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The Removal of Biogenic Compounds and Suspended Solids in a Constructed Wetland System

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Abstract

A hydrophyte treatment system was constructed in Bielkowo in order to protect drinking water intake for the city of Gdansk against surface and point sources of contaminants. The system consists of two subunits: a wet unit (pond), filled with water all the time and a dry unit (extension of the pond), designed for storm water. In the wet unit are placed dams constructed of medium size sand. The system, especially dams, is inhibited with macrophytes. The drainage system collects water percolating through dams, and directs it downstream. The system was constructed in 1997. After implementation of the system substantial improvement in water quality occurred.

Keywords: hydrophyte, constructed wetland, rural areas, water protection

Introduction

Polish environmental policy in recent years has paid much attention to the question of reducing the re-contamination of surface waters. Either untreated sewage or sewage treated in conventional wastewater treatment plants, without removing nutrient elements (nitrogen and phosphorus), impose a possible threat for surface waters. Another source of nitrogen and phosphorus compounds are aerial sources of pollution - rainwater run-off containing contaminants washed away from the soil.

Improper farming methods, insufficient number of sewer systems, uncontrolled discharges of pollutants as well as unsustainable development are considered to be the main reasons of surface water pollution in the rural areas.

In the 1970s 45.9% of wastewater was discharged to the recipients without treatment, while the amount of biologically treated sewage was only 8.1%. In the late 1980s intensive actions were undertaken for constructing new wastewater treatment plants and modernization of the existing ones.

The 1990s saw substantial growth in the number of new wastewater treatment plants, which amounted to 300 new facilities per year, on average, as well as modernization of many existing facilities. In spite of the undertaken actions, improvement of the water quality was too slow. This resulted from the long years when the problem was neglected, causing accumulation of the pollutants in the soils and bottom sediments of surface water reservoirs. Up till now protection of surface and ground water against contamination was limited to the protection zones of water intakes, the areas of infiltration of rainwater alimentating groundwater aquifers and nature conservation areas.

In recent years constructed wetland systems simulating marsh ecosystem conditions have become popular in Poland. These systems allow for retention of con-

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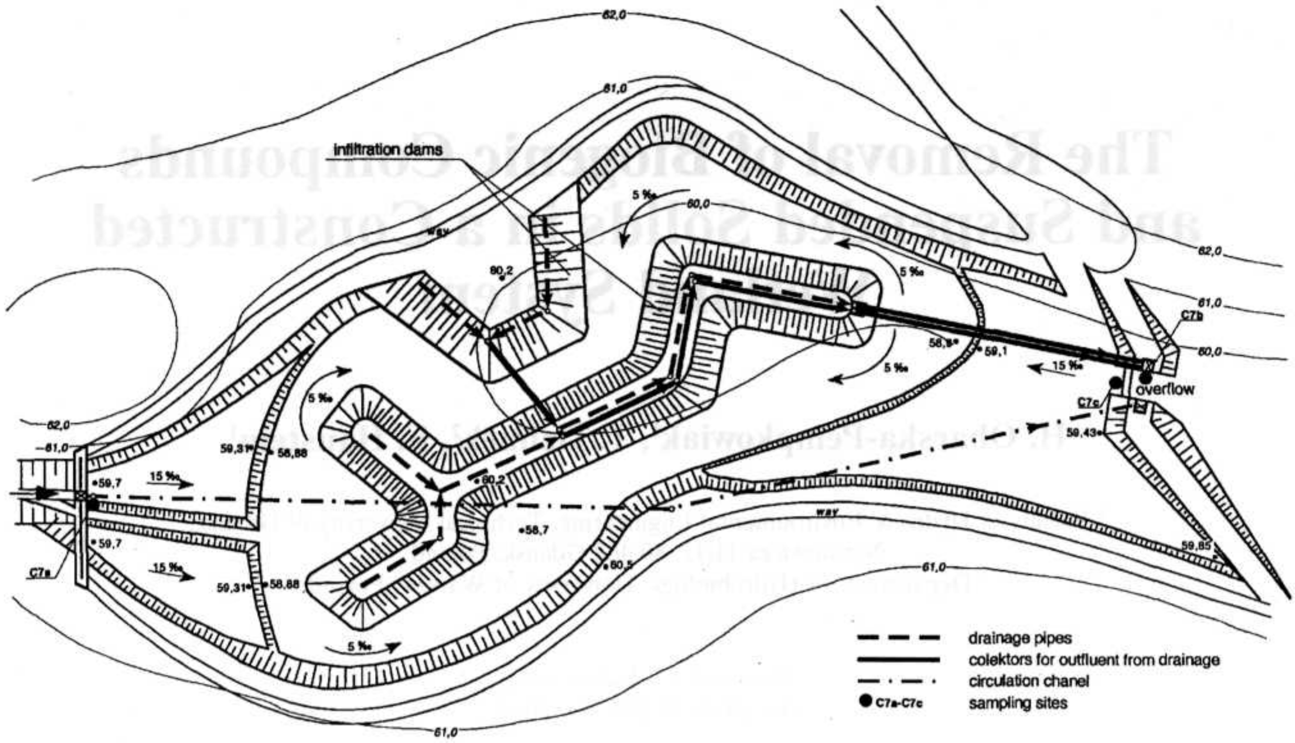

