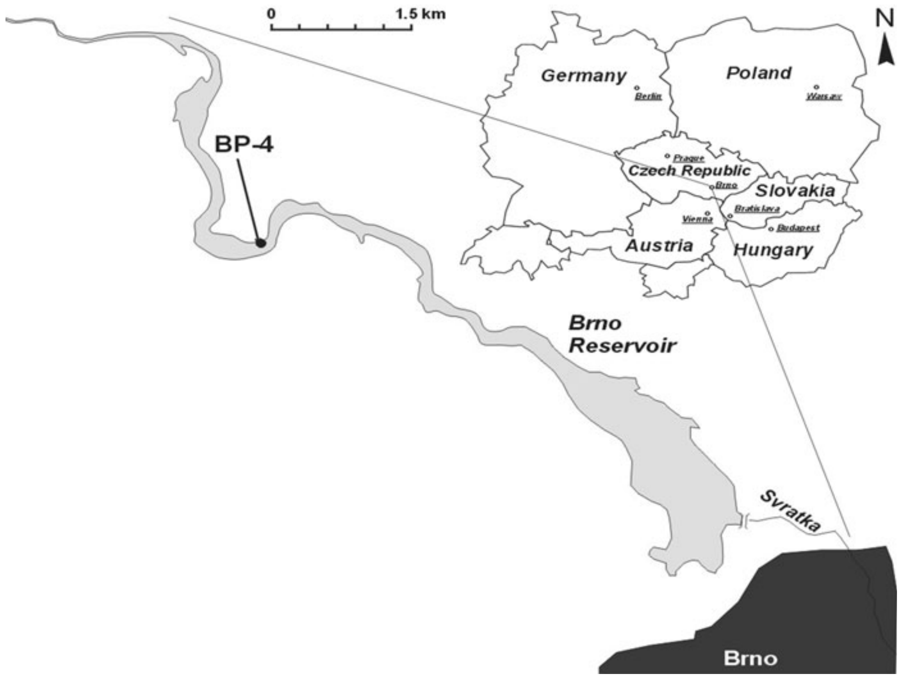

Fig. 1 Sketch map of the studied area with the location of the coring hole

2010), which showed that sampling in the central part of the reservoir would be inappropriate due to the erosional effect of the stream and regular reservoir management. The sediment thickness in the central part of the reservoir (close to the dam) is generally <1 m (Franců et al. 2010). The distance of the coring site from the ordinary inflow point, where the reservoir water level affected the Svratka River inflow (area of raised water level) is approximately 2 km. Our drilling was oriented in the path of the fluvial inflow away from the possible transverse input of material from reservoir walls. The Svratka River has an incised meandering fluvial pattern here (49°15′30.26″N, 16°27′42.05″E and 220.5 ± 0.5 m a.s.l.), and the apical left-bank point bar position was selected for drilling. The coring site was temporarily accessible due to the exceptional reservoir level decrease of more than 10 m in the winter to early spring of 2008 due to a water release to revitalise the reservoir because of a summer cyanobacterial bloom made its recreational use impossible.

Sampling was performed in March 2008 using a Makita vibration hammer and Eijkelkamp coring tubes. The obtained core of 292.5 cm in length was placed into a plastic sleeve and divided immediately into two equal parts. One part of the core was frozen and stored, and the other part was photo documented, lithologically described and subdivided into 121 samples, each about 2.5 cm thick.

Facies analysis, magnetic susceptibility, analysis of grain size, TOC content and both ^{137}Cs and ^{210}Pb concentrations were used to establish a geological framework of the core. Grain size was measured by laser diffraction methods using a Cilas 1064 granulometer for the 0.0004–0.5-mm fraction. Ultrasonic dispersion and washing in sodium polyphosphate were used prior to the grain size analyses to avoid flocculation of analysed particles. The average grain size is demonstrated by the graphic mean (Mz) and the uniformity of the grain size distribution by the standard deviation (σI) (Folk and Ward 1957). Lithofacies analysis followed the rules of Walker and James (1992), Tucker (1988) and Nemec (2005). Environmental magnetic susceptibility (MS) was measured as mass susceptibility (χ) in 10^{-9} m^3 kg^{-1} using an MFK1-FA Kappabridge at a magnetic field of 200 A m^{-1} in the AGICO, Ltd. For further summary of magnetic parameters and terminology, see Evans and Heller (2003). All samples were subjected to elemental analysis of total organic (TOC) and inorganic carbon (TIC) using a Metalyt CS 1000 S apparatus (ELTRA GmbH, Neuss, Germany). The method of total carbon assessment is based on the infrared detection of carbon dioxide released by combustion at 1,200°C. Inorganic carbon content is measured as carbon dioxide exhibiting phosphoric acid acidification. Subtracting the inorganic carbon from the total carbon yielded TOC. Historical changes of organic pollutant levels were studied throughout the core by Franců et al. (2010). The magnetic susceptibility values were not corrected for the diluting effect of organic carbon as TOC levels were low.

Maximum daily discharge measurements from the period of 1939 to 2007 were evaluated (unpublished Povodí Moravy data) for the gauging station Veverská Bítýška at 228.1 m a.s.l., which is located approximately 2 km upstream from study site. Continuous data from the 68-year period of the dam's history were analysed using the Pearson method (Brázdil 1995).

