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Właściwości osadów zbiornika zaporowego w Porąbce
The properties of sediments of the dam reservoir at Porąbka

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Abstract — The paper reports on the degree of silting up of the reservoir and of the vertical and horizontal differentiation of the physicochemical properties of its sediments. On the basis of the vertical variability of the sediments, conclusions were drawn as to changes in time of the degree of trophicity of the particular zones of the reservoir. The dependence of the chemical properties of sediments on the intensity of erosion, the geological and soil structure of the drainage area, and the quality of water of the river are discussed.

A knowledge of the quantity and character of sediments being deposited on the bottom of dam reservoirs is of great importance not only for the determination of the losses in their capacity and the degree of erosion of the drainage area, but also for the explanation of some changes occurring in the chemical composition of their water and biological productivity. The course of the last-mentioned phenomena is related above all to the physicochemical properties of the sediments. It is of particular importance to learn these properties in the case of reservoirs for storage and water supply.

The state of silting up in many Polish reservoirs, among others also in that of Porąbka, has in the past years been the subject of numerous investigations and publications (Mikucki and Wiśniewski 1960, Prochal 1960, Chomiak 1960, Chomiak and Mikulski 1963, Cyberski 1964, Bolesta 1966, Wiśniewski 1963, 1967). On the other hand, relatively few detailed data are found in the home literature concerning the physicochemical properties of sediments. So far, some chemical properties of sediments of the upper part of the Rożnów Reservoir have been determined by Reniger (1955), of its surface layer by Wróbel (1965), and of sediments of exposed zones

of the bottom of the reservoir at Porąbka by Prochal (1960). In sediments of the reservoir at Myczkowce only the organic matter was determined (Wiśniewski 1967).

The chief aim of the present work was to investigate the physico-chemical properties of sediments of the vertical section of the bottom of the Carpathian reservoir at Porąbka before putting into use the higher situated reservoir at Tresna. It is only on the basis of such data that conclusions can be drawn on the changes taking place with time in the trophic conditions of reservoirs.

The grain composition of sediments was determined by the Casagrande-Prószyński method, their reaction electrometrically, the content of coal and organic matter according to the Alten method, the total nitrogen by the Kjeldahl method, and the freely soluble phosphorus according to the Wondrausch (1951) method. Extracts of sediments in 20 per cent HCl for a complete chemical analysis were made according to Tokarski's (1957) method.

Characteristics of the drainage area of the reservoir

The reservoir at Porąbka is situated in a deep narrow, valley of the river Soła in the section of its gorge through the Little Beskid. It closes the mountain catchment basin (with very steep slopes in its source sections), occupying an area of 1089 sq. km., of which 45 per cent is constituted by forests, 34 per cent by arable land, and 16 per cent by pasture. The substratum of the mountain part of the catchment basin is built of Magura sandstone and schist rocks with a moderate content of basic chemical components, and of Godula and Istebna rocks of similar type, very poor in these components. In the substratum of the Żywiec Basin with part of the adjacent valleys of the streams Koszarawa and Łękawka, Krosno sandstones and shales occur, fairly rich in calcium, as well as hieroglyphic shales and sandstones very poor in this element, and others. In the mountain part of the catchment basin clayey skeletal soils, strongly degraded by erosion, prevail and in the Żywiec Basin and drainage areas of the streams mentioned above silt and sour clayey soils are dominant (Pasternak 1960). The mean gradient of the river Soła to the reservoir amounts to 7.89‰. Owing to the great density of the streams and river system (1.12 km/km^2) and the considerable falls of slopes, the river Soła has an exceptionally high catastrophic unit run-off (1351 l/s/km^2) and a fairly high (in spite of the considerable building up of streams) index of erosion of the river basin (162 m^3/km^2). According to Prochal (1960), linear erosion is particularly strongly marked in the catchment basin.

