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Dopływ azotu i fosforu do zbiornika zaporowego w Goczałkowicach w latach 1973—1975*

Inflow of nitrogen and phosphorus to the dam reservoir at Goczałkowice in the years 1973—1975

Wpłynęło 30 grudnia 1975 r.

A b s t r a c t — On the basis of regression equations expressing the relation between flow and concentration, the loads of nitrogen and phosphorus flowing into the reservoir were calculated. Subsequently the balance of these elements in the reservoir and the plan of decreasing its trophic conditions were presented.

The phenomenon of shallowing and aging, not only of ponds (P a s t e r n a k 1958) and lakes (W i s z n i e w s k i 1953), but also of artificial dam reservoirs (P a s t e r n a k 1973), has been known for a long time. An important part in this process is played also by phosphorus and nitrogen mineral compounds causing eutrophication of the water and, hence, an increased production of organic matter deposited on the bottom. Municipal sewage, rich in trophic compounds, and ground-water run off from fields under cultivation enriched with larger and larger doses of fertilizers are the source of biogenous elements.

Man should be interested in inhibiting the process of eutrophication, or at least in extending it in time. For this purpose it is necessary to know the amount of mineral salts with which the reservoir is supplied. One of the conditions of planning ways to prevent excessive eutrophication should be the evaluation of the balance of biogenous elements and the prognosis of its changes.

* Praca została wykonana w ramach problemu węzłowego Nr 09.1.7.

Characteristic of the reservoir

The reservoir at Goczałkowice is the main reserve of drinking water for the Upper Silesian Industrial Centre. Water has constantly been drawn from it since 1955, in the amount of 2 to 3 m^3/sec., for the largest urban-industrial agglomeration in Poland.

The reservoir at Goczałkowice was built in the wide and flat valley of the River Vistula at the 67 km of its course. Its total surface area at maximum water level is about 32 km^2, its capacity 168 million m^3, and its average depth does not exceed 5 m. It is a large shallow reservoir of pond character. The intensity of the wind and the water turbulence connected with it have a great influence on the vertical distribution system of chemical components in the water of the reservoir.

The catchment area of the reservoir is 532 km^2, covering the montane and sub-montane regions of the Beskid Mts. The geological and soil science characteristics of this territory were given in detail by Pasternak (1962). According to that author the whole montane territory of the catchment area is covered with solid, shallow loams, average deep loams, and rocky soils. Solid loamy soils have besides a stony solid body a fairly large admixture of eluvium (top rock) with mechanical composition of dusty, average clay or mostly of light clay with a large admixture of sands. These are rather poor soils. The mechanical composition of clayey soils is usually that of heavy dusty soils; they are more fertile.

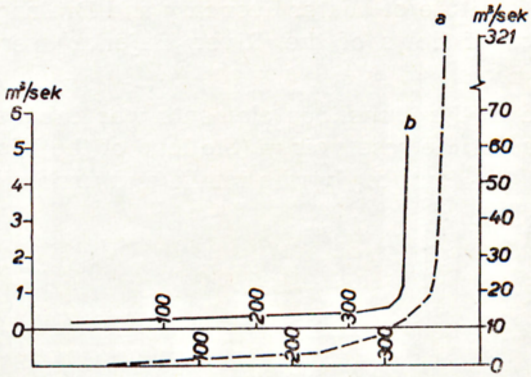
For the sub-montane territory of the catchment area dusty loams and fertile carbonate soils and loamy soils are characteristic. These soils are rich in potassium and fairly rich or poor in phosphorus.

In the flat part of the catchment area dusty loams, dusty loesses, valley peats, and small areas of loamy soils occur. However, in the valley of the River Vistula and its tributaries silts occur. These soils contain only small amounts of absorbable potassium and phosphorus.

34 per cent of the catchment area is covered with forest, these being mostly situated on montane territories, where they cover about 90 per cent of the area. In the lowlands fields under cultivation prevail.

In the montane part of the catchment area, in consequence of the large forest areas and the character of soil formation, the surface erosion is poor, in spite of steep slopes and heavy rainfall. With regard to the fact that the sub-montane territory of the basin is covered with fertile and dusty soils and its surface undulating and poorly covered with woods, it undergoes strong surface and considerable linear erosion. The flat territory, in spite of dusty soils, suffers only slight erosion (Pasternak 1962).

Four towns with a total number of inhabitants not exceeding 35 thousand are situated in the territory of the catchment area. The rela-



Ryc. 1. Krzywe częstości przepływów Wisły (a) i Bajerki (b) w latach 1972—1974
Fig. 1. Flow frequency curves of the River Vistula (a) and the Bajerka (b) in the years 1972 to 1974

tively low urban population increases greatly in the summer and also winter seasons owing to tourist and recreation activity.

The reservoir is supplied with water, apart from the already-mentioned main tributary, by the Vistula, carrying about 79 per cent of the water, with the waters of two small rivers, the Bajerka and the Knajka. The curves of flow frequencies of the Vistula and the Bajerka are given in fig. 1.

