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**Changes in the aquatic environment over many years
in three dam reservoirs in Silesia (southern Poland)
from the beginning of their existence - causes and effects**

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Abstract - Changes in the chemical composition of the water in three dam reservoirs are presented against the background of the chemical composition of their affluents, and the effect of these changes on the phytoplankton in terms of the chlorophyll *a* content, are discussed. Changes in the chemical properties of the water, an increase in trophic level, and the existing differences in the fertility of the water between the reservoirs are associated with the ways of utilization of the catchment basins and with their population density. On the basis of the whole collected material a scheme of the eutrophication of the examined reservoirs is presented.

Key words: dam reservoirs, affluents, nutrients, ion composition, chlorophyll, catchment basin utilization.

1. Introduction

The catchment basin and its character are of vital importance for the natural chemical composition of the water (Stangenberg 1958, Pasternak 1962). The waters flowing off from a catchment basin collect on their way various amounts of mineral, organic, and gaseous compounds, depending on the type of rock or soil material they contact or through which they infiltrate. These compounds enter into the composition of the waters (Pasternak 1976), which undergoes a radical change in industrial regions and large over-crowded areas (Wróbel 1988,

Dojlido, Woyciechowska 1989, Kościuszko, Prajer 1990) and as an effect of agricultural activity (Prochazkova et al. 1973, 1976, Prochazkova, Blazka 1986, 1989).

The chemical composition of the surface waters is also subject to the influence of the settling organisms (Berg et al. 1987) since in these waters the two basic processes of photosynthesis and respiration take place continuously (Starmach et al. 1976). In the course of the last several decades the waters have been rapidly enriched with compounds participating in photosynthesis, i.e. nitrogen and phosphorus, and as a result the balance between photosynthesis and respiration has been disturbed. This in turn leads to the accumulation of organic matter in the water and deep changes in its chemical properties, often resulting in the degradation of the water with respect to its suitability for consumption or any other practical application in industry or farming (Jankowski 1973, Kajak 1979, Kondrat'ev, Koplán-Díks 1988). The phenomenon of fertilization of waters leads also to significant changes in the flora (Trifonova 1988, 1989, Den Hartog et al. 1989) and fauna (Andronikova 1980, Opuszyński 1987).

There are 123 dam reservoirs in Poland (Głoddek 1985). Some of them are the subject of complex hydrobiological investigations, including the registration of changes in the plant and animal communities in these water bodies according to the chemical composition of the water (Krzyżanek, Kownacki 1986, Kajak 1989, Giziński et al. 1989, Galicka et al. 1990). Knowledge of the phenomena occurring in reservoirs, from the moment of their construction through subsequent years, and estimation of the effect of human activity on them may together create the minimum basis necessary for prediction of the trends of succession and for the undertaking of countermeasures intended for their planned protection (Kownacki, Starmach 1989). An example of long-term hydrobiological monitoring is the Goczałkowice Reservoir, which has been studied from the moment of its inundation in 1955 until today, using practically the same methods. The results of these investigations have been reported in 168 papers (Kasza 1991). Other models of complex monitoring studies are the Wisła Czarne and Rybnik Reservoirs (fig. 1).

The main part of the present study refers to the Goczałkowice Reservoir. It comprises the results of investigations carried out by the author in the period 1973-1989. Some of them have already been published (Kasza 1977, 1979, 1980, 1986a, Kasza,

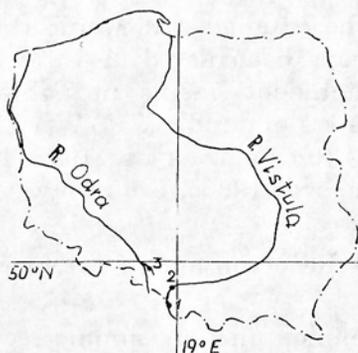


Fig. 1. Schematic representation of the location of the studied reservoirs in Poland.
 1 - Wisła Czarne Reservoir; 2 - Goczałkowice Reservoir; 3 - Rybnik Reservoir

Winohradnik 1986, Krzyżanek et al. 1986). Advantage has also been taken of the investigation results obtained by Domańska (1957, 1958), Tracz (1958, 1960), Bombówna (1962), and certain results made accessible by the Provincial Institute of Water Supply and Sewerage in Katowice. In the case of Wisła Czarne Reservoir, the material collected by Magosz (1976) including the investigations from the first two years of the reservoir's existence (1974-1975) and the author's own material from the period 1976-1984, published in part (Kasza 1986b) have been utilized. In the preparation of material referring to the Rybnik Reservoir the main source were the results of investigations conducted by the author in the period 1976-1981, published in part (Pasternak, Kasza 1978) as well as other, unpublished studies (Wróbel, Bombówna, Pasternak) from the period 1973-1981.

The aim of the present work was to trace the changes in the chemical properties of the water against the chemical composition of the affluents in three dam reservoirs, differing with respect to their morphological and geological conditions and destination, besides the interaction of anthropogenic factors, starting from the first years of their existence. It was also an attempt to determine the effect of changes in the chemical properties of the water in these reservoirs on the phytoplankton, expressed in terms of chlorophyll content and to find the main reasons for such changes.

2. Study area

To characterize the studied reservoirs their hydrological and morphometric data have been listed in Table I, and the structural features of their catchment basins in Table II and in figs 2-4 (Brykowicz - Waksmundzka, Waksmundzki 1975, Olszamowski, Rożnowska 1988, Pasternak 1962, Wróbel 1975, Kasza 1986c, Kozłowski et al. 1981).

2.1. The Wisła Czarne Reservoir and its catchment basin

This is a not large, montane, rheolimnic reservoir of great depth, placed on the upper Vistula. It is one of the highest situated Polish reservoirs. The surface inflow of water to it is provided by two mountain rivers, The Czarna Wiselka and Biała Wiselka (40 and 60% respectively of the inflowing water in the total balance)

Table I. Parameters of the studied dam reservoirs. * - normal water level;
FSL - full supply level

Parameter	Wisła Czarne	Goczałkowice	Rybnik
Geographical situation	49°36'N 18°56'E	49°51'N 18°52'E	50°07'N 18°28'E
Altitude (m)	540	260	220
Capacity (10 ⁶ m ³) FSL	4.9	168	24
Area (km ²) FSL	0.42	32	5.55
Maximum depth (m) FSL	30.0	11	11.0
Mean depth (m) FSL	11.6	5.3	4.3
Location of the sluice	at the bottom	at the bottom	at the bottom
Dist. from the source (km)	10	68	32
Mean annual inflow (m ³ s ⁻¹)	0.66	7.24	2.57
Retention time * (years)	0.10	0.63	0.26
Frequency of water exchange	10.4	1.6	3.8
Year of beginning of exploitation	1974	1955	1972
Purpose	water supply, flood inspection	water supply, flood inspection	industrial-cool- ing of steam from a power station
Ice cover	3-5 month	1-2 month	none
Exposure to wind	slight	strong	moderate

Table II. Parameters of the catchment basins of the studied dam reservoirs

Parameter	Wisła Czarne	Goczałkowice	Rybnik
Area (km ²)	28.8	532	280
Type of catchment basin and its use	montane, afforested, tourist centre	farmland and forests, urbanized	farmland and forests, strongly industrialized and urbanized
Affluents	Biała Wiselka, Czarna Wiselka	Vistula, Bajerka	Ruda, Nacyna
Land use %:			
forests	93.8	36.6	37.9
farmland	2.4	55.3	52.1
other	3.8	8.1	10.0
Population in 1988 (inhab. km ⁻²)	35.0	230.0	770.0
Annual runoff (dm ³ s ⁻¹ km ⁻²)	22.9	13.6	9.2
Annual precipitation (mm)	1370	1125	744
Geological formation	flysch rocks covered with eluvium of clay with rubble and shales, loamy sand	flysch sediments partly covered with Quaternary materials (loessy clays, sands, and Carpathian clays)	pleistocenic sediments (layers of clays, sands), holocenic sediments (fine, medium sands, alluvial clays)

(Magosz 1976). In the land use structure of the catchment area of this reservoir there forests prevail (Łajczak unpubl.). This region, with its outstanding advantages as a health resort lying in a natural, beautiful landscape, is an area of mass tourism, which has become a potential danger to the purity of the water in both rivers and in the reservoir; moreover, the Biała Wiselka receives the domestic and farmyard sewage from a small settlement in the river valley.

2.2. The Goczałkowice Reservoir and its catchment basin

This is a large, shallow reservoir, of pond type, located on the upper Vistula. The E-W location of its basin and the exposed terrain favour strong operation of the winds, which, together with the

consequent undulation, bring about frequent and thorough mixing of its waters.

The main source of water supply for the reservoir is the Vistula, providing 82%, and the small Bajerka stream which supplies 4% of the water. Atmospheric precipitation accounts for about 9% in the total water balance of the reservoir. The high proportion of precipitation can be ascribed to its morphometric features (K a s z a 1979).

The catchment basin of the Goczałkowice Reservoir comprises montane, submontane, and flat terrain. In its montane area it is exposed to the effects of tourism and forestry, while the remaining parts are utilized for farming. This catchment basin is moderately populated, with two small industrial towns and two small towns functioning as tourist centers. Its sewage, both industrial and municipal wastes, is carried away into the Vistula upstream from the reservoir. Only a small part of it undergoes purification treatment.

2.3. The Rybnik Reservoir and its catchment basin

This is a shallow, lowland reservoir, of medium size, in which the warm discharge waters from the Rybnik power station greatly affect the thermal currents and the evaporation of the water as well as its circulation and continuous mixing in the reservoir. In summer, the water temperature at the place where it enters the power plant is 25.6°C, while after passing through the cooling installations and flowing into the reservoir its temperature is 34°C. In the winter the reservoir does not freeze and the water temperature never falls below 3.9°C. The vegetation season in the reservoir water is about 2.5 months longer than that in other waters in the region. The amount of water evaporating from the surface of the reservoir in summer is close to the value of the minimum surface water inflow (K o z ł o w s k i et al. 1981).

The main source of water for the reservoir is the River Ruda and the periodical overflows of water from the River Nacyna. The greatest part of the water from the Nacyna is carried away through a pipeline outside the reservoir, as this water is exceptionally strongly polluted and salinated by mine waters from the Rybnik Coal Region.

The northern part of the catchment basin is covered with large forest complexes while the southern part is used for farming. The central area of the drainage basin is densely populated (in 1981 the population was 590 persons km⁻²) and industrialized, this being

responsible for the inflow of large amounts of industrial and municipal wastes to the reservoir.

3. Material and methods

The material include the results of investigations of the Wisła Czarne Reservoir in the period 1974-1984, the Goczałkowice Reservoir in the period 1957-1989, and Rybnik Reservoir in the period 1973-1981.

The chemical properties of the water were determined by the method recommended by Just and Hermanowicz (1955, 1964), Golterman and Clymo (1969), Hermanowicz et al. (1976). Chlorophyll was determined according to SCOR-UNESCO (Ausgewahlte Methoden der Wasseruntersuchung 1970).

The samples were usually collected at intervals of about one month until the appearance of ice cover. Location of the sampling stations is shown in figs 2-4.

The rivers flowing into the Goczałkowice Reservoir were investigated in certain periods (Kasza 1977, 1986a), depending

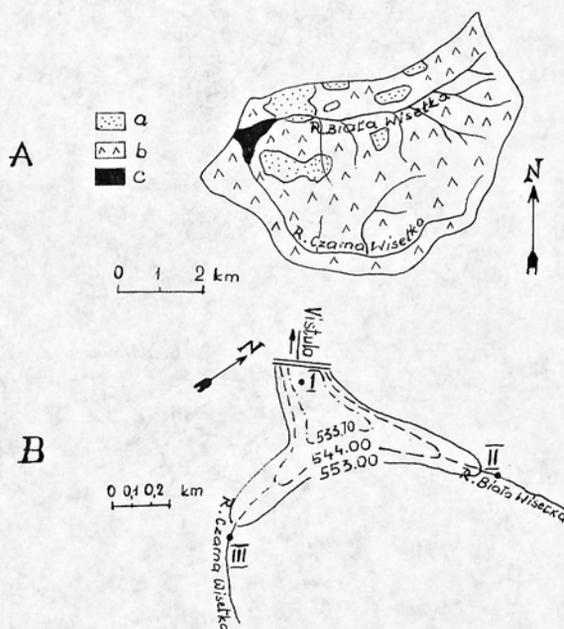


Fig. 2. Catchment basin of the Wisła Czarne Reservoir (A). a - meadows and arable land; b - forests; c - reservoir. Location of sampling stations (B)

on the research programme of the Institute of Freshwater Biology. Also in the Rybnik Reservoir the mineral nutrients were determined through monitoring, while the other components of the chemical composition of the water were determined only in some years.

The primary production of phytoplankton was investigated only in the Goczałkowice (Station I in the period 1987-1989) and Rybnik Reservoirs (Station I in the period 1975-1981) by the light and dark oxygen method (Pasternak, Kasza 1978). Primary production in the Wisła Czarne Reservoir was determined on the basis of the chlorophyll *a* content and the index $1 \text{ mg chl. } a = 30 \text{ mg C } 24 \text{ h}^{-1}$ (Bul'on 1984).

The data concerning the population density and the amounts of applied mineral fertilizers were derived from statistical year-books

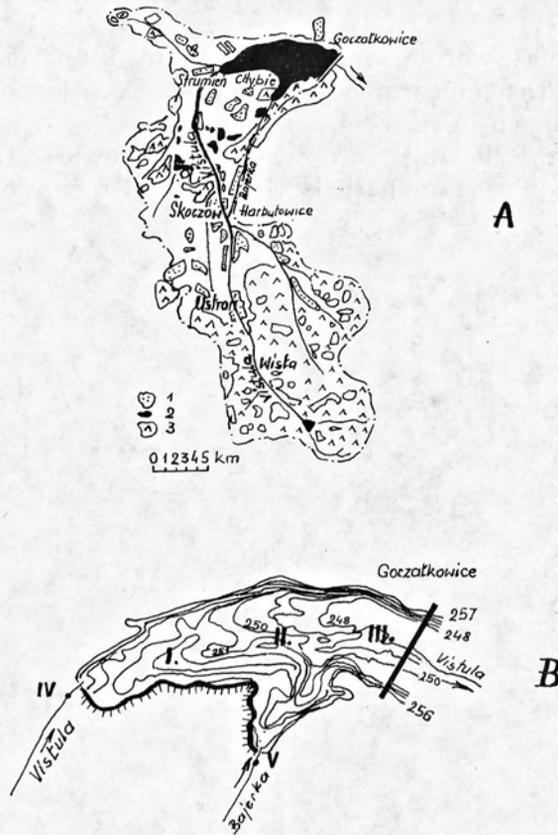


Fig. 3. Catchment basin of the Goczałkowice Reservoir (A). 1 - towns and settlements; 2 - waters; 3 - forests. Location of sampling stations (B)

for 1957-1989 and from materials obtained from the Provincial Office in Bielsko-Biała.

The loads of biogenic compounds flowing into the reservoirs were calculated according to the regression equations in terms of the dependence between flow and concentration (Kasza 1977) or by multiplying the mean concentration of the biogens in the water of the rivers by the annual water inflow (Kasza 1986b). The practical and theoretical problems of calculating the loads are discussed in a study by Nesmerak (1986a), and the description of the four basic methods of calculating the inflow of nutrients together with literature data can be found in the work by Krummenacher (1976).

