phnidae. At that time a drastic fall in the abundance of *Daphnia longispina*-group was followed by a development of *Daphnia pulex*-group. It was also the beginning of the domination of the planktonic species *Bosmina longispina*.

2 – the boundary shows an almost complete decline in the abundance of all species of Bosminidae and the beginning of dominance of littoral species, especially of *Alona*. *A. rectangula*, which often accompanies a process of changing trophy, became dominant and persisted almost until the present day.

3 – the boundary presents a renewed expansion of species from the family Bosminidae. After this time the eutrophic species *Bosmina longirostris* dominated among the Bosminidae, replacing *Bosmina longispina*, which had been dominant until then. The abundance of this species in Lake Gościąż during the periods of human activity was much lower than in other lakes studied in Poland. However, considering the particular character of this lake, the fluctuations in the development of this genus (even very small) should be regarded as connected with the settlement fluctuations. A strict analysis of the concentration curve of *Bosmina longirostris* and other indicator species of eutrophy (Figs 8.29, 8.30) shows a great coincidence of their development phases with the phases of supposed settlement, recorded in a pollen diagram and confirmed by archaeological data (Pelisiak & Rybicka 1993, Ralska-Jasiewiczowa & van Geel, Chapter 9.1.3).

4 – the boundary separates the sediments accumulated during the last two centuries. In these sediments a special cladoceran succession was observed. This short-lasting period (Cladocera zone VIIc) was characterized not only by the domination of planktonic forms but also by the coexistence of all species of Bosminidae and Daphnidae. Also among Chydoridae was a high abundance of *Alonella nana* and *Chydorus sphaericus*, which are often planktonic in character in deep lakes and invade the pelagic zone (Frey 1986b).

Fluctuations of the water level may be studied by the analysis of the relations between planktonic and littoral Cladocera (Barry et al. 1984, Korhola 1990, Tikkanen & Korhola 1993). Two species were excluded from the comparative analysis, *Bosmina longirostris* from planktonic taxa and *Chydorus sphaericus* from littoral taxa. In unsuitable conditions, *Bosmina longirostris* often moves to the littoral zone (Goulden 1964), and in conditions of high trophy it may become the only representative of Bosminidae. Thus, it indicates then an increasing eutrophy, not a higher water-level (Goulden 1964, Hofmann 1986, Matveev 1986, Szeroczyńska 1991). The littoral species *Chydorus sphaericus* is often found in the planktonic zone (Alhonen 1970, Frey 1988, Goulden 1964, Hofmann 1978), often connected with existence of Cyanobacteria, or with a cold climate. In the cold climate it may be the only representative of Chydoridae (Szeroczyńska 1984). Thereby, it is an indicator of cool conditions not of a developed littoral zone.

Two diagrams of planktonic/littoral species ratio (traditional one and with *Bosmina longirostris* and *Chydorus sphaericus* excluded) were made for comparison (Fig. 9.18, Chapter 9.1.4). According to the curves of dominating planktonic species in profile G1/87 a higher water-level in Lake Gościąż occurred in the Late-Glacial time (Fig. 7.36, Chapter 7.5.2), in the Preboreal, Boreal, and early Atlantic, and partly in Subboreal and Subatlantic periods (Fig. 9.18, Chapter 9.1.4).

Because of an absence of species of Bosminidae during the Atlantic period (Cladocera zone V) and their poor representation during the next two periods, fluctuations of water-level during these periods cannot be accurately defined. A strong predominance of Chydoridae may indicate a very low water level with “an absence” of the planktonic zone, a situation impossible in such a deep lake. A possible explanation may be that during these periods, the pelagic zone of Lake Gościąż was poorly oxygenized, thereby making the existence of planktonic species impossible. Thus an analysis of Cladocera index P/L for these periods is useless, because it gives a false suggestion of the water-level changes in the Lake Gościąż.

