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ESTIMATION OF KIND, AMOUNT AND MECHANISM OF SEDIMENTATION IN THE ZEMBORZYCE RESERVOIR NEAR LUBLIN

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Summary. In this paper we report on the results of examination of bottom deposits accumulated during 34 years of functioning of dammed reservoir on the Bystrzyca River near Lublin. Based on the analysis of cores taken with undisturbed structure, the lithology of deposits and the amount of sedimentation were estimated. Based on laboratory analyses, the geochemistry and origin of the deposits was determined. The mechanism and rate of sedimentation and main sources of supplied material are presented. General balance of material supply to the reservoir was made.

Key words: reservoir sedimentation, dammed reservoir, Zemborzyce Reservoir

INTRODUCTION

Dammed reservoirs have important and different ecological, economic and social functions. They have been a source of renewable energy for hundreds years. They store great amounts of water and, owing to this fact, they reduce the results of high and low water flows, and enable flood prevention. Many reservoirs serve as sources of water for industrial and municipal purposes. Their recreational assets are also important, especially in areas with scarcity of surface water. However, the supply of a considerable (compared to the reservoirs' volume) amount of material causes their quick eutrophication and water quality deterioration. Besides sedimentation of mineral deposits, accumulation of organogenic deposits occurs faster. Depth and useful reservoir capacity decrease, and their recreational assets deteriorate. Such unfavourable changes affect especially shallow reservoirs with flow, and with short period of water exchange [Kasza 1999].

The above-mentioned features characterize also the Zemborzyce Reservoir near Lublin [Michalczyk (ed.) 1997, Radwan (ed.) 2006). Its bottom deposits have been examined qualitatively [Misztal and Smal 1980, 1983/84, Ligęza and Smal 2002] but quantitative analyses have not been made till now and the sedimentation mechanism has not been determined, either. Biochemical processes, typical of such reservoirs [Kasza 1999], cause a consistent deterioration of ecological conditions in the Zemborzyce Reservoir [Radwan (ed.) 2006]. Increased eutrophication and biological production also accelerate its filling. In order to define the possibilities of slowing down this process it is necessary to determine the conditions, causes and rate of sedimentation. That is essential for further functioning of the reservoir, and the examination of the amount and kind of the deposits is necessary for their potential exploitation. Besides, the understanding of the evolution mechanisms can be useful for prediction of development of newly constructed or designed objects.

STUDY AREA

The study object was the Zemborzyce Reservoir, an artificial lake near Lublin. It was built in 1974 by damming of the narrowing of the Bystrzyca River valley with a 0.5 km long earth dam that raised the water level by about 5 m. The reservoir area is 278 ha, average depth about 2 m, total capacity $6.3 \cdot 10^6$ m^3, and useful capacity – with the 1 m change of damming up datum (178.5–177.5 m a.s.l.) – $2.5 \cdot 10^6$ m^3. The useful flood volume, with the maximum possible damming up level of 179 m a.s.l., is almost $5.2 \cdot 10^6$ m^3. Mean water discharge to the reservoir from the catchment of 725 km^2 in area is 2.8 m^3 s^{-1}, i.e. $88.3 \cdot 10^6$ m^3 annually [Włodarczyk 1991, Michalczyk (ed.) 1997]. The reservoir was built mostly as a storage reservoir, and the memorable flood in Lublin in the spring of 1964 had a considerable influence on the decision concerning it construction [Bryński 1965]. Together with the village of Zemborzyce, the whole reservoir was within the administrative boundaries of Lublin town. Due to the proximity of the town, good road network and accessible shores, the reservoir is a recreation base for town inhabitants, especially in the summer. The situation of the Zemborzyce Reservoir is given by geographical coordinates: φ – 51°10'00''-51°11'35''N and λ – 22°30'40''-22°32'35''E.

In physiographical respect the Zemborzyce Reservoir is situated on the border of subregional units of the Lublin Upland. According to Chałubińska and Wilgat [1954] these are: from the west – the Bełżyce Plain, and from the east – the Giełczew Height. According to Maruszczak [1972] these are the Bełżyce Plateau and the Łuszczów Plateau, respectively. The boundary of the subregions is the Bystrzyca River valley cut in the Upper Cretaceous-Palaeocene opokas and gaizes that are exposed east of the dam. The valley if filled with Quaternary deposits, mostly Pleistocene glaciofluvial and fluvial sands. They form vast higher

