

Removal of alkali metals and their sequestration in plants in constructed wetlands treating municipal sewage

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Abstract This study is aimed at retention of K, Na, Mg, and Ca in two constructed wetlands (CWs) in the Czech Republic, and on the evaluation of particular standing stocks in both above- and belowground plant biomass. The study revealed that CWs with horizontal subsurface flow are not effective in retention of studied elements. Removal of K, Na, Mg, and Ca averaged only 10.6, 7.4, 6.1, and 1.4%, respectively. In general, concentrations of studied elements in various parts of *Phragmites australis* and *Phalaris arundinacea* were found within the range of concentrations reported from both natural and CWs. Aboveground standing stocks for K, Na and Mg were comparable with those reported from natural stands for both *Phalaris* and *Phragmites*, but Ca aboveground standing stocks found in our study were lower compared to those found in several natural *Phragmites* wetlands. Aboveground to belowground standing stock ratio was

generally >1.0. However, this amount formed usually <1% of the annual inflow load of particular elements. The results of this study provide comprehensive information on retention and sequestration of K, Na, Mg, and Ca in vegetation during municipal wastewater treatment in CWs with subsurface horizontal flow.

Keywords Alkali metals · Common reed · Constructed wetlands · Macrophytes · Reed canarygrass · Wastewater

Introduction

Most studies on macronutrients in both natural and constructed wetlands (CWs) have dealt with nitrogen and phosphorus (e.g., Richardson, 1985; Bowden, 1987; Vymazal, 2004, 2007), while other macronutrients have been assessed only sporadically (e.g., Allen & Pearsall, 1963; Květ, 1973; Ho, 1979a, b; Kaul et al., 1980; Bernard & Lauve, 1995; Eckhardt et al., 1999). Kadlec & Wallace (2008) pointed out that sodium (Na), potassium (K), calcium (Ca), and magnesium (Mg) are rarely the object of regulatory concern, because under most circumstances they do not pose any toxicity threat. Only very high concentrations of sodium may be toxic for plants and could limit the use of water for irrigation (Pitter, 2009). Soils with an accumulation of exchangeable Na are often characterized by low permeability making them

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unfavorable for plant growth. Na adsorption ratio (SAR, Eq. 1) characterizes salt-affected soils. When the SAR rises above 12–15, serious physical soil problems arise and plants have difficulty absorbing water (Munshower, 1994).

$$\text{SAR} = (\text{Na}^+) / \left\{ \left[(\text{Ca}^{2+}) + (\text{Mg}^{2+}) \right] / 2 \right\}^{0.5} \quad (1)$$

where concentrations of Na^+ , Ca^{2+} , and Mg^{2+} are given in meq/l.

Potassium regulates the opening and closing of stomata on plant leaves and is also used as an enzyme activator in protein synthesis in most cells (Kadlec & Wallace, 2008). Potassium, together with nitrogen and phosphorus, is the nutrient that most frequently limits plant growth, and does not appear to be structurally bound in the plants, but is highly mobile (Hopkins, 1999). The concentration of K in plant biomass is, like all nutrients associated with metabolism, highest when leaves or other organs are first produced, then declines, first as the concentration becomes diluted by increasing quantities of cell-wall material during biomass expansion, then by resorption during senescence (Lambers et al., 1998). Potassium concentration in plants varies widely between 1 and 10% dry matter, but most commonly it is between 1 and 4% dry matter (Boyd, 1978; Vymazal, 1995; Lambers et al., 1998; Kadlec & Wallace, 2008).

Sodium belongs to the so-called “beneficial elements” as it is not generally required by plants (Hopkins, 1999). Brownell & Crossland (1972) reported that Na is generally essential as a micronutrient for C_4 plants and in lower concentrations for most C_3 plants. Most freshwater wetland macrophytes have low Na requirements, with concentrations in the aboveground biomass lower than 2,000 mg/kg (Boyd, 1978; Vymazal, 1995).

Calcium, which is highly associated with cell walls and is not resorbed, increases continuously through leaf development (Lambers et al., 1998). Ca is important to dividing cells as it is also required for the physical integrity and normal functioning of membranes, and it has been implicated as a second messenger in certain hormonal and environmental responses. The typical Ca concentration in the plant biomass is about 5,000 mg/kg (Hopkins, 1999). Magnesium is generally less abundant in soils than Ca, but is required by plants in relatively large amounts, and Mg has several important functions in plants. By far

the largest proportion is found in the porphyrin moiety of the chlorophyll molecule, but it is also required to stabilize ribosome structure and is involved as an activator for numerous critical enzymes (Hopkins, 1999).

Constructed treatment wetlands are usually not designed with the major aim of removing Na, K, Mg, and Ca. The major reason is the fact that, within the European Union Water Framework Directive and the “Council Directive concerning urban waste water treatment”, there are no limits imposed on concentrations of these metals in treated wastewater. This study focuses on retention of K, Na, Mg, and Ca in two CWs in the Czech Republic and on the evaluation of particular standing stocks in both above- and below-ground plant biomass, because of their role in wetland functioning, and to fill a knowledge gap.

Methods

The experiments were carried out at two CWs with horizontal sub-surface flow in the Czech Republic. The Mořina and Břehov CWs were designed to treat municipal wastewater from 700 and 100 population equivalents. The Mořina CW was built in 2000, was filled with crushed rock (4–8 mm), and planted with combination of common reed (*Phragmites australis*) and reed canarygrass (*Phalaris arundinacea*). The CW Břehov was built in 2003, was filled with pea gravel (4–8 mm), and planted with the same combination of plants.

