Influence of lake basin morphology on recent sedimentation rates based on the example of Lake Raduńskie Górne, N Poland

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Abstract: The study relates to the use of the ^{210}Pb method for determining sedimentation rates, sedimentation accumulation rates and identifying post-depositional processes. The analysis was based on seven cores of recent sediments collected from different parts of Lake Raduńskie Górne, which is a typical channel lake with diverse bottom morphology. We used alpha spectrometry to determine ^{210}Pb activities in sediment samples and a CF:CS dating model to obtain mean sediment accumulation rates. The results show significant differences between coring sites with highest values in the deepest part of the lake and lowest within the shallow and flat bottom areas. The reason for such a large diversity is the lake basin morphology, e.g. steep slopes and complex configuration of the lake bottom, most probably responsible for the post-depositional sediment replacements.

Key words: lake sediments, ^{210}Pb , CFCS model, sediment accumulation rate, channel lake

Introduction

Lake sediments serve as a very good archive of environmental changes (e.g. Digerfeldt 1972; Berglund 1986; Ralska-Jasiewiczowa et al. 1998; Goslar et al. 1999; Lavrieux et al. 2013; Wulf et al. 2014). However, the results of many geochemical or sedimentological analyses would be incomplete and difficult to interpret without specifying the exact time scale that allows, for instance, the level of contamination to a specific period of time to be identified. The age of lake sediments can be determined using a variety of methods. Among them, the natural radioisotope ^{210}Pb is well recognised, and its reliability has been proven in numerous scientific studies when comparing the results obtained by this method with the results of dating with other natural and artificial radionuclides, as well as pollen analysis (e.g. Robbins and Edgington 1975; Robbins et al. 1978). Due to the relatively short half-life of ^{210}Pb (22.3 years), its application allows the age of deposits up to about 150 years to be specified (Appleby and Oldfield 1978, 1983). Besides dating ages of the sediment, this method is also able to estimate sedimentation rates expressed in length units per year (e.g. cm yr^{-1}) and sediment accumulation rates expressed in mass units (e.g. $\text{g cm}^{-2} \text{yr}^{-1}$).

Dating modern lacustrine sediments with the ^{210}Pb method is possible because of the presence of this nuclide in the atmosphere. The source of ^{210}Pb in the environment is a uranium series (^{238}U), within which we can distinguish a radium subseries (consisting of the last 10 nuclides of the uranium series), starting from ^{226}Ra , which decays to gaseous radon (^{222}Rn) and then to ^{210}Pb . Therefore, the source of ^{210}Pb present in the atmosphere is ^{222}Rn emanating from the Earth's surface. As a result of radioactive decay, ^{210}Pb decays via ^{210}Bi to ^{210}Po , which makes it possible to determine the activities of ^{210}Po and ^{210}Pb by using alpha spectrometry.

The goal of this study is to determine range of spatial variation in mean sediment accumulation rates in different parts of the basin of Lake Raduńskie Górne. This could be applied in a much wider context, for example, the selection of representative coring locations within morphologically complex lakes.

Study site

Lake Raduńskie Górne ($54^{\circ}13.9' \text{ N}$, $17^{\circ}58.2' \text{ E}$, 161.6 m a.s.l.) is located in the central part of the Kashubian Lakeland (Fig. 1). The lake occupies the

Fig. 1. Location of Lake Raduńskie Górne

south-west part of the Radunia-Ostrzyce channel, which is part of the river-lake system of the upper Radunia River. The direct catchment of the lake is over 65 km² (Bajkiewicz-Grabowska 2007); it is comprised of a diversified relief with typical features of the postglacial landscape, which was formed during the Pomeranian Phase of the Vistulian Glaciation. It is covered with outwash plains in the north-west, erosion-accumulative terraces in the south-east as well as undulated morainic plateaus in the north, fragmented into small parts by glacial channels (Gołębiewski et al. 2005).

