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CHANGES IN GEOMORPHOLOGY OF NEW SHORELINE AFTER THE FILLING OF THE WŁOCŁAWEK ARTIFICIAL LAKE

Abstract: This long-term (35 year) study of the coastal zone of the Włocławek Reservoir on the River Vistula presents three stages in its evolution: 1) acceleration of the transformation rate, 2) variable falling rates of transformation, 3) a dynamic equilibrium. These stages may be regarded as typical for medium sized lowland valley artificial lakes (20-100 km^2 in area and 0.1-1.0 km^3 in volume) with low water level fluctuations (annual amplitudes of ≤ 1 m, and daily amplitudes of 10-20 cm).

Key words: lacustrine bank transformation, abrasion, landslides, Włocławek Reservoir.

1. Introduction

Dam lakes, mostly built during the second half of the 20th century, constitute important hydrographic features. Their combined area of 400 000 km^2 accounts for 15.4% of the overall lake area and the 6500 km^3 of volume accounts for nearly 4% of overall lake volume (Avakian 1998). In Poland the respective percentage values are even greater at 365 km^2 (17.8%) and 3.6 km^3 (20.7%) (*Atlas hydrologiczny...*.1986).

When a dam or a step structure is erected, a new phase of river bank transformation begins with the higher water surface levels. The scale and form of this transformation depends on the lake size, physical geography of the valley and dam operating regimen.

Lake Włocławek is a lowland, valley type through-flow water body of medium size on a world scale; it is also Poland's largest lake by area (70 km^2) and second largest by volume (408 million m^3). Its water level fluctuations are irregular but low (the annual amplitude ≤ 1 m, and daily amplitude of 10-20 cm).

Many other artificial lakes in Poland (Zegrzyński, Koronowski, Jeziorsko, Siemianówka, Krzynia, Konradowski and Bytowa) and abroad (Nehranice in the Czech Republic, Orawa in Slovakia, Gorkowski, Irkucki and Bracki in Russia) have had studies made of their banks. In most cases these were short-term one-off studies, sometimes limited to geodynamical mapping of selected bank sections. The one artificial lake bearing the most resemblance to the Lake Włocławek in terms of its bank landform, geology and water level fluctuations, and the best researched, is Lake Zegrzyński on the River Narew. Other lakes differ in terms of size, water level fluctuation and age.

As coastal zone research in the artificial lakes has developed, attempts have been made to identify periods, phases, stages and cycles in the course of their evolution. Abrasion was chosen as the lead criterion in those identifications. At first, two periods were identified: 1) unstable development, i.e. the youthful period, 2) stable development, i.e. the maturity and old age period (Vendrov 1979). Almost at the same time other terminology was used: 1) bank formation driven by abrasion, 2) stabilisation driven by accumulation (Shirokov 1984). As understanding of the coastal zone developed, those initial periods were subdivided into shorter units, i.e. stages, cycles, phases and legs (Finarov 1986). There are few available long term studies of a single site (dam lake) by a single research team in Poland and worldwide. Most of the studies involve one-off or short-term studies spanning several years at most. On the other hand, there are many forecasts that nearly nobody verifies. This paper is an attempt to generalise coastal zone change in time.

2. Method

Lake Włocławek on the Lower River Vistula has the longest history of coastal zone research of all those lakes about which material has been published in Polish literature. For the first 22 years after the completion of the filling operation in 1970, many aspects of the coastal zone were studied systematically (Banach 1994), after which they have been studied periodically over the last 13 years (1992-2005). Geodesic surveys of coastal zone changes were performed along dozens of transects. Both the submerged and exposed parts of the banks were repeatedly levelled while points on the surface of landslides (e.g. trees, pipes, boulders and building foundations) were surveyed with a tachymeter from at least two locations outside the landslides. On a few occasions, geodynamic mapping was performed, each time identifying the boundaries of the various bank types. Aerial photos from various periods were also employed. During 1969-1998, a research project was carried out by the Institute of Geography and Spatial Management of the Polish Academy of Sciences in Toruń, which was followed by seven years of studies at the Institute of Geography at Słupsk Teacher Training College (Pomorska Akademia Pedagogiczna w Słupsku), as part of its own and statutory activities.