To obtain a more detailed characterization of the organic compounds occurring in the water of the Rivers Ruda and Nacyna,

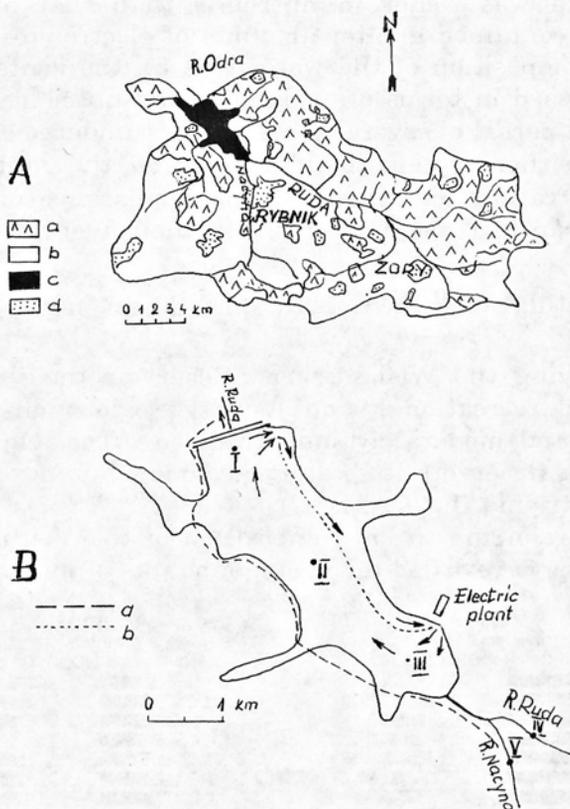


Fig. 4. Catchment basin of the Rybnik Reservoir (A). a - forests; b - arable land; c - reservoir; d - towns and settlements. Location of sampling stations (B). a - pipeline of the River Nacyna; b - dam controlling water movement

calculation of the ratio of oxidability and BOD_5 to COD on the basis of the mean values from 1981 (B o m b ó w n a unpubl.) was used.

4. Results

4.1. Changes over many years in selected chemical parameters of the water in rivers feeding the reservoirs

4.1.1. Rivers flowing into the Wisła Czarne Reservoir

Chemical investigations of the waters of the Biała and Czarna Wiselka did not reveal the presence of pollutants. The water of the Biała Wiselka was richer in nutrients than that of the Czarna Wiselka and contained greater amounts of electrolytes (fig. 5).

The ion composition of the water (fig. 5), the content of organic matter expressed in terms of oxidability and nutrient concentration (fig. 6) over a period of several years, did not undergo any significant changes in either stream, both as regards the mutual relations between the cations or anions or the appearance of any distinct tendency for an increase or decrease in their average values.

4.1.2. The Vistula above the Goczałkowice Reservoir

When leaving the Wisła Czarne Reservoir the Vistula collects waters from recreational and tourist regions and then from agricultural and moderately industrialized areas. On entering the Goczałkowice Reservoir its waters are more abundant in mineral salts and nutrients (fig. 7A, B, C).

The data referring to ion composition of the Vistula water over many years have revealed increasing amounts of macroelements and

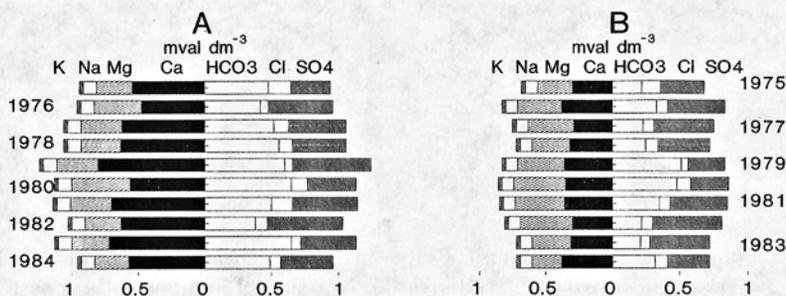


Fig. 5. Mean ion composition of water in the Rivers Biała (A) and Czarna Wiselka (B)

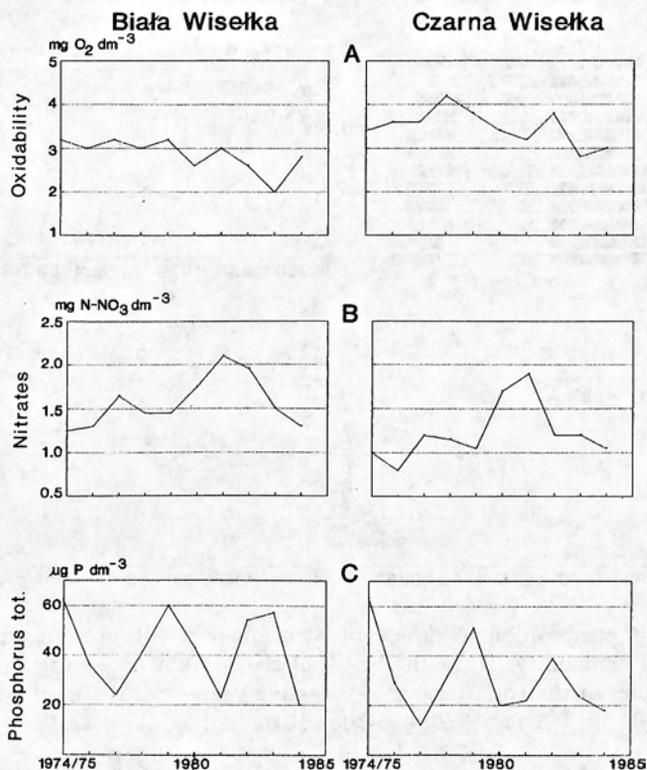


Fig. 6. Mean values of oxidability (A), content of nitrates (B), and total phosphorus (C) in the Rivers Biała and Czarna Wisetka

changes in the proportion of their concentration (fig. 7A). With calcium and the associated carbon dioxide still prevailing, there appeared a tendency towards a gradual replacement of carbonates by the ions of strong acids, i.e. by chloride and sulphide ions. In spite of a continued increase in absolute cation concentrations, their mutual percentage relations in the ion composition did not undergo any essential changes.

Over a 29 year period, the amount of nitrates, which are the main source of the mineral forms of nitrogen in the water of the Vistula, increased about 4 times, and that of total phosphorus (studied from 1973) 3 times. The tendency towards a gradual increase in the amount of both nutrients was described using a linear equation, in which time was regarded as the independent variable (fig. 7B, C).

The oxidability of water in the Vistula showed no significant changes during the investigated period (7D).

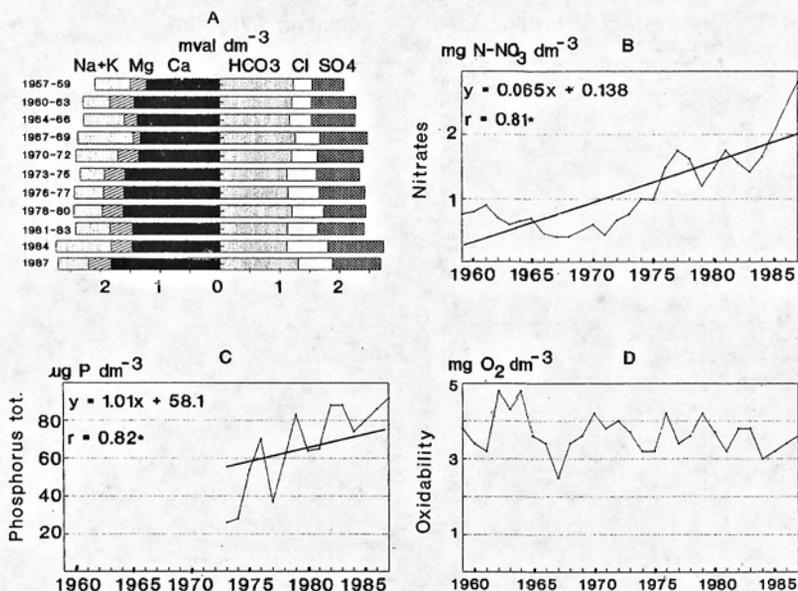


Fig. 7. Mean ion composition (A), the content of nitrates (B), and total phosphorus (C) and oxidability (D) in the water of the Vistula above the Goczałkowice Reservoir. In the equations: x - successive years of investigations, e.g. for P_{tot} : $x = 1$ for 1973, $x = 2$ for 1974, etc; * - $P = 0.001$

4.1.3. Rivers flowing into the Rybnik Reservoir

The waters of the Rivers Ruda and Nacyna differed from each other distinctly as regards the content of macroelements, being of the sodium-chloride type. The waters in both rivers were polluted with domestic and industrial wastes from the towns Żory and Rybnik (the water of the Nacyna receives, moreover, a considerable amount of underground waters from the mines of the Rybnik Coal Region) and were characterized by a prevalence of the content of chlorides, sulphates, and sodium, over that of calcium carbonates (fig. 8). The rivers revealed very great differences in the concentration of salt, as the mean sum of anions and cations, e.g. in the Ruda water, was relatively low (9.7 mval dm^{-3}) as compared with their content in Nacyna ($150.3 \text{ mval dm}^{-3}$). In the course of the nine years of investigations of the affluents of the Rybnik Reservoir a gradual increase in the concentration of the components of the ion composition of the Ruda water was observed, the increase in the amount of calcium carbonates being the highest (fig. 8). Both rivers also carried enormous quantities of nitrogen and phosphorus

compounds (fig. 9A, B) and organic matter expressed in terms of oxidability (fig. 9C). Among the mineral bonds of nitrogen the ammonia form distinctly prevailed over the nitrate form.

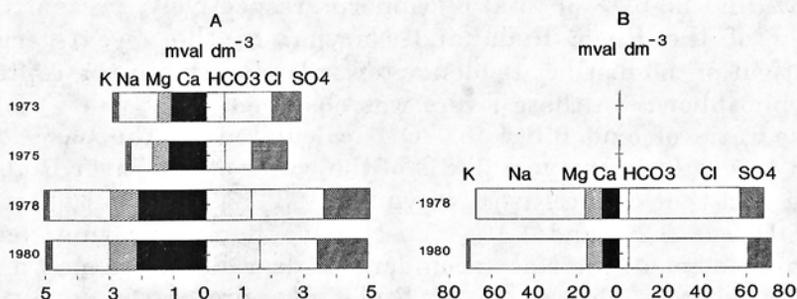


Fig. 8. Mean ion composition of water in the Rivers Ruda (A) and Nacyna (B)

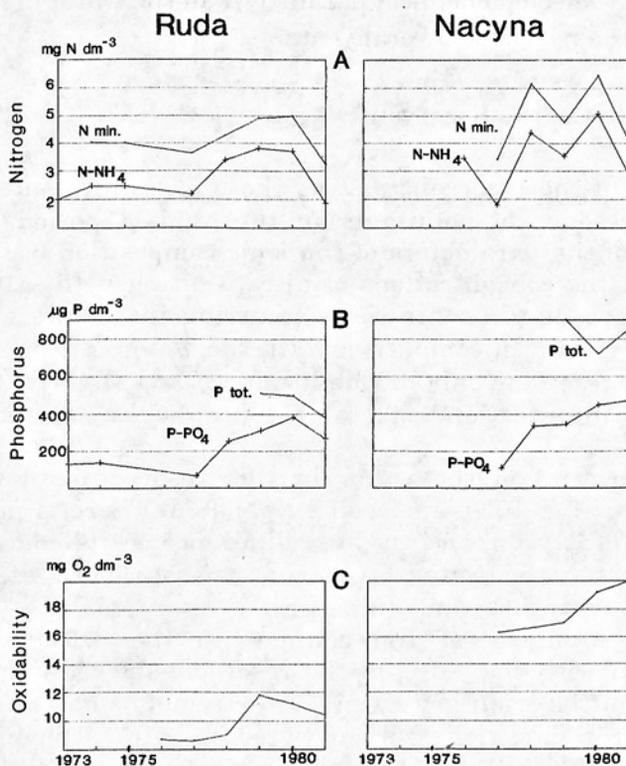


Fig. 9 Mean content of mineral nitrogen (A), phosphorus (B), and oxidability (C), in water of the Rivers Ruda and Nacyna

In the period 1973-1981 the concentration of phosphate phosphorus in the River Ruda doubled, and in the River Nacyna it increased 4-fold (fig. 9B). Phosphate phosphorus accounted for 60-70% and 38-62% of total phosphorus respectively, present in the waters of the River Ruda and Nacyna. In the 3-year-period of investigation no distinct tendency towards changes in the content of total phosphorus in these rivers was observed.

The ratio of oxidability to COD (calculated on the basis of the mean values from the year 1981) of the water of the River Ruda was 13.3% and that of the River Nacyna only 3.2%. The relation of BOD to COD was 9.2% and 1.1% respectively, thereby proving that the organic matter in the Nacyna undergoes degradation to only a small extent, whereas in the River Ruda this process is much more advanced.

4.2. Changes in selected chemical parameters in the water of the reservoirs over a period of several years

4.2.1. The Wisła Czarne Reservoir

The water in the reservoir, just as those of its affluents, did not reveal the presence of pollutants in the studied period, and the mean values of the parameters of the ionic composition of the water (fig. 10A) and the concentrations of nitrate nitrogen (fig. 10B) were the resultant of the concentrations occurring in the waters of the two tributary rivers. In comparison with the waters of the affluents, in that of the reservoir only oxidability increased slightly (fig. 10C), while the concentration of total phosphorus decreased (fig. 10D).

The temperature of the water in this reservoir is low, rarely exceeding 18°C (fig. 10E), and well oxygenated. There is no distinct stratification of oxygen, the greatest difference in its concentration observed between the water layer near the surface and over the bottom being 1.7 mg O₂ dm⁻³ (fig. 10F).

A detailed analysis of the changes in the extent of water mineralization with the aging of the reservoir showed, similarly as in the water of the tributary rivers, an extremely small variation in the ion composition of the reservoir water (fig. 10A). During the five years of its existence the content of nitrates increased slightly with each year, from 1981 slightly decreasing to reach after 10 years the same concentration value as in the first year of exploitation (fig. 10B). The amount of total phosphorus only in two first year after

inundation (1974/1975) was twice as high as in the remaining years, in which the phosphorus concentration differed only slightly from each other. Nor was any distinct tendency towards an increase or decrease in the content of this component observed. The oxidability of the water, except in the year 1976, did not undergo any significant changes, demonstrating the same values throughout the whole period of study (fig. 10C).

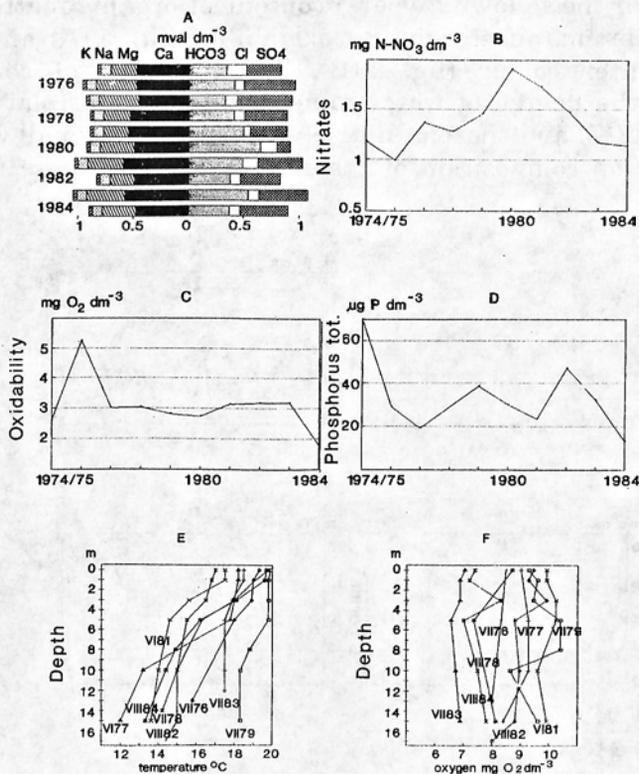


Fig.10. Mean ion composition (A), content of nitrates (B), oxidability (C), concentration of total phosphorus (D), temperature (E), and oxygen content (F) in water of the Wisła Czarne Reservoir

4.2.2. The Goczałkowice Reservoir

The hydrochemical investigations of the reservoir carried out over several years enabled three periods in its development to be distinguished. The first comprised the years during which the reservoir was gradually attaining stabilization, i.e. from the moment of inundation until 1961. The second period from 1962 till 1985, was

one of gradual eutrophication, during which the maximum values of the chlorophyll *a* content did not exceed $30 \mu\text{g dm}^{-3}$. The third period began in 1986 and continues until today. During this period the maximum annual values of the chlorophyll *a* content were higher than $50 \mu\text{g dm}^{-3}$ with the occurrence of water blooms.