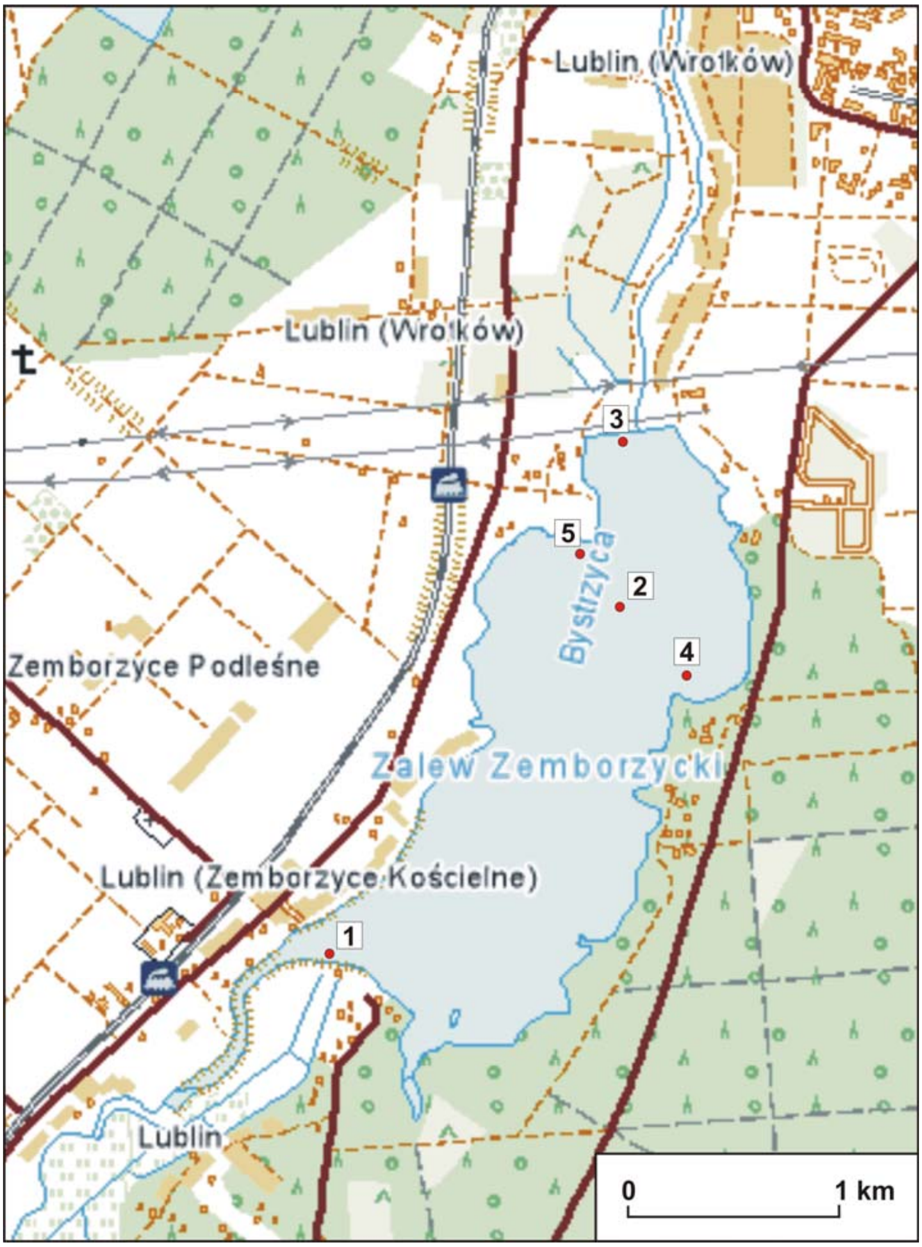

Fig. 1. Location sketch of the Zemborzyce Reservoir with the research sites

terraces on both sides of the valley, their slopes forming the present shores of the reservoir. The terrace on the west side is occupied by the Zemborzyce village, with fields under cultivation and the „Marina" recreation complex situated in the place of the former manor farm, while a pine forest and the „Dąbrowa" recreation complex occupy the terrace on the east side (Fig. 1). A ca. 3 km long section of the 0.7–1.2 km wide Holocene floodplain (formerly meadowland) is flooded. This terrace is composed of sandy alluvial soils and organic-mineral muds with numerous peat infillings of the palaeochannels [Bałaga and Maruszczak 1981]. Steep shores of the reservoir (terraces' slopes), especially on the east side, until recently were subjected to intensive abrasion that was stopped by stabilization of the shore with concrete wall.

OBJECTIVE, SCOPE AND METHODS OF RESEARCH

The research was made on the basis of an order of the Lublin Municipal Council as part of the hydrobiological monitoring program conducted under Prof. Tadeusz Chmielewski's management [Chmielewski (ed.) 2009]. The main aim of the study was to examine the lithology and origin of bottom deposits in the Zemborzyce Reservoir in places where benthos fauna was collected (Fig. 1). We examined the present bottom deposits and their direct substratum, i.e. sedimentary succession of the top part of the biogenic-mineral valley series. Physicochemical features of the deposits were also analysed, and an attempt was made to determine the rate, mechanism and origin of the present biogenic-mineral accumulation in the reservoir.

