Two-year performance of single-stage vertical flow treatment wetlands planted with willows under cold-climate conditions

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Abstract

Climate-related issues constitute an important obstacle for the development of treatment wetland (TW) applications in regions with freezing winter temperatures. The aim of the present study was to evaluate the efficiency of a new configuration of TWs based on the vertical flow (VF) configuration. The proposed TWs system is planted with a willow species (*Salix miyabeana* SX67) and including design adaptations for cold climate operation. Two different flow modes for winter-time operation were proposed: percolated and saturated with continuous artificial aeration. The pilot-scale systems were tested with municipal wastewater, at an organic loading ranging from 5 to 20 g $CBOD_5$ m^{-2} d^{-1}.

The pilot TWs were successfully operated for 22 months despite freezing winter temperatures reaching as low as -32 °C. Willow development was normal, with evapotranspiration ranging from 19 to 23 mm/d in July 2017 for the pilot TWs at an organic loading of 10 g $CBOD_5$ m^{-2} d^{-1}. Organic matter removal efficiency was high for all pilot TWs, with an average 91 % COD and 81 % TSS removal. Nitrification was essentially complete during the summer period and remained high for pilot TWs operated under percolating flow mode in winter but was lower for the saturated flow mode, probably due to insufficient air supply. Our study confirms the successful application of a modified version of VF TW in regions with freezing air temperatures.

Keywords: treatment wetland; cold climate; willow; artificial aeration; percolating flow; saturated/percolating downflow

1. Introduction

The implementation of treatment wetland (TW) systems in regions with freezing winter temperatures presents a challenge when year-round wetland loading is targeted. This is particularly the case for northern regions with a long winter period and freezing temperatures, including days with very low air temperature (less than -25 °C). Freezing can damage the distribution system and the filtering bed. Furthermore, low temperatures in a filtering bed reduce bacterial activity and thus affect treatment performance by reducing organic matter removal and nitrogen transformation processes. The major mechanisms of nitrogen removal in TWs - nitrification and denitrification - are critically influenced by water temperature. The favourable range of temperatures for nitrification in TWs is between 16 and 36 °C (Faulwetter et al., 2009). The best denitrification rate has been found to be between 20 and 25 °C; below 5 °C, both mechanisms function at a very low rate and proceed slowly (Brodrick et al., 1988; Werker et al., 2002; Vymazal, 2007; Saeed and Sun, 2012).

Climate-related risks have slowed the development of TW applications in climates with long and freezing winter conditions. Several studies have shown that, under particular conditions, TWs may be a suitable solution for treating wastewater in cold climate (Jenssen et al., 1993; Jenssen et al., 2005; Smith et al., 2006; Wang et al., 2017). Most successful cold climate applications have used horizontal sub-surface flow (HSSF) TWs, which do not expose the piping system and water directly to air temperature (Ouellet-Plamondon et al., 2006; Yates et al., 2016; Wang et al., 2017). However, HSSF TWs present certain disadvantages, including low oxygenation, which affects removal processes, and poses higher risk of clogging (Saeed and Sun 2012).

In comparison, the French vertical sub-surface flow (VSSF) design, usually planted with *Phragmites australis*, shows a much higher organic matter and nitrification removal capacity, and a lower risk of clogging (Molle et al., 2005; Wang et al., 2017). This TW configuration is considered one of the most efficient water treatment technologies and is widely used in Europe, particularly in France, to treat different types of wastewater. However, standard French VSSF TW cannot be directly transposed to climates with very low freezing temperatures. In addition to the risk of freezing, *Phragmites australis australis* should not be used in regions where this plant species is invasive, such as in North America (Albert et al., 2015; Mozdzer et al., 2013). To take advantage of the benefits of VF TWs configuration in regions with long freezing winter periods, three principal aspects should be modified: the filtering bed (composition; depth), operation conditions (hydraulic and organic loading; flow mode; water level fluctuation; type and frequency of effluent flow distribution; aeration) and species planted. These modifications aim to favor a more homogeneous hydraulic distribution, thus avoiding preferential flow patterns and enabling better temperature maintenance in the filtering bed (Munoz et al., 2006); they also avert the risks involved in using an invasive species. In the present study, we tested experimental systems with specific design modifications that address the impact of a cold climate on these three aspects.

First, the systems were designed to be more compact, with a one-stage TW instead of the two successive stages used in the French classical system. This configuration is similar to a compact version of the VF TW, but without recirculation or classical feeding and resting periods, to reduce cooling during winter and facilitate maintenance of the TW system. The compact VF TWs were initially implemented to reduce the overall footprint and could also reduce heat loss during the treatment process, while maintaining a high pollutant removal rate (Prost-Boucle and Molle, 2012; Paing et al., 2015).

Second, operating conditions were adapted to maintain a high treatment efficiency of the system in winter by testing two downflow modes: percolated, and saturated with artificial aeration. The aims of the forced aeration in the saturated beds were to increase pollutant removal efficiency and to reduce risks of freezing by inducing water movement. The surface of TWs was insulated with a mulch layer. Different flow modes and water levels were tested to determine the best approach for providing increased natural insulation with ice and snow.

Third, since the study was to take place in North America, we selected a willow (*Salix* sp.) as a replacement for *Phragmites australis australis*. Willows (*Salix* sp.) are among the most widely used woody plants for wastewater and soil treatment purposes (Perttu and Kovalik, 1997; Kuzovkina and Volk, 2009; Grebenshchykova et al., 2020). Several willow species have beneficial morphological and physiological characteristics for treatment wetlands, such as rapid growth rate, high biomass production, deep root system with high density, high evapotranspiration rate, high nutrient uptake and resistance to chemical contaminants (Tharakan et al., 2005; Kuzovkina and Volk, 2009; Frédette et al., 2019). Willows tolerate different types of extreme weather conditions and habitat-related ecological stresses (Perttu and Kowalik, 1997; Verwijst, 2001; Major et al., 2017). Due to these characteristics, willows are commonly used to treat different types of wastewater: domestic wastewater (Gregersen and Brix, 2001; Lachapelle-T et al., 2019), landfill leachate (Duggan, 2005; Białowiec et al., 2007; Justin et al., 2010) and sewage sludge (Listosz et al., 2018).

The objective of present study was (i) to evaluate the development of willows in TW conditions in regions exposed to very low winter temperatures for several months per year, (ii) to evaluate the performance of secondary treatment of the modified VF TWs under these climatic conditions and (iii) to compare percolating and saturated downflow modes during winter.

