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Nature-based solutions for managing the urban surface runoff: an application of a constructed floating wetland

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ABSTRACT

Nature-based solutions for managing the urban surface runoff: an application of a constructed floating wetland

Urban surface runoff strongly contributes to the degradation of river ecosystems. Innovative and nature-based solutions have been applied to face such environmental problems. In this regard, constructed wetlands – a low-cost green treatment technology – represent a successful example of a solution that results in social and environmental benefits. Constructed floating wetlands (CFW) is a relatively new water treatment technique that consists of emergent macrophytes planted on floating structures. The CFW has been tested for the treatment of wastewater and stormwater runoff. However, few studies assess the system's capability over short periods of retention time and its performance under hydraulic shock-loading. This research reports the performance of CFW applied to treatment of simulated urban surface runoff. The removal efficiency of total nitrogen (TN) and total phosphorus (TP) was investigated for two macrophyte species: *Typha domingensis* and *Schoenoplectus californicus*. Total organic carbon, wet biomass, chlorophyll-*a*, dissolved oxygen (DO), pH, oxygen reduction potential (ORP), conductivity, temperature and turbidity were also measured. A commercial floating structure without growth medium was employed. The experiment utilized batch mesocosms, first with a seven-day retention time and second, under hydraulic shock-loading with 24, 2, and 4 h retention times. Differences between treatments and controls were analysed by PERMANOVA and ANOSIM tests. The results for a seven-day batch indicated that *T. domingensis* was more efficient than *S. californicus* (removal efficiency of TP = 47 %, TN = 78 % and TP = 11 %, TN = 30 %, respectively). There was a significant difference in nutrient removal for retention times of 24 h and 4 h for *T. domingensis*. No significant nutrient removal was noticed for *S. californicus* when the retention time was less than seven days.

Key words: surface runoff treatment, emergent macrophytes, constructed floating wetlands

RESUMO

Soluções inspiradas na natureza para gerenciar o escoamento superficial urbano: aplicação de um sistema flutuante de* wetlands *construídos

O escoamento superficial urbano contribui de maneira significativa para a degradação dos ecossistemas fluviais. As soluções inovadoras e inspiradas na natureza vêm sendo aplicadas para enfrentar esses problemas ambientais. Nesse sentido, os wetlands *construídos – uma tecnologia de tratamento verde e de baixo custo – representam um exemplo bem-sucedido de uma solução com benefícios sociais e ambientais. O sistema Flutuante de* Wetlands *Construídos é uma técnica de tratamento de água relativamente recente que consiste em macrófitas emergentes plantadas em estruturas flutuantes. O sistema tem sido testado para o tratamento de águas residuárias e de escoamento superficial urbano. Contudo, poucos estudos avaliam a capacidade dos sistemas durante curtos períodos de tempo de retenção e seu desempenho sob cargas de choque. Essa pesquisa relata o desempenho de um sistema flutuante de wetlands construídos aplicado ao tratamento de escoamento superficial urbano sintético. A eficiência de remoção de nitrogênio total (NT) e fósforo total (PT) foi investigada para duas espécies de macrófitas:* Typha domingensis *e* Schoenoplectus californicus*. Carbono orgânico total, biomassa úmida, clorofila-*a*, oxigênio dissolvido (OD), pH, potencial redox (ORP), condutividade, temperatura e turbidez também foram analisados. No trabalho foi empregada uma estrutura flutuante comercial, sem meio de crescimento. O experimento se deu através de bateladas, em* *mesocosmos, inicialmente com 7 dias de tempo de retenção e em seguida sob cargas hidráulicas de choque com 24, 2 e 4 h de tempo de retenção. As diferenças entre os tratamentos e os controles foram analisadas pelo teste estatístico PERMANOVA e ANOSIM. Os resultados para a batelada de sete dias indicaram que a* T. domingensis *obteve melhor eficiência de remoção em relação ao* S. californicus *(eficiência de PT = 47 % e NT = 78 %; PT = 11 % e NT = 30 %, respectivamente). Houve diferença significativa para a remoção de nutrientes para os tempos de retenção de 24 h e 4 h para a* T. domingensis. *Não houve remoção significativa para o* S. californicus *nos tempos de retenção inferiores a sete dias.*

Palavras chave: *tratamento do escoamento superficial, macrófitas emergentes,* wetlands *construídos flutuantes*

INTRODUCTION

Urban surface runoff strongly contributes to the degradation of river ecosystems, either due to alterations on water quality (Paul & Meyer, 2001) or hydrogeomorphic modifications (Navratil *et al.*, 2013). The water drained from pavement, sidewalks and drainage pipes has high pollution loads, high nutrient concentrations (Lee & Bang, 2000; Liu *et al.*, 2013) and heavy metals (Wijesiri *et al.*, 2016). Furthermore, the volume of stormwater runoff and flooding, amplified by climate changes, require urban adaptation strategies to mitigate those impacts (Zölch *et al.*, 2017).

Innovative and nature-based solutions have been applied to address such environmental problems. Kabisch *et al.* (2017) showed that green and blue spaces help reduce urbanisation-related risk factors to human health. Permeable and porous pavements can be effective nature-based solutions to mitigate the impact of paving upon the water and carbon cycle, besides promoting sustainable urbanisation (Fini *et al.*, 2017). Wetlands are known as provisioners of ecosystem services and thereby have great potential as nature-based solutions to address a variety of environmental, social and economic challenges (Thorslund *et al.*, 2017).

