Water Practice & Technology Vol 6 No 3
doi:10.2166/wpt.2011.052

Potential of hybrid constructed wetland system in treating milking parlor wastewater under cold climatic conditions in northern Hokkaido, Japan

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Abstract

A real scale hybrid constructed wetland (CW) system (656 m^2), with a configuration of VFA-VFB-HF beds constructed in series is operating since November 2006 in northern Hokkaido, Japan. The system was experimented to assess its capability in purifying 4.5 m^3d^{-1} of high strength milking parlor wastewater under colder climate. Annual mean air temperature at site was recorded as 6.4 ^oC (extremes vary as -22.8 ^oC at lowest and 30.6 ^oC at highest). From the monthly sampling from November 2006 to January 2010, average loading and removal rates of TSS, COD_{cr}, BOD_5, TN and TP were 5.4 g m^{-2} d^{-1} (98%), 30.3 g m^{-2} d^{-1} (88%), 11.5 g m^{-2} d^{-1} (89%), 1.2 g m^{-2} d^{-1} (76.4%) and 0.2 g m^{-2} d^{-1} (76%). System did not stop for a single day, efficiently worked even during snow covered periods and was tolerant to the load fluctuations.

Keywords: cold region, hybrid reed bed system, milking parlor wastewater

INTRODUCTION

Based on design, constructed wetlands (CWs) can be categorized into 3 groups, such as surface flow (SF), subsurface flow (SSF) (horizontal and vertical flow), and hybrid CWs. SF CWs are popular in United States, particularly for large wastewater flows and polishing of nutrients (Wood, 1995), but these systems has limitations of relatively large area requirement, bad odor and are difficult to operate in extremely colder climates. SSF CWs on the other hand are well suited for colder climates because treatment occurs below the ground surface (Werker *et al*, 2002). Among SSF CWs, horizontal subsurface flow (HSSF) CWs can remove BOD and total suspended solids (TSS) and can be a viable alternative for wastewater treatment for small sources of pollution especially when organics and suspended solids are the treatment targets (Vymazal, 2005), but are unable to transfer oxygen at sufficient rate to achieve full nitrification (Cooper, 1999). Vertical subsurface flow systems (VSSF) possess good aerobic conditions and provide nitrates (Molle *et al*, 2008) by oxidizing ammonia-N from the wastewater (Cooper and Green, 1995). Hybrid systems, which are combinations of vertical and horizontal flow beds in series (Vymazal, 2005) achieve higher nitrogen removals by utilizing nitrification potential of VSSF CWs and denitrification potential of HSSF CWs (Molle *et al*, 2008). Thus these systems are capable of producing extremely high quality effluents (Cooper, 2005).

It has been documented that CWs provide reliable treatment in temperate climates. However, the efficacy of this technology in areas with severe temperature extremes still needed to be studied because of the limiting factor of colder temperatures on physical and biological activities. In past studies, many researchers reported dairy/milking parlor wastewater treatment using CWs system but most of the designs were SF CWs (Newman and Clausen, 1997; Newman *et al*, 2000; Jamieson *et al*, 2001; Schaafsma *et al*, 2000; Shamir *et al*, 2001). The treatment potential of hybrid SSF CWs for dairy/milking parlor wastewater is yet to be explored.

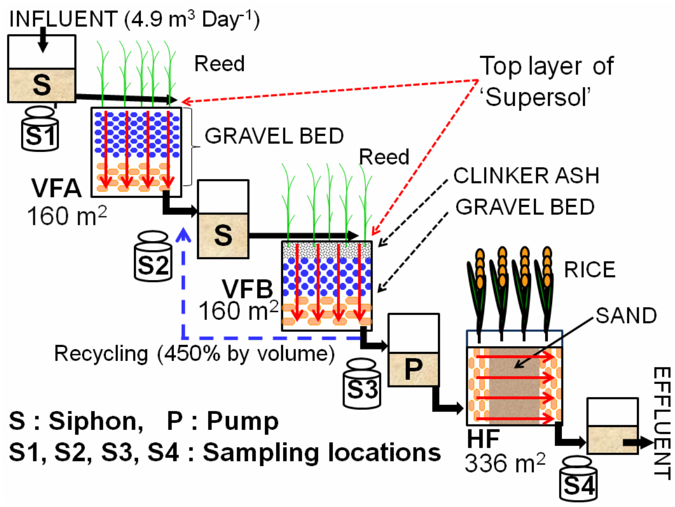

Figure 1 | Schematic diagram of hybrid reed bed system of Embetsu, Hokkaido, Japan.

