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# The effect of the Goczałkowice dam reservoir on the hydrochemical conditions of the River Vistula below the dam (Southern Poland)*

**Henryk Kasza**

Polish Academy of Sciences, Institute of Freshwater Biology
Hydrobiological Station, 43-230 Goczałkowice, Poland

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Abstract — In the period 1982—1983 the physico-chemical properties of the River Vistula waters were investigated at 4 stations: above the inflow to the reservoir, directly below the dam, and 1 km and 20 km below the reservoir. When compared with the entering waters, those flowing out from the reservoir are poorer in mineral compounds of nitrogen and phosphorus but richer in organic matter. In summer, the waters below the reservoir contain far less oxygen than those flowing in. The reservoir has a negative effect on the purity of the River Vistula.

Key words: river, dam reservoir, nutrients, organic matter, water purity.

## 1. Introduction

The increasing demand for water compels the building of new dam reservoirs and water stages. Every blocking of a river leads to hydrological changes and, in consequence, changes in the physico-chemical parameters of the water and in the biocoenosis below the damming constructions. The course of such changes is the subject of growing interest (Ward, Stanford 1979a).

There are but a few works in Poland describing the effect of dam reservoirs on the hydrochemical conditions of a river (Dojlido et al. 1967, Bierwagen et al. 1972, Wróbel, Bombówna 1976, Wróbel, Szczęsny 1983).

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At the Institute of Freshwater Biology of the Polish Academy of Sciences in Kraków a complex study was undertaken of the hydrochemistry, phytoplankton, zooplankton, and zoobenthos of the river-reservoir-river complex.

The present work is a part of that study and aims at presenting the physico-chemical changes in the River Vistula water after flowing through the Goczałkowice reservoir and the effect of this reservoir on its purity.

## 2. Study area

The characteristics of the Goczałkowice reservoir have been presented in several works (W r ó b e l 1975, K a s z a 1977, 1980).

The River Vistula is the main inflow of the reservoir (fig. 1), providing in the general water balance about 80% of water (K a s z a unpubl.). Up to the inlet it has the features of a mountain river with swift current and a stony-gravel bottom (W r ó b e l 1983).

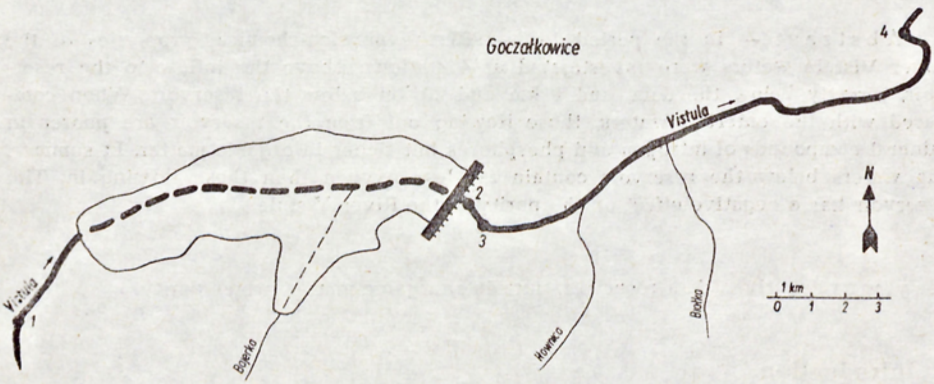


Fig. 1. Localization of sampling stations on the River Vistula (1—4 number of stations)

The average depth of the Goczałkowice reservoir is 5.2 m. It has a bottom sluice whose position depends on the damming ordinate at a depth of 10—12 m. This outflow depth was obtained by channelling a new riverbed in the bottom of the reservoir. The obligatory discharge is 0.45 $m^3 sec^{-1}$, the maximum being 240 $m^3 sec^{-1}$.

The water flowing out of the sluice in a section about 1 km long is dammed so that in this part of the river, with minimum outflow, it flows with a velocity of several cm $sec^{-1}$. In the dammed section, waters flow into the river from fish ponds and the blank riverbed of the Vistula, carrying the run-off from fields and woods. Below the weir the river assumes a lowland character (W r ó b e l 1983). Along its further course, in the investigated section, it is swollen by two tributaries, the Rivers Iłownica and Białka (fig. 1), whose waters are polluted by municipal and industrial sewage.