2. Materials and Methods

2.1 Experimental design

Four experimental pilot-scale units of single-stage VF TWs planted with willows were set up at the water resource recovery facility (WRRF) of Saint-Roch-de-l'Achigan in Quebec, Canada. The climate in this region is characterized by a cold period of five months (from November to March) with an average temperature of -5.5 °C (extreme minimum temperature of -36.4 °C in January 2009) and a warm period from April to October with an average temperature of 14.4 °C (extreme maximum temperature of 36.1 °C in July 2018). The average annual precipitation is 1114 mm (all values were calculated for a period of 10 last years from 2009 to 2018; National Climate Data and Information Archive, 2018). Southern Quebec (Canada) is a representative example of the climate-related need for an alternative sustainable solution for treatment of wastewater from small-scale municipalities (Werker et al., 2002). In Quebec, municipalities need to treat wastewater at least up to a secondary level (<BOD_5 25 mg/L; TSS <25 mg/L, absence of acute toxicity; MDDELCC, 2010).

The pilot units were fed with primary settled municipal wastewater for 22 months, from July 2016 to May 2018 (Figure 1). The primary treatment installation included three septic tank compartments and a pumping tank to feed the TWs.

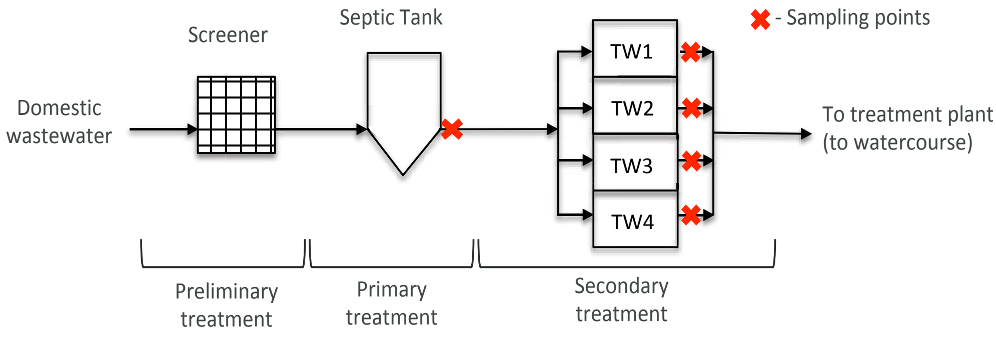

Figure 1. Schematic representation of the pilot treatment system used for experimentation with the position of sampling points.

Each pilot TW had a surface of 11.3 m^2 (4.5 m x 2.5 m), and a total filtering bed depth of 1.2 m. The filling material was the same for all pilot units and was chosen to create a single stage filter providing a high physical filtration capacity. From top to bottom, each filtering bed contained three principal layers of 30 cm each of a mix of gravel 14-20 mm and 20-40 mm; gravel 2.5-5 mm and a layer of sand (Table 1). Three additional layers of different sizes of gravel with a total thickness of 30 cm were added at the bottom for water drainage.

Table 1. Filtering bed composition (from top to bottom).

Thickness (cm)	**Media type**	**Media size** (mm)
30	Gravel	20 – 40 & 14 – 20
30	Gravel	2.5 – 5
30	Sand	$D_{10} = 0.34$
10	Gravel	2.5 – 5
5	Gravel	14 – 20
15	Gravel	20 – 40

Two parallel pipes 2.5 cm in diameter and 3.9 m in length were used to distribute the influent on top of each filter. Each pipe was perforated every 60 cm; the diameter of each perforation was 3.5 mm. Each distribution pipe was covered with a half round pipe of larger diameter (7.6 cm) in order to insulate the mulch from the influent. Three drains 7.6 cm in diameter were installed at the bottom of the filter and connected with the effluent tank. Artificial aeration was installed at a depth of 60 cm in order to oxygenate the two principal gravel layers of the filtering bed without risking undesirable finer sand displacement in the deeper sand layer. It consisted of a flexible pipe 18.3 m in length and 1.3 cm in diameter that was perforated every 30 cm (Figure 2).

Depth	60 cm
Total length of flexible pipe	18.3 m
Diameter of flexible pipe	1.3 cm
Number of air diffusers	61 (every 30 cm)
Type of air diffuser	On-line drip emitters

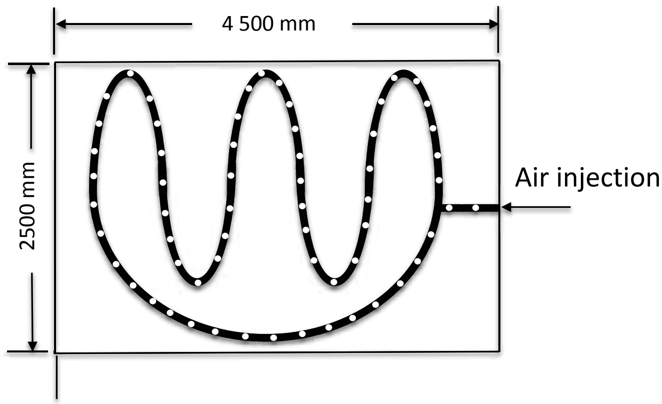

Figure 2. Characteristics and schematic plan view of the artificial air distribution system.

The flexible pipe was connected to a linear septic air pump Hiblow HP-200 (rated loading pressure: 20 kPa; airflow volume: 200 L/min) outside the filter zone. The air pump was insulated in a box to maintain a constant air temperature > 3 °C during winter.

2.2 System insulation

A mulch layer of 20 cm was added on top of each filter to insulate the bed and the influent distribution pipe on the filter surface, as recommended by Wallace et al. (2001). All external pipes between the septic tank and the distribution pipes on the filter surfaces were surrounded by heating cables covered with aluminum foil. Insulation with extruded polystyrene foam and plywood was added to protect the pipes from precipitation and freezing temperatures in winter.

2.3 Plant species

A willow cultivar, *Salix miyabeana* “SX67”, was chosen for planting due to its favorable characteristics such as high biomass productivity, high level of weed competition and good resistance to diseases and parasites (Tharakan et al., 2005). Although native to Asia, this cultivar developed at the University of Toronto does not reproduce naturally by clonal propagation or seed germination, and thus should not represent an invasion threat to surrounding native ecosystems (Labrecque and Teodorescu, 2005; Kuzovkina and Volk, 2009). One-year-old willow plants grown from cuttings were planted in each filter at a density of 4 plants/m^2 (45 plants/pilot unit) to ensure uniform root distribution and complete surface coverage by the aboveground biomass in the long-term. Two “willow screens” were planted on each side of the two external pilot TWs to insure that all four TWs were similarly bordered on each of their lateral sides by willows (Figure 3).