8.5. LAKE-LEVEL CHANGES AND PALAEOHYDROLOGICAL RECONSTRUCTIONS DURING THE HOLOCENE

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Bogumił Wicik & Kazimierz Więckowski

Reconstruction based on sediments and landforms

The record of lake-level changes and groundwater fluctuations during the Holocene is not well marked because of the dominance of steep shores and small water-level variations, which are connected with the sandy substratum and the continuous supply of groundwater from the south. The detailed examination of deposits in the lake bottom and shore zone (see Chapter 5) made it possible to distinquish several oscillations up to +1 m above and to –3 m below the present lake level (Figs 8.31, 8.32). At the same time the reconstruction of ^{14}C content variations in the lake water was made as it is related to the water volume (Fig. 8.33).

The information concerning the Preboreal period is scarce, but we may infer a lowering of the water level from the change of lacustrine to bog sedimentation in shallow depressions, as well as from the rise of Fe_2O_3 content in sediments (see Chapter 5.2, Fig. 5.12). Probably by the end of this phase the segments of Ruda stream connecting the deeper water bodies were joined (Fig. 8.34), starting the drainage of the lakes by the Ruda to the Vistula River.

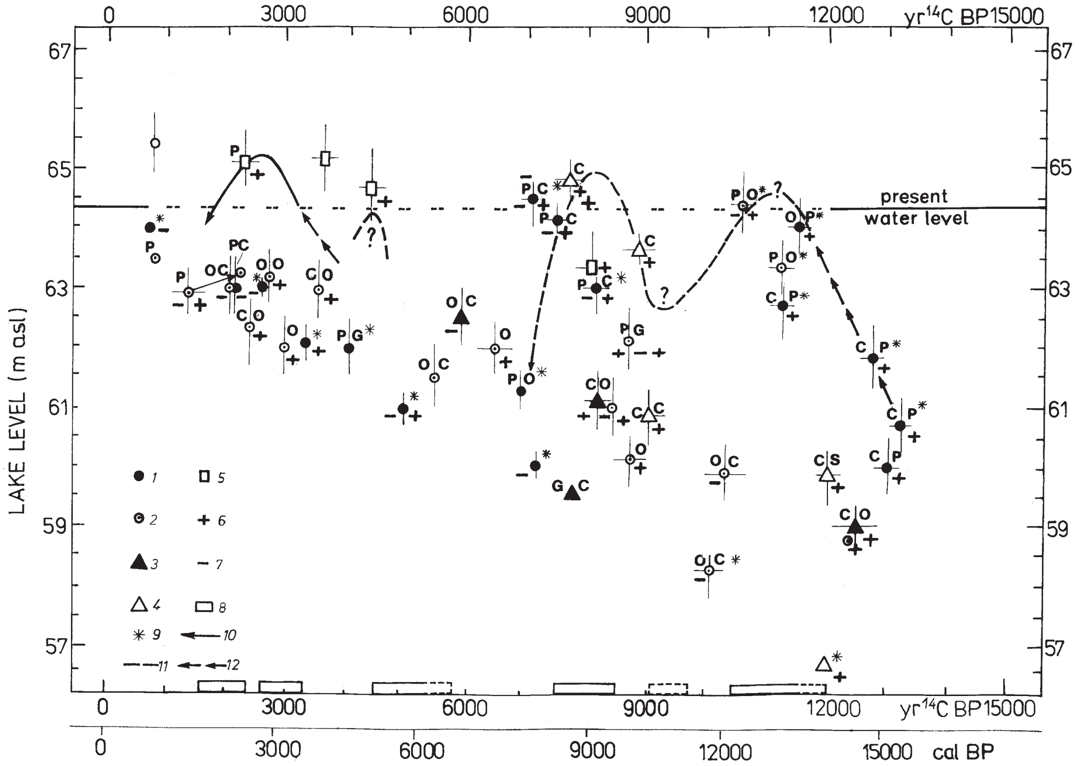

Fig. 8.31. Reconstruction of lake-level variations based on dated horizons in various lake and coastal profiles (by L. Starkel). 1 – peat layer, 2 – organic gyttja, 3 – calcareous gyttja (conv. age), 4 – calcareous gyttja (corrected age), 5 – organic horizon in coastal deposits, 6 – rising water-level tendency, 7 – lowering water-level tendency (on the right side – below the dated sample, in the left – above the dated sample), 8 – phases of higher iron content indicating lowering of water level shown at the bottom of diagram (after B. Wicik), 9 – localities outside Lake Gościąż, 10 – lake-level well documented, 11 – probable fluctuations of lake level, 12 – general tendency to lake-level rise. Letters indicating sediment type (on the right side of the line – below the dated sample, on the left – above the dated sample): P – peat, C – calcareous gyttja, O – organic gyttja, G – soil calcareous concretions, S – sand (after Starkel et al. 1996).