3. Research results

In 1970, following the completion of the filling of the lake behind the dam, the River Vistula water level rose by nearly 11 metres and its width more than doubled. Median islets were covered. The continuous water body was 1.2-2.0 km wide and 30 km long. Its depth considerably increased especially along steep formerly high erosion banks. The slopes were permeated with water up to the water level reducing their compactness and the friction between deposit particles. Initially the littoral zone corresponding to the path of oncoming waves was quite deep allowing high-energy waves to strike and expend that energy in the process of washing and degrading the banks. Crevices, land slumps, downfalls and new landslides developed along the steep slopes close to the waterline and the development rates of existing mass movement landforms accelerated. This happened primarily on the right bank of the lake between the city of Płock and the town of Włocławek, thus forming the largest area of continuous landslide on the Polish Lowlands (Banach 1977, 1985).

The large open lake favoured the development of waves which during the first years after the completion of the lake damaged the banks at a much faster rate than the earlier floodflow erosion of the River Vistula. Such a vast scale of destruction was caused by the lack of a gradual slope foot, which would have played a stabilising and supporting role. At a time of rough water, the wash tide found no obstacles and poured onto the banks damaging them, while currents flowing along the banks transported the sorted material to greater depths and bays that were much more numerous than today.

A detailed analysis of the data collected during the course of the surveys and investigations of the coastal zone transformations over the full 35 years that the Włocławek dam has operated leads to the identification of three stages (legs): 1) an accelerating rate of transformation, 2) variable falling rates of transformation, 3) a dynamic equilibrium.

The first stage lasted three to eight years and involved an acceleration of the rates of bank and slope processes (Figure 1). In parallel to the degradation of the high and steep banks, deposits were accumulated in the littoral zone and transferred *en masse* away from the bank towards greater depths. The high banks were the fastest to recede. The largest amount of washed deposits were transported to deep areas and bays (Table 1, Figure 2). The landslide material was moving at the rate of 2.6-3.6 m per year in the central and lower parts of the landslides surveyed, i.e. nearly 40% faster than before the filling of the lake (Table 2). This was caused by an increase in the washing rate of the colluvia deposited on the lake banks. The intensity of the washing even exceeded 20 m^3 per year, per running meter of high cliffs (Table 1). As this stage came to an end, abrasion began along the low and gradual banks that until then had only been degraded, or ‘licked’ by the waves, at a very slow rate. This was the stage of forming new banks of the River Vistula or the stage of unstable development, or the youthful stage (Vendrov 1979).

During the second stage, lasting between nine and 12 years, the intensity of bank abrasion and landslide activity varied but tended to subside overall (Figure 1). The coastal shallows grew to a sizable area (16-20 metres in width) and an increasing proportion of the deposits washed by the waves were transported along the bank rather than away from it to the depths. Point bars formed in the bays and on the lee sides of convex bank forms. Mouths of canyons and small valleys were cut off by sandbars and the resulting lagoons were slowly filled with deposits from permanent and periodic watercourses. The length of lithologically uniform bank sections materially increased, along which bedload travelled over the coastal shallows. In sections with landslides the waterline, which had previously receded, began to move lakewards as a result of a considerable reduction in the rate of abrasion. The rate of slope processes dropped to 1.0-1.7 m per year, i.e. below the rate prior to the damming of the river (Table 2).

After 12 to 20 years, the coastal zone reached a dynamic equilibrium in its third development stage where both the slope and bank processes (bank abrasion and accumulation) slowed down considerably. The coastal shallows had already been fully developed with