Hokkaido is the largest milk-producing region in Japan. In 2009, there were 7,860 dairy farms in Hokkaido (34.0% of the total number of dairy farms in Japan) and 823,200 head of dairy cattle (54.9% of Japan's total number). Average annual milk production in 2008 was 3.91 MT (49.2% of Japan's total product). In 2008, there were 1,374 milking parlors in Hokkaido. These milking parlors discharge large volume of wastewater every day. Presently in Japan, wastewater discharge of less than 50 m^3 d^{-1} per establishment is out of regulatory target. Thus it is either infiltrated underground or discharged into nearby river/pond without a prior treatment, causing ground and surface water pollution.

With an objective to assess the potential of hybrid SSF CWs system for the treatment of high strength milking parlor wastewater under extremely cold climates, a real scale hybrid SSF CW system was built in Embetsu, northern part of Hokkaido, in November 2006.

MATERIALS AND METHODS

Meteorology

The climate of Embetsu is characterized by an average precipitation of 1,053 mm y^{-1} and daily average air temperature of 6.4 °C. Daily average vary between -7.9 °C as lowest at the end of January and 20.3 °C as highest in the beginning of August. Average of annual record of minimum and maximum temperature is -22.8 °C and 30.6 °C for the period of 1978 to 2009. The cold period represents about 4 months from December to March. Snow covers the terrain during this period.

Design of the system

A hybrid reed system was designed and constructed in November 2006. It consists of three beds (VFA-VFB-HF) constructed in series (**Figure 1, Table 1**). The first and second beds are vertical subsurface flow beds (VFA and VFB), both 160 m^2 in area with a depth of 0.71 m. On top of both VF beds, porous floating material (Supersol®) with a density of 0.4 g cm^{-3} has been laid (Kato *et al*, 2009).

doi:10.2166/wpt.2011.052

This floating material is made from recycled glass. It is very light in weight and has two benefits. Firstly, when wastewater is applied to the bed, it floats on surface of bed, acts as an obstruction in the way of flowing wastewater and traps as well as settles down the SS from the wastewater. Secondly it acts as an insulating material during winter periods and helps in preventing freezing conditions on the bed surface. In the second (VFB) bed, it consists clinker ash as upper middle layer with a thickness of 0.20 m. Kato *et al* (2005) reported from the laboratory experiment that clinker ash is a good filter media for removal of total carbon from the milking parlor wastewater. The clinker ash consists of alkaline sulfates and is efficient in removing phosphorous load from the wastewater. Third bed is horizontal subsurface bed (HF), 336 m^2 in area with a depth of 0.7 m. HF bed was filled with washed sand from top to bottom. Near the wastewater inflow and outflow points a layer of gravel was put in place to facilitate the flowing of incoming and outgoing water. The bottoms of all beds are lined with high-density polyethylene liner to avoid seepage of wastewater to underground water, and circumferences of the beds are kept high to protect against inflow from the surroundings. At the bottom of VFA & VFB beds a network of interconnected perforated pipes are placed to collect and drain the treated wastewater from the beds.

Table 1 | Details of filter media and vegetation of the each bed

Bed	Area (m^2)	Filter material		Size / density	Thickness (cm)	Surface vegetation
VFA	160	Top	Supersol®	0.4 g cm^{-3}	5	*P. australis*
		Middle	Coarse gravel	5 - 15 mm	30	
		Bottom	Fine gravel	5 - 25 mm	36	
			Total		71	
VFB	160	Top	Supersol®	0.4 g cm^{-3}	1	*P. australis*
		Upper middle	Clinker ash	d_{10}∽0.06 mm	20	
				d_{60}∽1.50 mm		
				d_{60}/d_{10}∽25		
		Lower middle	Coarse gravel	5 - 15 mm	25	
		Bottom	Fine gravel	5 - 25 mm	25	
			Total		71	
HF	336	Top to bottom	Washed sand	d_{10}∽0.25 mm	70	Rice (2007, 2008) *P. australis* (2009 -)
				d_{60}∽0.49 mm		
				d_{60}/d_{10}∽1.7		

Common reed (*Phragmites australis*) seedlings were grown in nursery and planted in VFA and VFB beds in November 2006 in a density of 1.4 plants m^{-2}. In HF bed four different varieties of forage rice were planted for assessing the nutrient recycling using nutrient uptake process of rice. Rice was planted in end of May and harvested in October in year 2007 and 2008. In August 2009, porous floating material was added on the HF bed surface (0.05 m thickness) and 300 reed plants replaced rice.