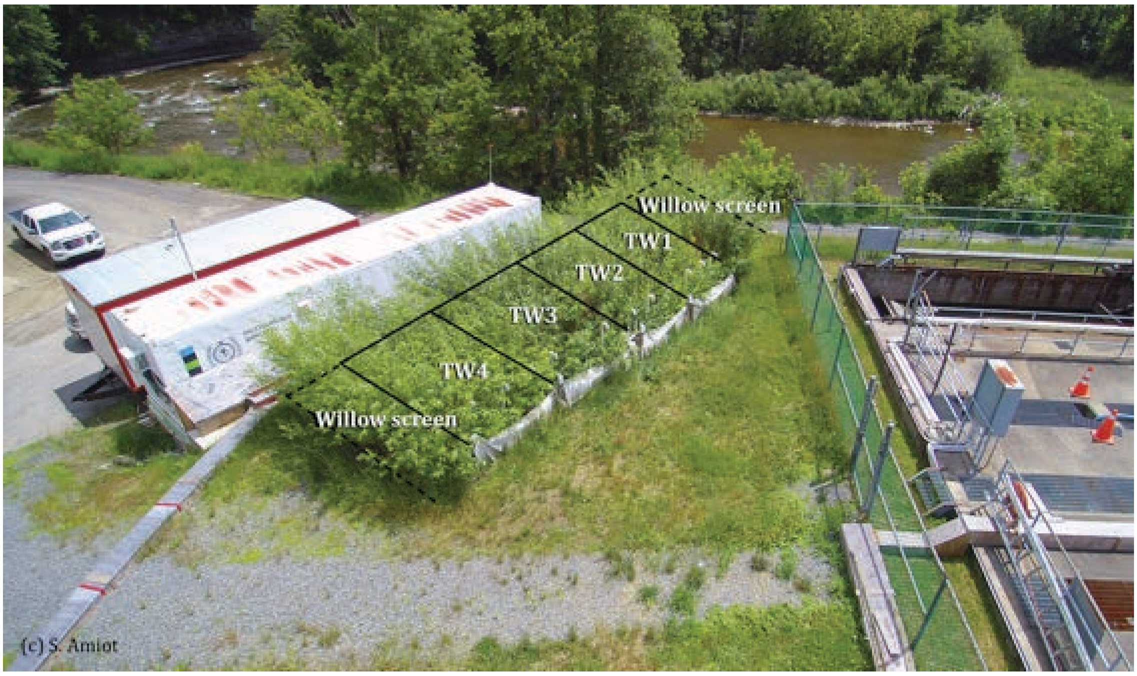

Figure 3. Aerial view of the experimental VF TW pilot systems.

2.4 Operating conditions

A percolating flow mode was used for all pilot units during the summer period. During wintertime, two operation modes were tested: percolating for pilot units 1 and 4, and saturated with artificial aeration for pilot units 2 and 3. Two types of saturated level were tested to limit heat loss in the filtering beds: for the first winter, the high water level was maintained 5-10 cm above the surface, while for the second winter the high water level was maintained 5-10 cm below the mulch layer.

The organic loading rate was chosen to avoid organic overloading during the wintertime. Thus, the TW footprint was lower than recommended for compact versions of French TWs for temperate climates: 33 – 42 $CBOD_5$ m^{-2} d^{-1} (raw wastewater) (Paing et al., 2015) versus 5 – 20 $CBOD_5$ m^{-2} d^{-1} (primary treated wastewater) recommended for cold climate VF design by DWA (2006) and ÖNORM (2009). Two organic loadings of 5 and 10 $CBOD_5$ m^{-2} d^{-1} were tested from July 2016 to September 2017. From

September 2017 to May 2018, the organic loading was doubled to 10 and 20 $CBOD_5$ m^{-2} d^{-1} to test the limits of the TWs during cold temperatures in terms of organic loading (Table 2).

The feeding strategy for TWs was chosen to minimize heating loss in the filtering beds in winter using the natural heat of wastewater. The TWs were fed automatically with batches of 200 L each. The total number of batches applied per day was from 2 to 4 during the first year (every 12 and 6 hours, respectively), and from 4 to 8 batches per day during the second year (every 6 and 3 hours, respectively).

Table 2. Operation conditions.

<table>
<tr><th rowspan="2">Pilot</th><th colspan="2">Organic loading ($g\ CBOD_5\ m^{-2}\ d^{-1}$)</th><th colspan="2">Nb of batch events per 24 h</th><th colspan="2">Flow mode</th></tr>
<tr><th>Year 1</th><th>Year 2 (winter 2)</th><th>Year 1</th><th>Year 2 (winter 2)</th><th>Winter</th><th>Summer</th></tr>
<tr><td>TW1</td><td rowspan="2">10</td><td rowspan="2">20</td><td rowspan="2">4</td><td rowspan="2">8</td><td>percolating</td><td rowspan="4">percolating</td></tr>
<tr><td>TW3</td><td>saturated with aeration</td></tr>
<tr><td>TW2</td><td rowspan="2">5</td><td rowspan="2">10</td><td rowspan="2">2</td><td rowspan="2">4</td><td>saturated with aeration</td></tr>
<tr><td>TW4</td><td>percolating</td></tr>
</table>

The artificial aeration required for saturated flow mode was calculated according to the actual oxygen requirement (AOR) as follows (Kadlec and Wallace, 2008):

$$AOR = COD_{B\ applied} \times f_{CODB\ mineralized} + (TKN \times 4.57) \times f_{TKN\ nitrified} \quad (1)$$

where $COD_{B\ applied}$ is the applied biodegradable COD (g/d), $f_{CODB\ mineralized}$ the expected mineralized fraction of the applied COD (85 %), TKN is the TKN applied (mg N/L) multiplied by the stoichiometric factor of 4.57, and $f_{TKN\ nitrified}$ is the theoretical nitrified fraction of the TKN applied (85 %).

Continuous air supply was provided at a flowrate of 18 (pilot unit 2) and 25 L/min (pilot unit 3) during the first winter experimentation period, and 28 (pilot unit 2) and 55 L O_2/min (pilot unit 3) during the second winter experimentation period. The first winter period lasted 91 days (from January 16 to April 17, 2017), and the second lasted 180 days (from September 27, 2017 to April 23, 2018).

2.5 Monitoring

Grab samples were collected every two weeks at the end of the primary treatment (influent) before a batch event, and after completed treatment in each pilot unit (effluent) after a full batch event. There were no significant differences between the four tested seasons regarding the principal influent characteristics (Table 3).