Water samples were taken on a monthly basis during the years 2004 and 2006–2008. The samples were taken at the inflow and outflow from studied CWs and analyzed the same day in the laboratory. The samples were mineralized with HCl and HNO_3 (APHA, 1998), diluted to 100 ml and analyzed for K, Na, Ca, and Mg using Inductively Coupled Plasma Mass Spectrometer PQ-ExCell (VG-Thermo Elemental, Winsford, Cheshire, UK). Quality control (QC) samples consisted of triplicate samples and spiked samples. For the evaluation of measurement precision and accuracy the standard material “SPS-WW1 Batch 108—Reference Material for Measurement of Elements in Wastewaters” from Spectrapure Standards, Oslo, Norway, was used. The reproducibilities expressed as a relative standard deviation of the QC samples were less than 5%. The recoveries between

found and certified values were in the range of 88–104% for all measurements.

The aboveground biomass was sampled in all years during the period 2004–2008 for *Phalaris*, whereas *Phragmites* biomass was sampled during the period 2004–2007. Belowground biomass was sampled in 2004, 2005, and 2007. Four samples of biomass were taken during the peak standing crop, i.e., at the beginning of July for *Phalaris* and at the beginning of September for *Phragmites*. The plants were harvested from four 0.25-m² squares, two at the inflow part and two at the outflow part of the filtration bed. The aboveground biomass was clipped at the ground level, divided into stems, leaves (including leaf sheaths), and inflorescence (flowers). Belowground biomass was dug out from the same squares down to 50 cm, divided into roots and rhizomes and thoroughly washed with pressure water in a large jar in order to preserve fine roots. The biomass was dried at 70°C until constant weight and then homogenized samples were mineralized in pressure microwave apparatus MARS-5 using HNO₃ + H₂O₂ + HF + H₃BO₃ under high temperature and pressure (Sucharová & Suchara, 2006). Mineralized samples were analysed for Ca, Na, K, and Mg using Inductively Coupled Plasma Mass Spectrometer PQ-ExCell. The biomass values have been reported elsewhere (Vymazal & Kröpfelová, 2010).

For all measurements in biomass samples, standard QC was performed with samples consisted of triplicate samples and spiked samples. For the evaluation of measurement precision and accuracy, the standard materials BCR-RM 060 *Lagarosiphon major* and BCR-RM 279 *Ulva lactuca* (European Commission, Community Bureau of Reference, Brussels, Belgium) were used. The reproducibilities expressed as a relative standard deviation of the QC samples were

less than 5%. The recoveries between found and certified values were in the range of 80–120% for all measurements.

Data were tested for normality using a Shapiro–Wilk test and the results showed that the data are distributed normally (Shapiro & Wilk, 1965). Differences between *Phalaris* and *Phragmites* were evaluated through the Student's *t* test at a significance level of $p < 0.05$.

Results

Concentration in wastewater

Concentrations of the studied metals in wastewater in both CWs were comparable to concentrations commonly found in surface waters in the Czech Republic. Results presented in Table 1 indicate very low retention of studied macronutrients in all monitored CWs. Removal of K, Na, Mg, and Ca averaged only 17.1, 6.9, 5.2, and 13.3%, respectively. The SAR calculated for both CWs changed only slightly after the passage through the systems. In Mořina CW, SAR decreased from 2.54 to 2.35, while at Břehov CW, the SAR increased from 2.12 to 2.25.

Concentrations in biomass

The results presented in Table 2 indicate that the K concentrations in both *P. arundinacea* and *P. australis* are similar for both plants ($p > 0.05$). The potassium concentration was higher in leaves (L) than in stems (S), with the L/S ratio of 1.54 and 1.71 for *Phragmites* and *Phalaris*, respectively. Root (R) concentration of K was lower than in leaves, with respective R/L ratio of 0.70 and 0.45.

Table 1 Removal of K, Na, Mg and Ca in Mořina and Břehov constructed wetlands in the Czech Republic

	CW Mořina			CW Břehov			Mean
	In	Out	Eff	In	Out	Eff	Eff.
K	20.7 (5.5)	17.8 (4.4)	14.0	94 (65)	75 (28)	20.2	17.1
Na	113 (52)	103 (32)	8.8	79 (43)	75 (42)	5.0	6.9
Mg	21.3 (7.9)	19.2 (4.0)	9.9	17.9 (6.3)	17.0 (5.1)	0.5	5.2
Ca	114 (27)	113 (27)	0.9	75 (13.9)	55.7 (18.7)	25.7	13.3

Concentrations in mg/l, standard deviations in parentheses

In inflow, Out outflow, Eff treatment efficiency (%), $n = 28$

Table 2 Concentration of potassium (mg/kg) in leaves (L), stems (S), roots (R) and rhizomes (RH) of *Phalaris arundinacea* (PH) and *Phragmites australis* (PG) in constructed wetlands Mořina and Břehov

