

## Water quality of two Carpathian rivers, the Soła and Skawa (southern Poland)

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Manuscript submitted July 8, 1988, accepted January 26, 1990

**Abstract** — On the basis of physico-chemical and bacteriological analyses carried out under variable hydrological conditions, the surface water quality in the catchment basins of the River Soła and Skawa is described. Particular attention was paid to the stations at Broszkowice (the Soła) and at Graboszyce (the Skawa), where the water intakes for the drinking water reservoir at Dzieńkówice are located. A detrimental effect of various types of pollution was indicated and ways of action to protect the water supplying the reservoir are presented.

**Key words:** mountain rivers, point, diffuse and nonpoint pollution, drinking water reservoir.

### 1. Introduction

The catchment basins of the Rivers Soła and Skawa have been the subject of numerous investigations. The characteristics of the River Soła basin in respect of its geographical situation, morphology, and gradients were given by Bombówna (1960) and those of the River Skawa by Musiał et al. (1963) and Bombówna (1976). The subsoil and soil cover in both basins were the subject of investigations by Pasternak (1960, 1976), while a detailed hydrography of them was made by Punzet (1971, 1976). Prochal (1960) characterized the process of the water erosion of soils of the upper part of the Soła catchment basin.

20—30 years ago detailed hydrochemical investigations of the Soła catchment basin were made by Musiał et al. (1958), Bombówna (1960), and Maultz (1972), while 15—30 years ago Musiał et al. (1963), Maultz (1972), Bombówna (1976), and Brański. (1980)

carried out the same investigations of the River Skawa. In consequence of the increase in population, improvement of sanitary conditions, economic development, and of no following actions aimed at protecting the water, a considerable increase in the pollution loads occurred, flowing into the waters of the two catchment basins.

The aim of the present work was to analyse the water quality in these basins, carried out in periods of low water level and under the best conditions for estimation of the effect of point and diffuse pollution on the surface waters. Furthermore, in the variable hydrological conditions, together with the effect of non-point pollution, the dependence between the water flow and the parameters of water quality were studied.

In recent years the waters of the lower courses of the Rivers Soła and Skawa have been pumped to supply the reservoir in a worked out sandpit at Dzieńkowice, which in the next few years is to be a main source of drinking water for Upper Silesia, the largest industrial region in Poland. For this reason, particular attention has been paid to the water quality of the rivers at the places, of their entry to the reservoir (the River Soła — the Station at Broszkowice, the River Skawa — the Station at Graboszyce).

## 2. Study area

The Rivers Soła and Skawa are rightbank tributaries of the Vistula. Both are of mountain character, 90% of the catchment basin surface of the Soła and 94% of that of the Skawa being in the Carpathian region. The average annual flow of the Soła in the mouth section is  $22.2 \text{ m}^3 \text{ s}^{-1}$ , while that of the Skawa is  $16.4 \text{ m}^3 \text{ s}^{-1}$ .

Both rivers are characterized by very favourable conditions for the selfpurification process. They generally carry shallow, widely spreading waters with a fast, mainly turbulent, current. The stony or stony-gravelly bottom is a good habitat for the development of epiphytic and benthic organisms. These organisms participate actively in the biochemical changes of the compounds contained in wastes, leading to their mineralization. Conducive to that process is the high oxygenation of the waters of both catchment basins.

The selfpurification of the water is very important, as in the basins of the two rivers numerous point pollutions (PP) occur, carrying large loads of wastes to the surface waters (figs 1, 2). Besides, domestic and agricultural wastes, originating from settlements without sewage systems as diffuse pollution (DP), is a threat to the waters, particularly in the upper courses of the two rivers, and also to those of their tributaries, the Koszarawa, Żylica, Skawica, Stryszawka, and Paleczka.



Fig. 1. Catchment basin of the River Soła. Location of point pollution sources of sampling stations. a — limits of the catchment basin; b — limits of the partial catchment basins of the investigated tributaries; c — sampling stations; d — point pollution sources; e — water intake



Fig. 2. Catchment basin of the River Skawa. Location of point pollution sources and sampling stations. Explanations as in Fig. 1

The basins of the Rivers Soła and Skawa are of agricultural-forest character. The relief, soil cover, and meteorological conditions produce in both basins favourable conditions for water surface erosion of the soil. This process is the main cause of the occurrence of non-point pollution (NP) in southern Poland. At times of higher water level NP causes an increase in suspension, oxidability,  $P_{tot}$ ,  $N-NH_4$ ,  $Fe_{tot}$  concentrations (Stachowicz 1986). Prochal (1960) found that in the upper part of the Soła basin the water surface erosion of soils is considerable and its occurrence on arable land was noted already at slopes over 6%. In the region of forest-covered mountains the erosion is very slight, but in the Żywiec Valley and in the valleys of the upper part of the catchment basin it is strong and occurs almost every where.

As results from the above given data, the catchment basins of the Soła and Skawa exhibit many similar features important from the point of view of the chemical composition of waters. The important feature differentiating the studied catchment basins is the presence on the Soła of the cascade formed by three dam reservoirs.

### 3. Materials and methods

In the Soła catchment basin 8 stations were chosen along the river course and 2 at the mouths of the tributaries Koszarawa and Żylca (fig. 1), and in the Skawa basin samples were collected at 7 stations along the river course and at 3 at the mouths of the tributaries Skawica, Stryszawka, and Paleczka (fig. 2).

The methods of investigating water quality in the two basins differed according to the hydrological conditions. At low water levels when optimum conditions occurred for estimation of PP and DP effects, 5 samples at a time were drawn at all stations. The samplings were carried out in all seasons in the period November 1984 to October 1985. The range of analysis covered 33 physico-chemical and 3 bacteriological parameters.

In periods of medium and high water level, besides PP and DP also NP affects the water quality. The water quality of the River Soła and Skawa were analysed under variable hydrological conditions at two stations, where the intakes for supplying the Dzieńkowice Reservoir are located (the Soła — Station 8 at Broszkowice, and Skawa Station 7 at Graboszyce). The investigations were carried out from November 1984 to June 1986. 41 water samples were drawn from the Soła and 37 from the Skawa. The range of analyses included the following parameters: suspension, oxidability, BOD<sub>5</sub>, N—NH<sub>4</sub>, N—NO<sub>3</sub>, N<sub>org.</sub>, P<sub>tot.</sub>, PO<sub>4</sub>, SO<sub>4</sub>, Cl, Na, K, Ca, Mg, Fe<sub>tot.</sub>, soluble parts, and electrolytic conductivity. The two sets of data obtained were subjected to preliminary statistic estimation and than to regression and correlation analysis, to determine the dependence between the flow and the concentration of the above-mentioned parameters of water quality. The choice of regression function and the method of curve selection were described in a previous paper (Stachowicz 1986). All determinations were carried out according to the methods given by Hermanowicz et al. (1976). Heavy metals were determined by the method of atomic absorption spectroscopy, using a Pye-Unicam Sp-190 apparatus. The number of psychrophilic bacteria at 20°C and of mesophilic ones at 37°C were determined by the dilution method, and the coli titre by the test-tube fermentation method in a lactose medium at 44.5°C. The hydrological data were provided by the Institute of Meteorology and Water Economy

## 4. Results

### 4.1. Water quality at times of low water level

Tables I and II show the results of physico-chemical and bacteriological analysis of the water in the Soła and Skawa catchment basins at times of low water level.

