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Aquatic Macrophytes as Biomonitors of Pollution by Textile Industry

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Aquatic plants play a crucial functional role in aquatic ecosystems by taking up, storing, releasing and depositing nutrients (Fairchild et al. 1998). These plants may be able to serve as a sink for toxic chemicals, removing and possibly metabolising them before they can impact these and other biota in the ecosystem (Karen et al. 1998). Aquatic macrophytes have also aroused great interest because of their ability to sequester heavy metals (Lee et al. 1998) and have been commonly recommended for use in regulatory testing (Fairchild et al. 1998). Anthropogenic disturbance, such as the introduction of toxicants into aquatic systems, can alter the structure and function of their communities (Fairchild et al. 1998). Investigations of macrohydrophytes have reveiled spatial differences and time trends in concentrations of heavy metals which are valuable for the identification of sources of pollution (Berg and Steinnes 1997; Viskari et al. 1997).

The area along the Brzeczek river in Poland houses a textile industry that produces sewage rich in Cu, Cr and Zn, dyes containing sulphur compounds, fats, mineral oils, soaps, sulphuric and other inorganic acids, organic acids, CS_2, different forms of nitrogen (especially ammonia nitrogen), alkali lye and chlorides. Although the sewage is being purified by a cleaning system (mechanical and bacteriological), the treated wastewater effluents still cause serious pollution, accompanied by discoloration (red and dark blue) of the water in the river. The low efficiency of this purification system is partly caused by overload of the "sprinkling bed" (percolating filter with bacteria). In the present study we used native species of aquatic macrophytes to monitor the pollution of the Brzeczek river (Sowie Mountains, Poland) by the local textile industry.

MATERIALS AND METHODS

Investigations took place in the Brzeczek river (Fig. 1), a mountainous left side tributary of the Pilawa river, which together with the Bystrzyca river forms part of the Odra river catchment area in the Sowie mountains (part of the Sudety Mountains, SW Poland).

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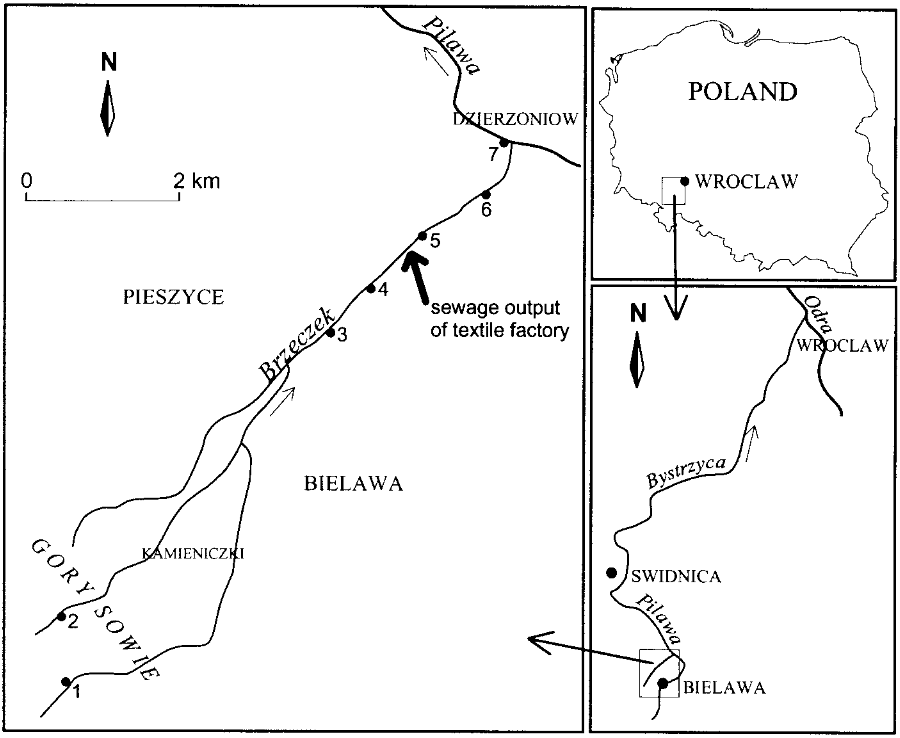

Figure 1. Location of the sampling sites and sewage outlet along the Brzeczek river

Seven sampling sites were selected, where the macrophytes were preferably available and abundant (Fig. 1):

Sites 1 and 2 were selected as controls for water and sediment in the forested mountainous and relatively unpolluted source area of the stream.

