Design and performance of hybrid constructed wetland systems for high-content wastewater treatment in the cold climate of Hokkaido, northern Japan

K. Kato, T. Inoue, H. Ietsugu, H. Sasaki, J. Harada, K. Kitagawa and P. K. Sharma

ABSTRACT

The performance of six multistage hybrid constructed wetland systems was evaluated. The systems were designed to treat four kinds of high-content wastewater: dairy wastewater (three systems, average inflow content 2,400–5,000 mg·COD l^{-1}, 3–6 years of operation); pig farm wastewater, including liquid food washing wastewater (one system, 9,500 mg·COD l^{-1}, 3 years); potato starch processing wastewater (one system, 20,000–60,000 mg·COD l^{-1}, 3 years); and wastewater containing pig farm swine urine (one system, 6,600 mg·COD l^{-1}, 2.8 years) (COD = chemical oxygen demand). The systems contained three or four vertical (V) flow beds with self-priming siphons and surface partitions and no or one horizontal (H) flow bed (three to five beds). In some V flow beds, treated effluents were recirculated (Vr) through the inlet to improve performance. Mean annual temperature was 5–8 °C at all locations. To overcome clogging due to the high load in a cold climate, we applied a safety bypass structure and floating cover material to the V flow beds. Calculated average oxygen transfer rates (OTRs) increased proportionally with the influent load, and the OTR value was Vr > V> H. The relations of load–OTR, COD–ammonium, and a Arrhenius temperature-dependent equation enable the basic design of a reed bed system.

Key words | cold climate, dairy wastewater, hybrid wetland system, oxygen transfer rate, potato starch processing wastewater, swine urine treatment

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INTRODUCTION

The treatment of dairy milking parlor wastewater, potato starch processing wastewater, and swine urine wastewater is a significant challenge in Hokkaido, northern Japan, where such wastewaters are polluting rivers and groundwater. Conventional mechanical wastewater treatments are expensive. Thus, an urgent need exists for a low-cost technology to treat such wastewater. Constructed wetlands for pollution control have progressed greatly over the past 20 years (Kadlec *et al.* 2000; Cooper 2009; Vymazal 2009). Moreover, hybrid systems have been used since the 1980s (Vymazal & Kröpfelová 2011). Several important studies about the selection of filter media, the treatment performance at low temperature, and the recirculation effect have been conducted in cold climates (Poldvere *et al.* 2009; Jenssen *et al.* 2010; Speer *et al.* 2012). However, issues of clogging and freezing remain in the treatment of high-content wastewater in cold climates. To overcome these problems, we designed and constructed multistage hybrid reed bed systems in 2005 with a safety bypass and a floating cover to treat high-content wastewater in the cold climate of Hokkaido, Japan (Kato *et al.* 2006, 2009, 2013). Our hybrid systems are basically a combined hybrid system (Obarska-Pempkowiak & Gajewska 2003; Poldvere *et al.* 2009; Vymazal & Kröpfelová 2011), including a French-type reed bed system (Molle *et al.* 2005) and a Danish-type system with recirculation in a vertical (V) flow reed bed (Brix & Arias 2005). Herein, we describe the design and performance of six hybrid systems.

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SYSTEM DESIGN AND METHODS

System design, climate, and other information

Six multistage hybrid wetland systems were designed for treating high-content wastewater in the cold climate of Hokkaido, northern Japan (Sharma *et al.* 2011; Kato *et al.* 2013). The location, mean temperature, rainfall, assessment period, sampling times, and average inflow of the monitored wetland systems are listed in Table 1. The system of dairy farm K is located at 43°26′ N and 144°52′ E, dairy S system is located at 44°45′ N and 141°48′ E, dairy N system is located at 43°28′ N and 145°04′ E. Pig food A system is located at 43°21′ N and 141°26′ E, starch P system is located at 43°49′ N and 144°33′ E, and pig urine O system is located at 42°49′ N and 41°44′ E. The annual average air temperature was 5–8 °C at all locations. The lowest monthly average daily temperatures in Bekkai, Embetsu, Atsuta, and Chitose were −14.2, −11.9, −8.4, and −12.7 °C, and the highest monthly average temperatures were 18.1, 20.0, 20.7, and 20.8 °C, respectively. All reed bed plants were active throughout the year, except at the potato starch processing plant, which was designed to work only during the growing season.