Method

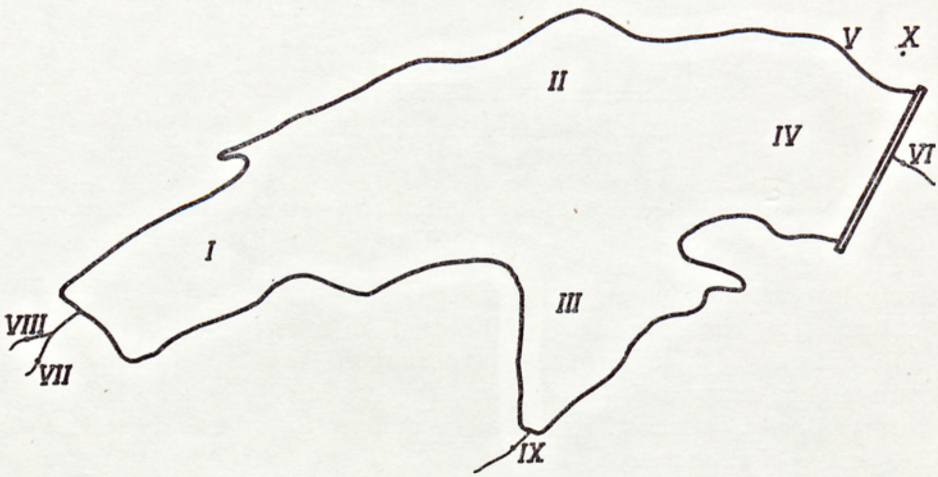
The localization of the water and sediment sampling stations is shown in fig. 2. At the stations situated in the reservoir (I, II, II, IV) and at the water intake (V) a mean sample from 0, 1, 2.5, and 5 m in dependence on the depth was taken and another from the layer contacting the bottom, and bottom sediments being taken from its surface layer. At the bottom outlet (VI) of the Rivers Vistula, Bajerka, and Knajka one sample was taken at a depth of 0.1 to 0.2 m. Samples were collected at intervals of two weeks to l month, in an attempt to observe the diverse conditions prevailing in the reservoir and extreme flows in the rivers. At station X, situated on the territory of the Hydrobiological Station, rainfall was measured.

Interstitial water was obtained by centrifuging the sediments.

For analysis, methods given by Just and Hermanowicz (1955), Golterman (1969), and Lityński et al. (1968) were used.

Water indication observations of the River Vistula, and data concerning the amount of water discharged by the undersluice and the amount of water drawn off for drinking purposes were made available by the District Institute of Water Economy and Drainage at Goczałkowice. Investigation of flows of the River Bajerka were carried out by D. Augustyn.

The balance of the biogenous elements was calculated according to the scheme: load of the reservoir = (the load of the Vistula, Bajerka and Knajka, rainfall) — (outflow by the intake and undersluice).



Ryc. 2. Zbiornik Goczałkowice — rozmieszczenie stanowisk. I, II, III, IV — stanowiska na zbiorniku; V — ujęcie wody; VI — upust denny; VII — Wisła; VIII — Knajka; IX — Bajerka; X — Stacja Hydrobiologiczna

Fig. 2. Reservoir at Goczałkowice — distribution of stations. I, II, III, IV — stations in the reservoir; V — water intake, VI — bottom outlet; VII — the Vistula; VIII — the Knajka; IX — the Bajerka; X — Hydrobiological Station

For calculation of annual loads of the inflowing and outflowing nutrient compounds methods were applied, which can be divided into three groups:

1. It was assumed that concentration does not change between particular dates of water sampling

$$l = \sum_{i=1}^{n} (x_i \cdot y_i) \qquad (1)$$

where: l — load,
x — flow,
y — concentration.

In this way amounts of biogenous salts outflowing from the reservoir through the sluice and intake and, for the sake of comparison with the subsequently described method, the loads of the Vistula and the Bajerka were determined.

2. Mean concentration was calculated from particular determinations

$$1 = \frac{\sum_{i=1}^{n} y_i}{n} \cdot x \qquad (2)$$

This method was used for calculating the magnitude of the load carried by the River Knajka. Since on this river no hydrological measurements were carried out, the mean flow equalling 0.435 m^2/sec was calculated from the years 1954 to 1956 (Przetocki 1956).

3. The regression function was found expressing the relation between flow and concentration

$$y = f(x) \quad 1 = \sum_{i=1}^{n} y_i \cdot x_i \qquad (3)$$

In this way the loads of phosphorus and nitrogen brought in by the Rivers Vistula and Bajerka were calculated.

Regression equations for calculating nitrogen and phosphorus loads brought in by the Rivers Vistula and Bajerka

In calculating the amounts of biogenous salts brought into the reservoir according to formulas 1 or 2, often at high water levels in the rivers when the chemical composition of the water differs from the average, this state was not taken into consideration.

At the highest water levels in the river, the content of some components present in it increases in consequence of being washed out from the soils of the catchment area, while the concentration of other components decreases at that time as a result of dilution. Hence, it seems reasonable to determine the load flowing in the river by determining the relation between the flow and concentration of salts in the water of the tributary. This relation, calculated for the River Bajerka and for the Vistula, could be given in the present paper in the form of a logarithmic curve, and after transformation, in that of a linear function

$$y = a + b \log x \qquad (4)$$

where:

x, y — denotations as in (1),

a, b — coefficients of regression.

The parameters of simple regression determined by the cracovian method are given in Table I.

The positive correlation found between the magnitude of flow and the content of trophic compounds investigated in the Vistula and the Bajerka shows that the nitrogen and phosphorus from these two tributaries originate from water erosion of the soils of the catchment area. However, the lack of mutual relation of organic phosphorus in the Vi-

Tabela I. Współczynniki do obliczenia ładunku rzek z równań regresji oraz współczynniki korelacji

Table I. Coefficients for calculation of the river load from equations of regression and coefficients of correlation

Rzeka River	Składnik Component	Współczynnik regresji Coefficient of regression		Współczynnik korelacji Coefficient of correlation r
		a	b	
Wisła Vistula	azot mineralny mineral nitrogen	1.4557	0.2235	0.31
	fosforany phosphates	0.0143	0.0034	0.36
	fosfor organiczny organic phosphorus	-	-	0.08
Bajerka	azot mineralny mineral nitrogen	- 3.6272	2.0105	0.48
	fosforany phosphates	- 0.0770	0.0408	0.38
	fosfor organiczny organic phosphorus	- 0.3891	0.1753	0.59

stula provides evidence of an irregular rhythm of sewage discharge, this corroborating the already-mentioned fact that during the period of holiday seasons the catchment area of the River Vistula is a place of mass tourist activity.

