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Adam Łajczak

DELTAS IN DAM-RETAINED LAKES IN THE CARPATHIAN PART OF THE VISTULA DRAINAGE BASIN

Abstract: Delta growth rates in dam-retained lakes depend as much on the volume and granularity of the supplied sediment material, as on the lake's capacity to permanently retain the sediment. The shape of deltas in these water bodies is influenced by the valley floor morphology and also by relationships between seasonal fluctuations in the lake's water level and the annual river water and suspended and bedload supply pattern. The fastest growing deltas form in long and deep valley lakes featuring a slow water exchange cycle and large amounts of material, mainly suspended. Nearly all of the deltas considered in this study are of the low-energy type, as they mainly consist of sandy and dusty material. The role of gravel can only be expected to grow as the lakes are gradually filled in with deposits. There is a difference between deltas forming in lakes with high water level fluctuations and in lakes with a more stable water level with the former forming a longer, smoother longitudinal profile without a discrete boundary between the topset, foreset and the bottomset. Such a fuzzy boundary is caused by a cyclical shifting movement of the zone with the most intensive process of alternating deposition and erosion which occurs at the boundary of the permanently submerged and periodically exposed part of the delta.

Key words: dam retained lake, delta, Flysch Carpathian Mts., suspended matter.

1. Introduction

The largest morphological impact of a valley dam is observed along the upper backwater reach just below the river mouth, where the current, drained of its carrying energy, deposits vast quantities of material (Gradziński et al. 1986, Bloom 1998). Deltas forming in this part of artificial lakes are classified as hyperpicnal because the flood flow density of the river (especially in summertime) is almost always greater than that in the lake. The fluvial material therefore drops near the bottom of the lake and forms a density current that may be deposited in the deep water environment at any point up to the dam (Gradziński et al. 1986, Bloom 1998, Bhattacharya 2003).

Deltas in dam-retained lakes grow rapidly providing an indirect indication of the large quantities of transported material and of intensified erosion in the drainage basins (Łajczak 1995). While rapid growth rates of dam-retained lake deltas are observed in various morphological and climatic zones, they are particularly high in semi-dry climates and in mountains or uplands with low forest cover and an agricultural land use (Głodek 1985).

This study aims to explain the conditions of delta development in large dam-retained lakes in the Carpathian portion of the River Vistula basin in southern Poland. Particular attention was paid to the possibility of delta development under the influence of mutual interaction between the seasonal cyclicality of the water level fluctuation in the lake and the seasonal differences in the water and material supply from the river. Against this background, differences were picked out in the conditions of delta development between dam-retained lakes and water bodies with more stable water levels. Earlier published research is available which investigates delta development in a study area including three dam-retained lakes with different silting rates (Klimek 1979, Klimek et al. 1989, 1990).

2. Data and methodology

The study is based on the author's own delta fieldwork, as well as an analysis of topographic maps and aerial photos featuring the dam-retained lakes, reviews of hydrological documents made available courtesy of the dam managers and of the state hydrological services. The author's and other studies into the rates of silting in dam-retained lakes in the Carpathians were also used.

3. Factors in the development of deltas in dam-retained lakes

Delta development rates depend on a number of factors, such as (Łajczak 1995): the supply of material and its granularity, the intensity of washing away of the lake banks within the delta, the size and shape of the lake, its morphological situation (valley, basin, foreland), water exchange cycles in the lake (e.g. annual), frequency and intensity of resuspension through wave action, the location of spillways on the dam structure and the frequency of a partial or complete emptying of the lake. This multitude of conditions decides whether the deposits accumulated in the delta are permanent or periodic and may expose them to periodically intensified erosion (Łajczak 1995, 1996). The quantity of deposits accumulated in the delta depends as much on the volume and granularity of the material supplied by the river, as on the lake's capacity to permanently retain such deposits that is defined by the shape, hydrological parameters and water management of the lake. Delta morphology, in turn, is influenced by the shape of the valley floor prior to the erection of the dam, the landform energy in the drainage basin, water level fluctuations and horizontal movement of water in the lake. This is why deltas in dam-retained lakes of the Carpathian Vistula drainage basin mostly belong to the low-energy type, according to criteria given by Postma (1990) and by Orton and Reading (1993).