Locality	Plant	<i>n</i> ^a	L	S	R	RH	L:S	R:L
CW Mořina	PH	20/	13,823	7,435	6,048	6,085	1.86	0.46
		12	(4,278)	(1,271)	(2,164)	(1,743)	(1.01)	(0.21)
CW Břehov	PH	20/	26,929	16,252	10,985	11,950	1.55	0.43
		12	(8,749)	(4,396)	(3,276)	(3,711)	(0.76)	(0.14)
Mean		40/	20,376	11,844	8,517	9,018	1.71	0.45
		24	(7,213)	(3,451)	(2,865)	(2,384)	(0.85)	(0.19)
CW Mořina	PG	16/	11,788	7,461	7,158	9,083	1.75	0.57
		12	(3,476)	(2,318)	(1,497)	(2,718)	(0.43)	(0.22)
CW Břehov	PG	16/	19,424	15,128	18,032	18,652	1.32	0.82
		12	(7,653)	(4,766)	(3,123)	(4,387)	(0.64)	(0.41)
Mean		32/	15,606	11,294	12,595	13,867	1.54	0.70
		24	(5,431)	(3,876)	(2,619)	(3,613)	(0.54)	(0.35)

Standard deviations in parentheses

^a First number is for aboveground samples, the second number is for belowground samples

Table 3 Sodium concentration (mg/kg) in *Phalaris arundinacea* and *Phragmites australis* in constructed wetlands Mořina and Břehov

Locality	Plant	<i>n</i> ^a	L	S	R	RH	L:S	R:L
CW Mořina	PH	20/	1,818	2,688	1,941	2,390	0.67	1.07
		12	(479)	(879)	(988)	(659)	(0.51)	(0.43)
CW Břehov	PH	20/	317	559	2,014	1,862	0.57	6.35
		12	(43)	(103)	(549)	(541)	(0.21)	(1.89)
Mean	PH	40/	1,072	1,623	1,978	2,126	0.62	3.71
		24	(245)	(431)	(681)	(601)	(0.37)	(1.34)
CW Mořina	PG	16/	1,407	910	1,672	1,466	1.54	1.19
		12	(438)	(184)	(543)	(753)	(0.45)	(0.21)
CW Břehov	PG	16/	622	894	2,815	1,091	0.70	4.53
		12	(133)	(56)	(801)	(406)	(0.61)	(1.23)
Mean	PG	32/	1,015	902	2,244	1,279	1.12	2.86
		24	(238)	(108)	(637)	(523)	(0.50)	(0.77)

For abbreviations, see Table 2

^a First number is for aboveground samples, the second number is for belowground samples

Sodium concentrations (Table 3) in leaves were comparable for *Phalaris* and *Phragmites*, but Na concentration in stems was higher in *Phalaris* ($p > 0.05$), resulting in lower L/S ratio for *Phalaris*. The root to leaf concentration ratio was comparable for both plants ($p > 0.05$).

Calcium concentrations (Table 4) were comparable in leaves, but in stems, calcium concentration was slightly higher in *Phragmites*, but the difference was

not significant ($p > 0.05$). On the other hand, belowground concentrations were higher in *Phalaris* compared to *Phragmites* ($p < 0.05$). As a result, the root to leaf ratio was higher in *Phalaris*, but the difference was not significant ($p < 0.05$).

Leaf concentration of Mg (Table 5) was substantially higher in *Phalaris* than in *Phragmites* ($p < 0.05$) while stem, root and rhizome Mg concentrations were not statistically different ($p > 0.05$). For both *Phalaris*

Table 4 Calcium concentration (mg/kg) in *Phalaris arundinacea* and *Phragmites australis* in constructed wetlands Mořina and Břehov

Locality	Plant	<i>n</i> ^a	L	S	R	RH	L:S	R:L
CW Mořina	PH	20/	4,774	1,173	9,569	2,787	4.06	2.01
		12	(1,628)	(541)	(2,934)	(1,527)	(1.34)	(0.89)
CW Břehov	PH	20/	4,053	809	3,055	1,122	5.00	0.75
		12	(1,156)	(453)	(896)	(786)	(2.31)	(0.34)
Mean		40/	4,414	991	6,312	1,954	4.97	1.38
		24	(1,412)	(502)	(1,761)	(1,097)	(1.79)	(0.61)
CW Mořina	PG	16/	5,207	897	2,916	376	5.80	0.56
		12	(1,346)	(127)	(1,213)	(88)	(1.67)	(0.39)
CW Břehov	PG	16/	3,339	1,697	3,157	595	1.96	0.95
		12	(1,006)	(881)	(1,056)	(138)	(1.22)	(0.66)
Mean		32/	4,273	1,297	3,037	486	3.88	0.76
		24	(1,225)	(534)	(1,123)	(105)	(1.44)	(0.45)

For abbreviations, see Table 2

^a First number is for aboveground samples, the second number is for belowground samples

Table 5 Magnesium concentration (mg/kg) in *Phalaris arundinacea* and *Phragmites australis* in constructed wetlands Mořina and Břehov

Locality	Plant	<i>n</i> ^a	L	S	R	RH	L:S	R:L
CW Mořina	PH	20/	3,153	1,088	1,123	621	2.89	0.36
		12	(564)	(321)	(346)	(111)	(1.22)	(0.11)
CW Břehov	PH	20/	2,033	682	1,128	585	2.98	0.55
		12	(654)	(222)	(419)	(241)	(1.03)	(0.23)
Mean		40/	2,593	885	1,126	603	2.94	0.46
		24	(599)	(287)	(401)	(186)	(1.16)	(0.18)
CW Mořina	PG	16/	1,474	977	2,199	948	1.51	1.49
		12	(381)	(419)	(1,103)	(418)	(0.88)	(1.13)
CW Břehov	PG	16/	1,588	632	1,360	713	2.51	0.86
		12	(624)	(234)	(541)	(121)	(1.24)	(0.33)
Mean		32/	1,531	805	1,780	831	2.01	1.18
		24	(451)	(321)	(759)	(277)	(0.95)	(0.63)

For abbreviations, see Table 2

^a First number is for aboveground samples, the second number is for belowground samples

and *Phragmites*, L/S ratios were higher than 2 while R/L ratio was 0.46 and 1.18 for *Phalaris* and *Phragmites*, respectively.

