ESTIMATING RECENT SEDIMENTATION RATES USING $^{210}$Pb ON THE EXAMPLE OF MORPHOLOGICALLY COMPLEX LAKE (UPPER LAKE RADUŃSKIE, N POLAND)

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Abstract: Upper Lake Raduńskie is a classical channel lake with a typical complexity of lake basin morphology. This study presents the results of $^{210}$Pb measurements in four cores of recent sediments taken from different parts of the lake. The unsupported $^{210}$Pb activity plotted on a logarithmic scale against the cumulative dry mass decreased almost linearly. Sedimentation rates were determined from the mean slope of the profile (CF:CS model). A diversity of calculated values was significant, the highest value was found in the core RAD02/6 located in the deepest part of the lake. Both $^{210}$Pb inventories and fluxes were higher than that expected from atmospheric fallout estimated for this part of Europe. Factors influencing differences between atmospheric fallout and sediment record may include inputs from the catchment and sediment focusing, which seems to be the main reason of sedimentation rates diversity in morphologically complex lakes.

1. INTRODUCTION

Investigating the process of recent sedimentation in water reservoirs is very significant as the sedimentation rate is one of the most important parameters of lake’s dynamics. An analysis of changes of sediment properties in representative cores must be preceded by an identification of sedimentation conditions which considerably influence the spatial diversity of sediment sequences. The rate and character of accumulated sediments are conditioned by various factors of natural and anthropogenic origin. In morphologically complex reservoirs the crucial role may be played by the lake basin morphology determining direct conditions of sediments deposition. The layout of lake basin determine the occurrence of sediment erosion, transportation and accumulation zones (Håkanson and Jansson, 2002), which is of crucial importance to the variability of sedimentation rates in different parts of the reservoir. An estimation of the value of these differences is possible thanks to dating the youngest sediments using radiisotopic methods of which the most often used and regarded as the most reliable one is $^{210}$Pb method (Smith, 2001). Also in literature concerning the Polish territory the use of this method is becoming increasingly popular, which is manifested in a growing number of papers (Goslar et al., 2000; Kotarba et al., 2002; Tylmann and Bia³kowski, 2002; Gsiorkowski and Hercman, 2003; Sikorski and Bluszcz, 2003; Tylmann, 2003). Theoretical basis for the use of this method have been described in detail many times (Robbins and Edgington, 1975; Krishnaswamy and Lal, 1978; Oldfield and Appleby, 1984; Appleby, 1998; Appleby, 2001) and will not be the subject of consideration here. The aim of this paper is the determination of the variability of sedimentation rate in four cores from Upper Lake Raduńskie and a discussion of its possible reasons.

2. STUDY SITE

As the study site was chosen Upper Lake Raduńskie situated in northern Poland ($17^\circ58'\ E,\ 54^\circ14'\ N$), in the central part of Kashubian Lakeland. It is a typical channel lake of considerable depth and complex morphology. The area of the lake is 387.2 ha, maximum depth 43 m
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and mean depth 15.5 m. The complex morphology of the bottom (Fig. 1) theoretically causes a high variety of sedimentation conditions within the basin, which should be reflected in sedimentation rate. The lake has been for several tens of years the subject of thorough investigations and the state of knowledge is in many areas very good. Also in the scope of bottom sediments investigations there were performed detailed works covering the full sequence of sediments (Gołębiowski, 1976), as well as the recent sediments (Jakubowska et al., 2003). One core of recent sediments was also dated by $^{210}$Pb (Gołębiowski et al., 2001).

3. METHODS

Coring sites were situated in morphologically different places within the lake basin (Fig. 1) in order to demonstrate the variability of sedimentation conditions. The chosen areas are: flat parts of the bottom at various depths (RAD02/1 and RAD02/4), the deepest site (RAD02/6) and slight flattening of the slope opposite the mouth of the main tributary – the Borucinka river (RAD02/3). The cores of recent sediments of thickness from 33 to 56 cm were taken using gravity corer with a 94 mm inner diameter Plexiglas core tube. Then the cores were subsampled at 1 cm sequences. Tightly packed samples were transported to the laboratory and stored in 4°C till the analyses.