Deltas in dam-retained lakes develop as a result of the extension of the lake bank from the river confluence towards the lake, built up with predominantly or exclusively fluvial material (Allen 2000, Bhattacharya 2003). In the Flysch Carpathian Mts. suspended matter, mainly silty-clayey in nature, constitutes up to 90% of the overall mineral mass, an observation confirmed for example by granulometric studies of dam-retained lake deposits (Łajczak 1995). In the study area the deltas also involve sandy material which becomes suspended during flood flows. Gravel is only deposited within the river channel and its contribution in the building of the deltas must be considered minimal (Klimek et al. 1989, 1990). Organic material, constituting 5-10% of the silt in the Carpathian dam-retained lakes, contributes a small proportion to the deltas studied (Łajczak 1995).

Overall, it is suspended mineral material supplied by the rivers that constitutes the crucial quantity of material deposited in dam-retained lakes and contributes to the development of deltas in the study area (Onoszko 1962, Wiśniewski 1969, Łajczak 1995).This results in the development of low-energy deltas in all the large dam-retained lakes of the area despite a highly mountainous hydrological regimen of the rivers and high amplitudes of water level fluctuations on many of the lakes. Only small deltas in minor lakes on upper mountain watercourses are largely or mostly built with gravel and can be regarded as of the high-energy type.

4. Types of dam-retained lake studied

Four types of dam-retained lake were identified in the study area based on their capacity to permanently retain the supply of material building the deltas (Łajczak 1995). The locations of the lakes are shown on Figure 1. including:

a) long and deep valley lakes in the Beskidy Mts. and in the Carpathian Foothills featuring the greatest capacity of permanent retention of the suspended matter and bedload. Here, the rates of delta development depend on the quantity of the material supplied and the amplitude of the lake level fluctuation, which exceeds ten metres, and its seasonal pattern;
b) shorter and shallower valley lakes in the Carpathian Foothills, mainly, directly downstream from the deep lakes. They receive a reduced quantity of suspended material and an insignificant supply of bedload. This causes much slower delta growth rates than in the deep lakes. There are even periods of delta erosion as a result of violent partial emptying of an upstream deep lake;
c) vast and relatively shallow valley lakes located on the flat floors of the basins of the Carpathian Foreland. In the study area there is only one such lake and it features a slow water exchange pattern, but frequent intensified wave action causing resuspension of the bottom deposits and producing restricted delta development conditions;
d) minor lakes, sometimes quite deep, and the so-called dry lakes and miniature lakes behind rubble retaining barrages, all of them located in the upper courses of mountain river valleys. They are filled in with deposits to differing extents and develop miniature deltas, often built of gravel as the finer material mostly passes through during flood flows.

5. Average supply of suspended material to dam-retained lakes

The amount of delta-building suspended material supplied to dam-retained lakes depends on the quantity present in the rivers supplying them. The latter is a function of the drainage area and the rates of eroded material discharged, which in turn