The coefficients of correlation given in Table I, as a measure of the relation of the two investigated features, indicate that there is no full agreement between the determined variables. Dispersion of the points around the straight line of regression is caused by the non-uniform physical state of soils of the catchment area in various seasons of the year. Also the frequency of rainfall, its intensity and distribution in the catchment area (H o f m a n n 1972), as well as oxidation and denitrification processes in the river (W a g n e r 1969), have a certain influence on

Tabela II. Procentowe porównanie ładunków soli biogennych wpływających do zbiornika, obliczonych wg równania regresji (100%) i równania (1)

Table II. Percentage comparison of load of biogenetic salts flowing into the reservoir calculated according to the equation of regression (100%) and equation (1)

Rzeka River	Składnik Component	1973	1974	1975
Wisła Vistula	azot mineralny mineral nitrogen	- 28.9	- 14.6	+ 11.9
	fosforany phosphates	- 47.9	-122.2	+ 52.5
Bajerka	azot mineralny mineral nitrogen	- 32.8	- 31.6	- 5.5
	fosforany phosphates	- 15.4	- 18.9	+ 21.5
	fosfor organiczny organic phosphorus	- 16.7	- 53.6	+ 8.4

the degree of correlation between the flow and concentration of the investigated nutrient compounds.

Table II shows in terms of percentage, a comparison of annual loads of nitrogen and phosphorus brought into the reservoir by the Bajerka and the Vistula, calculated according to the regression equations and formula (1), assuming that 100 per cent of the inflowing biogens are involved in equation $y = f(x)$.

The reason for a smaller amount of components carried into the reservoir in 1973 and 1974, calculated on the assumption of a constant concentration during the period between particular samplings, lies in the fact that nitrogen and phosphorus concentration variations at high flows were not taken into consideration (fig. 4a), this being particularly noticeable in the case of phosphates. In 1975, on the other hand, when samples were collected mainly at high water levels, small values of nitrogen and phosphates were neglected at low flows. Similarly, when comparing the load of nitrates and phosphates flowing in the River Argen with Unger's data from daily analysis in the course of one year, Wagner (1969) found a difference in nitrates and phosphates of -19 and $+13$ per cent respectively.

Exact evaluation of the amount of biogenous salts supplied to the reservoir has so far encountered many difficulties. In spite of the automatization introduced in sampling and analysis, it is still impossible to install automatic apparatus at every inflow. It is therefore necessary to elaborate methods which would permit the inflowing load of nutrient compounds to be calculated with great accuracy.

For calculating the balance of nutrient salts the "Polish standard" envisages sampling every ten days. Chalupa (1959), Ambühl (1960) collected samples at least once a week and Wiesner and Link (1970) took samples daily the whole year round. On the other hand, samples were also taken only once a month, e.g. by Kliffmüller (1960) and Nümann (1968).

Wagner (1969) and Unger (1970) remark that sampling at short and constant time intervals is not of great importance, it is very important, however, to determine the concentration in the whole scale of flows. Unger proves that from 11 samples the annual inflow of nutrient compounds can be calculated with satisfactory accuracy. These same authors drew attention to the importance of sampling during periods of high water. From such measurements regression equations expressing the relation between the flow and mineral salt concentration can be calculated.

Such equations for calculating the river loads were elaborated by Chalupa (1959), Mańczak (1968), Wagner (1969), Unger (1970), Bauer (1971), and Hofmann (1972).

Tabela III. Bilans azotu i fosforu w zbiorniku goczałkowickim

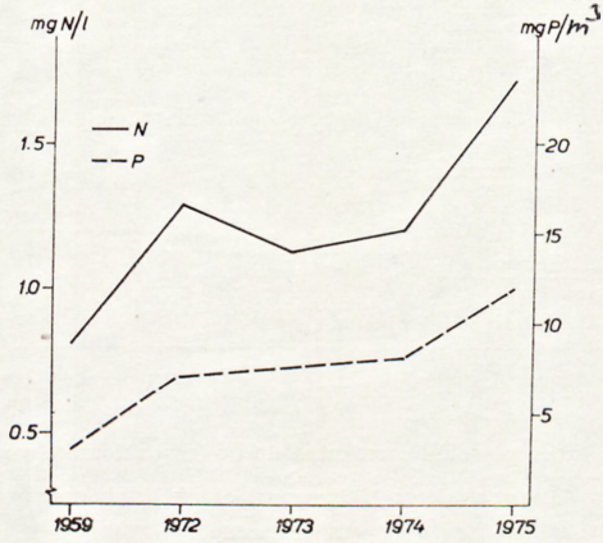
Table III. Balance of nitrogen and phosphorus in the Goczałkowice reservoir