Sites 3 and 4 were surrounded by agricultural fields, pastures and small industry.

Site 5 was located on short distance downstream from the sewage output of the textile industry where plants were absent.

Site 6 is located at about 1 km downstream from the sewage outlet.

Site 7 was situated in the Pilawa river, just below the mouth of the Brzeczek.

Samples of water and sediment were collected three times in the period from June to August. All available plant species were collected in ten replicates during the last sampling of water and sediment. The water samples were filtered using a Whatman glass microfibre filter (GF/C) and collected in bottles, which were kept on ice. Sediments were collected with a small core drill from a depth of 0-10 cm. Fresh water and sediment samples were used for direct (potentiometric) pH measurement. The pH in the sediment was measured in a mixture of one volume of sediment and one volume of distilled water (McLean, 1982).

After collection, leaves of the examined plants, or in the case of *Platyhypnidium riparioides*, *Callitriche verna* and *Spirogyra* sp. the whole plant, were washed thoroughly and immediately dried, together with the sediment samples, at 60 °C for preservation. Dried sediment and plant samples were homogenized in the laboratory.

The sampled plants were divided into submersed and emergent plants. Submersed plants included *Batrachium aquatile* (L.)Dum, *Potamogeton pectinatus* L., *Myriophyllum verticillatum* L., *Callitriche verna* L., the moss *Platyhypnidium riparioides* (Neck.)Fleisch. and the alga *Spirogyra* sp. Emergent plants included *Epilobium palustre* L., *Polygonum mite* Schrk., *Bidens frondosus* auct. and *Veronica anagallis* L. The distribution of the plants over the sampled sites is given in Table 3.

The water, sediment and replicate plant samples were analysed separately.

The following parameters were measured in the water samples (detection limits indicated between brackets): V (6.7 µg/L), Cr (2 µg/L), Co (4 µg/L), Mn (0.3 µg/L), Al (1.5 µg/L), Ba (0.07 µg/L), Zn (0.9 µg/L), Fe (1.5 µg/L), Ca (0.03 µg/L), Mg (0.1 µg/L) and K (10 µg/L) (ICPES Spectroflame SIMSFQ), Ni (5 pg), Cd (0.5 pg), Cu (1.8 pg) and Pb (2 pg) (AAS with graphite furnace Philips PU 9200X), phosphate (5 µg/L), nitrate and nitrite (both 2 µg/L), ammonia (2 µg/L) and chloride (300 µg/L) (colorimetric) and sulphate (2500 µg/L) (nephelometric) using a Technicon Autoanalyzer System II TRAAC 800.

Sediments were extracted for PO_4 by means of a solution of 0.3 *M* sodium citrate and 1 *M* sodium bicarbonate (Olsen and Sommers 1982) and for Ca, Mg and K by means of a 1 *N* ammonium acetate solution (Knudsen and Peterson 1982).

Plant and soil materials (200 mg) were digested in duplicate with nitric acid (65%, reagent grade) and hydrogen peroxide (30%, reagent grade), during which temperatures were raised to about 95 °C, until evolution of nitrous gas stopped and the digest became clear. The plant and soil digests (after dilution to 10 ml) and soil extracts were analysed for V, Fe, Cr, Co, Mn, Al, Cu, Ni, Zn, Cd and Pb, while the plant digests and soil extracts were additionally analysed for Ca, Mg, K, and P using the methods described above. Dried and pulverised plant and sediment samples were used for total N (detection limit 10 mg/kg) and S (detection limit 10 mg/kg) (Carlo Erba NA-1500 CNS Analyzer).

All elements were measured against standards (BDH Chemicals Ltd, reagent grade) and blanks prepared in 0.5 M nitric acid. All analyses were done in duplicate (the analytical standard deviation was less than 4%). All results for sediment and plants were calculated on a dry weight basis.

The reproducibility of these procedures, as compared to the results of an interlaboratory study on digesting and analysing reference material (Wageningen Evaluating Programmes for Analytical Laboratories, WEPAL), was found to be 100±4 %. The reference material consisted of pine needles and leaves of *Nymphaea alba*.

At each sampling site, the following biometrical features were measured: length of plants, number of leaves, length and width of the longest leaf and, in the case of *Platyhypnidium riparioides*, length of gametophytes.