Table 3. Influent characteristics.

Parameter	Units	Average	SD	Min	Max
Total COD	mg/L	264	103	114	647
TSS	mg/L	53	36	22	257
TKN	mg N/L	30.8	10.1	9.9	54.8
NH_4	mg N/L	21.3	6.9	6.4	37.0
TP	mg P/L	4.9	1.3	1.5	7.7

The removal efficiency of total chemical oxygen demand (total COD), total suspended solids (TSS), total Kjeldahl nitrogen (TKN), ammonium-nitrogen (NH_4-N), nitrite and nitrate (NOx-N), and total phosphorus (TP) was calculated with concentrations (mg/L) as the difference between influent and effluent concentration and expressed in percentage (%). Laboratory analyses were performed at the environmental engineering laboratory of Polytechnique Montreal according to Standard Methods (APHA et al., 2005). Dissolved oxygen (DO) was measured during the second winter by YSI 5000 Benchtop Dissolved Oxygen Meter in each TW effluent, immediately after sampling. The average daily evapotranspiration rate was estimated in July 2017, using the water balance method, as the difference between total inflow (sum of total influent and precipitation) and total outflow, for every day of the month. A Stratus Precision Rain Gauge measured rainfall twice a day at the treatment plant zone, providing precise rainfall at the site for evapotranspiration rate calculations. Air temperature, humidity and wind parameters during the experiment were provided by the L'Assomption meteorological station (#7014160 (Environment Canada) 45°48'34" N, 73°26'05" O, 21 m), located 13 km from the WRRF.

2.6 Statistical Analyses

The statistical relationships between the TWs pilot units and between seasons were tested using the non-parametric Kruskal-Wallis test. When significant, post-hoc comparisons (Pairwise Wilcoxon test) were conducted to determine the difference between groups. Differences were deemed significant at $p < 0.05$. All analyses were performed using R 3.4.2 software.

3. Results

During the investigation period, the average temperature of the coldest month (January 2018) was -11.7 ± 8.0 °C, and the average temperature of the hottest month (July 2016) was 20.7 ± 2.6 °C. The minimum temperature recorded on January 2, 2018 was -

32.5 °C and the maximum temperature recorded was 33.3 °C, on August 8, 2016 (National Climate Data and Information Archive, 2018).

3.1 Cold climate system adaptation

During the first winter, the TWs with lower organic loadings (5 g $CBOD_5$ m^{-2} d^{-1}) received two batches of wastewater of 200 L per 24 h (every 12 hours). This low frequency resulted in the partial freezing of the influent distribution pipes during the coldest periods. An increased frequency during second winter with batch feedings of 200 L every 6 hours was sufficient to maintain the functionality of the system during cold period without supplementary maintenance.

During the first winter, for TWs operated in saturated flow mode with the water level just above the surface, a partial ice layer formed that was too thin to reduce surface heat loss sufficiently. As a result, the snow layer was unstable throughout that winter, with frequent snow melting events. In the second winter, the water layer was kept below the surface, which allowed a layer of snow more than one meter thick to form and persist for most of that season, resulting in improved natural insulation of the distribution pipes and the filtering beds.

3.2 Willow adaptation

Willows planted in TWs showed good development and a fast growth rate. The very dense plantation resulted in the mortality of some willows located in the center of the pilots. Also, after the second winter, die-back was observed in the top parts of many willows, particularly those located at the edge of the experimental set-up. The same response was noted at the margin of large willow plantation located in the region. The willows affected resprouted back, and no negative effects were noted on treatment performances.

The average daily ET rate, measured during July 2017 for pilot units with a lower organic loading (TW2 and TW4), ranged from 10 to 14 mm/d. For pilot units under maximal organic loading (TW1 and TW3), ET ranged from 19 to 23 mm/d (Table 4).

Table 4. Average daily evapotranspiration rate for July 2017 obtained in the present experiment compared to results obtained by Frédette et al. (2019) and by Chazarenc et al. (2010) for TWs operated in the same area (Montreal region).

Source	**Pilot ID**	**Species planted**	**Average ET (mm/d)**	**HLR[4] (L m^{-2} d^{-1})**
Present study[1]	TW1	*Salix miyabeana* SX67	18.7 ± 2.9	73.2
	TW2		10.0 ± 2.4	37.8
	TW3		23.1 ± 3.2	73.2
	TW4		14.0 ± 3.2	37.9
Frédette et al., 2019[2]		*Salix miyabeana* SX67	28.7 ± 17.2	55.5
Chazarenc et al., 2010[3]		*Phragmites australis australis*	16.4; 16.7	30.0

Note: **[1]**: VF TWs, size: 11.2 m^2, plant density of 4 plants/m^2, July 2017; **[2]**: HF TWs, size: 48 m^2, plant density of 2.3 plants/m^2; July 2017; **[3]**: HF TWs, size: 1 m^2, plant density: *NA*, July – August 2001; **[4]**: for study 1: HLR = total influent (without precipitation).

The average ET obtained during the pilot scale experiment under maximal loading is within the range of those obtained from a pilot-scale treatment wetlands study by Frédette et al. (2019) conducted in the same geographical region (Table 4). Our results are also comparable to those of Chazarenc et al. (2010), obtained from a mesocosmscale study using the species most commonly used in TWs, *Phragmites australis australis* (Table 4).

3.3 COD, $CBOD_5$ and TSS removal

The average total COD removal was 91 ± 4 % during the experiment for all pilot units. In summer, when all pilot units were operated in percolating flow mode, no significant difference in total COD effluent concentration was observed between pilot units (Figure 4). In winter, the effluent concentration was significantly higher ($p = 0.026$) for pilot units 2 and 3, which were operated on saturated flow mode. With increased organic loading in winter 2 (Table 2) a significant increase ($p < 0.001$) in total COD concentration was observed for TW1 with percolating flow as well. During the last season, removal efficiency was lowest among all four seasons of the experiment. During this season, the maximum removal efficiency was observed for TW1 and TW4 with 91 ± 3 % and 92 ± 3 % respectively. For TW2 and TW3 this efficiency was lower, but still above 85 %.

The average effluent concentration for all tested periods was 21 ± 7 mg COD/L. Using a typical secondary effluent BOD_5 : COD ratio of 0.30 (Metcalf and Eddy-AECOM, 2014), the average BOD_5 was estimated as 6.4 ± 2.1 mg O_2/L, which is well under the maximum of 25 mg O_2/L.