Pochodzenie N i P Source of N and P		1973			1974			1975		
		N mineralny mineral	P mineralny mineral	P organiczny organic	N mineralny mineral	P mineralny mineral	P organiczny organic	N mineralny mineral	P mineralny mineral	P organiczny organic
Dopływy w tonach Inflow in tons	Wisła - Vistula	245.20	2.59	4.15	424.96	4.60	6.54	313.76	3.24	5.28
	Bajerka	14.45	0.26	0.54	20.02	0.37	0.97	22.79	0.42	1.20
	Knajka	14.79	0.89	0.93	14.79	0.89	0.93	14.79	0.89	0.93
	Opady atm. Rainfall	36.22	0.50	-	44.28	0.86	-	46.13	0.86	-
	Razem dopływy Total inflow	310.66	4.24	5.62	504.05	6.72	8.44	397.47	5.41	7.41
Odpływy w tonach Outflow in tons	Upust denny Bottom outlet	15.41	0.22	0.48	197.47	1.33	6.80	199.73	1.80	3.96
	Ujęcie Intake weir	43.34	0.44	1.95	61.08	0.38	1.24	75.07	1.28	1.41
	Razem odpływy Total outflow	58.75	0.66	2.43	258.55	1.71	8.04	274.80	3.08	5.37
Wynik bilansu Effect of balance	Retencja w t Retention in t	+251.91	+3.58	+3.19	+245.50	+5.01	+0.40	+122.67	+2.32	+2.04
	Retencja % Retention %	81.1	84.4	56.8	47.7	74.6	4.7	30.9	43.0	27.5
	Obciążenie zbiorn. w g/m^2/rok Load of reservoir in g/m^2/year	7.87	0.112	0.100	7.67	0.157	0.013	3.83	0.073	0.064

Nitrogen and phosphorus balance

The data concerning the amounts of salts flowing into and out of the reservoir, originating from various sources, are presented in Table III. As can be seen, in the investigated years different amounts of the nitrogen and phosphorus carried in remained in the reservoir. Thus, nitrogen and mineral phosphorus retention equalled 31 to 81 per cent and 43 to 84 per cent respectively. The reason for this diversity lies among other factors in the water balance of the reservoir. In 1973 only 41.7 per cent of the total amount of the inflowing water flowed out of the reservoir, whereas in the following years the percentage was 86.6 and 104.0 respectively.

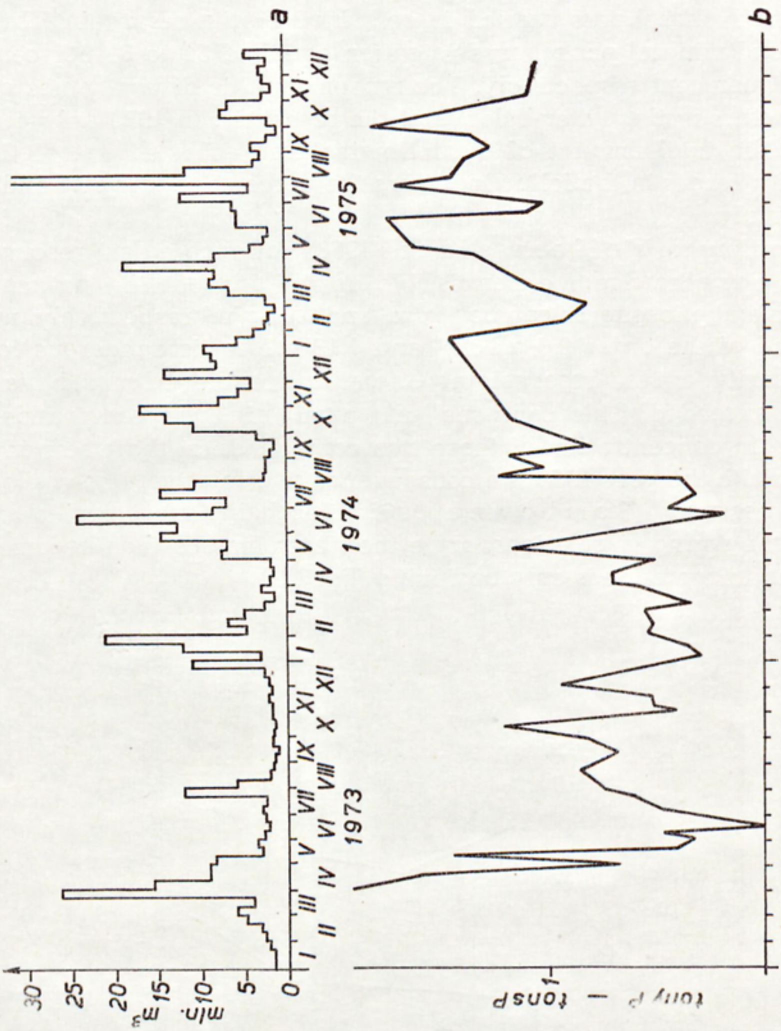
According to Vollenweider (1968), for such a dam reservoir as that at Goczałkowice the permissible annual load of the bottom with nitrogen and phosphorus can be 1 g/m² and 0.07 g/m² respectively, whereas a load of the order 2.0 g N/m² and 0.13 g P/m² is dangerous for the water purity. In the reservoir at Goczałkowice these limits have been greatly exceeded. This concerns, above all, nitrogen compounds. The increase in concentration of these two compounds in the water in comparison with the year 1959 is a consequence of a relatively heavy loading of the reservoir (Bombówna 1962), this being most easily noticed during the spring circulations, since the water masses then become well mixed and vegetation is only beginning (fig. 3).



