Design and performance of a coarse media, high hydraulic load polishing wetland for steel industry wastewater

Viet Anh Nguyen, Minh Phuong Nguyen, Karin Tonderski, Hai Do Thi and Anh Thi Kim Bui

ABSTRACT

This paper presents the design of a constructed wetland (CW) system in an area with limited land availability, resulting in high hydraulic loads. The CW was constructed to act as a buffering/ polishing step after stabilization ponds for steel industry wastewater post-treatment. A pilot test with two different filter media (50–100 mm vs 40–60 mm diameter) indicated that a flow rate increase from 49.5 m^3/h to 122.4 m^3/h would lead to a head loss increase from 2.9 cm to 8.7 cm, and more than double that for the finer gravel. This was substantially higher than the calculated theoretical values, though the relation with flow rate was similar. Four full scale wetland cells (CW1, CW2, CW3 and CW4) were constructed using the coarser gravel. A design value of total head loss of 1.01 m over the total system length, with a design flow of 36,000 m^3/day, was expected based on pilot test results. During the first operation year (September 2017 to July 2018), the pond-CW system has received wastewater already meeting required discharge standards. The effluent from the CWs had consistently lower concentrations of all measured variables, and met the predicted values for biochemical oxygen demand (BOD_5), total nitrogen (TN) and NH_4^+-N. Highest removal efficiencies were achieved for NH_4^+-N (>90%), Mn (>60%) and Fe (45%) with removal efficiencies for TN (14%), BOD_5 and chemical oxygen demand (COD) (around 30%). Concentrations of phenol, CN^- and Cr^{6+} were below 10, 4 and 3 μg/l, respectively, in in- and outflows. An appreciated benefit of the wetland was the 'green element' in the industrial landscape.

Key words | filter media, free water surface, head loss estimate, horizontal subsurface flow

Viet Anh Nguyen (corresponding author)
Institute of Environmental Science and Engineering (IESE),
Hanoi University of Civil Engineering (HUCE),
55 Giai phong Rd, Hanoi,
Vietnam
E-mail: *vietanhctn@gmail.com*

Minh Phuong Nguyen
Department of Environmental Technology,
Faculty of Environmental Sciences,
VNU University of Sciences,
334 Nguyen Trai, Thanh Xuan, Hanoi,
Vietnam

Karin Tonderski
Department of Physics, Chemistry and Biology,
Linköping University,
Sweden

Hai Do Thi
Hanoi University of Mining and Geology (HUMG),
No. 18, Pho Vien Street, Duc Thang Ward, Bac Tu Liem District, Hanoi,
Vietnam

Anh Thi Kim Bui
Institute of Environmental Technology (IET),
Vietnam Academy of Science and Technology,
18 Hoang Quoc Viet, Hanoi,
Vietnam

INTRODUCTION

Wastewater from the steel industry often contains organics, colour, and toxicants such as phenol, cyanides and sulphur compounds. Constructed wetlands (CWs) have been shown to be a cost-effective and environmentally friendly technology for pollutant removal from various types of wastewater, including from the steel industry (Xu *et al.* 2009; Yang & Hu 2005; Vymazal 2009; Huang *et al.* 2011). In a laboratory scale vertical flow CW with manganese ore substrate, Xu *et al.* (2009) reported that about 98% of iron and manganese concentrations in steel wastewater were removed, and attributed this to the presence of iron and manganese oxidation bacteria. The concentration reduction of chemical oxygen demand (COD), turbidity, N-NH_4^+ and total phosphorus were 55%, 90%, 67% and 93%, respectively. Similar rates were observed in a pilot-scale wetland with gravel mixed with only 4% manganese ore, providing further support for the role of biological oxidation. In another study, the mean reduction rates were 77% for COD and N-NH_4^+, 96% for turbidity and iron and 92% for manganese in a pilot scale subsurface gravel/manganese ore CW treating wastewater from a steel industry (Huang *et al.* 2011).

Although several studies of laboratory scale or pilot scale CWs treating steel industry wastewater show promising results, there are few, if any, examples of full scale application of the technology. This paper presents the initial experiences from a hectares scale constructed wetland treating wastewater from a steel industry in Vietnam.

The narrative was initiated by an emergency discharge of poorly treated steel industry wastewater and pipe cleaning solutions that resulted in a marine life disaster in central Vietnam in 2016. This prompted the Vietnamese government to request the Formosa Steel Corporation to improve their

doi: 10.2166/wst.2019.244

wastewater treatment with enhanced physico-chemical and biological processes, and to divert the treated flow (1,500 m^3 per hour) through a buffering pond system before discharge to the ocean. In response to this, it was decided to construct a pond and wetland system on an approximately 10 ha area. Besides serving as a polishing and bio-indicator step in the treatment system, the wetland cells should also serve to prevent wash out of algae to the ocean, and create a green element in the factory landscape. It was decided to build a combined pond and wetland system, consisting of two emergency tanks and three stabilization ponds in series followed by subsurface and free water surface CWs.