In the first period, the decomposition process of the flooded vegetation and the interaction of the original soil led to raised (as compared with the following years) content of organic matter in the reservoir water, manifested by its oxidability (fig. 11A) and a high degree of water colour (fig. 11B). The amounts of compounds determining the degree of water mineralization were relatively low (figs 11C-F, 12A), and those of nutrients were rather small (figs 11F, 12B). In the ion composition of the reservoir water there prevailed

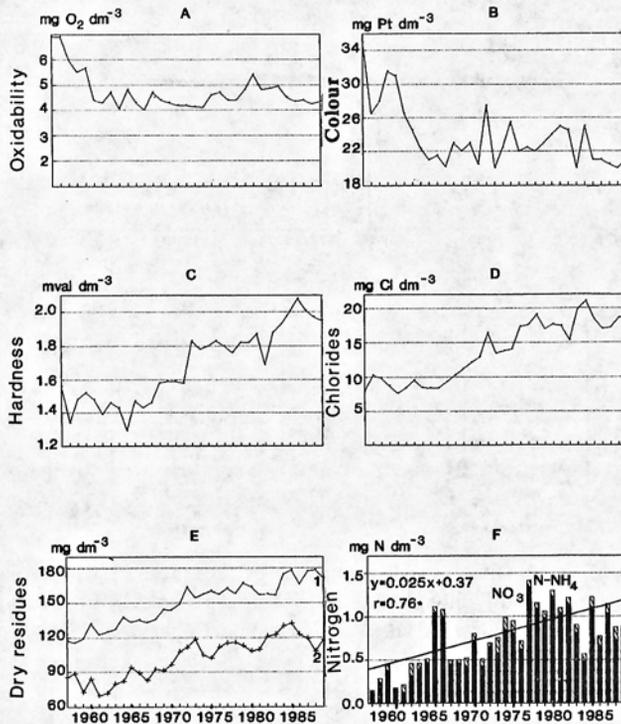


Fig.11. Mean annual value of the oxidability (A), colour (B), hardness (C), concentration of chlorides (D), dry residue (E; 1), remainder after calcination (E; 2), and concentration of mineral nitrogen (F) in water of the Goczałkowice Reservoir. Explanations as in fig. 7

calcium and the associated carbon dioxide in the form of hydrocarbonate and calcium carbonate (fig. 12A). In smaller amounts there appeared in sequence among the anions sulphates and chlorides and, among the cations, magnesium, sodium, and potassium. In summer the amounts of oxygen at a depth from 4-6 m to the bottom were smaller than $6 \text{ mg O}_2 \text{ dm}^{-3}$ (fig. 13).

During the second period of the reservoir development a constant and systematic increase in the mineralization and fertility of the water was observed. Such parameters as dry residue and mineral fixed residue showed a tendency towards an increase in the annual values almost every year (fig. 11E). The tendency towards increasing contents of the calcium and magnesium cations (fig. 11C), and of the chloride and sulphate anions (figs 11D, 12A respectively) was particularly visible. In spite of the fact that calcium carbonate continued to dominate in the carbonate form in the reservoir water, there appeared a tendency, similarly as in the water of the Vistula, to replacement of the carbonates by the chloride and sulphate ions. In spite of an increase in the absolute values of the cations the mutual percentage relations between them did not undergo any changes (fig 12A).

The concentration of the phosphate phosphorus in the reservoir water also increased twofold, while the concentrations of total phosphorus, studied from 1973, showed an increase almost every year (calculated on the basis of annual mean values) (fig. 12B). The oxygen conditions were good, though towards the end of this period the amount of oxygen in the deeper layers of the reservoir water slightly diminished (fig. 13).

When comparing the mean concentrations of the mineral nitrogen compounds from the first and second periods of the reservoir's history, an almost 2.5 times increase in the content of nitrates and about 1.5 times in the concentration of ammonia nitrogen can be observed.

In the third period of development a slight increase in the degree of water mineralization and its fertility was found to occur. The mean annual content of the macroelements determining the degree of water mineralization and of the nitrogen and phosphorus compounds (figs 11, 12) showed no constant increase. The water in the reservoir became strongly eutrophicated. The deterioration of water quality was manifested by water blooms. The oxygen conditions were relatively good and the period during which the its concentration in the deeper water layers was less than $6 \text{ mg O}_2 \text{ dm}^{-3}$ was longer than in the preceding period (fig. 13).

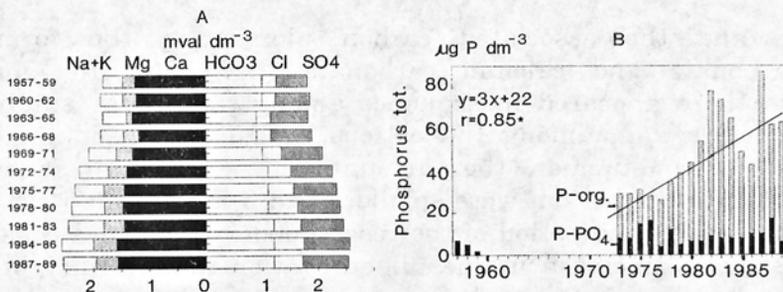


Fig. 12. Mean ion composition (A) and content of phosphorus (B) in water of the Goczałkowice Reservoir. Explanations as in fig. 7

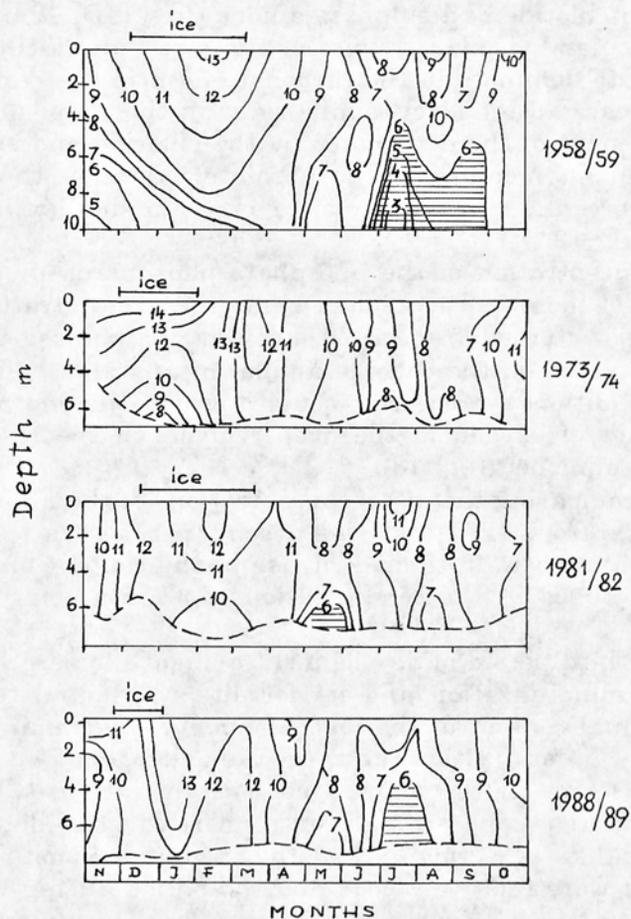


Fig. 13. Content of oxygen in water of the Goczałkowice Reservoir in individual selected years. Hatched areas - oxygen content smaller than $6 \text{ mg O}_2 \text{ dm}^{-3}$

4.2.3. The Rybnik Reservoir

The water in the reservoir is of the chloride-sodium type (fig. 14A). During the studied period, in the reservoir water the sulphate ions prevailed over the carbonate ones, and the degree of mineralization constantly increased. Besides the systematic and absolute increase in the water mineralization, with the aging of the reservoir the mutual percentage relations of the ion composition also changed. Among the cations the proportion of sodium and among the anions that of chlorides were distinctly on the increase.

With the passage of years the content of mineral soils in the reservoir water differed more and more from their concentrations in the water of the River Ruda. In 1973 their average content in the water of the reservoir and in the River Ruda was approximately the same, but in 1980 the amount of electrolytes in the reservoir was twice as much as that in the River Ruda. The concentrations of these mineral compounds in the reservoir, however, were many times lower than in the water of the River Nacyna (figs. 8, 14A).

Oxidability, when compared with the affluents, was distinctly lower in the reservoir water (fig. 14B). As the reservoir aged a tendency towards an increase in the content of organic matter in its

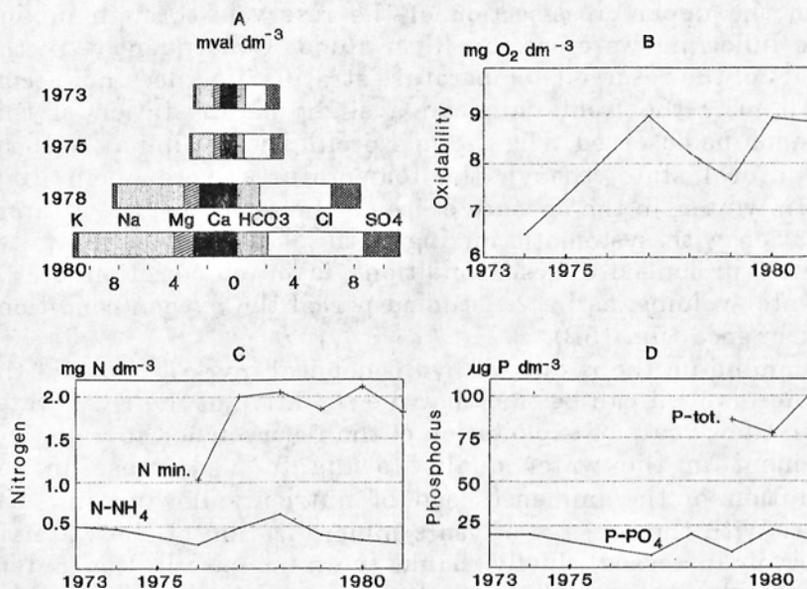


Fig. 14. Mean ion composition (A), oxidability (B), content of mineral nitrogen (C), and phosphorus (D) in water of the Rybnik Reservoir

water could be observed. In spite of considerable self-purification of the reservoir water of the excess of organic substances, the differences in the mean annual values of oxidability between River Ruda and the reservoir constantly diminished.

A change in water quality in the reservoir was also manifested by a decrease in nutrient concentration. The content of mineral nitrogen compounds in the reservoir water was many times lower than in its affluents (fig. 9A, 14C). The proportions of the concentrations of the various nitrogen forms changed. In the reservoir water, in opposition to the affluents, the nitrate nitrogen form distinctly prevailed over the ammonia one. The concentrations of phosphates and total phosphorus in the reservoir were also many times lower (fig. 14D). The concentrations of these nutrient salts, although lower than in the affluent waters, made the reservoir water very fertile, at times giving them a hypertrophic character. On a scale of many years, taking into consideration the annual mean values, the concentration of mineral nitrogen, after an initial increase, maintained a high, balanced level, and the amount of total phosphorus in the last year of the investigations increased from $86 \mu\text{g P dm}^{-3}$ to more than $100 \mu\text{g P}_{\text{tot}} \text{dm}^{-3}$.

Temperature measurements (fig. 15A) showed that the main stream of warmed-up water from the power station is intensely cooled in the upper cross-section of the reservoir through mixing with the inflowing water of the River Ruda. Consequently, in the upper part of the reservoir temperature stratification does not occur. Not until near the front dam can a slight manifestation of this phenomenon be observed. The thermal profiles were similar to those in the natural state, though the temperatures were about 10°C higher. In winter, in the absence of ice on the reservoir, the autumn stratification with systematic mixing of the upper and lower water layers was prolonged. These conditions favoured aeration of the entire water volume, as in the studied period the oxygen conditions were fairly good (fig. 15B).

In summing up the results of hydrochemical investigations of the Rybnik Reservoir it can be said that the retention of the river water in the first few years of exploitation of the reservoir led to a distinct improvement in the water quality owing to a decrease in the concentration of the immense load of nutrients flowing into the reservoir. With the passage of years mineralization of the water in the reservoir increased, chiefly thanks to an increase in the content of sodium chloride, as well as in the concentration of biogens and the amount of organic matter.

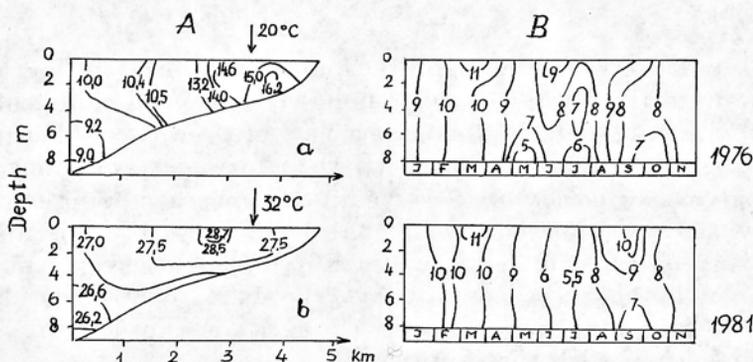


Fig. 15. Water temperature distribution (A) in winter (a) and in summer (b) in 1975 and oxygen content (B - mg O₂ dm⁻³) in 1976 and 1981 in the Rybnik Reservoir. Arrow denotes temperature of water flowing from the power station

4.3. The loads of nutrients carried into the reservoirs

The surface loading of the bottom of the particular reservoirs with nutrients was calculated on the basis of data from the surface runoff of nitrogen and phosphorus compounds and the frequency of water exchange at their normal level. The calculated values of the introduced load of nutrients in the three reservoirs show some differentiation. The Wisła Czarne Reservoir is the least and the Rybnik Reservoir the most loaded, especially with phosphorus. The obtained values of the introduced nutrients (Table III) reflect the above-described changes in the fertility of the water of the affluents, confirming the results obtained so far. In the affluent waters of the

Table III. Load with nutrients of the Wisła Czarne, Goczałkowice, and Rybnik Reservoirs (g m⁻² year⁻¹)

Reservoir, periods of investigation	N _{min.}	P _{tot.}
Wisła Czarne		
1974-1975	-	0.23
1976-1979	5.7	0.13
1982-1983	6.6	0.24
Goczałkowice		
1973-1975	5.4	0.18
1982-1983	10.6	0.47
1987	17.4	0.57
Rybnik		
1979-1981	16.9	1.84

Wisła Czarne Reservoir no definite tendency towards an increase or decrease in fertility was observed, hence no essential changes in the loading with nutrients in this reservoir were recorded. The loading of the Goczałkowice Reservoir both with nitrogen and phosphorus increased, over a period of 12-14 years this increase being threefold, similiary as was the case in its main tributary, the Vistula. The loads of nutrients introduced into Rybnik Reservoir, however, because of being recorded only over 3 years, cannot be used to determine the tendency towards changes in the loading of the reservoir bottom with these nutrients.

4.4. Changes in the chlorophyll *a* content in the reservoirs over many years

Changes in the chlorophyll *a* content in the waters of the examined reservoirs are presented as the mean annual changes for the vegetation seasons (fig. 16A) and shown in the list of its maximum content in the successive years of investigation (fig. 16B).

