Performance of Subsurface Vertical Flow Constructed Wetlands Receiving Municipal Wastewater

Article *in* Archives of Hydroengineering and Environmental Mechanics · December 2004

Piotr Kowalik
Gdansk University of Technology
34 PUBLICATIONS **2,297** CITATIONS
SEE PROFILE

Peter Randerson
Cardiff University
78 PUBLICATIONS **1,514** CITATIONS
SEE PROFILE

Archives of Hydro-Engineering and Environmental Mechanics
Vol. 51 (2004), No. 4, pp. 349–370

Performance of Subsurface Vertical Flow Constructed Wetlands Receiving Municipal Wastewater

Piotr J. Kowalik[1], **Michał Mierzejewski**[2],
Peter F. Randerson[3], **Haydn Gregg Williams**[3]

[1]Gdańsk University of Technology, Faculty of Civil Environmental Engineering
ul. Narutowicza 11/12, 80-952 Gdańsk, Poland
e-mail: pkow@pg.gda.pl, pmie@pg.gda.pl
[2]Pipelife Polska SA, ul. Torfowa 4, Kartoszyno, 84-110 Krokowa, Poland
[3]Cardiff University, School of Biosciences, CF10 3TL Cardiff, Wales, UK
e-mail: randerson@cardiff.ac.uk

(Received May 07, 2004; revised July 22, 2004)

Abstract

The efficiency of pollution removal from municipal sewage in two vertical flow constructed wetlands consisting of gravel filters with a surface area of 4 × 5 m, depth 60 cm, planted with reed (*Phragmites*) was assessed over a period of about two years. The flow of wastewater was 50 mm per day. Wastewater underwent only primary treatment before application to reed bed B, but reed bed A was supplied with wastewater after mechanical and biological treatment. Measurements were taken of sewage supply and discharge, precipitation and wastewater temperatures. The main indicator of efficiency was the elimination of suspended solids, BOD_5, nitrogen and phosphorus from the wastewater during treatment. The elimination of the pollution load was 2–25 g O_2 per square meter per day for the BOD_5 and 0–3.5 g per square meter per day for so-called "total nitrogen". Rates of pollution removal were between 2 and 4 times as high in bed B (after primary treatment) as in bed A (after biological treatment), but the loading rate of bed B was also substantially higher. The rate of BOD_5 removal and the coefficient k for BOD_5 were greatly dependent on temperature for reed bed B (primary tretament); less so for bed A (biological treatment). The difference between summer and winter temperatures indicates that the surface area of constructed wetland B with wastewater after mechanical treatment should be about 3 times greater during winter, to obtain the summer rate of BOD_5 pollution removal in the climatic conditions of Northern Poland (54°N).

Key words: constructed wetland, municipal wastewater, nitrogen, *Phragmites australis*, phosphorus, sewage, suspended solids, wastewater treatment

1. Introduction

This paper aims to evaluate the efficiency of the process of pollution removal from municipal sewage in constructed wetlands which are designed man-made complexes of saturated matrix, emergent or submergent vegetation, associated macroinvertebrate and microbial communities, and water, for the treatment of wastewater (Brix 1987, Brix 1993a, Kowalik et al 1995).

In vertical flow systems the wetland is flooded on the surface with the treatment water, which is allowed to flow vertically through a sand or gravel substrate and discharged via a drain. The bed is usually allowed to dry between applications of irrigated wastewater to promote diffusion of oxygen into it, and is bound by an impermeable layer preventing leaching into the surrounding environment.

Vertical subsurface flow systems (VF) have not been utilised extensively as they require more careful construction and selection of fill material compared to other constructed wetland systems (Heritage et al 1995). A design consisting of several beds laid out in parallel with percolating flow and intermittent loading will increase soil oxygenation several-fold compared to horizontal subsurface flow systems, stimulating sequential nitrification/denitrification processes (Brix 1993a).

The role of plants in constructed wetlands is not very clear. This is related to the limited ability of macrophytes such as reeds, to transfer oxygen into the soil (Belfiore 1997), but vertical flow systems (VF) have been shown to support ammonia oxidation (Felde and Kunst 1996). The roots, shoots and litter from the plants, along with the soil or other fill material used, support the biofilm, aerobic bacteria and associated organisms and fungi which are the functional components of the system (Hiley 1995). Plants also take up nutrients, so they are also "functional components" during vegetation growth. Rooted emergent aquatic macrophytes, such as *Phragmites australis* (common reed), are the predominant life form in wetlands in Europe, covering a significant fraction of the surface. These wetland plants grow naturally in flooded soils in deltas, the edges of rivers and many form rafts that extend into deeper water from the margins. They have the important ability of consolidating sediments and keeping their roots aerated in flooded anaerobic soils (Armstrong et al 1990, Brix 1990, Brix 1993b, Brix and Schierup 1990). It is the ability of wetland plants to maintain oxygen supply to their roots, to create a locally aerobic environment, and deal with the products of anaerobic root respiration that enables them to survive in anoxic/anaerobic sediments (Hiley 1995). These plants are adapted to growing in highly organic, anaerobic sediments and for this reason can tolerate sudden large loads of effluent with such characteristics (Mitchell et al 1995).

The main objectives of the research were to undertake systematic monitoring of the function of vertical flow constructed wetlands and obtain numerical values of operating efficiency with a view to improving future design and management of such systems and evaluate the reliability and predictability of constructed wetlands.

2. Construction of Two Experimental Wetlands

The experimentally constructed wetlands were located on the site of the ZA-SPA wastewater treatment plant (WWTP) in Gdańsk (Poland). The conventional WWTP was constructed in 1932 according to the design of K. Imhoff and is based on mechanical and biological treatment for municipal wastewater for about 100,000 people.

The pilot scale reed bed consists of two vertical flow beds, (A and B), both of 4 × 5 m, containing emergent vegetation (*Phragmites australis*) growing in 0.6 m deep gravel and sand fill material. There is only one replicate of each reed bed. Therefore, statistical comparisons between two beds are not possible, and only qualitative comparisons between the beds are made.

The surface was level to allow uniform distribution of the added wastewater. The two beds were made using four layers of mineral material (Fig. 1).

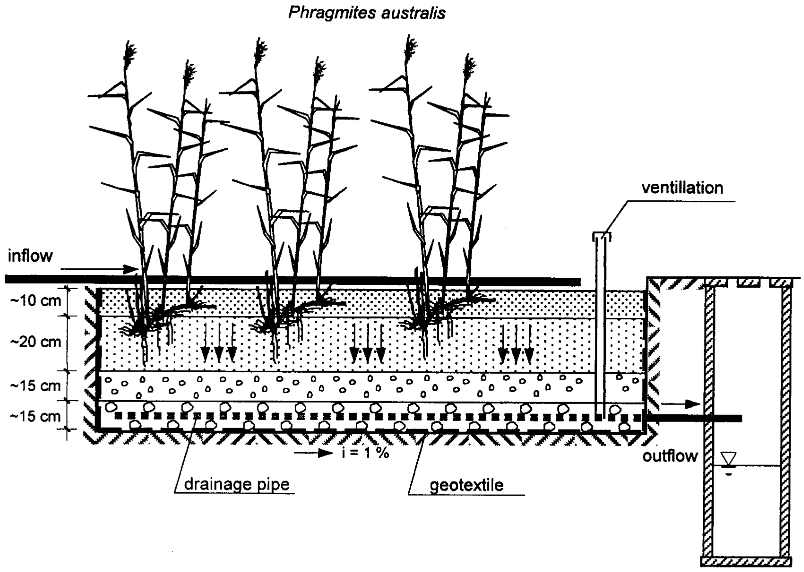

Fig. 1. Construction of the vertical reed bed

This material was prepared, washed and sorted outside of the plant, to prevent any content of organic matter and seeds of weeds. The surface layer (depth 10 cm), intended as a support for vegetation was constructed from sand grains 0.1–2 mm in diameter. Beneath this was a 20 cm depth layer of gravel of 2–8 mm diameter followed by a 15 cm depth gravel layer with diameter of 8–16 mm. The basal layer was a drainage bed 15 cm in depth comprising gravel and stones of 16–63 mm in diameter. Each reed bed was equipped for wastewater supply with a system of pumps, pressure pipes and distribution system at the sand surface. After draining through the bed, treated wastewater was collected in subsurface containers and pumped from these containers back to the wastewater treatment plant installation. After draining, a proportion of the wastewater remains as capillary water in the bed, amounting to about 0.10 of the total volume of the bed. A similar value was measured in column experiments by Kowalik et al (1979) and Kowalik & Obarska-Pempkowiak (1985). The pore-space retention time was determined from the active volume of the reed bed occupied by bio-film within capillary water and from the flow rate as:

$$t_r = V/Q, \tag{1}$$

where:

t_r – average retention time of wastewater in the reed bed (day),

V – capillary capacity equal to active volume of biofilm of the reed bed (m^3),

Q – mean average flow rate per day of wastewater through the system (m^3/day).

The vertical walls of the beds were made of timber. The bottom and sides were covered by plastic geomembrane sheet 1.5 mm thick to avoid any lateral flow or loss of wastewater into the surrounding soil. A system of drainage pipes at the bottom of the bed on the surface of the plastic sheet collects treated wastewater. These pipes were also connected with vertical pipes ending above the bed to allow ventilation of the lower gravel layers. The total mass of each bed was over 40 tonnes of selected coarse sand, fine gravel and coarse gravel with stones. During May 1996 the surface of the bed was planted with 5–6 rhizome cuttings of reed (*Phragmites australis*) on every square metre. Summer 1996 was dedicated to full development of the reed plants, irrigated intensively by wastewater in both cells. During the spring of 1997 the reed was fully developed, with deep roots and ready for flowering. During September 1996 it was possible to see the development of the biofilm on the surface of sand grains.

The supply of wastewater to these beds was taken from the treatment line of the main WWTP and, after passing by a combination of gravity and pump to the beds, returned to the plant. Reed bed A was supplied with wastewater from the secondary settler after mechanical and biological treatment in an activated sludge aeration tank. Reed bed B was supplied with sewage after mechanical treatment, which had undergone only a primary treatment for the removal of larger particles and suspended solids.

Inflow and outflow of wastewater was under automatic control, designed for the two beds separately, and included several security devices, protecting the system against possible failures. Two pumps bringing wastewater into the reed beds were connected with multifunctional control panels not only to switch the pumps on and off, but to monitor the duration of work of each pump and power supply. Because the capacity of each pump was constant, the duration of work was proportional to the amount of wastewater supplied, which was monitored by a flow meter. The pumps removing wastewater after treatment were under automatic control of float switches in the drainage containers (Mierzejewski 1999). On the surface 3 ridges (0.3 m height) were made from gravel for a distance of 1.5 m. On these ridges perforated plastic pipes were mounted, for uniform flooding.

After irrigation, the beds drain freely, allowing air to refill the bed. The next dose traps the air and this, together with the aeration caused by the rapid dosing into the beds, leads to good oxygen transfer and hence the ability of nitrification.

3. Materials and Methods Related to Wastewater Measurement

Wastewater was supplied into the reed beds in pulses 3 times per day (every 8 hours). The hydraulic loading rate was 16.7 mm every 8 hours, giving a daily intensity equal to 50 mm d^{-1}, or 1 m^3 per day in each bed. Measurements were performed from November 1996 until August 1998.

Based on BOD_5 of the wastewater entering reed bed A (after mechanical and biological treatment), the pollution loading rates R_p were:

$$R_p = QC_o/A, \tag{2}$$

where: R_p – pollution loading rate per square meter of reed bed per day (g O_2 m^{-2} day^{-1}); C_o – initial pollutant concentration at inlet (g O_2 m^{-3}; mg O_2 dm^{-3}); A – surface area of the reed bed (m^2). R_p values in reed bed A were found to vary from 2.5 g O_2 m^{-2} day^{-1} to 15 g O_2 m^{-2} day^{-1}. For reed bed B irrigated by the wastewater after mechanical treatment in the settler the load rates were between 6.3 and 26.5 g O_2 m^{-2} day^{-1}. Hence the loads applied to reed bed B after mechanical treatment were substantially higher than those of the reed bed A with wastewater after mechanical and biological treatment.

Wastewater samples were taken from the settlers of the wastewater treatment plant in the vicinity of the inlets to the pipes connected to the supply pumps, just before the pump started to work. Wastewater irrigation occurred for 2.4 minutes every 8 hours. The outflow from the bed was observed to stop after 17 minutes. Wastewater samples were taken from the collecting containers about 15 minutes after the beginning of irrigation. As the irrigation occurred 3 times a day, sampling every 10 days coincided with only one of 30 pulses of irrigation. It is important to stress that beds were equipped with both inlet and outlet flow meters to determine a balance of water entering and emerging. Average rates of precipitation at the site (measured as about 600 mm per year) and daily evapotranspiration were much lower than the 50 mm d^{-1} of irrigation.

The soil temperature of the reed beds at 0.00, 0.15 and 0.60 m depth was measured on each sampling occasion. Temperature of the waste water (input and output) was measured and the mean values of temperatures were used to relate to performance of the bed. Air temperature at a level of 2 m above the ground varied between -8°C and $+2^{\circ}$C during winter, but at a depth of 15 cm the soil temperature remained at approximately $+1^{\circ}$C, and at a depth of 60 cm the temperature was $+2^{\circ}$C.

Water chemistry analysis was carried out in the laboratory of the Gdańsk University of Technology in accordance with Polish Standards, which are similar to international regulations. The following parameters were monitored separately for reed beds A and B: BOD_5 (see: Polish Standard Methods PN-74/C-04578); suspended solids (see: Polish Standard Methods PN-72/C-04559); ammonia (NH_4^+); nitrite (NO_2^-); nitrate (NO_3^-) and Kjeldahl nitrogen (see: Polish Sandard Methods PN-73/C-04576); total phosphorus and orthophosphate (PO_4^{3-}) (see: Polish Standard Methods PN-73/C-04537). "Total nitrogen" was calculated as the sum of Kjeldahl nitrogen, nitrite and nitrate nitrogen. "Organic nitrogen" is determined by subtracting ammonia nitrogen concentration from Kjeldahl nitrogen.

For each of the time dependent variables measured over 2 years: $C_o(t)$, $C_e(t)$, $T_o(t)$, $T_e(t)$, where t – time (day), index o refers to inflow values and index e to outflows, the mean ($n = 37$), standard error of the mean, median, minimum and maximum values were calculated (see Tables 1–8). The derived time series were treated similarly: $\eta(t)$, $T_m(t) = T(t)$, $k(t)$, $R_r(t)$, where $\eta(t)$ is the efficiency of pollution removal over time t (Eqs. 3 and 4), $T(t)$ is the mean temperature of the wastewater ($T = T_m = (T_o + T_e)/2$); $k(t)$ is the first order kinetics coefficient of pollution removal (Eq. 5); $R_r(t)$ is a rate of pollution removal (Eq. 6). Constant parameters in the calculations were: surface area $A = 20$ m^2; volume of the biofilm equal to capillary capacity $V = 20 \times 0.6 \times 0.1 = 1.2$ m^3; hydraulic load $Q = 1$ m^3/d (see Eqs. 1 and 6), applied to BOD_5 and to total N.