An average TSS removal of 85 ± 11 % was determined for all pilot units. No significant differences were observed for effluent TSS concentration for all seasons except during summer 2, during which significantly higher effluent TSS concentration ($p < 0.001$) was reported for the two pilot units operated at the higher organic loading (TW1 and TW3). The average effluent TSS concentration for all pilot units was 7.1 ± 5.7 mg TSS/L, which is well under the discharge standards of 25 mg TSS/L required in the Province of Quebec.

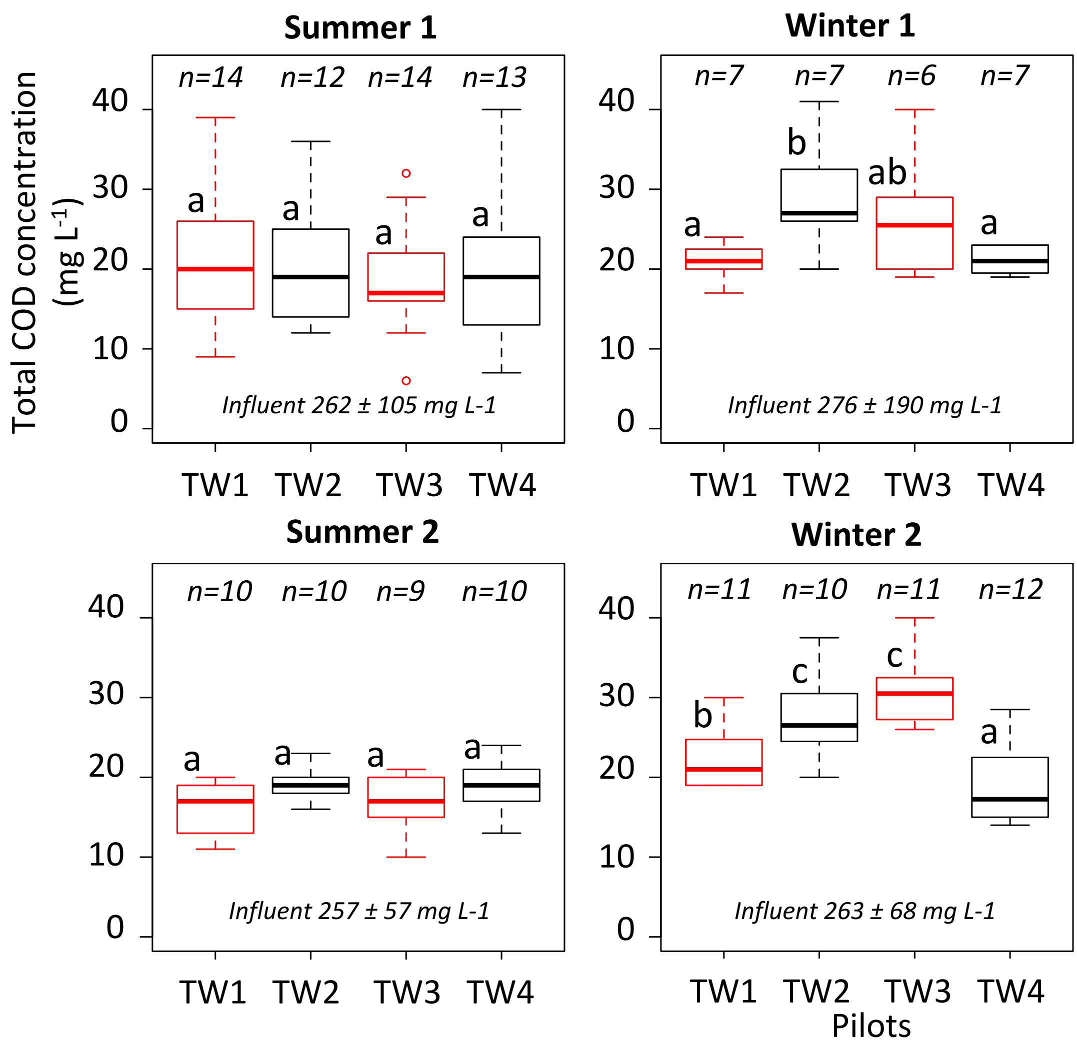

Figure 4. Effluent total COD concentration for summer and winter conditions for years 1 and 2. Different letters above the boxplots indicate significant differences ($p < 0.05$) in total COD concentrations between the pilot units in the same season. Boxplots of the same colour indicate equal organic loadings (additional details provided in Table 2).

3.4 Nitrogen removal

There were no significant differences between TWs in summer, with an almost complete nitrification (average NH_4-N for all pilot units was 0.12 ± 0.30 mg N/L; Figure 5).