For subsurface flow wetlands, the substrate composition is an essential component, and the substrate also makes up a substantial part of the total construction costs. The trade-off between achieving a high removal of particles and efficient sorption processes, and the desire to minimize the use of filtering substrate, causes a dilemma in the design phase. The available area at FHS company also posed a challenge with respect to the resulting high hydraulic load on the wetland. To address this, a pilot experiment was set up to select appropriate, locally available media, assess the head loss to be expected depending on choice of media material and to determine the design parameters for the full scale subsurface flow (SSF) wetland cells at FHS. Full scale construction of the wetland cells (CW1, CW2, CW3 and CW4) was initiated in March 2017 and they have been in operation since August 2017. This paper presents the results from the pilot experiments, the design calculations and the first treatment results from the full scale wetland system.

MATERIAL AND METHODS

Pilot experiments

Two parallel pilot CW cells were designed to study the hydraulic conductivity and assess the head loss for two filter media with different grain sizes, aiming at gaining data for design of the full scale wetland. The CW cell dimensions were: length × (width on top; width in bottom) × depth = 31.5 × (4.5; 4) × 1.0 m. Each cell was filled with 1 m of one of the two filter media to allow for maximum root system depth development (Grace 1989; Davis 2000; Borst *et al.* 2002). Cell A was filled with 10 cm of coarse sand at the bottom for protection of the HDPE liner; 60 cm of crushed limestone (50–100 mm) as the main filter media; 10 cm of peanut gravel (5–10 mm) for preventing top sand from entering the main media layer; and a top 20 cm of coarse sand for plant establishment (Figure 1). Cell B was filled identically except that the 60 cm crushed local limestone layer had a grain size of 40–60 mm.

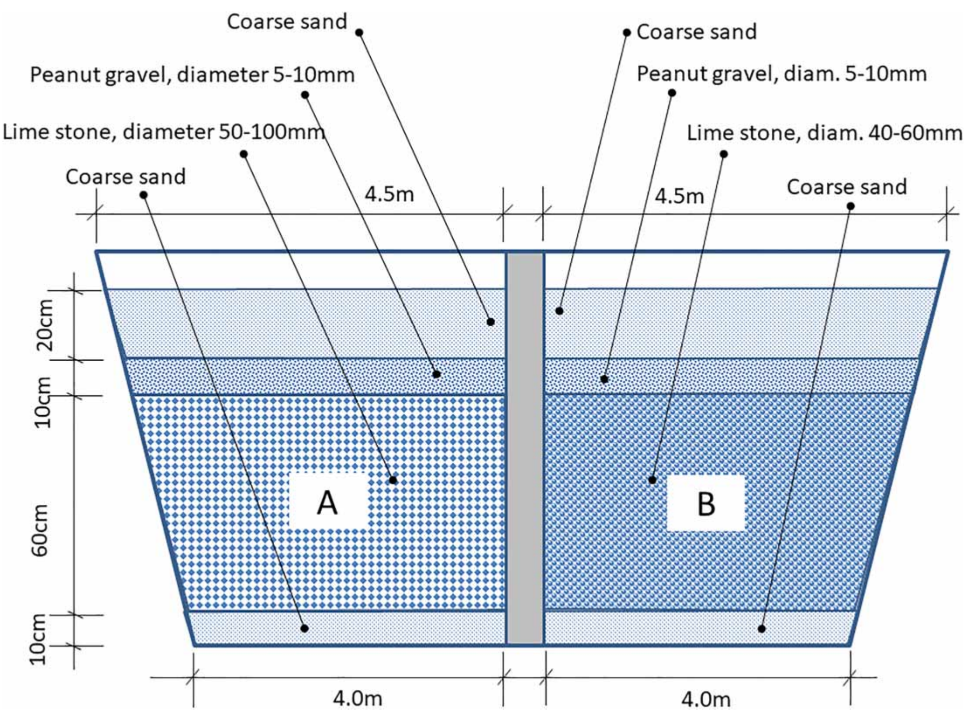

Figure 1 | Filter media layers in cell A and cell B of the pilot CW at Formosa Steel Company, Vietnam (not to scale).