Lake Raduńskie Górne is a flow-through lake, narrow and elongated, with a poorly developed shoreline. It has a diversified bottom topography, with numerous deeps, shallows and thresholds (Fig. 2). In some parts of the lake basin the slopes reach up to 13° (Okulanis 1966). The maximum depth is 43.0 m, mean depth is 15.5 m and total volume is 60 158.7 dam³. The water surface area is 387.2 ha (Bajkiewicz-Grabowska 2007). Because of distinct changes in the lake bottom configuration, the lake is divided into three parts (Okulanis 1966): the Borucino Basin (north-east part), Żuromino Basin (central part) and the Stężycza Basin (south-west part).

The catchment of Lake Raduńskie Górne belongs to the Radunia River basin, which is a left tributary of the River Motława (Hydrographic Division of Poland 1980, 1983). A fixed network of tributaries is confined to the River Radunia, which feeds the lake from the south, and the River Borucinka from the north (Fig. 2). The alimentation structure of Lake Raduńskie Górne is dominated by groundwater inputs, which exceed 50% and are conditioned by the geology of the basin (Jankowska 1985). The lake is also supplied with water from the outwash plain (both from the north and from the south), for which the lake is the drainage basin (Borowiak and Borowiak 2005).

Methods

Field work included the collection of seven short sediment cores from different locations (Fig. 2). The cores were taken from a boat using a gravity corer (Tyłmann 2007) equipped with a Plexiglas tube (internal diameter of 94 mm and a length of 100 cm). The cores were collected together with near-bottom water to be sure that the surface sediment layer was undisturbed.

Fig. 2. Activity of unsupported ^{210}Pb in the investigated cores (with morphology of lake basin and location of coring sites)

The cores were then continuously subsampled at 1-cm intervals in the field, samples were tightly packed and transported to the laboratory, where they were stored under coldroom conditions.

^{210}Pb activities in sediment samples were measured at the Department of Quaternary Geomorphology and Geology, University of Gdańsk. The applied meth-

od was indirect determination of ^{210}Pb by measuring ^{210}Po with α -spectrometry (7200-04 APEX Alpha Analyser, Canberra). Dried homogeneous sediment samples (0.25 g) were spiked with 0.2 ml of internal standard ^{209}Po and digested at a temperature of 120°C using concentrated HNO_3 , HClO_4 and HF . In the next step, the solution was transferred to a Teflon beaker, evaporated

with 6 M HCl to dryness and then dissolved in 0.5 M HCl. After digestion, ^{210}Po was deposited for four hours on a silver disc at a constant temperature (80–90°C). The silver disc was then placed for 24 hrs in a multi-channel α -counter equipped with detectors PIPS A450-18AM. The activities of ^{210}Po were taken as synonymous with ^{210}Pb in view of the isotopic balance between them (Faure 1977).

Results

In terms of lithology, the dominant type of sediment filling the basin of Lake Raduńskie Górne is calcareous gyttia (Dworniczak and Fedorowicz 2010). However, the sediment lithology is more variable in topmost parts where minerogenic gyttia (RDG-01, RDG-02 and fragments of the cores RDG-03 and RDG-07) occur. The sediment in the cores RDG-04, RDG-05 and RDG-06 is a typical calcareous gyttia showing the highest content of calcium carbonate (80%).

The activities of unsupported ^{210}Pb in all the analysed cores present significant differences (Fig. 2). Depending on the location of the coring site within the lake basin, unsupported ^{210}Pb is recorded at various sediment depths. For comparison, in the core RDG-01 collected in the deepest part of the lake it reaches a sediment depth of 55 cm, while in the core RDG-

04, located in the shallow shore zone, only a sediment depth of 10 cm. A limited range of sediment depth in terms of the presence of unsupported ^{210}Pb is also visible in the core RDG-05 (down to 18 cm), obtained from the flat and extensive bottom stretch of shallow depth. In other cores (RDG-02, RDG-03, RDG-06 and RDG-07), these values reach a depth of between 31–39 cm (Fig. 2).

In all the cores the distribution of unsupported ^{210}Pb shows some irregularities, and the highest values were recorded in the top parts. They range from 77.8 Bq kg⁻¹ (core RDG-03) to 277.1 Bq kg⁻¹ (core RDG-06) (Fig. 2), and are comparable with those previously published for Lake Raduńskie Górne (Tylmann 2004), and for channel Lake Kruklin in the Masurian Lakeland (Gąsiorowski and Hercman 2005).