Relationships between temperature (T) and the indices of pollution removal $k(BOD_5)$ and R_r were investigated graphically ($k(T)$: Fig. 3, and $R_r(T)$: Figs. 6 and 7) and by linear regression analysis to give the following trend lines (a and b are estimated intercept and slope parameters):

$$k = a + bT; \text{ for } k(\mathrm{BOD}_5) \text{ in both reed beds A and B}$$

$$R_r = a + bT; \text{ for both BOD}_5 \text{ and } N_{tot}, \text{ in both reed beds A and B.}$$

The statistical significance for each relationship (p-value of slope parameter) and the coefficient of determination R^2 (as a measure of scatter) are shown. Analysis of Covariance was used to test the difference between the slopes of the regression lines of beds A and B (Fry 1993), for each of the pollution removal indices.

4. Results and Discussion

Despite the constant hydraulic load it was noted that the concentration of different pollutants in the wastewater was changing greatly over time. Suspended solids were eliminated very efficiently in both reed beds (see Table 1).

The concentration of suspended solids in the wastewater entering bed B after mechanical treatment ranged from 64 to 577 mg dm^{-3}.

Efficiency of treatment was calculated from the mass loading:

$$\eta = [(QC_o - QC_e)/QC_o] \times 100 \tag{3}$$

and from concentrations:

$$\eta = [(C_o - C_e)/C_o] \times 100 \tag{4}$$

where: η – efficiency of pollution removal (%), C_o – initial inflow pollution concentration (mg dm^{-3}); C_e – final outlet pollution concentration (mg dm^{-3}); assuming the value of Q the same inflow and outflow of the reed bed.

Despite the variability of the inflow wastewater, the efficiency of elimination of suspended solids η ranged from 62 to 94% with a mean value of all sampled data of 79%. The concentration of suspended solids in wastewater supplied after mechanical and biological treatment, entering reed bed A, ranged from 12 to 125 mg dm^{-3} and the efficiency of suspended solids removal ranged from 29 to 95%, the mean value being 77%.

Values of wastewater temperatures are shown in Table 2.

Stable values of removal efficiency over time were recorded. In reed bed B the wastewater after mechanical treatment contains between 125 and 530 mg O_2 dm^{-3} BOD_5 (see Table 3 and Fig. 2), but the efficiency was relatively stable, between 67 and 99%, with a mean value of 89%.

In reed bed A, irrigated by wastewater after mechanical and biological treatment, the input values of BOD_5 of wastewater were between 43 and 309 mg O_2 dm^{-3}. Even with such variability, efficiencies of BOD_5 removal of 87 to 99% occurred, with a mean value of 94%.

Coefficient k for BOD_5 removal (Kickuth 1981; EPA Design Manual 1988, 1993, 1999; Cooper et al 1996) was calculated from:

$$k = -ln\frac{C_e/C_o}{t_r} \tag{5}$$

and is depicted in Fig. 3 as a function of temperature T. The results of monitoring during establishment phase of the beds (the first 3–4 weeks) were omitted from the relationships with temperature. This coefficient k is more sensitive to temperature in reed bed B than in reed bed A, the regression slopes being significantly different from each other ($p = 0.001$). In both cases the linear relationships $k(T)$ are also significant (p-values).

Table 1. Suspended solids monitoring, A – reed bed with wastewater after biological treatment, B – reed bed with wastewater after primary mechanical treatment, C_o – initial inlet pollution concentration (mg dm^{-3}), C_e – final outlet pollution concentration (mg dm^{-3}), η – efficiency of pollution removal (%)

Date	A	A	A	B	B	B
	C_o	C_e	η	C_o	C_e	η
13/11/96	125	68	46	577	41	93
27/11/96	116	38	67	392	70	82
11/12/96	12	2	83			
24/02/97	98	66	33			
20/03/97	48	18	62	108	30	72
09/04/97	58	8	86	130	20	85
23/04/97	24	12	50			
08/05/97	43	6	86	176	10	94
15/05/97	28	20	29	155	43	72
04/06/97	80	20	75	200	57	71
25/06/97	100	12	88	133	25	81
09/07/97	65	13	80	220	58	74
23/07/97	35	12	66	64	17	73
06/08/97	34	10	71			
20/08/97	95	17	82	180	65	64
27/08/97	76	7	91	113	26	77
01/10/97	120	27	77	216	51	76
09/10/97	24	8	67	98	6	94
30/10/97	14	7	50	132	16	88
18/11/97	33	3	91	119	8	93
27/11/97	34	8	76	174	43	75
04/12/97	37	5	86	130	35	73
22/01/98	49	4	92	123	33	73
29/01/98	90	11	88	227	56	75
11/02/98	58	9	84	165	29	82
25/02/98	53	19	64	200	42	79
04/03/98	64	7	89	173	31	82
19/03/98	78	4	95	204	37	82
08/04/98	71	8	89	196	32	84
29/04/98	41	14	66	143	55	62
13/05/98	72	9	87	206	52	75
27/07/98	69	7	90	186	48	74
10/06/98	63	7	89	214	41	81
25/06/98	76	8	89	187	39	79
08/07/98	68	6	91	174	35	80
29/07/98	76	9	88	211	32	85
12/08/98	69	7	90	197	29	85
mean	62	14	77	186	37	79
std error	5	2	3	16	3	1
median	64	9	84	176	35	79
min	12	2	29	64	6	62
max	125	68	95	577	70	94

Table 2. Wastewater temperature monitoring, A – reed bed with wastewater after biological treatment, B – reed bed with wastewater after primary mechanical treatment, T_o – initial inlet temperature (°C), T_e – final outlet temperature (°C), T_m – mean temperature of the wastewater in reed bed

Date	A	A	A	B	B	B
	T_o	T_e	T_m	T_o	T_e	T_m
13/11/96						
27/11/96	14.2	7.0	10.6	7.2	5.4	6.3
11/12/96	11.4	3.0	7.2			
24/02/97	16.2	4.2	10.2			
20/03/97	15.2	2.9	9.1	15.0	4.8	9.9
09/04/97	15.4	5.0	10.2	9.6	4.8	
23/04/97	15.2	5.6	10.4			
08/05/97	16.6	10.8	13.7	16.6	10.0	13.3
15/05/97	16.8	12.6	14.7	17.4	12.6	15.0
04/06/97	18.4	11.8	15.1	19.2	16.8	18
25/06/97	19.3	15.5	17.4	21.9	20.1	21
09/07/97	20.7	18.6	19.7	19.6	16.8	18.2
23/07/97	20.5	17.5	19.8	18.8	17.2	18
06/08/97	21.0	17.9	19.5			
20/08/97	21.9	20.3	21.1	20.9	19.8	20.4
27/08/97	22.2	21.0	21.6	21.3	20.9	21.1
01/10/97	21.7	16.71	19.2	21.2	19.0	20.1
09/10/97	19.9	13.3	16.6	21.6	20.4	21
30/10/97	17.6	5.9	11.8	7.7	16.2	12
18/11/97	19.1	16.7	17.9	13.4	3.4	8.4
27/11/97	21.2	18.4	19.8	14.9	5.5	10.2
04/12/97	16.2	5.8	11	15.8	3.2	9.5
22/01/98	15.6	4.4	10	14.2	5.1	9.7
29/01/98	12.2	3.9	8.1	13.2	2.6	7.9
11/02/98	17.9	10.5	14.2	18.2	12.0	15.1
25/02/98	16.8	10.4	13.6	17.7	10.5	14.1
04/03/98	17.4	10.2	13.8	18.1	11.7	14.9
19/03/98	14.1	3.4	8.8	14.0	3.5	8.8
08/04/98	14.8	3.2	9	14.5	5.5	10
29/04/98	18.2	11.2	14.7	17.2	7.8	12.5
13/05/98	15.2	9.8	12.5	15.0	10.0	12.5
27/07/98	19.2	14.3	16.8	18.9	11.1	15
10/06/98	19.5	15.5	17.5	19.3	14.2	16.8
25/06/98	19.3	18.2	18.8	19.1	15.9	17.5
08/07/98	20.4	18.3	19.4	20.1	17.4	18.8
29/07/98	21.2	18.8	20	20.9	19.1	20
12/08/98	22.0	20.5	21.3	21.8	20.7	21.3
mean	17.9	11.7		17.0	12.0	
std error	0.5	1.0		0.7	1.1	
median	18.05	11.50		17.90	11.85	
min	11.40	2.90		7.20	2.60	
max	22.20	21.00		21.90	20.90	