The water reaction in both rivers was alkaline (pH 7.5–9.0). Higher values (pH > 8.0) were found in the summer and autumn months. The highest reaction was recorded below the cascade of the dam reservoirs on the River Soła (Station 5).

The turbidity of water in the Soła had a much wider range (2–75 mg SiO<sub>2</sub> dm<sup>-3</sup>) than that in the Skawa (3–28 mg dm<sup>-3</sup>). Higher values were found in both rivers at the stations below the inflow of a large load of wastes (the Soła: Stations 4, 6, 8, and the Skawa: Station 6). The lowest turbidity of the water was recorded in the spring sections of both rivers and in the Soła at the station below the cascade of reservoirs.

The indices showing the level of water mineralization i.e. total hardness, total alkalinity, soluble parts, total residue, cations (Ca<sup>++</sup>, Mg<sup>++</sup>), and anions (Cl<sup>-</sup>, SO<sup>-</sup>) had much higher value in the Skawa. A considerably raised level of water mineralization was seen at Station 1, as the majority of the above-mentioned parameters reached maximum values here. The mineralization of the water showed a tendency to fall along the course of the Skawa. This regularity did not take place in the Soła.

Nutrients (N—NH<sub>4</sub>, N—NO<sub>2</sub>, N—NO<sub>3</sub>, PO<sub>4</sub>, P<sub>tot.</sub>) occurred in the water of both rivers in small quantities, except for N—NO<sub>3</sub>. Their maximum concentrations were recorded at the stations below the inflow of wastes (the Soła: Stations 4, 6, 8; the Skawa: Stations 6, 7). The tendency to an increase in nutrient contents along the course of both rivers was observed. That regularity was not found, however, in the case of N—NO<sub>3</sub>. The nitrate concentrations were sufficiently high and similar in the two rivers (the Soła:  $1.2 \leq \bar{x} \leq 1.6$ ; the Skawa:  $1.1 \leq \bar{x} \leq 1.4$  mg dm<sup>-3</sup>). The highest concentration of N—NO<sub>3</sub> (3.2 mg dm<sup>-3</sup>) was recorded in the Soła below Żywiec. The maximum P<sub>tot.</sub> concentration was found in the Soła at Station 8 (0.25 mg dm<sup>-3</sup>) and in the Skawa at Station 7 (0.30 mg dm<sup>-3</sup>).

At these stations also the highest N<sub>tot.</sub> concentrations were recorded, occurring in both river waters in fairly high quantities (the Soła:  $0.9 \leq \bar{x} \leq 2.7$ ; the Skawa:  $1.1 \leq \bar{x} \leq 2.3$  mg dm<sup>-3</sup>). Other indices of the content of organic matter assumed in both rivers characteristic values for clean or slightly polluted waters. The highest values of colour, BOD<sub>5</sub>, oxidability, and ether extract were recorded at the

stations below the inflow of municipal sewage (the Soła: Stations 4, 8; the Skawa: Stations 4, 6). Dissolved oxygen occurred in great quantities in both rivers. Oxygenation of the water sporadically fell to about 70%, the mean values, at all stations along the river courses exceeded 90%.

Phenolic compounds occurred in quantities characteristic for slightly polluted waters ( $0-20 \mu\text{g dm}^{-3}$ ). Generally, a higher level of concentrations was recorded in the Skawa, in particular at Stations 4 and 6.

Increased amounts of suspension were observed in the Soła and Skawa at most of the stations, though the mean values did not exceed the characteristic level for clean waters ( $\bar{x} \leq 20 \text{ mg dm}^{-3}$ ). In the Soła at Station 5, below the cascade of dam reservoirs, a 4-times lower value of the suspension than at Station 4 was found.

Among the investigated heavy metals (Zn, Pb, Cd, Cu) zinc occurred in the Soła and Skawa waters in the greatest quantities and cadmium in the smallest. A wide scatter of results was recorded, and frequently in both rivers characteristic values for polluted waters. The highest level of heavy metals was observed below the inflow of municipal sewage (the Soła: Stations 4, 8; the Skawa: Stations 3, 4, 6). In the Soła waters the maximum Zn concentration for that catchment basin was found at Station 1.

The bacteriological indices showed considerable pollution of both rivers, in particular at stations below the inflow of a high load of pollution (the Soła: Stations 4, 6, 8; the Skawa: Stations 6, 7). The lowest number of colonies of psychrophilic and mesophilic bacteria and the most favourable values of coli titre were observed in the Soła water below the cascade of dam reservoirs (Station 5).

The chemical composition of the water of the two largest tributaries of the Soła, the Koszarawa (Station 9) and Żylica streams (Station 10), showed properties similar to the main river with regard to the level of water mineralization, nutrient content, and organic compounds. Pb and phenolic compounds (Station 10) and Cu and  $\text{N-NO}_3$  (Station 9) were among the few parameters whose values exceeded the maximum concentrations observed in the Soła water.  $P_{\text{tot}}$  occurred in lower concentrations in the waters of both stream, whereas in the Koszarawa  $N_{\text{org}}$  also occurred. In the waters of both tributary streams a comparatively low level of bacteriological water pollution was found.

A different situation arose in the largest tributaries of the Skawa, i.e. the Skawica (Station 8), Stryszawka (Station 9) and Paleczka streams (Station 10). The smallest changes in the chemical composition of the water in comparison with the main river were observed at Station 8, where a lower mineralization level and higher  $\text{N-NO}_3$  concentration were recorded. However, at Stations 9 and 10 higher values than those of the Skawa of many parameters were observed, such as turbidity, colour,  $\text{BOD}_5$ , oxidability,  $\text{N-NH}_4$ , indicating

Table I. Ranges and mean values of physico-chemical and bacteriological parameters at the stations along the course of the Soła and at the mouth of the largest tributaries. Length in kilometres a.o. to Drynowska a.o. to Drynowska, Małka (1982) and Anon. (1986)