Fig. 1. The schematic of constructed wetland system in Bielkowo.

taminants in physical (sedimentation, filtration), chemical (oxidation, reduction) and biological processes (microbial transformations) taking place in the ground systems inhabited by some species of aquatic plants.

Up till now the main application of the constructed wetland systems was removal of organic substances. In western Europe (Denmark, Great Britain, Germany) they were applied as the second stage of wastewater treatment. In the USA and Scandinavian countries the constructed wetland systems were applied as level II or the III of wastewater treatment, that is after mechanical or mechanical and biological treatment, in order to improve elimination of nutrients [1].

A new application of constructed wetlands is employing them to remove pollutants from small streams, often carrying high loadings of pollutants discharged by dispersed inflows. For removal of nutrients and suspended solids from surface waters contaminated by surface run-off from the rural areas, constructed wetlands with surface flow of water, inhabited with emerged aquatic plants are considered to be suitable. Such systems are capable of retaining contaminated waters during freshets. The biomass of hydrophytes is considered to play a crucial role in accumulation of nitrogen and phosphorus [5]. The current work presents the analysis of the impact of the water reservoir inhabited with hydrophytes on the improvement of quality of a stream flowing in the rural area. An evaluation of removal efficiency of selected contaminants was also performed.

Site Description

A constructed wetland system was designed in order to improve quality of a stream originating near the village Bielkowo and inflowing to the Straszyn water reservoir, where the water intake for the city of Gdansk is located. The constructed wetland system was situated in a valley, behind the buildings of a former state farm property, close to the place where the regulated river channel turns into an open river bed. The system was built as a retention reservoir and consists of two subunits:

- the "wet" unit consists of dams with internal drain age. The unit is filled with water all the time. It is design ed for retention time 24 h and water flow $Q = 32\ 1\ s^{-1}$;
- the "dry" unit (extention of the pond) is filled with water periodically and designed for storm water reten tion: Q as $640\ 1\ s^{-1}$ and retention time of 0.5 h.

The dams in the wet unit are constructed of medium size sand (hydraulic conductivity $k = 40.0 - 86.4\ m\ d^{-1}$). The volume of the dams is $V_F = 1200\ m^3$. The dams are inhabited with reed. The drainage system collects water percolating through dams and directs it downstream.

In periods of dry weather the level of water in the pond decreases. The dry section emerges and becomes a meadow on such occasions. During freshets the water level increases until the water overflows the dams and is directed to the stream underneath. This allows for retaining the first and probably most contaminated wave/portion of storm water in the system for approximately 30 minutes.