Standing stock

Standing stock is the amount of nutrients sequestered in the biomass and it is usually expressed per unit area. Results shown in Table 6 indicate that the aboveground standing stocks were generally similar for

Phalaris and *Phragmites*, with the exception of higher standing stock of Na in *Phalaris* at the Mořina CW. Also, K aboveground standing stock was significantly higher ($p < 0.05$) at Mořina compared to Břehov. Belowground standing stocks were lower than corresponding aboveground standing stocks with the exception of Ca standing stock in *Phragmites* at the Mořina CW and Na standing stock in *Phalaris* at the Břehov CW. As a consequence, aboveground/belowground standing stock ratios were >1 (Table 7) with

Table 6 Potassium, sodium, calcium, and magnesium standing stocks (g/m^2) in the aboveground biomass of *Phalaris arundinacea* (2004–2008) and *Phragmites australis* (2004–2007) at constructed wetlands Břehov and Mořina

	Břehov		Mořina	
	<i>Phalaris</i>	<i>Phragmites</i>	<i>Phalaris</i>	<i>Phragmites</i>
K	30.03 (17.3) a	30.76 (17.8) a	16.11 (3.7) b	17.33 (3.7) b
Na	0.78 (0.58) a	1.11 (0.42) a	3.23 (0.15) b	2.01 (1.27) a
Ca	3.15 (1.22) a	4.08 (2.68) a	4.46 (0.43) a	5.47 (1.67) a
Mg	2.06 (0.88) a	2.11 (1.08) a	3.27 (1.05) a	1.93 (0.30) a

Standard deviations in parentheses, $n = 20$ for *Phalaris* and $n = 16$ for *Phragmites*. Different letters indicate significant differences at $\alpha = 0.05$ between standing stocks of individual elements in *Phalaris* and *Phragmites*

Table 7 Potassium, sodium, calcium, and magnesium aboveground/belowground standing stocks ratio in *Phalaris arundinacea* and *Phragmites australis* at constructed wetlands Břehov and Mořina

	Břehov		Mořina	
	<i>Phalaris</i>	<i>Phragmites</i>	<i>Phalaris</i>	<i>Phragmites</i>
K	5.69 (2.06) a	1.82 (1.02) b	8.40 (3.06) a	1.62 (0.44) b
Na	0.87 (0.66) a	1.15 (1.01) a	6.27 (2.33) b	1.24 (0.45) a
Ca	2.31 (0.38) a	3.86 (1.18) b	2.95 (1.56) ab	0.76 (0.57) c
Mg	3.10 (1.51) a	2.29 (0.62) a	11.0 (5.78) b	1.53 (1.33) a

Standard deviations in parentheses, $n = 12$. Different letters indicate significant differences at $\alpha = 0.05$ between standing stocks ratios of individual elements in *Phalaris* and *Phragmites*

Table 8 Potassium, sodium, calcium, and magnesium standing stocks (SS, g/m^2) in aboveground biomass of *Phragmites* ($n = 9$) and *Phalaris* ($n = 6$)

	<i>Phragmites</i>			<i>Phalaris</i>		
	SS	AIL (%)	TR (%)	SS	AIL (%)	TR (%)
K	24.0	5.2	34.7	23.1	0.83	31.9
Na	1.56	0.07	0.59	2.00	0.11	0.37
Ca	4.78	0.49	1.40	3.81	0.24	0.46
Mg	2.02	0.73	13.3	2.67	0.76	18.9

AIL = SS as percentage of annual inflow load, TR = SS as percentage of total removal

two mentioned exceptions. In general, the aboveground/belowground ratio was significantly higher in *Phalaris*, especially at the Mořina CW (Table 7).

In Table 8, comparison between aboveground standing stocks and annual inflow load is shown. The data reveal that the amount of monitored elements sequestered in the aboveground biomass is very low and for most studied elements this amount is lower than 1% of the annual inflow load. The highest amount was determined for K in *Phragmites*, and this value

amounted to 5.2% of the annual inflow load. Despite this, the aboveground standing stock may account for a substantial part of the total removed elements, especially for K (34.7 and 31.9% for *Phragmites* and *Phalaris*, respectively) and Mg (respective values of 13.3 and 18.9%).

Discussion

Potassium, calcium, magnesium, and sodium have been monitored only rarely during wastewater treatment in CWs. As a result, there is a lack of information on their removal or release during this treatment process. The study which was carried out between the years of 2004 and 2008 is, therefore, one of the most comprehensive studies so far carried out.

Concentration in wastewater

Very low retention of all studied elements in CWs has also been reported in the literature. Samecka-Cymerman et al. (2004) reported K, Ca, and Mg removal of

17, 13, and 32% for the surface flow CW planted with *P. australis* in Kotowice, Poland. The authors reported higher respective removals for sub-surface flow CW planted with *Salix viminalis* (36, 49, and 50%) and comparable results for another sub-surface flow W planted with *Populus canadensis* (28, 10 and 21%). Maine et al. (2009) reported the removal of 5, 34, 5, and 34% for K, Ca, Mg, and Na, respectively, in a free water surface CW in Argentina. Hawkins et al. (1997) reported treatment efficiency of -4.8, 36, 29, and -18% for K, Ca, Mg, and Na, respectively, in a free water surface CW in Louisiana. Kadlec & Wallace (2008) reported the removal of 6, 21, 12, and 9% for K, Ca, Mg, and Na, respectively, in a CW at Imperial, California. The fact that there is not much change in alkali metals concentrations from wetland inlet to outlet has been reported by Kadlec & Wallace (2008) in their review.