In each of these reservoirs different contents of chlorophyll *a* were found. In the water of the Wisła Czarne Reservoir its amounts were relatively low, the maximum concentrations not exceeding $9.8 \mu\text{g dm}^{-3}$, while the mean values from the particular vegetation seasons remained almost on the same level, varying about $3\text{-}5 \mu\text{g dm}^{-3}$ without any significant differences. For the entire period of the investigations 75% of the data describing the content of this pigment in the water of the Wisła Czarne Reservoir fell within the range $1\text{-}6 \mu\text{g dm}^{-3}$.

In the water of the Goczałkowice Reservoir the amounts of chlorophyll *a* were much higher than in the preceding one and increased with the age of the reservoir. Up to 1985 the maximum concentrations of this pigment did not exceed $30 \mu\text{g dm}^{-3}$, but since 1986 they have always been higher than $50 \mu\text{g dm}^{-3}$. In 1987 the highest concentration of the chlorophyll *a* in the reservoir water ($163 \mu\text{g dm}^{-3}$) was recorded. The values of mean concentrations of chlorophyll *a* from the particular vegetation seasons revealed a tendency towards a gradual increase in the content of this pigment in the reservoir water, which can be represented by means of a linear regression equation (fig. 16A). Mean concentrations of chlorophyll *a* in the vegetation seasons since the year 1987 have at least been equal to $20 \mu\text{g dm}^{-3}$.

The amounts of chlorophyll *a* found in the Rybnik Reservoir were the highest. In the first, 5 year-period, of the reservoir's existence,

the maximum content of chlorophyll *a* in the vegetation season was no higher than 35-37 $\mu\text{g dm}^{-3}$, but in the 6th year of its functioning the concentration of this assimilative pigment jumped to 148 $\mu\text{g dm}^{-3}$, to range in the following years from 87-164 $\mu\text{g dm}^{-3}$. The mean values from the particular vegetation seasons were also very high, i.e. up to 1977 18-20 $\mu\text{g dm}^{-3}$ and from 1978 28-34 $\mu\text{g dm}^{-3}$. The increase in the amount of chlorophyll *a* in the reservoir water manifested by the average concentrations from the particular vegetation seasons did not a linear character as was the case with the Goczałkowice Reservoir but was a sudden rise to a higher level of trophy.

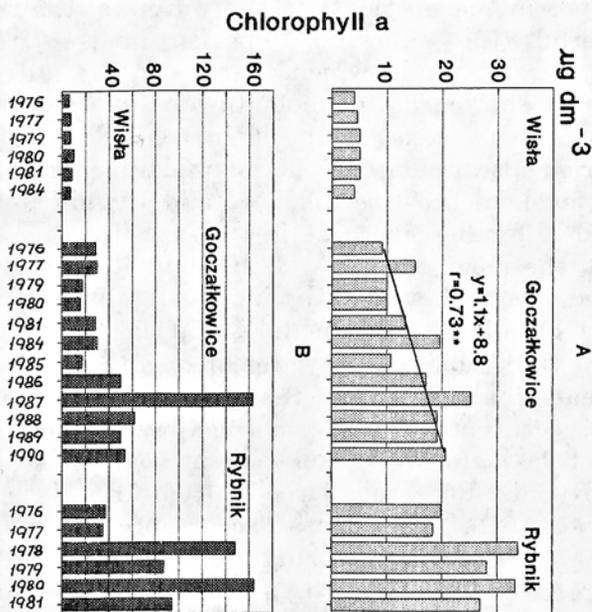


Fig. 16. Mean content of chlorophyll *a* from a vegetation season (A) and its maximum contents (B) in water of the studied reservoirs, ** - $P = 0.01$.

Explanations as in fig. 7

5. Discussion

5.1. Effects of changes in the water environment in the studied dam reservoirs

The literature data provide sufficient evidence that the excessive development of plant communities, especially the planktonic ones, is due to the enrichment of surface waters with mineral nutrients (Wróbel 1983, Bucka 1987, 1989, Burchardt 1987,

Burchardt, Pańczakowa 1987, Dumnicka et al. 1989, Szyszka 1990). A measure of the development of these communities is their quantity, quality, and production. The content of chlorophyll *a* may be an auxiliary indicator in determining the amount of phytoplankton. It may be a vivid illustration of the changes in the water environment, especially when the chlorophyll measurements are being carried out over a long period of time (Toth 1976, Starmach 1989).

The course of changes in the mean values of the chlorophyll *a* content from the vegetation seasons over several years (fig. 16A) and the changes in the nutrients in the waters of the three studied reservoirs permit the following remarks: in the Wisła Czarne Reservoir, i.e. a reservoir in which changes in the nutrient content over many years showed no tendency towards a rise or fall in their concentrations, the average amount of the assimilation pigment over the study period also underwent no significant changes, remaining on the same level. In the Goczałkowice and Rybnik Reservoirs, i.e. those in which a gradual increase in the concentration of nutrients was observed, the mean amounts of chlorophyll *a* in the vegetation season became over higher with the increasing fertility of the water.

An amount of chlorophyll *a* equal to $50 \mu\text{g dm}^{-3}$ represents the lower limit for the occurrence of water blooms (Barica 1981). An effect of increasing abundance in the waters of nutrient compounds was the mass occurrence of algae in the Goczałkowice Reservoir in the thirty-first year and in the subsequent years of its exploitation, and in the Rybnik Reservoir already from the sixth year of its existence (fig. 16B). The mass occurrence of algae in the Goczałkowice Reservoir during the period 1976-1982 (Krzyżanek et al. 1986, Pająk 1986) cannot be defined in terms of water blooms. This was noted by Bucka (1987) who suggests the use of the term "intensified development", when the number of individual cells, coenobia, or colonies of other types, or trichomes range from 10^2 to $5 \cdot 10^2 \text{cm}^{-3}$. Such amounts of algae were found in the Goczałkowice Reservoir in the period 1976-1985.

During the process of eutrophication of the water there occur not only quantitative changes in the biomass of the phytoplankton with a tendency towards its increase, but also structural changes in the phytoplankton communities (Trifonova 1988, 1989, Dumnicka et al. 1989). The changes in the qualitative composition of phytoplankton in the studied reservoirs with their aging are illustrated in figs 17-19.

In a monograph study of the Goczałkowice Reservoir (Krzyżanek, Kownacki 1986) it was found that shortly

after its inundation and during the period in which it was approaching stabilization there appeared single species water blooms, which were mainly attributed to the inflow of nutrients from the flooded soil and the decaying vegetation. K r z y ż a n e k et al. (1986) and P a j ą k (1986) from the year 1962, i.e. when the reservoir bottom had become stabilized, observed a decrease in the development of phytoplankton, which lasted till 1974. Starting from 1976 the development of phytoplankton became increasingly stronger together with the ever more frequent and intensive occurrence of the blue-green alga *Microcystis aeruginosa*, occasionally accompanied by the blue-green alga *Aphanizomenon flos-aquae*. An explosion in the development of these two species has been taking place since 1986. In that year there occurred water blooms of *M. aeruginosa*, and in 1987 and in the following years those of *A. flos-aquae* (fig. 18).

In the Rybnik Reservoir, from its inundation till 1974 the comparison succession of phytoplankton were typical for many dam reservoirs with natural thermal currents (W r ó b e l unpubl.). The maximum development of algae took place in March, April, and September. During the first period the diatoms developed and during the second the blue-green algae. From May till August there developed various species of green alga (W r ó b e l unpubl.). With the aging of the reservoir the numbers and the biomass of

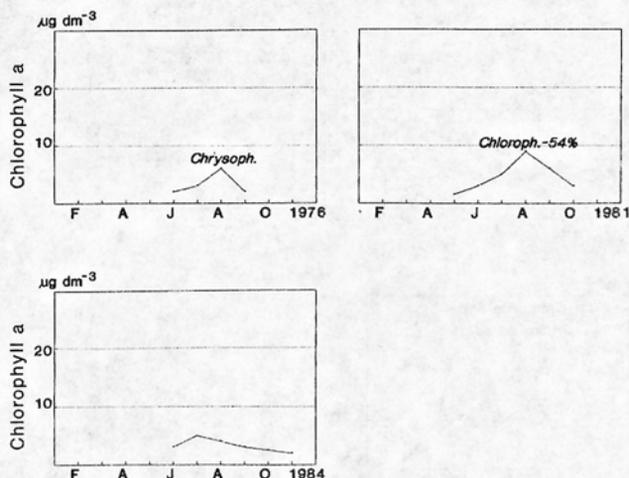


Fig. 17. Course of changes in chlorophyll *a* content in water of the Wisła Czarne Reservoir showing dominating plankton groups. Percentage values refer to participation of these groups in the total number in the period of maximum chlorophyll content (after Strzelecki unpubl., Pająk unpubl.)

phytoplankton increased. From 1975 till 1977 an intensive development of planktonic algae, with a domination of diatoms and subdomination of green algae and dinoflagellates, was observed. The blue-green algae *M. aeruginosa* and *A. flos-aquae* were also encountered in small numbers (Strzelecki unpubl.). In the period 1978-1980 there occurred single species water blooms of the blue-green alga *M. aeruginosa* and in 1981 two maxima of water blooms - in spring, caused by the diatom *A. formosa*, and in summer by the blue green algae *Anabena* sp. and *Oscillatoria* sp. (fig. 19).

The details concerning the physico-chemical features of the aquatic environment during the occurrence of the blue-green algal water blooms have been given by many authors (Kappers 1984, Bucka 1987, 1989, Burchardt 1987, Trimbee, Prepas 1988). Opinions concerning the effect of the aquatic environment on the occurrence of blue-green algae water blooms are often

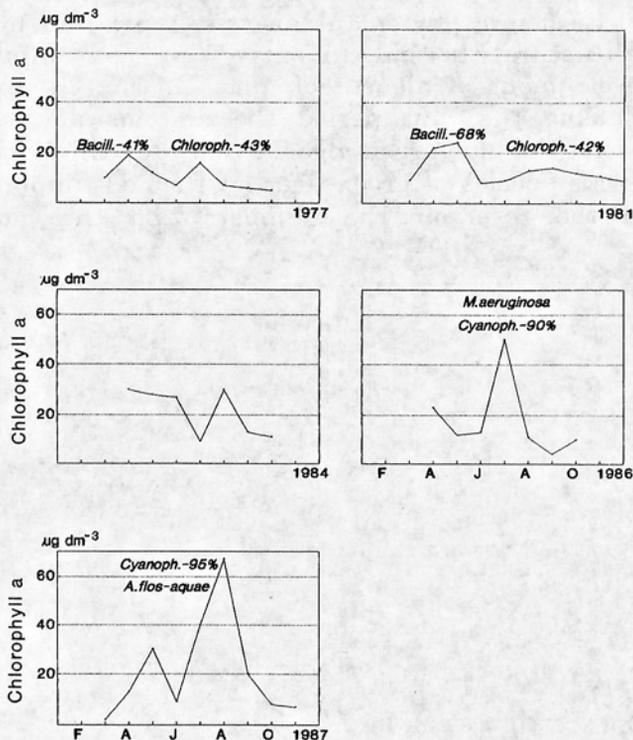


Fig. 18. Course of changes in chlorophyll *a* content in water of the Goczałkowice Reservoir showing dominating plankton groups. Percentage values refer to participation of these groups in the total number in the period of maximum chlorophyll content (after Pająk 1986, Pająk unpubl.)

controversial and, according to Buc k a (1989), require further research. In the Goczałkowice and Rybnik Reservoirs the physico-chemical properties of the aquatic environment are also diametrically different.

An important manifestation of increasing water trophy in the Goczałkowice Reservoir in recent years is the decreasing amount of oxygen, which is especially visible in summer. This is the consequence of the decomposition of excessive amounts of organic substance produced by phytoplankton. As the water here undergoes frequent, through mixing, the oxygen stratification typical of deep waters with an excess of nutrients is not observed. The absence of oxygen stratification has also been reported for the shallow, strongly eutrophicated Sulejów Reservoir (G a l i c k a et al. 1990).

Increased trophy and deteriorating oxygen conditions in the water of the Goczałkowice Reservoir undoubtedly contributed to the changes in the communities of bottom macrofauna. Starting from 1987, a gradual increase in the numbers and biomass of this group of animals has been observed (K r z y ż a n e k unpubl.). This refers mainly to the larvae of Chironomidae. The deteriorating environmental conditions may also be responsible for the reduction

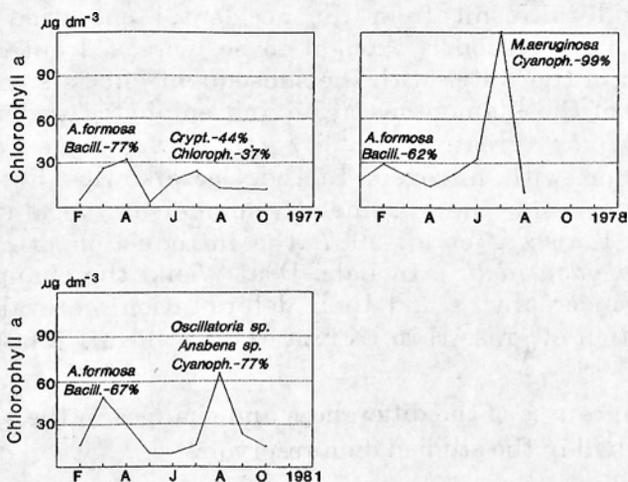


Fig. 19. Course of changes in chlorophyll *a* content in water of the Rybnik Reservoir showing dominating plankton groups. Percentage values refer to participation of these groups in the total number in the period of maximum chlorophyll content (after Srzelecki unpubl., Krzeczowska-Wołoszyn unpubl., Cierniak unpubl.)

of the number and biomass of the group Bivalvia, as well as the change in domination of the species *Unio pictorum* and *Anodonta cygnea*, replaced by *Unio tumidus* and *Anodonta piscinalis* (K r z y ż a n e k unpubl.). Both these species, dominating at present in the Goczałkowice reservoir, are characteristic of fertile waters (M u s a t o v 1979).

In the Goczałkowice Reservoir, from 1986, the macrophytes, especially the submersed ones, began to disappear (K a s z a et al. 1987). In 1987 the submersed vegetation disappeared almost completely as well as a considerable portion of the emergent vegetation. In the following years, submersed vegetation was practically not encountered, while swamp vegetation was found only in those parts of the reservoir sometimes exposed owing to variations in the water level (K u f l i k o w s k i unpubl.). The phenomenon of decay of higher plants in water bodies of various type in northwestern Europe and North America, and probably in other industrialized parts of the world, has become fairly common. It has been well documented on the basis of selected literature by D e N i e (1987). Signs of a recession of the macrophytes have also been reported in Poland (O z i m e k 1983, 1990, 1992, S z a j n o w s k i 1983, O z i m e k , K o w a l c z e w s k i 1984, K r ó l i k o w s k a 1987). In the above-cited literature the decay of plants is said to result from the accidental operation of many factors. The main reason is thought to be increased eutrophication and pollution of the water with the subsequent effects such as mass development of the filamentous algae and epiphytes, reduced water transparency, or greater fragility of, e.g., reeds owing to overfertilization with nitrogen. In the Goczałkowice Reservoir an additional cause of the decline of submersed vegetation was, according to K a s z a et al. 1987, the introduction of grass carp (*Ctenopharyngodon idella*). In Lake Dgał Wielki the changes in the structure of macrophytes and their deterioration were also due to the introduction of grass carp (K r z y w o s z et al. 1980).

5.2. The main causes of the differences and changes in the amounts of chlorophyll in the studied dam reservoirs

There are many factors which may affect the production and biomass of phytoplankton and thereby the amount of chlorophyll. The development of phytoplankton depends on upon a favourable combination of these factors, although the level of the nutrients is basic (K a j a k 1979).