The Goczałkowice reservoir provided the water-supply system with $183.9 \times 10^6$ m³ of water in 1982 and $154.8 \times 10^6$ m³ of water in 1983. This water, used for municipal economy returns, in principle, to the River Vistula only around the 60th km below the dam. During the investigation (1982—1983) the inflow of water to the reservoir was $193.1 \times 10^6$ m³ and $195.6 \times 10^6$ m³ (fig. 2) and the outflow through the sluice $59.7 \times 10^6$ m³ and

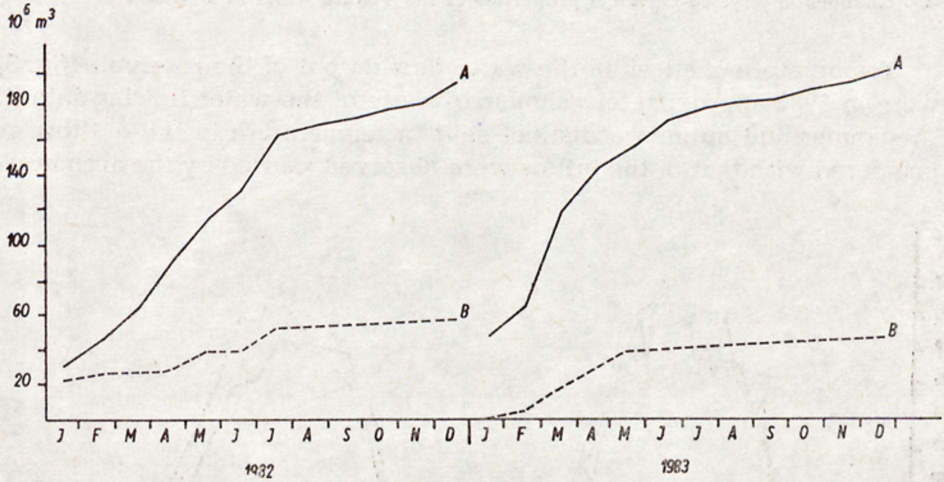


Fig. 2. Total inflow of water to the reservoir (A) and outflow through the bottom sluice (B) in the period 1982—1983

$48.9 \times 10^6$ m³ (data from the Water-Supply and Sewage Plant of Katowice). The outflow of water through the sluice in that period was exceptionally low (1/3 and 1/4 of the inflow amount) for they were dry years. In another period e.g. 1973—1975 when the meteorological conditions were close to the average, the water discharges through the sluice were larger, constituting about 1/2 of the inflowing water. In the years under discussion water did not flow out of the reservoir through the spillway.

The investigation was carried out from January 1982 until December 1983 at four stations (fig. 1): station 1, situated on the River Vistula 3 km above the inflow to the reservoir, station 2, about 100 m below the dam, station 3, about 1 km below the dam and 50 m behind the weir, station 4, 20 km from the reservoir at Góra.

## 3. Material and methods

The investigation at stations 1, 2, and 3 was carried out at 1—2 week intervals, 59 samples from each station being collected for water analysis. At station 4 water sampling was carried out only 5 times and in 1982.

The water was analysed by the methods described by Just and Hermanowicz (1964) and Golterman and Clymo (1969).

## 4. Results

### 4.1. Changes in physico-chemical properties of the Vistula water at station 2

Temperature changes in the water flowing out of the reservoir (fig. 3) were in 1982 approximately similar to those of the water flowing into it. In summer and autumn a distinct shift in temperature in the outflow as compared with that of the inflow were observed, caused by the accumula-