Constructed Floating Wetlands (CFW) are a relatively new water treatment technique that consists of emergent macrophytes planted on floating structures (Tanner & Headley, 2011; Lynch *et al.*, 2015). The system has other designations such as floating hydroponic root mats, constructed floating islands, artificial floating islands, etc. (Chen *et al.*, 2016). CFW have been tested for the treatment of wastewater (Weragoda *et al.*, 2012), stormwater runoff (Borne *et al.*, 2013; Winston *et al.*, 2013; Ladislas *et al.*, 2015), synthetic stormwater (Tanner & Headley, 2011; White & Cousins, 2013) and polluted rivers (Zhao *et al.*, 2012; Saeed *et al.*, 2016). However, few studies assess the system's capability during short periods of retention time and its performance under hydraulic shock-loading. Moreover, less work has been done in CFW systems without substrates (Geng *et al.*, 2017).

Nature-based solutions are directly relevant to several policy areas and, because of their systemic nature, they also interact with many other areas, such as land use and spatial planning (Raymond *et al.*, 2017). The amount of land that sustainable drainage systems may demand is a major issue in the redevelopment of existing built-up areas (Jones & Mcdonald, 2007). In that sense, CFW are profitable solutions, since their installation does not require additional land to be dedicated to treatment or diminish the space of the required storage volume for wet ponds (Winston *et al.*, 2013). Moreover, application of conventional constructed wetlands might be difficult because, the erratic nature of storm events affects establishment of vegetated littoral zones, algal growth and survival of sediment-rooted plants (Chang *et al.*, 2012). On the other hand, CFW may be applied on draining detention structures, combining flood control and surface runoff treatment (Lynch *et al.*, 2015). System implementation depends both on the presence of solar radiation and a minimal permanent water level of detention structures. Borne *et al.* (2013) and Ladislas *et al.* (2015), both report good results for CFW on existing water runoff ponds.

Within the context of surface runoff treatment, it is important to evaluate the efficiency of the systems for short retention periods and high loads. The variability (intensity, duration and frequency) of rainfall events is quite large, but it is in the first-flush phase that pollutants are concentrated (Alias *et al.*, 2014). Nitrogen and phosphorus are nutrient constituents of stormwater that influence the overgrowth of algae and other aquatic weeds in stormwater detention ponds (Chang *et al.*, 2012). Borne *et al.* (2015) suggest that the main factors contributing to the overall performance of retention ponds in the presence of a CFW are: dense root networks and attached biofilms, release of root organics and detritus, neutral pH and low redox potential.

CFW vegetated with different plant species may show a significant difference in removal performance of pollutants (Zhang *et al.*, 2014). *Typha* and *Schoenoplectus* are the most common genera applicable on constructed wetlands (Vymazal, 2013). Others genera commonly employed on FCW are: *Canna* (Saeed *et al.*, 2016), *Juncus* (Lynch *et al.*, 2015), *Cyperus* (Zhang *et al.*, 2014) and *Carex* (McAndrew & Ahn, 2017). Given that biological invasion has been identified as one of the major causes of loss of biodiversity in aquatic ecosystems (Allan & Castillo, 2007), the importance of native species during macrophyte selection should be considered. In spite of the fact that macrophytes represent an essential component of aquatic communities, invasive macrophytes negatively alter ecosystem properties (Fleming & Dibble, 2015).

This research reports the results of CFW applied to the treatment of simulated urban surface runoff. Two plant species were tested, using a floating structure without growth medium (substrates). This configuration of floating structure is innovative, and the structure was tested for the first time. The goals of this research were: a) to assess the nutrient removal efficiency of *Typha domingensis* and *Schoenoplectus californicus* during a seven-day batch period and b) to investigate the system removal performance of total nitrogen (TN) and total phosphorus (TP) under short retention times and hydraulic shock-loading.

MATERIALS AND METHODS

Construction of CFW

A mesocosm experiment was set up at the Hydraulic Research Institute of the Federal University of Rio Grande do Sul, Porto Alegre, Brazil, to evaluate the performance of native macrophytes in FCW. Each mesocosm consisted of 120 L tanks (43 x 62 x 45 cm). Six tanks were installed with two replicas for each treatment and

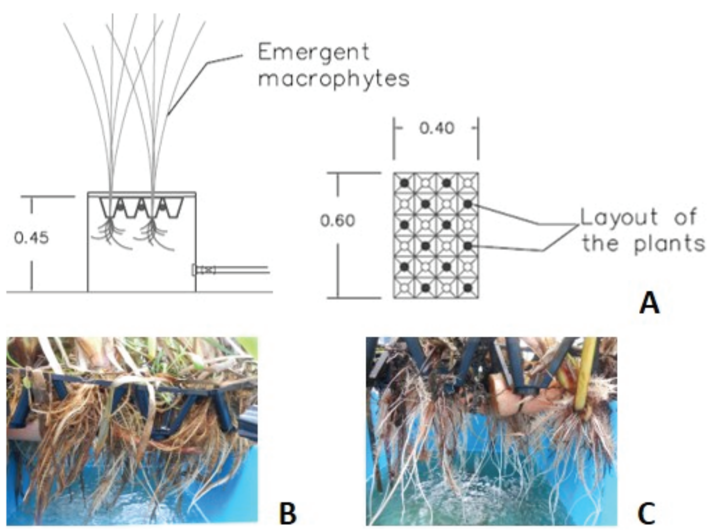


Figure 1. A. Floating structure details. The dimensions are in centimeters. **B.** Root growth of *Typha domingensis*. **C.** Root growth of *Schoenoplectus californicus*. ***A.*** *Detalhes da estrutura flutuante. As dimensões estão em centímetros.* ***B.*** *Crescimento das raízes da* Typha domingensis*.* ***C.*** *Crescimento das raízes do* Schoenoplectus californicus*.*