In the studied reservoirs phosphorus constitutes the factor determining the degree of trophy, this having been demonstrated in earlier studies on the basis of the weight ratio N:P (K a s z a 1977, 1986b, P a s t e r n a k, K a s z a 1978). It is also confirmed by the high values of the correlation coefficients in figs 20A, B. For the Goczałkowice Reservoir the mutual relations between chlorophyll *a* and phosphorus, presented for a five-year time interval (fig. 20B), also reveal the increasing eutrophication of this reservoir through gradually increasing amounts of chlorophyll *a* in the water with an increasing supply of phosphorus. The eutrophication role of phosphorus in the three reservoirs is also evidenced by the mutual correlation between the productivity of photosynthesis of phytoplankton expressed as the average production of organic carbon in a vegetation season and the mean annual concentration of phosphorus (fig. 20C).

The development of phytoplankton does not depend only on the current concentration of nutrients, but to a greater extent on their

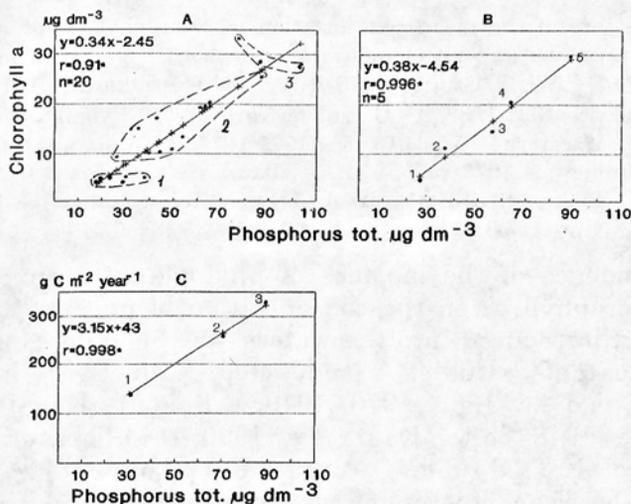


Fig. 20. Dependence of the mean concentration of chlorophyll *a* for a vegetation season upon mean annual phosphorus concentration for all years (A) (collection of data for: 1 - Wisła Czarne, 2 - Goczałkowice, 3 - Rybnik) and averaged results (B) (1 - Wisła Czarne 1976-1981, 2 - Goczałkowice 1976-1980, 3 - Goczałkowice 1981-1985, 4 - Goczałkowice 1986-1989, 5 - Rybnik 1979-1981) and dependence of primary production on the mean annual phosphorus content (C) in the studied reservoirs (1 - Wisła Czarne 1979-1981, 2 - Goczałkowice 1987-1989, 3 - Rybnik 1979-1981). * - $P = 0.001$

constant inflow (Uhlmann, Albrecht 1968, Vollenweider 1968, 1976, 1979). For the studied dam reservoirs a correlation was found to exist between the mean amount of chlorophyll *a* in a vegetation season and the annual load of inflowing phosphorus (fig. 21). At the same time, it was established that an increase in the loading of 1 m² of the bottom surface or 1 m³ of water with phosphorus led to an increase in the chlorophyll *a* concentration.

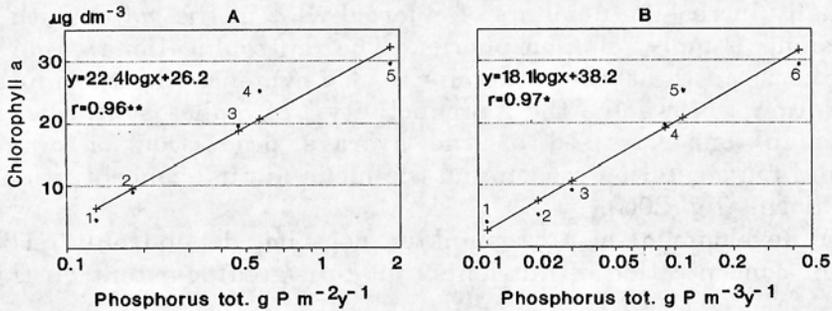


Fig. 21. Dependence of the mean concentration of chlorophyll *a* for a vegetation season upon the amount of inflowing phosphorus: A - per 1 m² of bottom surface (1 - Wisła Czarne 1976-1979, 2 - Goczałkowice 1973-1975, 3 - Goczałkowice 1982-1983, 4 - Goczałkowice 1987, 5 - Rybnik 1979-1981); B - per 1 m³ of water (1 - Wisła Czarne 1976-1979, 2 - Wisła Czarne 1982-1983, 3 - Goczałkowice 1973-1975, 4 - Goczałkowice 1982-1983, 5 - Goczałkowice 1987, 6 - Rybnik 1979-1981). Frequency of water exchange has been taken into consideration. * - $P = 0.001$; ** - $P = 0.01$

The dependence of the biomass of phytoplankton (expressed in terms of chlorophyll *a*) on the concentration of phosphorus as well as on its load introduced into the waters, has been demonstrated in many research studies conducted chiefly in lakes (Vollenweider 1968, 1976, 1979, Dillon, Rigler 1974, Rast, Lee 1978 - after Rippey 1990, Dillon et al. 1988). According to Kondrat'ev and Koplán-Diks (1988), correlations between chlorophyll *a* concentration and the load of inflowing phosphorus have been determined for over 800 lakes in the USA, Canada, Europe, and North Africa. The existence of such a correlation in Polish lakes was shown by Zdanowski (1982), Uchmański and Szeligiewicz (1988), and Szyszka (1990), though the number of studies demonstrating it for dam reservoirs is much smaller (Nush 1975, Walmsley, Butty 1980, Porcalova 1986, Chellapa 1990). These dependences have been expressed in terms of mathematical equations in linear, logarithmic, or even double logarithmic scale as the dispersion of the

data was very great. This follows from the fact that there occur certain differences in the chlorophyll concentration in a given reservoir over several years, although the concentration of phosphorus is similar, or vice versa as in the case in the Wisła Czarne Reservoir (fig. 20A). One of the reasons why the amounts of chlorophyll remain similar with varying phosphorus concentration in the waters of the Wisła Czarne Reservoir may be the occurrence there of large species of zooplankton (K r z a n o w s k i 1987). When the zooplankton is composed of large, filter-feeding cladocerans the biomass of phytoplankton is kept on a low level (K a j a k 1981, H r b a c e k et al. 1986, D a w i d o w i c z, G l i w i c z 1987) - much lower than that anticipated in the models associating phosphorus concentration with the biomass of phytoplankton (G l i w i c z 1986, V l u g t, K l a p w i j k 1988). Nevertheless, an attempt made by D i l l o n et al. (1988) to include the biomass of zooplankton as an additional independent variable did not help to explain the existing differences between the lakes investigated by those authors. Another reason for divergences in the relations between phosphorus and phytoplankton obtained by many authors are differences of methodological character (D i l l o n et al. 1988).

The dependence shown in a logarithmic scale in fig. 21 is evidence that the more phosphorus is carried into the reservoir the smaller the increase in chlorophyll. The reason for this phenomenon, which is of special importance for the Rybnik Reservoir, may be the precipitation of the inflowing phosphorus in the carbonate compounds, as both the reservoir and its affluents are very rich in calcium carbonates and often exhibit an alkaline water reaction (B o m b ó w n a unpubl.). In the case of the heated Konin lakes, the precipitation of calcium carbonates practically inactivated the total load of phosphorus flowing into the lakes as well as part of the indigenous load of this element (Z d a n o w s k i et al. 1988). When comparing the amounts of phosphorus compounds in the water of the Rybnik Reservoir with their content in the waters of the affluents, the reduction in the concentration of this nutrients in the reservoir is clearly seen.

In the studied reservoirs the loads of phosphorus calculated per unit area show great differentiation (fig. 21, Table III). The criteria of V o l l e n w e i d e r (1976) modified by the frequency of water exchange and determining the magnitude of the nutrient loads which do not yet distinctly accelerate eutrophication, since they may be neutralized by the ecosystem, are according to the author's own calculations for the Wisła Czarne Reservoir - $0.52 \text{ g P m}^{-2} \text{ year}^{-1}$, the

Goczałkowice Reservoir - $0.15 \text{ g P m}^{-2} \text{ year}^{-1}$, and the Rybnik Reservoir - $0.34 \text{ g P m}^{-2} \text{ year}^{-1}$. The loads of phosphorus carried into the reservoirs are higher: 4 times for the Goczałkowice Reservoir and 6 times for the Rybnik Reservoir. The excess inflow of phosphorus is the main reason for the intensified development of phytoplankton in the reservoirs. The load of phosphorus carried into the Wisła Czarne Reservoir is more than two times lower than the allowed limit, thus accounting for the smaller amount of algae (chlorophyll) here.

The question arises to what extent the heating of water in the Rybnik Reservoir affects the development and biomass of phytoplankton? Most algae are organisms able to live within a wide temperature interval. However, among them there exist certain taxonomic peculiarities manifested by a different extent of thermal tolerance and different optimum of thermal development and photosynthesis (Patrick 1969 - after Sosnowska (1984)). Increased temperature leads to changes in the structure of the algal communities, which consist in successive replacement of the communities of diatoms, green algae, and blue-green algae (Cairns 1969).

Most algae react to a rise in water temperature up to $25\text{-}30^{\circ}\text{C}$ by increased photosynthesis and reproduction (Morduchaj-Boltovskoj 1976). In the opinion of Wojciechowski (1987), a raised water temperature (caused by thermal pollution) adds to the ecological values of the limiting physical factors, this leading to an increase in the ecological capacity of the habitats in heated waters and is manifested, inter alia, by the condensation of the biomass of algae. Numerous investigations have revealed the stimulating effect of water temperature on the development of phytoplankton (Morduchaj-Boltovskoj 1970, Hickman 1974, Klaver, Hickman 1975, Eloranta 1982).

Hillbricht-Ilkowska and Zdankowski (1988) gave the characteristics of the main directions of changes brought about in a water ecosystem by the functioning of thermal-electric power station connected with it. These changes are of various kind, depending on the particular combination of habitat conditions in the reservoir. Besides, the heated waters are not separated from others sources of pollution and it is difficult to distinguish the effect of the discharge of heated waters from other causes. As a rule this is a synergistic action of the inflow of N and P on the one hand and of the discharge of heated waters on the other (Golterman 1976). The effect of such synergistic action upon the Rybnik Reservoir is the high biomass of the algae in the reservoir, high primary

production, and the water blooms of algae occurring each year since 1978.

The reported changes in the chemical composition of the water in the Rybnik Reservoir revealed a threefold increase in the salinity of its water within seven years. This salinity, calculated on the basis of water conductivity according to a formula used by Hart et al. (1990), amounted to 663-764 mg dm⁻³ in 1980. Changes in salinity occur slowly in this reservoir, which has enabled the water organisms gradually to become adjusted to the increase in concentrations of mineral salts and to avoid osmotic stress. Moreover, according to Hart et al. (1990), "the macroinvertebrates and plants (riparian vegetation, macrophytes, and micro-algae) were assessed to be the most salt-sensitive biological communities, with direct adverse biological effects likely to occur when salinity is increased to around 1000 mg dm⁻³." With the present degree of salinity of the waters of the Rybnik Reservoir it is difficult to say anything definite about its effect on the quantitative and qualitative changes in the phytoplankton. During the investigations of the algae of this reservoir only the appearance of a small number of the species *Cyclotella striata* (Strzelecki unpubl.) and *C. meneghiniana* (Krzeczkowska unpubl.), regarded as saltwater species (Siemińska 1964), was reported.

5.3. The main causes of increased water fertility in the studied reservoirs

As the runoff of nutrients is greatly intensified by farming (Fleischer, Hamrin 1988, Wróbel 1988), attempts were made to assess its function in the development of the trophy of the reservoirs. It was assumed that the volume of phosphorus runoff from the catchment basin is essentially determined by the size of the population inhabiting it, since in earlier investigations of the balance of nutrients in the Goczałkowice Reservoir it had been established that the principal source of phosphorus flowing into it is municipal sewage (Kasza 1980). In the case of the Rybnik Reservoir it was known that it receives an especially great load from the towns Rybnik and Żory. By comparing the values of phosphorus export from the catchment basins of the particular reservoirs and separately from the catchment basin of the Goczałkowice Reservoir with the density of population on their territories a distinct positive correlation between these parameters was obtained (fig. 22).

The values of the phosphorus runoff for the catchment basin of the Wisła Czarne Reservoir (29-38 kg P km⁻² year⁻¹) with a

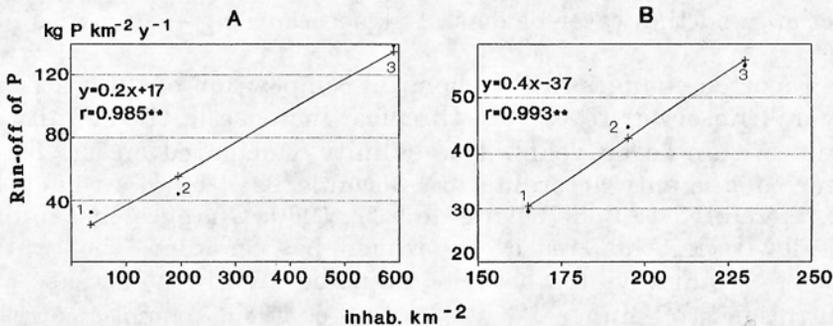


Fig. 22. Dependence of runoff phosphorus from catchment basins of the studied reservoirs (A) (1 - Wisła Czarne 1982-1983, 2 - Goczałkowice 1982-1983, 3 - Rybnik 1981) and from the catchment basin of the Goczałkowice Reservoir (B) (1 - 1973-1975, 2 - 1982-1983, 3 - 1987) upon population density. ** - $P = 0.01$

relatively small anthropopressure of the area (scarce population), are fairly high. Adopting a theoretical assumption of a complete depopulation of the catchment basin of the reservoir, on the basis of the equation from fig. 22A it was calculated that the runoff from it would be about 17 kg P km⁻² year⁻¹. According to the OECD report (K a j a k 1979) the surface runoff from the forests equals 1-13 kg P km⁻² year⁻¹. The scattering of the data may be considerable as the runoff depends to a great extent on the hydrological conditions in the particular years of investigation (B e u s c h o l d 1976). The threat of pollution of the clean waters of the Wisła Czarne Reservoir coming from the forests (which are not fertilized - M a g o s z 1976) is mainly due to the felling of trees, carried out on a small scale. The operations connected with felling and transport of timber may become lead to rapid erosion (C a m p b e l l , D o e g 1989), in view of the fact that this is a mountain area with considerable gradients.

In order to assess the effect of farming on the territory of the catchment basin upon the amount of phosphorus in the water of the reservoirs, an attempt was made to define the correlation between the extent of arable land in the catchment basins of the reservoir and the volume of elementary runoff of this biogen or its concentration in the rivers flowing through these basins. Mathematical analysis showed a lack such a dependence, thus confirming that another factor, i.e. sewage, is the dominating one. As is known from literature data, the losses of phosphorus resulting from use of the land for farming are rather small (P r o c h a z k o v a 1975, J o h n s o n et al. 1976, K o n d r a t ' e v , K a p l a n - D i k s 1988), yet phosphorus derived from this source may contribute to the eutrophication of

surface waters with all the resulting consequences (M a r g o w s k i 1976), since losses regarded as small from the point of view of the soil may represent considerable amounts from that of water eutrophication.

To investigate the effect of environmental factors on the level of mineral nitrogen washed out from the catchment basins of the examined reservoirs there were taken into consideration: the amount of water flowing out of the catchment basins, the population density, and the extent of utilization of the catchment basin for farming. Consideration given to the amount of outflowing water was because of the great ability of the mineral combinations of nitrogen, especially nitrates, to become washed out (M a r g o w s k i 1976, N e s m e r a k 1986b, W r ó b e l, W ó j c i k 1990). Combining the elementary runoff of nitrogen with selected elements of the catchment basin utilization and with their hydrographic features a multiple regression equation was obtained:

$$y = 197x_1 + 4.4x_2 + 21.5x_3 - 3694$$

where:

- y — runoff of mineral nitrogen from the catchment basin (kg N km⁻²)
- x₁ — water runoff (dm³ sec⁻¹ km⁻²),
- x₂ — density of population (inhab. km⁻²),
- x₃ — proportion of arable land in the catchment basin (%).