Parameter	River Soła											Tributaries of R. Soła	
	a	b	c	d	e	f	g	h	i	j	k	l	m
Station	1-76.0 km Rajcza	2-55.0 km Wąpierz	3-51.3 km Żywiec right bank	4-30.2 km Żywiec left bank	5-27.2 km Czerniec Reservoir	6-19.5 km below Kęty	7-8.2 km Grojec	8-0.6 km Brozskowice	9-0.3 km Kozzarawa stream	10-0.4 km Żyłca stream			
Temperature °C	1-18 7.5-8.2 7.9	1-21 7.9-8.6 8.2	1-21 7.9-8.5 8.1	1-21 7.6-8.1 7.9	1-19 7.9-9.0 8.1	1-20 7.8-8.4 8.0	1-20 7.8-8.4 8.0	1-20 7.5-8.1 7.8	1-22 7.8-8.4 8.1	1-19 7.7-8.0 7.9			
pH													
Colour mg Pt dm <sup>-3</sup>	6-9 8	7-12 9	5-19 13	4-21 15	6-20 13	7-22 15	9-20 11	11-23 17	9-20 11	7-16 11			
Turbidity mg SiO <sub>2</sub> dm <sup>-3</sup>	2-11 6	6-16 11	6-17 10	12-30 19	2-19 9	4-7.5 2.5	12-16 14	8-38 23	6-12 9	5-36 11			
Total hardness mval dm <sup>-3</sup>	2.7-3.8 3.0	2.6-3.3 2.9	2.3-2.6 2.5	1.9-2.9 2.5	2.0-3.6 2.6	2.0-3.0 2.4	2.0-3.0 2.4	2.6-3.2 2.9	2.1-2.6 2.4	1.4-2.7 2.1			
Alkalinity mval dm <sup>-3</sup>	1.6-2.2 2.1	1.3-2.0 1.8	1.4-1.7 1.6	1.3-1.8 1.7	1.3-1.6 1.4	1.3-1.7 1.3	1.3-1.6 1.4	1.4-1.7 1.6	1.3-1.8 1.5	0.7-1.2 1.0			
Chloride mg Cl dm <sup>-3</sup>	8.9-16.3 11.3	12.0-22.3 14.5	12.0-15.2 14.9	13.5-23.0 16.7	17.0-21.3 18.3	17.4-25.9 21.4	21.6-29.8 25.8	21.3-22.2 26.7	11.3-19.8 14.7	14.9-29.8 19.3			
Sulphate mg SO <sub>4</sub> dm <sup>-3</sup>	18.7-32.9 24.9	22.6-37.4 28.0	2.5-44.4 26.3	22.0-37.4 28.1	10.5-35.0 25.3	23.2-44.8 30.6	28.2-46.7 35.8	25.9-44.2 34.8	21.6-30.6 24.4	24.1-39.9 29.5			
Calcium mg Ca dm <sup>-3</sup>	26-46 41	21-43 38	23-40 36	29-44 38	25-42 37	32-38 35	34-40 36	38-45 41	30-40 35	20-36 29			
Magnesium mg Mg dm <sup>-3</sup>	3.3-12.4 7.4	4.6-11.1 6.9	6.4-7.3 7.0	5.9-11.1 6.8	3.9-5.9 4.2	2.6-7.8 5.0	4.6-13.0 8.8	3.9-9.8 7.0	3.9-5.9 5.5	4.5-12.4 6.9			
Ammonia mg NH <sub>4</sub> dm <sup>-3</sup>	0.0-0.14 0.06	0.0-0.14 0.12	0.0-0.34 0.12	0.05-0.25 0.19	0.05-0.27 0.18	0.12-0.35 0.34	0.04-0.34 0.20	0.1-0.38 0.22	0.0-0.14 0.13	0.04-0.30 0.12			
Nitrite mg N-NO <sub>2</sub> dm <sup>-3</sup>	0.003-0.014 0.006	0.005-0.014 0.009	0.003-0.014 0.009	0.008-0.018 0.014	0.005-0.021 0.012	0.013-0.049 0.029	0.006-0.024 0.013	0.012-0.028 0.017	0.005-0.016 0.008	0.003-0.017 0.011			
Nitrate mg N-NO <sub>3</sub> dm <sup>-3</sup>	1.1-2.0 1.6	0.2-2.4 1.2	0.2-2.6 1.4	0.2-3.2 1.5	0.3-2.0 1.5	0.5-2.2 1.3	1.2-2.6 1.5	0.7-1.9 1.2	0.2-2.8 1.5	2.6-5.9 3.6			
Organic nitrogen mg N dm <sup>-3</sup>	0.6-1.0 0.9	0.3-3.2 1.5	1.1-2.1 1.5	0.3-4.1 1.8	0.6-2.3 1.4	0.9-2.3 1.3	0.7-1.3 1.0	0.8-4.8 2.7	0.2-1.4 0.7	0.7-1.5 1.1			
Phosphate mg PO <sub>4</sub> dm <sup>-3</sup>	0.00-0.06 0.02	0.00-0.075 0.04	0.00-0.07 0.04	0.0-0.07 0.04	0.0-0.11 0.05	0.09-0.17 0.14	0.04-0.11 0.08	0.05-0.16 0.09	0.0-0.11 0.05	0.0-0.15 0.07			
Total phosphorus mg PO <sub>4</sub> dm <sup>-3</sup>	0.05-0.15 0.09	0.02-0.20 0.10	0.07-0.20 0.11	0.07-0.20 0.11	0.07-0.16 0.09	0.10-0.20 0.16	0.08-0.20 0.14	0.05-0.25 0.13	0.03-0.10 0.06	0.07-0.10 0.08			