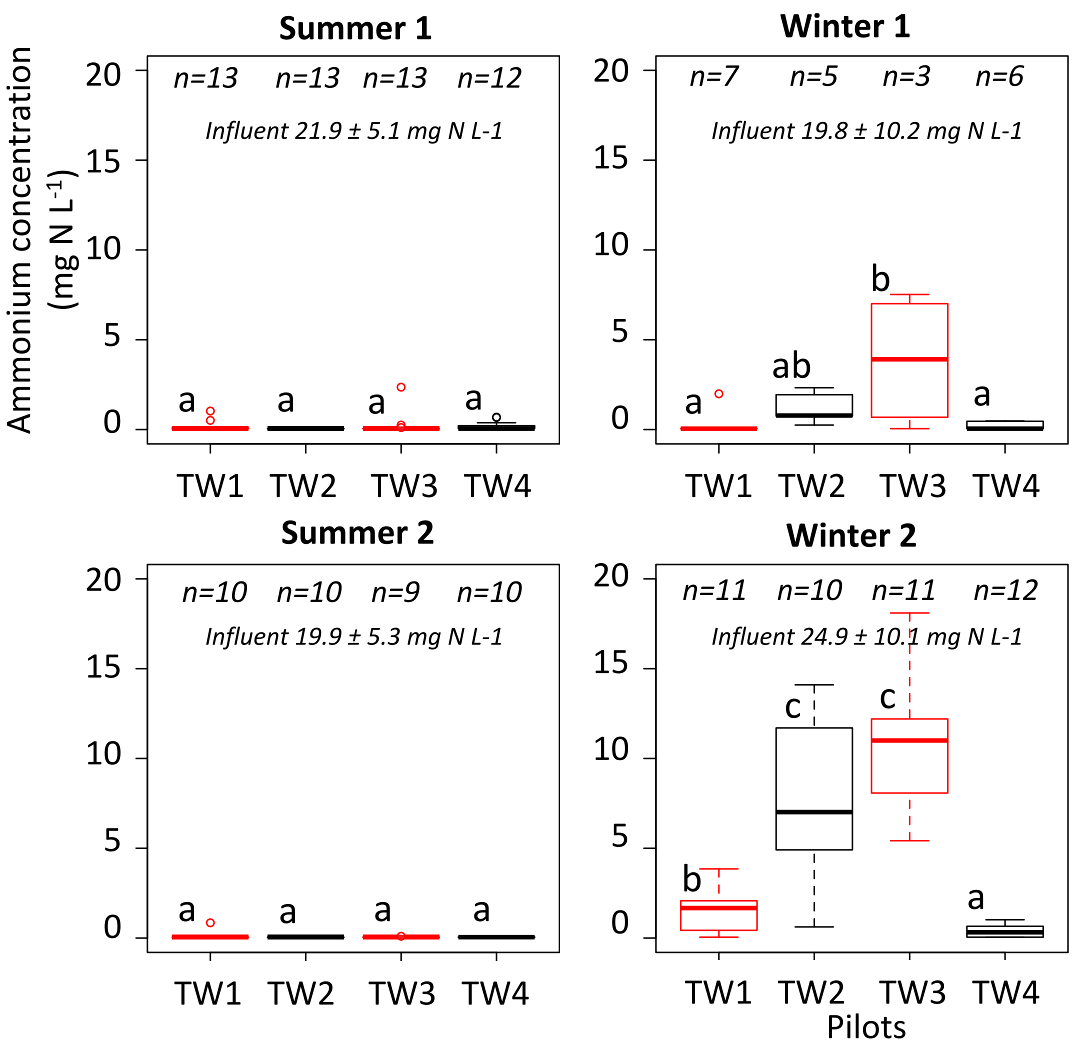

Figure 5. Effluent ammonium-nitrogen concentration. Different letters above the boxplots indicate significant differences ($p < 0.05$) in ammonium-nitrogen concentrations between the pilot units in the same season. Boxplots of the same colour indicate equal organic loadings (additional details in Table 2).

In winter, the ammonium-nitrogen concentration in saturated aerated flow mode (TW2 and TW3) was significantly higher ($p = 0.03$) than in percolating flow mode (TW1 and TW4). This trend was even more noticeable during winter 2, with a higher ammonium-nitrogen concentration. The ammonium-nitrogen concentration in percolating flow mode in winter 2 was significantly higher ($p < 0.001$) for TW1, with an organic loading of 20 $CBOD_5$ m^{-2} d^{-1}, but lower than TWs operated in saturated flow mode (TW2 and TW3). The effluent DO concentrations measured during winter 2 indicated a lower DO concentration in saturated TWs (TW2 and TW3), as a result of the higher ammonium-nitrogen concentration (Figure 6).

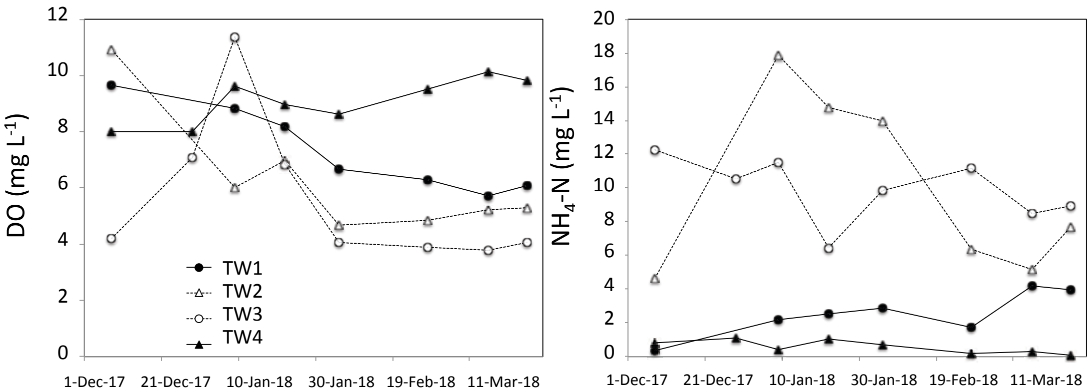

Figure 6. Dissolved oxygen concentration in effluent (*left*) and ammonium-nitrogen concentration in effluent (*right*) during winter 2.

Average nitrogen concentrations in the forms of nitrites + nitrates, ammonium-nitrogen and organic nitrogen are presented separately for the summer and winter seasons of the second year of the experiment, in Figure 7. In summer, all pilot units showed a similar concentration of each form of nitrogen with an average concentration of total nitrogen (TN) of 21 ± 1 mg N/L versus 33 mg N/L of TN in the influent. In winter, the effluent TN was lowest for TW2 (low organic loading + saturated flow mode), at 11 mg N/L.

The effluent TN concentration increased for TW3 (high organic loading + saturated flow mode), to a value of 15 mg N/L. The highest TN concentration was observed for TW1 (high organic loading + percolating flow mode) and for TW4 (low organic loading + percolating flow mode), at values of 21 and 27 mg N/L, respectively.

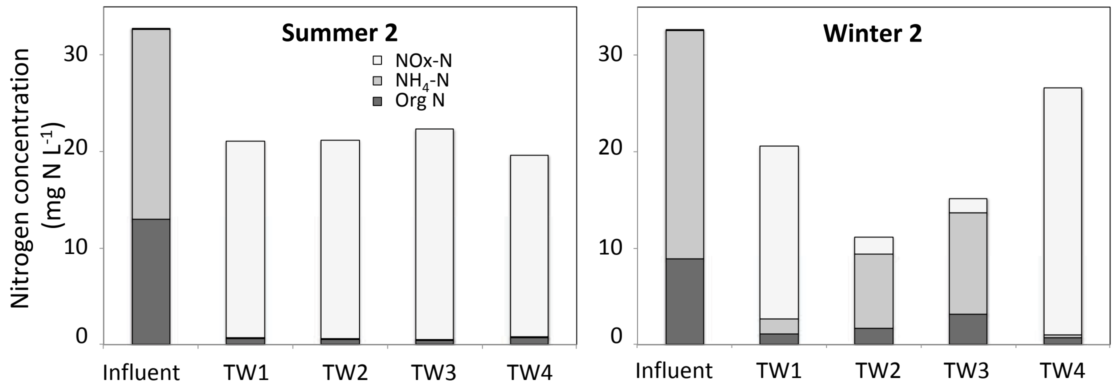

Figure 7. Average NOx-N, NH_4-N and Org N concentration in influent and effluent of four tested pilot units during the second year of the experiment.

