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Horizontal sub-surface flow constructed wetlands Ondřejov and Spálené Poříčí in the Czech Republic – 15 years of operation

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Abstract

Horizontal sub-surface flow constructed wetlands (HF CWs) Ondřejov and Spálené Poříčí have been in operation since 1991 and 1992, respectively, and are the oldest systems in the Czech Republic. CW Ondřejov treats sewage from 362 PE in a single 806 m^2 bed planted with *Phragmites australis*. CW Spálené Poříčí treated wastewater from 700 PE from a combined sewerage until 2001 and then another part for additional 700 PE was completed in 2002. At present, there are six beds planted with a mixture of *P. australis* and *Phalaris arundinacea* with a total area of 5000 m^2. Constructed wetland Ondřejov treatment performance has been very steady over the period of operation and exhibited "typical" efficiency for organics (average BOD_5 inflow and outflow concentrations of 198 mg l^{-1} and 18 mg l^{-1}, respectively) and suspended solids (average inflow and outflow concentrations 204 mg l^{-1} and 9 mg l^{-1}, respectively). Removal of phosphorus is steady but low with average inflow and outflow concentrations of 10.9 mg l^{-1} and 6.5 mg l^{-1}, respectively. Average ammonia-N removal amounted to only 19.4% with an average outflow concentration of 22.8 mg l^{-1}. Constructed wetland at Spálené Poříčí treated diluted wastewater until 2002. After that about 700 people were connected directly to the sewerage without local pretreatment. The average inflow and outflow BOD_5 concentrations for the whole period were 44.2 and 5.7 mg l^{-1}, respectively. Average TSS removal amounted to 89.1% with an average outflow concentration of 7.9 mg l^{-1}. Both systems are examples of well-operated constructed wetlands.

Keywords: Czech republic; Constructed wetlands; *Phragmites australis*; Sub-surface flow

1. Introduction

Constructed wetlands are engineered systems that have been designed and constructed to utilize the natural processes for removal of pollutants. They are designed to take an advantage of many of the same processes that occur in natural wetlands, but do so within a more controlled environment. Constructed wetlands

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have been used for wastewater treatment for about 40 years. The technology of wastewater treatment by means of constructed wetlands with horizontal sub-surface flow constructed wetlands (HF CWs) was started in Germany based on research by Käthe Seidel commencing in the 1950s [1–5] and by Reinhold Kickuth in the 1970s [6–9].

The first full-scale HF Kickuth's type CW for treatment of municipal sewage was put in operation in 1974 in the community Liebenburg-Othfresen, Germany [6]. The results from this system were exceptionally good but the validity of these data has later been seriously questioned [10]. In 1981, HF constructed wetland was built in Weinitzen near Graz, Austria [11], and in 1983, a large experimental 4-bed HF system was built in Mannersdorf, Austria. The research unit has been intensively investigated between 1983 and 1989 [12,13].

In 1983, German ideas were introduced in Denmark and by 1987 about 80 HF CWs were built [14,15]. In 1985, following visits to existing German and Danish systems, first two HF CWs were built in the United Kingdom (here called reed bed treatment systems) and by the end of 1986, more than 20 HF CWs were designed [16]. In the 1990s, HF CWs were built in many European countries and became the most widely used concept in Europe [17].

Horizontal flow constructed wetlands in Europe are mostly used to treat municipal or domestic wastewater [17–20]. However, recently HF CWs have been used for various types of polluted waters including agricultural wastewaters [21–25], industrial wastewaters [26–34], stormwater run-off [35–39] and landfill leachate [40–45].

The first constructed wetland in the Czech Republic was built in 1989. However, this system was just a temporary solution, and therefore it was closed after few years of operation. Constructed wetlands in Ondřejov and Spálené Poříčí were built in 1991 and 1992 [46], respectively, and these systems are still in operation. The objective of this paper is to describe the treatment performance of these systems over the 15-year period of operation.