During the Boreal period the lake level began to rise. In the shore transect C (Chapter 5.1, Fig. 5.6) the deposition of calcareous gyttja at the level of the present lake was dated at 8970±130 ^{14}C BP. In the delta zone of Ruda stream at the outlet of Lake Wierzchoń a sandy intercalation appeared after 8700 ^{14}C BP, and in its delta entering the Tobyłka Bay after 8390 ^{14}C BP. The calcareous gyttja from the younger Boreal was found in several cores from the littoral zone of Lake Mielec and farther downstream. In the isolated Lake Mrokowo the calcareous gyttja between 8500 and 7800 yr ^{14}C BP shows lamination during ca. 300 years, indicating a distinct water-level rise. In the western kettle of Lake Gościąż silty laminae formed in that period may reflect the disturbance of stability in the shore zone. The slumps on the eastern shore also registered this phase (transect A, Fig. 5.6 in Chapter 5.1). Finally, calcareous concretions in sands north of the lake ca. 0.7–0.8 m above the present lake level (transect C) are dated at the close of this phase. All these records indicate that at the decline of the Boreal chronozone (8300–7800 ^{14}C BP, Fig. 8.31) the lake level was 0.7–1.0 m higher than today.

The regression started from ca. 7770 ^{14}C BP, as marked by the end of calcareous sediment deposition and overgrowing of shallow littoral zones by peat (e.g. borings nos. G3/92, G2/92, see Fig. 5.1 in Chapter 5.1). In the delta entering Lake Wierzchoń the peat dated to 6500 ^{14}C BP was found 3 m below the present surface. The charcoal horizon at 3.5 m depth in sands on the ridge dividing the main lake from Tobyłka Bay is dated to 6100 ^{14}C BP. It is probable that in the Atlantic phase the lakes were not only separated but they also had no surficial outflow.

The beginning of the Subboreal chronozone is marked by the rise in the deposition rate in the main profile (Więckowski 1993, Goslar 1993, and Chapter 6). On the slopes of the central deep sandy flows occur. The water-level fluctuations are indicated by the sandy slumps overlying the organic horizon in the eastern shore (dated to ca. 4400 ^{14}C BP in the transect G) and by the end of lamination in the bottom sediments of Lake Brzózka after 4510±80 ^{14}C BP. Between 4000 and 3000 ^{14}C BP peat deposition dominated in the segment of Ruda River valley between existing lakes (Fig. 8.34).

The most distinct rise of lake level followed at 2500–2300 ^{14}C BP. It is clearly visible in the littoral zone including deltas, in form of the horizon of calcareous gyttja later buried by peat again. This transgression is evidenced also by the bench of spring fan-delta elevated ca. 0.7–1.0 m in transect J (Chapter 5.1, Fig. 5.6) and by shore ridges at other places. At that time the lake water level was about 0.8–1.0 m higher than today (Fig. 8.31).

Later on the water level started to drop down, and peat was deposited again on the shore of Tobyłka Bay and Lake Mielec. More detailed records on water-level changes during the last two millennia were not preserved.