For the gamma-spectrometric analyses, a high-purity Germanium well detector with a relative efficiency of 36.6% and a usable energy range between 40 and 2 MeV was applied. Sediment samples were dried, homogenised and loaded into glass vials prior to measurement. Depending on the mass of sediment available, measurement times varied between 1 and 6 days to limit some statistical counting uncertainties for all of the radionuclides in our range of interest. In addition to the anthropogenic ^{137}Cs (with a gamma energy of 661.7 keV), activity concentrations of natural ^{210}Pb (46.5 keV), ^{228}Ra (via its decay product ^{228}Ac at 911.2 keV) and ^{238}U (via its short-lived decay products ^{234}Th at 63.3 keV and ^{234m}Th at 1001.0 keV) were determined. For ^{226}Ra, its 186.2 keV decay energy was used after subtraction of the contributions of ^{235}U at this energy, which were determined from the 143.8 keV energy of this uranium isotope. This procedure was preferred to the measurement of ^{226}Ra via its short-lived progeny, ^{214}Pb, because loss of some ^{222}Rn from the glass vials could not be excluded. Count rates were corrected for summation effects where necessary.

Radionuclide chronology

The radionuclide ^{137}Cs (30.1 year half-life) is artificially produced by a nuclear fission processes. The nuclear weapons tests performed in the atmosphere between 1945 and 1980 caused global dispersion and deposition of this radionuclide. Due to the varying annual number and yield of atmospheric tests, deposition rates in the environment showed a pronounced maximum in 1963 (UNSCEAR 2000). Because ^{137}Cs is strongly associated with minerals (Alberts et al. 1989), the 1963 weapons testing peak has been preserved in most sediments to the present. In much of Europe and the Middle East, deposition of ^{137}Cs originating from the Chernobyl reactor accident in 1986 provides a further time marker that may be even more pronounced than the 1963 weapons peak.

The use of the natural isotope ^{210}Pb (22.3 year half-life) is based on its removal from the atmosphere by precipitation and integration into sediments where it subsequently decays to the stable isotope ^{206}Pb. In addition to this atmospherically derived ^{210}Pb (often called excess or unsupported ^{210}Pb), which is used for dating, there is a background concentration of this isotope (called supported ^{210}Pb) originating from the ^{226}Ra present in the sediment minerals.

There are two standard approaches to estimate sediment ages and sedimentation rates from the activity concentrations of excess ^{210}Pb measured in a sediment core, the constant initial concentration (CIC) and the constant rate of supply (CRS) model (Appleby 2001). Both models are based on the assumption of a constant annual flux in the density of excess ^{210}Pb fixed to particles across the water–sediment interface. The CIC model is applicable if sedimentation rates and sediment densities are also time invariant. For such a stationary sedimentation regime, excess ^{210}Pb shows an exponential decline within the sediment, which reflects its sedimentation rate. The CRS model focuses on varying sedimentation rates. Sediment ages are derived from the fraction of the depth-integrated excess ^{210}Pb present above the position considered. Thus, any deviations from an exponential decrease with depth of excess ^{210}Pb are interpreted by the CRS model to reflect a variation of the sedimentation rate.

Results

Facies analyses and depositional environment

The sedimentary succession can be subdivided into two main units (Fig. 2). The lower unit lies below a depth of 199.5 cm. Brown, greyish to greenish medium- to coarse-grained silty sands predominate within this unit. Sand is usually poorly sorted with

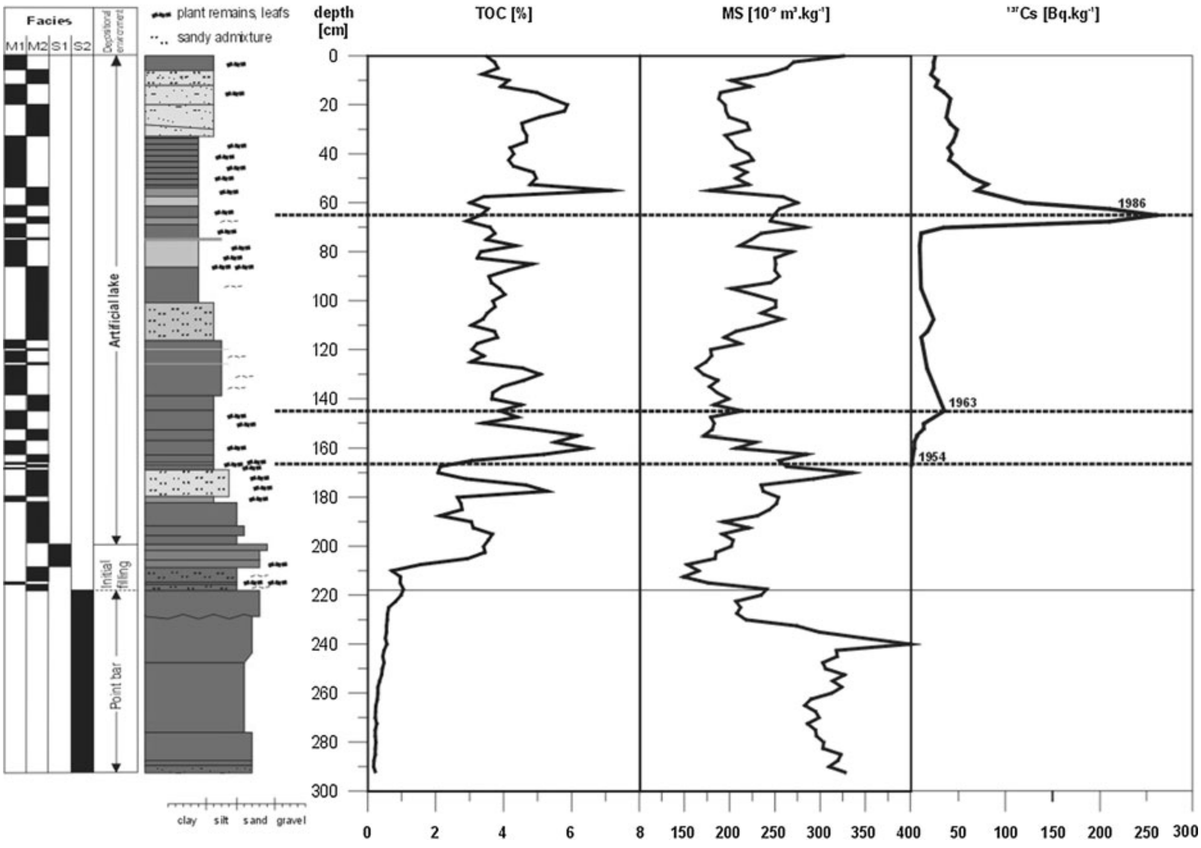

Fig. 2 Lithological profile of the studied core, facies distribution, total organic carbon (TOC) content, magnetic susceptibility (MS) values and the concentrations of ^{137}Cs throughout the studied profile