Differences between sampling sites in the mean concentrations of elements in the water were evaluated by one-way analysis of variance using the F Snedecor test.

The least significant difference was calculated (Parker 1983). The normality of analysed features was checked by the chi square test (Parker 1983).
For each of the groups of submersed and emergent plants, Pearson correlations were calculated to examine the relationships between the concentrations of elements in water and in plants (Parker 1983).
Additionally, Pearson correlations between individual features of *Polygonum mite* and chemical characteristics of its environment were calculated, as only this species was available at 3 sampling sites in sufficient numbers to provide the required number of samples for statistical calculations.
All calculations were done with the program STATISTICA for Windows (StatSoft, Inc. 2000).

RESULTS AND DISCUSSION

Mean concentrations of elements in the water, sediments and plants of the river are presented in Tables 1 - 3. Vanadium concentrations in water were below the detection limit (<6.7 µg/L) and have therefore not been included in Table 1.

The analysis of variance indicates that the water at all sites differed significantly in concentration of elements and the level of pollution increases significantly around the sewage output.

According to the values established by the Dutch Government (Ministerie van VROM 1992) for dissolved polluting elements in unpolluted surface water, the river (Table 1) exceed the upper limits (indicated in parentheses) for Ni (7 µg/L, sites 5 - 7), Cd (0.06 µg/L, sites 5 -7), Cu (1.3 µg/L, sites 3 - 7), Cr (2 µg/L, sites 3 - 7), Zn (30 µg/L, sites 3 - 7), ammonium (2 mg/L, sites 5 - 7), sulphates (100 mg/L, sites 4 - 7) and phosphate (0.15 mg/L, sampling sites 4 - 7). Concentrations of ammonium in particular dominated over all other nitrogen compounds at sites 5 - 7 (14.3 - 40 mg/L), while sulphates ranged from 171 - 482 mg/L, seriously exceeding the upper limits for unpolluted water. Phosphate concentrations in clean water ranged from 0.01 - 0.1 mg/L. The amounts of phosphates we found (4.9 - 6.9 mg/L at sites 5 - 7) indicate eutrophication of the river. Since phosphate concentrations around 10 µg/L can imply nutrient limitation in aquatic organisms (Christmas and Whitton 1998), the amounts of this element in the water of the Brzeczek exceeded the limiting values. The concentration of total inorganic nitrogen at sampling sites 4 - 6 (extremely high at site 5, which supports no aquatic vegetation at all) is typical of polytrophic waters (Papastergiadou and Babalonas 1993). The pH of the water samples varied between 7.1 and 8.3 (Table 1).

The concentrations of P, Ca, Mg, K and Fe in sediments at all sampling sites and those of N (at sites 4 - 7) were lower than the average values suggested by Markert (in mg/kg: P=200-800, Ca=1000-12000, Mg=500-5000, Fe=7000-42000, N=2000, K=2000-22000), which means that the sediments of the examined river are poor in macronutrients. The sulphur contents at sites 5 - 7 reveal the extent of the pollution with this element.

Table 1. pH and mean concentration ± SD ($n = 3$) of elements in water. Ss = sampling site. $F_{0.05}$ tab = 2.27.

Ss	pH	NH_4	NO_3	NO_2	$P0_4$	K	Ca	Mg	Fe	SO_4	Cl
				Concentrations in mg/L							
1	8.3±0.09	<0.002	1.36±0.1	<0.002	0.03±0.001	2.5±0.09	15±0.5	11±0.5	0.04±0.02	26±0.7	15±0.9
2	8.0±0.1	<0.002	1.39±0.14	<0.002	0.02±0.001	2.1±0.08	13±0.4	10±0.6	0.02±0.01	17±0.3	12±0.5
3	7.8±0.08	0.02±0.009	1.43±0.09	0.008±0.0008	0.12±0.007	3.7±0.01	42±1.1	16±0.8	0.35±0.03	76±1.4	42±1.6
4	7.6±0.1	0.07±0.01	8.63±0.3	0.01±0.003	0.18±0.009	3.4±0.02	38±0.6	18±0.5	0.35±0.02	171±2.1	39±1.1
5	7.4±0.1	40±0.90	5.30±0.26	0.20±0.005	6.93±0.3	17±0.8	33±0.3	11±0.3	0.80±0.07	482±10	105±3.4
6	7.5±0.1	30±0.40	4.03±0.37	0.23±0.014	4.93±0.1	16±0.6	37±0.5	12±0.2	0.89±0.06	381±8.1	180±4.7
7	7.1±0.1	14.3±0.2	8.33±0.66	0.18±0.01	5.23±0.2	140.2	43±0.9	18±0.8	0.45±0.01	290±2.3	175±3.8
LSD	0.1	0.94	0.66	0.004	0.35	0.15	0.5	0.6	0.07	1.9	2.5
F est	35	3564	107	77	231	887	119	32	106	348	943