During the field works profiles of bottom deposits were taken, and their positions were determined using a Garmin 76 type GPS unit. The field works were conducted in January 2009 when 20 cm thick ice cover on the reservoir was in good state. Five borings were made using the „Eijkelkamp Agrisearch Equipment (Netherlands)" corer with the „Instorf" peat-sampler, 50 cm long and 5 cm in diameter. Cores with undisturbed structure were taken from the 1.5–2 m thick top parts of the profiles that included the present bottom deposits of the reservoir, the top part of underlying deposits and their contact zone (Tab. 1). Lithofacial analysis was made, and the sediments were also described on the basis of the modified, non-genetic system developed by Troels-Smith [*vide* Tobolski 2000]. Based on the obtained results, the samples for geochemical analyses were selected.

For fifteen air-dried samples (three from each profile) of biogenic and biogenic-mineral deposits the following geochemical analyses were made:

– contents of dry mass, ash, and organic matter [Sapek and Sapek 1997],

– content of calcium carbonate by volumetric method using Scheibler device [Lityński *et al*. 1976],

– concentrations of total nitrogen and phosphorus; samples were digested using a mixture of 30% H_2O_2, selenium, lithium sulphate and concentrated sulphuric acid; nitrogen was determined by the spectrophotometric method proposed by Foster [1995], phosphorus – according to the method developed by Murphy and Riley [*vide* Kuo 1996],

– concentrations of total calcium, magnesium, iron and sodium; samples were digested using a mixture of hydrofluoric and perchloric acids in Teflon beakers according to the method proposed by Hossner [1996]. The elements mentioned were determined by the atomic absorption spectrometry using a Perkin-Elmer 3300 device.

Based on the field investigations and laboratory analyses, the kind, amount, rate and mechanism of sedimentation in the Zemborzyce Reservoir were estimated. These first quantitative examinations included also an attempt to balance the supply and deposition of material in the whole 34-year-long period of the reservoir existence. Data from publications and archival materials were also used. It was revealed that detailed interdisciplinary investigations are necessary to fully balance the reservoir deposits.

RESULTS

Physicochemical characteristic of deposits

Deposit sequences in four of the cores (No. 1, 2, 4, 5) are similar (Tab. 1). Their characteristic feature is distinct triplicity: biogenic-mineral substratum *in situ* → substratum deposits transformed by pedogenesis, and then in subaqueous conditions → deposits of present reservoir sedimentation. Synthetic profile, from bottom to top, is as follows: strongly decomposed herb peat (humopeat) → herb peat (peat-muck soil), partially redeposited and with gyttja → calcareous-clayey gyttja. Only in profile No. 3 (near the dam) the transition unit in the form of redeposited deposits is absent, and peats of the substratum are covered by sandy flood deposits of the bank near the former channel of the Bystrzyca River.

Dry mass of the present reservoir deposits contains rather a low amount of organic matter (Tab. 2), the mean content of which is 9.13%. Mineral material definitely predominates (88–93%), and carbonates ($CaCO_3$) constitute almost a half (42.4%) of it. Only in profile No. 1, near the Bystrzyca River mouth, the content of carbonates is rather low (only 6.5–16.5%). The content of clastic deposits is as much as 79% in this profile, while in the whole reservoir their mean content is 48.5%. Redeposited sediments are carbonate-free (except for 4% of $CaCO_3$ in profile 2), but they contain much more organic matter (17–61%). However, the highest content of organic matter (79–84%) is found in substratum deposits, except for sandy fluvial deposits in profile No. 3. These sands overlie calcareous mud, but all other deposits of the substratum are carbonate-free. The concentration of CaO is certainly closely related to the distribution of $CaCO_3$.

The concentrations of biogenic elements in the examined material from 5 profiles are related to the lithogenetic characteristics of individual deposit series. The content of nitrogen is closely related to the content of organic matter. The highest content of phosphorus occurs in redeposited deposits in profiles No. 2 (3.30–3.40 m) and No. 4 (2.40–2.50 m), in strongly decomposed sedge peat, secon-

Table 1. Description of deposits taken in 2009 from the bottom of the Zemborzyce Reservoir (profile numbers as in Fig. 1; depth from the water surface; description from the present bottom of reservoir)