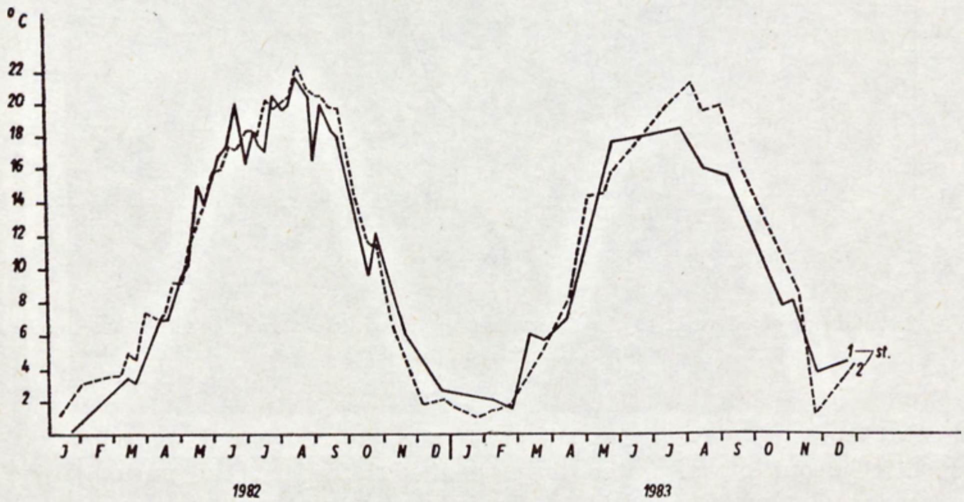


Fig. 3. The course of temperature changes of the River Vistula before joining the reservoir (station 1) and below the dam (station 2)

tion of heat in the reservoir. Only in winter and early spring (January--March) were the outflowing waters warmer than the inflowing ones. In 1983 the temperature maximum moved from the third decade of July in the inflow to the first decade of August in the outflow. Almost from July to the middle of November the waters flowing out of the reservoir were warmer than the inflowing ones. This increased temperature in the river below the dam was shifted in relation to the inflow for about 10—20 days.


Fig. 4. The range of variation of physico-chemical factors in the River Vistula at stations 1 and 2 and the average values (m)

Table I. Percentage changes in average values of physico-chemical parameters of the River Vistula waters at stations 2 and 3 in 1982-1983. Values from 1973-1975 according to Kasza (unpubl.). Values at station 2 in relation to station 1; values at station 3 in relation to station 2

| Factor \ Stations | 1982-1983 | | 1973-1975 |
|---|---|---|---|
| | 2 | 3 | 2 |
| pH | 100.6 | 98.3 | 100.0 |
| Oxygen | 87.7 | 100.9 | 92.7 |
| Oxygen saturation | 87.0 | 101.7 | 90.5 |
| Hardness | 99.8 | 105.9 | |
| Alkalinity | 105.3 | 114.3 | 100.0 |
| Calcium | 101.3 | 106.1 | 99.7 |
| Magnesium | 97.8 | 104.0 | 93.8 |
| Sodium | | | 71.2 |
| Potassium | | | 100.0 |
| Chlorides | 81.1 | 99.8 | 78.3 |
| Conductivity | 96.0 | 102.9 | 94.4 |
| Silica | 55.6 | 152.6 | 62.1 |
| Mineral nitrogen | 66.5 | 101.6 | 68.3 |
| Ammonia nitrogen | 124.5 | 146.4 | 120.9 |
| Nitrite nitrogen | 56.2 | 77.8 | 64.3 |
| Nitrate nitrogen | 60.9 | 92.4 | 59.2 |
| Organic nitrogen | 119.2 | 95.2 | |
| Total nitrogen | 76.9 | 102.1 | |
| Phosphates | 43.3 | 269.2 | 85.7 |
| Total phosphorus | 91.5 | 119.8 | 105.1 |
| Oxidability | 119.4 | 107.8 | 152.8 |
| $BOD_5$ | 105.4 | 112.6 | 100.4 |

In winter 1982/83 and at the end of 1983 the water below the dam was colder than the inflow water, and with temperatures below 0°C was quickly frozen in the whole dammed section.

The components of the ionic composition of the water, such as magnesium, calcium, and carbonates, flowing through the reservoir did not change their concentration or underwent but slight transformation (fig. 4). Only chloride ions in the reservoir showed a significant fall in concentration (Table I).

The water flowing out of the reservoir was characterized by a greater stability of concentration of the main electrolytes and by a smaller range of variation.