Schematic diagram

A schematic diagram of the hybrid wetland system is shown in Figure 1. Our systems are composed of three or four vertical (V) flow beds with a self-priming siphon and no or one horizontal (H) flow bed with a total of three to five beds. A French-type self-priming siphon was

Table 1 | Location, temperature, rainfall, assessment period, the number of sampling times, and average inflow of monitored constructed wetland systems

System	Town name	Mean air temperature in Celsius[a]	Mean rainfall mm/year[a]	Assessment period[b] month/year (years)	Number of sampling times	Mean inflow $m^3 \cdot d^{-1}$
Dairy K	Bekkai	5.3	1142	11/2005–11/2011 (6.0 yr)	113	28.5
Dairy S	Embetsu	6.8	1023	11/2006–11/2011 (5.0 yr)	75	4.8
Dairy N	Bekkai	5.6	1221	6/2008–5/2012 (4.0 yr)	40	16.8
Pig food A	Atsuta	8.3	1371	11/2008–10/2011 (3.0 yr)	29	4.1
Starch P1[c]	Kiyosato	15.1 (May–Aug.)	271 (May–Aug.)	5-9/2009–2011 (3 yr)	11	20.1
Starch P2[c]		9.0 (Sep.–Nov.)	252 (Sep.–Nov.)	9-11/2009–2011 (3 yr)	13	6.4
Pig urine O	Chitose	6.0	967	11/2009–8/2012 (2.8 yr)	58	13.7

[a]From the Automated Meteorological Data Acquisition System of the Japan Meteorological Agency.
[b]All systems operated throughout the year except the system at the potato starch factory P, which was designed to work from May to November.
[c]P1 was preserved wastewater from May to August and P2 was fresh wastewater from September to November.

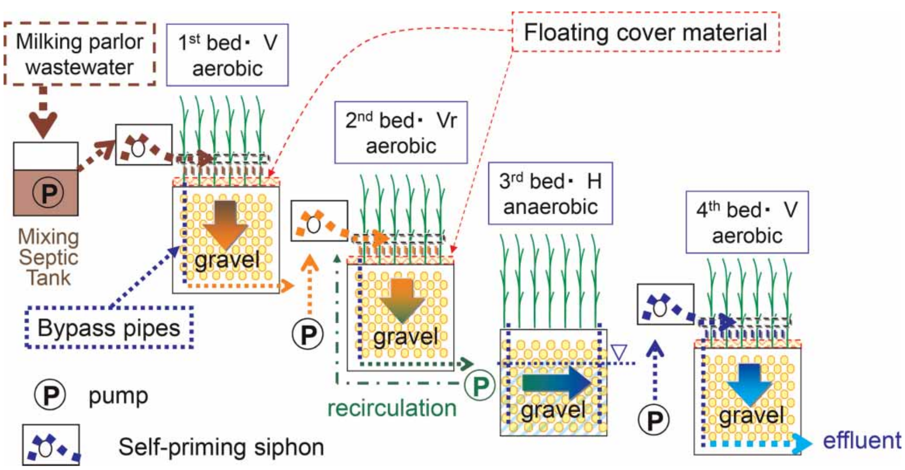

Figure 1 | A schematic diagram of the hybrid wetland system (example: Dairy N).

applied in the V flow bed with minor modifications; only one dosing pipe was used for a siphon to simplify maintenance (Kato *et al.* 2006, 2009). Some effluents were recirculated (Vr) to the inlet in some V beds with a pump to improve performance, mainly during the growing season. The water freezes if too much effluent is recirculated in winter.

Clogging and freezing countermeasures

The main challenges with dense wastewater treatment in cold climates are clogging and freezing. We applied a safety bypass structure at each bed and covered the V flow bed surface with a floating cover material (Supersol; TRIM Co., Ltd, Okinawa, Japan) to treat the dense wastewater and to overcome clogging in a cold climate (Kato *et al.* 2009, 2013). The bypass was composed of perforated pipes connecting the bed surface to the bed bottom. When the bed surface was temporarily clogged and percolation stopped, wastewater moved downward through the perforated pipes, and thus the water was drained. Although the nutrient removal efficiency of the bed decreased during the temporary clogging phase using this mechanism, the bypass structure removed the excess load and prevented fatal clogging. These two effects facilitated abundant reed and earthworm growth. The perforated pipes were often reinforced with a surrounding container cover, and perforated pipes inside the container were made with larger holes than those of the container to achieve sustainable percolation performance.