In the design project of the system, it was assumed that during 8-9 months each year the whole flow of the stream (average flow Q = 32 1 s^{-1}) will run through the "wet" part of the pond, with the retention time equal to 24 h (Fig. 1). During visits to the facility and collecting samples of water in the years 1998-2000, it was found out that the system is all the time working with the water dammed up above overflow crest. This means that the "dry" part was covered with water all the time and there were no periods when the "dry" part of the pond emerged. In such a situation there is no retention volume for storm water run-off in the system.

In the years 1997-98, due to weather conditions, the aquatic plants (mostly common reed) were not able to take their roots on the dykes. Therefore, the facility worked rather as a system of ground filters than a constructed wetland. The facility was inhabited with reed sweet-grass, broad-leaved cattails and common reed in spring 1999. During the first two years of operation, due to mass algae blooming and lack of roots cultivating the ground, the surface of the dams was covered with a thick mat of organisms. This was the reason for changing the conductivity of the dams and flooding the "dry" part with water.

Methods

In the period 1998-2000 investigations of the quality of water inflowing to and outflowing from the pond in Bielkowo were conducted. The measurement results from the 2000 were complemented with the results obtained from the Institute of Marine and Tropical Medicine in Gdynia. The following sampling points were selected: D - inflow to the pond, P - overflow, I - outflow of the drainage pipe collecting water percolating through the dams.

The averaged samples were collected twice a month. The following determinations were performed: BOD5, COD, suspended solids, N_{tot}, $N\text{-}NH_4^+$, $N\text{-}NO_2^-$, $N\text{-}NO_3$ and P_{tot}. The determinations were carried out according to Polish Standards [9] and to the guidelines given by Hermanowicz et al. [3]. The suspended solids were determined by the weight method with application of membrane filters. The concentration of organic substances given as BOD5 was determined respirometrically by an OxiTop apparatus produced by WTW, Germany. The concentration of organic substances given as COD was determined colorimetrically in the presence of potassium permanganate. The Kjeldahl nitrogen (the sum of organic and ammonia nitrogen) was determined after wet digestion with concentrated sulphuric acid catalysed with $CuSO_4$ + K_2SO_4. The digested samples were distilled after adding concentrated NaOH. Wet digestion was carried out in a Digestion System 1006 produced by Tecator, while distillation was performed in the Kjeltec System 1026, also produced by Tecator, Sweden. Nitrite nitrogen was measured colorimetrically using a-naphthylamine. Nitrate nitrogen was determined colorimetrically using sodium salicylate. Total phosphorus was determined after wet digestion of samples with a mixture of H_2SO_4 and HNO_3, due to the guidelines given by Hermanowicz et al. [3]. Then phosphorus was determined colorimetrically using ammonium molibdate in the presence of glycene and $SnCl_2$. Mineralization of samples was carried out in the Digestion Systems 6 1006 apparatus and colorimetric analyses were performed in the Aquatec 5400-Analyzer, both produced by Tecator. Average water outflow from the drainage pipeline was 9.6 dm^3 s^{-1}. The pollutant removal efficiencies were calculated after evaluation of the load discharged by the overflowing water (L_P) and the infiltrating water (L_I), using the following formulas:

$$\eta_P = \frac{L_D - L_P}{L_D} \quad \text{and} \quad \eta_I = \frac{L_D - L_I}{L_D}$$