Ss	Al	Ba	Co	Cr	Mn	Ni	Zn	Cd	Cu	Pb
					Concentrations in μg/L					
1	7±0.3	35±1.1	4±0.2	<2	0.5±0.04	1.2±0.1	11±0.8	0.02±0.005	0.7±0.01	0.2±0.005
2	5±0.2	27±0.9	<4	2±0.06	0.4±0.05	0.9±0.07	9±0.03	0.01±0.003	0.4±0.01	0.4±0.006
3	8±0.4	46±1.4	19±0.8	5±0.1	0.8±0.07	3.2±0.02	37±0.9	0.03±0.001	1.8±0.09	0.3±0.002
4	12±0.4	48±1.6	5±0.1	12±0.6	0.5±0.05	4.3±0.1	94±4.5	0.05±0.01	3.7±0.07	0.6±0.01
5	21±0.8	29±1.1	18±0.9	15±0.4	107±2.8	297±4.2	103±4.8	0.07±0.01	10.5±0.2	1.0±0.1
6	37±0.6	28±1.2	17±0.9	33±0.5	103±1.2	283±5.1	186±5.2	0.09±0.02	19.4±0.3	0.7±0.05
7	11±0.3	26±0.5	13±0.5	24±0.5	21±0.9	212±2.3	158±3.3	0.06±0.02	18.5±0.2	0.9±0.07
LSD	0.6	1.1	0.9	0.5	0.3	1.8	4.7	0.01	0.1	0.1
F est	2143	3154	845	914	3178	958	247	326	943	481

Table 2. Mean concentration ± SD (mg/kg, $n = 3$) of elements in sediments. Values are in dry weight. Ss = sampling site. $F_{0.05}$ tab = 2.27.

Ss	N	P	K	Ca	Mg	Fe
1	2240±120	36±7	360±38	510±31	170±10	1.5±0.2
2	2350±130	45±6	350±31	540±38	190±19	2.0±0.1
3	2000±110	41±8	320±41	560±52	190±26	2.3±0.2
4	1510±80	29±8	210±32	480±36	170±17	3.2±0.1
5	1100±100	59±12	15±3	120±13	36±3	6.6±0.1
6	1210±80	73±14	19±3	200±21	31±3	7.8±0.2
7	2070±120	75±17	27±3	370±27	70±7	7.7±1.4
LSD	65	7	8	21	13	0.1
F est	3495	4287	935	6398	74123	97

Ss	S	Al	Ba	Cd	Co	Cr
1	69±7	6850±53	56±9	0.7±0.1	1.5±0.1	3.0±0.1
2	51±3	6280±74	62±11	0.6±0.1	1.6±0.2	3.8±0.2
3	180±12	6370±65	85±13	2.8±0.2	3.6±0.1	4.7±0.2
4	410±15	1560±41	31±8	1.2±0.1	5.4±0.2	7.0±0.1
5	790±31	3400±52	51±10	1.6±0.1	20±1.2	20±1.2
6	880±36	4090±67	60±13	2.0±0.2	30±1.1	165±13
7	780±31	6950±78	141±16	2.7±0.2	65±2.1	114±11
LSD	13	34	11	0.1	0.2	2.1
F est	5267	7488	67389	96	572	5632

Ss	Cu	Mn	Ni	Pb	V	Zn
1	0.5±0.1	138±20	1.4±0.1	4.7±0.3	17±0.9	13±1.1
2	8.9±0.8	115±19	1.2±0.1	5.9±0.2	14±0.6	10±0.3
3	31±1.9	149±26	1.7±0.1	15±0.8	34±1.2	44±1.8
4	9.0±0.5	114±14	12±0.7	18±0.2	18±0.4	47±1.2
5	28±2.1	176±19	21±1.5	30±1.3	18±0.5	77±2.3
6	41±3.8	193±12	21±1.3	59±2.3	29±0.7	232±4.8
7	48±2.7	247±23	43±2.3	90±3.1	35±1.6	159±8.4
LSD	0.4	13	0.2	0.5	0.8	1.9
F est	7934	82431	3412	4749	85	538

According to the values established by the Dutch Government (Ministerie van VROM 1992) for heavy metals in unpolluted sediments the investigated sediments in the Brzeczek (Table 2) exceeded the upper limits (indicated in parentheses in mg/kg) for Zn (140, sites 6 - 7), Cd (0.8, sites 3 - 7), Cu (36, sites 6 - 7), Ni (35, site 7), Pb (85, site 7), Cr (100, sites 6 - 7) and Co (20, sites 5 - 7). The pH of the sediments varied between 6.6 and 7.1.