No	Depth, m	Lithogenetic description	T-S formula
1.	0.75–1.60	Clayey gyttja; grey to olive-grey; water-saturated in the top part	As3, Lc1, Ld++, nig.2, strf.0, elas.1, sicc.3, part. test (moll.); HCl++
	1.60–1.90	Sedge peat; moderately decomposed; brown	$Th^3$4, Sh+, nig.3, strf.0, elas.3, sicc.2, lim.2; HCl–
	1.90–2.00	Sedge-reed peat; strongly decomposed; dark brown	$Th^4$4, Sh++, nig.3, strf.0, elas.2, sicc.2, lim.1; HCl–
2.	2.60–3.25	Calcareous-clayey gyttja; light grey to olive-grey	As2, Lc2, Ld++, nig.1-2, strf.0, elas.1, sicc.1-2; HCl+++
	3.25–3.50	Sedge peat; strongly decomposed, with gyttja; brown	$Th^4$3, Ld1, Sh+, nig.2-3, strf.0, elas.2, sicc.2, lim.2, part test. (moll.); HCl+
	3.50–4.00	Sedge peat; strongly decomposed; dark brown to black	$Th^4$4, Sh+, nig.3-4, strf.0, elas.3, sicc.2, lim.3; HCl–
3.	3.20–4.00	Calcareous-clayey gyttja with alluvium; dark grey to grey-olive; water-saturated in the top part	As2, Lc2, Ld++, nig.2, strf.0, sicc.1-2; HCl++
	4.00–4.40	Fine sand; organic; dark grey	Ga3, Sh1, nig.3, strf.0, elas.0, sicc.2, lim.3; HCl–
	4.40–4.45	Calcareous mud with detritus of mollus-can shells; light grey	Ag 3, As 1, nig.1, elas.0, sicc.2, part. test (moll.), lim.3; HCl+++
	4.45–4.50	Herb peat (humopeat); strongly decom-posed; dark grey	$Th^4$2, Sh2, Ag++, nig.3, strf.0, lim.2; HCl–
4.	2.10–2.30	Calcareous-clayey gyttja; light grey to olive-grey	As2, Lc2, Ld++, nig.1-2, strf.0, elas.1, sicc.2; HCl+++
	2.30–2.50	Sedge peat; strongly decomposed, with gyttja; dark brown to black	$Th^4$3, Ld1, Sh++, nig.3, strf.0, elas.2, sicc.2, lim.3; HCl–
	2.50–3.00	Sedge peat; strongly decomposed; dark brown to black	$Th^4$4, Sh+, nig.3-4, strf.0, elas.3, sicc.2, lim.1; HCl–
5.	2.30–3.00	Calcareous-clayey gyttja; light grey to olive-grey	As2, Lc2, Ld++, nig.1-2, strf.0, elas.1, sicc.1-2; HCl+++
	3.00–3.15	Sedge peat; strongly decomposed, with gyttja; dark brown to black	$Th^4$3, Ld1, Sh++, nig.3, strf. 0, elas.2, sicc.2, lim.3; HCl–
	3.15–3.60	Sedge peat; strongly decomposed, with gyttja, clayey in the top part; dark brown	$Th^4$2, Ld1, As1, Sh++, nig.2-3, strf.0, elas.2, sicc.2, lim.2; HCl–
	3.60–4.00	Sedge peat; strongly decomposed; dark brown to black	$Th^4$4, Sh++, nig.3-4, strf.0, elas.3, sicc.2, lim.3; HCl–

Table 2. The results of geochemical analyses of the deposits taken from the bottom of the Zemborzyce Reservoir in January 2009 (profile numbers as in Fig. 1)

No	Depth from water surface, m	Genetic sequence of deposit	Bulk density*	MCF**	Dry mass	Ash content	Organic matter	$CaCO_3$	N total	P total	CaO	MgO	Fe_2O_3	Na_2O
			$g \cdot cm^{-3}$		%				$g \cdot kg^{-1}$					
1	0.90–1.00	subaqueous	0.45	1.01771	98.26	92.77	7.23	6.53	8.66	1.23	75.65	3.35	14.74	6.32
	1.50–1.60	subaqueous	0.28	1.03562	96.56	88.27	11.73	16.49	14.43	1.67	124.91	5.54	24.65	4.69
	1.70–1.80	redeposition	0.25	1.10796	90.26	60.60	39.40	0.00	28.40	1.54	28.69	6.96	22.89	5.02
2	2.60–2.70	subaqueous	0.22	1.02028	98.01	91.83	8.17	50.63	13.25	1.38	238.09	3.98	14.96	1.86
	3.30–3.40	redeposition	0.49	1.06835	93.60	72.99	27.01	3.99	27.80	2.30	68.63	6.38	27.51	5.28
	3.60–3.70	substratum	0.17	1.14484	87.35	21.19	78.81	0.00	54.87	1.95	122.35	5.17	19.23	1.71
3	3.30–3.40	subaqueous	0.17	1.02588	97.48	90.55	9.45	51.49	13.57	1.34	231.62	4.11	15.02	0.86
	3.80–3.90	subaqueous	0.43	1.02535	97.53	90.66	9.34	40.83	10.31	1.08	214.12	4.14	15.09	1.80
	4.00–4.10	substratum	1.20	1.00731	99.27	97.18	2.82	0.00	5.07	0.46	7.27	1.28	6.97	3.00
4	2.20–2.30	subaqueous	0.22	1.02283	97.77	89.67	10.33	53.55	16.44	1.15	239.78	3.70	14.28	1.72
	2.40–2.50	redeposition	0.08	1.10615	90.40	38.96	61.04	0.00	50.82	2.00	64.43	5.64	16.65	4.29
	2.60–2.70	substratum	0.15	1.14974	86.98	16.06	83.94	0.00	66.88	1.61	165.42	7.51	10.11	0.95
5	2.30–2.40	subaqueous	0.27	1.02160	97.89	91.73	8.27	50.15	14.34	1.32	235.86	3.85	13.35	1.41
	3.00–3.10	redeposition	0.57	1.04732	95.48	82.84	17.16	0.00	17.15	1.35	19.20	9.00	33.62	6.17
	3.20–3.30	redeposition	0.38	1.05959	94.38	77.39	22.61	0.00	17.25	1.10	14.93	9.49	31.91	5.47