two controls with no plants. The tanks, which housed the aquatic macrophytes, were protected from direct rain by the installation of a transparent plastic cover. The mesocosms were supplied with synthetic effluent prepared in a reservoir of 800 L. The synthetic effluent was composed of a dilute Hoagland nutrient solution: $Ca(NO_3)_2$, KNO_3, $NH_4H_2PO_4$, $MgSO_4$, $CuSO_4$, $ZnSO_4$, $MnSO_4$, H_3BO_3, $(NH_4)_6Mo_7O_{24}$ and FeDTPA. After dilution of the solution components, pH was controlled in the range of 6.5 and 7.0 with addition of H_2SO_4 or KOH.

The structure was comprised of plug-in modules with dimensions of 40 cm x 40 cm consisting of rigid recycled polypropylene plastic material and polyethylene floats. Therefore, the structure did not have a growth medium and the source of nutrients came exclusively from the synthetic effluent. For each mesocosm, a module and a half was used to completely cover the surface area of the tanks. The final structure dimension was 40 cm x 60 cm. In the floating structure of each tank, 12 seedlings were planted in an intercalated way (Fig. 1A).

Macrophytes

Two species were selected among the native emerging macrophytes: *Typha domingensis* Pers. and *Schoenoplectus californicus* (CA Mey.) Soják. These macrophytes are considered non-endemic and have a regular occurrence in Southern Brazil. The selection of both species was based on their origin, their reproduction potential and growth, in addition to the applicability in phytoremediation and possible commercial application (Wille *et al.*, 2017; Hidalgo-Cordero & García-Navarro, 2018). The species were collected on May 18, 2017. About 30 seedlings were collected for each species. The seedlings were selected according to size and vitality. *S. californicus* was collected from the littoral zone of Guaíba Lake, whereas *T. domingensis* was collected from a wetland area on the university campus. Both species were collected in Porto Alegre, RS in Southern Brazil. On the day of collection, the plants were transported to the experiment site where they were installed in the floating structure: 12 seedlings were planted in each tank. Some seedlings of each species were set aside in case of difficulties with plant adaptation. The system was supplied with synthetic effluent for 11 weeks to provide macrophyte establishment and root growth (Fig. 1. B, C).

System operation

Seven-day batch

After the macrophytes were established, the batch was started with the application of the synthetic effluent. The initial sampling was then conducted, and the system was exposed to 0.5 mg/h of TP and 2.8 mg/h of TN loads at the 20 cm level for four weeks, corresponding to a seven-day hydraulic retention time (HRT).

Hydraulic shock-loading

Following the seven-day batch, we conducted the hydraulic shock-loading stage. The system was exposed to 24 h of HRT at the 20 cm level with 3.2 mg/h of TP and 19.4 mg/h of TN loads. After sampling, the tanks were filled with an additional 20 cm of water, for a total of 40 cm. From this stage on, samples were collected within 2 and 4 h of HRT to quantify the effluent concentrations under hydraulic shock-loading. The loading applied was 77.4 mg/h of TP and 465.4 mg/h of TN load for 2h of HRT, and, 38.7 mg/h of TP and 232.7 mg/h of TN load for 4 h of HRT. At the end of the 4 hours, the level was reduced to 20 cm, followed by exposure for the remaining 6 days of the batch before final collection.

Sampling and water quality analyses

In the field, pH, redox potential, conductivity and temperature were measured with the use of a multiparameter probe (YSI-Pro Plus). One sample of water was collected for the analysis of phosphorus, nitrogen, total organic carbon (TOC), chlorophyll-*a*, turbidity and colour.

In the laboratory, turbidity (Hach-2100N) and colour (Digimed-DM-COR) were measured and 500 mL of sample was immediately filtered and frozen. Total phosphorus (TP) and orthophosphate (PO_4^{3-}) analyses were performed with the

Stannous Chloride Method 4500P-D (APHA, 2005). Nitrate (NO_3^-) was analysed by ion chromatography with chemical suppression of eluent conductivity 4110-B (APHA, 2005). TN and TOC analyses were made in a TOC analyser (SHIMADZU- TOC- VCPN) using the wet oxidation method. Chlorophyll-*a* was extracted using the Nusch (1980) method and the absorbance was read by a spectrophotometer (CARY-UV/VIS) and determined by Lorenzen's equations (1967). Wet biomass was obtained through the selection of four plants from each mesocosm which were weighed before and after pruning. The same plants were identified and weighed at the end of the experiment.