Plants of the genus *Potamogeton* can be found in almost any water type (Wiegleb

Table 3. Mean concentration ± SD ($n = 10$) of elements in plants. Values are in dry weight. $F_{0.05}$ tab = 1.85.

Sampling site/plant	N	P	K	Ca	Mg	Fe	S	Al
			concentration in g/kg					
1/*P. riparioides*	21.3±0.4	5.1±0.2	21.3±0.2	12±0.2	6.4±0.1	5.3±0.09	3.1±0.2	3.1±0.15
2/*P. riparioides*	20.6±0.2	5.3±0.2	18.8±0.2	15±0.3	7.2±0.1	5.5±0.11	2.9±0.1	3.5±0.18
3/*B. aquatile*	19.5±0.3	6.0±0.3	19.4±0.3	54±0.9	28.2±0.4	1.0±0.04	3.3±0.3	0.8±0.02
3/*P. pectinatus*	28.5±0.2	12.0±0.4	19.2±0.2	50±0.8	15.6±0.3	1.5±0.04	3.8±0.3	0.7±0.03
4/*M. verticillatum*	16.5±0.1	5.2±0.1	14.1±0.1	106±1.0	12.6±0.3	1.7±0.06	3.8±0.3	1.4±0.06
4/*E. palustre*	18.5±0.2	9.2±0.4	22.6±0.4	57±0.7	21.4±0.4	0.6±0.02	5.9±0.3	0.7±0.04
4/*P. mite*	20.5±0.2	5.6±0.1	13.8±0.3	47±0.6	11.4±0.2	1.8±0.06	3.1±0.4	1.1±0.08
4/*B. frondosus*	17.0±0.1	8.4±0.3	18.8±0.3	48±0.7	14.8±0.3	0.5±0.02	2.6±0.3	0.1±0.02
4/*V. anagallis*	29.5±0.3	13.0±0.4	24.9±0.5	51±0.8	13.1±0.2	0.4±0.03	3.2±0.3	0.3±0.03
4/*C. verna*	31.5±0.4	22.8±0.4	26.2±0.4	39±0.6	16.8±0.4	13.6±0.25	5.5±0.4	0.6±0.05
4/*Spirogyra* sp	20.5±0.3	3.2±0.1	15.6±0.3	71±0.7	10.0±0.2	3.6±0.11	8.0±0.2	3.9±0.08
6/*P. mite*	14.9±0.2	3.6±0.1	13.3±0.2	53±0.7	23.1±0.4	1.6±0.09	4.6±0.1	0.7±0.04
7/*P. mite*	17.0±0.3	5.7±0.3	17.1±0.4	47±0.6	20.1±0.4	2.2±0.08	3.7±0.1	0.1±0.02
LSD	0.5	0.5	0.6	1.1	0.4	0.2	0.3	0.1
F est	25913	6249	52881	38366	94114	53972	53779	68235

Table 3 continued.

