Elevation of water table	64.3 m a.s.l.
Mean bottom gradient	$4^{o}29'$
Mean gradient of the slope from the isobath of 16 m to 24 m	$11^{o}21'$

The comparison of the above data with the corresponding parameters of Jaczynowski (Lencewicz 1925) proves that the lake area is now smaller by ca. 5 ha and shallower by ca. 2 m. The change in the area can result from permanent overgrowing of the lake. The difference in the depths can be partly attributed to the low accuracy of earlier measurements.

Analysis of morphometric data shows that Lake Gościąż can be assigned to the medium-sized lakes of the Gostynińskie Lake District. It is the second deepest lake in the region (after Lake Białe). If the original basin (without lake deposits) were considered, however, Lake Gościąż would be the deepest one in the region (44 m). Lake Gościąż is also unique with respect to gradient of the slopes. Although the average bottom gradient ($4^{o}29'$) can be accepted as a high mean value, the gradient of the deep hole, below 16 m, reaches $11^{o}21'$, which is an extreme value rarely encountered. The average gradients of other lakes vary from 2^{o} to 5^{o}. Moreover, relative depth (ratio of maximum depth to the square root of the area) of Lake Gościąż is 0.04, a rather large value as well. This value allows comparison of vertical and horizontal dimensions of the lake basin, and is more characteristic for cirque than for lowland lakes.

Large relative depth of similar order of magnitude has been recorded in the case of Lake Dzielno (0.042) and Lake Kocioł (0.082) (see Churski, Chapter 2.4). For comparison, the relative depth of Lake Zdworskie is 0.003 and that of Lake Rakutowskie 0.0013 (Jaczynowski 1929).

It should be emphasized that the present plan can constitute background for tracing further changes in depth, area, and shore line. In order to make such surveying possible, a network of benchmarks corresponding to the present-day topographic framework was established at the lake.

3.3. HYDROLOGY AND SEDIMENTATION CONDITIONS IN LAKE GOŚCIĄŻ

Zygmunt Churski & Włodzimierz Marszelewski

Lake Gościąż is located in the Vistula River valley and belongs to the drainage basin of the Ruda, which is the left tributary of the Vistula. The topographic catchment of Lake Gościąż occupies an area of ca. 588 ha, including the Lake Gościąż area of 41.7 ha, i.e. 7.1% (Fig. 3.3). The highest site in the lake drainage basin is located on the watershed in the southern part of the catchment (97.5 m a.s.l.), while the lowest point occurs where the Ruda flows out of the lake (64.3 m a.s.l.). The absolute difference in elevation reaches 33.2 m. The surface of the lake drainage area reveals a slope from SE to NW and therefore controls directions of surface and groundwater drainage. Directions of groundwater flow have been determined on the basis of groundwater contour lines (Fig. 3.3). Surface deposits of the drainage basin are mainly highly permeable loose sands. Almost the entire area of the drainage basins is covered with forest.

Maximum depth of the lake at the period of its formation was 44 m. At present the lake basin is half-filled with nearly 20 m of sediments. Mean rate of accumulation is more than 1 mm per year. Regarding that the lake occurs in flat, forested terrain and that no large river enters it, this rate is large. The nature of the deposits provides evidence of continuous sedimentation (Goslar, Chapter 6), which indicates permanent water supply to the lake and exceptional regularity of seasonal changes in thermal regime and water dynamics.

In order to describe the lake hydrology as well as its thermal regime and water dynamics, systematic field studies (in monthly intervals) were performed in 1990–1993. Hydrogeological, hydrological, and limnological investigations have been organized to elucidate lake stability and formation of laminated deposits.

The field studies, lasting only three years, were attempted to explain conditions of water supply to the lake and their seasonal and multi-year stability, as well as to explain variability in water level, thermal conditions, and chemistry of lake water and to gain insight into water balance and water regime in the lake catchment. Particular emphasis was placed on the contribution of groundwater to the lake budget. In order to determine conditions at the contact of groundwater and lake water, geoelectrical measurements were performed at 40 spots along 4 meridional and parallel transects on each side of the lake. The layout of gauging spots allowed the study of aquifers in the direct vicinity of the lake, and evaluation of possibilities of water supply to the lake from deeper aquifers. The measurements were taken by vertical electroresistance sounding method in the symmetric scheme of Schlumberger. Power line separations AB/2 were of 120 to 200 m, which facilitated penetration to a depth of ca. 70 m. The network of measurement sites is presented in Fig. 3.3.