The dating of sediments by $^{210}$Pb method was performed in the Department of Marine Chemistry and Biochemistry of the Institute of Oceanology of the Polish Academy of Sciences. $^{210}$Pb was determined indirectly by measuring $^{210}$Po using α-spectrometry method. $^{209}$Po as an internal standard was added to the samples of dried sediment (0.2g) and then each sample was digested in conc. HF and HClO4. After acid digestion $^{210}$Po was spontaneously deposited for four hours on a silver disc which was then placed in α-counter for 24 hours. Alpha activity was measured using multichannel analyser TRISTAN 1024 (Polon) with surface-barrier Si detector (Canberra) and 570/Genie-200 Alpha Analyst with Si PIPS detector (Canberra).

4. RESULTS

The taken sediments belonged to mineral and carbonate gyttjas of dark brownish and dark grey colour. The organic matter content did not exceed 25%. Detailed results of analyses were presented by Jakubowska et al. (2003).

Unsupported $^{210}$Pb was determined on the basis of the distribution of total $^{210}$Pb (Fig. 2) by subtracting the values obtained in lower segments of the cores regarded as supported $^{210}$Pb. The value of supported $^{210}$Pb for all the cores was determined as 8 Bq kg$^{-1}$. The supported $^{210}$Pb was determined in core RAD02/1 at depth 45 cm, in core RAD02/3 – 49 cm, and in core RAD02/4 – 33 cm. Difficulties occurred in core RAD02/6 in which the highest activity in the whole profile was recorded. The thickness of the core (34 cm) appeared to be insufficient for fixing the value on a stable level. Moreover, $^{210}$Pb activity in the basal zone of the core (102 Bq kg$^{-1}$) considerably exceeds the supported $^{210}$Pb, which suggests a much greater scope.

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**Fig. 1.** Morphology of lake basin (after Okulanis 1966, simplified) and location of coring sites; A – bathymetric chart, B – average slope of bottom
of unsupported $^{210}$Pb. Unfortunately, taking a longer core appeared to be impossible due to technical problems connected with the considerable depth in the site (43 m). The activity of supported $^{210}$Pb was thus extrapolated from the other cores.

Activity of unsupported $^{210}$Pb decreases with depth in all the cores. Irregularities or even values were observed only in surface layers. Despite these irregularities the activity of unsupported $^{210}$Pb activity plotted on a logarithmic scale decreased with depth expressed as cumulative dry mass almost linearly (Fig. 3), and the estimated exponential equations explain 86-98% of variances. Thus it may be stated that the assumptions of CF:CS model (Oldfield and Appleby, 1984) are fulfilled and activity of $^{210}$Pb in sediments changes with cumulative dry mass (m) according to the formula:

$$C(m) = C_0 e^{-\lambda m / r}$$

where:
- $C_0$ – activity of $^{210}$Pb on the surface of sediment;
- $\lambda$ – $^{210}$Pb radioactive decay constant (0.03114 y$^{-1}$);
- r – sedimentation rate (g cm$^{-2}$ y$^{-1}$).

If the unsupported $^{210}$Pb activity is plotted on a logarithmic scale against the cumulative dry mass, the resulting $^{210}$Pb profile will be linear, with slope $-\lambda / r$. Mean sedimentation rate can be determined from the slope of the profile using a least-squares fit procedure.

Values calculated in this way are presented in Table 1. The variability of obtained values is considerable and ranges between 0.21 and 1.28 cm yr$^{-1}$ (0.055 - 0.211 g cm$^{-2}$ yr$^{-1}$). The calculated sedimentation rate in cores RAD02/1 and RAD02/4 was similar. A clearly higher value was calculated for core RAD02/3, and the definitely highest value was recorded in core RAD02/6 situated in the deepest part of the lake.

The most characteristic flattening of $^{210}$Pb profile in surface layers covering about 25% of the profile was recorded in core RAD02/3. Such significant disturbances of the $^{210}$Pb distribution may introduce an error into the calculated values. Thus it was decided to calculate the sedimentation rate in this core using only this part of the profile which shows a continuous decrease in activity with depth (13-45 cm). The obtained value was by 20-30% lower than the ones calculated on the basis of the whole profile.

On the basis of measured activities, the inventory and flux of unsupported lead was also calculated in all the cores, using the following formulae:

$$A_\Sigma = \sum_{i=1}^{\infty} m_i C_i$$

and:

$$^{210}\text{Pb}_{\text{flux}} = \lambda A_\Sigma$$

where:
- $A_\Sigma$ – unsupported $^{210}$Pb inventory in core;
- $m_i$ – mass depth (g cm$^{-2}$) of a given layer;
- $C_i$ – activity of unsupported $^{210}$Pb in a given layer;
- $\lambda$ – $^{210}$Pb radioactive decay constant (0.03114 y$^{-1}$).