In the Czech Republic, the legislation for discharged wastewater does not allow the use for direct irrigation, and treated wastewater must be discharged into surface waters. However, the results suggested that CWs with horizontal subsurface flow do not affect the SAR value of treated water and, in this case, the SAR values remained well below the values which may negatively affect the soil properties.

Concentration in biomass

Potassium concentrations in various parts of both plants (Table 2) found in our study were comparable with those found in other CWs or natural wetland stands (Table 9). The root to leaf concentration ratio in our study was substantially lower than 1.0 for both *Phalaris* and *Phragmites*. This low ratio was also observed in both plants growing in natural and CWs (Table 9). The leaf to shoot concentration ratio was slightly higher in our study (1.54–1.71) than in other wetlands (0.96–1.39) (Table 9). In general, K concentration in the aboveground biomass of both *Phalaris* and *Phragmites* seems to be slightly higher in CWs as compared to natural stands, while K concentrations in roots are comparable (Table 9).

Sodium concentrations in the biomass in our study were higher than those reported in the literature from both constructed and natural wetlands (Tables 3 and 10). Results presented in Table 10 also indicate that concentrations of Na in *Phalaris* are comparable in natural and CWs, but in *Phragmites*, higher

concentrations were recorded in CWs for wastewater treatment (Table 10). In our study, the leaf to shoot concentration ratio was <1 in *Phalaris* and >1 in *Phragmites*, but the data presented in Table 10 exhibit the opposite pattern. Root to leaf concentration ratios found in our study fell into the range reported in the literature (Table 10).

Calcium concentrations in leaves of *Phragmites* and *Phalaris* (Table 4) were similar to those reported in the literature from CWs for wastewater treatment. These concentrations are lower than those reported from natural stands (Table 11). For stems, plants from natural wetlands also exhibited higher Ca concentrations. With the exception of lower value for *Phalaris* L/S concentration ratio in natural wetlands (1.57), the L/S ratio was usually between 3 and 4 in both natural and CWs (Table 11). The L/S values found in our study were 3.88 and 4.97 for *Phragmites* and *Phalaris* (Table 4). The mean R/L concentration ratio varied from 0.24 and 1.75 in the literature, while in our study it varied between 0.76 and 1.38 for *Phalaris* and *Phragmites*, respectively.

Concentrations of Mg in *Phalaris* and *Phragmites* in our study (Table 5) were comparable with results reported in the literature (Table 12). Leaf Mg concentration was higher in *Phalaris* compared to *Phragmites*, while stem Mg concentrations were comparable. Consequently, the L/S concentration ratio was higher for *Phalaris* (Table 5). The root to leaf concentration ratio was very low for *Phalaris* (0.46), but comparable with results reported from natural stands (0.35) and CWs for wastewater treatment (0.38). For *Phragmites*, this ratio was higher (1.18), and it was between the mean values found for CWs (0.65) and CWs (1.60), as shown in Table 12.

Standing stocks

Potassium aboveground standing stocks were similar for *Phalaris* and *Phragmites* in both CWs, but in the Břehov CW, the values were nearly double (Table 6). The recorded values are within the range reported in the literature. Dykyjová (1973) reported an aboveground K standing stock of 25.5 g/m² in *P. australis* growing in the Opatovický fishpond in the Czech Republic. Dykyjová & Květ (1982) reported the aboveground K standing stock in *P. australis* to be up to 37.4 g/m² in fishponds in south Bohemia. Ho (1981) found an aboveground K standing stock in *P. australis*

Table 9 Concentrations of potassium (mg/kg) in various parts of *Phragmites australis* (PG) and *Phalaris arundinacea* (PH) growing in constructed wetlands for wastewater treatment and natural stands

Locality	Plant	L	S	R	RH	L:S	R:L	Ref. ^a
Lake, Forfar, Scotland	PH	17,210	18,610	4,380		0.93	0.25	1
Lake, Balgavies, Scotland	PH	23,480	25,000	6,111		0.93	0.26	1
Lake, Lowes, Scotland	PH	19,980	19,510	4,890		1.02	0.25	1
Natural marsh Ithaca, NY	PH	15,000		6,000	6,000			2
Mean natural wetlands	PH	16,092	21,040	5,345	6,000	0.96	0.26	
HF CW Chmelná, CR	PH	27,800	32,450			0.86		3
HF CW Zásada, CR	PH	15,125	14,600	8,150		1.04	0.54	3
HF CW, Fenton, NY	PH	19,000		3,000	6,000			2
HF CW, Muscle Shoals, AL	PH	20,000	15,000	6,000		1.3	0.30	4
Mean constr. wetlands	PH	20,481	20,683	5,716	6,000	1.07	0.42	
Lake, Forfar, Scotland	PG	17,200	22,230	8,420	18,780	0.77	0.49	5
Lake, Balgavies, Scotland	PG	13,630	18,410	7,790	14,620	0.74	0.57	5
Lake, Lowes, Scotland	PG	13,850	18,210	5,700	13,250	0.76	0.41	5
Nesyt Pond, Czech Rep.	PG	3,300	7,000			0.47		6
Mirrool Creek, Australia	PG	9,200	5,950	11,500	14,500	1.55	1.25	7
Opatovický pond, CR	PG	12,000	8,500	7,050	12,000	1.4	0.59	8
14 fishponds, CR	PG	15,843	9,457			1.86		9
Mean natural wetlands	PG	12,146	12,822	8,092	14,630	1.07	0.66	
HF CW Čičenice, CR	PG	21,975	17,750			1.23		3
HF CW Ondřejov, CR	PG	23,800	17,000			1.4		3
HF CW Koloděje, CR	PG	22,500	21,263			1.06		3
HF CW, Muscle Shoals, AL	PG	23,000	20,000	9,000	11,000	1.15	0.39	4
HF CW, South Africa	PG	17,240	8,320			2.1		10
HF CW, NY, leachate	PG	7,760		6,210	9,000		0.8	11
FWS CW, Poland	PG	7,233						12
Mean constr. wetlands	PG	17,644	16,866	7,605	10,000	1.39	0.60	