The V flow beds were covered with a floating material called Supersol, which is a lightweight porous material manufactured from waste glass bottles (TRIM Co., Ltd 2013). Its density is 0.4 g cm^{-3} and it floats on water. Pores inside the Supersol are not connected to the outside, so Supersol floats stably. In vertical flow beds, the water stands on the surface for a while before it percolates when the water is dosed. Partial surface flow will subsequently occur when the bed surface is partially clogged. Supersol floats on the flooded surface and acts as an obstruction to trap bulky organic matter before the water flows into the perforated bypass pipes. Thus, Supersol changes the partial flooded surface flow to shallow horizontal subsurface flow. In this way, Supersol helps to prevent clogging of the bed surface and keeps the bed dry. During the winter months, Supersol acts as an insulating material and helps to prevent freezing conditions at the top of the bed (Kato *et al.* 2009, 2013).

Bed type, area, material, surface partition, and vegetation

The bed type, area, surface cover material, main bed material, number of surface partitions, and vegetation are described in Table 2. The area of each reed bed for treating wastewater from the dairy farm milking parlor was designed using the estimated chemical oxygen demand (COD) and NH_4–N removal rates reported in previous studies (Cooper 2005; Molle *et al.* 2005). The systems were designed to treat a higher organic load per area for denser nondairy wastewater treatment. Volcanic pumiceous gravel or sand, river gravel or sand, shale gravel, and coal-fired electric power station clinker ash were used as the main bed materials. Volcanic pumice, shale, and clinker ash are porous, whereas river gravel and sand are nonporous. Some of the bed surfaces were covered with three kinds of materials to act as a heat-resistant layer in the cold climate, including larch wood chips, lightweight porous glass (Supersol), and autoclaved aerated lightweight concrete (ALC). The depth of these surface cover materials was 4–5 cm. The Supersol and ALC floated on the water due to their low specific gravity (0.4 and 0.5–0.6 g cm^{-3}, respectively). The surface of the early-stage V flow bed was partitioned into two or three zones like the French systems. Each zone was used alternately every other week to maintain dry conditions during the growing season (Molle *et al.* 2005). The resting and feeding periods were 1–2 weeks. The benefit of surface drying during the growing season was to accelerate percolation by adding cracks in the organic clogging cover on the surface. Sufficient evapotranspiration to dry the surface was expected during the growing season. The number of partitions in each bed is listed in Table 2. Common reeds (*Phragmites australis*) grown from seeds or reed stems were planted as seedlings in pots. Cattails (*Typha latifolia*) were planted as seeds directly in several beds mixed with common reeds. Wild weeds were allowed to grow freely in almost every bed. In some H flow beds, we experimentally planted rice, upland crops, wetland flowers, and fruits such as blueberry and haskap (*Lonicera caerulea* var. *emphyllocalyx*).

Flow measurement

Water flow was calculated by monitoring the change in the water table at each self-priming siphon or pumping hall. The change in the water table was measured every 5–10 min with a pressure-type water-level gauge and a data logger (DL/N70; Sensor Technik Sirnach (STS) AG, Sirnach, Switzerland or S&DL Mini; Oyo Corp., Tokyo, Japan) throughout the year.

Table 2 | Bed type and area, surface cover material, main bed material, surface partitions, and vegetation

System	1st	2nd	3rd	4th	5th	Total
	Bed type[a]/Bed area (m^2) Suface cover material[b]/Main bed material[c]/No. of surface partitions[d] Main vegetation[e]					
Dairy K 1[f]	V/256 SS/PG/no Ph, C, O	V/256 no/RS/no Ph	H/512 WC/PG/no Ph	V/150 ALC/PG/no Ph, O	–	1,174
Dairy K 2[f]	V/512 SS/PG/2 Ph, C, O	V- > Vr[g]/512 SS/RS/2 Ph, O	H/512 WC/PG/no Ph	V/150 ALC/PG/no Ph, O	–	1,686
Dairy S	V/160 SS/RG/2 Ph	Vr/160 SS/CA/2 Ph	H/336 ALC/RS/no RE, Ph, C, O	–	–	656
Dairy N	V/645 SS, ALC/PG/2 Ph, C, O	Vr/484 ALC/PG/2 Ph, O	H/484 ALC/PG/no WE, O, FE	V/176 ALC/PG/no WE, O	–	1,789
Pig food A	Vr/96 SS/SG/3 Ph	Vr/48 ALC/SG/2 Ph	V/24 ALC/SG/no Ph	–	–	168
Starch P	Vr/990 ALC/PG/3 Ph, O	Vr/510 ALC/PG/2 Ph, O	Vr/294 ALC/PS/2 Ph, O	H/210 no/PG/no UE, O	Vr/147 ALC/PS/2 Ph, O	2,151
Pig urine O	V- > Vr[g]/572 ALC/PG/3 Ph, O	V- > Vr[g]/446 SS, ALC/PG/2 Ph, O	V/184 SS, ALC/PG/2 Ph	H/195 no/PG/no UE, FE	V/75 SS, ALC/PG/no Ph, O	1,472