* in 105ºC
** moisture corrector factor (ratio of deposit weight in 20 and 105ºC)

darily enriched with gyttja. The distribution of iron resembles that of phosphorus. The distributions of other examined components are also regular. The content of MgO is considerably lower in the present organogenic deposits in comparison with the peats of the substratum and transition series. A high content of Na_2O is found in the transition redeposited deposits, and in the present subaqueous deposits of profile No. 1 near the Bystrzyca River mouth. The present subaqueous deposits examined in other profiles are similar in respect of their geochemical composition (Tab. 2).

Thickness of deposits and deposition rate

Thickness of the distinguished deposition units is different in the individual profiles (Tab. 1). In the case of redeposited humopeats with a large amount of gyttja it ranges from 20–25 cm (profiles No. 2 and 4) to 50 cm (profile No. 5). The thickness of the present reservoir deposits (calcareous-clayey gyttja) is distinctly asymmetric across the reservoir. It changes from 20 cm (profile No. 4) near the east shore to 65–70 cm in the central part (profile No. 2) and near the west shore (profile No. 5). Taking into account the 34-year-long period of the reservoir existence (1974–2008), the accumulation rate reaches „only" 0.6 cm/year in its eastern part, while in the central and western parts it is 1.9 and 2.1 cm/year, respectively. The greatest thickness of the present reservoir deposits is found in profile No. 1 (85 cm) near the river mouth and No. 3 (80 cm) near the dam. Mean annual deposition here is 2.5 and 2.4 cm, respectively. The top parts of deposits in these profiles are strongly saturated with water, which indicates a considerable supply of material by currents connected with inflow and outflow of water (Tab. 1).

Taking into account overrepresentation of profiles with the greatest thickness, the mean thickness of the present deposits in the Zemborzyce Reservoir is estimated at 59.4 cm, with mean deposition rate of 1.75 cm/year (Tab. 3). Based on these results, the volume of annual accumulation is calculated at $48.5 \cdot 10^3$ m^3, and total deposit volume at $1.65 \cdot 10^6$ m^3. With such a rate of regular accumulation,

Table 3. Selected physico-chemical features of the present bottom deposits of the Zemborzyce Reservoir

Feature	Measure	Minimum	Maximum	Mean
Thickness	cm	20	85	59.4
Sedimentation rate	cm r^{-1}	0.6	2.5	1.75
Bulk density*	g cm^{-3}	0.17	0.45	0.27
Ash content	%	88.27	92.77	90.9
Organic matter content	%	7.33	11.73	9.13
$CaCO_3$ content	%	6.53	53.55	42.4

* in 105ºC

the reservoir would be filled with deposits to the datum of low water (177.5 m) after 44 years, i.e. in the 2050s. The assumption of steady and non-differentiated rate of deposition in the whole reservoir is a considerable simplification justified by the importance of the problem and the small number of data.

Density of deposits and sedimentation mass

Bulk density of the collected deposits, calculated for 105°C, is very varied, both laterally and vertically (Tab. 2). The greatest density (1.20 g cm^{-3}) is found in substratum sands (profile No. 3), while substratum peats are less compact (0.15–0.17 g cm^{-3}). The density of transition redeposited deposits is very variable (0.08–0.57 g cm^{-3}), and distinctly dependent on the thickness of the overlying reservoir deposits. When the reservoir was filled with water, the decomposed top part of peats probably was loosened (rose), and now they become compact under the pressure of accumulated deposits. Less differentiated is the density of the present reservoir deposits (0.22–0.27 g cm^{-3}), except for two outermost profiles (No. 1 and 3) with the greatest thickness. Near the dam the density of deposits increases with depth (0.17→0.43 g cm^{-3}). Near the Bystrzyca River mouth the reservoir deposits are characterized by density inversion (0.45→0.28 g cm^{-3}) caused by the encroachment of alluvial fan on the mostly biogenic deposits (Tab. 2).