Table 3. BOD$_5$ monitoring, A – reed bed with wastewater after biological treatment, B – reed bed with wastewater after primary mechanical treatment, C_o – initial inlet pollution concentration (mg O$_2$ dm^{-3}), C_e – final outlet pollution concentration (mg O$_2$ dm^{-3}), η – efficiency of pollution removal (%)

Date	A	A	A	B	B	B
	C_o	C_e	η	C_o	C_e	η
13/11/96	80	3	96	125	6	95
27/11/96	258	2	99	441	9	98
11/12/96	81	2	97			
24/02/97	162	11	93			
20/03/97	112	7	93	194	10	95
09/04/97	309	3	99	480	2	99
23/04/97	170	2	99			
08/05/97	43	5	87	179	4	98
15/05/97	67	8	88	135	3	98
04/06/97	168	9	94	352	8	98
25/06/97	172	5	97	437	8	98
09/07/97	230	7	97	388	22	94
23/07/97	117	7	94	216	9	96
06/08/97	238	7	97			
20/08/97	298	16	95	530	25	95
27/08/97	150	16	89	330	15	95
01/10/97	109	6	95	173	11	93
09/10/97	102	6	94	176	10	94
30/10/97	90	5	94	170	35	80
18/11/97	66	6	92	128	33	74
27/11/97	101	4	96	209	44	79
04/12/97	88	7	92	168	55	67
22/01/98	89	9	90	141	47	67
29/01/98	85	9	89	209	34	83
11/02/98	87	7	92	186	18	90
25/02/98	73	8	89	173	23	87
04/03/98	101	7	93	170	15	91
19/03/98	129	11	92	196	54	72
08/04/98	143	12	92	148	35	76
29/04/98	117	8	93	229	38	83
13/05/98	235	18	92	178	30	83
27/07/98	168	10	94	169	19	89
10/06/98	211	12	94	183	17	91
25/06/98	135	7	95	216	16	92
08/07/98	116	6	95	203	12	94
29/07/98	99	5	95	178	8	95
12/08/98	137	3	98	201	6	97
mean	138	7	94	230	21	89
std error	11	1	0.5	19	3	2
median	117	7	94	186	16	93
min	43	2	87	125	2	67
max	309	18	99	530	55	99

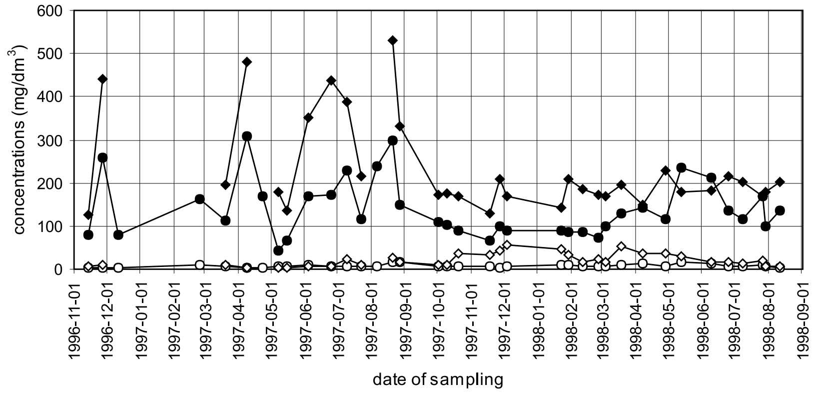

Fig. 2. BOD_5 (mg O_2/dm^3) in inflow (black circles) and outflow (open circles) for wastewater after biological treatment (bed A); BOD_5 [mg O_2/dm^3] in inflow (black diamonds) and outflow (open diamonds) for wastewater after mechanical treatment (bed B)

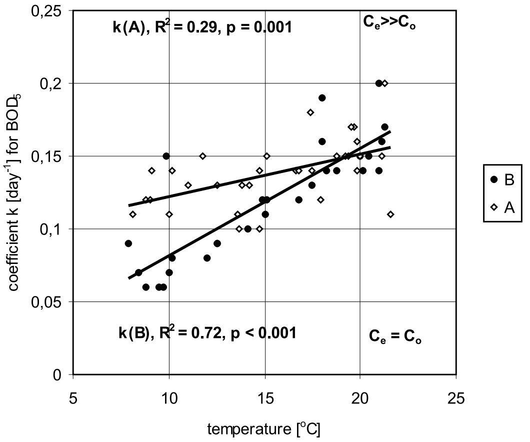

Fig. 3. Coefficient k [day^{-1}] for BOD_5 removal in vertical reed-beds

$$k(T),\quad k = 0.0926 + 0.00295T \text{ (reed bed A)}:\; p = 0.001,\quad R^2 = 0.29,$$

$$k(T),\quad k = 0.0074 + 0.00741T \text{ (reed bed B)}:\; p < 0.001,\quad R^2 = 0.72.$$

The relationship with temperature is more scattered for reed bed A than for B (R^2 values) indicating a poorer predictive capacity for the trend line, despite its high significance.

Some forms of nitrogen were removed efficiently by the reed beds. For the wastewater after mechanical treatment in reed bed B, the input values of Kjeldahl nitrogen concentrations varied from 36 mg dm^{-3} to 101 mg dm^{-3}. The efficiency

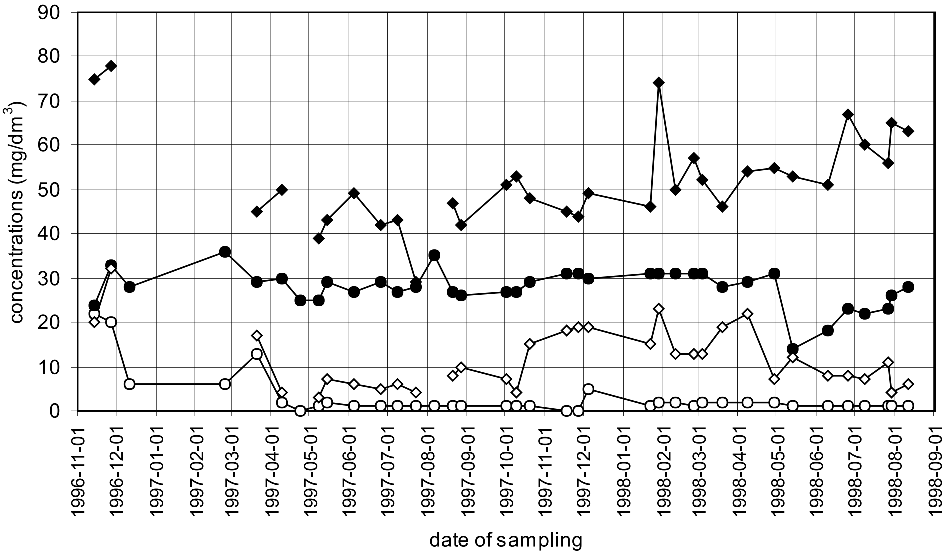

Fig. 4. Ammonia nitrogen (mg/dm^3) in inflow (black circles) and outflow (open circles) for wastewater after biological treatment (bed A); ammonia nitrogen (mg/dm^3) in inflow (black diamonds) and outflow (open diamonds) for wastewater after mechanical treatment (bed B)

of Kjeldahl nitrogen removal was between 45 and 92%, but after the spring of 1997, after about one year of operation of the reed bed, the efficiency of nitrogen removal was largely stable at about 77% for the rest of the period of the experiment (for the next year) (see Table 4).