Ryc. 3. Zawartość azotu i fosforu mineralnego w okresie wiosennej cyrkulacji w zbiorniku

Fig. 3. Nitrogen and mineral phosphorus content during spring circulation in the reservoir

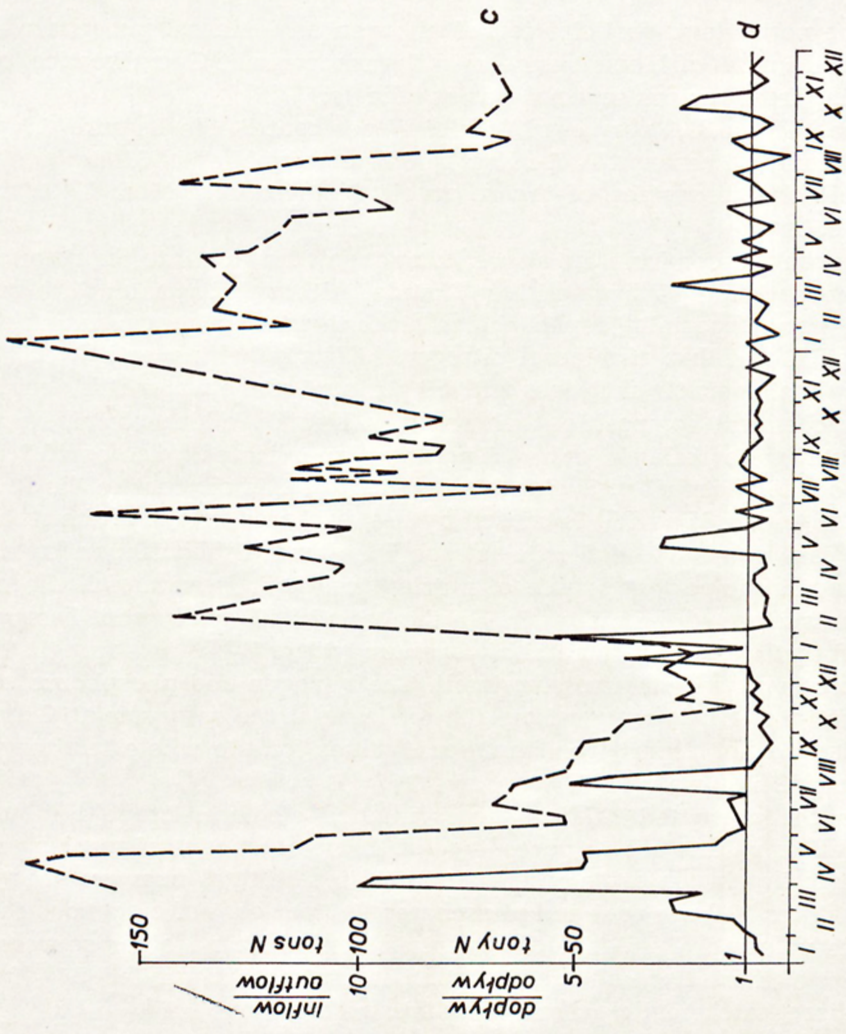
According to S t u m m (1964), the relation of nitrogen to phosphorus in the plankton biomass is approximately 7.2 : 1, hence the demand for these compounds in the reservoir should be similar. It may be concluded from the N : P ratio which element is in excess or inhibits the develop-



Ryc. 4. Ładunek fosforanów (b) i azotu mineralnego (c) w zbiorniku w zależności od dopływu wody (a) i bilansu wodnego (d): $\frac{\text{dopływ}}{\text{odpływ}} > 1$ = przybór wody; $\frac{\text{dopływ}}{\text{odpływ}} < 1$ = ubytek wody

Fig. 4. Phosphate (b) and mineral nitrogen (c) load in the reservoir in dependence on the water inflow (a) and water balance (d): $\frac{\text{inflow}}{\text{outflow}} > 1$ = rise of water; $\frac{\text{inflow}}{\text{outflow}} < 1$ = fall of water

ment of algae. The calculation made for the reservoir at Goczałkowice showed that the amounts of mineral nitrogen considerably exceeded the required relation, which varied in the period of investigation from 26 to 846 : 1, the lowest values occurring during the autumn circulation, where-



as the N : P ratio was high during phytoplankton vegetation. A similar annual distribution of N : P was observed in the reservoir at Lubachów (S o l s k i 1972).

As for phosphorus, the water in the reservoir showed in June 1973 and 1974 (fig. 4b), i.e. during intensive vegetation by aquatic organisms, only trace amounts or a complete absence of this element. This is one of the proofs that this element can periodically limit the development of phytoplankton. On the other hand, in 1975, in consequence of an increased inflow of phosphates to the reservoir in autumn 1974, its mean content was not lower than 10 μg P/l. This relatively large amount was the cause of a mass development of *Microcystis aeruginosa*, which, according to Beeton (cit. Solski 1972) indicates a high degree of trophism in lakes.

The percentage participation of nitrogen and mineral phosphorus in the total inflow of biogenous salts in the reservoir at Goczałkowice, originating from various sources, was as follows:

the Vistula 81.2 per cent N and 63.7 per cent P, the Bajerka 4.7 per cent N and 6.4 per cent P, the Knajka 3.7 per cent N and 16.3 per cent P, rainfall on the surface of the reservoir 10.4 per cent N and 13.6 per cent P.

As can be seen from the above, components flowing into the reservoir are mainly supplied by the River Vistula. Although its waters are relatively poor, especially in phosphates, since their mean concentration was 18 μg P/l, and that of mineral nitrogen 1.674 mg N/l, nevertheless, supplying the reservoir as it does with 79 per cent of the water it is decisive in its chemical composition, whereas the Knajka, which contributes in the total water balance only 5.5 per cent, supplies as much as 16.3 per cent of the phosphates. Such a high content of this element in the River Knajka (mean 65 μg P/l) is caused by the discharge into it of the waters from carp ponds and domestic sewage from the neighbouring villages.