The activities of unsupported ^{210}Pb , expressed in the logarithmic scale, decrease with mass depth almost linearly (except for the core RDG-07) (Fig. 3). Irregularities are recorded only in the top sections of the cores. This situation allows one of the three most common dating models to be used – CF:CS (Constant Flux: Constant Sedimentation), which is based on linear regression and gives a good approximation of mean sedimentation rates and sediment age (Carroll and Lerche 2003). The assumptions of the CF:CS model (Oldfield and Appleby 1984) are: constant atmospheric ^{210}Pb flux

Fig. 3. Sedimentation rates in analysed cores (unsupported ^{210}Pb activity versus mass depth)

and constant sediment accumulation rate. Model calculations were carried out according to the formula:

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

where: $C_{(0)}$ – activity of ^{210}Pb on the surface of sediment; λ – ^{210}Pb radioactive decay constant (0.03114 yr^{-1}); r – sediment accumulation rate ($\text{g cm}^{-2} \text{ yr}^{-1}$).

Sedimentation rates are expressed in cm per year and sediment accumulation rates are expressed in mass units per unit of the bottom area in time ($\text{g cm}^{-2} \text{ yr}^{-1}$), which can largely eliminate the influence of compaction on the obtained values. The average sediment accumulation rate is quite variable and ranges from $0.018 \pm 0.003 \text{ g cm}^{-2} \text{ yr}^{-1}$ for the core RDG-07 to

Fig. 4. Sediment accumulation rates, sedimentation rates, ^{210}Pb inventories and fluxes (with morphology of lake basin and location of coring sites)

$0.104 \pm 0.009 \text{ g cm}^{-2} \text{ yr}^{-1}$ for the core RDG-01 collected from the deepest place in the lake (Fig. 4).

Significant differences in the results can also be observed in the total inventories of unsupported ^{210}Pb and mean annual fluxes. In the core RDG-01 the unsupported ^{210}Pb inventory is $6240 \pm 90 \text{ Bq m}^{-2}$, while the mean annual flux reaches $194 \pm 3 \text{ Bq m}^{-2} \text{ yr}^{-1}$. At the same time, in the cores RGD-02 and RGD-06 mean fluxes are similar ($109 \pm 2 \text{ Bq m}^{-2} \text{ yr}^{-1}$ and $125 \pm 4 \text{ Bq m}^{-2} \text{ yr}^{-1}$, respectively), and inventories of unsupported ^{210}Pb reach $3500 \pm 40 \text{ Bq m}^{-2}$ and $4020 \pm 120 \text{ Bq m}^{-2}$, respectively. The lowest values are observed in the core RDG-04, where the mean annual flux is at a level of $63 \pm 3 \text{ Bq m}^{-2} \text{ yr}^{-1}$ and the inventory is $2020 \pm 80 \text{ Bq m}^{-2}$ (Fig. 4).

Discussion

Changes in the ^{210}Pb activities in sediments occur with increasing depth, which is due to changes in the extent of nuclide flux, diverse sedimentation rate and post-depositional processes. Irregularities and breakdowns of the activity curve in the surface layers (e.g. in the cores RGD-04, RGD-05 and RGD-06) may be interpreted as a result of an increased sedimentation rate in the most recent period, or as a result of bioturbation and mixing of sediments due to physical processes in the surface layer (Jones and Bowser 1978).

In the light of previous studies (Gołbiewski et al. 2001; Tylmann and Białkowski 2002; Pempkowiak et al. 2006; Tylmann et al. 2007), the present day sedimentation rate in the lakes of northern Poland is $0.1\text{--}0.5 \text{ cm yr}^{-1}$. The values obtained for Lake Raduńskie Górne fall within the specified range, and they exhibit certain regularities: the sedimentation rate is comparable both within the flat bottom (0.15 and 0.19 cm yr^{-1}), and within the slopes (0.35 and 0.33 cm yr^{-1}). These values are slightly lower than the results obtained by Tylmann (2004), who described the sedimentation rate for the flat lake basin areas as 0.21 and 0.26 cm yr^{-1} . Moreover, the detected values of sediment accumulation rates are much lower compared to studies of Lake Łazduny (Tylmann et al. 2013) and Lake Żabińskie (Tylmann et al. 2016), both located in the Masurian Lakeland.

