GEOCHRONOMETRIA Vol. 23, pp 21-26, 2004 – *Journal on Methods and Applications of Absolute Chronology*

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

WOJCIECH TYLMANN

Department of Geomorphology and Quaternary Geology, Gdańsk University, Dmowskiego 16a, 80-264 Gdańsk, Poland, (e-mail: geowt@univ.gda.pl)

Key words:
SEDIMENTATION RATE,
SEDIMENT FOCUSING,
^{210}Pb, CHANNEL LAKE,
LAKE RADUŃSKIE

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 radioisotopic 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 Białkowski, 2002; Gąsiorowski 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°58´E, 54°14´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 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 (Gołębiewski, 1976), as well as the recent sediments (Jakubowska *et al.*, 2003). One core of recent sediments was also dated by ^{210}Pb (Gołębiewski *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 $HClO_4$. 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 obtained 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

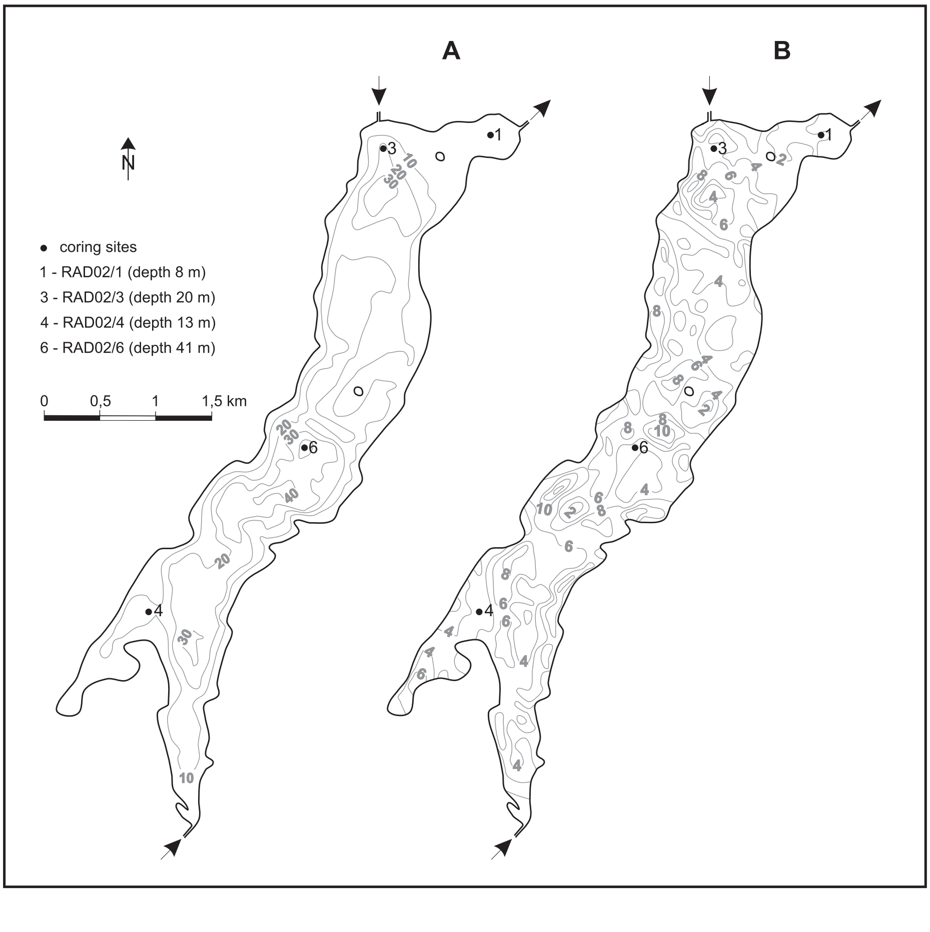

Fig. 1. *Morphology of lake basin (after Okulanis 1966, simplified) and location of coring sites; A – bathymetric chart, B – average slope of bottom*

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:

$$C_{(m)} = C_{(0)} e^{-\lambda m / r} \tag{4.1}$$

where:
$C_{(0)}$ – activity of ^{210}Pb on the surface of sediment;
λ – ^{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 - λ/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:

$$A_{\Sigma} = \sum_{i=l}^{\infty} m_i C_i \tag{4.2}$$

and:

$$^{210}\mathrm{Pb}_{flux} = \lambda A_{\Sigma} \tag{4.3}$$

where:
A_{Σ} –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;
λ – ^{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.