where r|P and r|i are the pollutant removal efficiencies for water flowing through the pond and infiltrating through the dams, respectively. The inflowing load was calculated as a product of multiplication of the concentration of pollutant in the inflowing water and average flow (32 dm^3 s^{-1}). In 2000 the crop of biomass and concentrations of nitrogen and phosphorus in the above ground parts of plants were also measured. These measurements were performed three times: at the beginning (May), in the middle (July) and at the end (October) of the vegetation season. The plant material was collected using a frame (dimensions 25 cm x 25 cm) from the five sampling points at the inflow to and the outflow from the facility. Mineralization of plant material was performed in the following way: 5 g of powdered material was put into the Kjeldahl flask, then 55 cm^3 of a mixture of acids HNO_3, $HC1O_2$ and H_2SO_4 (the volumetric proportion of mixture was 7: 2: 1) was added. The samples were heated until red-brownish smoke, indicating nitrogen oxide appeared. Incineration was seized for a few minutes and then continued until white vapor of sulphuric acid appeared. After another 5-minute break the samples were combusted until the white smoke of sulphur oxides was obtained. The samples were heated for the next 10 minutes at a low temperature, then the temperature was increased and the samples were heated until they became colour-free. The combusted material was moved to a 250 cm^3 measuring flask. Distilled water was poured into the flask to reach the volume of 250 cm^3. The nitrogen and phosphorus concentrations were then determined as described above in the case of water samples.

Results and Discussion

The average concentrations and the ranges of analyzed pollutants in the waters inflowing to and outflowing from the hydrophyte pond in Bielkowo are presented in Table 1. In Table 2 the average concentrations of total nitrogen and total phosphorus in the vegetative and non-vegetative seasons are given. Analysis of results indicates that the concentrations of pollutants in water decreased after flowing through the hydrophyte pond, although not enough to cause improvement in water quality class. Substantial decrease of the concentrations of suspended solids, total nitrogen and total phosphorus was recorded, while the decrease of BOD_5 and COD concentrations was smaller (the concentrations of BOD_5 and

Table 1. Concentrations (mg dm^{-3}) of pollutants in water $\left(\frac{\text{min. – max.}}{\text{average}}\right)$ * of the hydrophyte system in Bielkowo in the period 1998-2000

Pollutant	1998			1999			2000		
	D	P	I	D	P	I	D	P	I
Suspended solids	17.0 – 29.0 / 23.1	12.0 – 28.0 / 18.2	7.0 – 22.0 / 12.7	10.0 – 26.0 / 17.3	9.0 – 16.0 / 12.4	6.0 – 11.0 / 9.1	6.6 – 20.0 / 11.3	4.8 – 14.0 / 9.8	3.0 – 10.0 / 7.0
COD_{Mn}	7.8 – 14.4 / 11.4	9.8 – 14.1 / 11.3	7.4 – 11.8 / 9.9	7.9 – 12.3 / 10.4	7.2 – 13.3 / 9.2	4.8 – 13.0 / 9.1	7.1 – 12.3 / 9.5	4.8 – 11.6 / 9.1	4.2 – 9.9 / 7.6
BOD_5	3.6 – 11.1 / 6.4	4.8 – 7.6 / 5.9	3.4 – 6.8 / 5.1	4.2 – 6.7 / 5.6	3.9 – 6.3 / 4.9	2.6 – 5.9 / 4.3	2.2 – 5.8 / 4.0	2.3 – 5.4 / 3.7	1.7 – 4.9 / 3.3
$N_{tot.}$	1.9 – 3.3 / 2.5	1.9 – 3.0 / 2.1	1.4 – 2.1 / 2.2	1.3 – 2.6 / 1.9	1.0 – 2.6 / 1.7	1.2 – 2.2 / 1.6	0.4 – 2.2 / 1.6	0.7 – 2.0 / 1.5	0.5 – 1.8 / 1.3
$P_{tot.}$	0.10 – 0.20 / 0.17	0.07 – 0.16 / 0.12	0.07 – 0.15 / 0.10	0.01 – 0.19 / 0.11	0.02 – 0.16 / 0.08	0.01 – 0.14 / 0.07	0.04 – 0.15 / 0.08	0.03 – 0.11 / 0.07	0.04 – 0.10 / 0.06
Water quality	II	II	II	II	II	II	I	I	I

$\left(\frac{\text{min. – max.}}{\text{average}}\right) = \left(\frac{\text{minimum – maximum}}{\text{average}}\right)$

COD satisfied the demands for the I or the II water quality class.

The results indicate that mineralization of organic substance of antropogenic origin occurred before the stream entered the pond. Lower concentration of pollutants in overflowing and infiltrating water during the vegetation season confirms effective contribution of plants in the treatment process.