[a]V, vertical flow; H, horizontal flow; Vr, vertical flow with recirculation pump; Vr, recirculation within a single bed.
[b]SS, Supersol (lightweight porous recycled glass); ALC, autoclaved lightweight aerated concrete; WC, wood chips. The depth of all surface cover material was 4–5 cm.
[c]PG, pumiceous gravel; PS, pumiceous sand; RG, river gravel; RS, river sand; SG, shale gravel; CA, clinker ash.
[d]The partitioned beds were used alternately to maintain dry conditions during the growing season.
[e]Ph, *Phragmites* (common reed); C, cattails; O, other weed; RE, rice for trial during the first and second growing seasons; UE, upland crops for trial; WE, wetland flowers for trial; FE, fruits (blueberry and haskap) for trial. Haskap is a Japanese wild fruit that grows in Hokkaido.
[f]System K was upgraded from K1 to K2 due to increases in wastewater since March 2010.
[g]V -> Vr indicates that an additional recirculation pump has operated since Aug. 2010 in both Dairy K and Pig urine O.

Sampling and quality measurement

Water samples were collected at every inlet and outlet of each reed bed. Samples were taken once per month and the water was analyzed immediately for COD, NH_4–N, total nitrogen (TN), and total phosphorus (TP). COD was measured by spectrophotometer (DR2800; Hach, Loveland, CO) using a digital reactor (Hach DRB200) and disposable COD digestion vials (Hach). NH_4–N was measured using a segmented-flow analysis system (QuAAtro; SEAL Analytical GmbH, Norderstedt, Germany). TN was measured with an elemental analyzer (Elementar vario MAX; Elementar Analysensysteme GmbH, Hanau, Germany). TP was measured with a colorimeter using the molybdenum blue ascorbic acid reduction method after decomposition by peroxodisulfate (JIS K0102 46.3.1, Japan).

RESULTS AND DISCUSSION

System running conditions

The minimum air temperatures during the months of December to March were −28.0, −24.5, −15.2, and −23.1 °C at Bekkai, Embetsu, Atsuta, and Chitose, respectively. All systems worked throughout the assessment period and did not freeze during the winter. The minimum effluent water temperature was around 1–3 °C, and the lowest temperatures were observed during the snowmelt season.

The surface partition method and floating cover material were not used in the V flow bed of the first system, dairy farm K, in its first year of operation, and consequently, the system became clogged during spring and autumn that year. We started to partition the bed to alter the drying portion in 2006, the second growing season. We covered the surface with the floating material (Supersol) in 2007, the third growing season. The safety bypass in the V flow bed was reinforced at dairy farm K in 2008. The clogging material then disappeared gradually. Since 2008, both a reinforced safety bypass and floating cover material have been adopted, and no severe clogging has been observed at dairy farm K. Because Supersol is relatively expensive, ALC was used as an alternative floating material in the third system (dairy farm N) in 2008. ALC also initially floated on water, but it gradually sank and was less stable than Supersol. Therefore, mainly Supersol is used as the floating cover material for new reed bed systems.

Concentration decrease in the interstage data

The average pollutant concentrations in the interstage samples and inflow and removed loads are listed in Table 3. Each pollutant (COD, TP, NH_4–N, and TN) decreased through the reed bed stages in the nondairy and dairy farms. Even the starch factory wastewater influent with a content of >50,000 mg·COD l^{-1} decreased to <5,000 mg.COD l^{-1}, which is almost the same content as the dairy wastewater influent. Thus, decreasing the wastewater content was possible by adding reed bed stages.