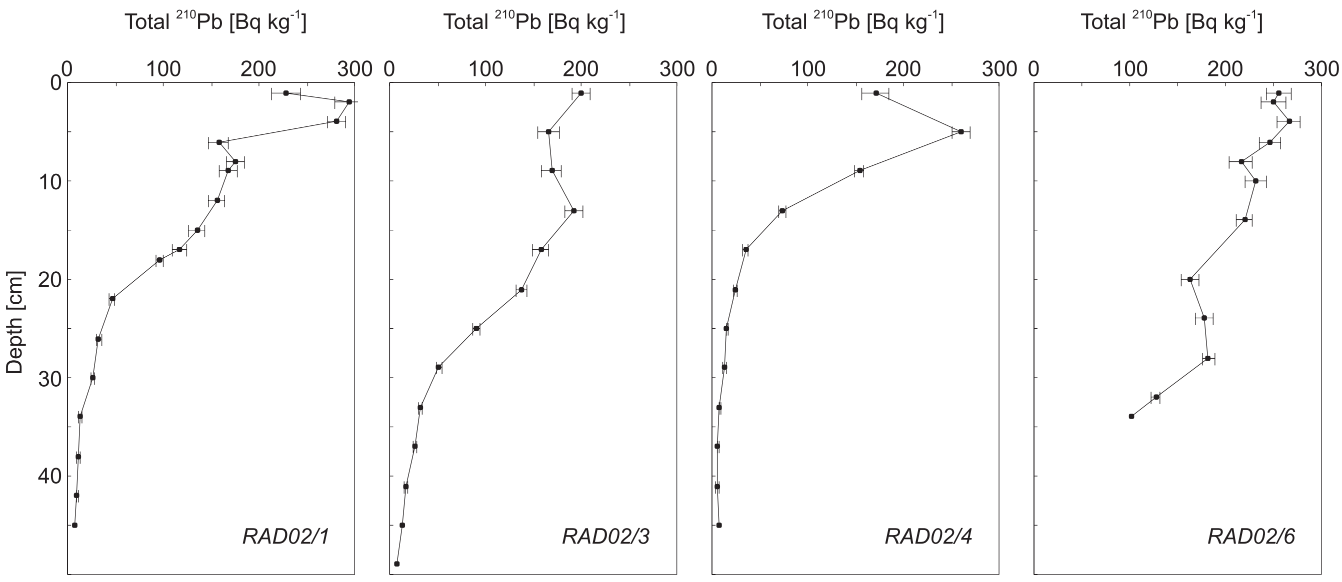

Fig. 2. *Specific activity of total ^{210}Pb in analysed cores*

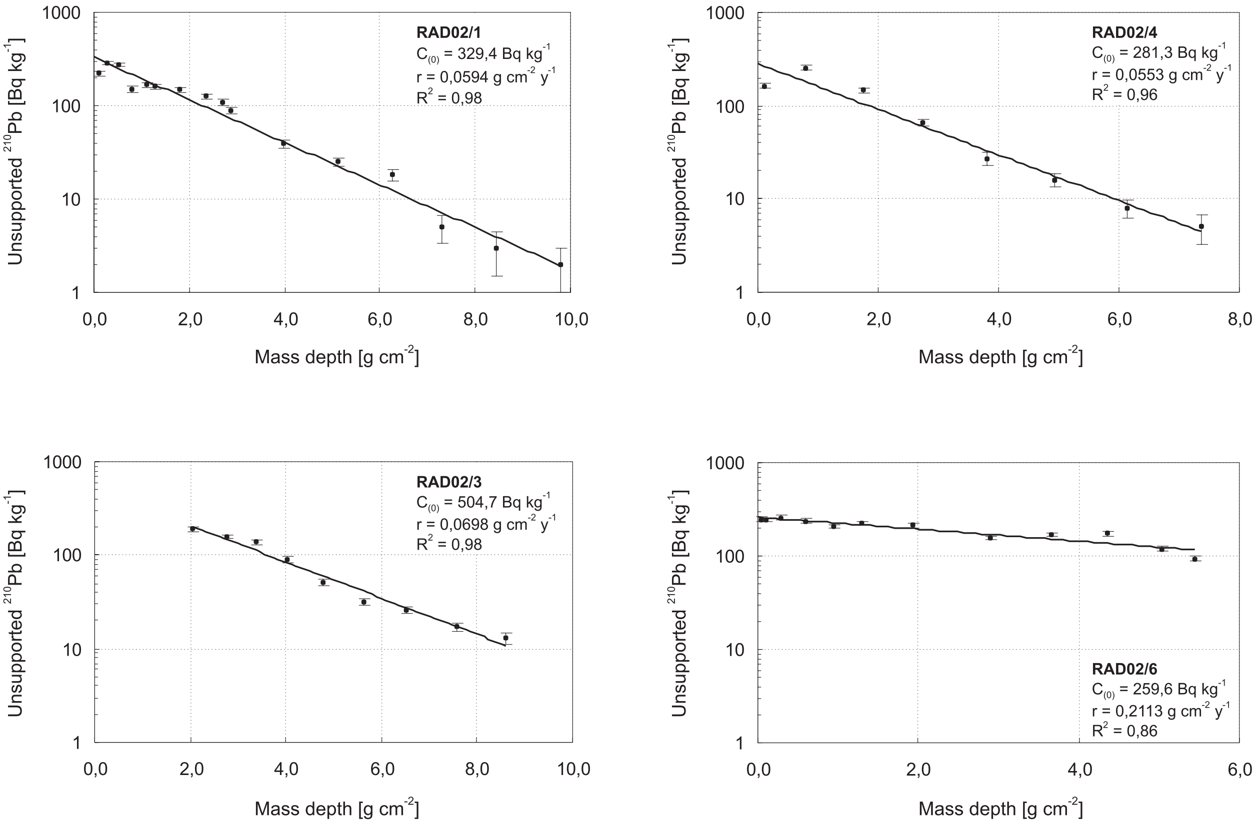

Fig. 3. *Unsupported ^{210}Pb activity versus mass depth and calculated mean sedimentation rate in investigated cores*

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}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}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}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}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}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}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}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}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}Pb is deposited near the mouths of tributaries. In the case of Upper Lake Raduńskie, emphasising the role of inflow from the catchment may be risky, as the lake is supplied mainly by underground waters (over 55%), and only in about 36% by surface inflow (Okulanis, 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}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-

Table 1. Mean sedimentation rates, ^{210}Pb inventories and fluxes

	Sedimentation rate (CF:CS model)		^{210}Pb Inventory	^{210}Pb flux
Core	**(cm yr^{-1})**	**(g cm^{-2} yr^{-1})**	**(Bq m^{-2})**	**(Bq m^{-2} yr^{-1})**
RAD02/1	0.26	0.059	6365 ± 90	198 ± 3
RAD02/3	0.34 (0.47*)	0.070 (0.087*)	7412 ± 227	231 ± 7
RAD02/4	0.21	0.055	5569 ± 304	173 ± 9
RAD02/6	1.28	0.211	≈10039 ± 294	≈313 ± 9

* – values calculated on the basis of the whole profile RAD02/3 including mixing zone.