CR Czech Republic, AL Alabama, NY New York, PL Poland. For other abbreviations, see Table 2

^a 1, Ho (1979a); 2, Bernard & Lauve (1995); 3, Dušek & Květ (1996); 4, Behrends et al. (1994); 5, Ho (1981); 6, Úlehlová et al. (1973); 7, Hocking (1989a, b); 8, Dykajová & Hradecká (1976); 9, Květ (1973); 10, Wrigley & Toerien (1988); 11, Eckhardt et al. (1999); 12, Samecka-Cymerman et al. (2004)

of 28.2 g/m² in Scottish lochs, and Wiltshire (1981) reported values of 34.4 g/m² in natural *P. australis* stands in South Africa. Behrends et al. (1994) reported the aboveground K standing stock values between 29.7 and 34.5 g/m² in *P. australis* in experimental CWs in Alabama, USA. A higher aboveground K standing stock (9.3 g/m²) as compared to belowground standing stock (7.3 g/m²) was also reported by Peverly et al. (1995) from a CW treating landfill leachate in Tompkins County, New York.

Bernard & Lauve (1995) reported an aboveground K standing stock of 21.1 and 32.5 g/m² in

P. arundinacea growing in a natural stand and CWs for landfill leachate in New York, respectively. Behrends et al. (1994) reported aboveground K standing stock values between 4.9 and 10.5 g/m² in *P. arundinacea* in experimental CWs in Alabama, USA. Lukavská (1989) reported the aboveground K standing stock in the range of 8.9 and 15.5 g/m² for *P. arundinacea* growing in wet meadows in the Czech Republic.

Sodium aboveground standing stocks were comparable for *Phalaris* and *Phragmites*, but in contrast to potassium, standing stocks values were higher in Mořina. In the literature, there is very limited information on Na

Table 10 Concentrations of sodium (mg/kg) in various parts of *Phragmites australis* (PG) and *Phalaris arundinacea* (PH) growing in constructed wetlands for wastewater treatment and natural stands

Locality	Plant	L	S	R	RH	L:S	R:L	Ref. ^a
Lake, Forfar, Scotland	PH	1,130	1,030	2,150		1.1	1.9	1
Lake, Balgavies, Scotland	PH	450	320	1,020		1.4	2.3	1
Lake, Lowes, Scotland	PH	520	260	1,050		2.0	2.0	1
Mean natural wetlands	PH	700	537	1,406		1.50	2.07	
HF CW Chmelná, CR	PH	100	100			1.0		2
HF CW Zásada, CR	PH	600	1,575	4,000		0.38	6.7	2
Mean constr. wetlands	PH	350	838	4,000			6.7	
Lake, Forfar, Scotland	PG	490	960	3,350	1,230	0.51	6.8	3
Lake, Balgavies, Scotland	PG	460	1,050	2,450	1,560	0.44	5.3	3
Lake, Lowes, Scotland	PG	320	820	3,540	1,980	0.39	11.1	3
Nesyt Pond, Czech Rep.	PG	120	560			0.21		4
Mirrool Creek, Australia	PG	460	560	1,415	1,225	0.82	3.1	5
14 fishponds, CR	PG	501	795			0.71		6
Mean natural wetlands	PG	392	790	2,689	1,499	0.51	6.58	
HF CW Čicenice, CR	PG	250	900			0.28		2
HF CW Ondřejov, CR	PG	500	1,450			0.35		2
HF CW Koloděje, CR	PG	213	763			0.28		2
HF CW, South Africa	PG	550	670			0.82		7
HF CW, NY, leachate	PG	5,160		7,500	2,760		1.5	8
Mean constr. wetlands	PG	1,334	946	7,500	2,760	0.43	1.5	

CR Czech Republic. For other abbreviations, see Table 2

^a 1, Ho (1979a); 2, Dušek & Květ (1996); 3, Ho (1981); 4, Úlehlová et al. (1973); 5, Hocking (1989a, b); 6, Květ (1973); 7, Wrigley & Toerien (1988); 8, Eckhardt et al. (1999)

standing stock in plants growing in CWs for wastewater treatment. Wrigley & Toerien (1988) reported an aboveground Na standing stock of 4.0 g/m² in *Phragmites* biomass in a South African study. Bernard & Lauve (1995) found a range of 0.3–1.1 g/m² in the aboveground biomass of *P. arundinacea* in experimental CWs in Alabama. There is considerably more information for *P. australis* in natural wetlands, and the results indicate that the values measured in our study fall within the range reported there. For aboveground Na standing stock in *Phragmites*, Kaul et al. (1980), Ho (1979b, 1981), Dykyjová (1973), and Úlehlová et al. (1973), reported values of 2.9–5.5, 1.78–4.63, 0.6–0.9, and 0.68 g/m² for India, Scotland, and Czech Republic, respectively. For *Phalaris*, the literature data for aboveground Na standing stock in natural stands are much less frequent, and varied between only 0.06 and 0.24 g/m² (Lukavská, 1989).