The main stream in the drainage basin of Lake Gościąż is the Ruda stream, which flows out from swamps in the trough upstream of Lake Wierzchoń, ca. 2.7 km upstream from Lake Gościąż. The Ruda flows through four lakes (Wierzchoń (Jazy), Brzózka, Gościąż, and Mielec) and discharges into the Włocławek Reservoir. The Ruda is 9 km long. In its middle course it is dammed by a weir ca. 3 m high, which is also a water discharge gauging site. The backwater affects the upper course of the Ruda, including Lake Gościąż itself. Despite the damming some seasonal variability in water level

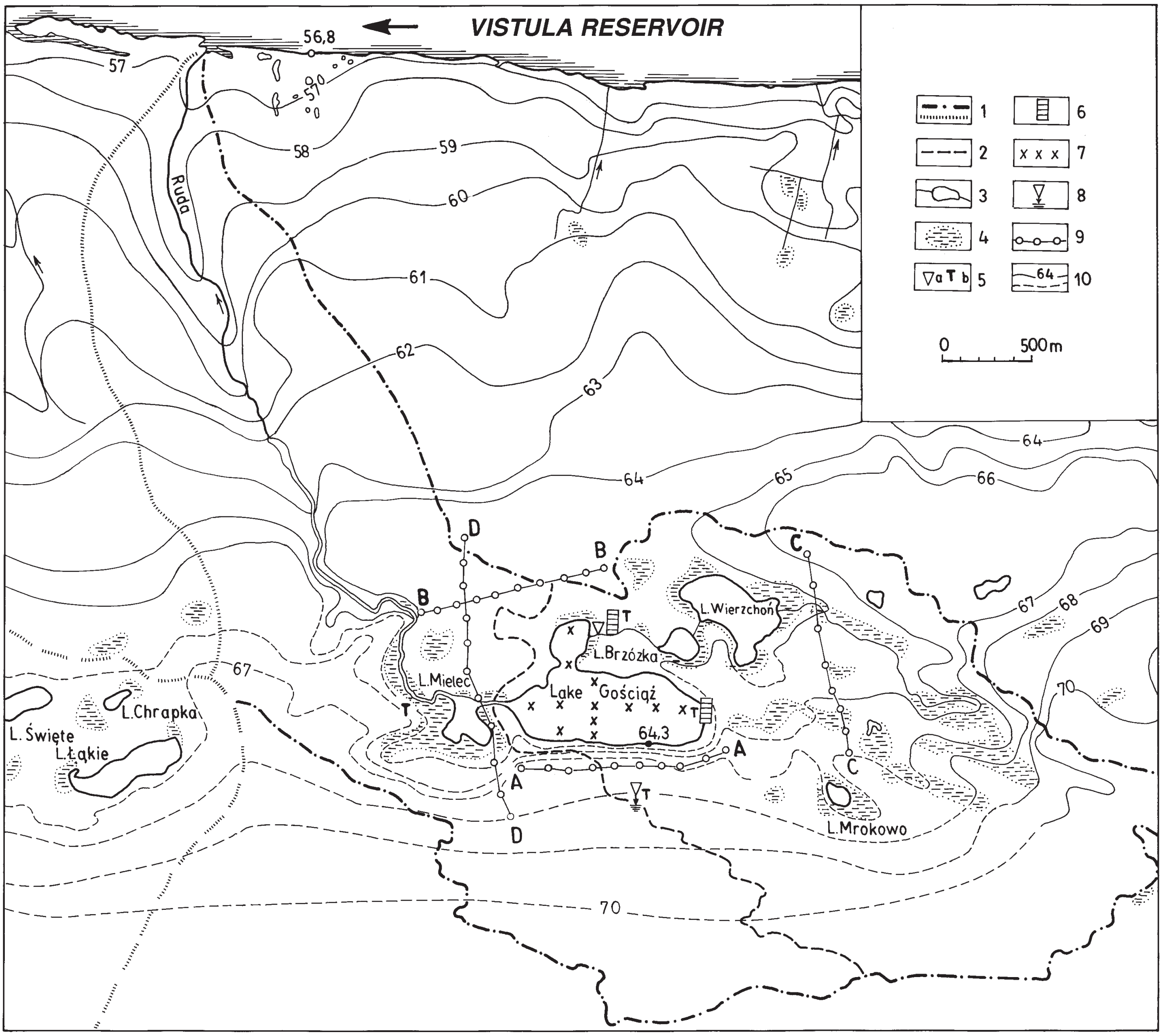


Fig. 3.3. Map of the Lake Gościąż drainage basin. 1 – watershed of the catchment and the Ruda stream; 2 – watershed of Lake Gościąż; 3 – streams and lakes; 4 – swamps; 5 – discharge gauging sites (a) and temperature measurement sites (b); 6 – water-level staffs; 7 – gauging spots on Lake Gościąż; 8 – piezometer; 9 – profiles of geoelectrical measurements; 10 – groundwater contours (partly after R. Glazik 1978).