The water of the river Soła is characterized by a high O_2 content,

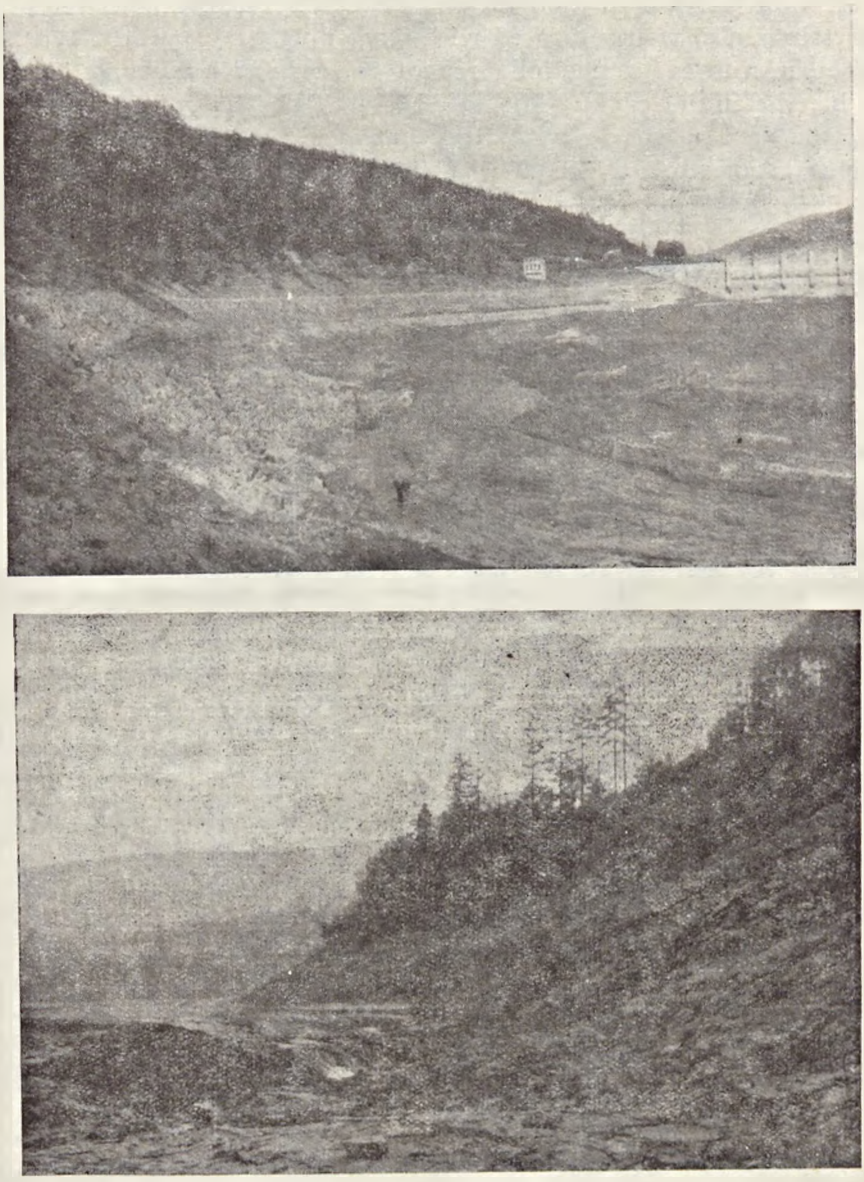

Fig. 1. Steep western bank of the reservoir at Porąbka

a low total hardness (4.0—6.3°n), and low content of potassium, iron, ammonia, nitrites, and usually of phosphates, being rich only in nitrates. On the whole, it has a low oxidability and weak colouring (B o m b ó w n a 1960). The effect of industrial wastes and domestic sewage (from the region of the town Żywiec) is weakly marked in the results of chemical analyses, since the river is endowed with a considerable

capacity of self-purification (M u s i a ł et al. 1958). The water of the reservoir is also well saturated with oxygen (S m a g o w i c z 1963).