3.5 Phosphorus removal

During summer 1, there was no significant difference between effluent TP concentrations. The TP removal during this period was 78 ± 14 %. During winter 1, the TP removal of TW1 and TW4 (both operated in percolating flow mode) was significantly less efficient ($p = 0.02$) at 28 ± 40 % and 52 ± 17 %, respectively. Better TP removal was observed in TWs operated in saturated flow mode, with values of 81 ± 8 % and 70 ± 9 % for TW2 and TW3, respectively. During the second year, the same trend was observed for each season, but at a higher effluent total P concentration (Figure 8). During summer 2, the TP removal efficiency decreased for all pilot units: 21 ± 18 % for TW1, 71 ± 20 % for TW2, 39 ± 34 % for TW3 and 32 ± 18 % for TW4.

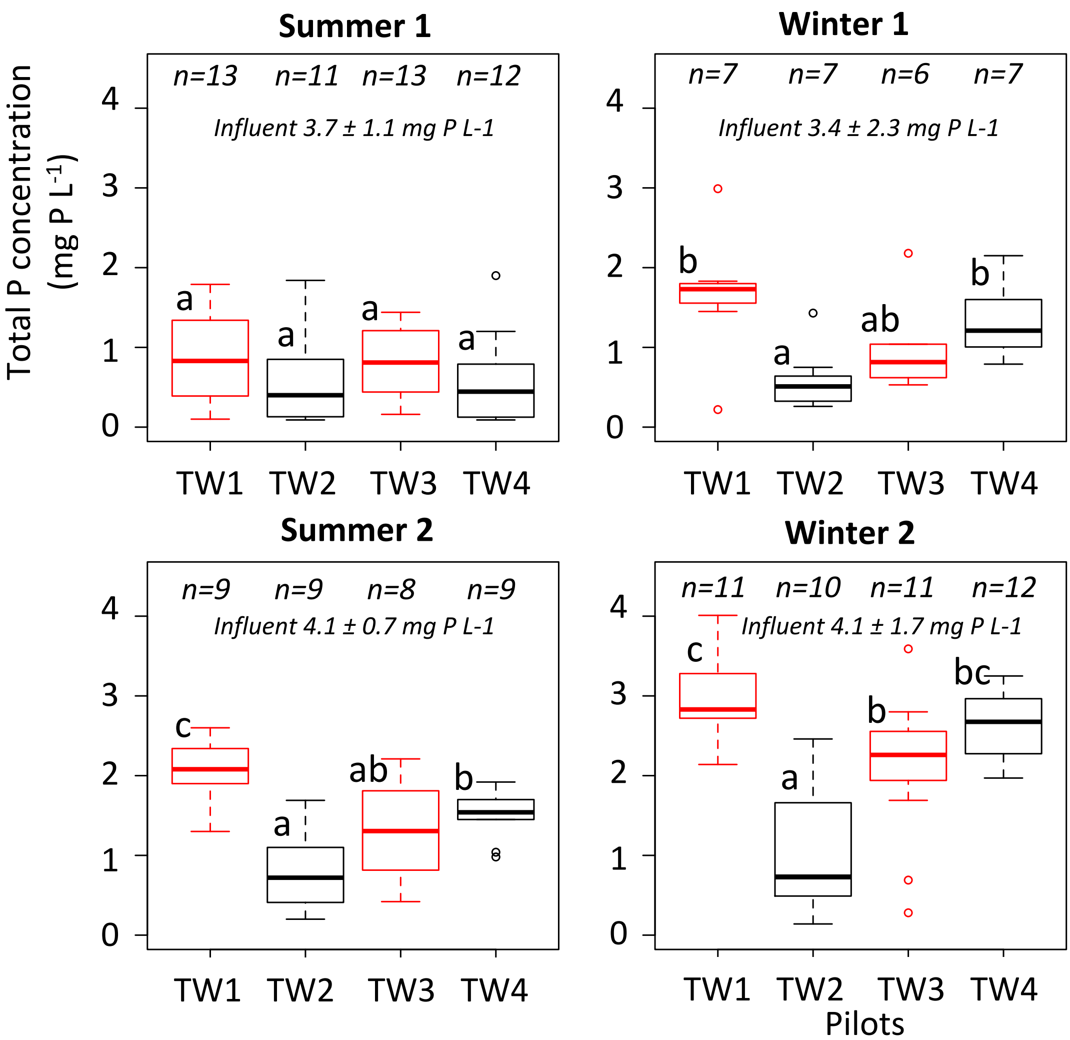

Figure 8. Effluent total phosphorus (TP) concentration for summer and winter, for years 1 and 2. Different letters above the boxplots indicate significant differences ($p < 0.05$) in total P concentrations between the pilot units in the same season. Boxplots of the same colour indicate equal organic loadings (additional details in Table 2).

4. Discussion

The tested TW system was operated successfully during year-round wetland loading, even during extremely low air temperatures (-32 °C in January 2018). The type of wastewater distribution and feeding frequency of the TWs are important considerations for cold period conditions. For this study, the distribution pipe was installed on the TW surface under a mulch insulation layer, allowing for an appropriate balance between pipe insulation and access in case of ice clogging. A proper TW feeding frequency contributed to successful operation during winter. A minimum feeding frequency of once per 8 hours at a hydraulic rate of 18 L/m^2 was efficient. The percolating flow mode was maintained in winter without any modification. To minimize excessive surface heat loss from the filtering bed in saturated flow mode, a water level 5 to 10 cm below the TW surface is recommended. This configuration allowed a layer of snow more than one meter thick to build up and persist for most of the winter, even though there were days with positive temperatures, which should occur more frequently as a result of climate change.

Willow showed fast growth, and its high ET rates (ranging from 25.6 % to 36.9 % of applied HLR during the measured period), is comparable to the ET rate of the common *Phragmites australis*. A high ET rate increases HRT in TWs and helps to concentrate the effluent. One of the important consequences of high ET in TWs is an improved removal efficiency of TKN (He and Mankin, 2001; Chazarenc et al., 2010). Our results confirm the successful use of willows in TW conditions in cold climate proposed by previous studies (Khurelbaatar et al., 2017; Grebenshchykova et al, 2020). In winter, when ET rate is null, the woody stems favor the accumulation of snow cover on the TW surface to better insulate the filtering bed. During the experiment, the willows were not coppiced. Coppicing of willows is recommended every 3-4 years for optimal willow growth in plantations (Labrecque and Teodorescu, 2005; Tharakan et al., 2005). Future studies should clarify the optimal stem density to avoid stems mortality and the best strategy for willow biomass maintenance in TWs.