Another important source of nutrient compounds is rainfall directly on the surface of the reservoir. On the basis of 198 analyses it has been found that 1.68 mg of mineral nitrogen and 28 μg $P\text{-}PO_4$ are brought into the reservoir with 1 litre of rainfall. The nitrogen and phosphorus concentrations in rain-waters from the territory of the reservoir at Goczałkowice do not depart from the mean values for the whole territory of Poland (Chojnacki 1970).

In the presented balance the mentioned elements brought in with rainfall constitute a high percentage of the total amount of trophic components flowing into the reservoir. Thus, in the total balance, nitrogen constitutes 10.7 per cent and phosphates 13.2 per cent of biogenous salts. These values are undoubtedly overestimated since no other sources of inflow of these two components, such as surface and ground flow from the direct catchment area, are taken into account.

Using Stumm's formula (1964), it can be proved stechiometrically that the phosphorus carried in with the rainfall suffices for a high production of organic matter. According to Chalupa (1960), the phosphorus from atmospheric precipitation is the source supplying the trophogenous layer of oligotrophic and thermally stratified reservoirs (Hoffman 1972), since rain-water is sometimes lighter and remains in the surface layers.

The inflow from bottom sediments is another important source of nutrient components deciding the concentration of mineral salts in the reservoir. Nutrient components released in the process of decomposition of organic matter enrich the interstitial water, whence they pass into the water lying immediately above the sediment (Norton, Sasseville 1975, Rühle 1971, Sasseville et al. 1975, Tessenow 1972).

The occurrence of this process in the reservoir at Goczałkowice can be assumed on the basis of differences in the mean content of mineral nitrogen and phosphates in the water of the reservoir and in the interstitial water. The amounts of these components were as follows:

in the water of the reservoir: 0.91 mg N/l and 8 μg P/l, in the water contacting the sediment 0.97 mg N/l and 15 μg P/l, in the interstitial water 3.47 mg N/l and 104 μg P/l.

It follows from the presented data that the "active" layer of sediments (Sasseville et al. 1975) can be a rich source of nutrient components, this being corroborated by Norton and Sasseville's (1975) investigations.

No relationship, on the other hand, was found between nitrogen and phosphorus concentration in the interstitial water and their content in the water contacting the sediment. Bengtsson (1975) did not find this correlation in his investigations on liberation of phosphorus from sediments either.

The above-cited results give the mean value of nitrogen and phosphorus content calculated from 123 measurements. As concerns the interstitial water, nitrogen and phosphorus content ranged in it from 0.73 to 10.21 mg N/l and 20 to 336 μg $P\text{-}PO_4$/l respectively.

The high extreme values which occurred between nitrogen and phosphorus content demonstrate of a great periodical variability in the content of these components, this being shown in figs 5 and 6 in the form of season coefficients, after statistical elaboration. The largest amounts of these two components in the interstitial water occurred in the summer months when the organic matter of the warmed sediments decomposes intensively.

A positive correlation was found between the total nitrogen and phosphorus content in the sediments and their temperature and between the concentration of these two components in the interstitial water. These relations may be expressed in the form of regression equations:

$$y_1 = -2.315 + 0.150\,x_1 + 0.743\,x_2 \qquad (5)$$

$$y_2 = 0.075 + 0.002\,x_1 + 0.046\,x_2 \qquad (6)$$

where:

y_1 — mineral nitrogen content in interstitial water,

y_2 — phosphate content in interstitial water,

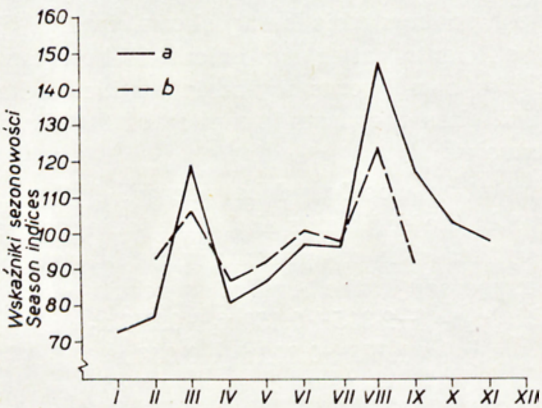
x_1 — sediment temperature,

x_2 — content of total nitrogen (equation 5) and total phosphorus (equation 6) in sediments.

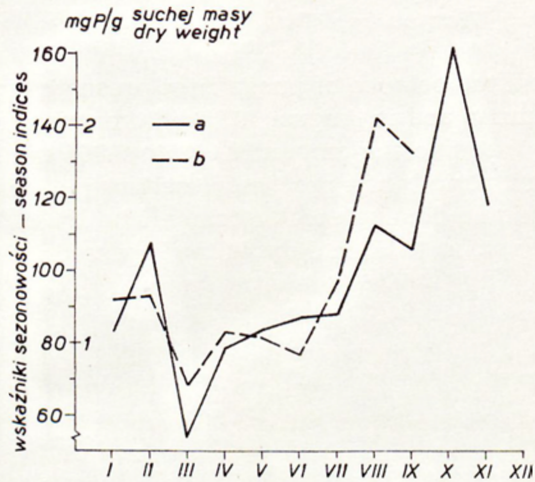
The coefficient of multiple correlation for the equation determining the nitrogen concentration in the interstitial water was $r = 0.73$ at the number of samples $n = 72$ and for phosphorus $r = 0.58$ at $n = 71$.