2. Material and methods

Constructed wetland Ondřejov, the first full-scale operational constructed wetland in the Czech Republic, was built in late 1991. It consists of a horizontal grit chamber, Imhoff tank and a single 806 m^2 bed filled with gravel (3–15 mm) and planted with common reed (*Phragmites australis*) (Fig. 1). It is designed for 362 PE, and the average measured flow over the monitored period was 56.3 $m^3 d^{-1}$. Constructed wetland in Spálené Poříčí near Pilsen in western Bohemia was built in late 1992 for 700 PE (Fig. 2). It consisted of Vortex-type grit chamber, Imhoff tank and four beds (2500 m^2 total area, 625 m^2 each) filled with gravel (2–4 mm) and planted with *P. australis* and reed canary grass (*Phalaris arundinacea*) planted in bands perpendicular to water flow. In 2001, another part of equal size was added to treat wastewater from 700 PE. This time two beds (1250 m^2 each) were filled with gravel (4–16 mm) and planted with the same plants as the first wetland (Fig. 2). The average flow over the monitored period was 201 $m^3 d^{-1}$.

Both constructed wetlands were sampled for BOD_5, COD, TSS, TP, ammonia-N, and TN; CW Ondřejov was also sampled for nitrate-N and TKN. CW Ondřejov was sampled bimonthly until 1996; since then it has been sampled mostly quarterly. CW Spálené Poříčí was sampled monthly until 1999; since then it has been sampled bimonthly. All analyses were performed according to the Czech National Analytical Standards [47].

In both wetlands, sampling of aboveground biomass of *Phragmites* was carried out until 2003. Aboveground biomass was sampled during the peak standing crop in the period end-August

Fig. 1. Constructed Wetland Ondřejov. Top = overall layout; bottom = detail of the inflow distribution zone. Photos by Jan Vymazal.

to mid-September. Plant shoots were cut at the ground level, separated into stems and leaves including sheaths and inflorescence, and dried at 70°C to a constant weight. Two samples from the inflow and two samples from the outflow zones were taken from a 0.25 m^2 quadrant every year. The vegetation in Spálené Poříčí was regularly mowed in early spring every year. Constructed wetland at Ondřejov was harvested only once, in winter 2000/2001.

3. Results and discussion

Constructed wetland Ondřejov treatment performance has been steady over the period of operation and exhibited "typical" efficiency for organics (Table 1, average BOD_5 raw, inflow and outflow concentrations of 192 $mg\,l^{-1}$, 157 $mg\,l^{-1}$ and 18 $mg\,l^{-1}$, respectively, and average COD raw, inflow and outflow concentrations of 432 $mg\,l^{-1}$, 344 $mg\,l^{-1}$ and 53 $mg\,l^{-1}$,

Fig. 2. Constructed Wetland Spálené Poříčí. Top = few months after start-up in December 1992; bottom = new wetland cells built in 2001. Photos by Jan Vymazal.

respectively) and suspended solids (Table 2, average raw, inflow and outflow concentrations of 170 mg l^{-1}, 137 mg l^{-1} and 8.3 mg l^{-1}, respectively). Organic loading of vegetated beds was quite high with an average value of 110 kg $BOD_5 ha^{-1}$ d^{-1} resulting in an average specific area of 5.5 m^2 PE^{-1}. Removal of phosphorus (Table 2) is steady but low with average raw, inflow and outflow concentrations of 11.6 mg l^{-1}, 10.1 mg l^{-1} and 7.0 mg l^{-1}, respectively. Average ammonia-N removal (Table 3) amounted to only 14.8% (and 23.9% for vegetated beds only) with an average outflow concentration of 24.2 mg l^{-1}. The system performed well in terms of nitrate removal (Table 3) with an average outflow NO_3-N concentration of only 0.58 mg l^{-1}. The average removal of total nitrogen (Table 4) was 41%

Table 1
Removal of BOD_5 and COD in constructed wetland Ondřejov during the period 1991–2004. Raw = raw wastewater; In = inflow to vegetated beds after pretreatment; Out = final outflow. Minimum and maximum values in parentheses