The maximum inundation area of the reservoir amounts to about 400 ha, the initial capacity being 32.2 hm.^{3}. The basin of the reservoir near the dam is narrow with steep banks (fig. 1); in the upper part it becomes somewhat wider. The plan of the reservoir and points of sampling the sediments are shown in fig. 2. Besides the river Soła,

Fig. 2. Plan of the reservoir at Porąbka showing points of sampling the sediments

several other streams partitioned by hydraulic jumps and dams flow into the reservoir. Apart from the least steep, inhabited upper section of the western bank, almost the whole terrain of the immediate catchment basin is wooded (spruce, fir, beech). On account of the favourable configuration of the slide-slopes of banks and their high content of stones (fig. 3), the denudation of the bordering zone and the shifting

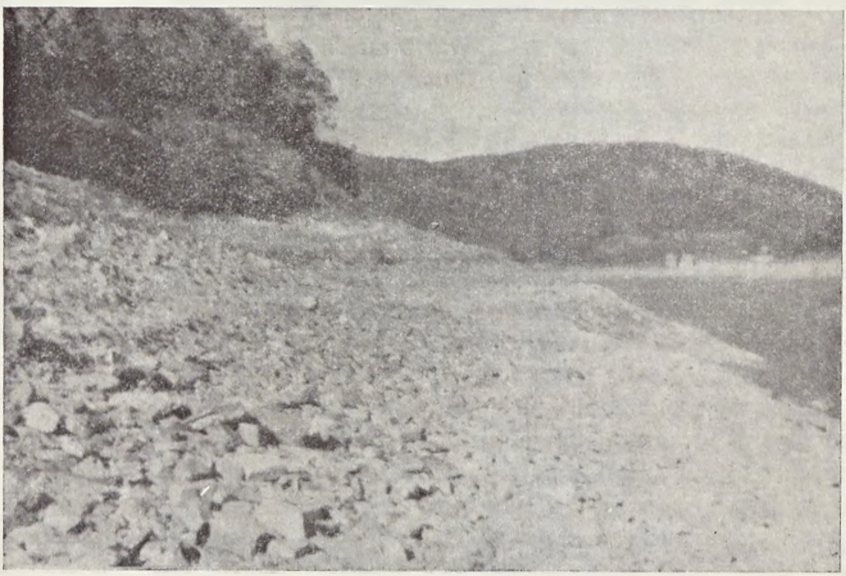

Fig. 3. Configuration of the bank of the middle part of the reservoir at Porąbka

of its line in the last few years is relatively insignificant as compared with other reservoirs, in spite of considerable fluctuations of the water level (Pasternak 1964, Cyberski 1965). The upper, periodically submerged parts of the bottom of the reservoir are overgrown with flowering plants. The reservoir serving for the storage of water and motive purposes is characterized by a fairly rapid interchange of water (rheolimnic). During flood, apart from channels to the power station, outlet sluices are put into operation in the dam.

Results of investigations

Investigations of sediments *in situ* were carried out in the reservoir during a period of drainage (25. IX—15. XI. 1965) for purposes of repair. It was found that the sediments deposited in the course of 28 years had almost evened over the old depressions in the bottom of the reservoir, which indicates that the suspended matter flows into the depressions of the bottom in a large mass. This is probably due to the fact that the water carrying the suspended matter differs in density from that of the reservoir and therefore does not mix with it immediately but, falling slowly to the bottom, flows down over its slope not only towards the dam but also into the lateral depressions. Moreover, there occurs above these depressions of the bottom a fairly thick layer of little mobile water, from which a considerable mass of dead plankton and suspended matter can precipitate, their transport from these places being less intense. The deep ditches in the bottom of the reservoir were formed only secondarily as a result of carrying away the total amount of sediments from the old river and stream channels in the course of its drainage (fig. 4). The washing out of sediments from the reservoir as a means of prolonging its existence is considered to be little effective on account of the possible damage caused by the silting up of the drainage equipment in the further course of the river (Bolesta 1966). On the average, the sediments are thickest (ca. 2 m., fig. 5) in the upper part of the reservoir at some distance from the inflow of the river, being of medium and fairly even thickness (ca. 1.4 m., fig. 6) in the widest and largest middle part of the reservoir, and the least thick (ca. 1 m.) in the zone nearest the dam. According to measurements carried out along the bed of the river, the mean thickness of the sediments in the greater part of the reservoir is about 1.4 m., i.e. the one-year layer amounts to about 5 cm. As concerns the degree of silting up, the reservoir at Porąbka occupies among the Polish reservoirs the second place after the Rożnów Reservoir (Wiśniewski 1963). Judging by earlier measurements of silting (Mikucki and Wiśniewski 1963), it appears that in the last years its rate has somewhat increased.