System receives wastewater from nearby milking parlor of a dairy farm having 120 cows. Designed influent volume was 4.5 m^3 day^{-1}. Wastewater was pretreated in a sedimentation tank (5.4 m^3) for settling suspended solids and adjusting pH condition of the influent. French design based siphons (Molle *et al*, 2005) with following modifications were used at inlet of VFA and VFB beds for dosing the wastewater (Kato *et al*, 2009).

- Single siphon dosing pipe instead of plural pipes used in French siphon.
- Single inlet hole of siphon float.
- Diameter of the dosing pipe is 1.4 times bigger than the diameter of dosing pipe of French siphon for dosing same volume of wastewater.

An electric pump is in use for dosing wastewater from VFB bed to HF bed because of hydraulic limitations.

doi:10.2166/wpt.2011.052

Analytical procedure

Four Sampling locations S1, S2, S3, and S4 were selected at inlet and outlet of each bed (**Figure 1**). The water flow and water temperature monitoring equipments were installed at all sampling locations. Thermometer for air temperature and rain gauge were installed near S2 location. Regular water samples were collected once in a month, preserved and analyzed for TSS, COD_{cr}, BOD_5, NH_4-N, NO_3-N, TN, TP, PO_4-P, total coliform and total carbon. DO, pH, ORP and EC were measured at field during sampling time. Beside these, to assess system's efficiency and flexibility for wastewater purification under high water flow fluctuations during snow melting season, daily sampling was carried out at final discharge point (S4) in early spring of 2008. An automatic water sampler was fixed at S4 location for taking samples once in a day from 5th March to 17th April 2008.

System efficiency for pollutant removal

Besides monitoring the changes in concentration and load, the efficiency of hybrid reed bed system was calculated in terms of purification and removal rates of all selected parameters of wastewater. Purification and removal rates were calculated using following formulae.

$$purification\ rate\ (\%) = \frac{(Influ.conc. - Efflu.conc.)}{Influ.conc.} \times 100$$

$$removal\ rate\ (\%) = \frac{(Influ.load - Efflu.load)}{Influ.load} \times 100$$

RESULTS AND DISCUSSION

Hydrology, temperature, pH, DO and ORP

The average physico-chemical characteristics of water at S1, S2, S3 and S4 sampling locations are presented in **Table 2**. Results are of 48 samples taken from November 2006 to January 2010. Actual average inflow was 4.9 $m^3\ d^{-1}$ (7.5mm d^{-1}) and it fluctuated from 1.2 to 28.0 $m^3\ day^{-1}$ (1.8 to 42.7 mm d^{-1}) during study period. Highest inflow was received during snow melting period due to mixing of snowmelt water from the surroundings. Daily mean temperature of influent during the observed period was 12.8 ^{o}C with a range of 3.6 to 22.5 ^{o}C. Effluent daily mean, lowest and highest temperatures were observed as 8.4, 0.5 and 22.6 ^{o}C (**Figure 2**).

Table 2 | Physico-chemical parameter of influent from milking parlor (S1) and treated water at S2, S3 and S4 sampling locations (average from Nov. 2006 to Jan.2010)

Item	Unit	S1 (Influent)	S2 (VFA out)	S3 (VFB out)	S4 (HF out =Effluent)
pH		6.6	6.9	6.9	6.8
Temp.	^{o}C	13.0	10.8	9.6	9.1
DO	mg L^{-1}	1.7	1.9	1.9	2.3
ORP	mV	+221	+235	+218	+258
EC	mS cm^{-1}	1.3	1.3	1.1	0.9