Samling site/plant	Ba	Cd	Co	Cr	Cu	Mn	Ni	Pb	V	Zn
			concentration in mg/kg							
1/*P. riparioides*	124±19	0.1±0.01	< 0.2	1.2±0.2	5±0.5	15±0.9	0.4±0.05	0.1±0.02	1.7±0.1	30±2
2/*P. riparioides*	112±15	0.2±0.02	< 0.2	1.3±0.1	4±0.2	19±0.6	0.5±0.02	0.6±0.03	1.9±0.1	29±1
3/*B. aquatile*	58±7.8	0.3±0.02	6.30±0.7	3.8±0.1	40±1.1	266±10	2.9±0.2	13.1±0.2	6.2±0.8	51±4
3/*P. pectinatus*	24±3.8	0.7±0.05	4.60±0.4	2.6±0.1	44±0.9	176±10	1.0±0.1	10.8±0.1	4.0±0.4	56±3
4/*M. verticillatum*	75±8.5	1.1±0.1	9.00±0.7	6.2±0.3	65±1.8	273±12	6.1±0.3	14.4±0.2	8.4±0.7	72±5
4/*E. palustre*	30±5.2	2.0±0.08	5.30±0.3	5.5±0.4	58±1.5	124±8	5.0±0.2	19.7±0.3	5.5±0.3	91±7
4/*P. mite*	68±4.8	1.5±0.05	13.00±0.8	7.7±0.6	51±1.2	564±14	7.5±0.2	25.5±0.5	6.4±0.6	139±11
4/*B. frondosus*	10±0.6	2.1±0.1	9.70±0.6	3.8±0.2	41±0.8	154±7	3.2±0.1	13.6±0.1	3.9±0.2	97±8
4/*V. anagallis*	12±0.4	1.4±0.1	5.90±0.3	6.2±0.4	36±0.4	60±6	2.0±0.1	7.4±0.07	4.6±0.2	50±3
4/*C. verna*	155±14	2.4±0.2	11.00±0.5	8.6±0.5	87±2.1	1850±58	11±0.1	24.0±0.2	9.8±0.6	478±31
4/*Spirogyra* sp	97±6.8	3.2±0.2	15.00±0.8	14.0±0.8	93±2.5	628±17	35±0.3	30.0±0.6	22.0±0.2	242±25
6/*P. mite*	41±2.2	1.6±0.1	38.00±1.2	17.0±0.7	109±3.7	687±21	15±0.2	19.0±0.2	5.0±0.1	397±26
7/*P. mite*	32±1.3	1.1±0.1	34.00±0.9	15.0±0.5	96±3.2	446±18	13±0.2	12.0±0.3	3.0±0.1	291±17
LSD	16	0.1	0.2	0.5	1.9	16	0.2	0.3	0.7	14
F est	76822	11823	191422	6725	19932	9813	69821	21991	34992	253219

et al. 1991), with *Potamogeton pectinatus* preferring eutrophic waters (Tremolieres et al. 1994). Accumulation of heavy metals by species of the *Potamogetonaceae* increases with increasing metal concentrations in the surrounding waters (Pip 1990, Greger and Kautsky 1991), with metals being accumulated mainly by the leaves of *Potamogeton pectinatus* and *Myriophyllum verticillatum* (Lewander et al. 1996). Some of these species demonstrate a significant tolerance for Cd and Ni and *Veronica* spp. have the capacity to accumulate and tolerate Cu (Sawidis et al. 1995). *Myriophyllum* species have a higher adsorption capacity than other aquatic plants and show good potential for metal removal (Lee et al. 1998). Additionally, *Myriophyllum verticillatum* is a good accumulator of Ni, Co, Cu, Pb, Zn, Cr and As (Mudroch and Capobianco 1979). Thus the selected species should meet the requirements of good bioindicators of pollution and should be useful for evaluating the spatial distribution of elements in the Brzeczek. Only at sampling site 5, in the vicinity of the outlet of the sewage system, did the pollution of this river cause the disappearance of aquatic macrophytes. Increases in the concentration of elements in plants compared to those in the water are given in Table 4.

As was pointed out in the introduction, all examined species respond rather indifferently to water quality. Of these species, *Polygonum mite*, which grew both upstream and downstream of the sewage outlet, seemed to have the greatest tolerance for the high levels of pollution with ammonium nitrogen (up to 30 mg/L) and sulphates (up to 381 mg/L), as well as for the heavy metals Cr, Ni, Zn and Cu in water and S, Co, Cr, Ni, Zn, Cu and Pb in sediments; it thus appeared to be the best bioindicator of heavy metal pollution in the Brzeczek river. Recently it was also found (Qian et al. 1999) that *Polygonum* species are good bioaccumulators and are resistant to pollution.

The concentrations of the heavy metals Cd, Co, Cr, Cu, Mn, Ni, Pb, V and Zn (Table 3) in all the plants examined (except those at sampling sites 1 and 2) were higher than the average values as given in the literature (Markert 1992, Kabata-Pendias and Pendias 1993).

The increased concentrations of heavy metals in plants seem to reflect their increased concentrations in the environment. Aquatic macrophytes concentrate elements and integrate temporal fluctuations in water chemistry, which makes them useful for monitoring purposes, as an addition to chemical analyses of water and sediments (Jones 1985).