Similarly for reed bed A, where the wastewater was irrigated after mechanical and biological treatment, input values of Kjeldahl nitrogen ranged from 31 to 64 mg dm^{-3}. The efficiency of removal ranged from 15 to 97% and after April 1997 was very stable during the next year at a mean level of 93% (Table 4).

Ammonia nitrogen in reed bed B was removed with a high degree of efficiency (Fig. 4). Inputs ranged from 29 mg dm^{-3} to 78 mg dm^{-3}, but after April 1997 about 79% of this pollutant was eliminated, even with relatively high concentrations in the irrigated wastewater. In reed bed A the situation was similar, but the efficiency of removal of the ammonia nitrogen was higher than in reed bed B. After April 1997 the mean efficiency of removal was about 95.4%, despite input values ranging from 14.1 to 36.2 mg dm^{-3} (Table 5).

Nitrite nitrogen is shown in Table 6 and nitrate nitrogen in Table 7.

Total nitrogen concentrations as a sum of Kjeldahl nitrogen, nitrite and nitrate nitrogen are shown in Fig. 5.

Removal of so-called total nitrogen was not very efficient (Fig. 5). Total nitrogen was assumed to be eliminated by plant uptake and denitrification, but these processes need more research in the future. Both ammonia and Kjeldahl nitrogen

Table 4. Kjeldahl nitrogen monitoring, A – reed bed with wastewater after biological treatment, B – reed bed with wastewater after primary mechanical treatment, C_o – initial inlet pollution concentration (mg dm^{-3}), C_e – final outlet pollution concentration (mg dm^{-3}), η – efficiency of pollution removal (%)

Date	A	A	A	B	B	B
	C_o	C_e	η	C_o	C_e	η
13/11/96	50	43	15	101	45	55
27/11/96	38	22	43	91	34	63
11/12/96	32	9	73			
24/02/97	38	8	80			
20/03/97	42	21	49	66	27	60
09/04/97	37	4	89	64	6	90
23/04/97	31	1	97			
08/05/97	31	6	81	51	8	85
15/05/97	35	7	80	52	10	80
04/06/97	35	3	90	63	11	83
25/06/97	32	3	91	56	8	86
09/07/97	36	3	93	50	8	83
23/07/97	35	2	93	36	6	85
06/08/97	40	2	95			
20/08/97	34	1	96	54	9	83
27/08/97	31	2	95	55	11	80
01/10/97	42	1	97	69	8	89
09/10/97	41	2	95	74	6	92
30/10/97	40	3	93	100	23	77
18/11/97	46	2	96	69	25	64
27/11/97	44	1	97	66	27	58
04/12/97	64	7	89	74	40	45
22/01/98	47	3	94	67	22	68
29/01/98	50	5	90	100	31	69
11/02/98	48	4	92	74	18	76
25/02/98	51	3	94	86	20	77
04/03/98	52	3	94	78	19	75
19/03/98	42	4	90	74	28	62
08/04/98	37	4	90	84	30	64
29/04/98	48	3	93	82	25	70
13/05/98	35	3	92	78	23	70
27/07/98	33	2	94	85	21	76
10/06/98	34	2	94	78	17	78
25/06/98	43	2	95	93	18	81
08/07/98	41	2	95	89	15	83
29/07/98	47	2	95	91	13	85
12/08/98	50	2	95	90	11	87
mean	41	5	87	74	19	75
std error	1	1	3	3	2	2
median	40	3	93	74	18	77
min	31	1	15	36	6	45
max	64	43	97	101.	45	92

Table 5. Ammonia nitrogen monitoring, A – reed bed with wastewater after biological treatment, B – reed bed with wastewater after primary mechanical treatment, C_o – initial inlet pollution concentration (mg dm^{-3}), C_e – final outlet pollution concentration (mg dm^{-3}), η – efficiency of pollution removal (%)

Date	A	A	A	B	B	B
	C_o	C_e	η	C_o	C_e	η
13/11/96	24	22	10	75	20	73
27/11/96	33	20	39	78	32	60
11/12/96	28	6	78			
24/02/97	36	6	83			
20/03/97	29	13	55	45	17	63
09/04/97	30	2	94	50	4	93
23/04/97	25	0	98			
08/05/97	25	1	96	39	3	92
15/05/97	29	2	93	43	7	83
04/06/97	27	1	98	49	6	87
25/06/97	29	1	98	42	5	89
09/07/97	27	1	95	43	6	86
23/07/97	28	1	96	29	4	87
06/08/97	35	1	98			
20/08/97	27	1	97	47	8	84
27/08/97	26	1	96	42	10	77
01/10/97	27	1	95	51	7	87
09/10/97	27	1	97	53	4	92
30/10/97	29	1	98	48	15	69
18/11/97	31	0	98	45	18	60
27/11/97	31	0	98	44	19	58
04/12/97	30	5	84	49	19	60
22/01/98	31	1	96	46	15	68
29/01/98	31	2	93	74	23	69
11/02/98	31	2	93	50	13	74
25/02/98	31	1	96	57	13	77
04/03/98	31	2	94	52	13	75
19/03/98	28	2	93	46	19	58
08/04/98	29	2	95	54	22	59
29/04/98	31	2	94	55	7	88
13/05/98	14	1	93	53	12	78
27/07/98	23	1	95	56	11	79
10/06/98	18	1	96	51	8	83
25/06/98	23	1	95	67	8	88
08/07/98	22	1	97	60	7	88
29/07/98	26	1	97	65	4	94
12/08/98	28	1	96	63	6	90
mean	28	3	90	52	12	78
std error	1	1	3	2	1	2
median	28	1	95	50	10	79
min	14	0	10	29	3	58
max	36	22	98	78	32	94

Table 6. Nitrite nitrogen monitoring, A – reed bed with wastewater after biological treatment, B – reed bed with wastewater after primary mechanical treatment, C_o – initial inlet pollution concentration (mg dm^{-3}), C_e – final outlet pollution concentration (mg dm^{-3})