cont. tab. I

a	b	c	d	e	f	g	h	i	j	k
Dissolved oxygen mg O <sub>2</sub> dm <sup>-3</sup>	$\frac{9.6-16.5}{12.2}$	$\frac{7.2-19.2}{12.6}$	$\frac{10.9-15.1}{12.8}$	$\frac{8.9-13.7}{10.8}$	$\frac{9.3-17.0}{12.7}$	$\frac{9.3-17.1}{14.2}$	$\frac{10.2-17.3}{14.1}$	$\frac{8.0-14.2}{11.6}$	$\frac{9.4-16.0}{12.6}$	$\frac{9.7-15.8}{12.5}$
Oxygen saturation %	$\frac{72-116}{100}$	$\frac{66-134}{104}$	$\frac{98-132}{110}$	$\frac{79-116}{96}$	$\frac{93-119}{102}$	$\frac{99-151}{126}$	$\frac{101-137}{119}$	$\frac{79-120}{93}$	$\frac{82-150}{109}$	$\frac{86-118}{105}$
PO <sub>5</sub> mg O <sub>2</sub> dm <sup>-3</sup>	$\frac{0.6-4.2}{2.5}$	$\frac{0.0-4.4}{2.3}$	$\frac{1.6-4.0}{2.8}$	$\frac{2.5-13.2}{5.4}$	$\frac{1.8-8.9}{3.6}$	$\frac{1.2-5.0}{3.7}$	$\frac{1.9-4.0}{3.2}$	$\frac{2.7-4.2}{3.4}$	$\frac{0.2-4.0}{2.1}$	$\frac{1.2-5.1}{2.4}$
Oxidability mg O <sub>2</sub> dm <sup>-3</sup>	$\frac{1.5-2.2}{1.6}$	$\frac{1.3-2.5}{1.9}$	$\frac{0.9-2.5}{1.9}$	$\frac{2.2-2.2}{2.6}$	$\frac{1.7-2.3}{2.4}$	$\frac{2.1-4.0}{2.7}$	$\frac{1.6-2.9}{2.4}$	$\frac{3.1-2.7}{3.2}$	$\frac{1.3-2.3}{1.7}$	$\frac{1.4-2.6}{2.1}$
Total residue mg dm <sup>-3</sup>	$\frac{145-212}{183}$	$\frac{161-218}{164}$	$\frac{141-226}{177}$	$\frac{155-240}{196}$	$\frac{155-245}{199}$	$\frac{162-242}{200}$	$\frac{187-225}{231}$	$\frac{189-232}{218}$	$\frac{139-201}{189}$	$\frac{161-226}{188}$
Dissolved matter mg dm <sup>-3</sup>	$\frac{145-197}{177}$	$\frac{156-211}{179}$	$\frac{139-223}{167}$	$\frac{154-234}{189}$	$\frac{168-241}{196}$	$\frac{162-213}{188}$	$\frac{159-201}{209}$	$\frac{190-223}{199}$	$\frac{139-278}{182}$	$\frac{142-226}{180}$
Total suspension mg dm <sup>-3</sup>	$\frac{0-15}{5}$	$\frac{2-7}{5}$	$\frac{2-27}{41}$	$\frac{0-28}{12}$	$\frac{0-5}{5}$	$\frac{0-22}{12}$	$\frac{1-24}{7}$	$\frac{10-43}{19}$	$\frac{0-16}{7}$	$\frac{0-19}{8}$
Total ferrum mg Fe dm <sup>-3</sup>	$\frac{0.09-0.14}{0.06}$	$\frac{0.00-0.12}{0.05}$	$\frac{0.00-0.18}{0.08}$	$\frac{0.00-0.18}{0.10}$	$\frac{0.0-0.23}{0.09}$	$\frac{0.0-0.41}{0.17}$	$\frac{0.0-0.18}{0.09}$	$\frac{0.20-0.40}{0.26}$	$\frac{0.02-0.18}{0.09}$	$\frac{0.0-0.18}{0.10}$
Zinc mg Zn dm <sup>-3</sup>	$\frac{78-232}{167}$	$\frac{57-298}{135}$	$\frac{43-150}{91}$	$\frac{76-137}{112}$	$\frac{53-194}{125}$	$\frac{97-169}{111}$	$\frac{29-247}{103}$	$\frac{57-292}{137}$	$\frac{28-148}{93}$	$\frac{69-254}{137}$
Copper mg Cu dm <sup>-3</sup>	$\frac{1.2-23.2}{8.6}$	$\frac{6.2-34.2}{9.7}$	$\frac{0.0-23.2}{8.1}$	$\frac{0.0-17.8}{9.0}$	$\frac{1.6-89.0}{29.3}$	$\frac{0.0-37.1}{17.4}$	$\frac{2.8-24.7}{10.6}$	$\frac{0.0-21.0}{11.1}$	$\frac{1.4-17.8}{7.4}$	$\frac{0.0-7.6}{28.4}$
Lead mg Pb dm <sup>-3</sup>	$\frac{0-44}{9}$	$\frac{0-137}{48}$	$\frac{0-112}{42}$	$\frac{0-192}{94}$	$\frac{0-82}{26}$	$\frac{0-94}{20}$	$\frac{0-112}{45}$	$\frac{0-269}{74}$	$\frac{0-212}{51}$	$\frac{0-36}{14}$
Cadmium mg Cd dm <sup>-3</sup>	$\frac{0.0-6.2}{3.7}$	$\frac{0.0-8.6}{7.6}$	$\frac{0.0-11.2}{5.0}$	$\frac{0.0-7.2}{18.0}$	$\frac{0.0-11.1}{5.9}$	$\frac{0.0-13.8}{8.0}$	$\frac{0.0-11.1}{4.3}$	$\frac{0.0-16.5}{8.0}$	$\frac{0.0-10.0}{5.2}$	$\frac{0.0-12.4}{6.5}$
Phenolic compounds mg dm <sup>-3</sup>	$\frac{0-7}{2}$	$\frac{0-7}{2}$	$\frac{0-7}{3}$	$\frac{0-10}{3}$	$\frac{0-6}{2}$	$\frac{0-5}{1}$	$\frac{0-2}{0}$	$\frac{0-7}{1}$	$\frac{0-22}{7}$	$\frac{0-6}{2}$
Ether extract mg dm <sup>-3</sup>	$\frac{6.4-9.9}{7.5}$	$\frac{5.2-7.8}{6.5}$	$\frac{5.2-7.6}{6.1}$	$\frac{2.4-12.5}{8.0}$	$\frac{3.6-8.6}{5.1}$	$\frac{6.3-10.7}{6.3}$	$\frac{4.9-8.2}{6.1}$	$\frac{1.8-7.2}{4.7}$	$\frac{5.0-8.8}{5.8}$	$\frac{2.9-9.2}{5.7}$
Total number of psychrophilic bacteria	10-900	300-1600	560-12000	1200-7000	240-480	5000-15000	620-900	1500-4000	900-1500	900-1500
Total number of mesophilic bacteria	6-450	17-300	36-150	450-1200	1-27	110-1800	18-40	28-460	28-49	24-29
Faecal coliform titre	2-0.004	0.2-0.02	0.08-0.04	0.02-0.004	17-0.4	0.04-0.0002	4-0.002	0.02-0.002	0.2-0.002	0.4-0.04

Table II. Ranges and mean values of physico-chemical and bacteriological parameters at the stations along the course of the Stara and at the mouth of the largest tributaries, length of the river in kilometres acc. to Dynowski, Miazka (1932) and Anon. (1956)

