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RECENT CHANGES OF SEDIMENTATION RATE IN THREE VISTULA OXBOW LAKES DETERMINED BY ^{210}Pb DATING

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Abstract: **Sediments of three oxbow lakes located in Vistula valley near Warsaw (Poland) were analysed for activity of ^{210}Pb. The sediment age was calculated applying the CRS model. The sedimentation rate was determined for each lake based on the sediment age and thickness under the assumption of constant deposition between dated layers. Sedimentation rate varies in time and between lakes. The major changes of sedimentation rate were correlated with flood events and construction of flood dams that isolate the lakes from the river. The recent differences between the lakes seem to be related to different trophy state and productivity.**

1. INTRODUCTION

Oxbow lakes and floodplain wetlands are very important elements of a river system. The different generations of oxbows are usually located differently in relation to the river. The river supplies these lakes with detrital matter and nutrients during the short periods of floods. Between these episodes, the lakes develop in distinct manner. This results sometimes in a different character of even closely located lakes. The flood events could be recorded in oxbow sediments. According to the energy of the floodwater, the lake sediments could be eroded or buried by fluvial sediments. Therefore, the flood events are recorded not only by the changes of sediment type, but also by the changes of the sedimentation rate.

^{210}Pb dating is one of the most powerful methods for the establishment of chronologies in recent lake sediments (Goldberg, 1963; Krishnaswami *et al.*, 1971). It was possible to apply it to dating the youngest sediment ($T_{1/2}$ = 22.26 yr) deposited during the last two centuries and to tracking processes of mixing, focusing and re-deposition (San Miguel *et al.*, 2003; Sonke *et al.*, 2003). Consequently, this method seems to be one of the best for tracking flood events recorded in oxbow lakes' sediments.

2. STUDIED SITES

The Vistula valley near Warsaw is diversified by a lot of small lakes. Their genesis is related to the cutting off of the river channels. All these water bodies have some similarities; they are strongly elongated, shallow (maximum depth 2-4.5 m), and small (up to 10 ha). The lakes' location, close to the city, strongly affects its present trophy state, water level, flora, and fauna.

Three Vistula oxbow lakes were selected for the present study (**Fig. 1**). Two of them, Kazuńskie Górne (KAG) and Kazuńskie Dolne Lake (KAD), are closely located lakes situated northwest of Warsaw. Third, Lisowskie Lake (LIS) is located in southern part of the Warsaw metropolis. The lakes are located at a flood terrace at an altitude of 71.1 (Kazuńskie Lakes) and 83.8 m a.s.l. (Lisowskie Lake), but have no connection to the river today because of artificial flood dams.

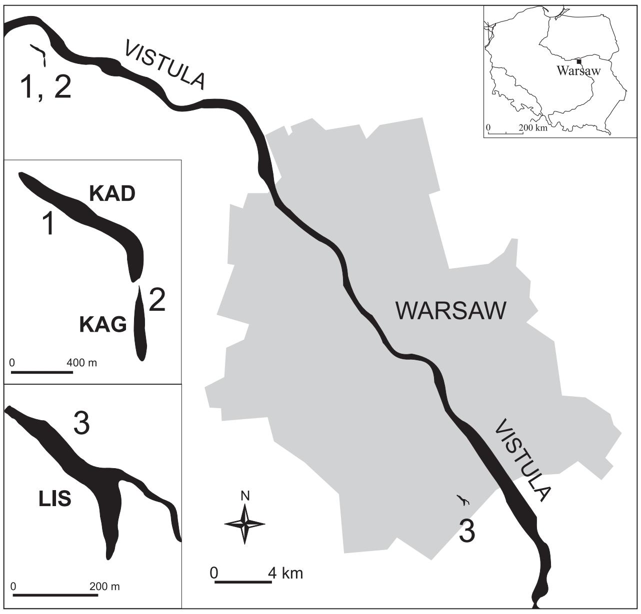

Fig. 1. Location of the studied lakes and the border of Warsaw territory. KAG - Kazuńskie Górne Lake, KAD - Kazuńskie Dolne Lake, LIS - Lisowskie Lake.

3. METHODS AND MATERIALS

The sediment cores were collected from the deepest site of each lake with Kajak-type gravity corer. The cores were divided into 1-centimeter thick pieces and stored in plastic bags. Then sediments were sub sampled in the laboratory. Three-cubic-centimetre sample was taken from each level. The fresh samples were weighted and dried to determine the bulk density and water content. The dried sediment was heated for 1 hour at 550°C to partially decompose of organic matter.