Statistical analyses

Non-Metric Multidimensional Scaling (nMDS) was performed using Euclidian distance to represent the distribution of samples according to nutrient and physicochemical data (software Primer 6 version 6.1.15). In addition, analysis of similarities (ANOSIM) was performed to evaluate the differences between controls, inflows and outflows of nMDS groups. Besides indicating *p*-value, ANOSIM indicated R values that varied from 0 to 1. Box-plot graphics were used to illustrate the differences between treatments and controls (R Core Team, 2018) and ANOSIM was performed to evaluate the contribution of both

Table 1. Statistics of input and output of experimental physicochemical parameters to 7-days batch (n = 8). T- *Typha domingensis*; S- *Schoenoplectus californicus*; C- Control. *Estatísticas de entrada e saída dos parâmetros físico-químicos para a batelada de 7 dias (n = 8).*

		T input	T output	S input	S output	C input	C output
Temperature (°C)	min	14.9	13.4	14.9	13.1	14.8	12.9
	mean	16.2	15.9	16.2	15.7	16.2	15.5
	max	18.4	21.7	18.5	21.5	18.4	21.2
pH	min	6.57	5.46	6.56	6.29	6.47	6.54
	mean	6.75	6.21	6.76	6.46	6.80	6.82
	max	6.96	6.67	7.09	6.60	7.15	7.06
Conductivity (µS/cm)	min	134.3	61.5	138.8	135.6	138.9	145.5
	mean	153.9	89.2	154.1	147.0	154.3	158.6
	max	163.0	110.8	162.8	159.7	163.2	182.3
DO (mg/l)	min	7.74	4.78	7.89	5.84	7.69	7.64
	mean	8.63	7.20	8.53	7.73	8.49	9.19
	max	9.09	8.91	8.90	9.09	9.51	10.15
Redox potential (mV)	min	-125.1	-145.0	-34.5	-168.0	-176.5	-185.9
	mean	15.2	-108.2	24.4	-135.2	12.0	-140.5
	max	76.2	-55.9	78.5	-105.7	106.0	-77.6
Turbidity (NTU)	min	0.35	0.70	0.61	0.51	0.56	0.47
	mean	0.67	0.91	0.80	0.71	0.70	0.77
	max	0.86	1.22	0.97	1.02	0.86	1.25
Colour	min	0.0	2.6	0.0	3.6	0.0	0.0
	mean	1.3	8.2	1.6	7.7	1.6	1.4
	max	3.1	13.1	3.9	13.3	3.4	4.2

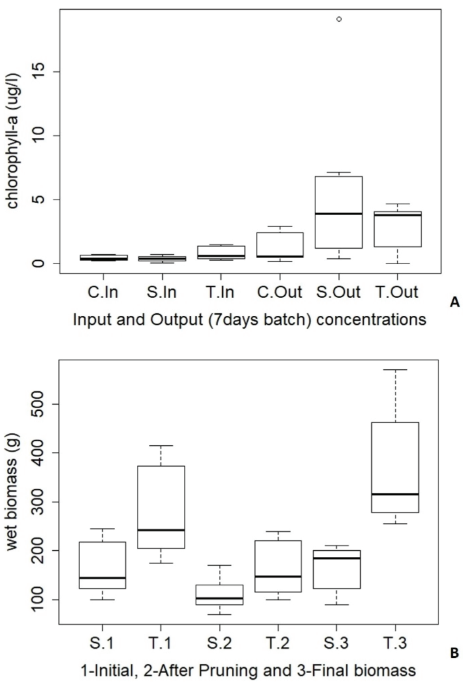


Figure 2. **A.** Results from input and output of chlorophyll-*a* concentrations to 7-days batch. C- Control; S- *Schoenoplectus californicus*; T- *Typha domingensis*. **B.** Results of wet biomass. 1- Initial biomass; 2- After Pruning biomass; and 3- Final biomass. S- *Schoenoplectus californicus*; T- *Typha domingensis*. ***A.*** *Resultados iniciais e finais das concentrações de clorofila-*a *para a batelada de 7 dias. C- Controle; S-* Schoenoplectus californicus*; T-* Typha domingensis*.* ***B.*** *Resultados da biomassa úmida. 1- Biomassa inicial; 2- Biomassa após a poda e 3- Biomassa final. S-* Schoenoplectus californicus*; T-* Typha domingensis*.*

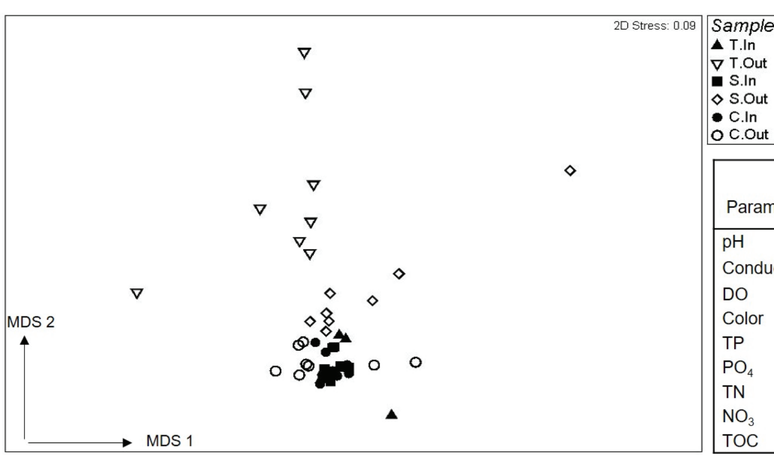
species to carbon elimination and to the increase in the biomass of *T. domingensis* in relation to *S. californicus*. The nutrient removal differences were also analysed by permutational multivariate ANOVA based on distances (PERMANOVA) using software Primer 6. The distance matrix (Euclidian distance) was created with normalized data of nutrients (TP, PO_4^{3-}, TN and NO_3^-). The statistic used (t-statistic) is analogous to Fisher's F-ratio and is constructed from sums of squared distances or dissimilarities within and among groups (Anderson, 2001).