Oxygen transfer rate (OTR) and type of reed bed

The performance of each bed was evaluated by calculating oxygen transfer rates (OTRs) (Cooper 2005). The influent COD load plus NH_4–N was defined as the load of oxygen necessity (LON). The OTR and LON were calculated using Equations (1) and (2). In our experiment, the average influent and effluent biochemical oxygen demand (BOD)/COD ratio was approximately 0.5, and thus, the ratio of BOD/COD was set to 0.5 in the calculation. This

Table 3 | Average pollutant concentrations in the interstage samples and average inflow and removed loads

		Concentration $mg \cdot L^{-1}$						$g \cdot m^{-2} \cdot d^{-1}$	
	System	In	1st	2nd	3rd	4th	5th	Inflow loads[b]	Removed loads[b]
COD	Dairy K	2382	948	468	197	108	–	49.9	46.4
	Dairy S	3973	1209	579	239	–	–	29.2	26.6
	Dairy N	5002	1819	630	342	211	–	42.7	40.2
	Starch P1[a]	20311	13403	9813	6624	6546	6041	234	147
	Starch P2[a]	59335	27311	13541	5985	4949	3569	165	156
	Pig food A	9555	3839	1640	579	–	–	219	203
	Pig urine O	6556	3802	2691	2284	1665	1161	66.7	54.3
NH4-N	Dairy K	30.5	35.7	24.7	20.7	7.4	–	0.58	0.36
	Dairy S	70	50	32	16	–	–	0.51	0.35
	Dairy N	38	40	22	15	7	–	0.33	0.24
	Starch P1[a]	928	786	768	582	538	456	10.7	4.8
	Starch P2[a]	1393	1105	695	450	430	280	3.9	3.3
	Pig food A	7	33	17	9	–	–	0.16	–0.11
	Pig urine O	1199	778	636	575	508	429	10.4	6.1
TN	Dairy K	100	62	42	27	29	–	2.08	1.41
	Dairy S	160	84	48	25	–	–	1.18	~~0.35~~
	Dairy N	198	86	43	26	22	–	1.69	1.43
	Starch P1[a]	1236	939	819	601	548	475	14.4	8.3
	Starch P2[a]	4222	2058	1143	622	550	399	11.3	10.2
	Pig food A	202	103	48	23	–	–	4.7	3.9
	Pig urine O	1371	956	783	727	623	595	12.2	6.4
TP	Dairy K	19.8	14.1	9.4	6.7	5.9	–	0.40	0.25
	Dairy S	25.2	17.3	11.6	5.3	–	–	0.19	0.13
	Dairy N	37.6	22.2	13.2	6.8	4.5	–	0.32	0.27
	Starch P1[a]	146	96	79	55	50	44	1.93	1.40
	Starch P2[a]	340	129	80	44	41	31	0.95	0.84
	Pig food A	18.5	12.8	3.9	1.4	–	–	0.44	0.39
	Pig urine O	132	54	41	31	22	16	1.25	1.08

[a]P1, preserved potato starch wastewater from May to August; P2, fresh wastewater from September to November.
[b]Inflow and removed loads are weighted average during the assessment period.

is quite similar to the BOD/COD ratio in fresh domestic sewage in the United Kingdom (Cooper 2005). The units for COD, NH_4–N, flow rate, and bed area are $mg\,l^{-1}$, $mg\,l^{-1}$, $m^3\,d^{-1}$, and m^2, respectively:

$$\mathrm{OTR} = \text{flow rate}\,\{0.5\ (\text{COD in} - \text{COD out}) + 4.3\,(\mathrm{NH_4\text{–}N\,in} - \mathrm{NH_4\text{–}N\,out})\}/\text{bed area} \quad (1)$$

$$\text{Load of oxygen necessity (LON)} = \text{flow rate}(0.5\ \text{COD in} + 4.3\ \mathrm{NH_4\text{–}N\ in})/\text{bed area} \quad (2)$$

Temperature effect

Several biogeochemical processes that regulate nutrient removal in wetlands are affected by temperature, which influences the overall treatment efficiency. The temperature effects of surface flow treatment wetlands are often described through a modified Arrhenius temperature-dependent Equation (3), as follows (Kadlec *et al.* 2000; Kadlec & Reddy 2001):

$$k = k_{20}\theta^{(T-20)} \quad (3)$$

where k represents the areal removal rate constant, k_{20} is the areal removal rate constant at 20 °C, T is temperature (°C), and θ represents the temperature coefficient.