The ^{210}Pb activity of the sediments was determined indirectly by means of alpha-spectrometry measurements of the ^{210}Po (α = 5.31 MeV, $T_{1/2}$ = 138 d) activity (Flynn, 1968). ^{210}Po is generated by the decay of ^{210}Pb and later ^{210}Bi. It is assumed that ^{210}Po is in equilibrium with the parent isotopes. As an internal yield tracer, a known amount of ^{208}Po was added to the weighted sample. Polonium was separated from the sample using strong hydrochloric and nitric acids and was deposited on silver disks (Flynn, 1968). The activity of ^{210}Po and ^{208}Po was measured using an OCTETE PC alpha spectrometer produced by EG&G ORTEC. A constant rate of unsupported ^{210}Pb supply model (CRS) was used to calculate the sediment age (Appleby, 2001). This model assumes a variable sedimentation rate, sediment compaction, and mixing. The activity of unsupported (allochthonous) ^{210}Pb was calculated by subtraction of supported (autigenic) ^{210}Pb activity. The supported ^{210}Pb was determined by measurements on old sediments that contain no allochthonous ^{210}Pb assuming constant activity of autigenic ^{210}Pb along the sediment column. The sedimentation rate was calculated basing on the age of sediment layers at uncompacted depth and assuming constant deposition rate between dated points. The sediment was assumed to be uncompacted on the basis of changes of its porosity determined previously by measuring the water content (loss of sample mass after drying at 105°C for 24 hours).

The collected sediments (**Fig. 2**) are limnic clay, mud, and gyttja (silty gyttja and sandy gyttja). Fluvial sand was cored only in the bottom part of Lisowskie Lake core. The major component of the sediment is quartz and other thermally inactive substances (at 950°C). Organic matter

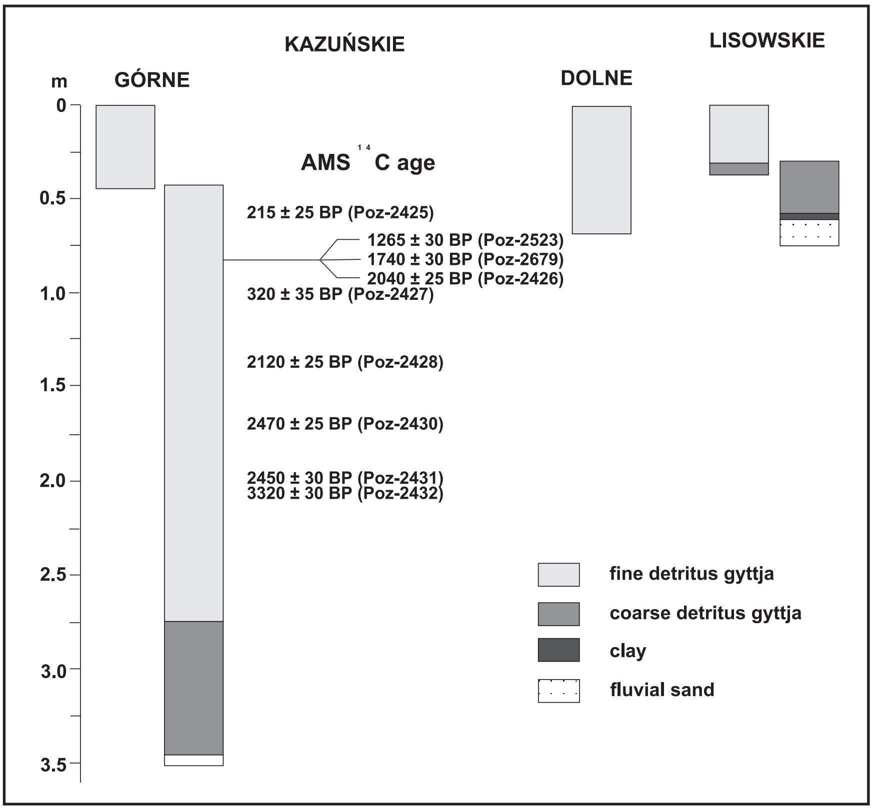

Fig. 2. Simplified lithology of the collected sediments. The short cores were collected using a gravity corer and the long core of Kazuńskie Górne Lake sediments using Russian corer. The long core with conventional AMS ^{14}C dates indicated. Dates performed by Poznań Radiocarbon Laboratory.

content, determined indirectly by loss-on-ignition (LOI) at 550°C in 1 hour varied from 3% for fluvial sands, up to 5-10% for clay and silt, and 15-25% for silty and sandy gyttja (**Fig. 3, Table 1**).