Changes of water level derived from model

Mass-balance equations describing the whole carbon and ^{14}C content of a lake (Broecker & Walton 1959) were applied by Benson (1978, 1991, 1993) and Peng et al. (1978) to correct the ^{14}C ages of carbonate sediments, using estimated values of V/A (lake volume to area) and other parameters incorporated in this model. Laminated sediments of Lake Gościąż provide an independent absolute chronology and thus permit calculation of initial ^{14}C activity of bicarbonates from measured ^{14}C ages of carbonate fractions of lake marl. The model equations in this case may be rewritten to provide estimates of the ratio V/A, which may be interpreted as mean water depth of the lake, H (H = V/A). The relation between relative changes of mean water depth, H/H_o, (H_o = the value of mean water depth at present) and dilution factor of ^{14}C isotope in lake carbonates, q, at the moment of their sedimentation, may be written as follows (Pazdur & Starkel 1989, Pazdur et al. 1995):

$$H/H_o = A\,q - B$$

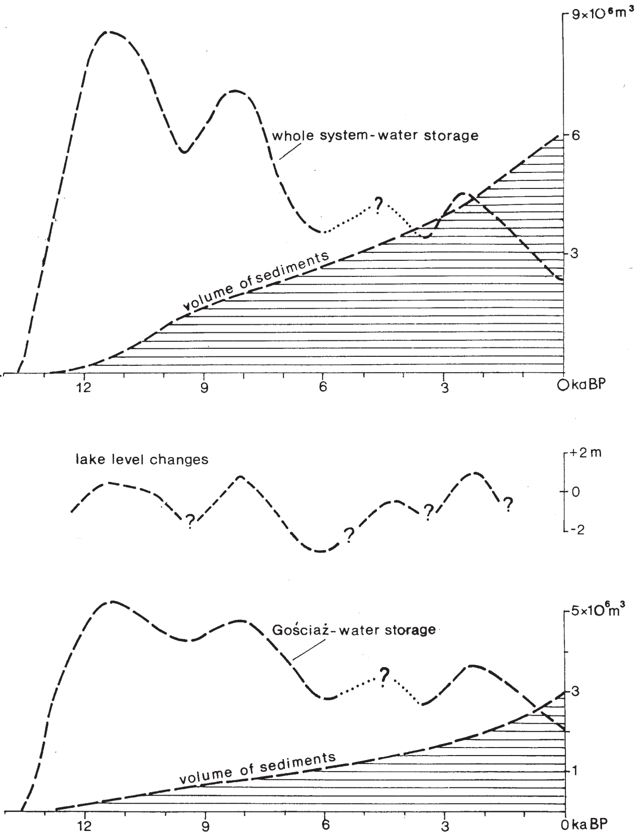

Fig. 8.32. Changes of the water storage (volume of lakes) and deposition during last 11,000 ^{14}C BP. Above – the whole Na Jazach lake system; below – Lake Gościąż only, in the middle – water-level changes of Lake Gościąż (after Starkel et al. 1996, completed).

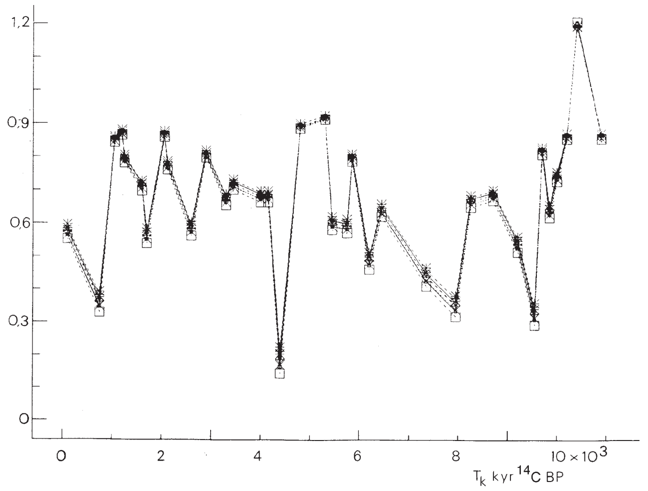

Fig. 8.33. Reconstructed changes of relative mean lake depth (H/H_o) plotted in radiocarbon time scale for different values of model parameters. Modelled changes were obtained for synthetic varve chronology based on varve counts and correlation of cores G1/85, G1/87 and G2/87 (Goslar 1993) (after Starkel et al. 1996).