Fig. 4. Sediments washed out by the river in the course of draining the reservoir at Porąbka

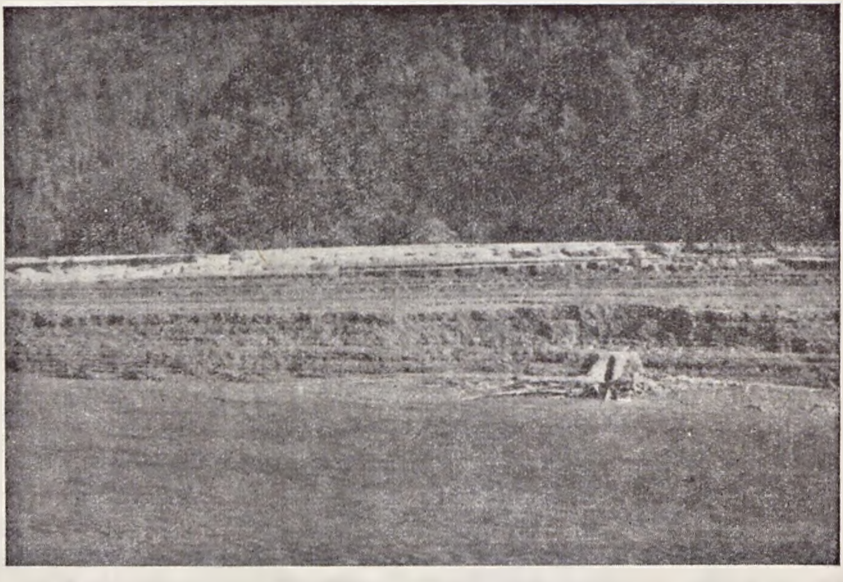

Fig. 5. Profile of sediments in the upper part of the reservoir at Porąbka

Fig. 6. Profile of sediments in the middle part of the reservoir at Porąbka

At present, in connection with the putting into operation of the higher situated reservoir at Tresna, one can expect that the silting of the reservoir at Porąbka will again be less intense.

On account of the fairly uniform stratigraphy and morphology of sediments in the vertical section of the bottom of the greater part of the reservoir, only one entire profile of sediments from its most representative, middle part was subjected to a detailed analysis. In this place the effect of river currents and erosion of the bordering zone is quite insignificant. To determine the horizontal variability of sediments, samples taken from their upper layer in various zones of the reservoir were analysed.

With regard to morphology, four levels can be discriminated in the vertical section of the sediments. In the two upper levels of similar grey colouring and similar grain composition there distinctly appear on the background of the greater part of their mass microlayers 0.3—0.7 cm. thick. The two lower levels are separated by a 1—2 cm. thick layer of sand; they are grey in colour with a light yellow tint and their grain composition is more differentiated. Bands of sediments with a higher content of sand are visible in their section.

As can be seen from the analyses of their mechanical constitution (Table I), the sediments in the whole vertical profile are composed of heavy clay, less silt and clay (< 0.02 mm.) and more sand and silt being present in the lower levels. A considerable differentiation in the grain

Table I. Mechanical composition of bottom sediments in the Porąbka Dam Reservoir in %.