In Table 3 average pollutant removal efficiencies for overflowing and infiltrating water in 1998-2000 and total removal efficiency are presented. The results confirm the crucial role of infiltrating dams in removal of contaminants. The average removal efficiency of suspended solids, N_{tot} and P_{tot} for infiltrating waters was 83.0%, 74.6% and 80.2%, respectively. The average removal efficiency for overflowing waters was lower - 44.6%, 37.7% and 46.2%, respectively.

The improvement of pollutant removal efficiency in 1999 resulted from good establishment of emergent macrophytes in sediments and their more intensive growth and development in comparison to 1998.

The average concentration of dry matter content in hydrophytes collected from a unit area of 1 m^2 at the inflow to and the outflow from the facility is presented in Table 4. In cases of broad-leaved cattails and reed sweet-grass biomass of plants was higher at the outflow. The highest biomass of these two species (broad-leaved cattails and reed sweet-grass) was recorded in the middle of the vegetation season (in July), while in the case of common reed the highest biomass was observed at the end of the season (in October).

Table 5 presents seasonal changes of average concentrations of total nitrogen and total phosphorus in aboveground parts of three analysed species of macrophytes. The highest concentration of nitrogen was recorded in reed sweet-grass (21.7 mg $g^{-1}{}_{d.m.}$) in October and the lowest (12.4 mg $g^{-1}{}_{d.m.}$) also in reed sweet-grass. The highest concentration of phosphorus (2.5 mg $g^{-1}{}_{d.m.}$) occurred in broad-leaved cattails in May, and the lowest one (0.5 mg $g^{-1}{}_{d.m.}$) in July.

The contents of nitrogen and phosphorus in macrophytes depends on a number of abiotic factors, but mostly on concentrations of these elements in interstitial water of sediments, on temperature, pH and proportion of C: N: P, as well as on physiological condition of the plants. The concentration of N and P for the same species from various habitats can be significantly different [2]. The habitats situated at the same water reservoir may have different fertility. The content of nitrogen in the tissues of reed sweet-grass was lower at the inflow than at the outflow during the entire vegetation season, while such a phenomenon was not recorded in the case of phosphorus. The content of nitrogen was stable during the season, while the content of phosphorus was three times lower in summer and autumn than in spring (Table 5).

Reed sweet-grass in Bielkowo contained three times less nitrogen in comparison with the highest concentrations reported by Ozimek [7] or Ozimek and Klekot [6] for this species grown in the pond to which the treated sewage from a conventional wastewater treatment plant was discharged.

Also, the dry matter per 1 m^2 (Table 4) was lower than in the cases of reed sweet-grass from fertile habitats [7]. Due to low biomass production and low content of nitrogen and phosphorus, 1 m^2 of hydrophyte pond at the inflow accumulated 9 g of nitrogen in spring and 16 g in winter. Accumulation was higher at the outflow because the plant biomass per unit area as well as the content of nitrogen in the plant tissues was greater (Tables 4 and 5).

The highest content of nitrogen and phosphorus in broad-leaved cattails was recorded in summer, both at the inflow and at the outflow. Dry matter content per 1 m^2 in spring and summer was higher at the outflow than at the inflow, while in autumn both values were similar (Table 5).

The higher biomass and content of nitrogen in the plants indicates that at the outflow the sediments are more fertile productive in comparison to the inflow. This could result from sedimentation and accumulation of organic matter near the outflow from the pond.

Table 2. Contents (%) of nutritional elements in growing/non growing seasons in the period 1998-2000.

Pollutant	1998			1999			2000		
	D	P	I	D	P	I	D	P	I
$N_{tot.}$	2.6/2.3	2.1/1.8	1.9/1.8	1.9/2.0	2.0/1.7	1.7/1.6	1.1/1.8	1.1/1.7	0.9/1.2
$P_{tot.}$	0.20/0.14	0.11/0.13	0.07/0.13	0.10/0.10	0.05/0.07	0.06/0.09	0.06/0.13	0.05/0.10	0.05/0.07

Table 3. Pollutant removal efficiencies in the years 1998-2000, *[%]*.