4. RESULTS

The total activity of ^{210}Pb in the uppermost samples was 0.1489 Bq/g in Kazuńskie Górne Lake, 0.1308 Bq/g in Kazuńskie Lake and 0.1517 Bq/g in Lisowskie Lake. The activity of supported ^{210}Pb was 0.0116 Bq/g, 0.0215 Bq/g and 0.0075 Bq/g, respectively. The specific activity of unsupported ^{210}Pb was calculated assuming constant activity of supported ^{210}Pb along the entire profile (**Table 1**). The specific activity of unsupported ^{210}Pb was plotted versus compacted sediment depth (**Fig. 4**). Generally, the activity of ^{210}Pb decreases with depth until reaching a constant background value, as expected. However, slight disturbances of the activity profile for Kazuńskie Dolne Lake and Lisowskie Lake (e.g. higher activity of the second sample then the first one) may indicate mixing of the uppermost part of the sediment.

Sediment dates calculated using CRS model are shown on the **Fig. 5**. The mean sedimentation rate for each lake could be calculated by simply dividing the sediment thickness by the sediment age. However, analysing changes of the age-depth relation (**Fig. 5**) one can conclude, that sedimentation rate was changing in time. Moreover, these changes occurred unexpectedly strongly as shown in **Fig. 6**.

At the beginning of the sediment record (short cores), the sedimentation rate was very different in each lake (from $0.4^{+0.2}_{-0.1}$ cm/yr in Lisowskie Lake to $1.7^{+0.3}_{-0.3}$ cm/yr in Kazuńskie Dolne Lake). Then sedimentation rate increased in all lakes. Moreover, the time and the scale of these changes were different in individual lakes (**Fig. 6**). The sedimentation rate peaked earlier in Kazuńskie Dolne Lake (~100 yr ago) than in Kazuńskie Górne (~85 yr) and Lisowskie Lake (~75 yr). The strongest increases were in Kazuńskie Dolne Lake (to $2.7^{+0.5}_{-0.4}$ cm/yr), Lisowskie Lake ($1.8^{+9.0}_{-1.2}$ cm/yr) and Kazuńskie Górne Lake ($1.3^{+2.6}_{-0.6}$ cm/yr). The sedimentation rates declined after culminations in all lakes. Subsequently, sedimentation rate gradually increased in Kazuńskie Dolne Lake and decreased in Lisowskie Lake and Kazuńskie Górne Lake. The recent sedimentation rate is significantly different in specific lakes (**Fig. 6, Table 2**). The highest is recorded in Kazuńskie Dolne Lake ($1.1^{+0.4}_{-0.4}$ cm/yr in the last 2 years) and the lowest in Lisowskie Lake ($0.4^{+0.2}_{-0.2}$ cm/yr during the last 3 years of record).