Parameter	R I V E R S K A W A										Tributaries of R. Skawa		
	a	b	c	d	e	f	g	h	i	j	k	l	m
Station	1-89.0 km Spytkowice	2-57.0 km below Maków	3-44.4 km below Maków	4-37.8 km below Sucha	5-24.4 km above Madowice	6-17.0 km below Madowice	7-10.2 km Gracowoyce	8-0.5 km Skawica stream	9-0.1 km Stryzawke stream	10-0.3 km Palciska stream			
Temperature °C	1-15 7.8-8.2	1-18 7.7-8.6	1-18 8.2-8.7	1-18 8.1-8.8	1-18 8.1-8.8	1-19 7.6-8.2	1-19 7.9-8.5	1-17 7.7-8.5	1-17 7.4-8.5	1-17 7.4-8.5	1-18 7.8-8.2		
pH	8.0	8.1	8.3	8.3	8.3	8.0	8.2	8.1	8.1	8.1	8.2		
Colour	5-21 14	8-21 13	9	8-32 18	9	8-31 14	9-20 14	2-8 7	10-30 18	16-33 23	7-8-8.2		
Turbidity	2-15 8	6-15 9	7-22 13	8-20 13	11	8-28 15	11-18 14	5-16 10	8-34 22	36-140 86	16-33 23		
Total hardness	4.4-5.8 4.9	2.8-4.6 4.1	3.0-3.8 3.4	2.5-3.7 3.2	3.0	2.5-2.8 3.5	2.2-4.1 3.4	2.2-4.1 2.8	1.8-3.4 2.8	2.8-3.4 3.2	2.8-3.4		
Alkalinity	3.6-5.1 4.4	2.4-3.3 2.9	1.9-2.8 2.5	1.8-2.8 2.2	3.0	1.7-2.7 2.2	1.7-2.4 2.1	1.3-2.0 1.7	1.4-3.0 2.1	2.1-2.6 2.4	2.1-2.6		
Chloride	17.7-58.8 29.0	18.4-21.3 19.5	17.0-26.2 21.0	18.1-48.6 21.0	21.5	14.9-26.9 22.5	20.0-29.1 22.5	10.7-20.5 19.3	17.0-24.1 19.4	46.5-93.9 65.7	46.5-93.9		
Sulphate	24.4-56.0 44.7	33.2-45.0 39.6	29.6-41.6 35.9	27.1-47.1 34.4	34.7	27.8-56.8 38.1	28.4-42.6 35.5	21.6-31.3 25.2	24.5-41.2 31.7	33.1-54.1 52.1	33.1-54.1		
Calcium	69-92 82	50-62 60	44-54 50	39-58 47	46	38-50 45	36-58 49	27-42 36	32-54 41	49-53 54	49-53		
Magnesium	11.1-15.6 13.3	5.2-11.7 7.6	3.0-19.5 10.2	2.6-13.7 7.8	5.7	7.8-13.0 10.3	6.2-19.0 10.0	2.8-13.6 7.3	2.6-11.1 6.6	2.7-9.1 7.1	2.7-9.1		
Ammonia	0-0-0.41 0.18	0.02-0.41 0.20	0.05-0.70 0.26	0.22-0.78 0.44	0.32	0.09-0.65 0.32	0.16-0.41 0.25	0.10-0.31 0.17	0.17-1.78 0.70	1.06-8.20 3.40	1.06-8.20		
Nitrite	0.003-0.030 0.013	0.011-0.012 0.007	0.008-0.016 0.010	0.015-0.027 0.019	0.015	0.003-0.024 0.019	0.009-0.040 0.021	0.003-0.008 0.005	0.009-0.248 0.055	0.007-0.038 0.020	0.007-0.038		
Nitrate	1.28-1.48 1.40	0.72-1.54 1.30	0.48-1.54 1.10	0.16-1.64 1.12	1.16	1.16-2.16 1.44	0.52-1.64 1.10	1.14-2.56 1.72	0.0-1.84 1.13	0.52-1.72 0.97	0.52-1.72		
Organic nitrogen	1.2-3.4 2.3	0.6-1.6 1.1	1.1-2.5 1.8	1.0-1.8 1.3	1.3	1.5-2.5 2.0	0.8-3.9 2.2	0.8-1.4 1.0	0.6-1.4 1.1	1.0-2.4 1.7	1.0-2.4		
Phosphate	0.0-0.13 0.05	0.0-0.13 0.06	0.0-0.07 0.04	0.0-0.21 0.09	0.09	0.03-0.17 0.10	0.10-0.17 0.12	0.0-0.20 0.07	0.02-0.45 0.18	0.0-0.15 0.06	0.0-0.15		
Total phosphorus	0.12-0.15 0.13	0.03-0.10 0.06	0.05-0.06 0.055	0.0-0.13 0.06	0.15	0.07-0.22 0.16	0.04-0.30 0.19	0.10-0.15 0.12	0.10-0.30 0.18	0.07-0.15 0.10	0.07-0.15		

g	b	o	d	e	f	g	h	i	j	k
Dissolved oxygen mg O <sub>2</sub> dm <sup>-3</sup>	7.9-14.2 11.3	10.3-18.2 14.0	2.5-20.1 14.6	10.9-18.2 13.3	2.9-18.4 12.8	2.1-18.6 12.9	2.9-17.3 13.2	10.1-17.5 13.5	10.1-19.1 12.3	7.5-13.2 9.8
Oxygen saturation %	70-99 80	91-133 111	88-141 116	89-133 113	97-129 108	84-131 109	108-122 112	97-123 110	71-134 104	71-104 89
BOD <sub>5</sub> mg O <sub>2</sub> dm <sup>-3</sup>	0.4-6.1 2.4	1.2-6.4 2.3	0.6-6.0 4.0	2.4-8.8 5.0	1.4-5.4 2.6	1.8-10.6 5.0	1.7-6.4 3.8	1.8-5.4 3.1	2.4-35.5 11.4	4.6-28.5 15.9
Oxidizability mg O <sub>2</sub> dm <sup>-3</sup>	1.5-3.8 3.0	1.7-3.1 2.4	1.6-2.8 2.2	2.2-6.5 4.3	1.3-3.7 2.4	1.4-6.2 2.8	2.2-3.5 2.9	1.1-2.4 1.6	2.5-14.5 6.0	5.3-22.7 12.9
Total residue mg dm <sup>-3</sup>	277-440 394	216-262 243	189-288 232	146-314 220	180-254 214	166-258 220	186-252 224	134-182 160	162-270 206	235-442 325
Dissolved matter mg dm <sup>-3</sup>	266-436 347	212-261 247	183-284 222	140-293 212	161-236 207	163-258 211	169-255 213	127-178 155	161-240 197	225-409 305
Total suspension mg dm <sup>-3</sup>	4-11 6	0-5 2	5-20 10	0-21 8	0-22 7	0-38 19	0-38 11	0-10 5	0-22 9	4-20 20
Total ferrum mg Fe dm <sup>-3</sup>	0.0-0.10 0.04	0.0-0.06 0.03	0.0-0.11 0.05	0.0-0.18 0.09	0.02-0.23 0.11	0.0-0.22 0.10	0.06-0.18 0.09	0.0-0.10 0.05	0.0-0.23 0.12	0.08-0.36 0.13
Zinc mg Zn dm <sup>-3</sup>	49-120 51	58-124 54	20-88 70	29-647 171	38-128 84	27-137 99	54-213 103	41-84 64	34-96 64	77-113 93
Copper mg Cu dm <sup>-3</sup>	2.5-19.3 9.1	7.2-27.1 15.2	0.9-17.7 6.6	1.3-21.2 2.1	0.0-126.6 32.4	2.8-27.4 16.8	2.8-23.3 13.1	0.9-11.3 5.6	0.0-176.0 80.0	2.5-23.3 11.0
Lead mg Pb dm <sup>-3</sup>	0-158 43	0-112 59	0-131 65	0-62 14	0-156 43	0-187 48	0-200 53	0-250 82	0-137 41	0-162 78
Cadmium mg Cd dm <sup>-3</sup>	0.0-6.3 3.1	0.0-12.4 7.1	0.0-19.6 3.7	0.0-20.6 5.0	0.0-19.6 5.9	0.0-21.6 6.3	0.0-10.0 3.5	0.0-11.1 4.3	0.0-13.6 4.3	0.0-2.5 4.0
Phenolic compounds mg dm <sup>-3</sup>	0-6 2	0-6 3	0-5 1	0-35 9	0-6 1	0-23 7	0-22 6	0-5 2	0-8 3	1-40 20
Ether extract mg dm <sup>-3</sup>	2.0-5.8 4.1	2.8-6.4 4.5	1.0-6.4 4.3	0.6-10.2 6.7	0.6-8.4 4.3	1.2-7.6 4.2	2.6-8.0 3.2	2.6-8.0 5.1	4.0-8.8 5.9	4.2-6.2 5.2
Total number of psychrophilic bacteria	540-1200	480-900	47-1500	1500-2000	47-1500	8000-15000	4000-15000	57-400	300-7500	580-7500
Total number of mesophilic bacteria	22-48	8-32	14-36	28-44	6-24	850-8000	60-4500	3-19	560-5600	11-750
Faecal coliform titre	0.04-0.4	2-0.2	0.04-0.08	0.8-0.08	17-0.02	0.004-0.0004	0.04-0.004	8-0.2	0.004-0.0002	4-0.002