In comparing the amount of dissolved oxygen in the inflow and outflow water of the reservoir (fig. 5) it was observed that there was less in

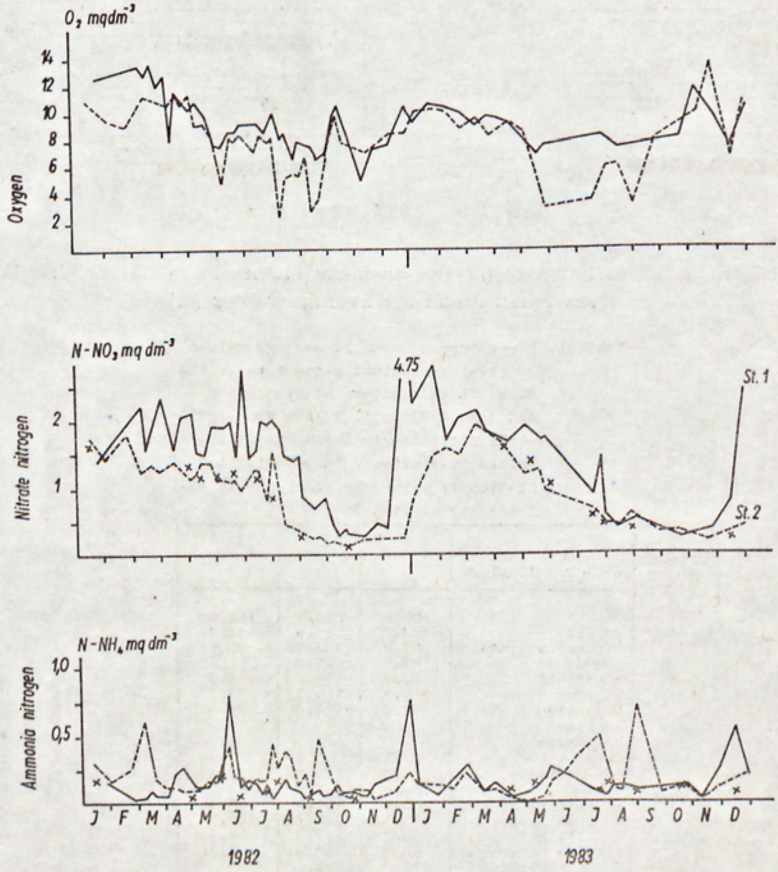


Fig. 5. Changes in the concentration of oxygen, nitrate nitrogen, and ammonium nitrogen in the water of the River Vistula at stations 1 and 2. x — concentration in the reservoir water

the outflow. This smaller amount of oxygen in the outflow waters is clearly visible in the period May-September when the oxygen content in the water below the reservoir was often below 6 mg $O_2$ $dm^{-3}$. In that period in 3 cases the observed oxygen value was below 3 mg $O_2$ $dm^{-3}$, while the inflow waters were well oxygenated.

At other times the differences in oxygen content between the inflow and outflow water were not so distinct.

The silica flowing through the reservoir becomes reduced in concentration, 56% that penetrating the reservoir with the inflow being carried away through the sluice to the river below the dam (Table I).

Nitrate and nitrite nitrogen were eliminated in the reservoir (Table I), the waters flowing out it containing a smaller amount of these compounds