Since the coefficient values in the above equation are positive, it can be assumed that the amount of nitrogen penetrating from the catchment basin is the effect of the operation of all the considered parameters.

An attempt was also made to determine the dependence of nitrogen runoff from the fields to the waters and its concentration in the Goczałkowice Reservoir upon mineral fertilization (fig. 23). The analysis revealed, similiary as in the case of the reservoirs in former Czechoslovakia (P r o c h a z k o v a et al. 1976, P r o c h a z k o v a 1980, N e s m e r a k 1986b, P r o c h a z k o v a, B l a z k a 1989), the existence of a correlation between the amount of nitrogen fertilizers introduced into the soil and the concentration of nitrate nitrogen, accounting for 86% of the mineral forms of nitrogen in the reservoir water (K a s z a, W i n o h r a d n i k 1986). Although the interpe-dence found is statistically highly significant ($r = 0.703$ with $n = 31$), it must be remembered that the magnitude of nitrogen runoff to the Goczałkowice Reservoir is also affected by the nitrogen inflow from sewage, which is illustrated by the positive regression coefficient at the variable x_2 in the above-quoted formula.

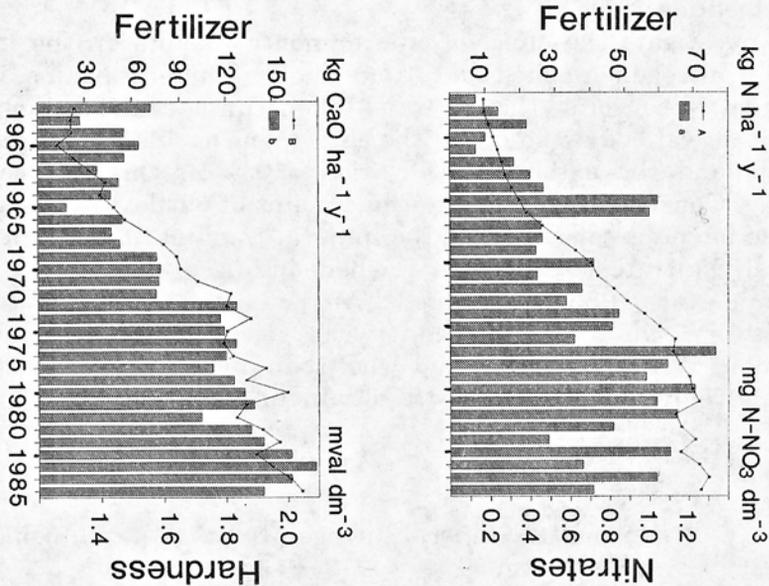


Fig. 23. Mean annual concentration of nitrates (A) and water hardness (B) in the Goczałkowice Reservoir as compared with the doses of nitrogen (a) and calcium (b) fertilizers used in Poland

5.4 Causes of changes in the ion composition of the waters of the examined reservoirs

The ion composition of the reservoir waters is closely associated with the chemical composition of the water of its tributaries (Prochazkova, Blazka 1989): when the ion composition of the tributary water changes so does the chemical composition of the reservoir water.

The results of many years of investigation of the water have shown that in the Wisła Czarne Reservoir, situated in the mountains where human activity in the territory of its catchment basin was almost nil, the ion composition of the water, in spite of some differences between successive years, rather remained constant on the scale of many years. From this it follows that the ion composition of the water in this reservoir is basically affected by

the geological-soil structure of the substratum and its relief. According to Magosz (1976), the small changes in the chemical composition of the water in the Rivers Biała and Czarna Wisłka depend on the amount and composition of dry and wet fallout in the catchment basin. According to a map cited by Juda (Kozłowski 1986), the catchment basin of the Wisła Czarne Reservoir is situated in the zone of mean annual SO_2 concentrations above $20 \mu\text{g m}^{-3}$, which corresponds to the emission of stream of sulphur compounds of $7.5\text{-}10 \text{ t km}^{-2}$. Such amounts of sulphur dioxide may be responsible for the occurrence of acid rains as well as the dry deposition of sulphur compounds. The period of investigation may have been too short to assess the possible tendencies towards changes in the relations of ion occurrence. In the opinion of Wróbel and Szczesny (1990) and Grodzińska-Jurczak (1991), the areas in the neighbourhood of Czarna Wisłka are in danger of acid rains.

In the water of the reservoirs affected by moderate (Goczałkowice Reservoir) and strong (Rybnik Reservoir) anthropopressure the degree of water mineralization increased gradually and the proportions in the quantities of the occurring ion changed. Over a period of 31 years, i.e. from 1957 to 1987, the degree of mineralization expressed as the amount of meq dm^{-3} in the water of the Goczałkowice Reservoir rose about 40%. On the other hand, the amount of strong acid anions, i.e. the chloride and sulphate anions, increased 2.2 and 1.9 times respectively, at the cost of a decreasing amount of carbonates. The absolute quantity of cations increased 1.4 - 1.5 times.

Prochazkova and Blazka (1989) consider the direct and indirect inflow of components of the ion composition (especially SO_2) from the atmosphere and the mineral fertilizers used in the catchment basin to be the main causes of increased mineralization of the water in the Slapy Reservoir and changes in the relations between the ions. The gradual increase in the extent of water mineralization in the Goczałkowice Reservoir cannot be fully explained by attributing it to increasing doses of mineral fertilizers, since its catchment basin is not only used for farming. Although by relating the amount of the applied doses of calcium fertilizers to the water hardness in the reservoir (fig. 23) a high value for positive linear correlation was obtained, nevertheless the degree of hardness and the state of mineralization of the reservoir water are the result of a joint action of other factors, such as sewage, dry and wet fallout in the catchment basin and on the reservoir surface, as well as an increased rate of rock weathering and the susceptibility of ions to

become washed out by acid rains. According to Juda (Kozłowski 1986), in the catchment basin of the Goczałkowice Reservoir the annual SO_2 concentrations exceed $60 \mu\text{g m}^{-3}$, which corresponds to a stream of sulphur compounds of $20\text{-}50 \text{ t km}^{-2}$, and the amount of SO_2 emitted into the atmosphere in Poland in 1980 was 13.0 t km^{-2} (the mean for Europe is 2.3 t km^{-2}). Thus, the above amounts of the stream of sulphur compounds coming from all the sources of SO_2 emission and calculated in relation to the area of the catchment basin of the Goczałkowice Reservoir are rather high. The phenomenon of the relative loss of carbonates and acid carbonates and their replacement by strong acid ions in the waters of the Vistula and the Goczałkowice Reservoir may be attributed, inter alia, to the action of acid rains.

Considering the phenomena taking place in the Goczałkowice Reservoir and its catchment basin, as regards the Rybnik Reservoir the ultimate cause of the rapid rate of changes in the ion composition (3.5-fold increase in the degree of water mineralization within a period of 7 years) can be seen in the sewage penetrating into the reservoir from the overflowing of the River Nacyna which, according to the author's own calculations, supplies 5-7% of total inflow of water. The reservoir and the catchment basin are also exposed to the danger of the fallout of chemical compound emitted into the atmosphere by industrial plants in the neighbourhood. According to the Juda (after Kozłowski 1986), the stream of sulphur compounds in the Rybnik Coal Region ranges from 50 to 100 t km^{-2} and the amount of dust produced there exceeds 1800 t km^{-2} (Kassenberg 1986). The reservoir and the catchment basin are also likely to collect dust from the chimney of the power station. Dusts of this type contain toxic substances, compounds responsible for the increased salinity and hardness of the water (Pidgajko 1971, Gallup, Hickman 1975, Larimore, Tranguili 1981, Hillbricht-Ilkowska, Zdanowski 1988). The increase in the degree of mineralization of this reservoir may also be due to evaporation of the water, which is fairly high and amounts, depending on the time of year, from $0.15 \text{ m}^3 \text{ sec}^{-1}$ in March to $0.47 \text{ m}^3 \text{ sec}^{-1}$ in June.

5.5. General model of eutrophication of the studied dam reservoirs

From complex monitoring investigations carried out in the Goczałkowice Reservoir (Krzyżanek, Kownacki 1986) concerning the development, structure, and succession of its

communities, the results given in the present study, investigations of the Rożnów Reservoir (D u m n i c k a et al. 1989) and also data obtained from foreign literature (V o r o p a e v, V e n d r o v 1979, D e n i s o v a et al. 1989) it is possible to distinguish several stages in the life of the dam reservoirs, constructed on rivers (K o w n a c k i, S t a r m a c h 1989).

The first stage is a period during which the hitherto existing river and land communities on the flooded areas are destroyed and pioneer water organisms characteristic of dam reservoirs begin to appear. This stage lasts for a few months (K r z y ż a n e k, K o w n a c k i 1986).

In the second period, usually lasting for 2 to 10 years from the moment of inundation, a general increase in the fertility of the reservoir takes place. This period is characterized by the absence of a chemical and biological balance. The sediments are not yet fully developed and large amounts of mineral nutrients are released into the water from the flooded soil and from the decaying flooded vegetation (P e u k e r t 1970, P r i y m a c h e n k o - S h e v c h e n k o et al. 1976). As a result, the mass development of some forms of the phytoplankton may take place as, for example, in the Goczałkowice Reservoir (P a j ą k 1986).

In the third stage, lasting up to 20 years, the whole ecosystem becomes stabilized and the fertility of the reservoir is reduced. K o w n a c k i and S t a r m a c h (1989) called this period a stage of "oligotrophication". The newly forming sediments cut off the water from the primary soils, thus diminishing the amounts of mineral components in the water and consequently that of phytoplankton.

In the fourth period, as a result of the constant inflow of mineral biogenic components and organic matter carried by the water, the fertility of the reservoir water again increases. With increased water trophy the biocoenoses of the reservoir undergo changes and the mass appearance of algae with subsequent water blooms is more and more frequent. The reservoir passes into the fifth stage of its development, when a mass appearance of algae occurs every year. The blue-green algae become the dominating group in the phytoplankton.

The duration of the first and of the second stage depends on the proper preparation of the substratum of the area to be flooded. The third stage is the most advantageous from the point of view of utilizing the reservoir as a water supply system and it should begin as early as possible and last as long as possible. The duration of this period depends on the degree of pollution of the tributary river(s).

In the Wisła Czarne Reservoir the first and second stages lasted altogether for about 2 years. As its affluents are relatively clean and only slightly exposed to the effects of anthropopressure, the third stage of development continues and should last for a fairly long time if the land use in the catchment basin is not changed.

The period required to attain a stabilized condition in the Goczałkowice Reservoir took 6 years. From 1962 the fertility of its water began gradually to increase with the increasing abundance of nutrients in the Vistula, this causing the third stage to last for a relatively short time. Since 1986 there have occurred mass water blooms of the blue-green algae.

In the Rybnik Reservoir the first four development stages lasted altogether for 5 years; however, the occurrence of the third and fourth stages has not been observed since, owing to the inflow of a great load of nutrients from the Rivers Ruda and Nacyna, there took place a sudden jump in the trophy to a higher level. Starting from the 6th year of its functioning there have been water blooms of the blue-green algae every year.

On the basis of the observed changes in the chlorophyll content as well as an analysis of the development of the qualitative and quantitative composition of the phytoplankton in the reservoirs (Krzyżanek et al. 1986, Pająk 1986, Cierniak, Pająk, Strzelecki, Krzeczowska-Wołoszyn, Urbaniec-Brózda unpubl.), a general scheme for the evolution of the biomass of phytoplankton (chlorophyll) in the reservoirs has been constructed in relation to the content of total phosphorus (fig. 24). It is limited to a hydrometeorological situation, typical for a period of many years, with no sudden flooding or flood waves. At the same time, this scheme allows changes to be predicted in the biomass of phytoplankton (chlorophyll) in the annual cycle in the reservoirs, depending on the degree of water fertility, thus providing a basis for planning their protection.

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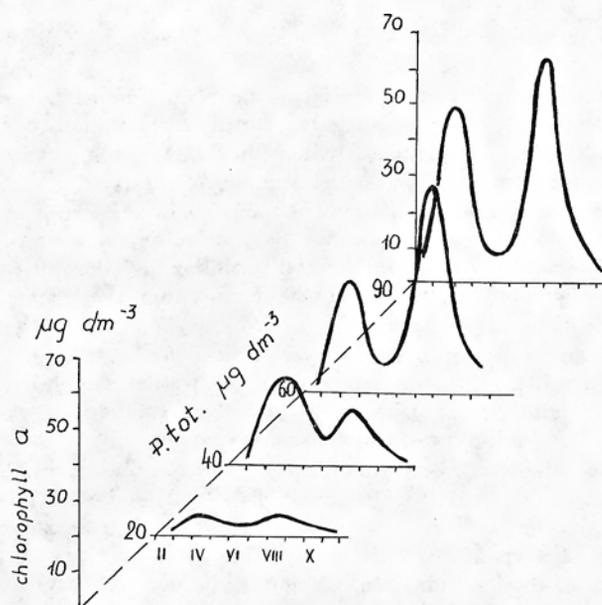


Fig. 24. Schematic representation of the evolution of chlorophyll *a* in relation to the content of total phosphorus in the studied dam reservoirs

6. Polish summary

Wieloletnie zmiany środowiska wodnego w trzech zbiornikach zaporowych na Śląsku (Polska południowa) od początku ich istnienia - przyczyny i skutki

Badano trzy zbiorniki zaporowe (Wisła Czarne, Goczałkowice, Rybnik) różne pod względem morfologicznym, geologicznym, przeznaczenia i oddziaływania czynników antropogennych (ryc. 1-4, tabele I, II).

Przedstawiono wyniki badań właściwości chemicznych wody zbiorników i ich dopływów (ryc. 5-14). W zlewniach rzek o dużym zalesieniu i znikomej działalności gospodarczej człowieka (zlewnia Białej i Czarnej Wisłoki) zmiany we właściwościach chemicznych wód były niewielkie (ryc. 5, 6). W zlewniach zurbanizowanych i poddanych przemysłowej oraz rolniczej działalności człowieka zachodził stały i prawie coroczny wzrost mineralizacji i żyzności odpływającej z nich wody (ryc. 7-9). W zbiornikach, których wody dopływów ulegały określonej tendencji zmian, zmieniały się parametry chemiczne, wyrażające się poprzez stopniowy wzrost stężenia elektrolitów i zmianę proporcji ilościowego ich występowania, a także poprzez wzrost żyzności (ryc. 10-12, 14). W górskim zbiorniku Wisła Czarne, w którym parametry wody dopływów w perspektywie wielolecia nie podlegały istotnym zmianom, właściwości chemiczne wody, pomimo rozpiętości stężeń, były raczej stałe (ryc. 10).

W badanym okresie w zbiornikach warunki tlenowe były względnie dobre (ryc. 10, 13, 15).

W zbiorniku Wisła Czarne przeciętne ilości pigmentu asymilacyjnego na przestrzeni badanych lat nie ulegały istotnym zmianom. W zbiornikach Goczałkowice i Rybnik, średnie ilości chlorofilu "a" w sezonie wegetacyjnym były coraz wyższe w miarę wzrostu żyzności ich wody (ryc. 16). Ponadto zachodziła w tych zbiornikach stopniowa zmiana dominacji podstawowych grup systematycznych fitoplanktonu. Po początkowej przewadze Bacillariophyceae następował stopniowy spadek ich dominacji, a w fitoplanktonie rósł udział grup Chlorophyta z jednoczesną ekspansją sinic (Cyanophyta), które stały się dominantem tworzącym letnie zakwity wody (ryc. 17-19).