Table 1. Bank abrasion on the Lake Włocławek at Dobrzyń

No	Section	*km of Wisła course	Lithology	Age	Bank-cliff hight [m]		Period	Number of years	Abrasion			
									Linear [m]		Volumetric [m³ per running meter]	
					Minimum-maximum	Average			Sum	Annual average	Sum	Annual average
1	Dobrzyń	661.9	kol	Q, Pl	1.4-2.6	2.0	1977-92	15.9	11.8	0.7	16.9	1.1
					0.2-2.6	1.3	1970-92	21.9	41.9	1.9	52.2	2.4
2	Dobrzyń	661.4	g	Q	4.7	4.7	1977-92	15.8	1.4	0.1	6.6	0.4
					4.7-4.5	4.6	1970-92	22.1	6.4	0.3	27.4	1.2
3	Dobrzyń-Góra Zamkowa	661.1	kol	A, Q, M	45.0	45.0	1977-92	16.0	7.0	0.4	315	19.7
					45.0	45.0	1970-92	22.1	**12.0	0.5	495	22.4
4	Dobrzyń	660.8	i	Pl	0.5-1.5	1.0	1970-92	22.1	32.6	1.5	32.6	1.5
5	Dobrzyń Zjazd str.	660.6	pł, g	Q, Pl	6.0	6.0	1977-92	16.5	4.0	0.3	24.0	1.5
					3.0-6.0	4.5	1970-92	22.0	12.4	0.6	55.8	2.5
6	Dobrzyń	660.0	i	Pl	2.0-6.0	4.0	1970-92	22.0	19.0	0.9	76.0	3.4
1-6	6 sections				0.5-45.8	11.8	1970-92	22.0	14.9	0.7	110.2	5.6

Explanations: * – kilometrage in 1970; ** – average value for whole cliff. Lithology: pł – dusts, I – loams, g – clays, kol – colluvia. Age: A – Anthropogene, Q – Quaternary, Pl – Pliocene, M – Miocene.

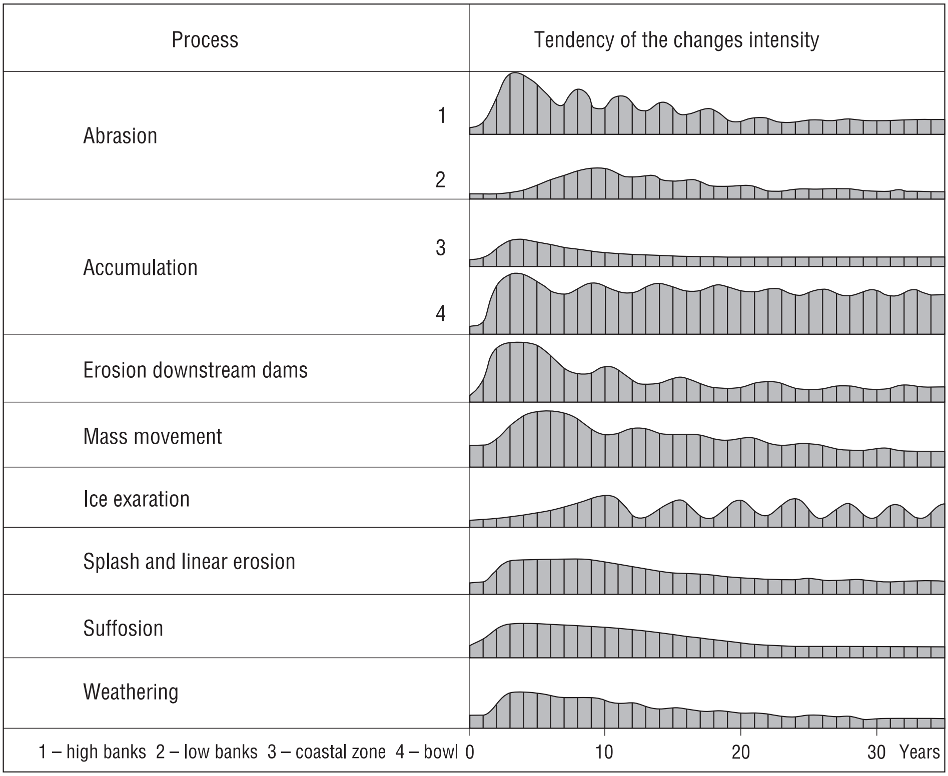


Figure 1. Course of geomorphological processes on Lake Włocławek

stable surfaces, as indicated by the existence of submerged plant life and benthos, especially Zebra Mussel (*Dreissena polymorpha*), which requires a stable subbase and is sensitive to sandy bedload movement which irritates and hurts its filtration system. Vegetation colonised the tops of the high cliffs and inactive downfalls and screes and the sharpness of the landslide morphology was largely softened. The intensity of certain slope and bank processes, such as landslides, rainwash and linear wash, as well as weathering, dropped below that from prior to the filling of the lake. This had primarily been caused by:

– a sixfold reduction in the River Vistula water level fluctuation to one metre from a former six metres,
– a reduction in the river surface gradient and flow rate,
– a reduction in the underground water level gradient and fluctuation amplitude,
– the development of a coastal shallows, which has effectively replaced the submerged slope foot and plays a stabilising role helping expend wave energy,
– a nearly complete abandonment of the utilisation of slopes for more than 18 years now, (for cattle grazing, harvesting grass, crops and orchards) helping their revitalisation. This stage will last for decades.

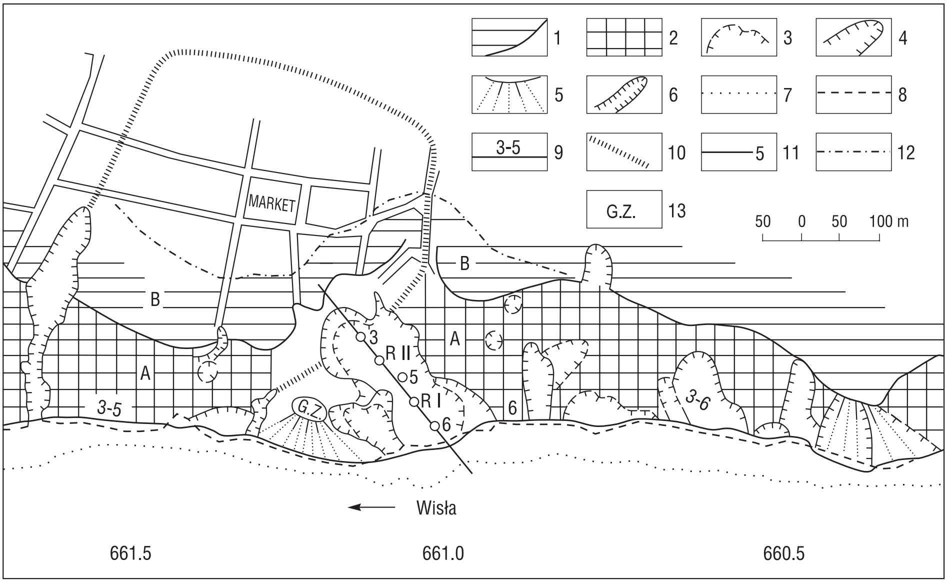


Figure 2. Morphodynamic map of the Vistula valley slope at Dobrzyń

Explanations: 1 – edge of morainic high plain, 2 – old inactive landslides, 3 – landslides active before the Vistula dam construction (until 1970), 4 – landslides formed after the Vistula dam construction (1970-1983), 5 – slope earth falls and screes, 6 – erosion incisions, 7 – the Vistula bank before damming (1964), 8 – the Vistula bank after damming (1970), 9 – the Vistula bank in 1983, height of cliff in m, 10 – former moat, 11 – the axis of the central slide with the location of the points examined, 12 – range of relative safety of the escarpment (slope) according to A. Kühn (1973): A – danger zone, B – relative safety zone, 13 – Góra Zamkowa.

Source: Banach 1985, generalized.