RESULTS

Removal efficiency of the seven-day batch

Physical, chemical and biological parameters

Table 1 presents the summary statistics of experimental physicochemical parameters which were monitored weekly. The mean daily insolation was 6 h during the total experimental period (August and September). The experiment protection did not control the effects of variation in air temperature. Mean air temperature ranged from a minimum of 14.3 °C to a maximum of 25.4 °C (INMET, 2017). The mean values of water temperature ranged from a minimum of 14.0 °C to a maximum of 20.0 °C during the period



nMDS correlations

Parameters	MDS1	MDS2
pH	0.084	-0.829
Conductivity	0.431	-0.820
DO	-0.252	-0.768
Color	0.182	0.792
TP	0.326	-0.871
PO_4	0.184	-0.916
TN	0.237	-0.888
NO_3	0.207	-0.897
TOC	0.248	0.712

Figure 3. nMDS diagram and Pearson correlation values related to nMDS axis to 7-days batch. T- *Typha domingensis*; S- *Schoenoplectus californicus*; C- Control. *Diagrama nMDS e valores das correlações de Pearson relativas aos eixos do nMDS para a batelada de 7 dias.*

assessed. pH values decreased for both *T. domingensis* and *S. californicus* after the seven-day batch. Conductivity results pointed to the efficacy of the removal process, showing lowest values for *T. domingensis*. During the seven-day, DO values decreased for both species. Redox potential values became negative in outflows, a reduced condition is favorable to nitrogen and phosphorus uptake (Saad *et al.*, 2016; Borne *et al.*, 2015). Turbidity had little variation, and colour values showed that the dissolved substances increased for both species.

Chlorophyll-*a* concentrations increased in output effluent (Fig. 2A). Interestingly, concentrations in macrophytes treatment were higher than in control tanks. Wet biomass increased from initial to final data (Fig. 2B). The ANOSIM showed the increase of wet biomass of *T. domingensis* to *S. californicus* (3.S to 3.T, R = 0.583 and $p = 0.001$). Additionally, there was no significant difference between the species after pruning (2.S to 2.T, R = 0.12 and $p = 0.115$).

Nutrient removal

The separation among the samples according to removal efficiency is illustrated on the nMDS graph in Figure 3, where it was observed that control and input samples presented a greater similarity to each other than to *T. domingensis* outputs and *S. californicus* outputs. Pearson correlation values of parameters explained the distribution of samples related to nMDS axes. The statistical test among nMDS groups presented a large difference between *T. domingensis* outputs and control outputs (R = 0.73 and $p = 0.001$). A difference between *T. domingensis* outputs and *S. californicus* outputs was also observed, but it was less expressive (R = 0.403 and $p = 0.001$). Furthermore, there was no significant difference between inputs of species (R = 0.024 and $p = 0.579$) and controls (T.In to C.In, R = 0.047 and $p = 0.769$; S.In to C.In, R = 0.047 and $p = 0.659$).

The removal efficiency of *T. domingensis* was superior to the one of *S. californicus*. *T. domingensis* presented 78 % TN removal efficiency and 47 % TP removal, while *S. californicus* removed 30 % and 11 % TN and TP, respectively (Fig. 4A, B). Controls showed 5 % TN increase and 2 % TP removal efficiency. Both species presented carbon concentration increases in output samples (Fig. 4C). ANOSIM confirmed the graphic results. *T. domingensis* outputs did not present differences in relation to *S. californicus* outputs (R = 0.073 and $p = 0.166$). There was no difference between input and controls (T.In to C.In, R = 0.048 and $p = 0.662$; S.In to T.In, R = 0.161 and $p = 0.069$; C.In to C.Out, R = 0.055 and $p = 0.192$). In addition, there was difference between *T. domingensis* outputs and control (R = 0.539 and $p = 0.002$) and *S. californicus* outputs and control (R = 0.603 and $p = 0.001$). The patterns of

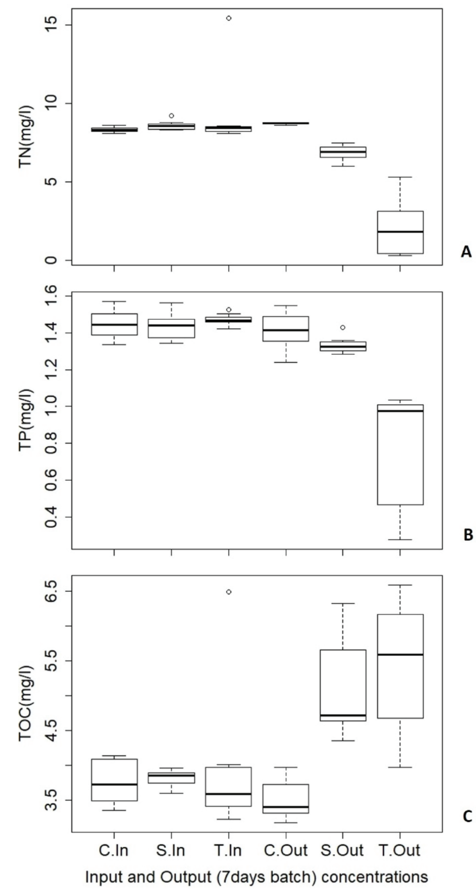


Figure 4. 7-days batch nutrients concentration results. C- Control; S- S*choenoplectus californicus*; T- *Typha domingensis*. A. Total Nitrogen (mg/l). B. Total Phosphorus (mg/l). C. Total Organic Carbon (mg/l). *Resultados das concentrações de nutrientes para a batelada de 7 dias.*

nutrient removal were also confirmed through PERMANOVA tests. There was a significant difference ($p < 0.05$) between input and output samples for both *T. domingensis* and *S. californicus*. Differences in species and controls were also identified. Furthermore, pairwise tests confirmed that output results differed between the two species assessed (Table 2).