Czynnikiem decydującym o stopniu trofii jest fosfor. Stwierdzono zależność przeciętnej ilości chlorofilu "a" i produkcji pierwotnej fitoplanktonu za sezon wegetacyjny od średniej rocznej koncentracji fosforu ogólnego w wodzie badanych zbiorników (ryc. 20). Ładunki fosforu wnoszonego do zbiorników są 4-krotnie wyższe dla zbiornika Goczałkowice i 6-krotnie dla Rybnika, zaś dla zbiornika Wisła Czarne dwukrotnie niższe od wartości dopuszczalnych (ryc. 21, tabela III). Podstawowymi przyczynami mającymi wpływ na wielkość odpływu fosforu ze zlewni są gęstość i zmiany zaludnienia (ryc. 22). O ilości odpływającego azotu z poszczególnych zlewni decyduje, oprócz gęstości zaludnienia, stopień rolniczego wykorzystania zlewni (ryc. 23).

Przedstawiono generalny schemat ewolucji chlorofilu "a" w relacji do zawartości fosforu ogólnego w badanych zbiornikach (ryc. 24).

7. References

- Andronikova I. N. (Red.), 1980. *Izmenyeniya v soobshchestvye zooplanktona v svyazi s protsessom evtrofirovaniya*. Leningrad, Nauka, 78-99.
- Barica J., 1981. Hypereutrophy - the ultimate stage of eutrophication. In: Barabas S. (Ed.): *Eutrophication: a global problem - part 2*. Water Quality Bull., 6, 95-98.
- Berg K., O. M. Skulberg, R. Skulberg, 1987. Effects of decaying toxic blue-green algae on water quality - a laboratory study. *Arch. Hydrobiol.*, 108, 549-563.
- Beuschold E., 1976. Einfluss von Massnahmen der Naehrstoffrueckhaltung im Einzugsgebiet von Trinkwassertalsperren auf die Phytoplankton Produktion und die Aufbereitungskosten. *Limnologia*, 10, 557-580.
- Bombóna M., 1962. Sedimentieren von Sinkstoffen im Staubecken Goczałkowice. *Acta Hydrobiol.*, 4, 65-118.
- Brykowiec-Waksmundzka K., K. A. Waksmundzki, 1975. Kompleksowa mapa sozologiczna źródłowej części zlewni Wisły [A complex sozological map of the spring section of the Vistula catchment area]. *Karpaty*, 3, 3-7.
- Bucka H., 1987. Ecological aspects of the mass appearance of planktonic algae in dam reservoirs of southern Poland. *Acta Hydrobiol.*, 29, 149-191.
- Bucka H., 1989. Ecology of selected planktonic algae causing water blooms. *Acta Hydrobiol.*, 31, 207-258.
- Bul'on V.V., 1984. *Pyervichnaya produktsiya planktona*. Leningrad, Gos. N.I.O.R.Kh., 16-32.

- Burchardt L., 1987. Zmiany populacyjne fitoplanktonu Jeziora Świętokrzyskiego na tle zmian warunków środowiskowych - Populational changes in phytoplankton of the Świętokrzyskie Lake against the background of changes in the environmental conditions. Poznań, Wyd. Nauk. Uniw. A. Mickiewicza, Biologia, 1-90.
- Burchardt L., J. Pańczakowa, 1987. Qualitative and quantitative changes in phytoplankton on the background of physico-chemical changes in the water of Świętokrzyskie Lake in the years 1977-79. Pol. Arch. Hydrobiol., 34, 193-214.
- Cairns J. jr., 1969. The response of freshwater protozoan communities to heated waste waters. Chesapeake Sci., 10, 177-185.
- Campbell I. C., T. J. Doeg, 1989. Impact of timber harvesting and production on streams: a review. Aust. J. Mar. Freshwat. Res., 40, 519-539.
- Chellapa N. T., 1990. Phytoplankton species composition, chlorophyll biomass, and primary production of the Jundiai Reservoir (northeastern Brazil) before and after eutrophication. Acta Hydrobiol., 32, 75-91.
- Dawidowicz Z., Z. M. Gliwicz, 1987. "Biomaniplucja". 3. Rola bezpośrednich i pośrednich zależności pomiędzy fitoplanktonem i zooplanktonem [Biomaniplucation. 3. The role of direct and indirect relationship between phytoplankton and zooplankton]. Wiad. ekol., 33, 259-277.
- Den Hartog C., J. Kvet, H. Sukopp, 1989. Reed. Acomon species in decline. Aquat. Bot., 35, 1-4.
- De Nie H. W., 1987. The decrease in aquatic vegetation in Europe and its consequences for fish populations. EIFAC/CECPI, Occ. Pap., 19, 52 pp.
- Denisova A. I., V. M. Timchenko, E. P. Nakshina, B. I. Novikov, A. K. Ryabov, Ya. I. Bass, 1989. Hidrologiya i gidrokhimiya Dnyepra i yevo vodokhranilishch. Kiyev, Nauk. Dumka, 216 pp.
- Dillon P. J., F. H. Rigler, 1974. The phosphorus-chlorophyll relationship in lakes. Limnol. Oceanogr., 19, 767-773.
- Dillon P. J., K. H. Nicholas, B. A. Locke, E. De Grosbois, N. D. Yan, 1988. Phosphorus-phytoplankton relationships in nutrient-poor soft-water lakes in Canada. Verh. Int. Ver. Limnol., 23, 258-264.
- Dojlido J., J. Woyciechowska, 1989. Water quality classification of the Vistula river basin in 1987. Ecol. pol., 37, 405-417.
- Domńska R., 1957. Badania fizyko-chemiczne wody zbiornika i jego dopływów [Physico-chemical investigations of waters of a reservoir and its affluents]. Biul. Kom. do Spraw Górnośl. Okr. Przem., Warszawa, PAN, 8, 87-103.
- Domńska R., 1958. Omówienie badań fizyko-chemicznych wody rzeki Wisły i jej dopływów na odcinku Wisła Czarne - Wisła Strumień [Discussion on physico-chemical investigations of the River Vistula and its tributaries between Wisła Czarne and Wisła Strumień]. Biul. Kom. do Spraw Górnośl. Okr. Przem., Warszawa, PAN, 19, 73-88.
- Dumnicka E., A. Amirowicz, H. Bucka, M. Jelonek, J. Zięba, R. Żurek, 1989. Biocenozy zbiornika rożnowskiego. Materiały Symp. "Dunajec - wczoraj, dziś i jutro" [Biocoenoses of the Rożnów Reservoir. Proc. Conf. "Dunajec - yesterday, today, and in future"]. Niedzica, 63-73.
- Eloranta P., 1982. Seasonal succession of phytoplankton in a ice-free pond warmed by a thermal plant. Hydrobiologia, 86, 87-91.

- Fleischer S., S. F. Hamrin, 1988. Land use and nitrogen losses - a study with the Laholm Bay drainage area of Southwestern Sweden. Verh. Int. Ver. Limnol., 23, 181-192.
- Galicka W., A. Korczyńska, A. Drożdżyk, 1990. Charakterystyka limnologiczna zbiornika Sulejowskiego w latach 1972-1987. W: Kajak Z. (Red): Funkcjonowanie ekosystemów wodnych, ich ochrona i rekultywacja. Cz. 1. Ekologia zbiorników zaporowych i rzek [Limnological characteristic of the Sulejów reservoir in the period 1972-1987. In: Kajak Z. (Ed): Functioning of aquatic ecosystems, their protection and recultivation. Part 1. Ecology of dam reservoirs and rivers]. CPBP, 04.10.08., 226-237.
- Gallup D. N., M. Hickman, 1975. Effects of the discharge of thermal effluent from a power station on Lake Wabamun, Alberta, Canada. Hydrobiologia, 46, 16-30.
- Giziński A., L. A. Błędzki, A. Kentzer, R. Wiśniewski, R. Żytkowicz, 1989. Hydrobiological characteristic of the lowland, rheolimnic Włocławek reservoir on the Vistula river. Ekol. pol., 37, 359-403.
- Głowacz Z. M., 1986. "Biomaniplacja". 1. Czym teoria ekologii służyć może praktyce ochrony środowiska wodnego? - Biomaniplation. 1. Can ecological theory be applied in management of freshwater habitat?. Wiad. ekol., 32, 155-170.
- Głodek J., 1985. Jeziora zaporowe świata - The world's dam lakes. Warszawa, PWN, 174 pp.
- Golterman H. L., 1976. Some theoretical considerations of thermal discharge in shallow lakes. H₂O negende Jaargang, 1, 1-8.
- Golterman H. L., R. S. Clymo, 1969. Methods for chemical analysis of fresh water. Oxford, Blackwell Sci. Publ., IBP-Handbook, 8, 180 pp.
- Grodzińska-Jurczak M., 1991. Czy polskim jeziorom i rzekom także grozi zakwaszenie? [Are the Polish lakes and rivers exposed to a danger acidification?]. Wszechświat, 9, 187-188.
- Hart B. T., P. Bailey, R. Edwards, K. Hortle, K. James, A. McMahon, Ch. Meredith, K. Swadling, 1990. Effects of salinity on river, stream and wetland ecosystems in Victoria, Australia. Wat. Res., 24, 1103-1117.
- Hermanowicz W., W. Dożańska, J. Dojlido, B. Kozirowski, 1976. Fizyczno-chemiczne badania wody i ścieków. [Physico-chemical investigations on water and sewage]. Warszawa, Arkady, 846 pp.
- Hickman M., 1974. Effects of the discharge of thermal effluent from a power station on Lake Wabamun, Alberta, Canada. The epilimnetic and epipsammic algal communities. Hydrobiologia. 45, 199-215.
- Hillbricht-Ilkowska A., B. Zdanowski, 1988. Changes in lake ecosystems connected with the power-generating industry (the outline of problems): The Konin lakes (Poland) as the study sites. Ekol. pol., 36, 5-21.
- Hrbacek J., O. Albertova, B. Desortova, V. Gottwaldova, J. Popovsky, 1986. Relation of the zooplankton biomass and share of large Cladocerans to the concentration of total phosphorus, chlorophyll-a and transparency in Hubenov and Vrchlice reservoirs. Limnologica, 17, 301-308.
- Jankowski A., 1973. Głony źródłem mikrozanieczyszczeń wód powierzchniowych ujmowanych przez wodociągi komunalne - na przykładzie sinicy *Oscillatoria rubescens* (DC) Gom. - Algae as source of micropollution of surface water used

- for communal water works - on example of *Oscillatoria rubescens* (DC) Gom. Zesz. Nauk. Inst. Gosp. Komn., Zakł. Inf. Nauk.-Techn. i Ekon., 36, 1-40.
- Johnson A. H., D. Bouldin, E. Goyette, A. Hedges, 1976. Phosphorus loss by stream transport from a rural watershed quantities, processes, and sources. J. Environm. Quality, 5, 148-157.
- Just J., W. Hermanowicz, 1955. Fizyczne i chemiczne badania wody do picia i potrzeb gospodarczych. [Physical and chemical examination of water for drinking and for economic purposes]. Warszawa, PZWL, 368 pp.
- Just J., W. Hermanowicz, 1964. Fizyczne i chemiczne badania wody do picia i potrzeb gospodarczych [Physical and chemical examination of water for drinking and for economic purposes]. Warszawa, PZWL, 310 pp.
- Kajak Z., 1979. Eutrofizacja jezior [Eutrophication of lakes]. Warszawa, PWN, 233 pp.
- Kajak Z., 1981. Skuteczność różnych metod rekultywacji jezior w celu poprawy czystości ich wód - Effectiveness of various methods of recultivation of lakes for purity of their waters. Wiad. ekol., 27, 331-357.
- Kajak Z. (Ed.), 1989. Limnology of two lowland impoundments, central Poland. Ekol. pol., 37, 209-417.
- Kappers F. J., 1984. On population dynamics of the cyanobacterium *Microcystis aeruginosa*. Acad. Proefschr., Univ. Amsterdam, 176 pp.
- Kassenberg A., 1986. Obszary ekologicznego zagrożenia - nowa kategoria planistyczna - Areas of ecological danger: new term in planning activities. Kosmos, 1, 153-160.
- Kasza H., 1977. Input of nitrogen and phosphorus to the dam reservoir at Goczałkowice in the years 1973-1975. Acta Hydrobiol., 19, 23-42.
- Kasza H., 1979. Rainfall waters as a source of nutrient components for the reservoir at Goczałkowice. Acta Hydrobiol., 21, 279-289.
- Kasza H., 1980. The development of the catchment areas of the Goczałkowice reservoir and its effect on the amount of nitrogen and phosphorus migration from it. Acta Hydrobiol., 22, 37-53.
- Kasza H., 1986a. The effect of the Goczałkowice dam reservoir on the hydrochemical conditions of the River Vistula below the dam (Southern Poland). Acta Hydrobiol., 28, 83-97.
- Kasza H., 1986b. Hydrochemical characteristics of the Wisła Czarne Reservoir (Southern Poland) in the period 1975-1984. Acta Hydrobiol., 28, 293-306.
- Kasza H., 1986c. Development and structure of the Goczałkowice reservoir ecosystem. 2. Characteristics of the catchment area. Ekol. pol., 34, 313-322.
- Kasza H., 1991. Bibliography of Goczałkowice Reservoir (southern Poland) for the period 1955-1990. Acta Hydrobiol., 33, 161-174.
- Kasza H., W. Krzanowski, W. Krzyżanek, T. Kuflikowski, 1987. Biocenotic changes in the Goczałkowice Reservoir caused by the impact of grass carp (*Ctenopharyngodon idella* Val.) on macrophytes. Bull. Acad. Pol. Sci., Biol. Sci., 35, 189-198.
- Kasza H., J. Winohradnik, 1986. Development and structure of the Goczałkowice Reservoir ecosystem. 7. Hydrochemistry. Ekol. pol., 34, 365-395.
- Klaver D.M., M. Hickman, 1975. The effect of thermal effluent upon the standing crop of epiphytic algal community. Int. Rev. ges. Hydrobiol., 60, 17-62.
- Kondrat'ev K. Ya., J. S. Koplanski, 1988. Evolyutsiya krugovorota fosfora i evtrofirovaniye prirodnykh Vod. Leningrad, Nauka, 204 pp.