and discharge is noticeable in this reach of the Ruda. Maximum discharges were recorded in winter and spring seasons and reached to 36 dm^3/s upstream and to 82 dm^3/s downstream of Lake Gościąż (data for hydrologic year 1992 and 1993), respectively. During summer (from June to August) discharges of the Ruda were decreasing. A subsequent increase in discharges was observed in autumn (Tab. 3.2). Changes in specific runoff of the Ruda were as follows: in the upper reach they varied from 1.3 $dm^3/s \cdot km^2$ in August to 6.7 $dm^3/s \cdot km^2$ in March, while in the lower reach (downstream of the lake) from 3.7 $dm^3/s \cdot km^2$ to 10.5 $dm^3 s \cdot km^2$, respectively (Tab. 3.2). This proves a strong contribution of groundwater to Lake Gościąż.

Alimentation of Lake Gościąż by groundwaters is fully confirmed by geoelectrical measurements performed in the vicinity of the lake. Based on the relationships between resistivity of deposits and their lithology as well as on the information from the borings located in the neighbourhood, geological analysis of the results showed the location of strongly and weakly permeable layers in the surrounding of Lake Gościąż. Geoelectrical cross-sections illustrate the position of the lake basin with respect to the layers of various resistivity (Fig. 3.4).

Geoelectrical investigations (carried out by the Hydroconsult Company) proved the existence of 3 to 5 complexes differing in specific resistance and occurring at depths from 50 to 70 m. In a subsurface zone up to ca. 10 m thick, a layer of extremely high resistivity (from 1000 to over 10,000 Ohm-metres) was identified as dry sands in the aeration zone. Below is a complex of sandy water-saturated deposits with resistance from 100 to 1000

Ohm-metres. Characteristic differentiation of resistance provides evidence of variation in grain size of sandy deposits belonging to this complex. The total thickness of the complex ranges from 10 to 40 m. The whole complex may be interpreted as the Pleistocene terrace and dune deposits.

The basal limit of these deposits (marked on the cross-sections in Fig. 3.4) is the interface between the Tertiary and Quaternary deposits. The data allowed for determination of geometry and layout of the complex of the weakly permeable deposits that separate the Quaternary and Tertiary aquifers. It has been stated that the entire basin of Lake Gościąż occurs within these two aquifers. In the initial phase of development, Lake Gościąż was water-fed by both the aquifers. At present, due to a significant filling of the lake basin with deposits, the Tertiary waters may reach the lake only through hydrological windows, the presence of which has been confirmed by differences in the water temperature (Gierszewski 1993, Wicik & Więckowski 1991, Churski et al. 1993). The Tertiary waters are strongly perched and feed the lake only periodically, as evidenced by measurements of water temperature on 12 July 1990 (see Fig. 3.6). Waters of the Pleistocene deposits contribute most significantly to the supply of the lake. These waters infiltrate from the upland through the highly permeable layers of coarse sands and gravels. They also feed the lake through natural inlets occurring on the southern shore ca. 0.4 m above the lake water table. Their efficiency during a year does not vary too much, but their influence on hydrological conditions of the lake is particularly evidenced by the ice cover, which forms much more slowly at the southern shore than in the other parts. Location within the aquifer facilitates abundant recharge of the lake by groundwater. Direction of the Pleistocene water outflow is shown by groundwater contour lines (Fig. 3.3), while movement of the Miocene waters follows the orientation of the Vistula valley.

Alimentation with groundwater directly controls water level, physical features of the lake, and dynamics of the lake water. Due to groundwater alimentation and the weir existing on the Ruda downstream of the lake, annual changes in the lake water level are small and reach only a few centimetres.

The seasonal changes in thermal conditions of Lake Gościąż are directly associated with changes in air temperatures. Nevertheless, an important role in modification of water temperature is played by such factors as the shape and depth of the lake basin and especially the manner of alimentation, including the contact between the lake and groundwater.