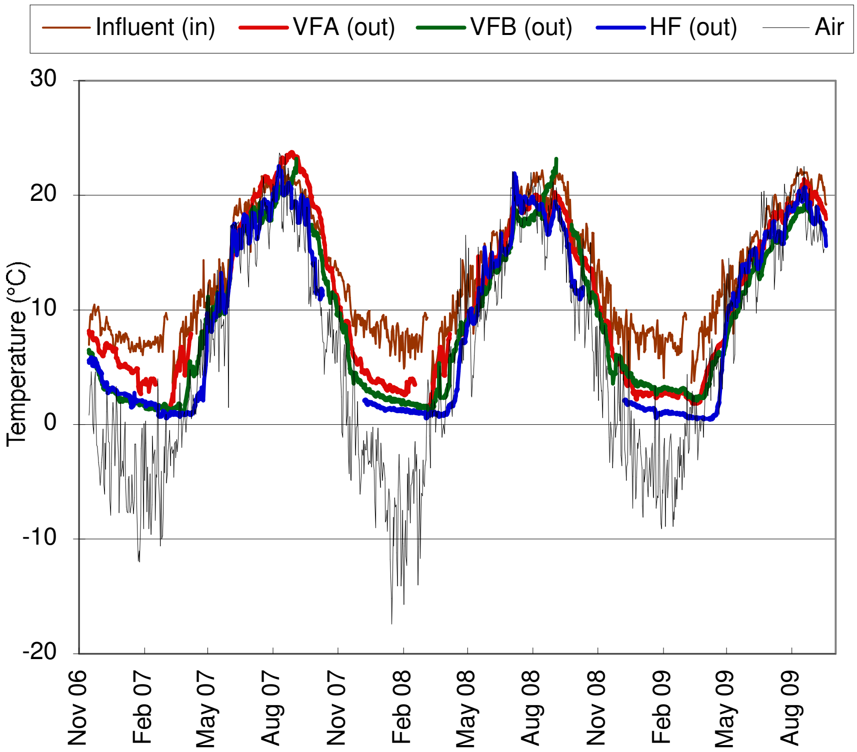

Figure 2 | Daily average water and air temperature at Embetsu Hybrid reed bed system.

Inflow and outflow pH did not change greatly. Series of VF beds resulted in a significant drop in average temperature (-3.4 ^{o}C) and slightly increase in DO (+0.2 mg L^{-1}). Increase of DO at HF bed (+0.4 mg L^{-1}) was considerably high during rice growing season (+0.93 mg L^{-1} in 2007 and +0.51 mg L^{-1} in 2008 growing season). This might be because of release of oxygen by photosynthetic activity due to algal growth on the water surface in HF bed. Also rice plant's roots might have released some amount of oxygen in the wastewater. Average DO was increased from 1.7 to 2.3 mg L^{-1} in final effluent. EC did not change in VFA bed but it dropped eventually in effluent. ORP did not show significant change from S1 to S4 location but slightly increased in the effluent, which indicates that more aerobic conditions prevailed during the treatment in the beds.

Total suspended solids (TSS)

Concentration and load of influent and effluent for TSS, COD_{cr}, BOD_5, each nitrogen and TP, with their purification and removal rates are shown on **Table 3**. Effluent TSS concentrations were below the stipulated standard value of 150 mg L^{-1} during study period. Higher effluent concentrations were observed between March to October 2007 due to high influent loading from the mixing of rejected milk along with the wastewater.

COD and BOD

Despite being high fluctuations in the loading rates, removal rates were nearly same throughout the study period. COD purification rates of VFA, VFB and HF beds were 61, 51 and 52%. VF beds, (especially VFA bed) were good in removing particulate COD by filtration process. Higher COD removal efficiency in HF bed is most probably because of longer retention time (Kadlec, 2009). Maximum BOD removal was achieved by HF (63%) bed followed by VFB (59%) and VFA bed (39%).

doi:10.2166/wpt.2011.052

Nitrogen, phosphorus and total coliform

Average TN purification rate of VFA, VFB and HF bed was 45, 41 and 45%. Purification rate as total system was 83%. Outlet concentrations were within the stipulated standard value of 60 mg L^{-1} except 3 samples (March, June 2007 and March, 2008). Average ammonium nitrogen (NH_4-N) purification rate of VFA, VFB, HF and total system was assessed as 20, 31, 48 and 71%. VFA and VFB beds showed higher purification of organic nitrogen than ammonium nitrogen, whereas HF bed in contrast resulted into higher NH_4-N purification than organic nitrogen (**Figure 3**). Average nitrate nitrogen (NO_3-N) concentrations at VFA, VFB and HF outlet were 7.8, 1.8 and 1.3 mg L^{-1}.