Table 2. 7-days batch results of PERMANOVA test between the treatments. Where: T- *Typha domingensis*; S- X*Schoenoplectus californicus*; C- Control; A and B- represent the treatment replicas; I- Input; O- Output. The bold values indicate significant difference. *Resultados para a batelada de 7dias do teste estatístico PERMANOVA realizado entre os tratamentos. Onde: T-* Typha domingensis*; S- Schoenoplectus californicus; C- Controle; A e B- representam as réplicas dos tratamentos; I- Entrada e O- Saída. Os valores em negrito indicam diferença significativa.*

Source	df	SS	MS	*Pseudo-F*	P(perm)
Treatment	11	399.78	36.344	3.7147	**0.001**
Residual	36	352.22	9.7838		
Total	47	752			
			Pairwise test between treatmets		
Treatment	**t**	***P***	**Treatment**	**t**	***P***
TAI, TAO	3.65	**0.02**	SAI, SAO	2.41	**0.03**
TAI, TBO	4.84	**0.02**	SAI, SBO	2.35	**0.04**
TBI, TAO	3.94	**0.03**	SBI, SAO	2.48	**0.03**
TBI, TBO	5.47	**0.02**	SBI, SBO	2.46	**0.04**
TAO, TBO	0.91	0.31	SAO, SBO	0.61	0.76
TAO, CAO	3.70	**0.03**	SAO, CAO	2.02	**0.03**
TAO, CBO	3.84	**0.03**	SAO, CBO	2.45	**0.03**
TBO, CAO	5.17	**0.02**	SBO, CAO	1.94	**0.03**
TBO, CBO	5.36	**0.02**	SBO, CBO	2.36	**0.03**
TAO, SAO	3.10	**0.03**	TBI, CBI	0.30	0.91
TAO, SBO	3.05	**0.03**	SAI, SBI	0.40	0.76
TBO, SAO	4.57	**0.03**	SAI, CAI	0.43	0.95
TBO, SBO	4.51	**0.02**	SAI, CBI	0.66	0.61
TAI, TBI	0.85	0.97	SBI, CAI	0.50	0.92
TAI, SAI	0.70	1.00	SBI, CBI	0.61	0.64
TAI, SBI	0.85	0.94	CAI, CBI	0.55	0.67
TAI, CAI	0.89	0.75	CAI, CAO	0.62	0.78
TAI, CBI	0.87	0.84	CAI, CBO	0.48	0.87
TBI, SAI	0.54	0.77	CBI, CAO	0.82	0.63
TBI, SBI	0.42	0.80	CBI, CBO	0.73	0.64
TBI, CAI	0.56	0.76	CAO, CBO	0.32	0.94

Performance under hydraulic shock-loading

Physical and chemical parameters

Physical and chemical parameters over short periods of time presented less variability than seventh-day values (Table 3). Mean temperature increased from 24 h to 2 h and 4 h of retention time, showing a daily variation. DO did not present the same tendency in both species, i.e., there was an increase in DO after hydraulic shock-loading in *T. domingensis*. The conductivity indicated the best performance in *T. domingensis*. The reduction of 16 % in 2 h for *T. domingensis* was similar to *S. californicus*' reduction at day seven. Turbidity values presented variation only in tanks with plant species; control tanks had little variation.

Nutrient removal

Typha domingensis revealed a better nutrient removal than *S. californicus*, considering all retention times assessed (Fig. 5). Only *T. domingensis* did not present any removal in retention time of 2 h for TP (Fig. 5B). However, the best efficiencies were observed for the retention time of 24 h and seven days.

PERMANOVA tests highlighted a significant difference in the retention times of 24 h and 4 h for *T. domingensis*, besides the efficiency reported for the seven-day batch. In contrast, no significant reduction was found for *S. californicus* when retention time was less than seven-day. Moreover, there was no significant difference between controls and initial values of input solution (Table 4).

DISCUSSION

Plant species used in CFW have different removal capacities of pollutants due to their specific biological properties such as uptake efficiencies for nutrients, growth rate and root types (Chang *et al.*, 2017). Wetland may be built with fibrous and thick root plants; however, most CFW are com-

Table 3. Mean values of physicochemical parameters to hydraulic shock-loading phase (n = 4). T- *Typha domingensis*; S- *Schoenoplectus californicus*; C- Control. *Média dos parâmetros físico-químicos para a etapa de carga hidráulica de choque (n = 4).*

		Temperature (°C)	pH	Conductivity (µS/cm)	DO (mg/l)	Redox potential (mV)	Turbidity (NTU)	Colour
T	**0**	21.7	7.00	169.7	8.21	-161.1	0.73	3.2
	24h	17.5	5.82	122.8	6.18	-210.3	1.26	7.3
	2h	18.6	6.16	142.6	7.02	-180.7	1.31	6.5
	4h	20.1	6.16	144.5	6.84	-191.3	1.77	6.5
	7d	17.8	5.47	64.6	6.20	-201.8	2.48	13.2
S	**0**	21.7	7.05	169.7	8.44	-141.8	0.68	4.4
	24h	17.6	6.44	153.6	7.82	-212.7	1.43	5.7
	2h	18.7	6.61	158.9	7.90	-180.0	1.29	4.7
	4h	20.6	6.61	165.1	7.80	-200.0	1.18	4.5
	7d	17.8	6.30	144.8	7.52	-205.8	2.15	11.5
C	**0**	21.7	7.07	169.6	8.41	-129.2	0.83	3.7
	24h	17.3	6.70	153.6	8.91	-213.7	0.98	1.2
	2h	18.7	6.87	159.4	8.19	-170.3	0.76	1.9
	4h	21.2	6.93	167.4	8.46	-191.4	0.81	1.4
	7d	17.4	6.94	158.6	9.20	-211.6	0.90	2.9