No profile	Depth in cm	Particle diameter in mm						Total
		1–0.1	0.1–0.05	0.05–0.02	0.02–0.006	0.006–0.002	0.002	0.02
1.	0–35	6	2	17	35	21	19	75
	35–70	5	4	18	31	22	20	73
	70–105	12	12	22	24	14	16	54
	105–137	11	11	17	28	16	17	61
2.	0–20	19	38	23	7	5	8	20
3.	0–20	6	2	10	33	26	23	82
4.	0–20	4	3	6	31	32	24	87
5.	0–20	5	3	19	32	23	21	76
6.	0–20	19	15	25	21	9	11	41
7.	0–20	11	9	26	26	14	14	54
8.	0–20	44	17	15	12	4	8	24

composition of sediments is observed in the longitudinal section of the reservoir. In its upper part, further from the bed of the river, the sediments are chiefly composed of medium-heavy loam or sandy and silty loam, or else of silty deposits, and near the bed even of sands. The more sandy and silty deposits occur in the region of the greatest accumulation of sediments, i.e. in the proximity of the in-flowing river. In the middle part of the reservoir, in accordance with the principles of sedimentation, the sediments have a much finer grading and are assigned to heavy loam or clay. Near the dam the content of silt and clay (< 0.02 mm.) decreases, whereas that of fine sand and silty matter grows larger (sample 2). This is presumably related to the more rapid drawing down of fine clay matter suspended in the water or to its washing out from the surface of the bottom by currents formed by the opening of outlet channels in the reservoir. The coarser fractions of sediments, especially those from the proximity of the dam, show a very high content of muscovite, this mineral, fairly resistant to weathering, being widely distributed in the Magura rocks of the catchment basin.

The reaction of sediments (Table II) both in the vertical section and surface layer of various points of the bottom of the reservoir shows no significant differences nor any regularity. It has a neutral or weak-alkaline character.

The content of organic matter in the surface layer of sediments in the upper and middle part of the reservoir is relatively low and little differentiated (Table II). It ranges from 2.93 to 3.95 per cent. The sediments from the proximity of the dam contain still far less organic matter. In this part of the reservoir it was also found that the amount of zooplankton is smaller by half than that present in the middle part (S m a g o w i c z 1963). It seems that, similarly as in the case of colloidal suspended matter, plankton organisms, in consequence of the action of

outflows in the dam, are more rapidly carried away from this zone beyond the reservoir than from the middle zone.

A marked differentiation in the content of organic matter also occurs in the vertical profile of sediments (Table II). Its amount increases from the lower to the upper layer of this profile. The relatively small difference in the content of organic matter between the upper layers may result from the more rapid mineralization to which organic compounds were subjected on the surface of the bottom during the period of dessication of the reservoir. When the reservoir is filled the organic matter mineralizes less intensely because, among other things, very soon it becomes covered by mineral suspended matter.

Table II. The content of organic substances, organic carbon, total nitrogen, available phosphorus and the reaction of bottom sediments in the Porąbka Dam Reservoir

No prof.	Depth in cm	pH (in H_2O)	Organic substance %	C %	N %	C : N	P_2O_5 mg/100 g of sediment
1.	0-35	7.30	3.76	2.18	0.17	12.8	8.0
	35-70	7.35	3.72	2.16	0.19	11.4	5.0
	70-105	7.00	3.00	1.74	0.15	11.6	11.0
	105-137	7.10	2.38	1.38	0.13	10.6	10.0
2.	0-20	7.50	2.07	1.20	0.08	15.0	15.0
3.	0-20	7.15	3.15	1.83	0.16	11.4	8.0
4.	0-20	7.00	3.95	2.29	0.21	10.9	8.5
5.	0-20	7.10	3.93	2.28	0.18	12.7	8.0
6.	0-20	7.20	3.31	1.92	0.16	12.0	10.0
7.	0-20	7.15	3.05	1.77	0.16	11.1	10.0
8.	0-20	7.30	2.93	1.70	0.14	11.9	11.0

The C : N ratio in the sediments indicates (Table II) that plant remains decomposing with difficulty and with low nitrogen content, brought in from the catchment basin, constitute a considerable admixture to the organic matter (of narrow C : N ratio) produced in the reservoir. This refers particularly to the narrowest part of the reservoir near the dam, where the washing away of these remains from the steep wooded banks is most intense.