The values of parameters A and B are determined by geochemical environmental conditions for carbonate sedimentation: rates of CO_2 exchange between lake and atmosphere, linear evaporation rate from the lake surface, and concentration of ^{14}C and of total carbon in water entering the lake and in the lake itself at present and in the past.

Relative changes of mean water depth of Lake Gościąż (H/H_o) calculated from the model equations are based on two slightly differing data sets (Pazdur et al. 1995). The curve presented on Fig. 8.33 is based on results of all ^{14}C measurements for cores G1/85, G1/87, and G2/87 (Pazdur et al. 1994) ordered according to the synthetic varve chronology developed by Goslar (1993). The irregular shape of the curve results from the larger number of data points included in the calculations. It seems, however, that some effects may be attributed to difficulties in correlations of the sampling depth in core G1/85 with the synthetic chronology, which is based on cores G1/87 and G2/87. The lowest point, occurring at ca. 4400 BP, seems to be influenced by miscorrelation.

Reconstruction of the water storage in lakes

The reconstruction of the lake water level by different methods shows many similarities. There are distinct phases of the high lake level at the end of Allerød, about

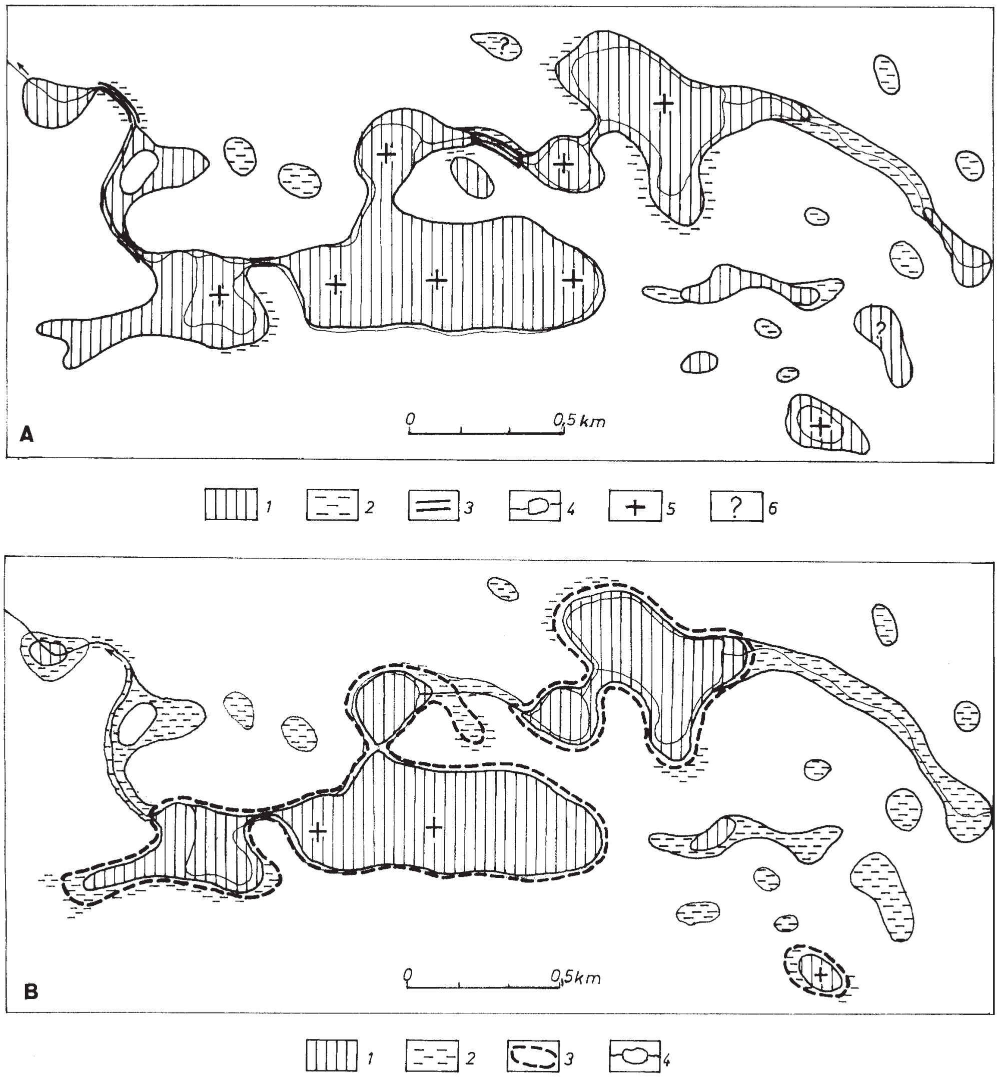

Fig. 8.34. Areal changes of the extension of lakes and bogs during selected phases of the Holocene. A – Early Holocene phase; 1 – lake area about 9500–8500 ^{14}C BP, 2 – bogs, 3 – valley sections formed during early Holocene, 4 – present Ruda stream and lakes, 5 – deep dead-ice hollows, 6 – depressions without borings and datings (reconstruction based only on extension of existing peatbogs). B – mid- and upper-Holocene phases; 1 – lake area during Atlantic regression (6000–5000 ^{14}C BP). 2 – former lakes occupied by bogs, 3 – extent of lake transgression about 2500–2200 ^{14}C BP, 4 – present Ruda stream and lake, 5 – deep dead-ice hollows.