In spring-summer season Lake Gościąż features thermal stratification typical of dimictic lakes. The thickness of epilimnion varied from 6 m in August of 1990 and 1992 to 3 m in 1994, indicating good mixing of the upper water layer of the lake (Fig. 3.5). The thickness of the metalimnion varied from 3.5 m to 4.0 m. The metalimnion was characterized by high gradients of water temperatures, which often exceeded 4°C/m. Such situations most frequently occurred in the deep holes. In the shallower parts (above 10 m) such a strong stratification has not been observed. During summer stagnation (August) a typical stratification was observed both along longitudinal and transverse profiles (Figs 3.6 A, B, D). The results

Table 3.2. Comparison of water inflow and outflow by Ruda stream to and from Lake Gościąż with the atmospheric precipitation in the hydrological year 1993.

Month	Inflow (in m^3)	Outflow (in m^3)	Precip. (mm)	Discharge ($dm^3/s \cdot km^2$)	
				Above lake	Below lake
XI	19 440	221 620	41	2.5	10.0
XII	24 110	265 160	36	3.0	10.4
I	32 140	267 840	44	4.0	10.5
II	46 570	241 920	25	6.3	10.5
III	53 560	268 000	20	6.7	10.5
IV	42 770	197 000	19	5.5	8.0
V	31 470	175 440	23	4.0	6.8
VI	20 740	150 980	67	2.7	6.1
VII	15 400	115 170	66	2.1	4.5
VIII	10 040	93 750	90	1.3	3.7
IX	35 640	241 060	150	4.6	9.8
X	37 500	230 300	8	4.7	9.1
Total	369 380	2 468 240	589	–	–
Mean	–	–	–	3.7	8.3

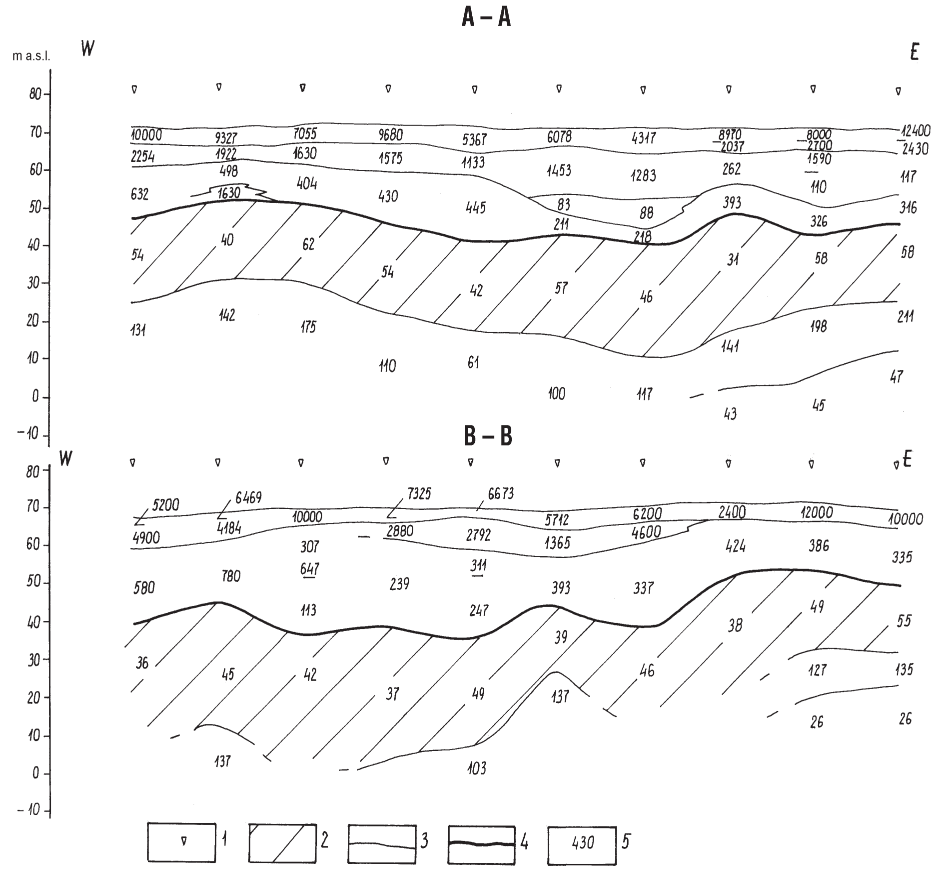


Fig. 3.4. Geoelectrical cross-sections of Lake Gościąż surroundings (see Fig. 3.3) with hydrogeological interpretation. 1 – measurement sites; resistivity in Ohm-metres.

of the temperature measurements of 12 July 1990 should be particularly emphasized. The temperatures recorded in the eastern part were lower (by ca. 4.5–5.0°C) than those in the other parts of the lake (Fig. 3.6 C). Thermal anomalies of this type could have occurred due to a sudden supply of the Tertiary waters through the hydrological windows described above.