some admixture of granules and a reduced occurrence of plant detritus. The bases of sandy beds are irregular or gradational. Sandy silt laminae with abundant plant detritus are sometimes intercalated in sandy facies. This unit is interpreted as fluvial succession deposited before filling of the dam from the contact and saltation load (bedload). This fluvial unit can be further subdivided into two subunits. The lower subunit (218.5–292.5 cm) comprises thicker (10–30 cm) beds of poorly sorted sand with reduced content of plant detritus (facies S2). This subunit was interpreted as a product of lateral accretion of fluvial material on the point bar (associated with the migration of the thalweg towards the right cut bank of the Svratka River in this part of the valley). The upper subunit was recognised at a depth of 199.5–218.5 cm and is formed by thin (<5 cm) sandy beds (S1 facies) alternating with silt laminae (M2 and M1 facies). Facies changes represent the alternating periods of quiet deposition (facies M1, M2) and more agitated deposition, with the migration of flow ripples and small dunes (facies S1). The formation of this subunit is interpreted as a response of the start of reservoir filling and the possible impact of the several floods during the initial reservoir water infill period of 1939–1941. This interpretation is supported by the upward coarsening trend of the subunit and the absence of fluvial sediments higher in succession. Three factors suggest that the initial prograding deltaic deposition in the marginal zone of the reservoir did not influence deposition at our study site, and these factors include the distance between our study site and the area of raised water level, the abrupt change in the grain size at the start of the deposition, and the lack of evidence for instability and slumping.

The upper unit (above 199.5 cm) consists of brownish, grey to greenish planar laminated silts and rarely of clayey or sandy silts. Graphic mean Mz (17 samples) varies between 0.025 and 0.012 mm (average

0.018 mm). Silts are relatively poorly sorted; their σI varies between 1.3 and 1.7 ϕ (average 1.5 ϕ). Thin sandy interlayers and sand admixture occur especially in the lower part of the succession (depths of 101–116.5 and 169–180 cm). Planar lamination is connected with alternation of slightly coarser and lighter laminae and those which are relatively finer grained and darker (higher content of organic matter). Two facies (M1 and M2) were selected according to the content of plant detritus and colour. The M1 facies is notably darker due to higher organic content (mainly plant detritus) than the lighter coloured M2 facies. Alternation of these facies can be followed within the succession. The upper unit is interpreted as the post-dam phase with sediments deposited mainly from graded and uniformly suspended loads. Alternation of the M1 and M2 facies and the presence of some intercalated sandy silt layers indicate the impact of various natural and anthropogenic processes affecting reservoir deposition. Such processes include variations in seasonal fluvial discharge (especially occasional floods), the annual vegetation cycle, variations in agricultural and industrial activities in the surrounding areas and fluctuations in the reservoir water level. Relatively monotonous facies arrangement and grain size within the upper unit point to generally stable sedimentary environment. Considerable consistency in particle size distribution throughout the upper unit of the core demonstrates that reservoir drawdown events have not resulted in redistribution of coarse sediments. The upper unit sediments were deposited in the reservoir accumulation zone and do not represent any type of marginal sediments affected dominantly by processes other than those involved in reservoir deposition. Input from rain splash and slope wash was not recognised because such processes preferentially remove fine particles, though coarser sediments may also be removed during high-intensity rainfall events or from steeply sloping marginal deposits (Shotbolt et al. 2005).

Organic carbon content and magnetic susceptibility

Changes in total organic carbon (TOC) content and environmental magnetic susceptibility (MS) throughout the profile reflect major changes in conditions during sedimentation. The lower fluvial subunit (below 218.5 cm), which is interpreted as being deposited by lateral fluvial accretion on the point bar, shows the lowest TOC content (typically <1%) with a slight increase towards the top (Fig. 2). In contrast, MS values are high (usually $>290.10^{-9}$ m^3 kg^{-1}) with a maximum of 407.10^{-9} m^3 kg^{-1} at the depth of 240 cm. Changes in MS reflect different inputs of ferromagnetic minerals from the Svratka River catchment, which correspond to changes in the grain size of sediments. Low organic carbon content is typical for fluvial deposition; its vertical increase may reflect shallowing of water due to lateral accretion on the point bar. The upper fluvial subunit (218.5–199.5 cm) shows a slight increase of TOC at its base, followed by its gradual decrease up to 210 cm and finally a rapid increase up to ~3.5% at its top. This fluvial subunit has the lowest MS values of the entire profile, reaching levels of $\sim 150.10^{-9}$ m^3 kg^{-1}. These variations indicate discharge changes in the time of the initial water filling of the reservoir.

Reservoir sediments (above 199.5 cm) reflect cyclic changes in both TOC and MS. These usually show negative correlations because higher organic carbon content implies a low energy sedimentary environment allowing deposition of fine-grained organic material. Conversely, larger and heavier ferromagnetic minerals are eroded and transported primarily during higher discharge events and deposited during more dynamic conditions. Variations in TOC and MS content are principally related to the discharge changes throughout the reservoir history. Large flood events or reservoir level drawdowns can be especially important.