8300–7800 ^{14}C BP, 2800–2200 ^{14}C BP, and less distinct at 5000–4500 ^{14}C BP. The other phases are recorded only in the peat profiles (Demske 1995) and in declines of the Fe_2O_3 content (Wicik, Chapter 5.2). The existing data make it possible to attempt the reconstruction of the lake-water storage during the late Vistulian and Holocene (Tab. 8.6). These changes depended on several factors: volume of lake basin, precipitation totals, and conditions of river outflow.

Changes in the volume of lake depressions depended first on deposition rate and then on lake water level. By estimation the mean thickness of deposits in kettles and other depressions, including valley segments (formerly under water), it was calculated that the whole system was filled by about 6×10^6 m^3 of lake and bog deposits. This means that the previous volume of the large Late-Glacial lake (of similar water level as at present) reached 8.3×10^6 m^3. The water storage continuously declined following deposition, which accelerated during the Younger Dryas and the last 2000 years (Fig. 8.32). In case of Lake Gościąż itself the water storage declined by ca. 58% from Allerød to present. The lacustrine sediments sealed the lake floors, making difficult the free inflow of groundwater to the lake and groundwater outflow from the lake. Therefore the mechanism of water recharge changed with time. Nowadays we can observe dozens of springs at the southern bank of lakes Gościąż and Mielec, feeding these lakes with dammed groundwaters. Simultaneously in the central kettle of Lake Gościąż the outflow of the groundwater from the deeper horizon in the Tertiary sediments may be not excluded.

Depending on the slowly diminishing area occupied by lakes and on the water-level changes from +1 to –3 m, the volumes of the lakes have shown distinct fluctuations.

Table 8.6. Area, depth and volume of lakes and deposits (after Lencewicz 1928, Glazik 1978, Więckowski 1993, Churski, Chapter 3.3, compiled by Starkel and Więckowski).