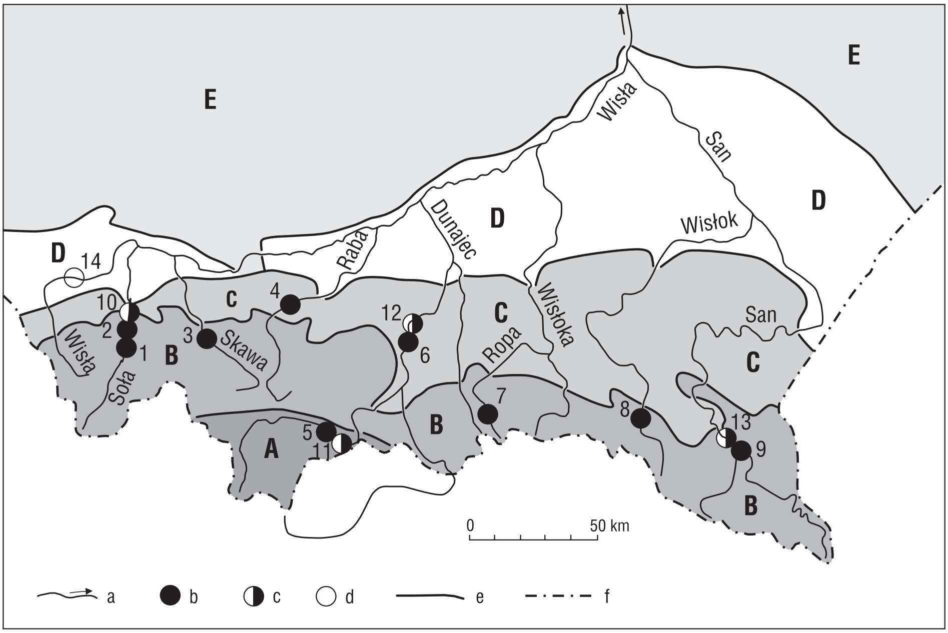

Figure 1. The location of larger dam-retained lakes in the Carpathian section of the River Vistula drainage area

Explanations: a – main rivers; b – type "a" lakes; c – type "b" lakes; d – type "c" lakes; e – boundaries of: A – Inner Carpathian Mts., B – Beskidy Mts., C – Carpathian Foothills, D – Carpathian Foreland Basins, E – Polish Uplands; f – national border. Dams: 1 – Tresna, 2 – Porąbka, 3 – Świnna-Poręba, 4 – Dobczyce, 5 – Czorsztyn, 6 – Rożnów, 7 – Klimkówka, 8 – Besko, 9 – Solina, 10 – Czaniec, 11 – Sromowce Wyżne, 12 – Czchów, 13 – Myczkowce, 14 – Goczałkowice.

may be largely influenced by human activity (deforestation or afforestation, farmland use and hydrotechnical structures, primarily dams, that capture transported material and reduce its quantity downstream). In the study area the annual supply of suspended material to the larger dam-retained lakes varies between several thousand tons to more than 800 000 tons (Łajczak 1995). The largest quantities are supplied to the deep cascaded lakes (group a), especially in the Carpathian Foothills. Until 1997, when the upstream Lake Czorsztyńskie was filled with water, the prime example here was Lake Rożnowskie which received on average more than 800 000 tons of suspended material annually. The River Soła supplies a little over 300 000 tons of suspended material into Lake Żywieckie and the River Raba supplies more than 100 000 tons into Lake Dobczyckie. Other deep valley lakes of the Polish Carpathian Mts. receive less than 100 000 tons per year and in the case of groups b) and c) shallow valley lakes, it is even less, typically between ten and twenty thousand tons, with the notable exception of Lake Czchowskie which receives more than 100 000 tons. Only minimal quantities of suspended material and comparable quantities of coarser material flow into the group d) lakes.

6. Capacity for the permanent retention of material in lakes

So far, the dam-retained lakes in the study area have shown an extremely wide range of capacity to retain suspended material, i.e. from 0 to 98% (Table 1). Group a) lakes are typified by a slow exchange of water (up to six times per year and up to 20 times in extreme cases), facilitating long-term sedimentation of the suspended matter supplied by rivers. As the dam almost entirely prevents any escape of this material, the lakes permanently retain nearly all of the suspended matter supplied and 100% of the bedload (sand), which is deposited within the delta. The only deposition of coarser bedload material (gravel) occurs within the delta channel. In long and narrow valley lakes resuspension through wave action is limited. The exchange of water in group b) lakes is much more frequent, between 100 and 500 times annually. Considering additionally the small size of these water bodies and a greater intensity of resuspension of bottom deposits, the capacity for permanent accumulation of the suspended matter is restricted and ranges between 0 and 49% in the lakes studied. Spillways of shallow lake dams tend to have a low location that allows the periodic discharge of large quantities of bedload, especially at a time of rapid build-up of a flood reserve capacity in upstream deep cascade lakes. In these circumstances the balance of material transport within deltas may even be negative. During other periods, deposition prevails over erosion. Group c) lakes also have limited capacity to retain material mainly because of a frequent and intensive resuspension of bottom deposits over vast areas of the lakes due to wave action, which peaks in autumn and wintertime. This process should be regarded as the main cause of the often negative balance of suspended material transport in the lake being studied. There is no data available on the balance of material transport and delta growth rates in group d) lakes. What is known is that the miniature lakes upstream of many rubble-retaining barrages built ca. 50-100 years ago, have been almost completely filled in with gravel.