Table 4. Mass balance of the deposits in the Zemborzyce Reservoir and supply of material (in $Mg \cdot 10^3$) calculated from different data

Kind of material	Transport or source of supply	Amount of supply			Sedimentation		
		$Mg \cdot 10^3$		Content in %**	$Mg \cdot 10^3$		Content in %
		annual	total		annual	total	
Organic	in situ*	-	-	-	1.2	40.7	9.1
Carbonate	fluvial	23.8	809.2	-	5.6	189.0	42.8
Ion sum		29.2	992.8	-	-	-	-
Clastic		4.4	149.6	69.0	6.3	215.8	48.5
	aeolian	0.15	5.2	2.4			
	wash	0.08	2.7	1.3			
	abrasion	1.63	55.5	25.0			
Total		35.5	1205.8	97.7	13.1	445.5	100

* mostly primary production in the reservoir
** calculated as percentage of total clastic sedimentation
– don't apply or lack of data

The mean density of the reservoir deposits, calculated from five profiles, is 0.27 g cm^{-3} at 105°C. Based on this result, their total mass was estimated at $445.5 \cdot 10^3$ Mg. The organic deposits constitute $40.7 \cdot 10^3$ Mg, and carbonates – $189.0 \cdot 10^3$ Mg. Therefore, the mass of other deposits, mostly clastic ones, is $215.8 \cdot 10^3$ Mg. The annual increase of the deposit mass is $13.1 \cdot 10^3$ Mg, in it $1.2 \cdot 10^3$ Mg of organic deposits, $5.6 \cdot 10^3$ Mg of carbonates, and $6.3 \cdot 10^3$ Mg of clastic deposits (Tab. 4).

DISCUSSION

Mechanism and conditions of sedimentation

The samples of deposits taken in the first years of the reservoir existence in the late 1970s contained material from disturbed substratum. This is evidenced, among other things, by increase of concentrations of most elements in the cross-section from west to east [Misztal and Smal 1980], similarly as in the redeposited deposits (Tab. 2). This tendency was not found in the reservoir deposits collected in 1999 [Ligęza *et al*. 2004, Ligęza and Smal 2005, Smal and Ligęza 2006] and in 2009 (Tab. 2). Based on the grain size composition, Ligęza and Smal [2002] characterized the reservoir deposits as silts or clayey silts. In the profiles situated near protruding promontories they contain a considerable admixture of sand, sometimes even exceeding 30%. The deposits sampled in 2009 were mostly biogenic, described according to the Troels-Smith code as calcareous-clayey gyttja (Tab. 1). Calcium carbonate in limnic deposits occurs mostly as calcite. Precipitation of $CaCO_3$ from water accompanies assimilation and physicochemical processes. On macrophytes, especially Charophyceae, even coarser sandy fractions of $CaCO_3$ can form [Tobolski 1995, Borówka 2007, Rutkowski 2007]. Decalcification of water flowing into the Zemborzyce Reservoir and embedding calcium ions in phytobiomass during the process of primary production was found [Radwan (ed.) 2006].

Low content of carbonates was found only in the deposits developed as clayey gyttja near the Bystrzyca River mouth, where sedimentation of river suspension prevails (Tab. 2). It is partially carried farther by the current flowing across the reservoir with lower velocity than the river current [Choiński 1995]. When water temperature in the Reservoir and in the Bystrzyca River is different, or suspension concentration increases during high water stages, this current, as gravity current, can use an old channel [Michalczyk (ed.) 1997, Radwan (ed.) 2006]. Gradual deposition from suspension is evidenced by the decrease of silt content and the increase of clay content in the bottom deposits from the Bystrzyca River mouth toward the dam [Ligęza and Smal 2002]. Deposition is favoured by a considerable electrokinetic potential of colloidal particles [Cieśla 2008]. It can be the cause of higher content of mineral material, in comparison with organic material, in the Zemborzyce Reservoir deposits, their greater density and lower water saturation than in the deposits of the Turawa Lake on the Mała Panew River [*vide* Teisseyre 1984]. Specific density is usually inversely proportional to the content of organic carbon, which was also confirmed by Ligęza and Smal [2005].

Typical clastic deposits, formed mostly by abrasion of shores caused by waves, probably predominate in the littoral zone of the Zemborzyce Reservoir. Less important is exaration by ice cover during winters with changeable weather conditions, e.g. during the winter of 1998/99. Abrasion is especially intensive in the first years of existence of dammed reservoirs, before the wave-cut platform is formed [*vide* Banach 1981]. Sand is sometimes transported by floating due to water surface tension. Finer material is mostly carried by density currents which form during strong winds rippling water surface [*vide* Teisseyre 1984].

In the Lublin environs the winds from western sector are predominant, especially as far as strong winds are concerned [Kaszewski 2008]. The Zemborzyce Reservoir is exposed from the west to strong wind, and mostly its eastern shores are subjected to wave action. The reservoir is only 800 m wide but at some wind directions the wave run-up can be two times longer (Fig. 1). During strong wind the wave-base and mixing zone can reach the bottom and disturb deposits near the eastern shore, especially late in autumn when the water level is lowered before the winter. Wind and waves cause a rise of the water level resulting in the formation of a compensatory near-bottom current with the opposite direction to the wind [*vide* Choiński 1995]. This kind of current in the Turawa Lake reaches the velocity of 0.2–0.4 m s^{-1} that is enough to cause erosion and to transport bottom deposits which are again put into circulation [Teisserye 1984]. Such a circulation undoubtedly causes a shift of the deposits in the Zemborzyce Reservoir resulting in their 3.5 times greater thickness in the western side in comparison with the eastern side. In the lakes of the Lublin region such a direction of asymmetric limnic deposition is common, and the rate of natural Holocene accumulation was lower by one order of magnitude [Okruszko *et al*. 1971, Bałaga *et al*. 1995].