MS can also be used for identification of the reservoir accumulation zone (Shotbolt et al. 2005). The zone is characterised by fine sediment deposited under low-energy conditions with no reworking and continuous stable sedimentation. The replicability of magnetic characteristics of core profiles was often used to identify this zone (Blais and Kalff 1995). There is visual similarity of the MS profiles of the studied core with published MS profiles from cores drilled approximately 1 km down in the studied (Sedláček and Bábek 2009), which further confirms that coring site was located in the accumulation zone.

Hydrology

Depositional rates in artificial lakes are generally proportional to rainfall intensities (Kashiwaya et al. 1997). The highest fluvial discharge of the Svratka

River at the gauging station Veverská Bítýška during the studied 68-year period was 240 $m^3 s^{-1}$ (March 10, 1941). Variations in fluvial discharges can be used to evaluate the significance of floods for the reservoir infill. Analysed data from the 68-year period of the dam history are presented in Table 1.

Significant differences between the maximum and average fluvial discharge favour variations in volume and grain size of transported material being successively deposited within the reservoir. This also affects the other proxy data, such as TOC, MS and concentrations of radionuclides originating from atmospheric deposition within the sedimentary sequence. Furthermore, strong seasonal variabilities are expected to result from the noticeable differences in discharge between the late winter/spring and autumn periods. These differences are typical for rivers with their upper catchment reaches in a humid climate. Here the maximum discharges mostly appear during the longer periods following snow melting (mostly in the period from February to April) and in some short periods following summer thunderstorm events with higher precipitation rates (from June to July). During autumn (October to November), the reduced discharge connected with lower precipitation prevails in Central Europe.

Fluctuating water levels represent serious limitation for continuous deposition in the reservoirs and impact on the sedimentary record. Moreover, changes in the location of the water's edge effectively extend and change the area of sediment exposed to redistributing processes. The extent and frequency of drawdown during the last 43 years (i.e. 1965–2008) can be followed according to data from the Povodí Moravy state enterprise. Annual water-level fluctuations are approximately 3–4 m, and only 5 fluctuations of approximately 5 m were recognised during this period, with the minimum measured level at

Table 1 Maximum fluvial discharges (Qmax.) during the studied years and their return value (*T*)

Year	Qmax. [m^3/s]	*T*	Year	Qmax. [m^3/s]	*T*	Year	Qmax. [m^3/s]	*T*
1939	69.90	2.42	1962	116.00	5.07	1985	123.00	5.93
1940	126.00	6.49	1963	20.60	1.06	1986	108.00	4.16
1941	240.00	100.12	1964	23.40	1.11	1987	105.00	3.71
1942	47.00	1.52	1965	55.40	1.75	1988	91.20	3.2
1943	27.40	1.14	1966	56.20	1.84	1989	58.90	2.06
1944	75.20	2.6	1967	50.30	1.59	1990	22.10	1.09
1945	134.00	7.98	1968	40.00	1.29	1991	18.10	1.01
1946	170.00	25.77	1969	74.60	2.51	1992	63.00	10.37
1947	169.00	18.79	1970	55.00	1.71	1993	61.50	2.26
1948	100.00	3.52	1971	38.30	1.25	1994	53.80	1.66
1949	43.70	1.37	1972	37.00	1.22	1995	59.10	2.12
1950	44.60	1.4	1973	18.10	1.03	1996	55.60	1.79
1951	51.20	1.63	1974	42.10	1.34	1997	115.00	4.72
1952	49.00	1.55	1975	59.50	2.19	1998	78.40	2.81
1953	106.00	3.92	1976	85.50	1.26	1999	110.00	4.42
1954	42.00	1.32	1977	140.00	12.19	2000	91.20	3.35
1955	121.00	5.47	1978	30.10	1.16	2001	21.70	1.07
1956	128.00	7.16	1979	82.00	2.93	2002	56.90	1.89
1957	57.00	1.94	1980	46.20	1.49	2003	135.00	9.02
1958	24.40	1.125	1981	148.00	14.79	2004	58.00	2
1959	18.40	1.04	1982	76.20	2.7	2005	137.00	10.37
1960	39.00	1.27	1983	46.00	1.46	2006	192.00	40.98
1961	35.40	1.18	1984	45.30	1.43	2007	36.60	1.2

T—return value

222.3 m a.s.l. Our coring site was located at 220.5 ± 0.5 m a.s.l., ~2.5 m below the constant reservoir water level (i.e. 223.1 m a.s.l.). The reservoir water-level fluctuation data shows that this coring site was first subaerially exposed during the 2007/8 winter and spring, when the water was released more than 5 m below the constant reservoir level.

Results of the grain size and MS study reveal that water-level fluctuations did not result in significant disturbances of studied deposits. Although drawdowns could sometimes have affected the coring site, no significant role of marginal and shallow water processes (wave action, rain splash and slope slaps) and redistribution of coarse material into the basin was recognised in the core. For much of the drawdown periods, there could only have been low and predominantly fine inputs of sediment to the submerged area where the coring site was located. An important role in such a limited redistribution of material from the studied position might be played by the time of the drawdown period (usually winter) and cohesiveness of bottom sediment, which limited erosion.

Radiometric dating and depositional rates

Trace concentrations of ^{137}Cs have been detected down to a sediment depth of 165 cm. The depth distribution of this anthropogenic radionuclide shows two marked peaks (Fig. 3). These can be unambiguously attributed to deposition of ^{137}Cs from the weapons testing fallout maximum in 1963 (at the 142.5–145.0-cm depth) and from the Chernobyl reactor accident in 1986 (at the 65.0–67.5-cm depth), respectively. From these peaks, mean depositional rates of 3.2 cm year^{-1} for the time period of 1986–2007 and of 3.4 cm year^{-1} between 1963 and 1986 are calculated. These results indicate that the sedimentation regime has been almost constant for the last 45 years. From the change in the sediment composition at 218.5 cm, which reflects the known start of reservoir filling in 1939, we can calculate a mean sedimentation rate of 3.1 cm year^{-1} for the time period of 1939–1963.