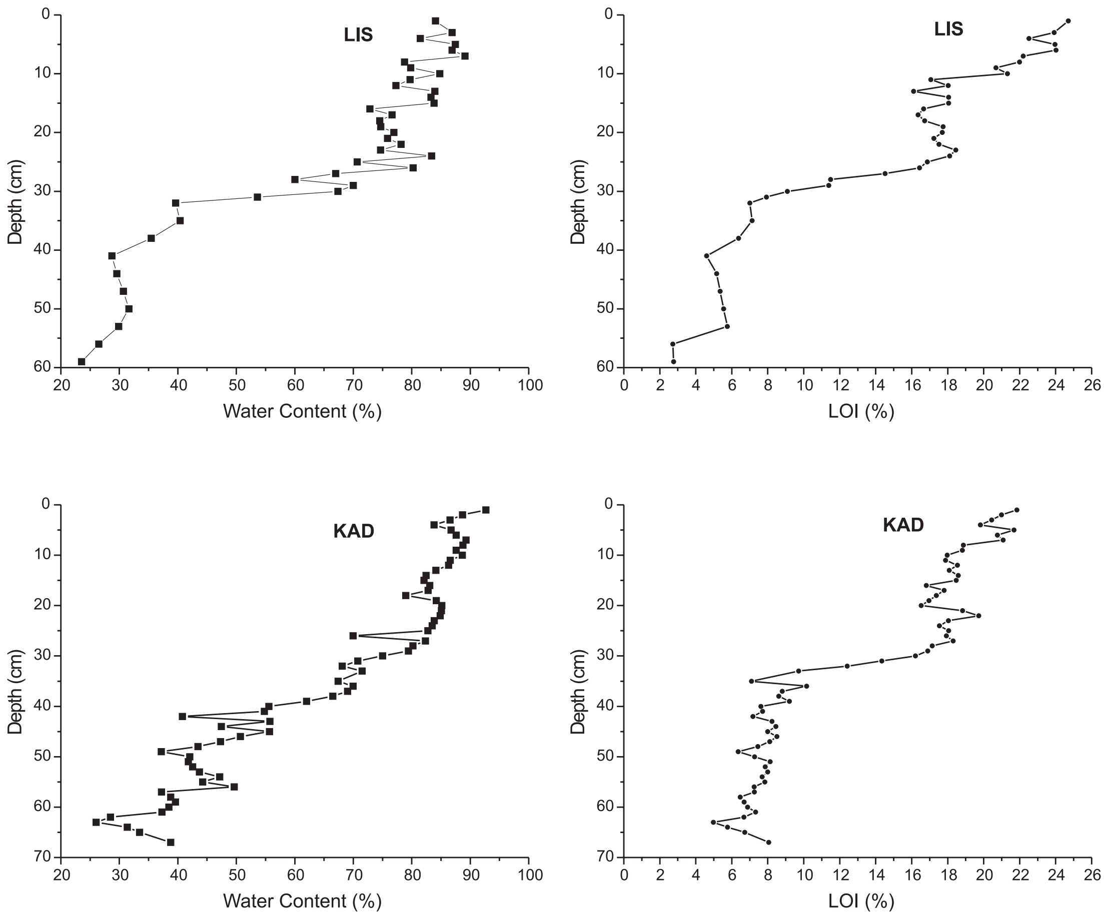

Fig. 3. *Water content of fresh sediments and loss-on-ignition of dried sediments from Kazuńskie Dolne Lake (KAD) and Lisowskie Lake (LIS).*

Table 1. Water content, loss-on-ignition, ^{210}Pb specific activity and calculated ages of sediments from Kazuńskie Górne Lake (KAG), Kazuńskie Dolne Lake (KAD) and Lisowskie Lake (LIS).

Sample No.	Water content (%)	Loss-on-ignition at 550°C (% of dried sample)	Uncompacted depth (cm)	Unsupported ^{210}Pb Specific Activity (Bq/g)	CRS model Age (yr)
			Kazuńskie Górne Lake (KAG)		
KAG 5	85.29	n.a	6.3	0.137±0.004	13.97±0.24
KAG 9	89.04	n.a	11.3	0.076±0.002	27.30±0.55
KAG 12	87.02	n.a	14.6	0.053±0.002	35.70±0.78
KAG 16	85.67	n.a	19.7	0.040±0.002	46.7±1.2
KAG 25	69.46	n.a	37.7	0.016±0.002	75±4
KAG 30	62.62	n.a	53.1	0.0041±0.0007	88±5
KAG 39	54.62	n.a	88.2	0.0115±0.0006	127±15
			Kazuńskie Dolne Lake (KAD)		
KAD 1	92.67	21.84	1.0	0.109±0.002	0.00
KAD 2	88.67	20.99	2.6	0.141±0.007	1.44±0.02
KAD 3	86.53	20.44	4.4	0.123±0.003	3.06±0.03
KAD 5	86.71	21.68	8.4	0.080±0.003	5.77±0.06
KAD 7	89.27	21.08	11.6	0.125±0.004	8.7±0.1
KAD 13	84.12	18.09	22.2	0.074±0.003	19.2±0.2
KAD 20	85.13	16.53	38.8	0.071±0.003	32.6±0.4
KAD 27	82.34	18.30	56.2	0.060±0.003	53±1
KAD 35	67.40	7.09	81.8	0.010±0.001	82±2
KAD 46	50.70	8.51	146.1	0.0082±0.0008	105±2
KAD 55	44.26	7.84	215.8	0.0041±0.0006	147±3
			Lisowskie Lake (LIS)		
LIS 1	84.04	24.70	1.5	0.144±0.003	0.00
LIS 3	86.89	23.92	2.7	0.151±0.004	3.45±0.04
LIS 5	87.45	23.96	5.5	0.115±0.003	7.0±0.1
LIS 7	89.09	22.20	7.7	0.121±0.003	10.5±0.1
LIS 11	79.70	16.06	14.8	0.090±0.003	18.3±0.2
LIS 13	83.96	16.10	18.3	0.088±0.002	22.2±0.3
LIS 21	75.86	17.23	34.9	0.064±0.002	42.4±0.5
LIS 25	70.66	16.87	43.5	0.046±0.002	54.7±0.7
LIS 32	39.64	7.00	67.5	0.005±0.001	72±2
LIS 35	40.41	7.13	73.0	0.011±0.002	75±2
LIS 38	35.46	6.38	78.9	0.022±0.001	83±2
LIS 44	29.58	5.16	91.9	0.009±0.001	106±2
LIS 53	29.88	5.75	110.9	0.0069±0.0005	153±6