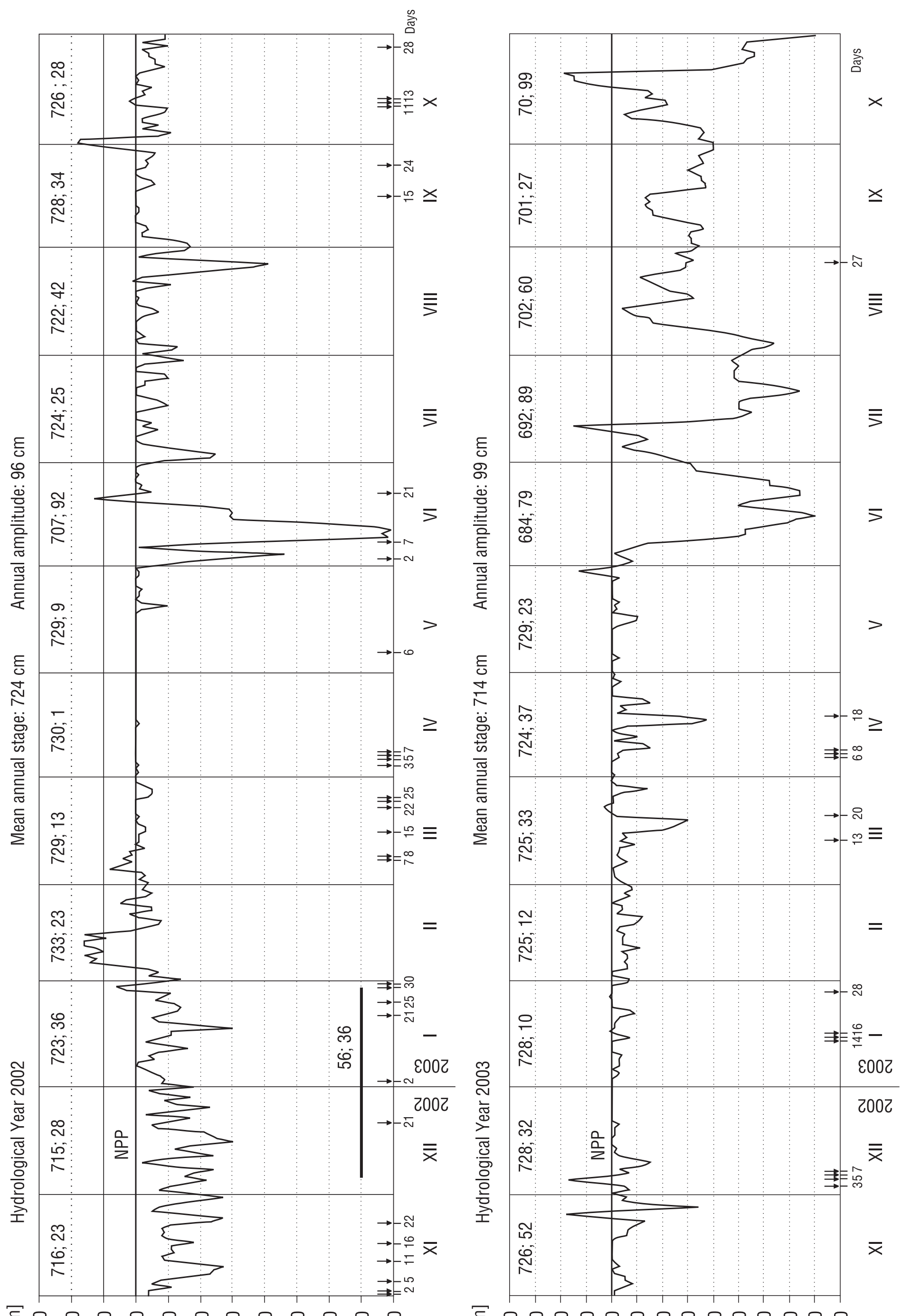
Table 2. Horizontal displacement (in metres) at the selected survey points (see figure 2); the central landslide at Dobrzyń in 1959-2002

No	Period	Number of years	5		6		R_I		R_{II}	
			Sum	m/year	Sum	m/year	Sum	m/year	Sum	m/year
1	1959-1970	11.00	-	-	29.00	2.60	-	-	-	-
2	1970-1974	4.13	10.54	2.55	15.00	3.63	-	-	-	-
3	1972-1982	9.50	-	-	-	-	24.50	2.58	-	-
4	1974-1982	7.42	-	-	-	-	-	-	18.50	2.49
5	1974-1983	8.38	21.20	2.53	27.20	3.25	-	-	-	-
6	1982-2002	20.68	-	-	-	-	33.00	1.60	36.00	1.74
7	1983-2002	19.63	27.50	1.40	19.00	0.97	-	-	-	-
8	1970-2002	32.21	59.22	1.84	61.00	1.89	-	-	-	-
9	1972-2002	30.17	-	-	-	-	57.50	1.91	-	-
10	1974-2002	30.08	-	-	-	-	-	-	54.50	1.81