In general, the concentrations of ^{238}U show higher values in the upper half of the analysed core than below, with a marked peak at the 130.0–132.5-cm layer. Using the ^{137}Cs chronology, this layer corresponds to the year 1967 (Fig. 3). Such a peak is also present for ^{226}Ra at the same position, but no concentration increase was measured for ^{228}Ra (Fig. 3). This suggests uranium-mining residues as a likely source of increased radionuclide concentrations at the 130–140-cm depth because such material is commonly enriched in ^{238}U and ^{226}Ra, but not in ^{228}Ra, a member of the ^{232}Th decay chain. This interpretation is supported by the results of a Spearman's rank correlation test, which showed no significant association of the concentration of ^{228}Ra and ^{238}U within the analysed sediment core (one-sided, $r_s = -0.077$, $p \gg 0.05$).

Concentrations of unsupported ^{210}Pb are highly scattered, showing almost no relationship with sediment depth (Fig. 3). Spearman rank correlation tests result in highly significant associations of the ^{238}U concentrations within the analysed core with both total and unsupported ^{210}Pb (one-sided, $p < 0.001$, with $r_s = 0.854$ for total and $r_s = 0.675$ for unsupported ^{210}Pb). This finding indicates that the major source of both ^{210}Pb fractions is material enriched in uranium and its decay products and not deposition from the atmosphere. This conclusion is supported by the fact that like ^{238}U and ^{226}Ra, both ^{210}Pb fractions show marked peak concentrations in the 130.0–132.5-cm layer.

The CRS model available for depth-to-age conversion of unsupported ^{210}Pb showing a non-exponential decline with depth within a sediment core is based on a time-invariant flux density of this tracer radionuclide across the water–sediment interface. This assumption, which has been validated for ^{210}Pb deposited annually from the atmosphere (Turekhian et al. 1977; Rangarajan et al. 1986), becomes highly questionable if the dominating source of unsupported ^{210}Pb in the sediment is likely to be uranium ore mining residues. Because the CRS model erroneously converts variations in time of the flux density of unsupported ^{210}Pb into the sediment into variations in sedimentation rates, ^{210}Pb concentrations in the Brno reservoir sediment cannot be applied for establishing a geochronology.

For the uranium decay chain members (^{238}U, ^{226}Ra and total ^{210}Pb), but not for ^{228}Ra, there is a pronounced step increase in concentrations above the ~210-cm depth, followed by another less pronounced increase above the ~150-cm depth (Fig. 3).

In the upper part of the Svratka River catchment, underground uranium ore mining commenced in