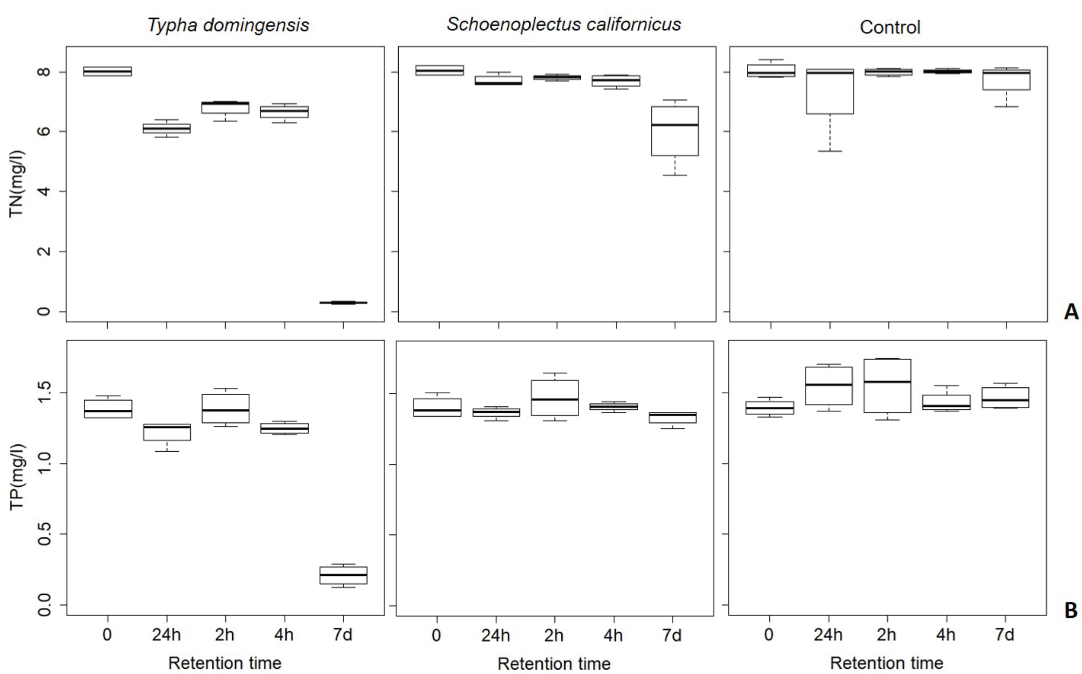


Figure 5. Results of nutrient removal under hydraulic shock-loading. A. Total Nitrogen concentrations (mg/l). B. Total Phosphorus concentrations (mg/l). *Resultados para a remoção de nutrientes sob a carga hidráulica de choque.*

posed of fibrous root plants (Chen *et al.*, 2016) since fibrous root plants have significantly higher TN removal rates (Li *et al.*, 2013). Both *T. domingensis* and *S. californicus* have fibrous roots, but the removal efficiency presented by *T. domingensis* was more expressive in all retention times tested. This result could be explained by the different species growth rates. In addition, the adaptation of *T. domingensis* was superior to *S. californicus* considering that the employed floating structure had no growth medium.

As well as in our results, studies evaluating the removal of pollutants showed that differences in the plant species affected the removal of pollutants in the CFW, and the above-ground biomass significantly affected the removals of pollutants, showing the importance of macrophytes in mediating the pollutant removals in the floating islands (Zhang *et al.*, 2014). The absence of growth substrate in the floating structures employed did not present a limiting factor to the removal process of nitrogen by *T. domingensis* (78 % TN removal efficiency). The removal efficiency of TP of both species tested was inferior compared to previous studies. Geng *et al.* (2017) found high rates of P removal (74–98 %) using hydroponic microcosms without growth substrate. Such results could be related both to HRT (of 10 days) applied by Geng *et al.* (2017), which enhanced the biotic processing and the retention of phosphorus and to the different design that used polyculture on treatments.

The reduced condition increases the solubility of nutrients (Jones *et al.*, 2004), phosphorus sequestration and denitrification (Borne *et al.*, 2015). In the present study, the negative redox potential was registered especially to output values. In addition, our results did not show different patterns between the two species. Saad *et al.* (2016) found differences in redox potential along the flow path to species *J. effusus* and *P. australis*.

Another factor that determines the CFW functioning is the percentage of coverage of the floating structure. This factor is very important for real scale applications. According to Chang *et al.* (2017), around 20 % cover seems optimal if the basin is to be maintained as an aerobic system without artificial aeration and still achieve good removal efficiency. Chang *et al.* (2017) argue that

Table 4. Hydraulic shock-loading results of PERMANOVA test between the treatments: T- *Typha domingensis*; S- *Schoenoplectus californicus*; C- Control. The bold values indicate significant difference. *Resultados para as cargas hidráulicas de choque do teste estatístico PERMANOVA realizado entre os tratamentos: T-* Typha domingensis*; S-* Schoenoplectus californicus*; C-Controle. Os valores em negrito indicam diferença significativa.*