The chemical composition of the surface layer of sediments (Table III) within the basin of the reservoir shows a similar zonal variability as in the case of the mechanical constitution. Thus, the sediments poorest in all chemical constituents soluble in 20 per cent HCl occur in the proximity of the dam and the richest in the middle main body of the reservoir, especially in its deepest places (sample 4). As concerns the amount of these constituents, sediments of the upper part of the reservoir occupy an intermediate place. Taken as a whole, the investigated

Table III. Chemical composition of a 20 % HCl-soluble part of bottom sediments in the Porąbka Dam Reservoir (air-dry sediments) Note: SiO_2 was activated with 5 % Na_2CO_3

No prof.	1.				2.	3.	4.	6.
Depth in cm	0-35	35-70	70-105	105-137	0-20	0-20	0-20	0-20
SiO_2	12.23	11.66	9.20	8.62	6.18	12.80	15.32	8.68
P_2O_5	0.12	0.10	0.10	0.08	0.10	0.10	0.14	0.12
Al_2O_3	7.99	8.22	6.12	5.84	4.50	8.98	9.67	5.89
Fe_2O_3	4.36	3.88	3.52	3.48	1.80	4.10	4.25	2.65
MnO	0.13	0.13	0.09	0.10	0.05	0.13	0.13	0.06
CaO	1.28	1.16	0.80	0.74	0.82	1.00	1.02	0.82
MgO	1.56	1.48	1.13	1.06	0.92	1.70	1.72	1.22
K_2O	1.18	1.11	0.91	0.88	0.67	1.19	1.23	0.82
Na_2O	0.32	0.27	0.27	0.29	0.38	0.40	0.35	0.37
SO_3	0.32	0.32	0.26	0.20	0.26	0.27	0.30	0.22
Total of soluble parts in HCl	29.49	28.33	22.40	21.29	15.68	30.67	34.13	20.85
H_2O (105°C)	2.21	2.30	1.92	1.83	0.86	2.64	2.71	1.68
Loss in ignition	6.93	7.50	6.00	5.62	3.54	6.95	7.28	6.30
Total of insoluble parts in HCl	61.40	61.95	69.72	71.35	79.93	59.82	56.00	71.22
Total	100.03	100.08	100.04	100.09	100.01	100.08	100.12	100.05

sediments are characterized above all by a relatively small (for sediments of a water reservoir) content of calcium and iron. Their content of these constituents is only quite insignificantly higher than in the less compact mineral sediments of the Tatra lakes with a very poor granite catchment basin (P a s t e r n a k 1965). For lack of appropriate comparative data it can only be said that the sediments of the reservoir at Porąbka have a content of magnesium, potassium, and aluminium similar to continental soils of this section of the Carpathians (L a z a r 1952, P a s t e r n a k 1960) and a definitely higher content of freely soluble phosphorus (Table II). The content of this form of phosphorus in the examined sediments is also much higher than in those of the reservoir at Rożnów of similar type (R e n i g e r 1955). The greatest quantity of total phosphorus (soluble in 20 per cent HCl) and the smallest of the freely soluble one was found in samples of sediments with the highest content of clayey matter.

The chemical composition of sediments changes also in the vertical

section of the bottom of the reservoir. Both the sum total of constituents dissolved in 20 per cent HCl and the number of the particular elements slightly increase from the bottom to the surface of the profile of the sediment. It should be noted that this variability shows no positive correlation with the vertical change in the mechanical constitution of sediments. Hence, these changes are chiefly related to the physico-chemical and biological processes taking place in the water of the reservoir. The elements whose content increases relatively the most towards the top of the profile of the sediment are calcium, potassium, manganese, and phosphorus. The smallest quantitative changes are noted in the vertical distribution of sodium and sulphates.