	BOD_5 ($mg\,l^{-1}$)			COD ($mg\,l^{-1}$)		
	Raw	In	Out	Raw	In	Out
1991	168 (90–233)	146 (90–177)	16 (6.2–26)	660 (390–1100)	387 (270–540)	62 (30–95)
1992	161 (40–420)	138 (20–354)	38 (1–67)	254 (70–420)	231 (105–440)	74 (10–210)
1993	152 (44–290)	108 (19–185)	28 (11–57)	445 (110–975)	315 (53–470)	88 (38–135)
1994	330 (15–1350)	114 (19–200)	16 (5.2–30)	719 (61–2550)	273 (69–480)	57 (24–120)
1995	83 (15–235)	80 (42–130)	13 (4.1–33)	188 (56–547)	189 (94–339)	35 (19–75)
1996	106 (52–189)	65 (21–175)	13 (1.6–52)	207 (191–237)	172 (53–480)	44 (18–104)
1997		83 (27–145)	13 (3.8–23)		217 (100–360)	45 (32–60)
1998		104 (49–175)	12 (5.1–19)		223 (120–330)	33 (18–45)
1999		378 (125–630)	27 (13–41)		935 (370–1500)	79 (43–115)
2000		438 (130–970)	30 (27–33)		670 (350–1200)	68 (66–70)
2002	169 (98–261)	143 (59–250)	15 (8.3–26)	190 (145–275)	334 (133–540)	36 (25–42)
2003	408 (155–670)	185 (170–200)	11 (7.9–14)	1047 (340–1700)	363 (330–395)	40 (28–52)
2004	148 (31–460)	63 (43–100)	6 (3.8–8)	182 (89–370)	160 (90–255)	26 (24–31)
Mean	**192**	**157**	**18.3**	**432**	**344**	**53**

Table 2
Removal of TSS and TP in constructed wetland Ondřejov during the period 1991–2004. Raw = raw wastewater; In = inflow to vegetated beds after pretreatment; Out = final outflow. Minimum and maximum values in parentheses

	TSS ($mg\,l^{-1}$)			TP ($mg\,l^{-1}$)		
	Raw	In	Out	Raw	In	Out
1991	108 (56–188)	50 (6.5–84)	5.3 (1–12.5)	14.2 (7.6–17.9)	12.6 (9.3–14.3)	2.5 (0.9–4.1)
1992	44 (8–141)	73 (6–236)	10.0 (3.5–28)	17.7 (3.9–20)	23.8 (5.7–23)	21.1 (7–25)
1993	257 (85–758)	158 (24–290)	17.6 (5–28)	6.4 (5.3–8.1)	6.6 (3–11.8)	5.8 (2.2–9.8)
1994	304 (25–941)	61 (22–136)	3.0 (0.2–7.2)	12.6 (1.7–33)	12.7 (2.9–18.8)	6.8 (1.3–11.8)
1995	67 (31–178)	67 (34–93)	5.2 (2.8–7.6)	4.2 (1.0–9.0)	5.3 (2.8–10.9)	4.8 (2.6–9.7)
1996	36 (24–50)	109 (18–352)	8.8 (2.0–20)		3.2 (1.6–6.7)	1.9 (0.6–3.4)
1997		116 (43–238)	22.5 (4.8–42)		8.5 (2.7–12)	6.0 (1.4–9.0)
1998		95 (77–141)	3.6 (3.1–4.4)		5.9 (4.2–7.7)	5.4 (1.8–7.8)
1999		417 (74–760)	6.5 (3.1–44)		14.7 (13.6–15.8)	8.1 (7.4–8.7)
2000		323 (191–598)	7.7 (5–13)		12.3 (8.0–15.3)	10.1 (8.8–12)
2002	66 (3.8–94)	129 (44–256)	2.4 (2.0–3.0)	8.3 (6.3–11.6)	8.8 (4.7–10.9)	7.0 (3.5–11.4)
2003	463 (203–806)	88 (50–125)	8.8 (4.5–13)	24.0 (10–51)	13.3 (1.5–18.1)	7.7 (5.0–12.6)
2004	183 (63–450)	100 (72–127)	6.1 (4.2–10)	5.0 (1.6–14)	4.0 (2.2–6.6)	4.0 (2.2–5.0)
Mean	**170**	**137**	**8.3**	**11.6**	**10.1**	**7.0**

Table 3
Removal of NH_4^+-N and NO_3^--N in constructed wetland Ondřejov during the period 1991–2004. Raw = raw wastewater; In = inflow to vegetated beds after pretreatment; Out = final outflow. Minimum and maximum values in parentheses