Date	A	A	B	B
	C_o	C_e	C_o	C_e
13/11/96	0.020	1.202	0.061	0.722
27/11/96	0.050	0.490	0.180	0.725
11/12/96	0.049	0.130		
24/02/97	0.049	1.170		
20/03/97	0.050	0.150	0.020	0.075
09/04/97	0.040	0.230	0.035	0.900
23/04/97	0.036	0.090		
08/05/97	0.040	1.650	0.035	1.500
15/05/97	0.025	0.135	0.016	1.550
04/06/97	0.020	1.850	0.025	1.100
25/06/97	0.026	0.754	0.070	0.850
09/07/97	0.035	0.260	0.021	0.765
23/07/97	0.021	0.158	0.021	0.363
06/08/97	0.040	0.115		
20/08/97	0.044	0.082	0.000	1.228
27/08/97	0.032	0.061	0.015	0.433
01/10/97	0.044	0.114	0.069	0.606
09/10/97	0.015	0.139	0.015	0.584
30/10/97	0.038	0.157	0.026	0.628
18/11/97	0.089	0.144	0.072	0.540
27/11/97	0.035	0.136	0.029	0.544
04/12/97	0.041	0.321	0.027	0.531
22/01/98	0.053	0.471	0.050	0.847
29/01/98	0.072	0.162	0.069	0.496
11/02/98	0.068	0.198	0.059	0.540
25/02/98	0.035	0.207	0.053	0.429
04/03/98	0.052	0.230	0.061	0.630
19/03/98	0.021	0.230	0.078	0.630
08/04/98	0.031	0.352	0.069	0.810
29/04/98	0.024	0.227	0.029	1.217
13/05/98	0.051	0.420	0.042	0.960
27/07/98	0.048	0.210	0.057	0.720
10/06/98	0.040	0.330	0.029	0.521
25/06/98	0.051	0.410	0.068	0.498
08/07/98	0.049	0.820	0.059	0.480
29/07/98	0.056	0.416	0.071	0.513
12/08/98	0.029	0.310	0.058	0.510
mean	0.041	0.393	0.048	0.710
std error	0.003	0.070	0.006	0.056
median	0.040	0.230	0.050	0.628
min	0.015	0.061	0.000	0.075
max	0.089	1.850	0.180	1.550

Table 7. Nitrate nitrogen monitoring, A – reed bed with wastewater after biological treatment, B – reed bed with wastewater after primary mechanical treatment, C_o – initial inlet pollution concentration (mg dm^{-3}), C_e – final outlet pollution concentration (mg dm^{-3})

Date	A	A	B	B
	C_o	C_e	C_o	C_e
13/11/96	2.27	6.50	6.50	9.75
27/11/96	0.12	14.10	0.45	7.50
11/12/96	0.35	15.00		
24/02/97	1.80	17.25		
20/03/97	0.17	8.30	0.32	4.50
09/04/97	0.24	15.00	0.37	23.00
23/04/97	0.20	19.60		
08/05/97	0.17	15.00	0.39	18.40
15/05/97	0.30	14.20	0.40	20.00
04/06/97	0.26	33.20	0.35	28.00
25/06/97	0.32	26.80	0.33	26.80
09/07/97	0.20	27.10	0.25	23.38
23/07/97	0.37	20.14	0.37	29.32
06/08/97	0.75	25.00		
20/08/97	0.35	30.30	0.00	24.97
27/08/97	0.40	31.58	0.61	20.43
01/10/97	0.35	35.15	1.49	23.53
09/10/97	0.35	29.13	0.52	21.01
30/10/97	0.42	31.84	0.45	10.33
18/11/97	0.45	34.64	0.50	11.17
27/11/97	0.53	34.64	0.47	9.20
04/12/97	0.45	33.11	0.63	6.75
22/01/98	0.32	41.28	0.42	19.44
29/01/98	0.40	30.16	0.84	9.06
11/02/98	0.38	36.12	0.74	14.56
25/02/98	0.40	37.19	0.67	21.78
04/03/98	0.41	35.86	0.69	17.43
19/03/98	0.25	31.12	0.86	21.42
08/04/98	0.32	33.14	0.78	18.60
29/04/98	0.47	35.41	0.63	7.65
13/05/98	0.43	30.12	0.79	9.24
27/07/98	0.39	33.12	0.81	11.80
10/06/98	0.39	41.10	0.63	6.78
25/06/98	0.36	35.12	0.85	9.07
08/07/98	0.41	39.60	0.68	18.62
29/07/98	0.37	32.11	0.85	9.24
12/08/98	0.42	38.40	0.69	13.12
mean	0.45	28.30	0.77	15.93
std error	0.07	1.55	0.18	1.24
median	0.37	31.58	0.63	17.43
min	0.12	6.50	0.00	4.50
max	2.27	41.28	6.50	29.32

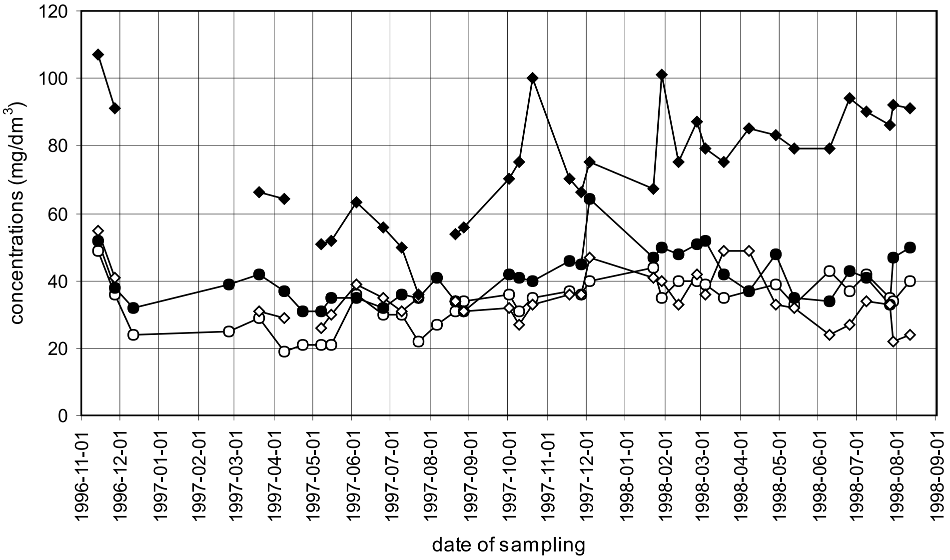

Fig. 5. Total nitrogen (mg/dm^3) in inflow (black circles) and outflow (open circles) for wastewater after biological treatment (bed A); total nitrogen (mg/dm^3) in inflow (black diamonds) and outflow (open diamonds) for wastewater after mechanical treatment (bed B)

removal is efficient, whereas total nitrogen removal is not. This is due to conversion in the bed of ammonia and organic N to nitrite and nitrate (Tables 6 and 7). Consequently, denitrification losses and plant uptake would appear to be small, perhaps due to the aerobic environment of VF beds allowing oxidation but not also denitrification.

Total phosphorus was eliminated only to a limited extent (see Table 8). All forms of phosphorus (total phosphorus and orthophosphates) were similar in input and output wastewaters. Phosphorus is kept in very limited amounts here by calcium, aluminium and iron ions and by organic matter on the surface of sand and gravel. In some periods the concentrations of phosphorus in the output were higher than in inputs, indicating the small retention and easy outflow of phosphorus from gravel beds. The mean efficiency of total phosphorus removal from wastewater after mechanical treatment in reed bed B was about 18%. In reed bed A irrigated by wastewater after mechanical and biological treatment the efficiency of removal of total phosphorus was only 8%. For orthophosphates (PO_4^{3-}) the efficiency of removal was 11% in reed bed B and 3% in reed bed A.

The coliform bacterial index was very changeable, possibly due to the random influence of wild birds and small mammals.