Source	df	SS	MS	*Pseudo-F*	P(perm)
Treatment	14	209.98	14.999	25.94	**0.001**
Residual	45	26.019	0.5782		
Total	59	236			
Pairwise test between treatmets					
Treatment	**t**	***P***	**Treatment**	**t**	***P***
TI, T24h	3.04	**0.03**	SI, S24h	1.67	0.20
TI, T2h	1.43	0.15	SI, S2h	0.97	0.47
TI, T4h	2.26	**0.03**	SI, S4h	0.90	0.54
TI, T7d	17.87	**0.03**	SI, S7d	2.49	**0.03**
T24h, T2h	2.30	**0.06**	S24h, S2h	1.95	0.16
T24h, T4h	1.30	0.15	S24h, S4h	0.94	0.24
T24h, T7d	17.25	**0.04**	S24h, S7d	1.70	0.06
T24h, C24h	2.04	**0.02**	S24h, C24h	1.19	0.21
T2h, T4h	1.45	0.26	S2h, S4h	1.14	0.25
T2h, T7d	17.03	**0.03**	S2h, S7d	2.30	**0.04**
T2h, C2h	1.59	0.16	S2h, C2h	0.56	0.56
T4h, T7d	20.38	**0.04**	S4h, S7d	1.87	0.11
T4h, C4h	4.14	**0.04**	S4h, C4h	1.26	0.24
T7d, C7d	18.08	**0.02**	S7d, C7d	2.14	**0.03**
TI, CI	1.05	0.28	SI, CI	1.71	0.18
CI, C24h	0.75	0.62	C24h, C4h	2.28	**0.03**
CI, C2h	1.72	0.14	C24h, C7d	1.73	0.06
CI, C4h	2.04	0.08	C2h, C4h	0.74	0.60
CI, C7d	1.58	0.17	C2h, C7d	0.62	0.77
C24h, C2h	1.82	0.08	C4h, C7d	0.73	0.76

the total coverage of the water surface by the system can lead to low levels of DO due to the loss of air contact area for oxygenation of water by diffusion. In our work, a coverage of 100 % of the surface area was used; however, the contents of DO remained acceptable within the period evaluated and under mesocosm conditions. The lowest values of DO occurred for the *T. domingensis* at the end of the seven-day batch. These results can be explained by the greater coverage of this specie in the structure. The multiplication by lateral rhizomes and adaptation of the *T. domingensis* in the structure was superior in comparison to the *S. californicus*, whose structure had more empty spaces between seedlings.

The empty space allowed greater penetration of light, which provided better conditions for the growth of photosynthetic microorganisms, as evidenced by the high values of chlorophyll-*a* for the *S. californicus* treatment. Furthermore, higher concentrations of chlorophyll-*a* were found in the macrophyte tanks as compared to the control tanks. A possible explanation for this is that algae benefited from the floating structure and the roots, and during sampling procedure, the biofilm possibly detached from them and remained suspended in the water column. FCW remove nutrient-pollution through biosynthesis and also benefit the biofilm of fungi, bacteria and beneficial algae that form along the roots and the floating structure (Chang *et al.*, 2012).

In addition to nutrient removal, wetlands are a potential carbon sink (Schultz & Pett, 2018). Carbon sequestration is a wetland ecosystem service that has received attention in the current climate scenario (Villa & Bernal, 2018). According to Means *et al.* (2016), the carbon storage potential is affected by the characteristics of each species. In this sense, we observed significant increase in carbon concentration in the final effluent of both species that could be attributed to carbon release which occurs in the rhizosphere (Dunn *et al.*, 2016). Carbon storage was also observed through wet biomass data. *T. domingensis* showed the best potential to produce and store carbon (though biomass increase) in relation to *S. californicus*.

The feasibility of implementing the CFW in the treatment of urban drainage depends on the area required by the system, which may be greater for conventional wetland systems. Also, plant assimilation of nutrients may be higher in a CFW compared with a sediment-rooted wetland since the roots hanging beneath the floating structure are in direct contact with the effluent to be treated (Tanner & Headley, 2011). Furthermore, considering our results, there is the possibility of applying the floating system in existing detention basins to improve nutrient removal. Whereas stormwater detention ponds are frequently designed to maintain a volume of water and to discharge surplus levels within 24 to 72 h (Chang *et al.*, 2012), the present study showed that *T. domingensis* had a removal efficiency for similar retention times. On the other hand, *S. californicus* presented no removal efficiency for retention times less than seven days under the conditions tested. Although nutrient removal efficiency could be enhanced through the application of biofilm carriers that increase surface area (Zhang *et al.*, 2018), this configuration was not employed in the present study. The short duration of the experiment, although it is in line with another experimental studies (Chang *et al.*, 2012; Lynch *et al.*, 2015; Geng *et al.*, 2017), did not allow us to assess the influence of seasonal patterns. Therefore, long term field studies are necessary to check the possible influence of environmental factors on CFW.

CONCLUSIONS

Typha domingensis achieved the best nutrient removal efficiency rates during the seven-day batch. The study also indicated that under hydraulic shock-loading, *T. domingensis* presented nutrient removal at 4 and 24 hours, whereas *S. californicus* showed nutrient removal just for seven-day batch. These results suggest that *T. domingensis* is best adapted to the floating structure applied, as well as its specific biological properties. The results of this research support the idea that the selection of macrophytes species is an important factor for the success of floating wetland systems. The scope of this study was however, limited to mesocosm design and short period of assessment time. Therefore, more research is needed to assess field application of the system and long term evaluation. But CFW could be applied to stormwater treatment under the framework of nature-based solutions with ecosystem service benefits and enhanced conservation of aquatic ecosystems.

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