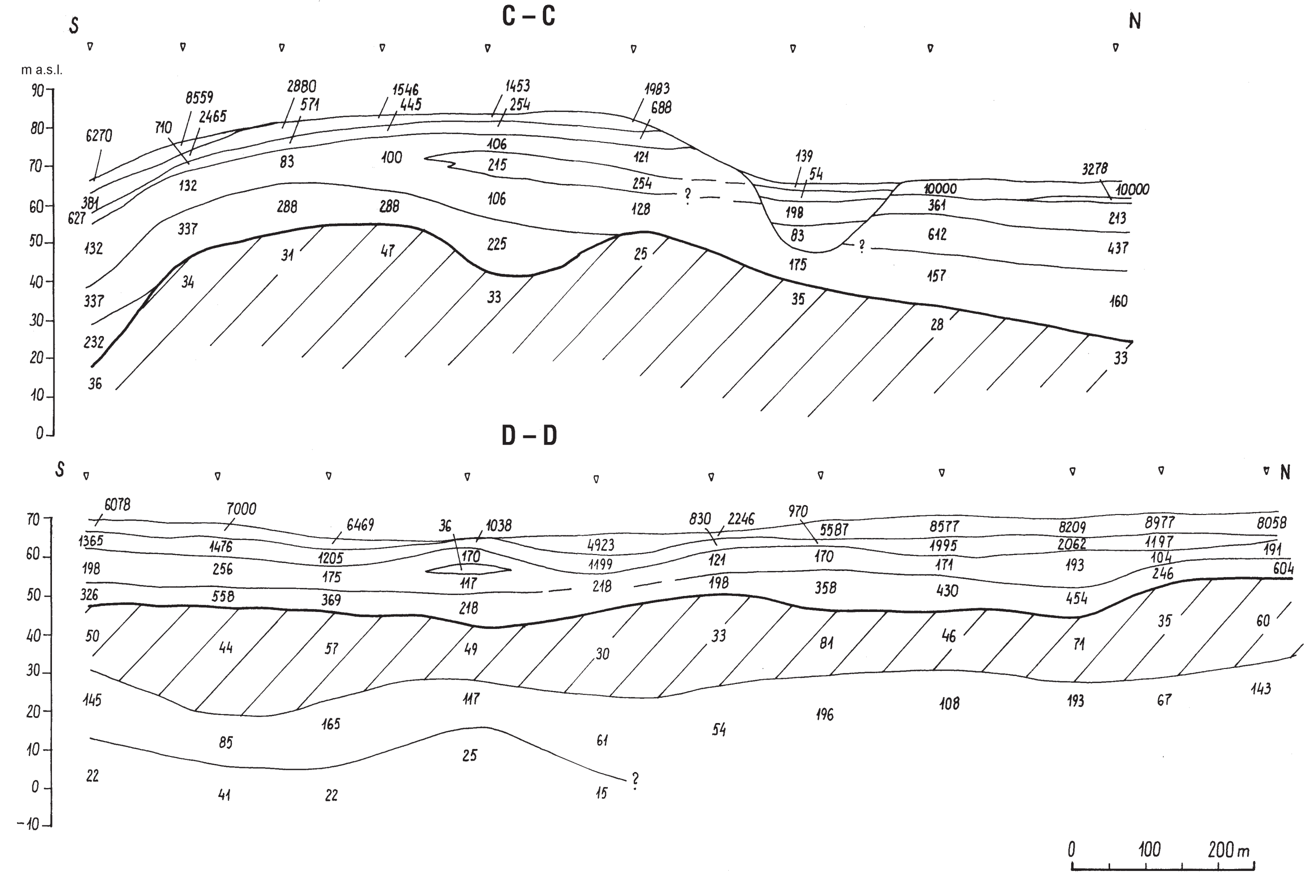
Regular monthly hydrological observations allowed identification of variability in vertical distribution of temperature in subsequent months (Fig. 3.7). Investigations in the deepest site of the lake proved that in Lake Gościąż periods of spring homothermal conditions were short and that summer stratification was initiated in the second half of April. The above is the evidence of bradymictic features of this lake. The bradymictic type of lake is characterized generally by weak circulation, resulting from such factors as: extended ice-cover and persisting snow-cover (sheltered location of lake), thermal and chemical stratification arising the very early spring, very short and weak vernal circulation and early formation of summer stratification (Paschalski 1963, Choiński 1995). During the major part of the observation period the deeper layers of water (below 10 m) were characterized by slight oscillations in temperature and therefore by weak circulation. It is confirmed by very low coefficients of thermal stratification, from 0.44 in August 1994 to 0.56 in August 1992.