Calcium aboveground standing stocks (Table 6) were also comparable for *Phalaris* and *Phragmites*

and higher in Mořina. *Phragmites* aboveground Ca standing stocks from CWs for wastewater treatment have been reported within the same range as the values of this study. Wrigley & Toerien (1988) and Behrends et al. (1994) reported the values of 4.0 and 4.1–5.8 g/m² from South Africa and Alabama, USA, respectively. On the other hand, the Ca aboveground standing stocks in *Phragmites* growing in natural wetlands were often reported to be much higher. Ho (1979b, 1981) reported values between 5.91 and 25.4 g/m² from Scotland, Kaul et al. (1980) reported the values between 15.5 and 30 g/m² from India, and Obstová (1989) reported values up to 9.9 g/m² from the Czech Republic. Květ (1973) reported a similar value of 4.0 g/m² in the Czech Republic, and Úlehlová et al. (1973), and Wiltshire (1981) reported lower values of 1.84 and 1.59 g/m² from the Czech Republic and South Africa, respectively. There are only a few data on belowground Ca standing stock: Dykyjová (1973) reported the aboveground/belowground Ca

Table 11 Concentrations of calcium (mg/kg) in various parts of *Phragmites australis* (PG) and *Phalaris arundinacea* (PH) growing in constructed wetlands for wastewater treatment and natural stands

Locality	Plant	L	S	R	RH	L:S	R:L	Ref. ^a
Lake, Forfar, Scotland	PH	7,200	4,510	1,580		1.6	0.22	1
Lake, Balgavies, Scotland	PH	8,320	5,470	2,050		1.5	0.25	1
Lake, Lowes, Scotland	PH	6,730	4,180	1,600		1.6	0.24	1
Natural marsh Ithaca, NY	PH	2,000		4,000	1,000			2
Mean natural wetlands	PH	6,063	4,720	2,308	1,000	1.57	0.24	
HF CW Chmelná, CR	PH	6,250	1,550			4.0		3
HF CW Zásada, CR	PH	6,800	2,150	2,775		3.2	0.41	3
HF CW, Fenton, NY	PH	700		2,000	1,000			2
HF CW, Muscle Shoals, AL	PH	4,000	2,000	3,000		2.0	0.75	4
Mean constr. wetlands	PH	4,438	1,900	2,592	1,000	3.07	0.58	
Lake, Forfar, Scotland	PG	9,730	5,140	4,680	4,540	1.9	0.48	5
Lake, Balgavies, Scotland	PG	8,530	4,580	3,340	3,610	1.9	0.39	5
Lake, Lowes, Scotland	PG	6,920	4,270	2,520	3,200	1.6	0.36	5
Nesyt Pond, Czech Rep.	PG	1,240	600			2.1		6
Mirrool Creek, Australia	PG	8,210	2,100	2,000	605	3.9	0.24	7
Opatovický pond, CR	PG	7,910	890	290	110	8.9	0.4	8
Lake Wielkie, Poland	PG	10,700						9
Lake Boszkowo, Poland	PG	12,400						9
Lake Dominickie, Poland	PG	5,610						9
14 fishponds, CR	PG	4,535	1,036			4.46		10
Mean natural wetlands	PG	7,579	2,930	2,566	2,413	3.53	0.37	
HF CW Čičenice, CR	PG	3,200	900			3.6		3
HF CW Ondřejov, CR	PG	6,450	1,900			3.4		3
HF CW Koloděje, CR	PG	3,760	1,330			2.8		3
HF CW, Muscle Shoals, AL	PG	4,000	1,000	4,000		4.0	1.0	4
HF CW, South Africa	PG	1,350	270			5.0		11
HF CW, NY, leachate	PG	7,130		17,675	2,210		2.5	12
FWS CW, Poland	PG	6,590						13
Mean constr. wetlands	PG	4,640	1,080	10,837	2,210	3.76	1.75	

CR Czech Republic, AL Alabama, NY New York. For other abbreviations, see Table 2

^a 1, Ho (1979a); 2, Bernard & Lauve (1995); 3, Dušek & Květ (1996); 4, Behrends et al. (1994); 5, Ho (1981); 6, Úlehlová et al. (1973); 7, Hocking (1989a, b); 8, Dykyjová & Hradecká (1976); 9, Szymanowska et al. (1999); 10, Květ (1973); 11, Wrigley & Toerien (1988); 12, Eckhardt et al. (1999); 13, Samecka-Cymerman et al. (2004)

standing stock ratio to be as high as 18.5 for *Phragmites* growing in the littoral zone of a fishpond.

Calcium aboveground standing stocks in *Phalaris* reported in the literature are lower than those in our study. Behrends et al. (1994) and Bernard & Lauve (1995) reported Ca aboveground standing stocks in *Phalaris* growing in CWs in the range of 1.2–2.1 and 0.7–1.1 g/m², respectively. For natural stands, the values were in the range 0.2–2.8 g/m² in the Czech

Republic (Lukavská, 1989) and 0.2–3.2 g/m² in the USA (Bernard & Lauve 1995).