In summary, the greatest amount of suspended matter deposition is found in deep lakes with a large supply of material and a high permanent retention capacity. In shallow lakes, even if the supply of material is considerable, the scale of deposition is incomparably smaller. The best conditions for a rapid delta build-up exist on Lake Rożnowskie on the River Dunajec. The River Soła delta on Lake Żywieckie has been developing at a much slower pace and other deltas in the study area have been growing even more slowly. In the shallow valley lakes of the Carpathian Mts. and their foreland, deltas have been incomparably slower to develop with the exception of Lake Czchowskie in the Dunajec valley, which is additionally supplied by the River Łososina. It is understandable that the rate of growth of the Łososina delta has outpaced that of the Dunajec delta (Klimek 1979).

7. The relation of seasonal variation of lake parameters to delta shape and growth rate

In the study area the peak supply of water and material to the dam-retained lakes occurs in summer, when flood flows are the greatest, followed by early spring (Łajczak 1995). This can be illustrated by the example of Lake Rożnowskie (Figure 2). The delta growth rates, however, do not follow the annual material supply cycle pre-

Table 1. The capacity of the lakes of the River Vistula drainage basin in the Carpathians to permanently retain the suspended matter supplied by the river, expressed as a percentage of the material supplied

River	Dam (dam-retained lake)	[%]
Type "a" lakes		
San	Solina (Lake Solińskie)	98
Raba	Dobczyce (Lake Dobczyckie)	96
Wisłok	Besko (Lake Beskie)	96
Ropa	Klimkówka (Lake Klimkowskie)	96
Dunajec	Czorsztyn (Lake Czorsztyńskie)	95
Soła	Tresna (Lake Żywieckie)	91
Dunajec	Rożnów (Lake Rożnowskie)	87
Soła	Porąbka (Lake Międzybrodzkie)	80
Skawa	Świnna-Poręba [a)]	95
Type "b" lakes		
San	Myczkowce (Lake Myczkowieckie)	49
Dunajec	Sromowce Wyżne (Lake Sromowieckie)	34
Dunajec	Czchów (Lake Czchowskie)	18
Soła	Czaniec (Lake Czanieckie)	0
Type "c" lakes		
Wisła	Goczałkowice (Lake Goczałkowickie)	35

Explanations: averages are based on calculations according the formulae of Brune's, Drozd and Hartung (Łajczak 1995). The location of the lakes is depicted in Figure 1. Only lakes of types "a", "b" and "c" were taken into account. [a)] – dam under construction.

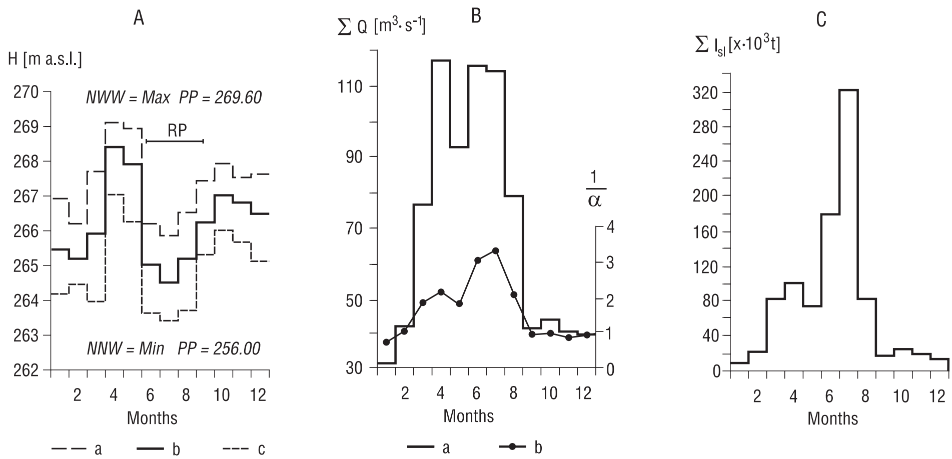

Figure 2. Seasonal variability of main hydrological parameters in a deep dam-retained lake using the case of Lake Rożnowskie