Periods of autumn homothermal conditions were slightly longer when compared with the spring ones (ca. by 6 weeks), and their duration depended on timing of ice-cover formation.

During frost periods typical reverse stratification was observed, and water temperature close to the bottom varied from 3.9°C to 5.0°C. This is additional evidence of the influence of groundwater on thermal conditions and dynamics of lake waters as well as of heat accumulated in bottom deposits. The temperature of the surface layer of bottom sediments was almost identical to water temperature at the bottom. However, the temperature of the bottom sediments was higher by a few °C already at a depth of several tens of centimetres.

Based on the results of these studies Lake Gościąż may be assigned to the lakes of eumictic type, with prevailing features characteristic for bradymixis.

Thermal phenomena in the lake directly affect oxygen circulation. Fast summer stratification reduces the possibility of oxidation of the deeper water layers. In Lake Gościąż at depths below 8–10 m a strong deficit of oxygen increases from the decline of spring (saturation of



2 – weakly permeable sediments; 3 – boundaries of the geoelectrically distinguished units; 4 – base of highly permeable sediments; 5 – specific

water with oxygen varied from 20% to 30%), leading to the lack of oxygen in August. Transparency of water is rather low as well. During spring and summer water transparency measured by Secchi disks reached from 1.2 m to 2.0 m. The highest transparency occurred in winter especially during the presence of ice cover and reached 5.0 m.

The properties given above provide evidence of an advanced eutrophy of Lake Gościąż, whose shores are subjected to intensive overgrowth. Increased eutrophication of the lake can be associated with artificial damming of the Ruda stream and thus with the reduced rate of water exchange in the lake, as well as with fisheries.

The studies have confirmed that the lake is permanently fed by groundwater and that this supply is not disturbed by inflow of surface waters. Moreover, exceptionally well preserved rhythm of thermal changes have been identified, with a definite stratification in summer and two periods of homothermal conditions in spring and autumn. These regular thermal changes conditioned weak circulation in summer and winter as well as vertical movement of water particles, which supported sedimentation in periods of homothermal conditions. Due to longer duration of autumn homothermal conditions the

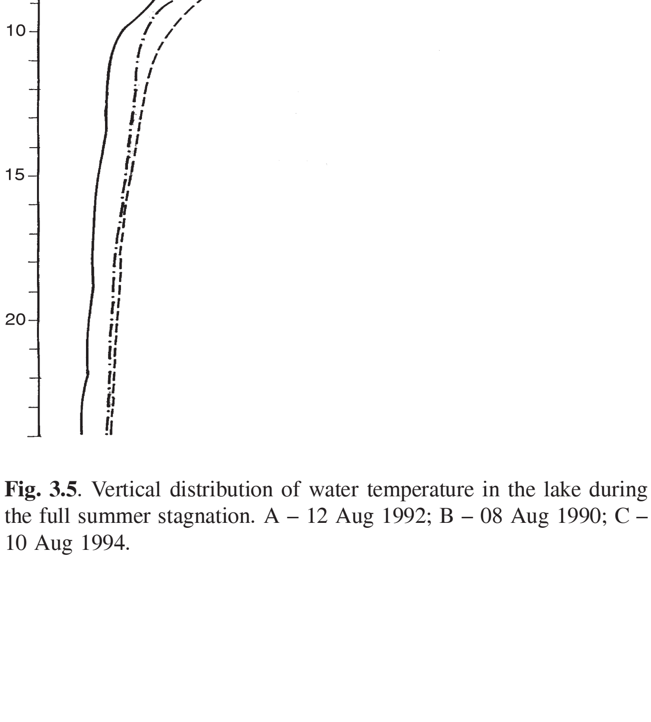


Fig. 3.5. Vertical distribution of water temperature in the lake during the full summer stagnation. A – 12 Aug 1992; B – 08 Aug 1990; C – 10 Aug 1994.