The concentrations of the nutritional elements P and N in the examined plants (Table 3) were within the range given in the literature (Markert and Wtorova 1992) and higher than the critical values of 1.0 g P/kg and 1.3 g N/kg (Gerloff 1975, Huebert and Shay 1991), which means that these elements were not limiting the growth of the plants investigated. The same applies to the nutritional elements Ca and Mg. For instance, the concentration of Ca in *Potamogeton pectinatus* was higher than the critical value of 0.22% w/w (Huebert and Shay 1991).

The iron content of the plants was much higher than the values given in the literature (Markert 1992). This was especially true for *Callitriche verna* from sampling site 4 (13.6 g Fe/kg). *Callitriche verna*, a submersed plant, is known to

Table 4. Increase in concentration of elements in plants compared to concentrations in water. Ratio's have to be multiplied by 100.

Sampling site/plant	N	P	K	Ca	Mg	Fe	S	Al	Ba	Cd	Co	Cr	Mn	Ni	Zn	Cu	Pb
1/*Platyhypnidium r.*	157	1700	85	8	5.8	1320	119	4430	35	50	0.1	-	300	3.3	27	71	5
2/*Platyhypnidium r.*	148	2650	89	11	7.2	2750	171	7000	41	200	-	6.5	475	5.6	32	100	15
3/*Batrachium a.*	134	500	52	13	18	29	43	1000	13	100	3.3	7.6	3325	9.1	14	222	437
3/*Potamogeton p.*	195	1000	52	12	9.7	43	50	875	5.2	233	2.4	5.2	2200	3.1	15	244	360
4/*Myriophyllum v.*	19	290	41	28	7.0	49	22	1170	16	220	18	5.2	5460	14	7.6	176	240
4/*Epilobium p.*	21	511	66	15	12	17	34	583	6.2	400	11	4.6	2480	12	9.7	157	328
4/*Polygonum m.*	23	311	41	12	6.3	51	18	916	14	300	26	6.4	11280	17	15	138	425
4/*Bidens f.*	19	467	55	13	8.2	14	15	83	2.1	420	19	3.2	3080	7.4	10	111	227
4/*Veronica a.*	34	722	73	13	7.3	11	19	250	2.5	280	12	5.2	1200	4.6	5.3	97	123
4/*Callitriche v.*	36	1270	77	10	9.3	389	32	500	32	480	22	7.2	37000	26	51	235	400
4/*Spirogyra* sp	23	178	46	19	5.6	103	47	3250	20	640	30	12	12560	81	26	251	500
6/*Polygonum m.*	4.3	7.3	8.3	14	19	18	12	189	15	178	22	5.1	67	0.5	21	56	271
7/*Polygonum m.*	7.4	11	12	11	11	49	13	91	12	183	26	6.2	212	0.6	18	52	133

be a better accumulator than helophytes or *Nymphaeaceae* (Manny et al. 1991, Reimer and Duthie 1993).

The sulphur content in all species was higher than the lower limit (0.6 g S/kg) (Markert and Wtorova 1992, Kabata-Pendias and Pendias 1993), which, together with the elevated levels of this element in water and sediments, reflects the pollution of the Brzeczek with sulphur compounds.

Table 5. Statistically significant relations (Pearson correlations) between chemical characteristics of water, sediments and plants.

Relations between	Significance level	r est
Submersed plants: *B. aquatile*, *P. pectinatus*, *M. verticillatum*, *C. verna*, *Spirogyra* sp., *P. riparioides*		
Cr in water and Cr in plants	0.013	0.86
Cd in water and Cd in plants	0.027	0.81
Cu in water and Cu in plants	0.0001	0.97
Pb in water and Pb in plants	0.047	0.76
Emergent plants: *E. palustre*, *B. frondosus*, *V. anagallis*		
Co in water and Co in plants	0.001	0.97
Cr in water and Cr in plants	0.003	0.95
Cu in water and Cu in plants	0.002	0.96
Ni in water and Ni in plants	0.006	0.94
Zn in water and Zn in plants	0.001	0.98
Co in sediments and Co in plants	0.04	0.83
Cr in sediments and Cr in plants	0.002	0.97
Cu in sediments and Cu in plants	0.006	0.93
Ca in sediments and Co in plants	0.013	-0.91
Ca in sediments and Cr in plants	0.012	-0.91
Ca in sediments and Ni in plants	0.021	-0.87
Ca in sediments and Zn in plants	0.003	-0.95
Mg in sediments and Co in plants	0.001	-0.98
Polygonum mite		
Cl in water and width of the largest leaf	0.024	-0.89
Co in water and width of the largest leaf	0.028	-0.99
Cr in water and width of the largest leaf	0.016	-0.98
Zn in water and width of the largest leaf	0.02	-0.97
Al in sediments and length of plants	0.018	-0.99
Co in sediments and length of plants	0.022	-0.97
Zn in sediments and width of the largest leaf	0.037	-0.99
Cr in sediments and length of the largest leaf	0.02	-0.99