Explanations: A – water level (H): a – high, b – average, c – low; B: a – combined total water supply from all tributaries (ΣQ), b – water exchange cycles (months)(1/α); C – suspended material supply from watercourses (ΣI_{sl}) into a dam-retained; RP – time to build-up flood reserve in a dam-retained lake.

cisely due to fluctuation of the lake water level with amplitudes exceeding ten metres. The emergence of deltas during the summertime, when the reservoir is building up flood reserve capacity, exposes the deltas to linear erosion during floods. For the rest of the year, the deltas are completely or nearly completely submerged and grow over their entire area. However, due to the small supply of material at that time the growth rates are incomparably lower than during the summertime when the submerged part of the deltas experience rapid accretion.

Deltas in deep lakes develop in a shuttling manner, which sets them apart from deltas in water bodies with stable water levels. As the lakes are dammed high almost their entire area is subject to a low-intensity deposition of mostly fine material (silt and clay). In the summertime, the topset is excluded from the deposition process, which only involves the submerged part of the delta, i.e. the foreset and bottomset, where the summertime deposition is at its greatest. The deposited material, primarily sand and silt, is not just supplied by the river, but also comes from the main and side channels of the delta exposed to linear erosion. The combination of the cyclical variations in the intensity of supply of fluvial material, the fluctuating lake water levels and the shuttling back and forth movement of the most intensive deposition zone within the delta (in the summertime advancing towards the lake and retreating from it for the rest of the year), produces a layered delta structure from its plain to the bottomset. In the summertime, the conditions are favourable for the accumulation of coarse grains, while during the rest of the year they are conducive for the deposition of finer material.

The lower intensity of deposition of clayey material on the permanently submerged part of the delta in the summertime is also due to the fact that the clay fraction largely flows through the dam. This is caused by an accelerated water exchange in the lake at that time of the year (less water in the lake + greater inflow of river water).

Deltas in the deep valley lakes with high water level fluctuations are typified by their more elongated and smoothed out longitudinal profile (Klimek et. al. 1990). Deltas in water bodies with stable water levels, including artificial lakes, feature an evident division into the topset, foreset and bottomset components. The boundaries between the proximal and distal parts of the delta in the studied dam-retained lakes are less obvious and tend to have the nature of transitional zones. The foreset is the most mobile part of deltas in dam-retained lakes which tend to build up quickly in the summertime with sandy material. This is where fluvial fans, sandy-silty, develop at the extension of the main and side channels. The channels are eroded in the summertime to their exposure above the water table. The fans expand into the bottomset area built mainly of clay. During the rest of the year there is less sandy deposition in the delta, this being restricted to the topset zone.

Conditions determining delta development in shallow valley lakes are different than those in deep lakes. Deposition of material supplied by the river can only occur at a time of low discharge from the upstream deep lake. In the summertime, especially in July, when very large quantities of water are rapidly discharged from the deep cascade lake during the creation of flood reserve capacity, shallow lake deltas are eroded. Minor water level fluctuations in shallow lakes have no material impact on the conditions of erosion or deposition in these water bodies.

In the deep valley lakes the main delta erosion factor is the water current running over the topset during large scale floods (mainly in the summertime) and the accompanying thermal/density current along the submerged part of the delta.In cascaded shallow valley lakes the main driver of the cyclical increase in the erosion rates at the deltas is the water current discharged from the deep lakes during the summer floods. During the rest of the year, except when the lake is frozen over, the delta deposits in both deep and shallow lakes are subject to erosion from wave action, but at a lesser rate than in the summertime. Resuspension of fines caused by wave action reaches considerable magnitudes in shallow valley lakes in the lowlands and in the Carpathian foreland. This process plays a greater role in the cyclical removal of delta deposits than the thermal-density current, as confirmed by a comparison of below-dam river turbidity at different seasons of the year (Łajczak 1995). In these types of lakes delta erosion is at its greatest in autumn and wintertime, when the supply of fluvial material drops particularly low.