Lake	Area in ha			Max. depth in m		Volume in $10^3 m^3$	Thickness of deposits in m		Volume of lacustrine deposits in $10^3 m^3$	% of filling of depressions
	1928	1963	1994	1928	1994		max.	min		
Gościąż	46.9	44.4	41.7	25.8	24.5	2073–2700	19.6	8	2960	58%
Wierzchoń	15.3	14.0		1.6		130–160	12.5	7	1050	<90%
Brzózka	3.1	2.4		1.4		18–20	11.5	7	190	>90%
Mielec	6.9	3.5		1.0		35–39	15.0	8	280	>90%
Other valley segments		ca 30–35				–	–	5	1500	100%
Total		95–100				2250–2300	–	6	ca 6020	>72%

In the case of a 1 m water-level rise in the early Subatlantic, the water volume increased by ca. 6×10^5 m^3, i.e. by more than 20%. A similar rise or drop at the beginning of the Holocene was connected with a twice greater change in water storage. Considering these relations the curve of lake-water storage during the last 12,000 yr BP was constructed (Fig. 8.32). It shows a distinct declining tendency. In this context we cannot evaluate the role of other factors such as deepening of the Ruda channel, which, before the construction of the weir, drained the surplus of water after heavy rains or snow melting. But simultaneous overgrowing of narrow and shallow parts of the valley, especially downstream of Lake Mielec, made the water outflow and deepening of channel more difficult. Therefore from one side the fluctuations of water level were controlled by the most dynamic factor (the inflow of groundwater), but from the other side these fluctuations could not be too high, because the extremes were regulated by the river outflow. This means that the distinct transgressions at ca. 8300–8000 and 2500–2300 ^{14}C BP were undoubtedly related to humid phases when over decades and centuries the increased inflow could not be levelled by outflow. The second of these phases coincided with the famous transgression of Lake Biskupin, for which one of the first calculations of the water budget was made (Skarżyńska 1965). In case of Lake Gościąż such full reconstruction would need the reconstruction of the input and output of both the groundwater and surficial water.

On the contrary, the lowerings of the water level caused by the drop in annual precipitation or by higher evaporation were reflected not only in the decrease of water storage but also in overgrowing of littoral zones and shallow parts of the longitudinal lake-valley depression. This led to the more and more restricted water storage during subsequent lake-level rises.

The water storage of the Na Jazach lake system is continuously declining. This causes the acceleration in the surficial runoff, which results in a quicker levelling of the groundwater surplus. In the last millennia the water cycle was more controlled by deforestation and changes in the fertility of the forest habitats.

8.6. OXYGEN AND CARBON ISOTOPE COMPOSITION OF AUTHIGENIC CARBONATES IN THE HOLOCENE PART OF THE LAKE GOŚCIĄŻ SEDIMENTS

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Factors controlling isotope composition of precipitated carbonates

Numerous isotopic studies of lacustrine sediments performed to date have demonstrated the usefulness of stable isotopes as a powerful tool in reconstructing past climatic and environmental changes on the continents (e.g. Siegenthaler et al. 1984, Gasse et al. 1990, Talbot 1990, von Grafenstein et al. 1992, Dean & Stuiver 1993, Gasse & Van Campo 1994). Lake sediments often contain authigenic carbonates and fossil shells whose carbon and oxygen isotopic composition is governed by climatically controlled properties of the given lacustrine system and its surroundings.

Oxygen-isotopic composition of authigenic carbonate is controlled by two physical properties of the lake in which calcite is being precipitated: the oxygen-18 content and the temperature of the lake water. The temperature dependence of oxygen-18 equilibrium fractionation factor between water and precipitated calcite amounts to -0.25‰ per °C for the temperature range and $\delta^{18}O$ values of water typical for Lake Gościąż (O’Neil et al. 1969). Possible kinetic fractionation effects during rapid growth of calcite crystals are thought to be associated mainly with the dehydration reaction induced by fast withdrawal of CO_2 from the epilimnion during periods of algal blooms (Clark & Lauriol 1992). They may lead to an additional enrichment in oxygen-18 of the precipitated calcite.

For open lakes with fast water turnover, the oxygen-18 isotope composition of the lake water is closely re-

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[*] This study was partly supported by grants from State Committee for Scientific Research Nos. 6 6252 91 01 and 2 2393 91 02, and from the International Atomic Energy Agency (Research Contract No. 5179).