5. DISCUSSION AND CONCLUSIONS

According to the obtained results, the collected sediments have been accumulated during the last 160 years. The peaks of the highest sedimentation rate were asynchronous in the studied lakes. These episodes of high sedimentation rates are not correlated with the increase of the organic matter content (**Fig. 3**). Therefore, we link these extra portions of material (mainly quartz and other substances inactive at 950°C) with flood events. The greatest flood events in 1888/1889 and 1924 were the best recorded in the sediments of the studied lakes (Plit, 1992). The increase of the sedimentation rate was the strongest in Kazuńskie Dolne Lake, so we conclude that this lake was stronger impacted by floods than Lisowskie Lake and Kazuńskie Górne Lake. Lisowskie Lake is located in a place of a paleochannel, where the river flooded temporarily but the energy of the flow was not very strong. In the place of the same paleochannel, today there are others oxbow lakes located (e.g. Powsinkowskie Lake, Wilanowskie Lake, Czerniakowskie Lake) and all of them are significantly distant from the recent main river channel. In Kazuńskie Lakes, especially Kazuńskie Dolne, the flood events were much clearly recorded. This phenomenon could be explained by the location of these lakes close to the major river channel and only 1 m over the mean river level. However, they were isolated from the river from almost all directions and the river water could flow into the lakes only from northwest. It also explains the much higher increase of the sedimentation rate in Kazuńskie Dolne Lake than in Kazuńskie Górne Lake (**Fig. 1** and **Fig. 6**).

A very significant change was found in the sediments deposited after the 1930's and 1940's. The strong decrease