Magnesium aboveground standing stocks were comparable for *Phragmites* and *Phalaris* in Břehov, but in Mořina, *Phalaris* standing stock was higher than in *Phragmites* (Table 6). The mean values found in our study for *Phragmites* (1.93–2.11 g/m²) fell within the lower end of the range 0.8–6.3 g/m² reported in the literature for CWs (Wrigley & Toerien, 1988;

Table 12 Concentrations of magnesium (mg/kg) in various parts of *Phragmites australis* (PG) and *Phalaris arundinacea* (PH) growing in constructed wetlands for wastewater treatment and natural stands

Locality	Plant	L	S	R	RH	L:S	R:L	Ref. ^a
Lake, Forfar, Scotland	PH	2,930	2,020	1,040		1.5	0.35	1
Lake, Balgavies, Scotland	PH	2,820	1,730	950		1.6	0.34	1
Lake, Lowes, Scotland	PH	2,630	1,340	910		2.0	0.35	1
Natural marsh Ithaca, NY	PH	1,000		2,000	1,000			2
Mean natural wetlands	PH	2,345	1,697	1,225	1,000	1.70	0.35	
HF CW Chmelná, CR	PH	3,250	1,950			1.7		3
HF CW Zásada, CR	PH	2,525	1,350	650		1.9	0.26	3
HF CW, Fenton, NY	PH	700		2,000	1,000			2
CW, Muscle Shoals, AL	PH	2,000	1,000	1,000		2.0	0.5	4
Mean constr. wetlands	PH	2,119	1,433	1,217	1,000	1.87	0.38	
Lake, Forfar, Scotland	PG	4,280	1,620	2,280	1,080	2.6	0.53	5
Lake, Balgavies, Scotland	PG	4,860	1,940	3,000	1,360	2.5	0.62	5
Lake, Lowes, Scotland	PG	4,440	1,580	1,340	1,220	2.8	0.30	5
Nesyt Pond, Czech Rep.	PG	1,050	520			2.0		6
Mirrool Creek, Australia	PG	1,690	870	2,550	1,230	1.9	1.50	7
Opatovický pond, CR	PG	2,040	480	610	620	4.3	0.30	8
Lake Wielkie, Poland	PG	7,380						9
Lake Boszkowo, Poland	PG	4,460						9
Lake Dominickie, Poland	PG	2,470						9
14 fishponds, CR	PG	1,524	451			3.39		10
Mean natural wetlands	PG	3,419	1,065	1,956	1,102	2.78	0.65	
HF CW Čičenice, CR	PG	1,550	650			2.4		3
HF CW Ondřejov, CR	PG	2,400	1,100			2.2		3
HF CW Koloděje, CR	PG	1,560	660			2.4		3
CW, Muscle Shoals, AL	PG	2,000		1,000			0.5	4
HF CW South Africa	PG	1,690	680			2.5		11
HF CW, NY, leachate	PG	2,270		6,120	596		2.7	12
FWS CW Poland	PG	2,703						13
Mean constr. wetlands	PG	2,024	772	3,560	596	2.38	1.60	

CR Czech Republic, AL Alabama, NY New York. For other abbreviations, see Table 2

^a 1, Ho (1979a); 2, Bernard & Lauve (1995); 3, Dušek & Květ (1996); 4, Behrends et al. (1994); 5, Ho (1981); 6, Úlehlová et al. (1973); 7, Hocking (1989a, b); 8, Dykyjová & Hradecká (1976); 9, Szymanowska et al. (1999); 10, Květ (1973); 11, Wrigley & Toerien (1988); 12, Eckhardt et al. (1999); 13, Samecka-Cymerman et al. (2004)

Behrends et al. (1994). In the natural wetlands, the range of standing stock values was much wider (0.12–11.1 g/m²) (Dykyjová, 1973; Květ, 1973; Úlehlová et al., 1973; Kaul et al., 1980; Obstová, 1989). The mean Mg standing stock values in *Phalaris* above-ground biomass found in our study (2.06–3.27 g/m²) were higher as compared to values of 0.4–0.8 g/m² reported by Behrends et al. (1994) from a CW in Alabama. Also, Mg aboveground standing stocks in *Phalaris* from natural stands were slightly lower and

varied between 0.1 and 1.7 g/m² (Lukavská, 1989; Bernard & Lauve 1995).

Conclusions

1. The study revealed that the monitored CWs with horizontal subsurface flow were not effective in retention of the studied elements. Removal of K,

Na, Mg, and Ca averaged only 10.6, 7.4, 6.1, and 1.4%, respectively. Sodium adsorption ratio (SAR) in the wastewater was not affected by the passage through the CWs.

- In general, concentrations of studied elements in various parts of *P. australis* and *P. arundinacea* were found within the range of concentrations reported from both natural and CWs.
- The concentrations of studied elements differed only slightly between *Phalaris* and *Phragmites*, and no particular trend was observed.
- Aboveground standing stocks for K, Na, and Mg were comparable with those reported from natural stands for both *Phalaris* and *Phragmites*. On the other hand, Ca aboveground standing stocks found in our study were lower compared to standing stocks found in several natural wetlands for *Phragmites*.
- In general, the aboveground to belowground standing stock ratio was higher than 1.0, indicating that during the peak standing crop, higher amount of monitored elements were sequestered aboveground. However, this amount usually formed less than 1% of the annual inflow load of particular elements.
- The results of this study provide comprehensive information on retention and sequestration of K, Na, Mg, and Ca in vegetation during municipal wastewater treatment in CWs. This information is usually missing in the constructed treatment wetlands studies.

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