considerable pollution of the water. Furthermore, higher concentrations of  $PO_4$ ,  $N-NO_2$ , and Cu were found at Station 9, while at Station 10 concentrations of chlorides, sulphates, phenolic compounds, Pb, suspension, and soluble parts appeared. At both stations considerable bacteriological pollution of the water was found, being in the Stryzawka at Station 9, the highest noted in the whole Skawa basin.

#### 4.2. Water quality under variable hydrological conditions

The regression and correlation analyses showed a strong functional dependence between the flow and concentrations of the water quality parameters given in Tables III and IV. In the set of data concerning the Soła, lower values of correlation coefficients ( $r$ ) are noteworthy,

Table III. Values and ranges of concentration ( $mg\ dm^{-3}$ ) of water quality parameters of the River Soła taken for supplying the Dziecko-wice Reservoir (Station 8).  $r$  - correlation coefficient; A, B, C, D - explanations in the text

Parameter	r	Concentrations calculated for discharges ( $m^3 s^{-1}$ )			
		A: 3.12	B: 9.1-63.4	C: 63.5-75.2	D: 3.0-30.0
Total suspension	0.578	16.9	21.3-61.4	61.5-70.2	16.8-36.7
BOD <sub>5</sub>	0.364	3.3	2.8-2.5	2.5-2.5	3.3-2.6
Oxidability	0.368	3.3	3.8-4.7	4.7-4.8	3.2-4.4
Nitrate	0.407	1.8	2.8-3.7	3.7-3.8	1.7-3.5
Organic nitrogen	0.466	2.4	1.9-2.4	2.4-8.4	2.4-1.1
Total phosphorus	0.499	0.17	0.16-0.29	0.29-0.67	0.17-0.16
Chloride	0.668	26.6	25.4-16.5	16.5-12.0	26.6-21.5
Calcium	0.543	40.9	38.8-33.7	33.7-47.2	41.0-33.7
Magnesium	0.416	7.3	5.8-5.1	5.1-5.0	7.4-5.2
Total ferrum	0.456	0.17	0.24-0.51	0.51-0.19	0.16-0.44
Dissolved matter	0.328	218	209-185	185-169	212-199
Conductivity $\mu s\ cm^{-1}$	0.508	293	279-234	234-297	293-244

Table IV. Values and ranges of concentration ( $mg\ dm^{-3}$ ) of water quality parameters of the River Skawa taken for supplying the Dziec-kowice Reservoir (Station 7).  $r$  - correlation coefficient; A, B, C, D - explanations in the text

Parameter	r	Concentrations calculated for discharges ( $m^3 s^{-1}$ )			
		A: 2.30	B: 5.13-27.0	C: 27.1-104	D: 2.0-30.0
Total suspension	0.910	12.8	14.8-46.8	47.0-218.7	12.6-53.5
BOD <sub>5</sub>	0.689	4.2	3.9-2.5	2.5-8.5	4.3-2.5
Oxidability	0.759	3.2	3.4-5.1	5.2-13.1	3.2-5.4
Nitrate	0.658	1.6	1.7-2.8	2.8-3.4	1.5-2.9
Chloride	0.748	28.4	21.8-17.4	17.4-16.8	30.2-17.3
Calcium	0.781	56.7	45.8-38.7	38.7-37.6	59.7-30.5
Magnesium	0.465	9.8	9.1-5.1	5.1-4.3	9.9-4.7
Total ferrum	0.931	0.11	0.11-0.33	0.34-2.15	0.11-0.40
Dissolved matter	0.523	241	211-192	192-189	249-192
Conductivity $\mu s\ cm^{-1}$	0.708	352	295-257	257-252	368-257

the weaker interrelation between the variables is caused by the disturbance of free flow of the Sola water owing to the cascade of dam reservoirs and the control of the water outflow from these reservoirs.

As the flow of water in the Skawa increased, a tendency to higher oxidability and suspension and total ferrum concentrations was observed (fig. 3). This trend reflects the influence of NP caused by the surface runoff and leaching of the soil. The shape of the curve depicting changes of BOD<sub>5</sub> value, showed a strong effect of PP and DP in times of low flows. With medium flows, the noticeable downward trend of BOD<sub>5</sub> was caused by the dilution of pollution of waste origin. In the range of high flows the increase in BOD<sub>5</sub> values was at first slow but then became very rapid (fig. 3). The chloride concentrations reached maximum values with low flows when the