It seems that the mouth of the Bystrzyca River and the vicinity of the dam are well protected against wave action. This fact is confirmed by the thickness of deposits and water saturation of their top parts that evidence quiet accumulation (Tab. 1). In profile No. 3, situated near the dam, the density of the reservoir deposits increases 2.5 times with the depth but other physical features are almost identical (Tab. 2). This fact indicates a considerable compaction that does not occur in limnic deposits with thickness < 3 m [Teisseyre 1984]. However, the difference in hydrostatic pressure in the substratum on both sides of the dam can cause intensive infiltration of water by suction and simultaneous compaction and leaching of deposits. This is indicated, among other things, by the decrease of the CaO concentration in the profile with depth (Tab. 2).

Sources and amount of material supply

The amount of mineral material supplied by river water was estimated based on the published measurement data. Mean solute concentration of the Bystrzyca River in the years 1981–1990 in the Zemborzyce measurement point was 331 g m^{-3} [Świeca 1998]. Thus, $29.2 \cdot 10^3$ Mg of mineral material is annually supplied as solute to the Zemborzyce Reservoir, and the total supply during 34 years has reached $992.8 \cdot 10^3$ Mg. A similar value resulted from the annual index of chemical denudation estimated in the Bystrzyca River catchment at about 40 Mg km^{-2} [Maruszczak *et al.* 1992]. Dissolved material is composed mostly of calcium carbonate originating mainly from leaching of rocks in the catchment. The content of $CaCO_3$ in water supplied from the Cretaceous horizon is about 270 g m^{-3} [Janiec 1997, Michalczyk (ed.) 1997], so 23.8·10^3 Mg of calcium carbonate can be supplied annually to the Zemborzyce Reservoir by the river (totally 809.2·10^3 Mg). The other components of dissolved material are: magnesium carbonate from denudation, and chlorides, sulphates, phosphates, nitrates and nitrites mostly from agricultural, municipal and industrial pollution [Michalczyk (ed.) 1997, Raport… 2002]. Besides, a considerable amount of different biogenic material gets to the water as e.g. bait for fish [Radwan (ed.) 2006].

The Bystrzyca River to the north of Lublin is estimated as extremely polluted [Świeca 1998], while to the south of Lublin, in respect of some indices, it is classified even in water quality class I [Raport… 2002]. However, only the substances from denudation can cause eutrophication of water in the reservoir. This is evidenced by high rate of sedimentation and high content of carbonates in deposits retaining 23.4% of calcium carbonate that is supplied from the catchment (Tab. 4). In the Bystrzyca River downstream of the Reservoir the content of mineral components considerably decreases, and that of biogenic material increases [Michalczyk (ed.) 1997, Raport… 2002, Radwan (ed.) 2006]. However, the number of data is too low to calculate the discharge of substances from the Reservoir. Taking into account the sedimentation conditions, it can be stated that discharge of terrigene material is very small.

In the years 1995–2000 mean annual concentration of suspended sediment in the Bystrzyca River in Zemborzyce was 15.5–62.5 g m^{-3} [Raport… 2002]. If we assume that the mean value from these years (32.2) is representative, the annual supply of suspended material is 2.84·10^3 Mg, and the sum for 34 years – 96.6·10^3 Mg. We also have to consider traction transport, the ratio of which to suspended sediment transport is 1 to 10 in upland rivers [Świeca (ed.) 2004]. Taking that into account, the amount of annual supply is 3.12·10^3 Mg, and total supply – 106.1·10^3 Mg. The latter value corresponds to 49% of clastic material accumulated on the bottom of the Reservoir, and it is underestimated, which results, among other things, from the calculation method not considering synchronicity of extreme discharges and concentrations of suspended sediment. This is confirmed by the comparison with annual index of mechanical denudation in the central part of the Lublin Upland (5–6 Mg km^{-2}), calculated from river transport of suspended material [Maruszczak *et al.* 1992]. Taking into account the catchment area, the obtained annual supply is 3.63–4.35·10^3 Mg. Adding the mean annual supply of suspended material (4·10^3 Mg) and 10% of this value (traction transport) we obtain 4.4·10^3 Mg of annual supply, and 149.6·10^3 Mg of total supply during the whole period of the reservoir existence. The river supply of mineral material calculated in this way is only 69% of the mass of clastic deposits in the Reservoir. These values indicate that supply from other sources is also important, i.e. shore abrasion, runoff from field and roads, and aeolian transport (Tab. 4).