A lower coefficient of correlation for phosphorus than for nitrogen should be explained by the fact that nitrogen is at least 85 per cent bound organically in sediments (Konsin 1939 — cit. Rühle 1971) and its freeing depends mainly on the microbiological activity. Phosphorus, however, apart from organic bonds, forms mineral compounds with iron, calcium, and aluminium, and is absorbed in the form of anions by silty minerals (Pasternak 1965, 1966). Stangenberg-Oporowska (1970) found in the sediments of carp ponds 20 to 78 per cent of mineral phosphorus content in the total amount of general phosphorus, hence it may be supposed that its transition into the water contacting the sediments and into the interstitial water is conditioned, by, among other factors, the pH and the oxide-reduction potential of sediments (Pasternak 1966, Mortimer 1941, 1942 — cit. after Tessenow 1972). It also follows from equations 5 and 6 that the temperature of sediments, and, hence, owing to microbiological activity, also the decomposition of organic matter influences to a higher degree the amount of nitrogen than that of phosphorus present in the interstitial water.

It should be noted that for derivation of the above-given equations the results obtained for stations I, II, IV, and II, III, IV, for nitrogen and phosphorus respectively were used after previous application of the test F of Snedecor, which showed that the mean contents of the investigated elements in the sediments did not differ essentially at these sampling stations.



Ryc. 5. Wskaźniki sezonowości zawartości azotu mineralnego w wodzie interstycjalnej (a) i azotu ogólnego w osadach (b) zbiornika goczałkowickiego w latach 1973 do 1975
Fig. 5. Coefficients of season content of mineral nitrogen in the interstitial water (a) and total nitrogen in the sediments (b) in the reservoir at Goczałkowice in the years 1973 to 1975



Ryc. 6. Wskaźniki sezonowości zawartości fosforanów w wodzie interstycjalnej (a) oraz zawartości fosforu ogólnego (b) w osadach zbiornika goczałkowickiego w latach 1973—1975

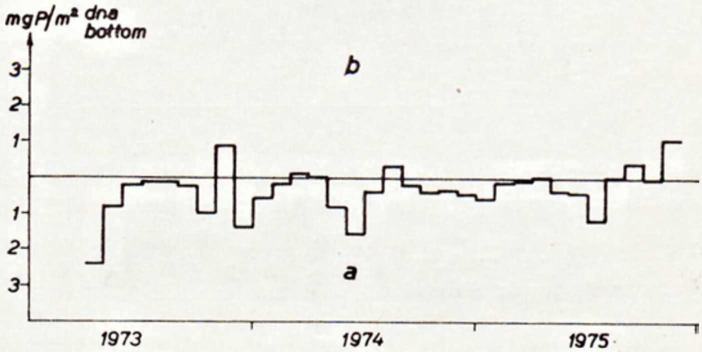
Fig. 6. Coefficients of season content of phosphates in the interstitial water (a) and total phosphorus content (b) in the sediments of the reservoir at Goczałkowice in the years 1973 to 1975

It clearly follows from the diagrams (figs 5, 6) and also from equations (5) and (6) that mineral nitrogen and phosphate concentration in the interstitial water depends on the content of these components in the sediments. The more there is of them in the sediments the richer in them is the interstitial water.

As has also been mentioned, the reservoir at Goczałkowice is exposed to a strong influence of the wind, so that sometimes the waves reach even 2.5 m in height (Pasternak 1964). Frequent winds blowing along the main axis of the shallow reservoir, mix the water thoroughly, so that determination of the amount of components released from the bottom in the water by means of establishing concentration stratification is difficult or even impossible. In this case elaboration of the balance (Lee 1970 — cit. after Bengtsson 1975) is the only sensible way of evaluating the influence of the bottom on the content of chemical components in the water. Although a number of studies have been carried out on the intensity and exchange mechanism between the bottom and the water e.g. Pasternak (1958), Rühle (1971), Tessenow (1972), Banoub (1975), Davis et al. (1975), Kamp-Nielsen (1975), these are laboratory investigations and the obtained results cannot be fully referred to natural conditions. In calculating the amount of phosphorus released from the bottom, a similar formula was used to that applied by Bengtsson (1975) for the sediments of Lake Södra Bergundasjon:

net sedimentation = Σ import — Σ export — Δ abundance of the lake water

It is seen from the balance of phosphates presented in fig. 7 that only in spring and autumn and in August 1974 did the sediments release phosphorus into the water to the amount 0.003 to 0.895 mg $P\text{-}PO_4/m^2$ in one day. In the other periods the process of sedimentation and phosphorus binding in the bottom dominated. For comparison, in Lake Södra Bergundasjon (B e n g t s s o n 1975) in July 44 mg P passed into the water from 1 m^2 in 24 hours.



Ryc. 7. Wielkość sedymentacji (a) i uwalniania się fosforu z osadów (b) obliczona na podstawie bilansu tego składnika w zbiorniku goczałkowickim

Fig. 7. Magnitude of sedimentation (a) and release of phosphorus from the sediments (b) calculated on the basis of the balance of this component in the reservoir at Goczałkowice

It seems that the reason for such a poor supply of phosphorus from the sediments in the reservoir at Goczałkowice may lie in the fact that release of phosphorus from the bottom is 3 times lower in aerobic conditions than in anaerobic ones (P a s t e r n a k 1965, B u r n s and R o s s 1972). In the water of the reservoir at Goczałkowice no disappearance of oxygen was observed during the investigation period. In the bottom layers of the water it was never less than 3.5 mg O_2/l. A relatively high oxygen saturation of the water in the near vicinity of the bottom is caused by the small depth of the reservoir, frequent mixing of the water in consequence of turbulence, and a low content of organic matter in the sediments; for example, in 1970 the sediment contained from 1.601 per cent to 4.754 per cent C (W r ó b e l 1975). Apart from this the organic matter is very humified, which may suggest a low bacteriological decomposition of organic substance of the bottom sediments.