Besides sediment dating, the ^{210}Pb method is used to determine post-depositional processes and their spatial differentiation. For this purpose, two values are used: total content of unsupported ^{210}Pb in a core, and mean annual flux (Brenner et al. 1999; Buscail et al. 1997). The ^{210}Pb fallout from the atmosphere onto the Earth's surface occurs at a constant rate; despite considerable regional variation in terms of its extent (Appleby 2001), it is assumed that in limited geographic areas it is approximately constant. For north Poland mean annual flux can be estimated for $110\text{--}130 \text{ Bq m}^{-2} \text{ yr}^{-1}$. After falling onto

the surface of the lake, isotope ^{210}Pb quickly moves to the bottom sediments, where it decays at about 3% per year. Atmospheric ^{210}Pb can also reach the lake basin indirectly, through inflows from the catchment. In such a situation, most ^{210}Pb is deposited close to the mouths of tributaries (Oldfield and Appleby 1984). In the case of Lake Raduńskie Górne the impact of this source should not be significant because groundwater inputs dominate in the water balance (Okulanis 1982). Furthermore, water exchange is relatively slow and retention time (RT), which is 2.14 yr (Borowiak 2003), may indicate that the loss of ^{210}Pb caused by outflow is not significant. It can therefore be assumed that the most important source of unsupported ^{210}Pb in the studied lake system is direct atmospheric flux. In this case, the variation of the mean annual flux of ^{210}Pb in different locations of the lake bottom corresponds to the lake basin morphology. The occurrence of deeps, thresholds and steep slopes leads to slow movements of strongly hydrated sediments on the slopes and their accumulation in the deeper sections of the lake basin. According to Håkanson and Jansson (2002), undisturbed accumulation of sediments occurs on the bottom areas if inclination does not exceed 4° ; in the range of $4\text{--}14^\circ$ gravity flow of deposits of varying intensity is observed; and on slopes steeper than 14° undisturbed sediment accumulation does not occur. A comparison of these values with the slopes of the Lake Raduńskie Górne basin was conducted by Tylmann (2004), confirming the existence of appropriate conditions for the formation of sediment gravity flows. The results presented in this study also confirm this assumption. The core RDG-01, located at the deepest part of the lake, surrounded by slopes of over 8° , displays the highest values of the mean annual flux of ^{210}Pb , which indicates sediment focusing manifested in the increased rates of sedimentation in this place. The cores taken from the flat areas of the lake basin, that is from places not prone to sediment gravity flows (RDG-03, RDG-04 and RDG-05), have a low level of the mean annual flux of ^{210}Pb and, at the same time, show modest rates of sedimentation. The high values obtained in the cores RGD-06 and RGD-07 may again be the result of gravity sediment flow within the slopes (due to an inclination of $6\text{--}8^\circ$) and their accumulation in the foothills or on small flat places within the slope. In the core located at a short distance from the mouth of the River Borucinka (RDG-02), the values of mean annual flux of ^{210}Pb do not indicate that the river inflow or the supply of ^{210}Pb from the catchment have a large role.

Conclusion

The ^{210}Pb method applied in this study not only enables a reliable chronology to be obtained but also

offers invaluable help in the observation of post-depositional processes and their spatial diversity. The results confirm that the deposition of sediments in a lake of varied bottom surface is diverse and depends on location within the lake basin. The highest values of both unsupported ^{210}Pb inventory as well as mean annual flux of ^{210}Pb were obtained in the deepest part of the lake. The lowest values were recorded for flat and shallow parts of the bottom. The main reason for a high excess is a complex lake basin morphology (occurrence of deeps as well as slope steepness and slope complexity) responsible for gravity movements of sediments, while rivers and the catchment play only a minor role in the supply of ^{210}Pb . This study confirms the effectiveness and usefulness of the ^{210}Pb radioisotope method in the study of recent lake sediments.

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