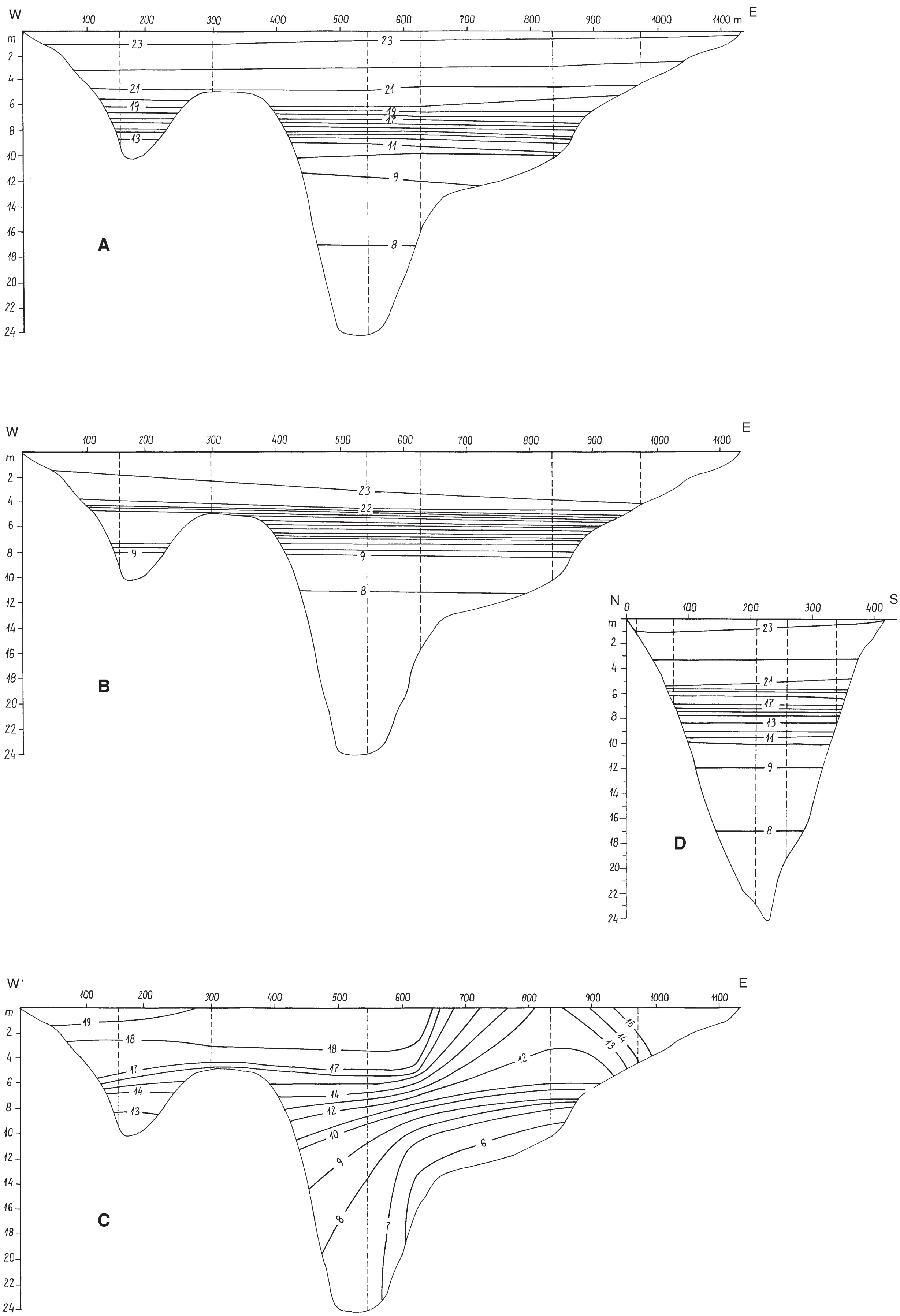


Fig. 3.6. Distribution of water temperature (in °C) along longitudinal profile of the lake (A – August 1990, B – August 1992, C – July 1990) and transverse profile of the lake (D – August 1990).