	NH_4^+-N (mg l^{-1})			NO_3^--N (mg l^{-1})		
	Raw	In	Out	Raw	In	Out
1992	19.6 (3.3–47.6)	23.5 (5.1–48.2)	17.8 (6.7–35)	0.80 (0–3.2)	0.40 (0–2.1)	0.20 (0–0.8)
1993	29.8 (16.4–55.2)	28.6 (12.5–54.5)	22.6 (12.6–37.3)	1.20 (0–2.2)	1.50 (0–5.7)	0.60 (0–1.2)
1994	39.1 (5.8–77)	35.6 (7.3–62)	21.6 (0.8–38)	1.30 (0–5.2)	2.10 (0–6.6)	1.40 (0–1.7)
1995	17.7 (4–46)	20.8 (9.1–52)	17.0 (7–31)	4.30 (0–13)	3.10 (0–8.2)	0.70 (0–1.9)
1996		14.0 (8.7–18.2)	10.7 (3.6–10.7)		4.50 (0–12)	2.90 (0–11)
1997		40.7 (10–60)	23.0 (7.9–34)		3.10 (0–9.3)	0.40 (0–1.2)
1998		18.3 (11.8–31.1)	25.5 (14–31.7)		4.90 (0–9.0)	0
1999		48.1 (37.7–58.4)	40.0 (32.5–47.5)		0.07 (0–0.2)	0
2000		55.3 (45.3–62.5)	41.6 (34.5–46.7)		1.20 (0.1–3)	0.70 (0–1.9)
2002	40.3 (23.8–60.5)	35.5 (16.8–53.3)	33.1 (12.2–49.6)	2.70 (0–4.2)	0.10 (0–0.3)	0
2003	39.6 (13–55.2)	49.7 (31.7–67.6)	20.8 (6.6–40)	2.30 (0–4.7)	2.30 (0–4.6)	0
2004	13.0 (4.5–32)	11.1 (8.5–13.8)	17.0 (5–24.5)	5.50 (0–8.3)	4.10 (0–7.4)	0.40 (0–0.6)
Mean	**28.4**	**31.8**	**24.2**	**2.60**	**2.30**	**0.58**

Table 4
Removal of TKN and TN in constructed wetland Ondřejov during the period 1991–2004. Raw = raw wastewater; In = inflow to vegetated beds after pretreatment; Out = final outflow. Minimum and maximum values in parentheses

	TKN (mg l^{-1})			TN (mg l^{-1})		
	Raw	In	Out	Raw	In	Out
1993	46.9 (23–120)	39.8 (18–70)	28.1 (16–42)	48.4 (26–120)	41.8 (24–70)	28.8 (17–44)
1994	61.6 (11–102)	46.9 (12–74)	26.5 (5.3–46)	63.2 (12–105)	49.8 (20–77)	28.0 (11–47)
1995	29.7 (6.8–66)	30.4 (15–59)	20.4 (10–39)	34.3 (11–67)	34.6 (20–61)	21.1 (12–40)
1996		21.6 (12–39)	12.4 (6.4–21)		26.1 (18–40)	15.4 (11–21)
1997		54.0 (13–79)	26.5 (8.9–39)		57.2 (23–79)	27.0 (11–39)
1998		30.6 (20–46)	28.8 (14–37)		36.3 (28–46)	28.8 (14–37)
1999		86.2 (81–91)	49.0 (42–56)		86.9 (81–92)	49.0 (42–56)
2000		80.3 (57–121)	43.1 (35–47)		81.5 (57–124)	44.1 (35–70)
2002	53.6 (41–80)	57.0 (25–85)	34.2 (14–51)	56.3 (39–84)	57.1 (25–86)	34.1 (14–51)
2003	82.2 (70–95)	55.8 (40–72)	28.5 (16–41)	85.2 (76–95)	58.2 (45–72)	28.5 (16–41)
2004	9.8 (6.5–14)	16.3 (9.6–25)	21.1 (17–25)	16.2 (15–17)	20.6 (17–25)	21.6 (17–26)
Mean	**47.3**	**47.2**	**29.0**	**50.6**	**50.0**	**29.7**

but the nitrogen loading to vegetated beds was high with the average value 1146 g Nm^{-2} yr^{-1} and maximum value of 1998 g Nm^{-2} yr^{-1}. Vymazal [48] reported in his review an average nitrogen loading for HF constructed wetlands of 644 g Nm^{-2} yr^{-1}.