Discussion of results

As can be seen from the data reported above, the silting up of the reservoir at Porąbka has been fairly intense, especially within the last few years. In the process of silting up of reservoirs of this character of drainage area the finest fractions of fluvial suspended matter play the essential part. The sediments of the investigated reservoir as compared with those of the Carpathian reservoir at Rożnów (R e n i g e r 1955, W r ó b e l 1965) have a similarly low content of organic matter, a very low content of calcium, and a fairly high content of soluble phosphorus. The content of organic matter in the sediments of the reservoir at Porąbka is, however, somewhat higher than in those of the reservoir at Rożnów or Myczkowce (W i ś n i e w s k i 1967). For the time being there is no possibility of comparing in detail the other determined chemical components of the sediments of the investigated reservoir on account of the lack of analogous determinations of components present in sediments of the other Carpathian reservoirs. The low content of organic matter in this type of mountain reservoir is probably chiefly due to the fact that the greater part of the mass of sediments depositing on their bottom represents a mineral material washed out from the drainage area and poor in organic matter (P o l a k 1965), while only an insignificant part constitutes organic matter produced in the reservoir. Particularly poor in organic matter is the suspended matter of a river whose substratum of the drainage area is subjected (as in the case of the river Soła) to an intense linear erosion. The share of organic matter in the sediments is also reduced by the fact that its production by plankton in the Carpathian reservoirs is relatively small, as was shown by S m a g o w i c z (1963) and B u c k a (1965) in their investigations. This, in S t a r m a c h's (1958) opinion, is in great measure related to the circumstance that the frequent exchange of water in dam reservoirs contributes to the predominance of the transport of organic matter

suspended in the water over its deposition on the bottom. According to Mackereth (1965), the considerable intensity of erosion of the drainage area also has an essential effect on the distribution and content of carbon in sediments of natural lakes. It can therefore be presumed that the lower content of organic matter in sediments of the reservoir at Rożnów than in that of Porąbka results above all from the difference in the rate of deposition of suspended matter on their bottom. The low content of calcium in sediments of the reservoir at Porąbka is indubitably related to the relatively small quantity of this component in the substratum of the greater part of the drainage area and in the water of the river. The considerable (as compared with the sediments of the Rożnow reservoir) content of freely soluble phosphorus in the investigated sediments is probably due to the periodical pollution of the river Soła by domestic sewage. The fact that some impurities reach the reservoir is ewidenced, apart from chemical analyses (Musiał et al. 1958), by the somewhat different composition of the benthos established by Kownacki (1963) at a site near the inflow of the river. It may be that the intensification of mineral fertilization in the area of the catchment basin also has a certain effect on the amount of phosphorus in the water of the reservoir. With respect to the earlier results of Prochal's (1960) analyses, the content of freely soluble phosphorus markedly increased.

The content of organic matter, magnesium, calcium, manganese, potassium, and phosphorus, successively increasing in the vertical section of sediments from the lower to the surface layer, indicates that the middle part of the reservoir at Porąbka undergoes with time an insignificant eutrophication. This, however, does not take place in its lower zone near the dam. On the contrary, this zone is continuously growing poorer in organic and mineral biogenous chemical components, which is probably due to the increased movement of water taking place here owing to the action of channels to the power station and outlet sluices in the dam, carrying away more intensely beyond the dam the organic and colloidal mineral suspension. It is owing to the accumulation of these substances that there occurs an insignificant increase, progressing in time in the amount of trophic and chemical components in the sediments of the middle part of the reservoir. The physicochemical precipitation of mineral salts from the water is of almost no significance here, their content in the water of the river Soła being extremely low.