- Kościeszko H., M. Prajer, 1990. Effect of municipal and industrial pollution on the biological and chemical quality of the water in the upper and middle course of the River Biała Przemsza (southern Poland). *Acta Hydrobiol.*, 32, 13-26.
- Kownacki A., J. Starmach, 1989. Ocena jakości wód Górnego Dunajca i kierunki zmian pod wpływem zabudowy hydrotechnicznej. *Mat. Symp. "Dunajec - wczoraj, dziś, jutro"* [Assessment of upper Dunajec water quality and changes under the impact of river impoundments. *Proc. Conf. "Dunajec - yesterday, today, and in future"*]. *Niedzica*, 95-108.
- Kozłowski S., 1986. Kierunki zmian w środowisku przyrodniczym - Trends of environmental changes. *Kosmos*, 1, 5-42.
- Kozłowski W., M. Karaś, K. Fiedler, 1981. Monografia zbiornika wodnego Rybnik [Monograph on the Rybnik Reservoir]. Warszawa, Wyd. Kom. i Łączn., 128 pp.
- Królikowska J., 1987. Reed (*Phragmites australis* (Cav.) Trin. ex Steud.) growth under conditions of increasing eutrophication of Lake Mikołajskie. *Ekol. pol.*, 35, 209-217.
- Krummenacher T., 1976. Die Naehrstoffbilanz des Alpnersees. Zuerich, Diss. ETH, 5689, 137 pp.
- Krzanowski W., 1987. Zooplankton of the Wisła-Czarne Dam Reservoir (Southern Poland) in the years 1975-1984. *Acta Hydrobiol.*, 29, 417-427.
- Krzywosz T., W. Krzywosz, J. Radziej., 1980. The effect of grass carp, *Ctenopharyngodon idella* (Vall.) on aquatic vegetation and ichthyofauna of lake Dgał Wielki. *Ekol. pol.*, 28, 433-450.
- Krzyżanek E., H. Kasza, W. Krzanowski, T. Kuflikowski, G. Pająk, 1986. Succession of communities in Goczałkowice Dam Reservoir, in the period 1955-1982. *Arch. Hydrobiol.*, 106, 21-43.
- Krzyżanek E., A. Kownacki (Eds), 1986. Development and structure of the Goczałkowice reservoir ecosystem. *Ekol. pol.*, 34, 307-577.
- Larimore R. W., J. A. Tranquili (Eds), 1981. The Lake Sangchris study - case history of an Illinois Cooling Lake. *Bull. Illinois Hist. Surv.*, 32, 279-337.
- Magosz S., 1976. Stan eutrofizacji zbiornika zaporowego Wisła Czarne w świetle spływów obszarowych zlewni. *Mat. Nauk. Sesja Bad. Jub.* [The state of eutrophication of the Wisła Czarne dam reservoir in the light of runoff from the catchment area. *Proc. Sci. Sess.*], Zabrze, 97-114.
- Margowski Z., 1976. Przenikanie podstawowych składników nawozowych do wód gruntowych. *Mat. Konf. "Nawożenie a eutrofizacja wód"* [Migration of nutrients from fertilizers into the ground water. *Proc. Conf. "Fertilization and eutrophication of water"*]. Zielona Góra, 75-97.
- Morduchaj-Boltovskoj F. D., 1970. The effect of the heated water discharged from the cooling system of the Kanakovskaja thermal power station on the hydrology and biology of the Ivankovskoe reservoir. In: Kajak Z., A. Hillbricht-Ilkowska (Eds): *Productivity problems of freshwaters*. Warszawa-Kraków, PWN, 291-295.
- Morduchaj-Boltovskoj F. D., 1976. Vliyanie teplych elektrostancy na fito- i zooplankton vodokhranilishcha na Volge. V: *Sbornik dokladov simposyuma po issledovaniyu vliyanija sbrasyvaemykh podogretykh vod na termichesku i biologichesku rezhim vodoemov, sostoyavshegosya v Varshave s 7-11 aprelya 1975 g.* Warszawa, Inst. Meteorol. Vodn. Chozyay., 403-421.

- Musatov A. P., 1979. Zoobentos. Gidrobiologicheskoye osobennosti vodokhranilishch. V: Voropayev G. V., S. L. Vendrov (Red): Vodokhranilishcha mira. Moskva, Nauka, 165-173.
- Nesmerak I., 1986a. Errors of determining material loads from a watershed. *Limnologia*, 17, 251-254.
- Nesmerak I., 1986b. Nitrates and mineral nitrogen fertilization. *Limnologia*, 17, 273-282.
- Nush E. A., 1975. Comparative investigations on extent, causes and effects of eutrophication in Western German reservoirs. *Verh. Int. Ver. Limnol.*, 19, 1871-1879.
- Olszowski Z., L. Rożnowska, 1988. Monografia zbiornika wodnego Wisła Czarne [Monograph on the Wisła Czarne Reservoir]. Warszawa, Wyd. Geol., 148 pp.
- Opuszyński K., 1987. Sprzężenie zwrotne między procesem eutrofizacji a zmianami zespołu ryb. Teoria ichtioeutrofizacji - A feed back dependence between the eutrophication process and changes in the fish community. The theory of ichthyoeutrophication. *Wiad. ekol.*, 33, 21-30.
- Ozimek T., 1983. Biotic structure and processes in the lake system of R. Jorka watershed (Masurian Lakeland, Poland). 10. Biomass and distribution of submerged macrophytes. *Ekol. pol.*, 31, 781-792.
- Ozimek T., 1990. Przebudowa roślinności zanurzonej w silnie eutrofizujących się jeziorach i jej konsekwencje dla ekosystemu jeziornego. W: Kajak Z. (Red): Funkcjonowanie ekosystemów wodnych, ich ochrona i rekultywacja. Eksperymenty na ekosystemach [Formation of submersed macrophytes in progressively eutrophicated lakes and its consequences for the lake ecosystem. In: Kajak Z. (Ed.): Functioning of aquatic ecosystems, Their protection, and recultivation. Experiments upon ecosystems]. CPBP, 04.10.08., 239-260.
- Ozimek T., 1992. Makrofity zanurzone i ich relacje z glonami w jeziorach o wysokiej trofii - Submerged macrophytes and their relationship with algae in eutrophic and hypertrophic lakes. *Wiad. ekol.*, 38, 13-34.
- Ozimek T., A. Kowalczewski, 1984. Long-term changes of the submerged macrophytes in eutrophic Lake Mikołajskie (North Poland). *Aquat. Bot.*, 19, 1-11.
- Pajak G., 1986. Development and structure of the Goczałkowice Reservoir ecosystem. 8. Phytoplankton. *Ekol. pol.*, 34, 397-413.
- Pasternak K., 1962. Geologiczna i gleboznawcza charakterystyka dorzecza Górnej Wisły - Geological and pedological characteristics of the upper basin of the Vistula river. *Acta Hydrobiol.*, 4, 277-299.
- Pasternak K., 1968. Skład chemiczny wody rzek i potoków o zlewniach zbudowanych z różnych skał i gleb - The chemical composition of waters of rivers and streams from drainage areas built of various rocks and soils. *Acta Hydrobiol.*, 10, 1-25.
- Pasternak K., 1976. Wpływ zlewni na skład chemiczny wód śródlądowych. W: Starmach K., S. Wróbel, K. Pasternak (Red.): *Hydrobiologia - Limnologia* [The effect of the catchment area on the chemical composition of inland waters. In: Starmach K., S. Wróbel, K. Pasternak (Eds): *Hydrobiology-Limnology*]. Warszawa, PWN, 59-80.

- Pasternak K., H. Kasza, 1978. Chemical relations and primary production of the phytoplankton in the warmed water of the reservoir Rybnik. *Acta Hydrobiol.*, 20, 305-322.
- Peukert V., 1970. Untersuchungen über den Einfluss von überstauten Fläachen auf die Wasserqualitaet von Talsperren. *Forstchr. Wasserchem.*, 12, 66-82.
- Pidgaiko M. L. (Ed.), 1971. *Gidrochimya i gidrobiologiya vodoemov ochladiteley teplovykh elektrostanciy SSSR*. Kiev. Nauk. Dumka, 248 pp.
- Porcalova P., 1986. Development of water quality in the Husinec reservoir. *Limnologica*, 17, 325-333.
- Priymachenko-Shevchenko A. D., A. I. Denisova, Y.U.M. Tulupchuk, 1976. Phytoplankton development in the Dnieper reservoirs in connection with dynamics of biogenic elements. *Limnologica*, 10, 525-528.
- Prochazkova L., 1975. Balances in man-made lakes (Bohemia). 2.1. Nitrogen and phosphorus budgets: Slapy Reservoir. In: Hasler A. D. (Ed.): *Coupling of land and water systems*. *Ecol. Stud.*, 10, 65-73.
- Prochazkova L., 1980. Agricultural impact on the nitrogen and phosphorus concentration in water. In: Duncan N., J. Rzóska (Eds): *Land use impacts on lake and reservoir ecosystems*. Proc. MAB Project 5 Workshop, Fac. Verl. Wien, 78-100.
- Prochazkova L., P. Blazka, 1986. Long-term trends in water chemistry of the Vltava River (Czechoslovakia). *Limnologica*, 17, 263-271.
- Prochazkova L., P. Blazka, 1989. Ionic composition of reservoir water in Bohemia: long-term trends and relationships. *Acta Hydrobiol., Beih. Ergebn. Limnol.*, 33, 323-330.
- Prochazkova L., J. Popovsky, B. Desortova, 1976. Field fertilization of nutrients in water bodies. *Limnologica*, 10, 287-292.
- Prochazkova L., V. Straskraba, J. Popovsky, 1973. Changes of some chemical constituents and bacterial numbers in Slapy Reservoir during eight years. In: Hrbacek J., M. Straskraba (Eds): *Hydrobiol. Stud.*, 2, Acad. Praha, 83-154.
- Rippey B., 1990. Implications for the design of artificial lakes of a study of the Craigavon Lakes. *Wat. Res.*, 24, 1085-1089.
- Siemińska J., 1964. Chrysophyta 2. Bacillariophyceae - okrzemki. *Flora Słodkowod. Polski*, 6, 609 pp.
- Sosnowska J., 1984. Uwagi o ekologii glonów w wodach podgrzanych - Some remarks on the ecology of algae in heated waters. *Wiad. ekol.*, 30, 131-142.
- Stangenberg M., 1958. Ogólny pogląd na skład chemiczny wód rzecznych Polski - A general outlook on the chemical composition of river waters in Poland. *Pol. Arch. Hydrobiol.*, 4, 289-359.
- Starmach K., 1989. Plankton roślinny wód słodkich. *Metody badania i klucze do oznaczania gatunków występujących w wodach Europy Środkowej* [Phytoplankton of fresh waters. Methods of investigation and key to the identification of species inhabiting waters of Central Europe]. Warszawa-Kraków, PWN, 496 pp.
- Starmach K., S. Wróbel, K. Pasternak, 1970. *Hydrobiologia-Limnologia* [Hydrobiology-Limnology]. Warszawa, PWN, 621 pp.
- Szajnowski F., 1983. Biotic structure and processes in the lake system of R. Jorka watershed (Masurian Lakeland, Poland). 11. Biomass and distribution of emergent macrophytes. *Ekol. pol.*, 31, 793-800.

- Szyszk a T., 1990. Zależność średnich letnich wartości parametrów fitoplanktonowych od koncentracji P w jeziorach eutroficznych. W: K a j a k Z. (Red.): Funkcjonowanie ekosystemów wodnych, ich ochrona i rekultywacja. Cz. 2. Ekologia jezior, ich ochrona i rekultywacja. Eksperymenty na ekosystemach [The dependence of average summer values of phytoplankton parameters on the P concentration in eutrophic lakes. In: K a j a k Z. (Ed.): Functioning of aquatic ecosystems, their protection, and recultivation. Part 2. Experiments upon ecosystems]. CPBP, 04.10.08., 44-50.
- T o t h L., 1976. On eutrophication process in Lake Balaton. *Eutrosym.*, 76, 372-380.
- T r a c z M., 1958. Omówienie badań fizyko-chemicznych wody zbiornika w Goczałkowicach i jego bezpośrednich dopływów [Discussion on physico-chemical investigations of the Goczałkowice Reservoir and its immediate affluents]. *Biul. Kom. do Spraw Górnośl. Okr. Przem., PAN. Warszawa*, 19, 55-71.
- T r a c z M., 1960. Podstawowe wskaźniki jakości wody zbiornika w Goczałkowicach [Primary indicators of water quality of the Goczałkowice Reservoir]. *Gosp. Wodna*, 20, 211-213.
- T r i f o n o v a I. S., 1988. Oligotrophic-eutrophic succession of lake phytoplankton. In: R o u n d F.E. (Ed.): *Algae and the aquatic environment*. Bristol, Biopress Ltd., 107-124.
- T r i f o n o v a I. S., 1989. Changes in community structure and productivity of phytoplankton as indicators of lake and reservoir eutrophication. *Arch. Hydrobiol., Beih. Ergebn. Limnol.*, 33, 363-371.
- T r i m b e e A. M., E. E. P r e p a s , 1988. The effect of oxygen depletion on the timing and magnitude of blue-green algal blooms. *Verh. Int. Ver. Limnol.*, 23, 220-226.
- U c h m a ń s k i J., W. S z e l i g i e w i c z , 1988. Empirical models for predicting water quality, as applied to data on lakes of Poland. *Ekol. pol.*, 36, 285-316.
- U h l m a n n D., E. A l b r e c h t , 1968. Biogeochemische Faktoren der Eutrophierung von Trinkwassertalsperren. *Limnologica*, 6, 225-245.
- V l u g t J. C. van der, S j. P. K l a p w i j k , 1988. Dose-effect relationships between phosphorus concentration and phytoplankton biomass in the Reeuwijk Lakes (The Netherlands). *Verh. Int. Ver. Limnol.*, 23, 482-488.
- V o l l e n w e i d e r R. A., 1968. Scientific fundamentals of the eutrophication of lakes and flowing waters with particular references to nitrogen and phosphorus as factors in eutrophication. *OECD Techn. Rep. DAS/CSI/68.27/*, Paris, 159 pp.
- V o l l e n w e i d e r R. A., 1976. Advances in defining critical loading levels for phosphorus in lake eutrophication. *Mem. Ist. Ital. Idrobiol.*, 33, 53-83.
- V o l l e n w e i d e r R. A., 1979. Das Naehrstoffbelastungskonzept als Grundlage fuer den externen Eingriff in den Eutrophierungsprozess stehender Gewaesser und Talsperren. *Z. Wasser u. Abwasser Forsch.*, 2, 46-50.
- V o r o p a e v G. V., C. L. V e n d r o v , 1979. *Vodokhranilishcha mira*. Moskva, Nauka, 287 pp.
- W a l m s l e y R. D., M. B u t t y (Eds), 1980. The limnology of some selected South African impoundments. *Nat. Inst. Wat. Res.*, Pretoria, 229 pp.
- W o j c i e c h o w s k i I. 1987. *Ekologiczne podstawy kształtowania środowiska* [The ecological fundamentals of environmental development]. Warszawa, PWN, 450 pp.
- W r ó b e l S., 1975. Some limnological aspects of the dam reservoir at Goczałkowice. *Pol. Arch. Hydrobiol.*, 22, 217-283.

- Wróbel S., 1983. Eutrofizacja Wisły. W: Kajak Z. (Red.): Ekologiczne podstawy zagospodarowania Wisły i jej dorzecza [Eutrophication of the River Vistula. In: Kajak Z. (Ed.): Ecological basis for management of the environment in the River Vistula catchment area]. Warszawa-Łódź, PWN, 417-434.
- Wróbel S., 1988. 2. Ekochemia wód śródlądowych. W: Tarwid K. (Red.): Ekologia wód śródlądowych [2. Ecochemistry of inland waters. In: Tarwid K. (Ed.): Ecology of inland waters]. Warszawa, PWN, 139-191.
- Wróbel S., B. Szczęsny, 1990. Zakwaszenie wód w Polsce i próby ich neutralizacji. W: Kajak Z. (Red.): Funkcjonowanie ekosystemów wodnych, ich ochrona i rekultywacja. Cz. 2. Ekologia jezior, ich ochrona i rekultywacja. Eksperymenty na ekosystemach [Acidification of waters in Poland and attempts at their neutralization. In: Kajak Z. (Ed.): Functioning of aquatic ecosystems, their protection, and recultivation. Part 2. Experiments upon ecosystems]. CPBP, 04.10.08., 194-206.
- Wróbel S., D. Wójcik, 1990. Wezbranie rzek a eutrofizacja zbiorników zaporowych. W: Kajak Z. (Red.): Funkcjonowanie ekosystemów wodnych, ich ochrona i rekultywacja. Eksperymenty na ekosystemach [Rising of rivers and eutrophication of dam reservoirs. In: Kajak Z. (Ed.): Functioning of aquatic ecosystems, their protection, and recultivation. Part 2. Experiments upon ecosystems]. CPBP, 04.10.08., 207-213.
- Zdanowski B., 1982. Variability of nitrogen and phosphorus contents and lake eutrophication. Pol. Arch. Hydrobiol., 29, 541-597.
- Zdanowski B., A. Korycka, A. Gębicka, 1988. Long-term variation in habitat and trophic factors in the Konin lakes (Poland) under the influence of heated-water discharge and pollution. Ekol. pol., 47-77.
- Ausgewaehlte Methoden der Wasseruntersuchung, 1970. Methoden zur Bestimmung der Bioaktivitaet. Chlorophyll. Jena, VEB G. Fisher Verl., 6 pp.