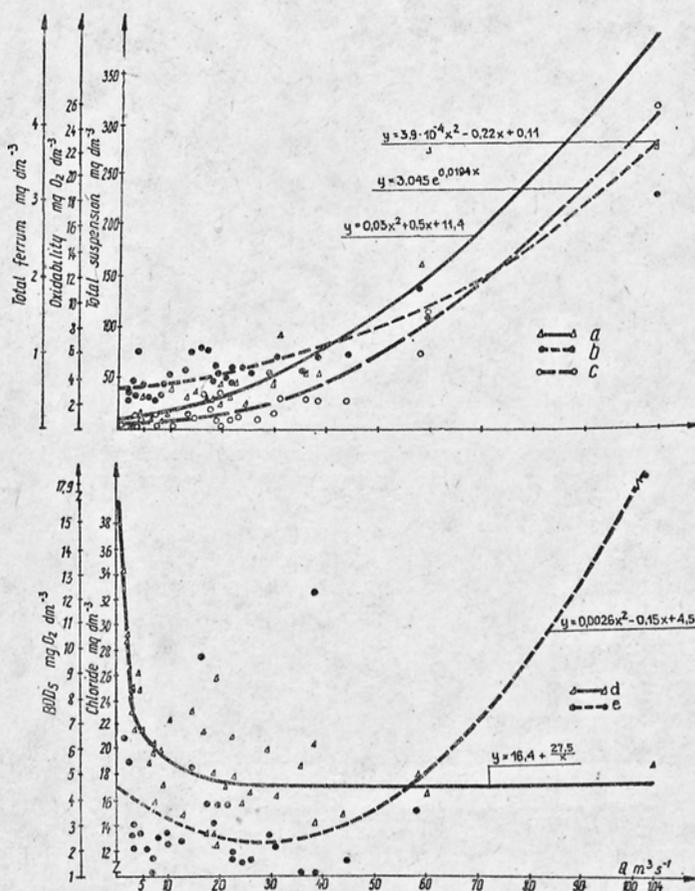


Fig. 3. Changes of suspension concentration values (a), oxidability (b), Fe<sub>tot.</sub> (c), chlorides (d), and BOD<sub>5</sub> (e) with rising flow in the River Skawa

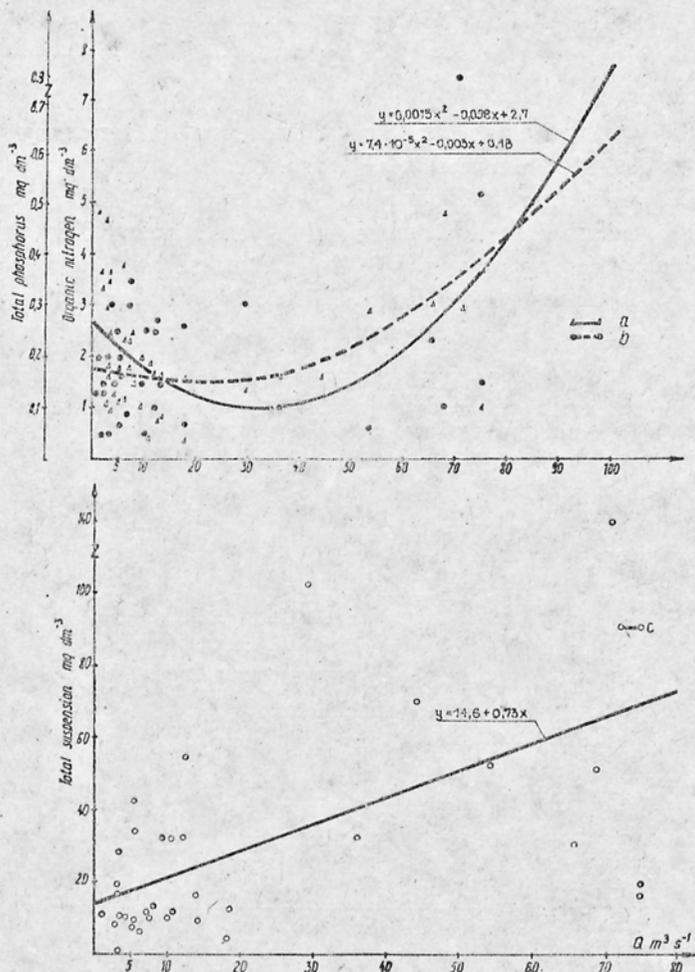


Fig. 4. Changes of  $N_{org}$ . (a),  $P_{tot}$ . (b), and suspension concentrations with rising flow in the River Soła

water quality of the Skawa was considerably affected by municipal sewage from PP and DP. As the flow increased the chloride quantities were at first rapidly and then slowly reduced (fig. 3). A similar character of changes of concentration values was observed for calcium, soluble parts, and electrolytic conductivity. In the Soła water changes of concentration values occurring with increased flow was of somewhat different nature. Above all, a much weaker tendency to increase in the suspension concentration was noted (fig. 4), mainly caused by the inflow of NP from the drainage basin. This is because in the dam reservoirs of the Soła cascade the sedimentation of the eroded soil material occurs in the upper part of the basin. The course of  $N_{org}$ .

and  $P_{tot.}$  changes were interesting (fig. 4). In both cases a downward tendency of concentrations was observed in low flow ranges, while at high flows a strong increase, in  $N_{org.}$  and  $P_{tot.}$  concentrations, caused by NP, took place.

The values represented in Tables III and IV complement the above-mentioned changes of water quality in both rivers. On the basis of hydrological data and regression equations, the values of concentration parameters were calculated, corresponding to characteristic flows of low, medium, and high level. The values given in column A (Tables III, IV) correspond to the medium low flows (MLQ). For the zone of medium level (column B) the concentration values corresponding to the lower and upper limits of the annual mean water (AMQ) were calculated. For the zone of high level (column C) concentrations were calculated for the lowest flow within this zone as well as for the highest among those flows from which water samples were drawn for the investigation. In column D are given the concentration values which should be expected with the most frequent flows.

## 5. Comparison of the present results with the previous investigations

The results of physico-chemical investigations carried out in the catchmentbasin of the Soła in 1955 by Musiał et al. (1958) and in 1959 by Bombówna (1960) served in carrying out the analysis of water quality changes during 30 years. For comparison were chosen the results analogical to the season of the year, hydrological conditions (low levels) and stations. It was found that the water quality of the Soła had deteriorated along its whole course. The strong increase in pollution of the Soła was shown by the following indices: colour,  $BOD_5$ , chlorides,  $N-NH_4$ , and  $N-NO_3$ . It is especially alarming that the greatest increase in pollution of the Soła was observed in its lower course, below Kęty. The very strong increase in  $N-NO_3$  concentrations in the water of the Żylica stream (at the mouth of the Tresna Reservoir) indicated the degrading effect of DP from the upper part of the stream basin (Szczyrk):

A similar tendency to increased pollution was observed in the River Skawa, when analysing the results of investigations carried out by Musiał et al. (1963) and Bombówna (1976) in 1956/1957 and 1970. The data given in the paper of Musiał et al. (1963) characterized in a descriptive way the state of water purity in the Skawa catchment basin, while Bombówna (1976) gave minimum and maximum values of water quality parameters. Comparison of those data with the present results showed that during 15 years, the maximum values of  $BOD_5$ ,  $PO_4$ , chlorides, sulphates,  $N-NH_4$ , and  $Fe_{tot.}$  had increased. This was

particularly strong in the case of the four first parameters, showing the deteriorious effect of municipal sewage. Among the stations analysed the highest increase in pollution occurred in the Paleczka and Stryszawka streams, as well as in the River Skawa below Wadowice and Zembrzyce. For example: BOD<sub>5</sub> values in the above-mentioned streams increased 10 times during 15 years, and N—NH<sub>4</sub> concentrations 10—30 times.