8. Long-term pattern of delta development in a dam-retained lake

Hypothetically, if dam structures were to be regarded as stable over very long periods (10^2-10^3 years), the topset and the foreset would expand, while the bottomset would shrink at a very advanced stage of delta development (Łajczak 1995, 1996).The mostly sandy deposits of the delta foreset, and especially the fluvial fans would overlap and increasingly encroach onto the deeper located finer, mostly clayey, bottomset deposits (Figure 3). The accumulation of the fine material building the bottomset and the lake bottom would

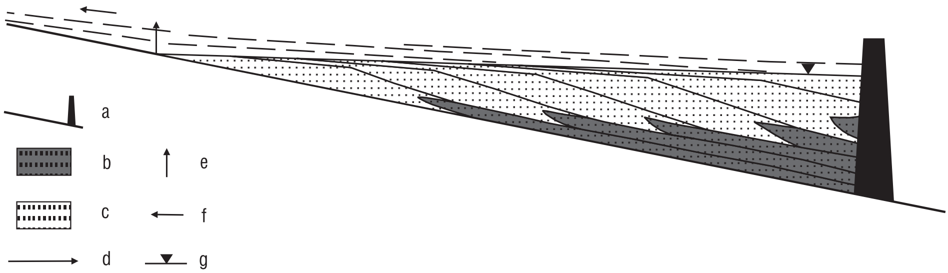

Figure 3. Delta development pattern in a deep valley lake with high seasonal water level fluctuation

Explanations: a – valley floor before the dam-retained lake and the dam structure; b – clayey, deep-water layered deposits; c – delta deposits, layered encroaching onto deep water deposits; d – delta development direction; e – vertical build-up of coarser material at an advanced stage of delta development; f – build up of gravel deposits upstream from the initial extent of the lake backwater; g – average water level. Length of arrow proportional to the intensity of change.

continue ever closer to the dam until the completion of the first phase of the lake silting up when the lake would still be capable of retaining suspended matter. As the distance to the dam would be shrinking the boundary between deep water and delta deposits would move higher on the foreset. During the second phase, the largely reduced and shallower lake would no longer be able to permanently retain suspended matter. At this stage the head of the delta would continue to move closer to the dam structure, but would not gather any significant amount of fine material. The silty-clayey and even to a large extent also sandy material would by then be able to pass through the lake. Upstream of the dam, within the area of a vast topset, gravel material would be increasingly retained and build up the river channel above the original backwater of the lake as a result of the retrograding process. The current status of delta development in the dam-retained lakes analysed, even those most silted up, remains far from an advanced filling up of the lake with deposits (Figure 4). Such a hypothetical delta development, as presented above, would obviously be interrupted upon the destruction of the dam, which would occur either because of technical reasons (increased cracking of the ageing dam) or natural reasons (e.g. very strong seismic tremors). This would lead to an excessive erosion of the deltas, suspended and bedload transport and accumulation downstream of the dam at a scale unprecedented in geological history. The profession of hydro engineers remains unable to answer the question when this scenario should be expected.

9. Conclusions

Deltas in dam-retained lakes located in mountains devoid of larger natural lakes should be regarded as unique forms because of their size, growth rate and certain morphological properties. In the long-term, delta growth rates follow the patterns of silting up of lakes. The quantities of deposition in deep lakes diminish with time and reflect the reduction of the volume of material retained within the delta (Łajczak 1995, 1996). Assuming a theoretical useful life of dams in the studied deep lakes at between hundreds