Treatment performance was better in percolating flow mode. During the investigation period, COD and TSS removal were high (> 85 %) and were not affected by low temperatures. Similar results were observed in previous studies (Smith et al., 2006; Prost-Boucle and Molle, 2012; Tunçsiper et al., 2015). The total COD concentration measured in TW effluents operated in a percolating flow mode (around 20 mg/L) likely corresponded to the soluble non-biodegradable fraction of typical municipal effluent. It can therefore be affirmed that the TWs in percolated flow mode completely removed the biodegradable part of total COD (92 % of the total COD according to Metcalf and Eddy, 2003). In saturated flow mode with aeration during wintertime, total COD removal was significantly less efficient (although still high at > 85 %) than in percolating flow mode (92 %).

In winter, nitrification was more efficient for TWs in percolating flow mode. With 20 g $CBOD_5$ m^{-2} d^{-1} of organic loading in winter, the nitrification in percolating flow decreased due to the lower activity of nitrifying bacteria and lower oxygenation from plant roots (Ouellet-Plamondon et al., 2006). In saturated flow mode, the lower nitrification rate can be explained by a lack of oxygen, as confirmed by a low DO correlated with a high ammonium-nitrogen concentration in effluent. This lower oxygen concentration could be attributed to a deficient air distribution system (Figure 2). In contrast, the higher denitrification observed in winter in saturated flow mode was most likely due to the favourable conditions provided in the deep layers of the filtering bed without artificial aeration (low oxygen concentration, slightly higher COD concentration).

Phosphorus removal from domestic wastewater using a subsurface TW with a standard neutral substrate is not efficient over the long-term. Previous studies showed that a low temperature does not have a negative influence on TP removal (Wang et al., 2017). Once short-term phosphorus surface retention has been saturated, the effluent phosphorus concentration increases, and a typical long-term TP removal is around 10-20 % (Smith et al., 2006; Kadlec and Wallace, 2008; Molle et al., 2012; Troesch et al., 2014; Dotro et al., 2017). In the present experiment, this period was relatively short. TW1, which was operated in percolating flow mode at a maximal organic loading, showed a phosphorus removal efficiency of about 20 %. The combination of two factors, a lower organic loading and a saturated flow mode in winter, allowed a slow rate of phosphorus saturation of the filtering bed. However, the trend of decreasing phosphorus removal held true for all TWs. When a low phosphorus concentration in effluent is targeted, a special media with a high phosphorus adsorption capacity must be used, or another treatment system must be installed downstream or upstream from the TWs to provide efficient removal (Jenssen et al., 1993; Mæhlum and Stålnacke, 1999; Vohla et al., 2011; Claveau-Mallet et al., 2013).

The present study suggests higher treatment performances of percolating flow mode in winter. With organic loading above 20 g $CBOD_5$ m^{-2} d^{-1}, the pollutant removal efficiency in percolating mode begins to decrease. The saturated flow mode with artificial aeration during cold period showed less pollutant removal efficiency in our study. However, we believe our aeration system was partly inefficient, so that this flow mode with properly designed artificial aeration remains a potential solution for full-scale application in regions with harsh winter conditions using an organic loading above 20 g $CBOD_5$ m^{-2} d^{-1}. A possible reason for the low nitrification rate in saturated TWs with artificial aeration during wintertime in this study was the creation of preferential air flows to the surface, which would result in non-homogeneous aeration of the filtering bed. Previous studies showed high nitrification in TW when artificial aeration is properly configured (Ouellet-Plamondon, 2006; Fan et al., 2013). An aeration system with proper air distribution pipe position (depth and density), and air emitter number and spacing (Nivala et al. 2018) should be considered as a solution to improve homogeneous distribution of air in filtering bed. As a consequence of these modifications, the nitrification rate - the principal limiting process in TWs tested in this study - should be improved. For continuous aeration, a wind-driven air pump can be used to keep costs down and TW technology as extensive as possible (Boog et al., 2016). Intermittent aeration, sometimes used in VF TWs, represents another interesting approach because it improves conditions for nitrification and denitrification in the same filtering bed (Dong et al., 2012; Wu et al., 2015). The potential of this type of aeration needs to be tested under real cold climate conditions, due to the high risk of TW freezing during periods without aeration.

We tested percolating flow and partial saturation of the bottom layer separately, but combining them may represent a potential promising solution by providing favorable conditions for total nitrogen removal. Silveira et al. (2015) showed a high performance of such system using a raw domestic wastewater, under a tropical climate. A particular adaptation strategy to protect from freezing would be necessary to apply this solution under cold climate.

Conclusions

This study demonstrated a successful application of a modified version of VF TWs in regions with freezing air temperatures for five months per year. *Salix miyabeana* was well-adapted to TW conditions in this climate. Applying either of two flow modes (percolating or saturated with artificial aeration) in cold period, the effluent concentrations were under the permitted discharge requirements (<BOD_5 25 mg/L; <TSS 25 mg/L). The tested design with percolated downflow mode can potentially receive at least two times higher organic loading (40 g $CBOD_5$ m^{-2} d^{-1}) and meet discharge standards, as it makes it possible to maintain a higher temperature within the TW system and thus better protection from freezing during winter. Properly designed artificial aeration in a saturated flow mode can potentially increase the organic loading capacity and may be essential for full-scale TWs in regions with very cold winter temperatures. More studies are needed to find the best configuration of artificial aeration system in extremely cold conditions.

A better understanding of the thermal regime inside the filtering bed is necessary to determine the optimal size of TW (balance between a small footprint and an acceptable risk of filtering bed cooling) for very cold climates.

Declarations of interest

None.

Acknowledgements

This study was part of the PhytoValP project which was funded by the Natural Sciences and Engineering Research Council of Canada (NSERC), the Consortium de recherche et d'innovation en bioprocédés industriels du Québec (CRIBIQ) and industrial partners: Agro Énergie, NORDIKeau, Bionest, Arcelor Mittal, Naturally Wallace Consulting, SINT, Minéraux Harsco and Ressources Aquatiques Québec (RAQ). The authors would like to thank the municipality of Saint-Roch-de-l'Achigan for access to the WRRF. The authors also thank Dirk Esser, Pascal Molle and Scott Wallace for their scientific contribution. The authors are grateful for laboratory assistance and technical support from Denis Bouchard, Mélanie Bolduc, Jérôme Leroy, Marc-André Labelle, Cristian Neagoe, Pascale Mazerolle and Roselyne Gagné-Turcotte. Helpful review and comments on a previous version of the manuscript were provided by Karen Grislis and Xavier Lachapelle-T.

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