Constructed wetland at Spálené Poříčí treated diluted wastewater until 2002 because local septic tanks were left in operation when the first beds were built and also drainage and run-off waters were collected by the sewer system. The annual average inflow BOD_5 concentrations were mostly $< 30\,mg\,l^{-1}$ with the exception of 2000 when two extremely high concentrations were recorded (Table 5). When additional 700 people were connected directly to the sewerage without local pretreatment in 2002, the inflow concentrations increased substantially since 2003 (Table 5). The average inflow BOD_5 concentrations were $24.5\,mg\,l^{-1}$ and $122\,mg\,l^{-1}$ in the first (until 2002) and second periods, respectively. The corresponding outflow concentrations were $4.2\,mg\,l^{-1}$ and $10.3\,mg\,l^{-1}$. A similar increase in inflow concentrations with either slight or no increase in outflow was observed for COD. Average inflow/outflow COD concentrations were $97/26\,mg\,l^{-1}$ and $204/36\,mg\,l^{-1}$, during the periods 1993–2002 and 2003–2006, respectively. There was no substantial difference in inflow TSS concentrations between the two periods because during the first period the inflow concentrations were already high due to stormwater run-off (Table 5). This ability to treat low-strength wastewaters gives HF constructed wetlands advantage over conventional systems, which are not able to handle wastewaters with low organic content. Therefore, HF constructed wetlands could be also used for tertiary treatment with organics and TSS as target parameters. This is already commonly used in the United Kingdom [18]. Also, HF constructed wetlands can successfully cope with fluctuating concentrations of pollutants in the inflow with a stable outflow (Fig. 3). Removal of TP and NH_4-N (Table 6) was quite low but this is a typical feature of HF constructed wetlands [48]. Removal of phosphorus, however, can be enhanced by the use of special media with high sorption capacity, such as lightweight clay aggregates or blast/electric arc furnace steel slags [20].

Table 5
Removal of BOD_5, COD and TSS in constructed wetland Spálené Poříčí during the period 1992–2006. Raw = raw wastewater; Out = final outflow.*26 values per year, Minimum and maximum values in parentheses

	BOD_5 ($mg\,l^{-1}$)		COD ($mg\,l^{-1}$)		TSS ($mg\,l^{-1}$)	
	Raw	Out	Raw	Out	Raw	Out
1992	8.2 (5.5–11)	2.4 (1.4–2.8)				
1993*	30.2 (7–88)	7.3 (2.4–20)	99 (60–143)	30 (15–46)	51.3 (12–94)	5.5 (2–9)
1994	19.6 (2.7–38)	4.4 (1.7–15)	75 (39–164)	26 (14–39)	33.3 (5–124)	4.3 (1–7)
1995	20.0 (2.6–58)	3.1 (1.6–7)	87 (10–220)	19 (9–28)	216 (10–738)	12.2 (1–53)
1996	15.8 (5–33)	3.0 (1–5.6)			160 (7–1084)	8.9 (3.1–26)
1997	13.1 (6.5–39)	3.6 (1.5–6.1)			55 (8–385)	9.0 (3.5–13)
1998	17.6 (4.8–64)	6.7 (3.3–23)	67 (35–155)	33 (10–60)	33.4 (7–138)	11.4 (5.4–30)
1999	15.9 (6.2–40)	3.9 (1.1–8.5)	68 (30–130)	24 (5–55)	21.5 (7–111)	8.8 (1.7–16)
2000	101 (11–450)	3.9 (2.4–6.6)	267 (45–1060)	25 (15–45)	312 (9–1489)	14.3 (3.4–19)
2001	15.8 (8–27)	3.7 (2.6–4.6)	64 (40–90)	26 (20–35)	19.3 (10.5–43)	12.0 (5.8–19)
2002	12.0 (5.9–23)	4.3 (3.0–7.0)	47 (25–85)	25 (16–40)	14.8 (6.2–27)	9.9 (4.4–22)
2003	78 (43–170)	13.1 (9–25)	122 (64–230)	40 (25–51)	54.5 (9–120)	5.0 (0.5–14)
2004	100 (46–220)	6.4 (3.5–14)	170 (68–350)	28 (10–74)	63.6 (21–170)	4.0 (0.5–9.5)
2005	134 (56–220)	9.9 (5.1–14)	224 (86–380)	39 (26–49)	75.7 (18–130)	3.6 (0.5–7)
2006	175 (87–240)	11.8 (9.3–15)	301 (160–410)	38 (21–57)	106 (52–210)	8.8 (4.5–16)
Mean	**50.4**	**5.7**	**133**	**29**	**83.0**	**8.4**