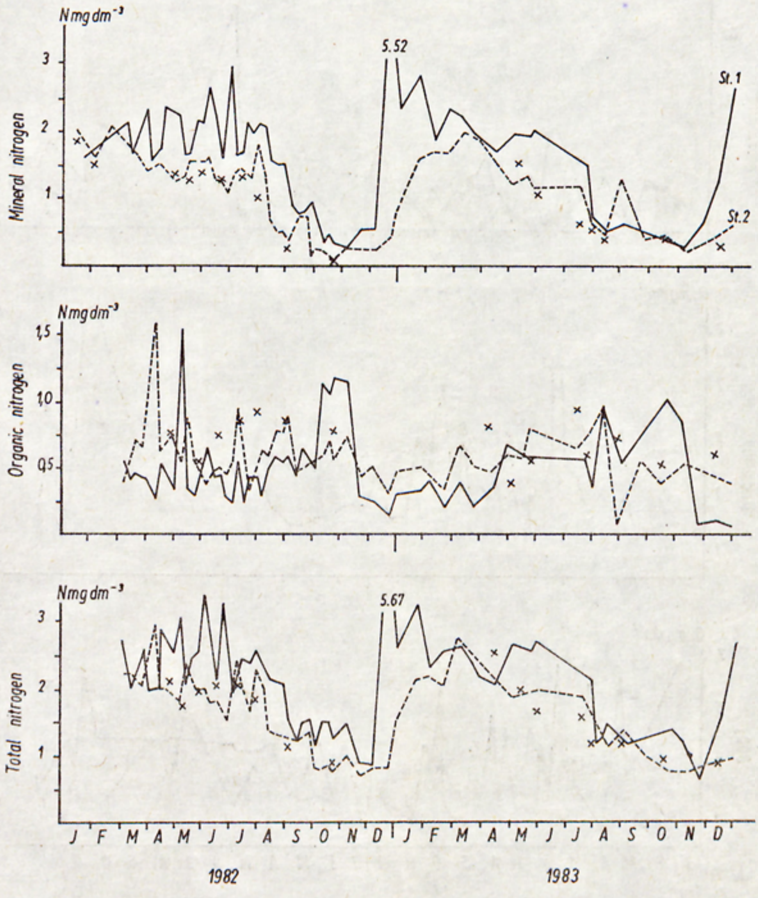


Fig. 6. Changes in concentration of mineral nitrogen, organic nitrogen, and total nitrogen in the water of the River Vistula at stations 1 and 2. x — concentration in the reservoir water

than those above the dam. In comparison with the Vistula before it enters the reservoir the average concentration was 61 and 56% of these forms of nitrogen respectively. The amounts of mineral and total nitrogen (fig. 6) were distinctly lower at station 2 than at station 1. The elimination of the percentage sum of the mineral forms of nitrogen (33.5%) was slightly smaller than that of nitrates (39%), since the outflow contained more ammonium nitrogen (124.5%) than the inflow. These increased amounts of ammonium nitrogen were observed in summer (fig. 5) and when the water below the dam was covered with ice. The concentration of organic nitrogen (fig. 6) in the water of the river below the dam was, on the average, 19% higher than in that above the reservoir. After taking

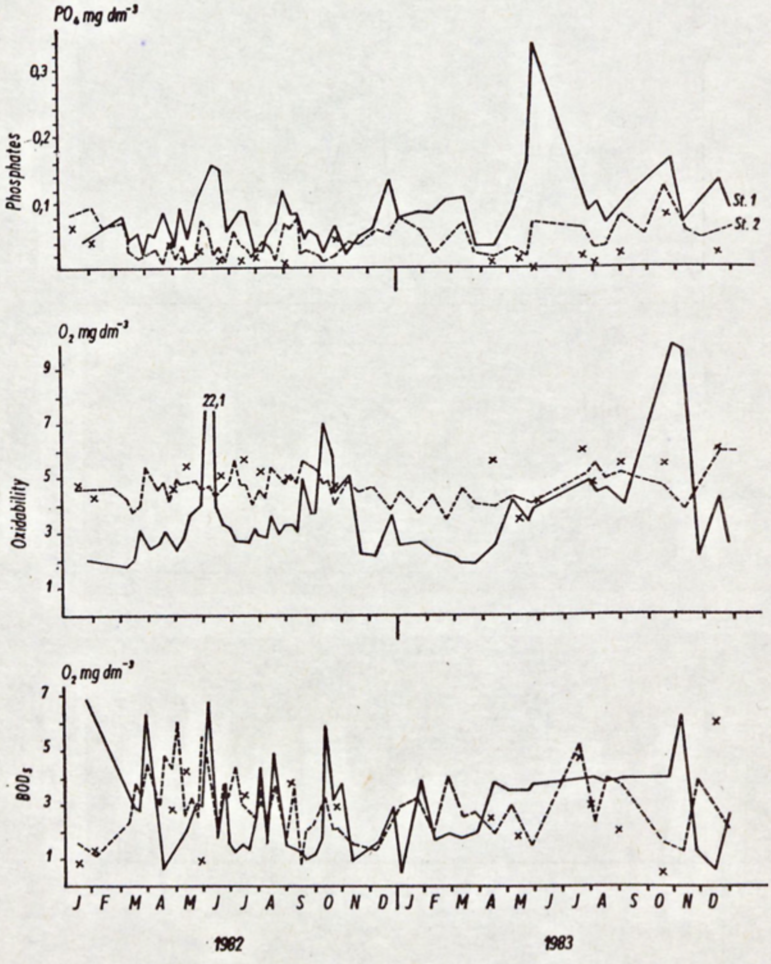


Fig. 7. Changes in concentration of phosphates, and values of oxidability and $BOD_5$ at stations 1 and 2. x — concentration in the reservoir water