The content of heavy metals has had an upward tendency during 13 years. In comparison with the results of investigations carried out by Pasternak et al. (1971) it was found that Pb, Zn, and Cd concentrations in the Soła and Skawa waters increased several times. In this period Cu concentrations increased 20—30 times.

## 6. Discussion

Comparative analysis of the chemical composition of the Rivers Soła and Skawa indicates higher mineralization of the Skawa water, which was observed both at low and increased levels. This observation is supported by the investigations of Maulitz (1972), who found that mean values of electrolytic conductivity, carbonates, chlorides, sulphates, Ca, Mg, Na, and K were higher in the Skawa than in the Soła.

The waters of the Soła and Skawa catchment basins were affected by pollution from numerous point and diffuse sources. Owing to the favourable conditions for the selfpurification process, the detrimental effect of sewage occurred at a few or not more than twenty kilometer sections of the river course below the inflow of concentrated sewage.

The Soła and Skawa water intakes for supplying the Dzieńkowice Reservoir under conditions of most frequent flows, lasting for 9—10 months of the year, were distinguished by a low content of organic and biogenic compounds, with the exception of N—NO<sub>3</sub>. The chemical composition of these waters showed differentiation, depending on the hydrological conditions. In periods of low level the Skawa water at Graboszyce was distinguished by a generally better quality. In comparison with the Soła, lower values of suspension, turbidity, colour, N<sub>org.</sub> Fe, Zn, Pb, Cd, and coli titre were found, while somewhat higher were the concentrations of biogenous components (Tables I, II). At higher levels the Soła water at Broszkowice indicated higher quality, much lower values of suspension, and also of BOD<sub>5</sub>, oxidability, and Fe<sub>tot.</sub> being observed (Tables III, IV).

The strong sewage inflow from Oświęcim, situated 4 kilometres away from Broszkowice, was the main cause of the worse quality of the water of the River Soła during low levels. Its better quality at higher levels is justified by the cascade of dam reservoirs on this river. In

the reservoirs selfpurification processes occur, consisting mainly in biochemical oxidation of the pollution (PP, DP) originating from Żywiec, Węgierska Górka, and Szczyrk as well as in the sedimentation of soil material eroded from the upper part of the basin (NP). According to Brański (1980), the reservoirs of the Soła cascade significantly limit the discharge of sediment carried from the basin.

The damming of the Soła waters caused a visible improvement in the sanitary condition illustrated by the bacteriological indices. As the result of the oxidation processes of organic pollution, a considerable reduction of BOD<sub>5</sub> value, oxidability, ether extract, and phenolic compounds was observed. Similar observations were made by Grzbiela and Kudela (1973). Also Kyselowa and Krzeczowska (1974), when investigating periphyton and seston of the Soła as well as plankton of the dam reservoirs, found an improvement of the purity of the water after flowing over the cascade of reservoirs.

The concentrations of heavy metals (Cu, Zn, Pb) in the Soła and Skawa waters were higher than the values determined for clean waters (Moore, Ramamoorthy 1984), only Cd concentrations not exceeding them. In neither basin did there occur any great sources of point pollution, discharging sewage containing heavy metals. Hence, it is suspected that air pollution transported to the region of the basin from Upper Silesia and Czechoslovakia is the main reason of pollution by these compounds of the Soła and Skawa waters.

The diffuse pollution (DP) was clearly influenced by the chemical composition of the streams flowing into the Soła and Skawa. When a concentration of DP occurred in the upper part of the stream basin, higher N—NO<sub>3</sub> concentrations were observed at the mouth section (the Skawica stream — DP from the village Zawoja, the Żylicza stream — DP from Szczyrk). In the Paleczka stream, where the inflow of sewage took place in its lower course, high N—NH<sub>4</sub> concentrations were observed in the mouth sector.

In order to protect the waters of the Rivers Soła and Skawa and indirectly also the Dzieńkowice Reservoir, it is imperative to limit to a maximum the deleterious effect of PP upon the waters of Soła catchment basin, above all in the region of Kęty and Żywiec, as well as upon the Skawa at Wadowice, Zembrzyce, and Sucha Beskidzka.

The activities connected directly with the protection of the Dzieńkowice Reservoir should consist in elimination of the sewage inflow to the Soła from Oświęcim, since its mineralization takes place in the reservoir. Moreover, it would be advisable to control the water consumption, i.e. in periods of low water level it would be more advantageous to take it from the Skawa and at medium and higher levels from the Soła.

## 7. Polish summary

### Jakość wody dwóch rzek karpackich: Soły i Skawy (południowa Polska)

Przedstawiono charakterystykę dorzeczy Soły i Skawy wykazując, że istnieje tam znaczne zagrożenie ze strony zanieczyszczeń punktowych (ZP) i rozproszonych (ZR), a równocześnie występują bardzo korzystne warunki do przebiegu procesu samooczyszczania. Cechy fizyczno-geograficzne zlewni sprzyjają powstawaniu zanieczyszczeń obszarowych (ZO).

Metody badań były zróżnicowane w zależności od warunków hydrologicznych. W okresach stanów niskich, gdy najsilniejszy był wpływ ZP i ZR, analizowano jakość wód na 20 stanowiskach w dorzeczu Soły i Skawy (ryc. 1, 2). Wyniki tych badań zamieszczono w tabelach I i II. Wskazują one na dużą efektywność procesów samooczyszczania, bowiem wody obu rzek wykazały ogólnie niewielki poziom zanieczyszczenia. Badania jakości wody przy stanach niskich, średnich i wysokich prowadzone były na stanowiskach w Broszkowicach (0,6 km biegu Soły) oraz w Graboszycach (10,2 km biegu Skawy). W tych przekrojach zlokalizowane są ujęcia wód Soły i Skawy, przeznaczone do zasilania zbiornika wody pitnej w Dzieńkowicach. Metodą regresji i korelacji określono tendencję zmian wartości stężeń parametrów obrazujących dopływ ZP, ZR i ZO do wód Soły i Skawy (ryc. 3, 4).

Stwierdzono, że kaskada zbiorników zaporowych na Sole wpływa dodatnio na stan czystości wód tej rzeki. W tabelach III i IV zamieszczono wartości oraz zakresy stężeń parametrów jakości wody, odpowiadające przepływom charakterystycznym dla stanów niskich, średnich i wysokich w Sole i Skawie.

Posługując się danymi z literatury wykazano, że jakość wody w dorzeczu Soły i Skawy w ciągu 15–30 lat uległa pogorszeniu.

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