Some publications predicted (Banach 1994, 1998) that this state of dynamic equilibrium might only be upset locally during a longer spell with a high water level and concurrent strong wave action at a time of intensive rainfall accompanied by reduced evaporation, i.e in wintertime or early spring. This is what happened in 2001 and even more in February 2002 when unusually high precipitation during two years in a row caused a considerable increase in moisture content in the slope and bank formations. With a total precipitation of 827 mm, 2001 was the record year during the 35 years of the lake's existence. The year 2002 was less wet (621 mm), but it featured an extremely heavy rainfall during wintertime when the February total of 101 mm exceeded the thirty year average (1971-2000) by a factor of 4.7. A substantial and permanent increase in the headwater height on the Vistula between February 2002 and early June 2003 by nearly 20 cm as compared to the average in 2001 and before (Figure 3) coincided with the wet period additionally enhancing the 'loosening' effect of the deposits along the water line and on the slopes. As a result bank abrasion intensified and landslides were revived, especially in the winter seasons of 2002 and 2003. However, the activation of the slope and bank processes represented just a minor 'momentary' episode in the overall trend which subsided with time.

The three stages of the Lake Włocławek bank transformation discussed above and their duration could be compared to other artificial lowland, valley-type lakes of medium size featuring similar water level fluctuations ($\leq$ 1 m per year). With the increase of a water body's area and its water level fluctuation, the duration of individual development stages grows. After ten years of operation, for example, Lake Jeziorsko on the River Warta still remains in its first stage of development as a result of its considerable annual water level fluctuations of 3.9-5.6 m recorded during 1995-1999 (Banach, Grobelska 2003). The coastal zone of Lake Bratsk on the Angara (Russia), which has been in existence for forty years now, is only now entering the second stage of its development because of its area (5470 km^2), but even more because of the large amplitudes of its water level fluctuations of four metres annually, but up to ten metres in the long term (Ovchinnikov et al. 1999). The coastal zone of the dam lakes in the River Słupia cascade, because of their small size (< 2 km^2) and water-level fluctuations (< 0.5 m in a year), reached their equilibrium after more than ten years. Today, after 80 years, the lakes, dams and hydrotechnical and power equipment constitute cultural heritage objects enhancing the value and ranking of the Dolina Słupi (Słupia Valley) Landscape Park.

The article does not consider the evolution of the coastal zones on artificial mountain lakes which normally are situated among high and steep slopes and feature high water level fluctuations (up to several dozen meters). Slope and bank processes are already activated along almost the entire perimeter of the water body during the filling stage (Kuskovsky, Khabidov 2002). Following the completion of the filling stage, during normal operation, the accumulation of material from degraded slope waste mantles accelerates. The coastal shallows are characterized by a step profile and significant gradient (up to 10^{o} or more). Landsliding is commonplace on the banks of artificial mountain lakes. The transformation process of the coastal zone tends to be longer and the reaching of the dynamic equilibrium stage normally takes decades.



Hydrological Year 2002
Mean annual stage: 724 cm
Annual amplitude: 96 cm
716; 23
715; 28
723; 36
733; 23
729; 13
730; 1
729; 9
707; 92
724; 25
722; 42
728; 34
726 ; 28
NPP
56; 36
2002
2003
XI
XII
I
II
III
IV
V
VI
VII
VIII
IX
X
Days
[cm]
Hydrological Year 2003
Mean annual stage: 714 cm
Annual amplitude: 99 cm
726; 52
728; 32
728; 10
725; 12
725; 33
724; 37
729; 23
684; 79
692; 89
702; 60
701; 27
70; 99
NPP

4. Conclusions

– The influence of dam lakes on their coastal zone is best understood because of the evident, spectacular nature of the bank transformation process and the threat to the land infrastructure. The influence on other components of the river valley environment, such as water quality, soils, climate, settlement and land use, is less evident and rapid, and thus less well understood.

– The coastal zones of small (≤ 2 km^2), minor (2-20 km^2) and medium sized (20-100 km^2) lowland dam lakes reach their dynamic equilibrium stage approximately 10-20 years from the filling of the lakes; the greater the water level fluctuation the longer the process takes.