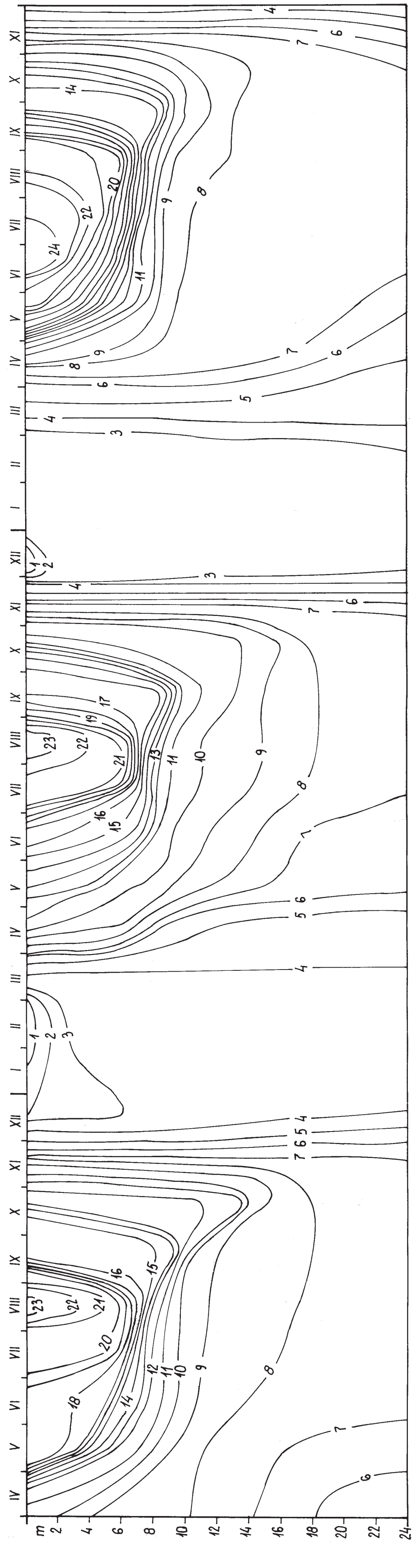


Fig. 3.7. Variability in thermal conditions (°C) in the deepest site of Lake Gościąż in 1990–1992.

accumulation of sediments was most intensive during that time of the year.

Summarizing, it can be said that the sedimentation develops best during autumn homothermal conditions and eventually during spring homothermal conditions. These periods of intensified dynamics of water movement were associated with thermal homogenization and with the increase in alimentation. Summer and winter periods are characterized by extreme calmness, interrupted only by inflow of the cool Tertiary waters. Inflow of water and dissolved substances to Lake Gościąż is controlled by variability in alimentation and is rather small in comparison to the lakes located on the plateau. Such situation results from lake location in the valley and from its intensified feeding by groundwater.

At present the basin of Lake Gościąż is filled with sediments which constitute ca. 50% of its capacity. In 1925 Jaczynowski determined the maximum depth as 25.8 m (Lencewicz 1925). At present the maximum depth is 24 m. It would indicate that ca. 2 m of the bottom deposits could have accumulated in the deepest part for 70 years, assuming that the earlier measurements were precise enough.

Due to overgrowing, the area of Na Jazach lake complex diminishes, though in Lake Gościąż, with steep slopes, this process is very slow. A larger extent of the lake in the past is evidenced by lake terraces in certain locations. The process of overgrowing is currently being stopped by artificial damming, which disturbs the rhythm of water-level oscillations in the lake and can induce changes in sedimentation conditions.

3.4. CHEMISTRY OF GROUNDWATERS IN THE NA JAZACH LAKES AREA

Bogumił Wicik

Lakes Na Jazach and the connecting Ruda stream as well as adjacent peatlands form a hydrological system fed by groundwaters of the Quaternary aquifer. The thickness of this aquifer in the area exceeds 20 m. Beneath the Quaternary aquifer are Pliocene clays and locally Miocene coals and carbonaceous sands or even Cretaceous limestones.

The pressure of the Cretaceous waters, in which mineralization does not exceed 0.5 g/dm^3, is 900–1200 kPa (Fabianowski & Olczak 1988). Near Lake Wierzchoń these waters stabilized at the level of 54 m a.s.l. in wells. Waters of the Miocene brown coal series are also weakly mineralized and are under subartesian pressure of 250–1300 kPa. When bored near Lake Wierzchoń these waters stabilize at ca. 39 m a.s.l. They contain up to 0.4 mg/dm^3 of manganese and in certain cases over 10 mg/dm^3 of iron.

The Quaternary waters in this part of the Płock Basin flow northward with an hydraulic gradient of ca. 1.5–2‰