Table 3 | Concentration and load of influent and effluent of hybrid reed bed system of Embetsu, with purification rate and removal rate

Item		Concentration		Load		Purification rate	Removal rate
		Influent mgL^{-1}	Effluent mgL^{-1}	Influent $gm^{-2}d^{-1}$	Effluent $gm^{-2}d^{-1}$	%	%
TSS	Ave.	770	17	5	1	98	98
	Max.	2,221	133	17	1	-	-
	Min.	99	1	1	0	-	-
COD_{cr}	Ave.	4,425	323	30	3	93	88
	Max.	12,465	1,269	90	0	-	-
	Min.	485	27	7	11	-	-
BOD_5	Ave.	1,574	138	12	1	91	89
	Max.	4,200	385	22	3	-	-
	Min.	960	41	5	0	-	-
TN	Ave.	183	32	1.22	0.27	83	76
	Max.	410	90	2.60	0.70	-	-
	Min.	26	3	0.50	0.05	-	-
NH_4-N	Ave.	77	22	0.57	0.18	71	64
	Max.	173	63	1.51	0.45	-	-
	Min.	16	-	0.12	-	-	-
NO_3-N	Ave.	0.4	1.3	0.0	0.0	-	-
	Max.	2.4	18.0	0.0	0.1	-	-
	Min.	-	-	-	-	-	-
TP	Ave.	29.0	5.0	0.19	0.04	83	76
	Max.	73.0	16.0	0.45	0.09	-	-
	Min.	4.0	0.1	0.07	-	-	-
coliform	Ave.	97,338	871	-	-	99	-
(No. mL^{-1})	Max.	1,000,000	13,700	-	-	-	-
	Min.	1,100	1	-	-	-	-

Purification rate of total phosphorus (TP) at VFA, VFB and HF bed was 37, 35 & 58%. HF bed showed better TP removal efficiency because of using sand as a filter media, which is better phosphorus adsorbent compared to gravel. Smith *et al* (2006) reported higher phosphorus removal during growing season but we did not observe any difference in TP removal rates during growing and non-growing seasons.

doi:10.2166/wpt.2011.052

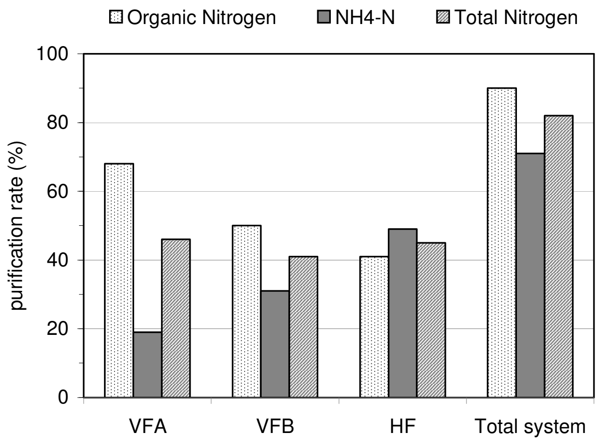

Figure 3 | Average purification rates of organic nitrogen, NH_4-N and TN by VFA, VFB, HF beds and total system.

Total coliform purification rate of VFA, VFB and HF bed was 24, 82 and 94%. HF and VFB beds reduced total coliform most effectively from wastewater because of possessing fine sized filter media. Average removal efficiency was similar to Newman *et al* (2000), Singh *et al* (2009) and Masi *et al* (2007). No significant difference in total coliform purification was observed between winter and summer seasons.

Flexibility of the system during snow melting season

Mean average air temperature during the snow melting sampling period of 2008 was recorded as 1.2 ^oC (min. -14.9, max.16.4 ^oC). **Figure 4** shows the influent and effluent water volumes during the snow melting season. Snow melt water mainly comes from snow deposited on the bed surfaces but some unintended inflow from surrounding area of sedimentation tank, located before S1 siphon also mixed with influent. Total influent volume from 5th March-17th April 2008 was 337.3 m^3. Assuming the average inflow from parlor from the previous year's study, total wastewater from milking parlor operations itself was 99.6 m^3 and rest 237.7 m^3 was estimated as snow melted water, which was mixed with influent at sedimentation tank from nearby area. Total effluent volume was 717.6 m^3 containing 380.3 m^3 snow melted water from all beds of the system. **Figures 5 and 6** shows Cl^{-1}, TN, TC, TP, PO_4-P and organic P concentrations in finally treated effluent during snow melting season of 2008 and non-snow melting period (from November 2006 to February 2008 excluding March-April 2007). Bar lines in the graphs show minimum, maximum and average values of each water quality index. **Table 4** shows the daily influent and effluent load and load removed by the system during both periods.