The balance of mineral phosphorus shown in fig. 7 gives only general information about the prevalence of sedimentation of this element on the bottom over its transition from the sediments to the water or vice versa, since these two processes proceed simultaneously. Moreover, the presented way of calculating the balance would have to have the same value during one month in every zone of the reservoir, which does not normally occur in natural conditions.

Possibilities of decreasing the load of the reservoir at Goczałkowice

According to Vollenweider (1968), the extreme nitrogen and phosphorus concentration in the surface water above which a mass increase of algae is observed equals 0.30 mg N/l and 0.01 mg P-PO_4/l. Those concentrations are considerably lower than those encountered in the water of the reservoir at Goczałkowice (figs 4b, 4c), since for the given values the reservoir should have at an average water level, at most 28.3 t N and 0.94 t P-PO_4. The conclusion can be drawn that the reservoir at Goczałkowice is threatened with a deterioration in the quality of the water in consequence of eutrophication. The size of the nitrogen and phosphorus load in the water of the reservoir (figs 4b, 4c) shows its strong dependence on the amount of water inflow (fig. 4a). Every increase in the water inflow, in spite of its frequently being immediately discharged by the undersluice in order to equalize the water balance of the reservoir (fig. 4d), is accompanied by an increase in concentration of these two components. Subsequently their amounts decrease, being taken up by the phytoplankton, to increase again at the next intensive water inflow. This suggests that, in order to decrease the amount of nutrient compounds carried in the reservoir, their supply by inflows should be limited by introducing a third stage of purification.

On account of the convenient estuary of the River Vistula into the reservoir, the possibility exists of building a dividing wall from bank to bank, reaching far into the reservoir and rising to a height of 2 m above the water surface at average water level. A small reservoir would then be formed between them, eliminating phosphorus. Another useful feature of this arrangement would be the inclusion of the water of the River Knajka, flowing here in a common river-bed with the Vistula, in the purification process.

On the basis of the author's own investigations it was found that in August 1975 the waters of the Vistula and Knajka contained between the mentioned embankments 48 per cent of mineral phosphate, more than the water of the upper part of the reservoir (station I). The proposed dam would increase the efficiency of elimination of this component since the small preliminary reservoir thus formed would have a water exchange period of a few days and the phosphorus used up by bacteria and phytoplankton would sediment there or in the upper part of the main reservoir.

Preliminary reservoirs such as the one proposed are in common use in GDR; for example, the building of such an arrangement at the dam reservoir at Seidenbach diminished the load of phosphates in the reservoir by a 55 per cent elimination during the whole year (Hofmann 1972).

Assuming the phosphate elimination efficiency for the dam reservoir at Goczałkowice as 50 per cent, the direct load would decrease below the extreme value 0.07 g P/m², i.e. the value considered safe for water purity.

STRESZCZENIE

Stwierdzono dodatnią korelację pomiędzy wielkością przepływu wody w Wiśle i Bajerce a stężeniem azotu i fosforu. Zależność ta dała się przedstawić w postaci funkcji liniowej. Parametry prostej regresji przedstawiono w tabeli I.

Obliczoną metodą równań regresji wielkość wnoszonych ładunków Wisłą i Bajerką, porównano z innym sposobem obliczeń, zakładającym stałe stężenie tych składników pomiędzy poszczególnymi terminami poborów prób (tabela II). Przyczyną powstałej różnicy wielkości ładunków, wyliczonych drugą metodą, jest nieuchwycenie wahań stężenia spowodowanego zmianami przepływu pomiędzy poborami prób.

Dane o ilości obu składników pokarmowych, dopływających do zbiornika i odpływających z niego z różnych źródeł, przedstawiono w tabeli III. Roczne obciążenie dna zbiornika jest wielokrotnie wyższe od wartości granicznych zaproponowanych przez Vollenweidera, będących niebezpiecznymi dla czystości wody zbiornika goczałkowickiego. Skutkiem zwiększonego dopływu azotu i fosforu do zbiornika jest wzrost ich stężenia w porównaniu z 1959 r. (ryc. 3).

Stwierdzono dodatnią korelację pomiędzy zawartością azotu i fosforu ogólnego w osadach oraz ich temperaturą, a koncentracją obu tych składników w wodzie interstycjalnej. Zależność tę przedstawiono w postaci równań regresji (wzory 5, 6).

Obliczono ilości fosforu mineralnego uwalniającego się z osadów dennych. Według przedstawionego bilansu (ryc. 7) proces akumulacji fosforu w osadach zbiornika goczałkowickiego znacznie przeważa nad uwalnianiem się z nich tego składnika.

Z wielkości stosunku N : P oraz okresowego braku fosforanów w zbiorniku stwierdzono, że jest on składnikiem limitującym wzrost i rozwój fitoplanktonu. W 1975 r. stężenie fosforu w wodzie zbiornika nie było niższe niż 10 µg $P-PO_4$/l. Skutkiem stosunkowo wysokiej zawartości tego pierwiastka był masowy rozwój *Microcystis aeruginosa*, która zdaniem Beetona jest wskaźnikiem znacznego stopnia troficzności jezior. W celu zmniejszenia dowozu składników pokarmowych do zbiornika przedstawiono projekt zmniejszenia jego obciążenia.

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