Pollutant	η_P			η_I			$\eta_{tot.}$		
	1998	1999	2000	1998	1999P	2000	1998	1999	2000I
Suspended solids	44.8	49.8	39.3	83.5	84.2	81.4	28.4	34.0	20.7
$N_{tot.}$	41.2	37.4	34.4	73.6	74.7	75.6	14.8	12.1	10.0
$P_{tot.}$	50.6	49.1	38.8	82.3	80.9	77.4	32.9	30.0	16.2

Table 4. Seasonal changes of dry matter content in vegetative aboveground parts of three species of macrophytes in constructed wetland in Bielkowo in 2000, [g m^{-2}].

Plant	Sampling site	Month		
		May	July	October
Broad-leaved cattails	inflow outflow	732.0/1427.8	2111.2/2856.6	539.4/508.4
Reed sweet-grass	inflow outflow	688.8/804.6	1204.6/2963.1	970.0/1211.8
Cammon reed	inflow	792	1490.4	2322

Table 5. Seasonal changes of total nitrogen and total phosphorus concentrations in vegetative aboveground parts of three species of macrophytes in constructed wetland in Bielkowo in 2000.

Plant	Pollutant	site	mg $g^{-1}{}_{d.m.}$			g m^{-2}		
			May	July	October	May	July	October
Red sweet-grass	N	inflow	13.1	13.3	12.4	9.0	16.0	12.0
		outflow	19.3	19.0	21.7	15.5	56.3	26.3
	P	inflow	2.1	0.8	0.7	1.4	1.0	0.7
		outflow	2.1	0.7	0.8	1.7	2.4	1.0
Broad-leaved cattails	N	inflow	19.7	15.5	15.6	14.4	32.7	8.4
		outflow	21.5	10.0	12.5	30.7	28.6	6.3
	P	inflow	1.8	0.5	0.6	1.3	1.1	0.3
		outflow	2.5	1.1	1.1	3.6	3.1	0.6
Common reed	N	inflow	15.7	19.9	12.5	12.4	29.6	29.0
	P	outflow	1.1	1.3	0.4	0.9	1.9	0.9

The results allowed for evaluation of nitrogen and phosphorus loads inflowing to and outflowing from the facility in 2000 and calculation of accumulation of theses elements in the biomass growing at 1300 m^3 of the pond. The calculation results are presented in Table 6.

Table 6. Nitrogen and phosphorus loads at the inflow and at the outflow and accumulated in the macrophytes in 2000 [$kgyear^{-1}$].

Pollutant	Inflow	Outflow	Macrophytes
$N_{tot.}$	1614.6	1403.2	28.3
$P_{tot.}$	80.7	67.6	1.9

Average total accumulation of nitrogen and phosphorus in the plant biomass was equal to 1.8% and 2.4%, respectively. Calculation of the balance indicates that apart from bioaccumulation in plants, other processes take place in the hydrophyte pond. Due to nitrification, denitrification and sorption of the contaminants on the bottom sediments 11.3% of nitrogen and 13.8% of phosphorus are eliminated.

Complex hydrobiological analyses, including algae of both pelagic and benthic origin were performed in 2001. Up till now no toxic algae and/or blue-green algae have been found in effluent and waters of the wetland.

Conclusions

1. The hydrophyte pond in Bielkowo allowed for ef fective removal of suspended solids, nitrogen and phos phorus.
2. Analyses of the species of macrophytes growing in the pond indicated that broad-leaved cattails and reed sweet-grass produce higher biomass and develop better than common reed.
3. The increase of macrophyte biomass was 43.8% higher at the outflow than at the inflow to the pond, which indicates better fertility of sediments at this part of the pond.
4. The share of emergent macrohyte was equal to 1.8% inflow of nitrogen and 2.4% of phosphorus.

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