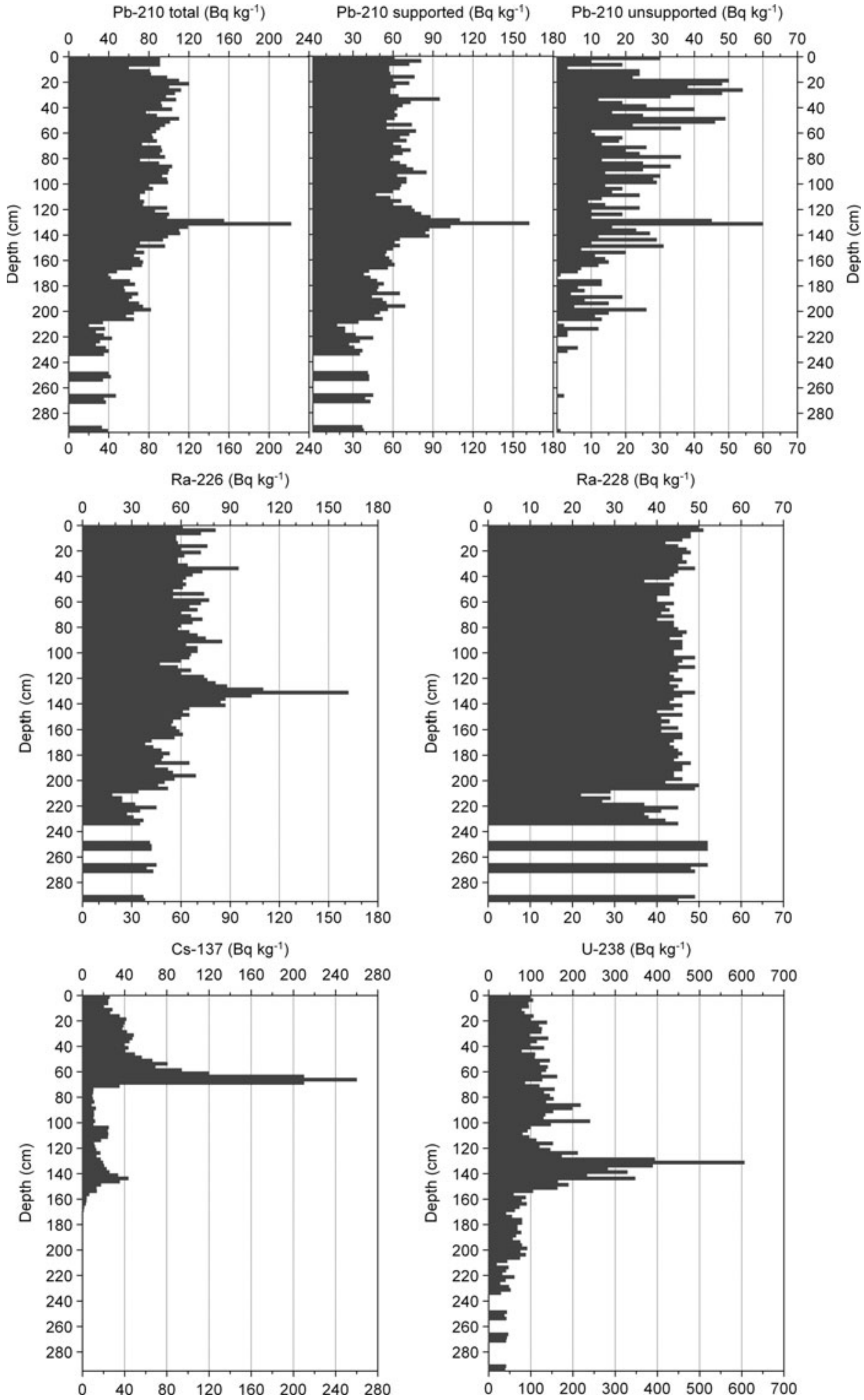

Fig. 3 Activity concentrations of the radionuclides of interest in the sedimentary profile. For ^{210}Pb, the supported and unsupported fractions are displayed separately. Uncertainties are usually <20%

1957 (ore deposit Rožná) and in 1959 (ore deposit Olší), producing extensive amounts of pit tips and pit waters. Based on our ^{137}Cs-based geochronology, the increase of ^{238}U, ^{226}Ra and ^{210}Pb at the ~150-cm depth corresponds to the years 1960 and 1961, which is in excellent agreement with the initiation of these industrial activities. The increase of these radionuclides at ~210 cm is likely to reflect changes of the watershed flow regime caused by the reservoir dam construction.

According to the Czech Hydrometeorological Institute, enhanced discharge in late winter 1966/67 caused a major redistribution of pit tips in the upper reach of the Svratka River catchment. This event is reflected in the marked peak of ^{238}U and its decay products in the 130.0–132.5-cm layer. Its ^{137}Cs-derived age shows exact correspondence.

Discussion

Detailed stratigraphic analysis has enabled us to track the sedimentary history of the reservoir infill in detail and to postulate the processes involved in this deposition. Sedimentation rates in reservoirs vary greatly. Phillips and Nelson (1981) described the average sedimentation rate of the artificial Lake Matahina at approximately 20 mm year^{-1}. Similarly Mulholland and Elwood (1982) suggested an average sedimentation rate for reservoirs of around 20 mm year^{-1}. Van Metre et al. (2001) found sedimentation rates in eight US reservoirs to vary between 6 and 66 mm year^{-1}, and Shotbolt et al. (2005) declared that the average sedimentation rate for UK reservoirs lies between 3 and 54 mm year^{-1}. Our analysis shows that the sedimentation rate was relatively high in the case studied here. A higher sedimentation rate limits the time that sediment spends at the reactive sediment–water interface.

Our study is based on a single core, so it cannot represent the sedimentation rate for the entire reservoir basin, but our results proved that the recorded sedimentary processes reflect deposition in an accumulation zone (Shotbolt et al. 2005) and, thus, sediments from the upper part of reservoirs with high trap efficiency potential can also produce valuable information. Mean depositional rates of 3.2 cm year^{-1} for the time period of 1986–2007 and of 3.4 cm year^{-1} between 1963 and 1986 were calculated. The step increase of ^{238}U, ^{226}Ra and ^{210}Pb above the 210-cm depth likely reflects reservoir completion and water filling (1940–1941). This could result from adsorption of the radionuclides to suspended organic material because TOC shows a parallel increase (Fig. 2). However, the almost unchanged concentrations of ^{228}Ra (and thus ^{232}Th) in the sediment indicate that an increased transport of uranium-rich minerals by the watershed and into the reservoir is likely to be of higher importance.

Although the sedimentation rates in the Brno reservoirs were relatively stable during the last 68 years, some slightly enhanced and decreased rates can be observed. Variations in depositional rate are primarily affected by fluctuations in sediment supply. According to Kashiwaya et al. (1997), the depositional rate in the reservoirs is roughly proportional to the rainfall intensity. Precipitation is related to surface erosion and sediment transport, although this relationship is obliterated by other factors, such as erodibility of the surface material, geology and geomorphology of the catchment area, precipitation season, etc. Depending on the energy of the floodwater, the reservoir sediments can be eroded as well as deposited. Floods are often the most dominant sediment contributor to the reservoirs (Zhang et al. 1998). A higher sedimentation rate can be connected with a greater role of stratified flows during the floods, whereas non-stratified flows dominate under normal flow conditions (Shotbolt et al. 2005). Therefore, the flood events are recorded not only from the changes of sediment type, but also from changes in depositional rate. Occurrence of thin sandy interlayers and sand admixture within the predominantly silty deposits of the reservoir in the studied profile (depths of 101–116.5 and 169–180 cm) could point to higher fluvial discharge during the flooding periods.