into account the rise in concentration of ammonium and organic nitrogen in the water of the river at station 2 (fig. 6), the elimination of total nitrogen was only 23.1%. In other words, the water of the River Vistula above the inflow contained, on the average for the 2 year investigation period, 2.140 mg $N_{total}$ $dm^{-3}$, and below the dam only 1.646 mg N $dm^{-3}$. The variation in concentrations of mineral and total nitrogen (fig. 4) in the outflow were more stable than in the inflow.

When analysing the changes in concentration of phosphates after the reservoir, a fall was observed (Table I), the outflow usually containing lower concentration than the inflow water from the river (fig. 7). On the average, the concentration of phosphates in the water below the dam constituted 43% of the amount contained in the inflow.

The concentrations of total phosphorus after passing through the reservoir decreased, but the differences in the average content of this element in the water above and below the dam were small, the average difference being 8.5%.

The oxidability of the water at station 2 on the River Vistula was usually higher in value than that at station 1 (fig. 7). Only during a short period was a higher oxidability of the water flowing into the reservoir observed several times. The differences in the values of water oxidability between the inflow and outflow were distinct. In earlier investigation (1973—1975) the inflow waters were characterized by a lower oxidability than the outflow ones (Table I). The sluice water was also characterized by a more stable oxidability than the inflow water and did not show any great variations in its value. The $BOD_5$ values of water below and above the dam differed varied in a wide range (fig. 7). The average value of river water $BOD_5$ directly below the dam was slightly higher that at station 1 (Table I).

### 4.2. Physico-chemical changes in property of the water of the River Vistula at stations 3 and 4

At station 3 the annual temperature of the water was 0.2°C lower than that at station 2. At station 3 the river was not frozen in the winter.

The percentage changes in the physico-chemical parameters of the water from station 3 in relation to the values from station 2 are shown in Table I. In the water of the Vistula after flowing over a distance of about 1 kilometre the content of ammonium nitrogen increased by 46%, of phosphates by 169%, of total phosphorus by 20%, of silica by 53%. The value of oxidability increased to a slightly smaller degree at this station (by 8%) as did that of $BOD_5$ (by 13%), whereas there was a decrease in the concentration of nitrite (by 22%), of nitrates (by 8%), and of organic nitrogen (by 5%). However, the sum of mineral forms of nitrogen and total nitrogen remained unchanged. A difference of only 2%

was observed between the average content of mineral and total nitrogen.

The remaining indices underwent certain changes in concentration but in relation to station 2 they were small (differences in value not greater than 6%). It is characteristic that at station 3 these parameters increased.

Determination of the physico-chemical properties of the water, carried out at station 4, showed strong pollution of the river. The chemical composition of the water was completely different from that of the reservoir outflow. The conductivity of the water was about 8 times greater, and in this connection the amount of electrolytes also rose, including chlorides, which rose 30 times. Among the mineral forms of nitrogen the amount of $N—NO_4$ increased about 20 times and $N—NO_2$ 12 times, but the concentration of $N—NO_3$ in the summer decreased 1.5 times. The amount of total nitrogen rose 4 times, the content of phosphates about 30 times, and of total phosphorus 5—10 times.

Oxygen concentration fell in the summer to 2—3.5 mg $O_2$ $dm^{-3}$.

## 5. Discussion

Two successive dry years undoubtedly had an effect on the quantity and quality of water flowing in and out of the reservoir. The economic utilization of the water also played a certain role in forming the hydrological and physico-chemical conditions of the water in the river below the dam.

With such a small inflow the time of water retention in the reservoir was about 0.8 of the year. According to Wróbel and Szczęsny (1983), a long period of water retention in this reservoir leads to deterioration in water quality because of biological processes.