The results of calculations are presented in Tab. 1. It should be emphasised that the values for core RAD02/6 are estimates as the taken core did not have a sufficient thickness. Yet, due to the fact that in the basal zone the activity of $^{210}$Pb falls substantially, it may be assumed that the great majority of unsupported lead was recorded and the error of calculations should not be significant. Similarly as in the case of sedimentation rate, close values of inventory and flux were obtained in cores RAD02/1 and RAD02/4, much higher in core RAD02/3 and definitely the highest in core RAD02/6.

Fig. 2. Specific activity of total $^{210}$Pb in analysed cores
5. DISCUSSION

The comparison of the sedimentation rates and other calculated parameters make it possible to identify the processes that may influence sedimentation dynamics in the study lake. Using the CF:CS model it was assumed that the sedimentation rate in individual cores was constant. This assumption was made on the basis of the distributions of unsupported $^{210}\text{Pb}$ which showed an almost linear course. Insignificant bends of tendency were recorded only in surface layers of the sediments. Similar facts are observed very often and explained usually as an effect of acceleration in sedimentation rate or mixing of sediments due to physical processes and bioturbation (Jones and Bowser, 1978). Another reason may be remobilisation of $^{210}\text{Pb}$ as a result of changes of oxygen conditions (Benoit and Hemond, 1991). More significant irregularities were recorded in core RAD02/3 located on a slope, which suggests a possibility of sediment displacement as a reason for the disturbances. It was observed that in the case of a considerable flattening of the profile in surface layers, the sedimentation rate calculated on the basis of complete profiles may be considerably overestimated with regard to the calculations based on parts of the profile characterised by a stable decrease in $^{210}\text{Pb}$ activity (Tab. 1). The latter values, based on the profiles excluding mixing zone, seem to be much more reliable.

Some information may be acquired from the analysis of $^{210}\text{Pb}$ inventory and fluxes calculated on this basis. Theoretically, the flux should be close to the value of atmospheric fallout coming from the decay of $^{222}\text{Rn}$ which in a longer period is constant for a given site. However, the spatial diversity of the fallout resulting from the geographical location and rainfall may be very high. The problem is that systematic measurements of the $^{210}\text{Pb}$ fallout are performed in very few sites. Thus there arises the necessity to extrapolate the value of fallout on the basis of a strong correlation with the precipitation level. On the basis of literature (Appleby, 2001) it may be assumed that the mean atmospheric $^{210}\text{Pb}$ fallout in northern Poland is about 110 Bq m$^{-2}$ yr$^{-1}$. Values calculated on the basis of the inventory in sediments are higher (Tab. 1), thus the source of the excess must be identified. Apart from fallout, $^{210}\text{Pb}$ may get into the lake together with the inflow from catchment area, while a loss occurs by outflow. Another source of the excess in some parts of the lake may be sediment focusing. According to Appleby (2001) the role of inflow is not very significant for the whole of the reservoir, as the great majority of $^{210}\text{Pb}$ is deposited near the mouths of tributaries. In the case of Upper Lake Raduńskie, emphasising the role of inflow may be risky, as the lake is supplied mainly by underground waters (over 55%), and only in about 36% by surface inflow (Okulanski, 1982). Outflow from the lake should not play an important role either, as the intensity of water exchange is not high. Water retention time is $RT=2.14$ yr (Borowiak, 2003), which indicated a hydrologically passive type of reservoir. The complex morphology of the lake basin suggests that the reason for the high excess of unsupported $^{210}\text{Pb}$ in two of the taken cores (RAD02/3 and RAD02/6) may be sediment focusing. The main causes of the phenomenon are (Crusius and Ander-
6. CONCLUSION

The presented results prove that in morphologically complex lakes there are considerable differences in sedimentation rates in different parts of the lake. The highest values were recorded in the deepest site and opposite the mouth of the main tributary. Several times lower rate was recorded in relatively flat areas of the bottom. The analysis of the calculated unsupported \(^{210}\text{Pb}\) inventories and fluxes as well as morphology of the lake basin suggests that the main cause of these differences may be sediment focusing on steep slopes.

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