Under Polish environmental regulations the permissible concentrations in treated wastewater outflows were, during experiments: total suspended solids < 50 mg dm^{-3}; BOD_5 < 30 mg dm^{-3}; total nitrogen < 30 mg dm^{-3}; ammonia nitrogen

Table 8. Total phosphorus monitoring, A – reed bed with wastewater after biological treatment, B – reed bed with wastewater after primary mechanical treatment, C_o – initial inlet pollution concentration (mg dm^{-3}), C_e – final outlet pollution concentration (mg dm^{-3}), η – efficiency of pollution removal (%)

Date	A	A	A	B	B	B
	C_o	C_e	η	C_o	C_e	η
13/11/96	6.01	4.72	21	17.16	4.50	73
27/11/96	6.93	8.25	–19	18.48	3.96	78
11/12/96	5.94	6.60	–11			
24/02/97	9.90	10.23	–3			
20/03/97	8.91	8.25	7	10.89	7.76	29
09/04/97	10.89	9.41	14	14.19	7.59	46
23/04/97	9.41	8.25	12			
08/05/97	7.92	8.84	–12	13.53	9.17	32
15/05/97	9.24	6.60	29	13.20	8.81	33
04/06/97	7.92	8.25	–4	12.05	9.24	23
25/06/97	8.75	8.25	6	12.61	10.23	19
09/07/97	8.05	6.80	16	12.41	8.05	35
23/07/97	6.07	5.81	4	4.75	7.46	–57
06/08/97	9.90	8.58	13			
20/08/97	5.47	5.87	–7	10.81	7.28	32.65
27/08/97	6.36	5.86	8	7.47	6.79	9
01/10/97	5.79	5.87	–1	9.51	8.46	11
09/10/97	6.54	6.48	1	8.08	7.22	11
30/10/97	6.24	5.45	13	8.92	6.24	30
18/11/97	9.25	7.56	18	8.98	9.59	–7
27/11/97	7.34	6.48	12	10.09	7.97	21
04/12/97	7.06	5.35	24	11.09	9.36	16
22/01/98	5.71	5.31	7	8.93	8.06	9.79
29/01/98	7.36	6.69	9	12.75	8.38	34
11/02/98	7.62	6.84	10	11.25	8.36	26
25/02/98	7.76	6.87	11	10.74	8.11	24
04/03/98	6.94	5.78	17	9.78	8.92	9
19/03/98	5.14	5.07	1	17.24	15.89	8
08/04/98	6.83	5.92	13	13.40	11.90	11
29/04/98	21.62	21.35	1	27.70	50.40	-82
13/05/98	11.20	9.80	12	12.60	11.82	6
27/07/98	9.60	8.73	9	10.16	9.12	10.24
10/06/98	8.70	8.25	5	9.34	8.11	13
25/06/98	7.60	6.12	19	12.42	8.78	29
08/07/98	6.24	5.86	6	10.13	9.01	11
29/07/98	6.38	5.89	8	11.08	8.93	19
12/08/98	7.12	6.04	15	11.40	9.01	21
mean	7.99	7.36	8	11.91	9.83	18
std error	0.46	0.45	2	1	1.32	5
median	7.36	6.60	9	11.09	8.46	19
min	5.14	4.72	–19	4.75	3.96	–82
max	21.62	21.35	29	27.70	50.40	78

< 6 mg dm^{-3}; nitrate nitrogen < 30 mg dm^{-3}; total phosphorus < 5 mg dm^{-3} (for USA see: Bastian et al 1989). In most cases these requirements were met, with the exception of phosphorus and some total nitrogen samples.

Changes in wastewater pollution loads have been calculated from the product of pollution concentration and the inflow volumes and used to compare the removal performance of reed beds:

$$R_r = Q(C_o - C_e)/A, \tag{6}$$

where A is the surface area of the reed bed (m^2). The rates of removal of BOD$_5$ and of total nitrogen expressed on a daily basis and per unit area of reed bed (g m^{-2} d^{-1}), were compared with respect to the measured temperatures of the reed beds (Figs. 6 and 7).

The rate of removal of BOD$_5$ was higher for higher temperatures, the linear regression relationship being highly significant for reed bed B, but only marginally so for A (Fig. 6). In both cases there is a high degree of scatter (R^2), especially for B at higher temperatures. The regression slopes for reed beds A and B differ only marginally ($p = 0.051$).

$$R_r(T),\quad R_r = 2.61 + 0.239T \text{ (reed bed A)}:\ p = 0.048,\quad R^2 = 0.12,$$

$$R_r(T),\quad R_r = 0.35 + 0.639T \text{ (reed bed B)}:\ p = 0.001,\quad R^2 = 0.36.$$

In winter the mean wastewater temperatures T were never below 8–10°C (even during frosty days) and in summer were in the range 20–22°C. At higher temperatures, reed bed B (wastewater after mechanical treatment) was eliminating almost two times more BOD$_5$ than reed bed A (wastewater after mechanical and biological treatment) and the removal rates were much more variable than in winter (Fig. 6). The rate of removal of BOD$_5$ varied between 5 and 25 g O$_2$ m^{-2} day^{-1} for wastewater after mechanical treatment (bed B); and between 2 and 15 g O$_2$ m^{-2} day^{-1} for wastewater after mechanical and biological treatment (bed A).

In the case of total nitrogen removal, in neither bed A nor B was there any apparent relationship with temperature (Fig. 7), nor did the slopes differ significantly ($p = 0.606$).

$$R_r(T),\quad R_r = 0.634 - 0.0158T \text{ (reed bed A)}:\ p = 0.214,\quad R^2 = 0.005,$$

$$R_r(T),\quad R_r = 1.96 + 0.0043T \text{ (reed bed B)}:\ p = 0.909,\quad R^2 = 0.001.$$

The rate of removal of total nitrogen varied widely between 0.05 and 3.5 g m^{-2} day^{-1} for wastewater after mechanical treatment (bed B); and between 0 and 1.2 g m^{-2} day^{-1} for wastewater after mechanical and biological treatment (bed A).

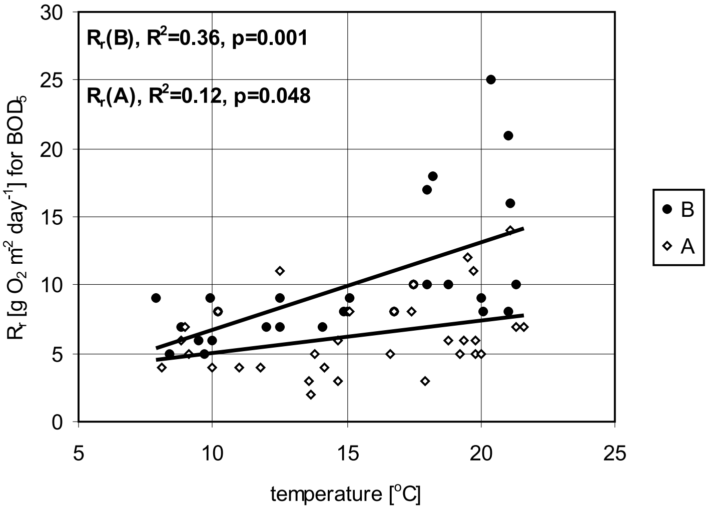

Fig. 6. Rate of pollution removal R_r [g O_2 m^{-2} day^{-1}] for BOD_5

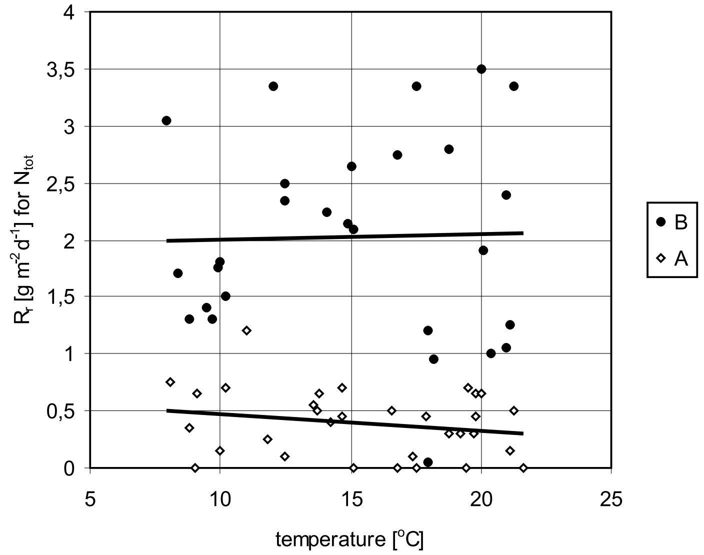

Fig. 7. Rate of polution removal R_r [g O_2 m^{-2} day^{-1}] for N_{tot}; for R_r(B) $R^2 = 0.001$, $p = 0.909$; for R_r(A) $R^2 = 0.0051$, $p = 0.214$

5. Conclusions

This paper presents new results of a controlled study of two 20 m^2 and 0.6 m deep vertical subsurface flow constructed wetland reed beds in Poland, one receiving primary effluent (B), and the other secondary effluent (A). Data tables and figures are provided for most values measured.