To compare the performance of the hybrid reed beds at different locations, OTR at specific temperature (T) was adjusted to a different temperature (T'). The adjusted OTR at temperature T' is called OTR′. The adjustment was made by using Equation (4), where this equation is derived from Equation (3). A temperature coefficient (θ) of 1.05 was assumed in the calculation, based on organic matter and ammonium nitrogen temperature coefficients reported in previous studies (Kadlec & Reddy 2001; Siracusa & La Rosa 2006):

$$\mathrm{OTR'}/\mathrm{OTR} = \theta^{(T'-20)}/\theta^{(T-20)} \quad (4)$$

Figure 2 illustrates the relationship between load and adjusted OTR′ ($T' = 10.0$ °C) using Equation (4). Each symbol represents the annual average data of each bed. The OTR′ increased in proportion to influent load. The rate of OTR′ increase was highest in the V flow beds with the recirculating pump (Vr), medium in the V flow beds, and lowest in the H flow beds. OTR′ values for high influent loads were >40 and some were >80, which were higher than the recommended OTR value of 28 (Cooper 2005). OTR′ values for low influent loads were almost the same or less than the recommended OTR value of 28.

One can design multistage reed bed systems with Vr, V, and H using the performance data shown in Figure 2. However, the relationship of load to OTR is expected to change depending on the properties of the wastewater, the climate, and the maturity of the wetland system. Thus, more data on loads and OTRs are needed to design a more accurate multistage wetland system.

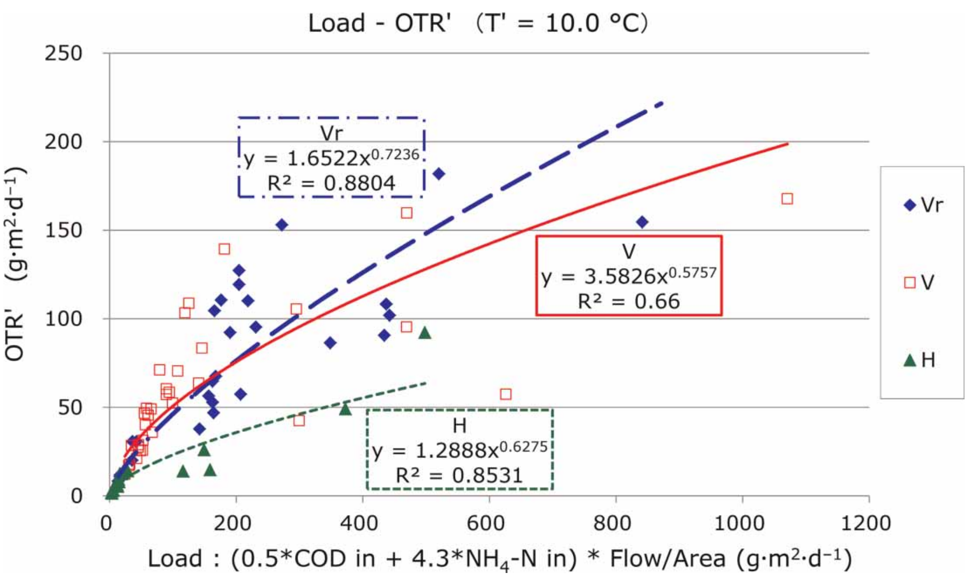

Figure 2 | Load of oxygen necessity (LON) and oxygen transfer rate (OTR′) values adjusted with the average air temperature.

Relationship between COD and ammonium nitrogen

The average COD and NH_4–N are shown in Figure 3. The value of COD decreased with that of NH_4–N through the multistage reed bed system depending on the properties of the wastewater. When designing a wetland system, the target effluent water quality should be estimated using the relationship between COD and NH_4–N.

Basic design procedure

The basic design procedure is depicted in Figure 4. The first step requires knowledge of four initial conditions: influent wastewater concentrations (COD and NH_4–N) in mg l^{-1}, influent water volume in m^3 d^{-1}, the annual average temperature in degrees Celsius, and the target concentrations of COD and NH_4–N in mg l^{-1}. Next, the first bed area is calculated according to the influent concentration, volume, and an ideal OTR value for the annual average temperature. After the first bed area is fixed, the effluent concentrations of the first bed are calculated using three relationships: the relation of load and OTR (Figure 2), the relation of COD and NH_4–N (Figure 3), and the Arrhenius temperature-dependent relationship (Equation (4)). The same calculation procedures are followed for subsequent bed stages until the calculated effluent concentrations become lower than the target concentrations. Finally, we obtain a reed bed system design that satisfies the target conditions.