Aeolian deposit on ice covering the Zemborzyce Reservoir was observed during dry winters (e.g. 1975/76). Mean annual dust (mostly mineral) deposition on cultivated fields of the Lublin Upland was 246.6 g m^{-2} in the years 1982–1990 [Repelewska-Pękalowa and Pękala 1991]. As short transport from local sources predominates, accumulation on non-eroded surfaces, such as meadows and also water reservoirs, is 4–5 times smaller. So on average 152 Mg of dust can fall annually on the area of the Reservoir, and during the whole period of its existence – $5.2 \cdot 10^3$ Mg, i.e. 2.4% of non-carbonate mineral bottom deposits (Tab. 4).

Railway and roads, parallel to the shore, limit the direct catchment of the Zemborzyce Reservoir to about 200 ha of forest used for recreation, about 50 ha of built-up and grass-covered area, and about 25 ha of fields that were cultivated until recently (Fig. 1). The supply of material from this catchment was estimated basing on the data from the Łódź Upland [Twardy 2008] that is similar in relief and cover deposits. Taking into account crop rotation, the mean annual runoff (surface wash) from fields under cultivation was estimated at 1.58 Mg ha^{-1}, and from built-up, grass covered and forest areas – at 0.073 Mg ha^{-1}. The annual supply from the Reservoir direct catchment is 80.6 Mg, and total supply – $2.74 \cdot 10^3$ Mg, i.e. 1.3% of mineral bottom deposit (Tab. 4).

Sands from the scarps of higher terraces are the predominant component of abraded material. Sand fraction constituted 12% of bottom deposits sampled in 1999 [Ligęza and Smal 2002]. Finer fractions were not taken into account but it can be balanced by smaller supply after stabilization of shores. For comparison – abraded material constituted 20% of the whole sedimentation in the Włocławek Reservoir after 10 years of its existence [Banach 1981]. So if abraded material constitutes 12% of the deposit mass in the Zemborzyce Reservoir at present, i.e. $53.5 \cdot 10^3$ Mg, it is 25% of mineral clastic deposits (Tab. 4). Altogether the estimated supply of terrigene material from river transport, aeolian transport, abrasion, and surface runoff constitutes 98% of clastic deposit mass. The amount of organic matter from these sources was not subtracted as it can be balanced by biogenic non-carbonate mineral deposition in the form of diatoms or iron compounds.

CONCLUSIONS

Based on the analysis of physicochemical features of the bottom deposits in the Zemborzyce Reservoir, the functioning of the reservoir in local environmental conditions was estimated in comparison with examples of other reservoirs in Poland. Because of the scant research material, only a general estimation and an approximate balance were made. However, that enables us to define the role of individual sources of material supply, to evaluate the condition of the reservoir, and to make a preliminary forecast of its further evolution.

The mechanism of sedimentation in the Reservoir is complex because biogenic, fluvial, littoral, and aeolian deposits are deposited and redeposited in it.

The majority of the deposits are formed in the Reservoir from the substances supplied by river water. The rate of present sedimentation, conditioned by high eutrophy, results from fertility of water flowing to the Reservoir, which supplies mineral compounds mostly from denudation and in small part from anthropogenic pollution. The content of terrigene clastic material in the bottom deposits, which is still high, should gradually decrease. The supply is reduced due to stabilization of the Reservoir shores, and renaturization of the catchment environment by lying fallow and afforesting of plough lands and less intensive use of meadows.

The high rate of filling up poses a threat that the essential functions of the reservoir will be lost in the foreseeable nearest future, and the operating costs of a useless reservoir can rise. Due to the mostly natural character of mineral material supply it is difficult to reduce it, and thus to restrict the formation of deposits. Exploitation of the deposits and use, e.g. as fertilizer, can be an alternative.

The decision about the kind of activities (or about abandoning them) should be preceded by thorough, detailed research. It is necessary to examine in detail the deposits and sources of material supply, as well as the mechanisms and conditions of sedimentation. The proximity of Lublin, big academic centre, gives possibilities to undertake several years' monitoring. An interdisciplinary team should be composed of scientists representing different environmental sciences: hydrology, hydrobiology, geochemistry, geomorphology, sedimentology, meteorology, and the like.

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OCENA WIELKOŚCI, JAKOŚCI I MECHANIZMU SEDYMENTACJI W ZALEWIE ZEMBORZYCKIM K. LUBLINA

Streszczenie. Praca przedstawia wyniki badań osadów dennych, akumulowanych w ciągu 34 lat funkcjonowania zbiornika na Bystrzycy koło Lublina. Na podstawie analizy pobranych rdzeni o nienaruszonej strukturze wykonano rozpoznanie litologiczne i wielkości sedymentacji. Na podstawie analiz laboratoryjnych wykonano rozpoznanie geochemiczne oraz określono genezę osadów. Przedstawiono mechanizm sedymentacji, określono tempo i główne źródła dostawy materiału oraz sporządzono ogólny bilans dostawy materii do zbiornika.

Słowa kluczowe. Zalew Zemborzycki, zbiorniki zaporowe, sedymentacja zbiornikowa