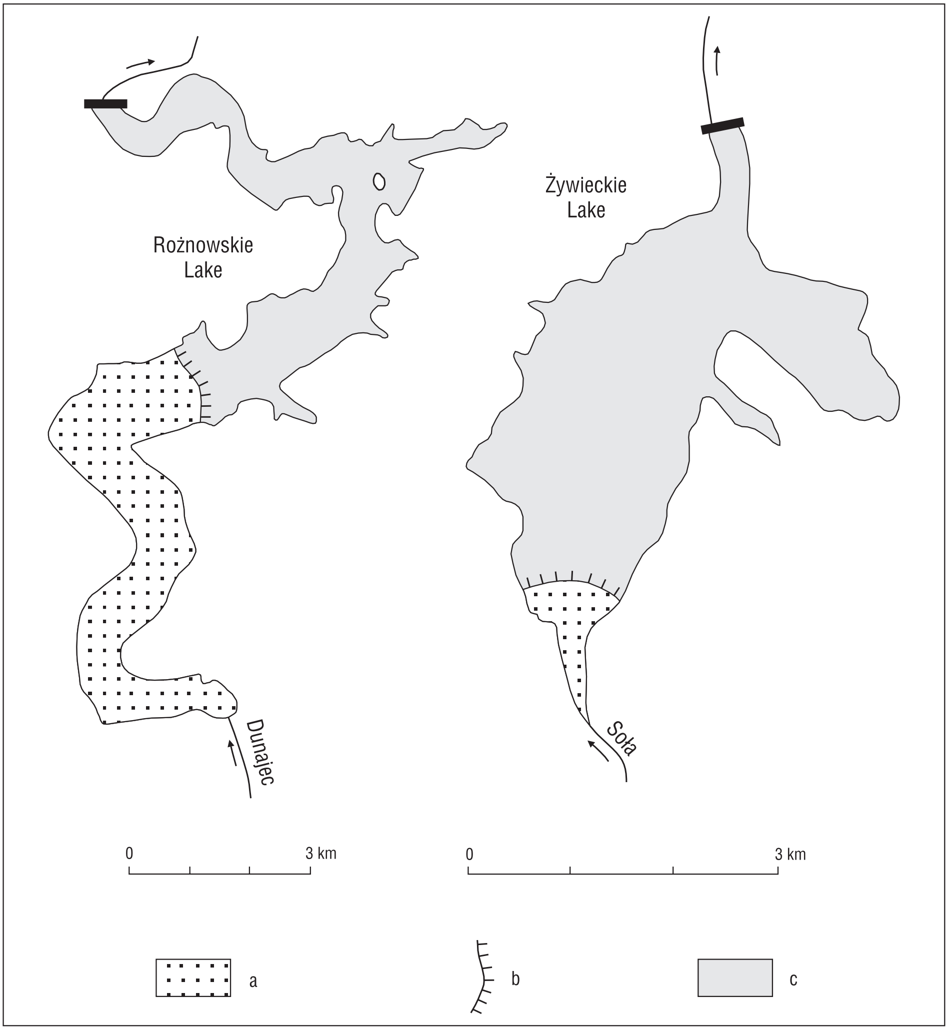

Figure 4. Current delta boundaries in Lake Rożnowskie and Lake Żywieckie (respective origins in 1941 and 1967)

Explanations: a – the topset exposed during low water periods; b – delta front (boundary between the topset and the foreset); c – portion of dam-retained lake where the deeper delta parts, including the foreset and bottomset, do not get normally exposed.

and thousands of years the lakes should be almost entirely filled with deposits – mostly delta deposits up to the actual dam – at the end of that period.

Deltas in dam-retained lakes with high water level fluctuations, regardless of their growth rates, differ from deltas in water bodies with a stable water level. The seasonal amplitude of water level fluctuations, sometimes exceeding ten metres and the mismatch of this parameter with the variation in the water and material discharge by the river make the longitudinal profile of the deltas in dam-retained lakes more elongated and evened--out than that of deltas in natural water bodies. This reflects the seasonal shuttle migration of the zone featuring the greatest intensity of alternating deposition and erosion in the delta area.

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Adam Łajczak
Department of Earth Sciences
University of Silesia
Będzińska 60
41-200 Sosnowiec
Poland