The removal rate per bed decreases as the load per area increases so the number of beds must be increased to meet the target concentration. However, the removal load per

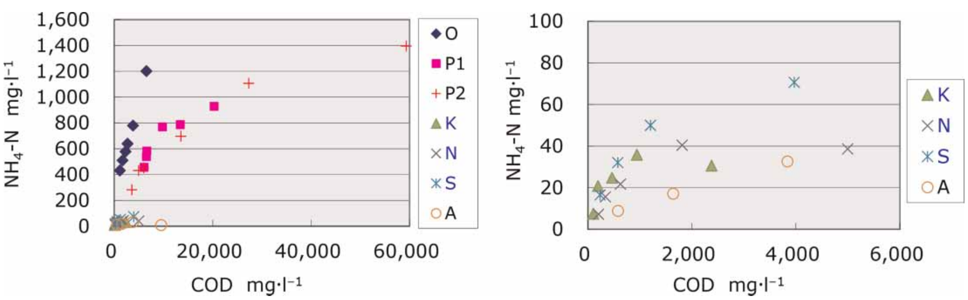

Figure 3 | Average COD and NH_4–N.

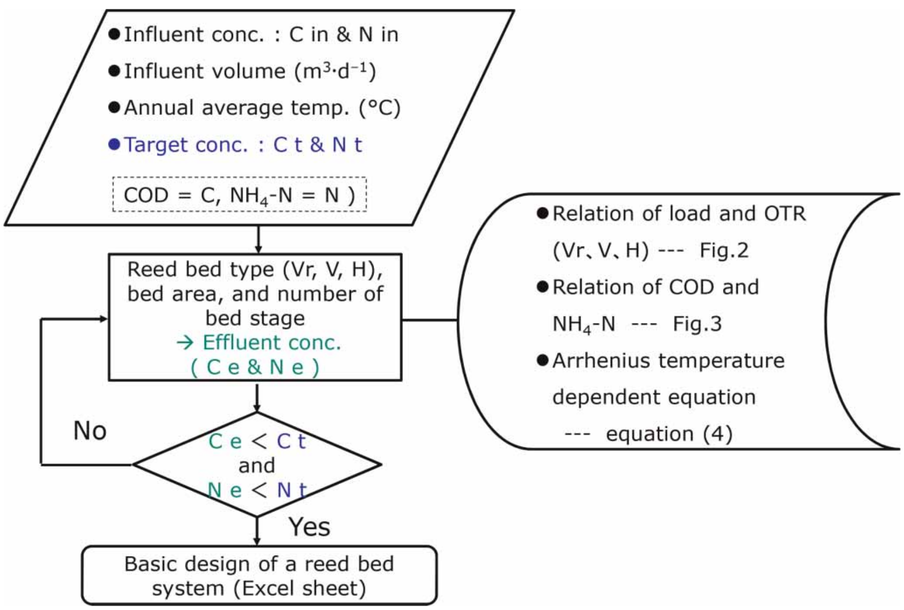

Figure 4 | Flowchart of the basic design procedure.

bed increases, and thus the total area of the system decreases. Therefore, the total area of the constructed wetland could be minimized by increasing the number of beds. A limit exists to the load of the system, so it is necessary to acquire more data about the limit of the organic load of the wetland system for many kinds of wastewater treatment over a long period of time.

CONCLUSIONS

The performance of six multistage hybrid wetland systems for treating high-content wastewater was evaluated in the cold climate of Hokkaido, northern Japan. A safety bypass structure and floating cover material were applied to the V flow bed to overcome clogging in the cold climate. The safety bypass structure and floating cover material helped to prevent clogging and freezing, and maintained dry conditions, resulting in abundant reed and earthworm growth. The calculated average OTR increased in proportion to the influent load. The OTR was the highest in V flow beds with a recirculating pump (Vr), moderate in the V flow bed, and lowest in H flow beds. Because the system was able to treat extremely high organic loads per area without clogging, the total area and cost could be minimized. The relations of load–OTR, COD–ammonium, and the Arrhenius temperature-dependent equation are available to develop the basic design of a reed bed system. However, more data are required to design a more accurate multistage wetland system.

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