STRESZCZENIE

Terenowe badania nad osadami zbiornika w Porąbce zostały przeprowadzone w okresie jego opróżnienia (25 IX — 15 XI 1965 r.), potrzebnego dla dokonania remontu. Z uzyskanych danych wynika, że intensywność zamulania tego zbiornika

do czasu uruchomienia zbiornika w Tresnej była dość duża. Orientacyjnie (wg pomiarów wzdłuż koryta rzeki) średnia grubość namułu większej części zbiornika waha się około 1,4 m, czyli jednoroczna warstwa wynosi około 5 cm. Najmniejszą miąższość mają namuły w przyzaporowej strefie. W procesie zamulania tego typu zbiorników zasadniczą rolę odgrywają najdrobniejsze frakcje unosin rzecznych. W górnej części zbiornika osady mają przeważnie skład glin średnich i lekkich lub utworów pyłowych, a w środkowym plosie glin ciężkich oraz iłów. W pobliżu zapory osady mają znowu mniejszą zawartość części spławialnych, a więcej drobnego piasku i frakcji pyłowych. Zmienność składu granulometrycznego w pionowym przekroju osadów jest nieznaczna (tabela I). Osady zarówno w przekroju pionowym, jak też w poziomym mają odczyn obojętny lub słabo alkaliczny (tabela II).

Zawartość substancji organicznej w powierzchniowej warstwie osadów w górnej i środkowej części zbiornika jest stosunkowo mała i mało zróżnicowana (tabela II). Jeszcze mniej substancji organicznej występuje w osadach w pobliżu zapory. W pionowym przekroju osadów zawartość materii organicznej wzrasta od spągu do ich powierzchni. Ogólnie mała zawartość materii organicznej w osadach tego typu podgórskich zbiorników wynika w zasadzie z tego, że osady takie tworzą się głównie z ubogich w organiczne substancje mineralnych części przyniesionych ze zlewni (zwłaszcza na skutek erozji liniowej). Udział w ogólnej masie osadów materii organicznej wyprodukowanej w zbiorniku (o wąskim stosunku C : N) jest bardzo niewielki. Stosunek C : N wskazuje (tabela II), iż znaczny odsetek materii organicznej osadów stanowią twarde resztki roślinności przyniesionej ze zlewni, o małej zawartości azotu.

Skład chemiczny powierzchniowej warstwy osadów wykazuje (tabela III) w obrębie misy zbiornika podobną zmienność strefową jak w przypadku składu mechanicznego. Najuboższe osady we wszystkie oznaczane składniki chemiczne występują w pobliżu zapory, a najbogatsze w środkowym plosie zbiornika, zwłaszcza w jego najgłębszych miejscach. Ogólnie biorąc, badane osady odznaczają się przede wszystkim małą zawartością wapnia i żelaza, a nieco większą niż inne zbiorniki karpackie ilością rozpuszczalnego fosforu. Taka zawartość wapnia wiąże się z małym zasobem tego składnika w podłożu zlewni i wodzie rzeki. Natomiast podwyższona ilość łatwo rozpuszczalnego fosforu łączy się prawdopodobnie z zanieczyszczeniami wody rzeki.

W pionowym przekroju namułu zawartość poszczególnych pierwiastków chemicznych wzrasta, podobnie jak ilość substancji organicznych, od dołu ku jego powierzchni. Zmiany te nie wykazują dodatniej korelacji z pionowym zróżnicowaniem w składzie mechanicznym namułu. A zatem wiążą się głównie z biologicznymi i fizyko-chemicznymi procesami zachodzącymi w wodzie zbiornika. Pionowa zmienność chemizmu osadów wskazuje, iż środkowa strefa zbiornika tylko bardzo nieznacznie wzbogaca się z czasem w zasadowe i troficzne składniki chemiczne. Natomiast jakość osadów w pobliżu zapory przemawia za tym, że w tej części zbiornika zachodzi raczej proces zubożania w biogeniczne składniki chemiczne. Ubytek tych składników jest prawdopodobnie skutkiem intensywniejszego wynoszenia z tej strefy zbiornika poza zaporę organicznej (plankton) oraz koloidalnej zawiesiny mineralnej, związanego z działaniem kanałów do elektrowni i upustów dennych.

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