Relations between concentrations of elements in water and in plants (Table 5) were calculated for two groups of aquatic macrophytes: submersed and emergent plants. Submersed plants were characterized by positive correlations between the concentrations of Pb, Cr, Cu and Cd in water and in plants. Emergent plants were characterized by strong positive correlations between concentrations of Co, Cu and Cr in sediments and in plants, and between concentrations of Co, Cu, Cr, Ni and Zn in water and in plants, indicating that these plants may be very useful (Jones et al. 1985) as an instrument for monitoring the pollution of the Brzeczek river by these elements.

The present study revealed significant negative correlations between concentrations of Co, Cr, Ni, Zn in emergent plants and the Ca content in sediments, as well as between the Co content in emergent plants and that of Mg in the sediments of the corresponding sampling sites (Table 5). Heavy metal accumulation seems to be directly associated with an exclusion of Mg and Ca, reflecting the well-known protective role of Ca and Mg against heavy metal pollution (Markert and Wtorova 1992).

The length of the examined plants growing in the Brzeczek was smaller than the average values given in the literature (Table 6). This is probably caused by the high levels of pollutants present in the river, and is in agreement with the significant negative correlations between the length of *Polygonum mite* and the contents of Al and Co in sediments, as well as between the width of the largest leaves of this species and the content of Cl, Co, Cr and Zn in water and Zn in sediments and between the length of the largest leaves and the Cr content in the sediments (Table 5).

Table 6. Mean biometrical features (in cm) ± SD (n = 10) of plants.

Sampling site/plant	Length of plants	Max. plant length in literature	Number of leaves	Length of the longest leaf	Width of the longest leaf	Number of plants/m^2
1/*P. riparioides*	9.9±1	12 *	-	-	-	-
2/ *P. riparioides*	10.4±1					
3/*B. aquatile*	34±2	150 **	12.0±2	2.0±0.3	2.3±0.2	4±2
3/*P. pectinatus*	40±3	300 **	6.8±1	5.7±0.2	1.3±0.1	5±3
4/*E. palustre*	46±3	70 **	47.0±4	3.2±0.2	0.9±0.1	4±1
4/*M. verticillatum*	48±4	200 **	0.0	0.0	0.0	2±2
4/*P. mite*	58±3	60 **	45.5±4	4.2±0.4	3.6±0.2	2±3
4/*B. frondosus*	46±2	100 **	0.0	0.0	0.0	2±2
4/*V. anagallis*	27±1	70 **	10.5±2	7.8±0.5	0.8±0.1	4±2
4/*C. verna*	48±3	150 **	-	-	-	-
4/*Spirogyra* sp.	-	-	-	-	-	-
6/*P. mite*	53±3	60 **	49.7±4	6.3±0.3	1.2±0.2	3±3
7/*P. mite*	47±2		69.3±5	6.8±0.2	1.9±0.3	3±2

*Szafran 1961, **Szafer et al. 1986.

The pollution caused by the textile industry in the downstream part of the Brzeczek is severe, resulting in the decline and even disappearance of an abundant plant community that is rich in species such as *Batrachium aquatile*, *Epilobium palustre*, *Potamogeton pectinatus*, *Myriophyllum verticillatum*, *Bidens frondosus*, *Veronica anagallis*, *Callitriche verna* and *Spirogyra* sp. Only *Polygonum mite* seemed to be able to survive in water characterized by this type of pollution. The ability of this species to accumulate high levels of Cd, Co, Cr, Cu, Mn, Ni, Pb, V and Zn could be used in the biotechnical purification of water. Trace element concentrations in *Polygonum mite* in the Brzeczek represent an integration of conditions over short or medium periods of time, rather than the momentary conditions measured using water samples (Carter and Porter 1997).

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