Maximum fluvial discharge can be used for evaluation of the significance of flooding for reservoir infill. Depositional rates of the studied reservoir deposits can be compared with periods of higher fluvial discharge of the Svratka River. The highest occurrence of pronounced flood events (i.e. >5-years water) was documented for the period from 1939 to 1963, and this period exhibits a slightly lower depositional rate. The highest depositional rate was observed for the time period 1963–1986, which is the period with the lowest occurrence of pronounced floods (Table 2). Gasiorowski and Hercman (2005) showed that the proximity to the major river channel and a position close to the mean water level are most suitable for the direct recording of the flood events. The inverse relationship of the depositional rate and the occurrence of pronounced floods further confirms that sediments in the studied core were not affected by redepositional processes and reflect a uniform

Table 2 Occurrence of pronounced flood events (i.e. >5-years water discharges) in the Svratka River gauging station Veverská Bítýška (immediately above the Brno reservoir) during the time period 1939–2006

Period	>20 years water	>10 years water	>5 years water	>3 years water	Average Q(max) m^3/s
1939–1963	2	1	5	2	82.2
1963–1986		2	1		64.4
1986–2006	1	1	2	5	77.0

sedimentary accumulation zone of the reservoir. Major floods may erode reservoir floors and generate sedimentary unconformities in some reservoirs (Haag et al. 2001). Such unconformities were not recognised in the studied core, and the higher depositional rate during the initial period of reservoir infill is supposedly due, in general, to an increase of accommodation space connected with the rise in the reservoir water level. The formation of available accommodation space was stable in later periods, and the depositional rate declined compared to the initial period. It can be speculated that the slightly lower mean depositional rate during the period of 1939–1963 could reflect some erosion events of reservoir deposits, possibly during the high 1962 discharge connected with the late-spring flood.

Identification of periods with high fluvial discharges/floods within the sedimentary record is a tentative problem. Such a speculative interpretation of the studied deposits is presented in Fig. 4. The sedimentary record was subdivided into the main above-mentioned periods based on radiometric dating, and individual years were selected according to the depositional rate calculated for each period. The curve of the maximum fluvial discharge was drawn for the 68-year period. Points with low levels of TOC and high levels of MS were detected within the sedimentary record and compared with higher fluvial discharges/floods. This approach allows us to deduce that approximately 15 floods can be recognised within the sedimentary record. It was found that 3–5-years water discharges are sufficient to affect the TOC and MS record. Moreover, the timing of the floods during the year plays an important role because only winter and early spring flooding events were identified in the sedimentary record. It should be stressed that, during the first period of reservoir infill, important floods (3–5-years water) occurred during the winter (February to early March). Since the mid 1980s, spring to summer floods have become more common.

Although the coring site was located in the upper part of the reservoir, the sedimentary record represents the accumulating zone (almost uniform fine grained deposits that are spatially consistent over a reasonable area with no major reworking of material and no admixture of coarse grains), which is representative of most of the reservoir showing an uninterrupted depositional record. Sediment input during water drawdowns is generally coarser, but fine sediments could be re-entrained at the margins during prolonged drawdown periods (Shotbolt et al. 2005). Such a situation could be identified by the increase in sedimentation rate. Our observation of no significant disturbances in the deposition rate confirm the consistency of sedimentation in the studied case. However, the occurrence of thin sandy interlayers and sand admixture within silts at depths of 101–116.5 cm in the studied profile could point to some role of fluctuation of the water level. This interval corresponds to the years 1969–1973 based on the ^{137}Cs geochronology. Two significant decreases of the water level of approximately 5 m were recorded during these years, and these years were generally dry in the Svratka River catchment with only low-level discharges (Fig. 4). The same is true for the sandy interlayer at depths of 169–180 cm, which must have been deposited during the drier years between 1948 and 1952 without any high-level discharge events. Despite fluctuations in water levels, the studied core contains undisturbed and consistently deposited sediments. The water-level fluctuations were not a very efficient agent for initiation of the redistribution of sediment. Although sedimentation rates were not entirely consistent, these variations did not significantly affect the usefulness of the sediment records because the majority of sediment was deposited under low energy conditions, and zones of atypical sediment influx were very rare, very thin and identifiable (Shotbolt et al. 2006).

Sediment is assumed to be deposited continuously and consistently throughout the year. In reality, the