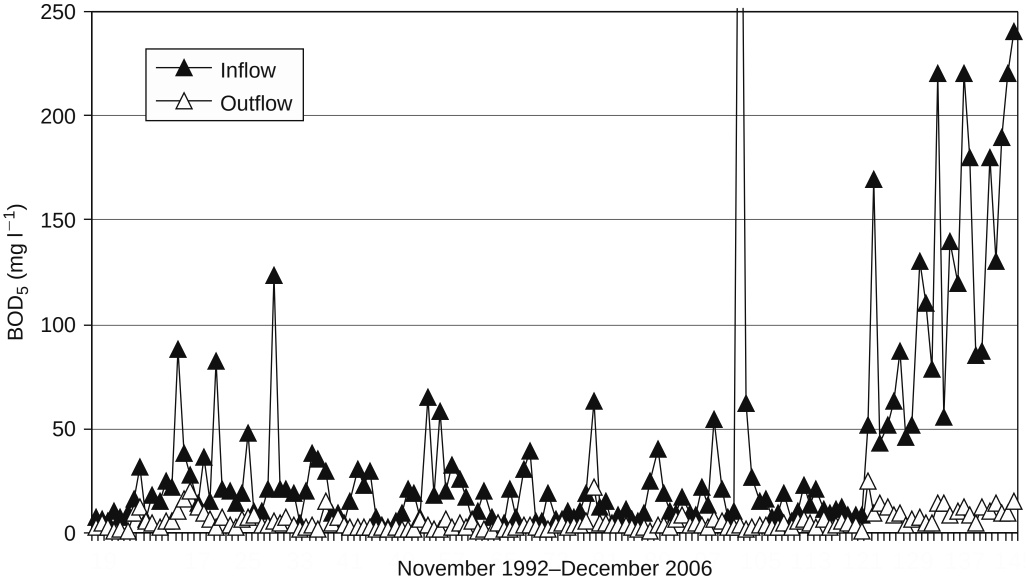

Fig. 3. Removal of BOD_5 in Constructed Wetland Spálené Poříčí During the Period November 1992–December 2006 (from Vymazal and Kröpfelová, 2008).

Table 6
Removal of TP and ammonia-N in constructed wetland Spálené Poříčí during the period 1992–2006. Raw = raw wastewater; Out = final outflow.*26 values per year, Minimum and maximum values in parentheses

	TP ($mg\,l^{-1}$)		NH_4^+-N ($mg\,l^{-1}$)	
	Raw	Out	Raw	Out
1992			7.6 (3.6–11.8)	5.9 (1.1–9.3)
1993*	1.6 (1.0–2.6)	1.2 (0.6–2.6)	13.7 (7.0–21.3)	11.9 (5.6–16.7)
1994	2.0 (0.8–2.9)	1.4 (0.1–2.5)	12.0 (3.1–21.9)	9.2 (4.2–13.2)
1995	2.4 (0.3–4.6)	1.4 (0.1–2.7)	7.3 (2.1–14.8)	5.5 (0.3–13.5)
1996	2.1 (0.1–4.8)	1.7 (0.4–5.1)	3.9 (1.8–21.1)	5.8 (1.0–10.3)
1997	1.7 (0.2–3.5)	2.4 (0.1–4.7)	11.2 (1.5–25.5)	11.4 (0.4–23.4)
2001	3.6 (2.3–4.3)	3.3 (1.8–4.4)	16.5 (13.7–24.7)	12.7 (9.0–15.5)
2002	2.6 (0.8–4.2)	3.0 (0.1–6.7)	13.2 (4.4–22.5)	10.2 (5.4–15.3)
2003	4.3 (1.9–6.4)	4.1 (1.4–7.4)	26.4 (22–40)	16.8 (4.6–26)
2004	3.6 (1.6–6.1)	3.4 (1.1–5.9)	20.3 (6.5–32)	11.3 (3.4–16)
2005	3.2 (1.5–5.6)	2.2 (1.2–3.7)	26.7 (14–42)	17.1 (8.5–26)
2006	3.0 (2.5–3.7)	1.9 (0.7–2.9)	26.8 (16–33)	18.5 (14–22)
Mean	**2.7**	**2.4**	**15.5**	**11.4**