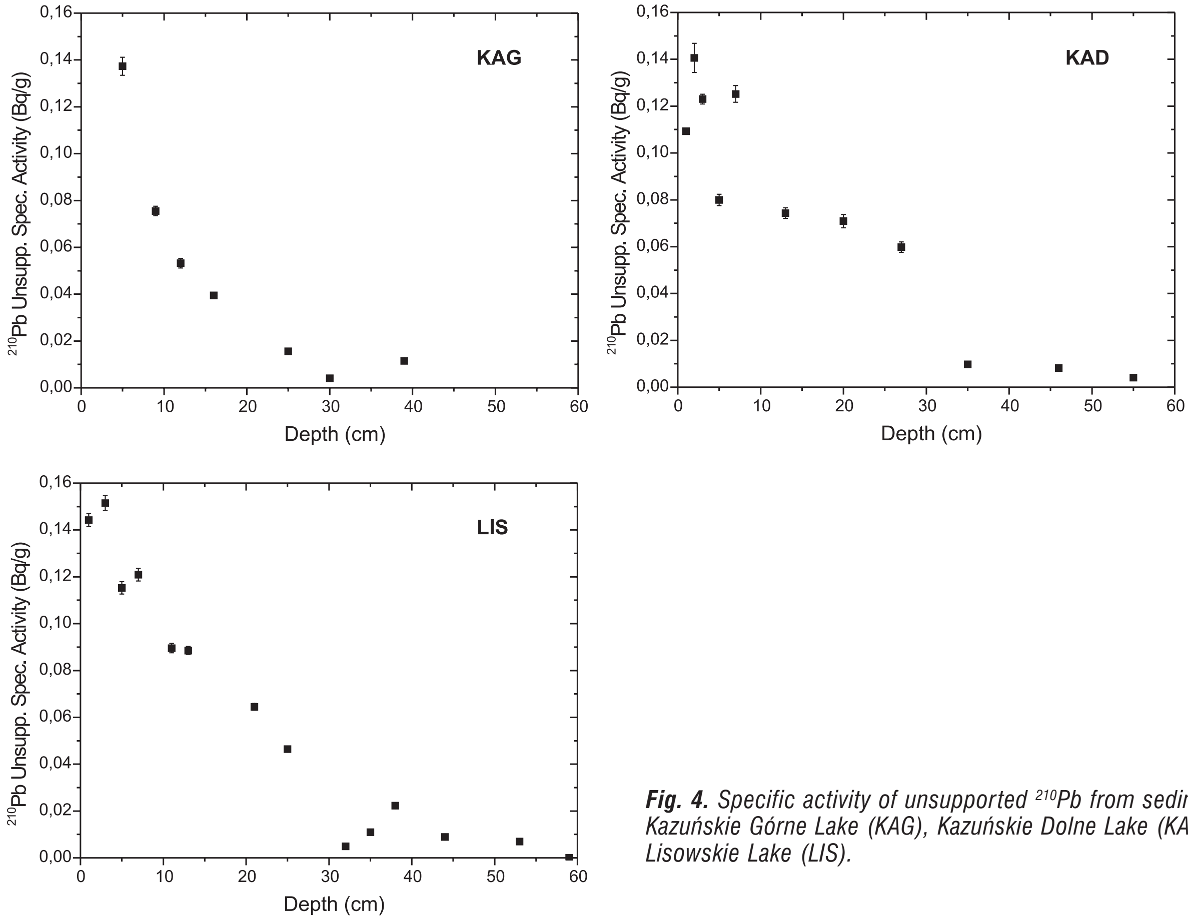

Fig. 4. *Specific activity of unsupported ^{210}Pb from sediments of Kazuńskie Górne Lake (KAG), Kazuńskie Dolne Lake (KAD), and Lisowskie Lake (LIS).*