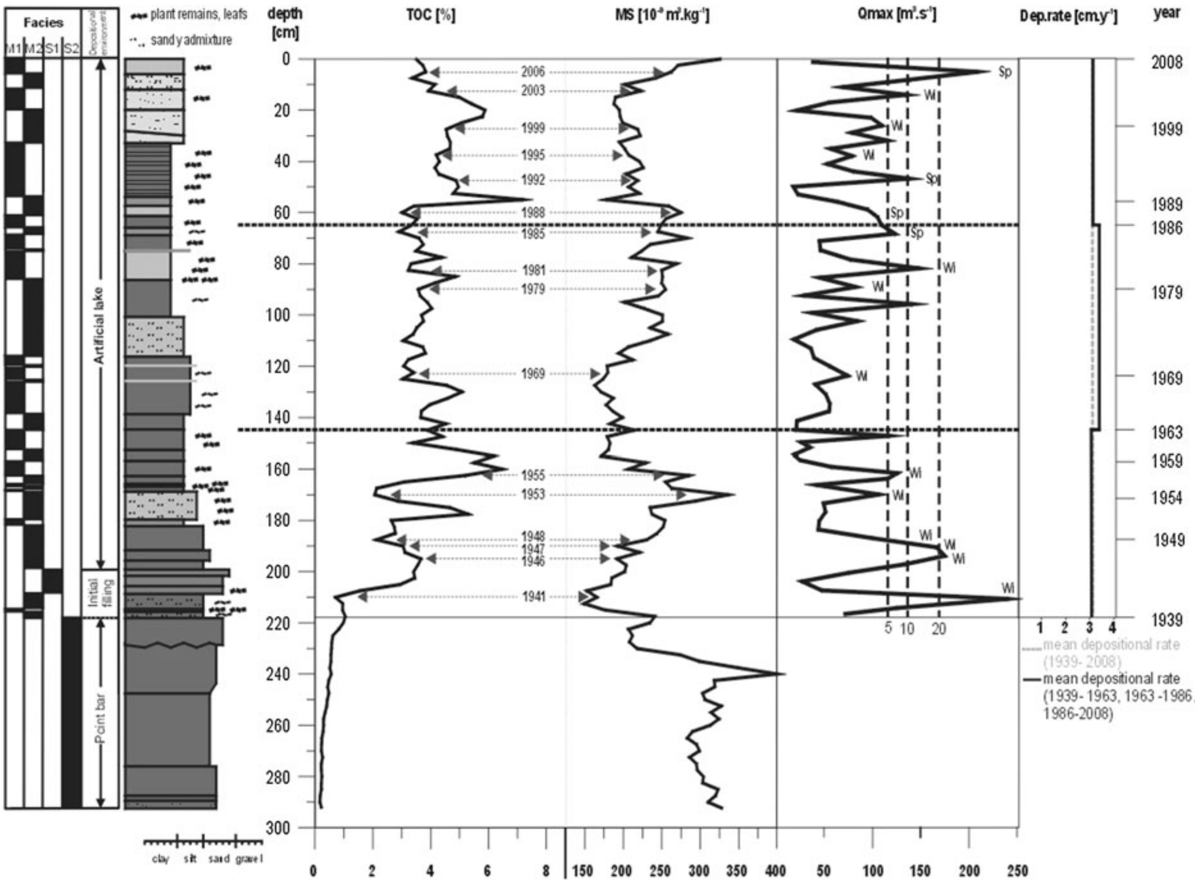

Fig. 4 Lithological profile of the studied core, facies distribution, total organic carbon (TOC) content, magnetic susceptibility (MS) value, maximum annual discharges (Qmax.), with indication of n-year water for the x-axis and the flood season (*Wi* winter, *Sp* spring) and possible correlation of the flood record with TOC and MS. The average depositional rate for the complete reservoir infill (1939–2007) and the mean depositional rate for the identified time periods (1939–1963, 1963–1986, and 1986–2007) are shown. *Thick dashed lines* represent ^{137}Cs-based time markers

sedimentary record is an amalgamation of deposits under different energy conditions and will contain particles of different size that are deposited at different rates during particular seasons of the year (Shotbolt et al. 2006).

With regard to radiometric dating, the sediment core that we analysed in this study has been found to be exceptional for two reasons. First, excess ^{210}Pb originates mainly from ^{210}Pb present in the watershed area from natural and industrial sources. Applicability of this radionuclide for dating recent sediments is, therefore, limited. Second, in areas with comparatively high uranium content in rocks and soils, changes in both the watershed flow regime and industrial mining activities influence the concentrations of ^{238}U and its long-lived decay products. Elevated concentrations of ^{238}U, ^{226}Ra and ^{210}Pb originating from uranium ore mining and milling were also observed in fluvial sediments in south-eastern Germany (Hoppe et al. 1996; Michel et al. 2005) and could be related to documented events (failure of the dam of a sedimentation pond, high water, termination of industrial activities). This finding confirms that such events may serve as time markers, which should be used to validate a ^{137}Cs-based geochronology.

Although uranium emissions into the watershed decreased after the initiation of a uranium dressing plant in Dolní Rožínka in 1968 (Křibek and Hájek 2005) and after the conclusion of mining activities at Olší in 1989, ^{238}U in the analysed sediment decreased only gradually during the last 40 years. This reflects both the elevated concentrations of this radionuclide and its decay products in the watershed and the impacts of the Rožná mine, which is still in operation.

Conclusions

Modern deposits of the Brno reservoir were studied in detail with the aim of reconstructing the sedimentary history of the reservoir and identifying of processes involved in deposition there.

The studied sedimentary succession can be subdivided into two main units. The lower unit, interpreted as a fluvial succession deposited before the Svratka River was dammed, is formed predominantly by medium- to coarse-grained silty sands that are usually poorly sorted with some admixture of granules and reduced occurrence of plant detritus. Sandy silt laminae with abundant plant detritus are locally intercalated in sands. This fluvial unit can be subdivided into two subunits. The lower subunit is interpreted as a product of lateral accretion of the point bar. The upper subunit was deposited in response to the beginning of reservoir filling and the possible impact of the several flood events during the years of 1939–1941. The upper unit of succession consists of brownish, grey to greenish planar laminated silts and rarely clayey or sandy silts. Thin sandy interlayers and sand admixture occur especially in the lower part of the upper unit. Planar lamination is connected with alternation of slightly coarser and lighter laminae and those that are relatively finer grained and darker (with higher content of organic matter). The upper unit is interpreted as reservoir sediments. Reservoir sediments reflect cyclic changes in both TOC and MS, which are usually negatively correlated.

Mean depositional rates of 3.2 cm year^{-1} for the time period from 1986 to 2007 and 3.4 cm year^{-1} between 1963 and 1986 were calculated. Based on the known age of the reservoir, which was constructed in 1939, the mean depositional rate was also calculated for the time period from 1939 to 1963, which is 3.1 cm year^{-1}. These results indicate that the sedimentation regime has been almost constant for the 68 years of the Brno reservoir's existence.

This study documents an environmental situation that precludes using only ^{210}Pb for sediment dating. Its main source here is ^{210}Pb present naturally in the catchment and from uranium mining activities. Because flux rates into the sediment are not time-invariant and depend on surface water runoff, application of the CRS model for depth-to-age conversion of excess ^{210}Pb is not possible.

Elevated concentrations of ^{238}U, ^{226}Ra and ^{210}Pb in the sediment core can be identified with particular events that are likely to have mobilised these radionuclides (completion of the reservoir, initiation of mining, enhanced fluvial discharge). These time markers can be used to validate the ^{137}Cs-derived chronology and to extend the geochronology back to the time of Brno reservoir construction in 1939. Therefore, when studies show uranium-rich minerals in sediments, we recommend that investigators determine whether specific human activities are responsible for elevated radionuclide concentrations because that information might prove helpful for establishing sediment chronologies.

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