Dam reservoirs with a hypolimnic outflow drastically change the thermal conditions of the water below them. They are regarded as heat traps and nutrient exporters (Odum — after Wróbel, Szczęsny 1983). They accumulate heat in summer, returning it in autumn and winter (Lowe 1979), and shift the minimum and maximum temperatures by about 1 month (Walker 1979) or even longer (Ward, Stanford 1979b).

In the Goczałkowice reservoir the change in thermal conditions is not so drastic. One of the reasons in the absence of thermal stratification in the relatively shallow reservoir (Wróbel 1975), the water being mixed throughout its depth. Thermal stratification is present only in winter under the ice and in other seasons in very short periods during windless weather. By warming, shallow dam reservoirs increase the temperature of the water in the river below the dam (Fraley 1979).

The fact that the river below the dam of the Goczałkowice reservoir freezes in winter in the dammed up section may be explained by the very low water velocity (a few cm $sec^{-1}$) and the small peat reserve of the scant outflowing mass (0.45 $m^3$ $sec^{-1}$).

Damming up of the river below the dam has also a significant effect on the amount of oxygen at this point of the river in summer. As in the reservoir water, thermal and oxygen stratification occurs rarely, therefore the small amount of oxygen is formed as a result of the decomposing processes of organic matter in the almost stagnant water just behind the dam.

In the Goczałkowice reservoir cations and anions undergoing transformation resulting from metabolic processes (nonconservative ions) did not change their concentration. Similar results were obtained from the Slapy reservoir (Prochazková et al. 1973), where changes in conductivity, alkalinity, and hardness after passing through the reservoir were slight.

In the water taken from station 2 chloride concentration, i.e. ions which, according to Hannan (1979), are among those compounds that do not undergo biological transformation (conservative ions), was lower than in the inflow. This tendency does not seem to be accidental, for a similar phenomenon of a fall in chlorides was observed in the period 1973—1975 (Table I).

The elimination of nitrates, amounting on the average to 39%, approaches the average results (37%) obtained from 4 dam reservoirs in GDR (Höhne, Hedlich 1976). These authors give the results from the communal water intake. There are also reservoirs in which the amount of nitrates increased in the outflow water (Prochazková et al. 1973, Stanford, Ward 1983).

A considerable fall in total nitrogen in the water after passing the Goczałkowice reservoir confirms the results obtained by other researchers from various reservoirs (Neel et al., Mortimer, Rohlich — after Prochazková et al. 1973). There are also reservoirs, as for example Slapy (Prochazková et al. 1973), where the difference in average concentration of total nitrogen between the inflow and outflow is non-significant.

Small differences in the average content of total phosphorus between station 1 and 2 were also observed in the investigations carried out in the period 1973—1975. Nevertheless, the retention of total phosphorus in the reservoir was at that time from 43% to 71% (Kasza unpubl.). This apparent contradiction results from the inflow of the basic load of phosphorus to the reservoir during an increased flow of water in the river and a basic outflow of water poorer in phosphorus than the water from the sluice of the municipal intake. The annual inflow of total phosphorus to the reservoir in these years was 12—18 tons, while the outflow through the sluice was 0.7—8.1 tons and through the intake 1.6—2.4 tons (Kasza 1977, Kasza unpubl.). However, there are reservoirs in which the amount of total phosphorus in the outflow water decreases quite considerably (Prochazková et al. 1973, Höhne, Hedlich 1976).

In the period 1973—1975 (Kasza unpubl.) the physicochemical composition of the water was investigated in the River Vistula above (station 1) and below the reservoir (station 2). When comparing the percentage values of changes in the physico-chemical parameters of that period with the present ones (Table I), similar regularities are observed for almost all the determined indices, i.e. reaction, oxygen, alkalinity, calcium, magnesium, chlorides, conductivity, nitrogen compounds, and $BOD_5$. Differences in the values of oxidability observed in 1973—1975 were greater than those in the present investigation, while phosphorus compounds underwent smaller elimination in the reservoir at that time.