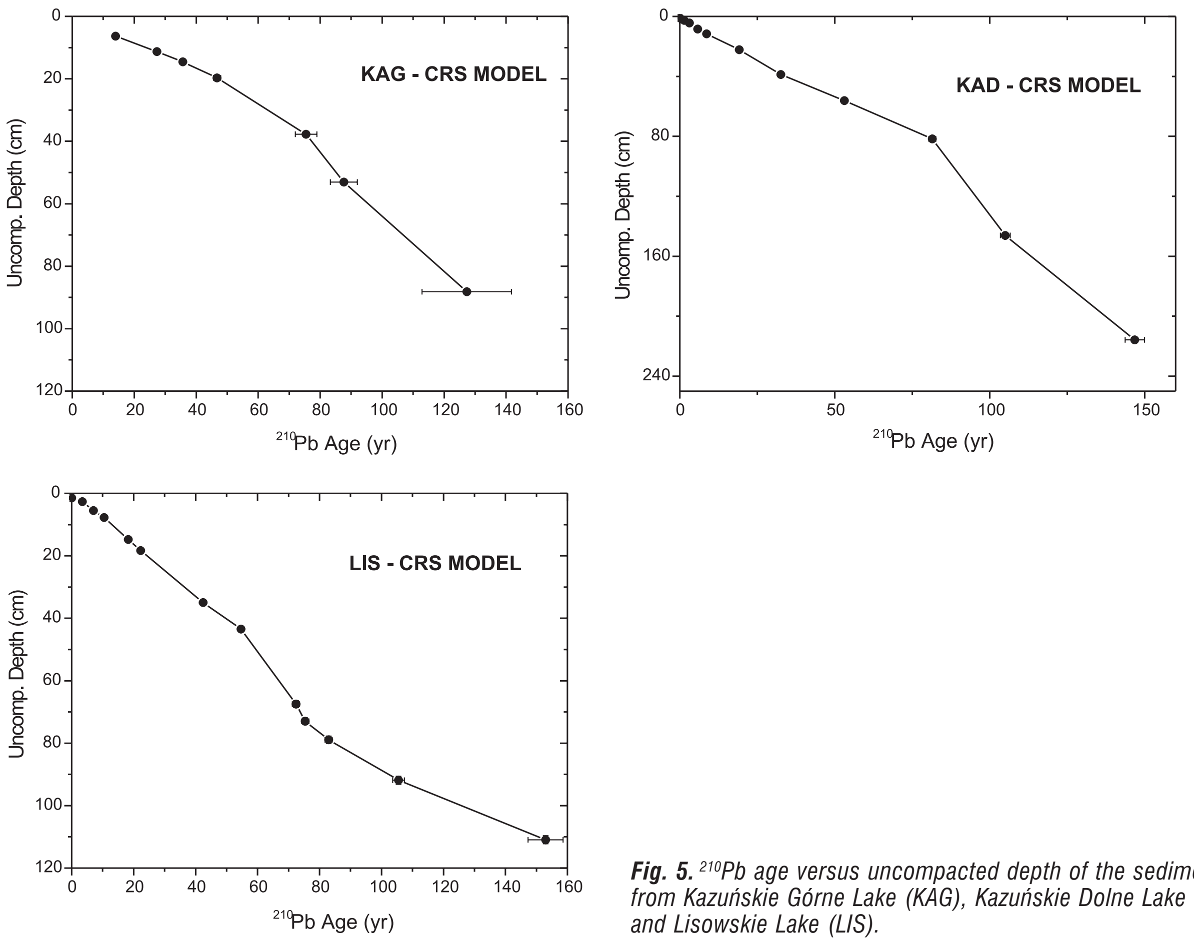

Fig. 5. *^{210}Pb age versus uncompacted depth of the sediments from Kazuńskie Górne Lake (KAG), Kazuńskie Dolne Lake (KAD) and Lisowskie Lake (LIS).*

of sedimentation rates and more stable sedimentation regime was detected in all lakes (**Fig. 6**). This shift is also expressed by a clear increase of organic matter (detected by LOI, **Fig. 3**). This change seems to be related to the beginning of the isolation of studied lakes from the Vistula River by the construction of anti-flood dikes, which was completed by the Germans during the World War II. It resulted in reduction of mineral matter (clay and sand) supplied by the river and accumulated in the lakes. It promoted water plant development at the same time, which resulted in gradual increase of the sedimentation rate in Kazuńskie Dolne Lake. Kazuńskie Górne Lake and Lisowskie Lake reacted in a different way. Their sedimentation rates were more stable or even decreased after the construction of the dikes (from $0.6^{+0.2}_{-0.2}$ cm/yr to $0.4^{+0.1}_{-0.1}$ cm/yr and from $0.9^{+0.3}_{-0.3}$ cm/yr to $0.4^{+0.2}_{-0.2}$ cm/yr, respectively). The dissimilarity in changes of the sedimentation rate in closely located Kazuńskie Dolne and Kazuńskie Górne Lakes is difficult to explain. The possible reason is a difference in the trophic state and productivity between these lakes. However, this thesis should be supported by future palaeobiological studies.

The completed analyses show that the oxbow-lake environment in the Vistula valley near Warsaw was very dynamic in last two centuries. There is strong evidence of a similar state in the past. The long core was collected from Kazuńskie Górne Lake. The selected macrofossils (plant parts) were dated by the AMS ^{14}C method. The ^{14}C date of the upper part of long core (level 57 cm) matches well with the ^{210}Pb age of the lowest part of the short core. The age calculated for level 57 cm basing on the ^{210}Pb age of the lowest part of the short core and assuming a constant sedimentation rate is 187±40 yr and agrees with the ^{14}C date of 215±25 yr. The results from level 81 cm did not show any stratigraphic order (**Fig. 2**). Moreover, from this level we obtain three significantly different data. Hence, we interpreted these fossils and sediments as material deposited from floodwater. The sedimentation rate calculated from the „upper" ^{14}C data for Kazuńskie Górne Lake was 0.39±0.22 cm/yr (the data for level 81 cm were omitted) and corresponds well with the data obtained with the ^{210}Pb method for the lowest part of the short core, i.e. $0.2^{+0.3}_{-0.1}$ cm/yr (both data for compacted sediments).

The construction of anti-flood dikes seems to be crucial for oxbow lake ecosystems. It results, directly and indirectly, in total change of the hydrological, sedimentological and biological behaviour of these water bodies. However, these changes are very difficult to predict. Even in closely located lakes (e.g. Kazuńskie Lakes), the same process may generate different reactions. Therefore, the manipulation and management in river valley should be support by careful and detail multi-proxy studies.

Table 2. *Sedimentation rate and its uncertainty for the youngest deposits from Kazuńskie Górne Lake (KAG), Kazuńskie Dolne Lake (KAD) and Lisowskie Lake (LIS).*