son, 1995): the occurrence of complete mixing (e.g. spring and autumn mixing), wave action, sediment sliding on steep slopes and random redistribution of sediments. According to Håkanson and Jansson (2002) the accumulation of sediments occurs without disturbances in area of the bottom with slopes less than 4°, in the range 4°-14° sediment focusing takes place with varied intensity, and on slopes greater than 14° accumulation practically does not occur. The comparison of these values with the actual inclination of slopes in the study lake (**Fig. 1**) gives ground to assume that there are favourable conditions for the phenomenon of sediment focusing. Certain indicator of the intensity of sediment focusing may be the Focusing Factor (FF) which is a ratio of the ^{210}Pb flux calculated for a given site to the atmospheric fallout (San Miguel *et al.*, 2003). Sites RAD02/1 and RAD02/4, which from the morphological point of view, are not exposed to intense sediment focusing, show only a slight excess of ^{210}Pb flux and small FF values (1.8 and 1.6) respectively. Higher values of ^{210}Pb flux in site RAD02/3 may be partially explained by inflow from the catchment as well as sediment focusing which may occur on a slope. In core RAD02/6 located in an overdeepening of very steep slopes (up to 11°) FF indicator reaches value 2.8. Such a considerable excess of unsupported ^{210}Pb may indicate intense sediment focusing. This is confirmed by the sedimentation rate which is several times higher in this site (**Tab. 1**).

In the light of the presented results there should be made a reference to the results of dating by ^{210}Pb method from Upper Lake Raduńskie published earlier. A comparison with the results of Gołębiewski *et al.* (2001) shows differences especially in the range of activity. In the surface layers unsupported ^{210}Pb activity was ca. 70 Bq kg^{-1} and the scope of ^{210}Pb into the sediment was only ca. 10 cm, thus the values were much lower than in the core RAD02/4 analysed in this study. As the coring site was very close and similar, in terms of the bottom morphology, it seems unlikely that such differences actually exist. Although it is not easy to directly compare the results between the two studies because of different subsampling strategy, the activity and shape of ^{210}Pb profiles suggests a conclusion that a possible cause of the differences is a loss of a surface part of the sediment (*ca* 10 cm) during coring operations. As a result the core from Gołębiewski *et al.* paper (2001) may be in fact only a part of the core without the surface sediments. The fact emphasises the importance of the proper sediment coring, which, especially in studying the recent sedimentation, is undoubtedly the most important and often the most difficult problem.

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}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.

ACKNOWLEDGMENTS

The author wishes to thank Ania Jakubowska for help in field work and performing ^{210}Pb determinations. I would also like to thank Professor Janusz Pempkowiak (Institute of Oceanology PAS, Sopot) for kind help and critical discussion of results and an anonymous referee whose critical suggestions substantially improved the original version of the manuscript.

REFERENCES

Appleby P.G., 1998: Dating recent sediments by ^{210}Pb: problems and solutions. In: Illus E., ed., Dating of sediments and determination of sedimentation rate. *STUK A-145, Finland*: 7-24.

Appleby P.G., 2001: Chronostratigraphic techniques in recent sediments. In: Last W.M. and Smol J.P., eds, *Tracking Environmental Change Using Lake Sediments. Volume 1 – Basin Analysis, Coring, and Chronological Techniques*. Kluwer: 171-203.

Benoit G. and Hemond H.F., 1991: Evidence for diffusive redistribution of ^{210}Pb in lake sediments. *Geochemica et Cosmochimica Acta* 55: 1963-1975.

Borowiak D., 2003: Influence of horizontal water exchange intensity on epilimnion depth: Case study on Upper Raduńskie Lake. *Limnological Review* 3: 17-24.

Crusius J. and Anderson R.F., 1995: Sediment focusing in six small lakes inferred from radionuclide profiles. *Journal of Paleolimnology* 13: 143-155.

Gąsiorowski M. and Hercman H., 2003: Blaski i cienie datowania osadów metodą ^{210}Pb – kilka przykładów z polskich jezior (Ups and downs of ^{210}Pb dating method - a few examples from Polish lakes), *VII Ogólnopolska Sesja Naukowa Datowanie minerałów i skał*. ING PAN, Warszawa: 25-29 (in Polish).

Gołębiewski R., 1976: *Osady denne Jezior Raduńskich*. (*Bottom sediments of the Raduńskie Lakes*.) GTN, Gdańsk: 90 pp. (in Polish).