Both reed beds show high efficiency of eliminating suspended solids, BOD_5, Kjeldahl nitrogen and ammonia nitrogen. Elimination of nitrogen pollution stabilised after one year of operation of the reed beds.

The removal rate for BOD_5 was about twice as big in reed bed B as in A, whereas for total N it was about 4 times as big. Rates of BOD_5 removal varied 3-fold with temperature in reed bed B (5 g O_2 m^{-2} day^{-1} at 8°C and 15 g O_2 m^{-2} day^{-1} at 22°C), but less so in reed bed A (rates 4 and 7 g O_2 m^{-2} day^{-1} respectively).

This difference between summer and winter indicates that the surface area of constructed wetland B should be about 3 times bigger during winter to obtain the summer rate of BOD_5 pollution removal in the climatic conditions of North Poland (54°N). The results clearly indicate the effect of temperature (T) on rate constant (k) for BOD_5 removal, but the loading rate (QC_o/A) also varies with temperature. The rate constant (k) is a functional parameter, not a true constant value.

The vertical flow reed bed was not efficient for removal of phosphorus.

Mathematical relationships are now available for estimating a system's ability to remove major pollutants.

Acknowledgements

This research was supported by a grant of Polish Committee on Research and Development (KBN), No. 084/P04/95/08 and by School of Biosciences, Cardiff University, U.K., "Salix Project". Great appreciation is given to the SAUR NEPTUN GDAŃSK Co. for the kind offer of the terrain, installations and buildings at the WWTP ZASPA Gdańsk, making the field research possible.

References

Armstrong W., Armstrong J., Beckett P. M. (1990), Measurement and Modelling of Oxygen Release from Roots of *Phragmites australis*, In: P. F. Cooper and B. C. Findlater (Eds.) *Proceedings of International Conference on the Use of Constructed Wetlands in Water Pollution Control*, Cambridge, UK, 41–51.

Bastian R. K., Shanagan P. E., Thompson B. P. (1989), Use of Wetlands for Municipal Waste Water Treatment and Disposal – Regulatory Issues and EPA Policies, In: D. A. Hammer (Ed.) *Constructed Wetlands for Waste Water Treatment, Municipal, Industrial and Agricultural*, Lewis Publishers, Chelsea, Michigan, 265–278.

Belfiore N. A. (1997), *A Pilot Study of a Vertical flow Constructed Wetland at 'ZASPA', Gdańsk, Poland*, MSc Thesis, Supervisor Dr P. F. Randerson, Department of Pure and Applied Biology, University of Cardiff, Wales, UK, p. 117.

Brix H. (1987), Treatment of Wastewater in the Rhizosphere of Wetland Plants – the Root-Zone Method, *Wat. Sci. Tech.,* 19, 107–119.

Brix H. (1990), Gas Exchange through the Soil-Atmosphere Interface and through Dead Culms of *Phragmites Australis* in a Constructed Reed Bed Receiving Domestic Sewage, *Wat. Sci. Tech.* 24(2), 259–266.

Brix H. (1993a), Wastewater Treatment in Constructed Wetlands: System Design, Removal Processes and Treatment Performance, In: G. A. Moshiri (Ed.) *Constructed Wetlands for Water Quality Improvement*, CRC Press, Boca Raton, 9–22.

Brix H. (1993b), Macrophyte-Mediated Oxygen Transfer in Wetlands: Transport Mechanism and Rates, In: G. A. Moshiri (Ed.) *Constructed Wetlands for Water Quality Improvement,* CRC Press, Boca Raton, 391–398.

Brix H., Schierup H. H. (1990), Soil Oxigenation in Constructed Reed Beds: the Role of Macrophyte and Soil-Atmosphere Interface Oxygen Transport, In: P. F. Cooper and B. C. Findlater (Eds.) *Proceedings of International Conference on the Use of Constructed Wetlands in Water Pollution Control*, Cambridge, UK, 53–66.

Cooper P. F., Job G. D., Green M. B., Shutes R. B. E. (1996), *Reed Beds and Constructed Wetlands for Wastewater Treatment,* WRc Swindon, UK, p. 184.

EPA Design Manual (1988), *Constructed Wetlands and Aquatic Plant Systems for Municipal Waste Water Treatment: Design Manual,* US EPA Publication 625/1-88/022, Cincinnati, USA, p. 83.

EPA Design Manual (1993), *Subsurfacee Flow Constructed Treatment Wetlands: Technology and Assessment,* US EPA Publication 832/R-93-008, Cincinnati, USA.

EPA Design manual (1999), *Constructed Wetland Treatment of Municipal Wastewater,* US EPA Publication 625/R-99/010, Cincinnati, USA.

Felde K., Kunst S. (1996), N and COD Removal in Vertical Flow Systems, In: *Proceedings of the 5th International Conference on Wetland Systems for Water Pollution Control*, Vienna, I/8-1 – I/8-8.

Fry J. C. (1993), *Biological Data Analysis, a Practical Approach*, IRL Press, Oxford, p. 418.

Heritage A., Pistillo P., Sharma K. P., Lantzke I. R. (1995), Treatment of Primary-Settled Urban Sewage in Pilot-Scale Vertical Flow Wetland Filters: Comparison of Four Emergent Macrophyte Species over a 12 Month Period, *Wat. Sci. Tech.,* 32(3), 295–304.

Hiley P. D. (1995), The Reality of Sewage Treatment using Wetlands, *Wat. Sci. Tech.,* 32(3), 329–338.

Kickuth R. (1981), Abwasserreinigung in Mosaikmatrizen aus Anaeroben und Aeroben Teilbezierken, *Grundlangen der Abwasserreiningung, GWF Schriftreihe Wasser-Abwasser,* 19, Oldenburg Verlag, Oldenburg.

Kowalik P. J., Obarska-Pempkowiak H. (1985), Determination of the Permissible Amount of Liquid Animal Waste Applied to Soil Filters, *Agricultural Water Management*, 10, 313–326.

Kowalik P. J., Barnes C. J., Smiles D. E. (1979), Oxidation of Liquid Animal Wastes in Soil, *Soil Science Society of America Journal*, 43(2), 255–260.

Kowalik P. J., Mierzejewski M., Obarska-Pempkowiak H., Toczyłowska I. (1995), *Constructed Wetlands for Wastewater Treatment of Small Communities,* Center of Environmental Studies, CENVIG, Gdańsk University of Technology, p. 70.

Mierzejewski M. (1999), *Efficiency of the Elimination of Nutrients on the Reed Beds with Vertical Flow*, PhD Thesis, Gdańsk University of Technology, Poland, p. 165 (in Polish).

Mitchell D. S., Chick A. J., Raisin G. W. (1995), The use of Wetlands for Water Pollution Control in Australia: an Ecological Perspective, *Wat. Sci. Tech.,* 32(3), 365–373.