Period (^{210}Pb yrs)		Sedimentation Rate (cm/yr)
Kazuńskie Górne Lake (KAG)		
from	to	
13.97±0.24	27.30±0.55	$0.4^{+0.1}_{-0.1}$
27.30±0.55	35.70±0.78	$0.4^{+0.2}_{-0.1}$
35.70±0.78	46.70±1.20	$0.5^{+0.2}_{-0.2}$
46.70±1.20	75.40±3.50	$0.6^{+0.2}_{-0.2}$
75.40±3.50	78.70±4.40	$1.3^{+2.6}_{-0.6}$
88.70±4.40	127.0±15.00	$0.9^{+0.9}_{-0.4}$
Kazuńskie Dolne Lake (KAD)		
from	to	
0.00	1.44±0.02	$1.1^{+0.4}_{-0.4}$
1.44±0.02	3.06±0.03	$1.1^{+0.5}_{-0.5}$
3.06±0.03	5.77±0.06	$1.5^{+0.4}_{-0.4}$
5.77±0.06	8.66±0.09	$1.1^{+0.3}_{-0.3}$
8.66±0.09	19.17±0.16	$1.0^{+0.1}_{-0.1}$
19.17±0.16	32.61±0.36	$1.2^{+0.2}_{-0.2}$
32.61±0.36	53.12±0.63	$0.8^{+0.1}_{-0.1}$
53.12±0.63	81.50±1.10	$0.9^{+0.2}_{-0.1}$
81.50±1.10	105.00±1.60	$2.7^{+0.5}_{-0.4}$
105.00±1.60	146.80±3.10	$1.7^{+0.3}_{-0.3}$
Lisowskie Lake (LIS)		
from	to	
0.00	3.45±0.04	$0.4^{+0.2}_{-0.2}$
3.45±0.04	7.05±0.07	$0.8^{+0.2}_{-0.2}$
7.05±0.07	10.48±0.10	$0.6^{+0.2}_{-0.2}$
10.48±0.10	18.28±0.18	$0.9^{+0.2}_{-0.1}$
18.28±0.18	22.25±0.21	$0.9^{+0.3}_{-0.3}$
22.25±0.21	42.40±0.50	$0.8^{+0.1}_{-0.1}$
42.40±0.50	54.70±0.70	$0.7^{+0.2}_{-0.2}$
54.70±0.70	72.40±1.10	$1.4^{+0.3}_{-0.3}$
72.40±1.10	75.40±1.20	$1.8^{+9.0}_{-1.2}$
75.40±1.20	82.90±1.20	$0.8^{+0.8}_{-0.5}$
82.90±1.20	106.00±2.00	$0.6^{+0.3}_{-0.2}$
106.0±2.00	152.90±5.60	$0.4^{+0.2}_{-0.1}$

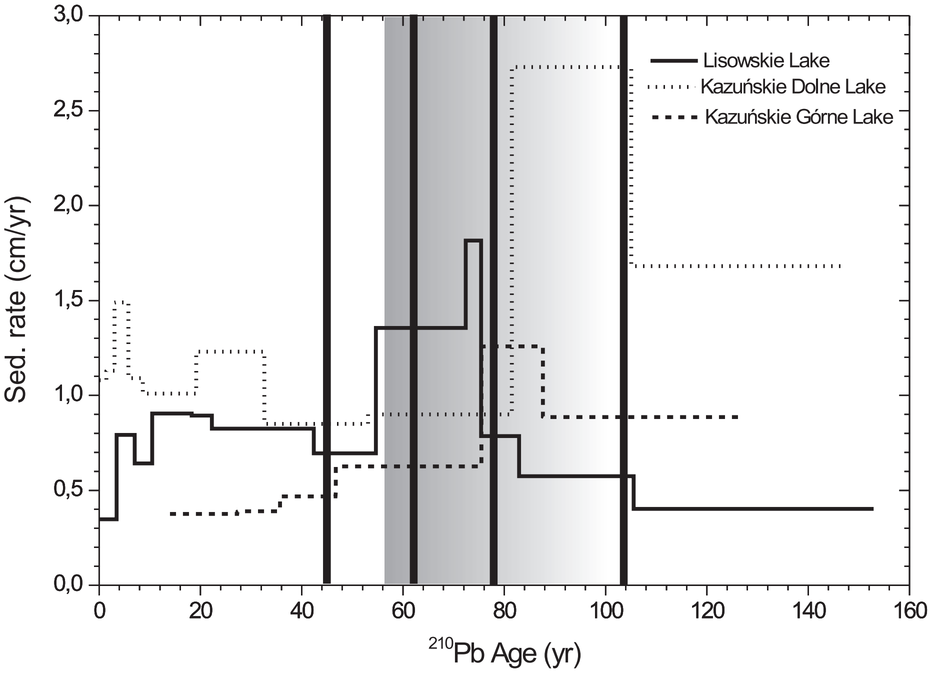

Fig. 6. *Changes of sedimentation rate during deposition of the youngest sediments of Kazuńskie Górne Lake (KAG), Kazuńskie Dolne Lake (KAD), and Lisowskie Lake (LIS). The black lines indicate the flood events and the shaded area marks the period of anti-flood dikes construction.*

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