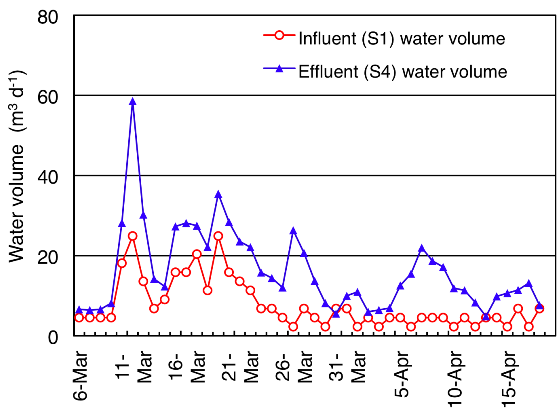

Figure 4 | Influent and effluent water volume during snow melting season of 2008 (5th March to 17th April).

doi:10.2166/wpt.2011.052

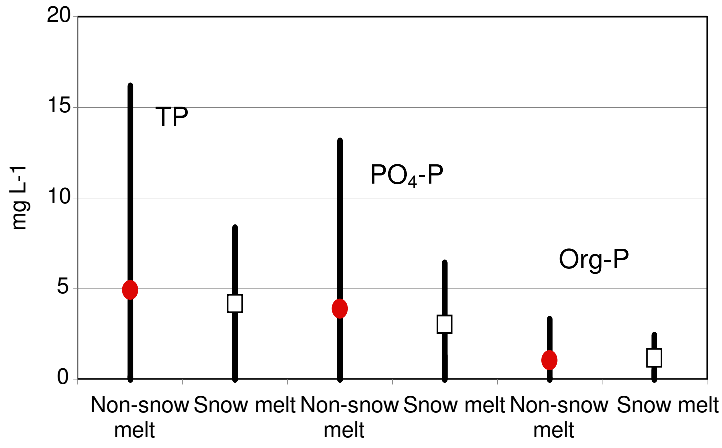

Figure 5 | Concentration of Cl^{-1}, TN and TC in effluent during snow melting and non-snow melting period.

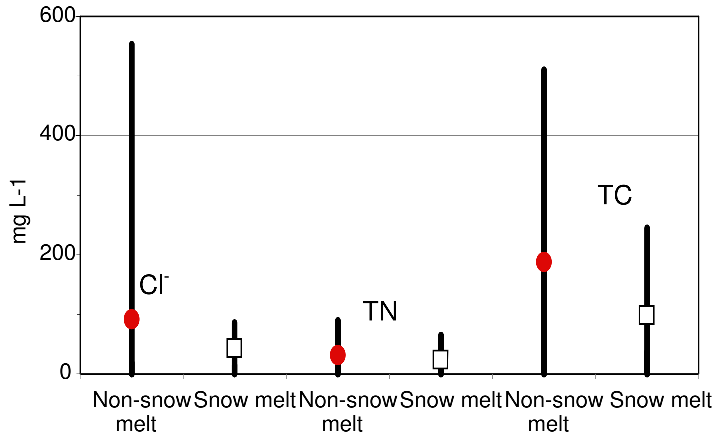

Figure 6 | Concentration of TP, PO_4-P, and Organic P in effluent during snow melting and non-snow melting period.

Table 4 | TN, TC, TP, PO_4-P and organic-P load in influent and effluent with amount of removed load during snow melting and non-snow melting period

		Load (g d^{-1})				
		TN	TC	TP	PO_4-P	Org.P
Snow melting period, 2008	Influent	820	5,601	113	83	31
	Effluent	568	2,358	98	70	28
	Load removed	252	3,243	15	13	3
Non-snow melting period	Influent	800	6,612	123	101	22
	Effluent	177	976	25	20	6
	Load removed	623	5,636	98	82	16

During snow melting season, surface flow occurred at HF bed due to excessive snow melt water. This seems to decrease the removal load during this period. Although removed load was decreased compare to non-snow melting period, effluent quality was satisfactory to discharge into downstream water body. Furthermore, this system worked without stopping for a single day. System's performance can further be improved by avoiding mixing of unintended inflow from outside and improving surface conditions of HF bed to maintain sub-surface flow for even snow melting season.

doi:10.2166/wpt.2011.052

CONCLUSION

Following conclusions can be drawn from the present study:

1. Hybrid SSF CWs gives promising results in terms of nutrient removal from milking parlor wastewater under colder climates.
2. System can efficiently work under cold climates and shows less seasonal effect on nutrient removal.
3. Hybrid SSF CWs possess good buffer capacity. System can tolerate high fluctuations in the wastewater load without affecting its nutrient removal efficiency.
4. During snow melting season, effective countermeasures to prevent mixing of surrounding water into influent are important for improving the treatment efficiency of the system.

ACKNOWLEDGEMENTS

The authors wish to thank Research Council of Ministry of Agriculture, Forestry and Fisheries (MAFF), Japan, for their support by granting funds for the project.

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