Gołębiewski R., Bojanowski R., Tylmann W., Białkowski M., Kępińska U. and Fedorowicz S., 2001: Tempo współczesnej sedymentacji osadów w jeziorach wybranych pojezierzy młodoglacjalnych (Recent sedimentation rates in lakes of the chosen late-glacial lakeland.). In: Karczewski A. and Zwoliński Z., eds, *Funkcjonowanie geoekosystemów w zróżnicowanych warunkach morfoklimatycznych. Monitoring, ochrona, edukacja*. Bogucki Wydawnictwo Naukowe, Poznań: 143-156 (in Polish).

Goslar T., Ganowicz M., Czernik J. and Sikorski J., 2000: First measurements of natural activities of ^{210}Pb in the Institute of Physics, Silesian University of Technology. *Geochronometria* 18: 29-34.

Håkanson L. and Jansson M., 2002: *Principles of Lake Sedimentology*. The Blackburn Press, Caldwell: 316 pp.

Jakubowska A., Tylmann W. and Dworniczak J., 2003: Zmienność współczesnych osadów dennych w zróżnicowanym morfometrycznie jeziorze rynnowym. Wyniki wstępne. (Recent sediments in morphologically complex, channel lake. Preliminary results). In: Gołębiewski R., ed., *Ewolucja Pojezierzy i Pobrzeży Południowobałtyckich*. Katedra Geomorfologii i Geologii Czwartorzędu UG, Gdańsk: 87-93 (in Polish).

Jones B.F. and Bowser C.J., 1978: The Mineralogy and Related Chemistry of Lake Sediments. In: Lerman A., ed., *Lakes. Chemistry, Geology and Physics*. Springer Verlag, New York: 179-235.

Kotarba A., Łokas E. and Wachniew P., 2002: ^{210}Pb dating of young Holocene sediments in high-mountains lakes of the Tatra Mountains. *Geochronometria* 21: 73-77.

Krishnaswamy S. and Lal D., 1978: Radionuclide Limnochronology. In: Lerman A., ed., *Lakes. Chemistry, Geology and Physics*. Springer Verlag, New York: 153-177.

Okulanis E., 1966: Morfologia i batymetria Jezior Raduńskich (Morphology and bathymetry of the Raduńskie Lakes). *Zesz. Geogr. WSP w Gdańsku* 8: 261-287 (in Polish).

Okulanis E., 1982: Rola jezior w kształtowaniu powierzchniowych zasobów wodnych Pojezierza Kaszubskiego (The role of lakes in the surface water supplies of the Cassubian Lake District). *Zesz. Nauk. UG. Rozprawy i Monografie* 37, Gdańsk: 233 pp. (in Polish).

Oldfield F. and Appleby P.G., 1984: Empirical testing of ^{210}Pb-dating models for lake sediments. In: Haworth E.Y. and Lund J.W.G., eds., *Lake Sediments and Environmental History*. Leicester University Press: 93-124.

Robbins J.A. and Edgington D.N., 1975: Determination of recent sedimentation rates in Lake Michigan using Pb-210 and Cs-137. *Geochemica et Cosmochimica Acta* 39: 285-304.

San Miguel E.G., Bolívar J.P. and García-Tenorio R., 2003: Mixing, sediment accumulation and focusing using ^{210}Pb and ^{137}Cs. *Journal of Paleolimnology* 29: 1-11.

Sikorski J. and Bluszcz A., 2003: Testing applicability of ^{210}Pb method to date sediments of human-made Lake Kozłowa Góra. *Geochronometria* 22: 63-66.

Smith J.N., 2001: Why should we believe ^{210}Pb sediment geochronologies?. *Journal of Environmental Radioactivity* 55: 121-123.

Tylmann W., 2003: Reliability of dating recent lake sediments on the example of a small and shallow reservoir (Pusty Staw, N Poland). *Limnological Review* 3: 255-260.

Tylmann W. and Białkowski M., 2002: Recent sedimentation rates in Lake Druzno (Vistula River Delta). *Limnological Review* 2: 417-424.