– On lowland dam lakes with minor but irregular water level fluctuation (≤ 1 m) in the moderate climatic zone, exaration (glacial erosion) remains an important factor where destruction is achieved as a result of the thermal and dynamic influence of a continuous ice sheet (Banach 1988, 1994, Gierszewski 1988). The impact of this factor is difficult to forecast.

– Low and gradual banks are subject to abrasion and exaration at a clearly later stage than high and steep banks. This pattern is true of all types of dam lakes regardless of their size and water management (Banach, Spanila 2000, Ovchinnikov et al. 1999, Ovchinnikov et al. 2002).

References

Atlas hydrologiczny Polski, 1986, t. 2, z. 2, Wyd. Geol., Warszawa.

Avakian A.B., 1998, *Problematyka zaporowych zbiorników wodnych*, Przegląd Geogr., 70, 1-2.

Banach M., 1977, *Rozwój osuwisk na prawym zboczu doliny Wisły między Dobrzyniem a Włocławkiem*, Prace Geogr. IGiPZ PAN, 124.

Banach M., 1985, *Geodynamika zbocza doliny Wisły w Dobrzyniu*, Przegląd Geogr., 57, 4.

Banach M., 1988, *Główne procesy a osady w strefie brzegowej zbiornika Włocławek*, Przegląd Geogr., 60, 3.

Banach M., 1994, *Morfodynamika strefy brzegowej zbiornika Włocławek*, Prace Geogr. IGiPZ PAN, 161.

Banach M., 1998, *Dynamika brzegów dolnej Wisły*, Dokumentacja Geogr. IGiPZ PAN, 9.

Banach M., Grobelska H., 2003, *Stan dynamiki brzegów zbiornika Jeziorsko*, Słupskie Prace Geogr., 1.

Banach M., Spanila T., 2000, *Geodynamic evolution of water reservoir banks*, Acta Montana IRSM AS CR, Ser. A, 15.

Figure 3. The water level (in cm) of Lake Włocławek in the hydrological years 2002-2003

Explanations: In the upper part of the graph, the average monthly level; after semicolon – the monthly amplitude. In the lower part of the graph, thick horizontal lines represent periods of icing (days): the second number after the semicolon – maximum ice cover thickness (in cm). Over the lower line of the graph: the arrows which indicate an approximate average wind speed ≥ 5m·s^{-1}. NPP – normal (estimated) level of the Vistula River lift at the Włocławek dam.

Finarov D.P. (Финаров Д.П.), 1986, *Геоморфологический анализ и прогнозирование переформирования береговой зоны и дна водохранилищ*, Наука, Ленинград.

Gierszewski P., 1988, *Zmiany brzegów wywołane termicznymi ruchami lodu na przykładzie zbiornika Włocławskiego*, Przegląd Geogr., 60, 4.

Kuskovsky V.S., Khabidov A.Sh. (Кусковский В.С., Хабидов А.Ш.), 2002, *Особенности формирования берегов предгорных и горных водохранилищ Сибири*, [in:] *Геоморфология гор и предгорий*, Изд. Алтайского Университета, Барнаул.

Ovchinnikov G.I., Pavlov S.Kh., Trzhsinskiy Yu.B. (Овчинников Г.И., Павлов С.Х., Тржцинский Ю.Б.), 1999, *Изменение геологической среды в зонах влияния Ангаро-Енисейских водохранилищ*, Наука, Новосибирск.

Ovchinnikov G.I., Trzhsinskiy Yu.B., Rzętała M., Rzętała M.A., (Овчинников Г.И., Тржцинский Ю.Б., Жентала М., Жентала М.А.), 2002, *Абразионно-аккумулятивные процессы в береговой зоне водохранилищ (на примере южного Приангарья и Силезской возвышенности,* Фак. наук о Земле Силезского унив., Инст. земной коры Сибирского отделения РАН, Сосновец-Иркутск.

Shirokov V.M. (Широков В.М.), 1984, *Основные особенности процессов формирования берегов и ложа водохранилищ Сибири*, [in:] *Изменение природных условий под влиянием деятельности человека*, Наука, Новосибирск.

Vendrov S.L. (Вендров С.Л.), 1979, *Проблемы преобразования речных систем СССР,* Гидрометеоиздат, Ленинград.

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