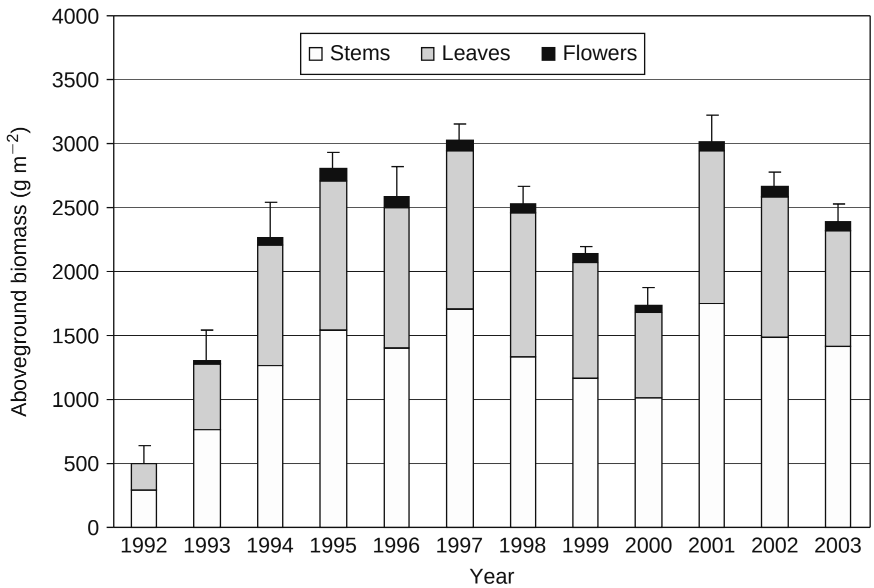

Fig. 4. Aboveground Biomass of *Phragmites australis* in Constructed Wetland Ondřejov.

The monitoring of *Phragmites* growth in Ondřejov (Fig. 4) revealed that it has taken four growing seasons to achieve its maximum biomass of 3013 g m^{-2}. After 1997, the biomass started to decline, but after the winter harvest in early 2001, it again increased to 3017 g m^{-2}, which is close to the average value of 3266 g DM m^{-2} reported for the *Phragmites* growing in HF constructed wetlands in the Czech Republic [49]. The maximum aboveground biomass in Spálené Poříčí (Fig. 5)

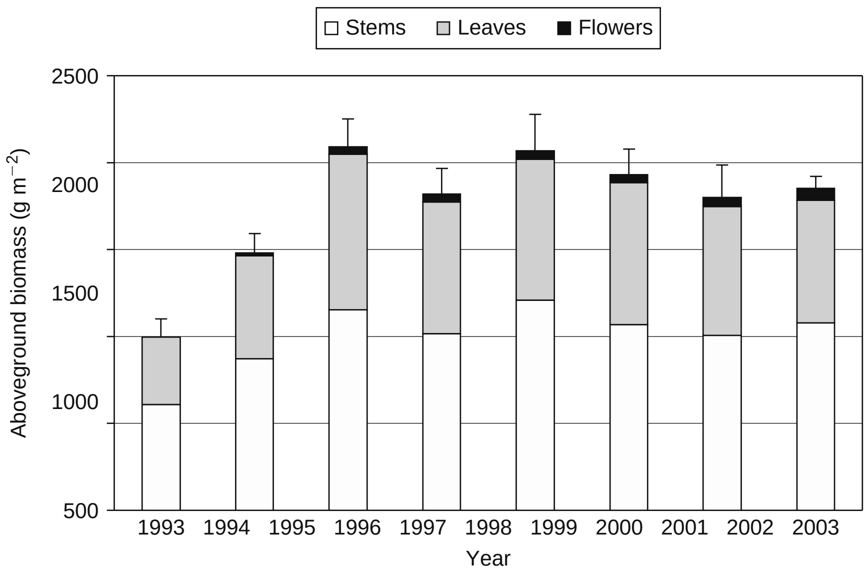

Fig. 5. Aboveground Biomass of *Phragmites australis* in Constructed Wetland Spálené Poříčí.

was also reached in the fourth growing season (2090 g DM m^{-2}) and then it fluctuated very little between 1800 and 2060 g DM m^{-2}. It was observed that *Phragmites* penetrated into *Phalaris* stands after 3 years and after six growing seasons it entirely out-competed *Phalaris*. However, this natural competition between two species does not affect the treatment performance of the system.

4. Conclusions

Constructed wetlands in Ondřejov and Spálené Poříčí have been in operation since 1991 and 1992, respectively, and both systems belong to the oldest constructed wetlands in the Czech Republic. Both systems exhibited high and steady removal of organics and suspended solids. Removal of ammonium-N and total-P was steady but very low. However, these parameters were not targeted when designing these systems. The results from Spálené Poříčí also indicate that constructed wetlands can be used as tertiary treatment systems to polish organics and suspended solids. Both systems are examples of the suitable use of constructed wetlands for treatment of wastewaters from small settlements.

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