Starmach (1958) and Uhlmann (1972) qualify dam reservoirs as waters with open metabolism. This depends mainly on the import of various chemical compounds (usually compounds and mineral materials prevail) and the constant outflow of products formed in the reservoir. The transformation of chemical compounds in the Goczałkowice reservoir is clearly visible on the example of organic matter expressed by oxidability, whose values in the outflow water are higher than those in the inflow. This phenomenon was confirmed in the earlier investigation (1973—1975) and also by Wróbel and Bombówna (1976).

The investigations of Höhne and Hedlich (1976) established that between the concentration of organic matter in the inflow (oxidability) and the degree of its elimination in a reservoir there is, above a certain limit, a positive correlation. If the concentrations of organic matter are lower than the threshold value then the correlation is negative, i.e. an increase on organic matter takes place. In the Goczałkowice reservoir the above-mentioned phenomenon occurs. According to Höhne and Hedlich (1976), the threshold value for oxidability is 8 mg $O_2$ $dm^{-3}$; the average value of oxidability of the Vistula water is 3.9 mg $O_2$ $dm^{-3}$.

The increase in some chemical compounds in the reservoir water at station 3 and the decrease of others can be explained not only by the process of secondary pollution in the very slow-flowing water but also by the constant inflow, in this short section, of waters from ponds and from the old and now blank Vistula riverbed draining the nearby fields and woods. The inflow of waters from these sources, with a slightly varied chemical composition visible even with a minimum river flow, as was undoubtedly the case in the investigated period, could have an important meaning in shaping the chemical properties of the water in the investigated section.

At station 4, situated 20 km away from the reservoir, the deterioration of water quality and greatly different chemical composition are caused by the inflow of rivers strongly polluted with sewage. The effect of the reservoir on hydrochemical conditions of the river at this station is such that by stopping the main mass of water for purposes of municipal water supply it inhibits the process of dilution of the inflow waters.

The result of changes in the chemical composition of the River Vistula water below the dam, of the rise in its fertility and pollution already at a distance of 1 km from the structure and further along its course, and of the changes in hydrological conditions in the river is the distinctive character of the bottom macrofauna communities at the investigated stations. Their abundance and zoobenthos biomass also change (Krzyżanek 1986).

To sum up, the effect of the reservoir on the purity of the River Vistula waters is rather negative. In the water below the dam oxidability and $BOD_5$ increase. There is also a rise in the concentration of ammonium nitrogen. In the summer, waters leaving the reservoir are poorer in oxygen (in 13 cases a content below 6 mg $O_2$ $dm^{-3}$ and in this in 7 cases less than 4 mg $O_2$ $dm^{-3}$.

The small outflow of water from the reservoir contributes to the forming of conditions of water stagnation just behind the dam, initiating the processes of secondary pollution. Moreover, the small amount of outflowing water inhibits the process of dilution of the polluted waters of the River Vistula tributaries.

## 6. Polish summary

**Wpływ zbiornika zaporowego w Goczałkowicach na warunki hydrochemiczne rzeki Wisły poniżej zapory (Polska Południowa)**

W latach 1982—1983 badano rzekę Wisłę przed ujściem do zbiornika oraz na trzech stanowiskach poniżej zapory (ryc. 1).

W badanym okresie odpływ wody upustem ze zbiornika był wyjątkowo niski (ryc. 2). Stwierdzono, że zbiornik goczałkowicki w niewielkim stopniu zmienia warunki termiczne rzeki poniżej zapory (ryc. 3). Komponenty składu jonowego wody, jak magnez, wapń, węglany, przepływając przez zbiornik, nie zmieniają swojej koncentracji lub podlegają przekształceniom w niewielkim stopniu (tabela I, ryc. 4).

W okresie letnim w wodzie rzeki poniżej zapory pogłębia się deficyt tlenowy oraz wyraźnie wzrasta ilość azotu amonowego (ryc. 5). Azotyny (ryc. 5), suma mineralnych postaci azotu (ryc. 6) i fosforany (ryc. 7), przechodząc przez zbiornik ulegają obniżce koncentracji. Ze zbiornika wypływają wody uboższe w związki pokarmowe.

W wodzie poniżej zapory wzrasta utlenialność i $BZT_5$ (ryc. 7).

Stwierdzono ujemny wpływ zbiornika goczałkowickiego na czystość rzeki Wisły

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