The same hydraulic load (flow rate) was set for both cells; that is, the expected rate for the full scale wetland. A design flow of 36,000 m^3/day and a first horizontal flow wetland cell with an inflow width of 74 m and a 0.6 m effective depth of filter media would result in a horizontal flow velocity of 33.8 m/h. Based on this, the flow rate to the pilot CW cells was regulated at various rates between 50 and 120 m^3/h, using valves on the discharge pipe of the feeding pumps. In addition, the CW cells outflow, Q_{out} (m^3/h), was measured as the accumulated volume of water V (m^3) in the outflow well over a certain operation time T (h): $Q_{out} = V/T$. The observed head losses at different flow rates were compared with theoretical head loss values, calculated using the Carmen–Kozeny formula (Equation (1); Quasim *et al.* 2000).

$$h_L = \frac{f}{F}\frac{1-e}{e^3}\frac{L}{d}\frac{v^2}{g} \tag{1}$$

f = friction factor; f = 150*(1-e)/N_R + 1.75.
N_R = Reynolds number; $N_R = d^* \nu^* \rho_w / m$.
ν = kinematic viscosity (=0.028 m^2/s).
ρ_w = density of water (=1,000 kg/m^3).
m = absolute viscosity (=1.518*10^{-3} N-s/m^2).
F = particle shape factor (usually 0.85 to 1.0).
e = porosity ratio, defined by experiment, measured volumetrically in the laboratory.
L = length of filtration module (m).
d = media grain diameter, m.
v = filtration velocity (m/s).
g = acceleration due to gravity (=9.81 m/s^2).

For comparative purposes, the equation was applied only to the 60 cm layer with limestone, ignoring the influence of the bottom layer with coarse sand, assuming a mean value for d = 0.075 m for the A cell and d = 0.05 m for the B cell. The measured porosity (e) was 0.45 for the coarse material (cell A) and 0.4 for the material in cell B.

Full scale wetland design

The full scale constructed wetland system consisted of 4 cells in series, with a total wet area of 4.32 ha, preceded by open ponds. The entire system of ponds and wetlands was dimensioned based on literature data; for common variables like biochemical oxygen demand (BOD_5), total nitrogen (TN) and NH_4^+-N, the Tanks-in-Series approach was used (Equation (2); Kadlec & Wallace 2009).

$$C_{out} - C^* = \frac{C_{in} - C^*}{(1 + k/N \times q)N} \tag{2}$$

where N = number of tanks in series, q = hydraulic load (m/yr), C^* = background concentration of the variable concerned, and C_{out} and C_{in} are concentrations in the outflow and inflow. CW1, CW2 and CW3 were subsurface horizontal flow CWs, planted with a mixture (multi-culture) of *Phragmites australis* Cav., *Typha angustifolia* L. and *Cyperus tegetiformis*. The final cell, CW4, was a free water surface wetland planted with *P. australis* Cav. and *T. angustifolia* L. *P. australis* (Cav.), *T. angustifolia* L. and *C. tegetiformis* were chosen because they are most tolerant to the local environment conditions, and the plants could be found locally. For design purposes, a conservative *N*-value of 3 was used for the entire system (to represent free water surface wetlands rather than subsurface flow).

Water sampling and analytical methods

From September 2017 to July 2018, water samples were taken weekly in the influent and effluent of each wetland cell (2 samples per site [morning and afternoon] × 5 sampling sites × 40 weeks) and water quality analysed following standard methods (APHA AWWA WEF 2012). pH was measured according to method 9040C, colour was measured by the platinum–cobalt method at 455 nm (method 110.2), COD was measured by the potassium dichromate colorimetric method (method 410.1), BOD_5 was measured according to method 405.1, Total suspended solids (TSS) were measured gravimetrically (method 160.2) and Cr^{6+} was measured by ion chromatography (method 218.7). Mn, Fe, Cd, Hg were measured by atomic absorption spectrometry (method 7000B), TN, NH_4^+-N and cyanide was measured by semiautomated colorimetry (method 351.2, 350 and 335.4) and phenol was measured by flame ionization detector gas chromatography (method 604). Total grease and fat was measured by hexane extractable gravimetry according to method 1664 (APHA AWWA WEF 2012).

RESULTS AND DISCUSSION

Determining hydraulic design parameters for the full scale wetland cells

The results from the pilot experiments showed significant differences in head loss between cell A and B. In cell B, with smaller grain sizes, the head loss increased from 6.6 cm to 16.3 cm when the flow rate was changed from 49.2 m^3/h to 82.7 m^3/h. In cell A, a flow rate increase from 49.5 m^3/h to 122.4 m^3/h caused an increase in head loss from 2.9 cm to 8.7 cm. The measured head losses exceeded the theoretical calculations using the Carmen–Kozeny formula but the relation with flow rate was similar (Figure 2), suggesting that the experiments gave reliable results regarding this aspect. Several assumptions in theoretical models of flows through packed beds can often not be met in real soil filtering systems, which has implications for the system design, as discussed by, for example, Schöpke (2007). One important reason that the measured head loss was higher than the theoretical in the current study was most probably that the filter media was not washed (i.e. contained finer particles), and was therefore neither homogeneous nor consolidated. This was important to consider when selecting and filling the media into the wetland cells. If a well sieved, uniform filter media cannot be used, a larger 'safety factor' for head loss increase must be accounted for in the design. In this case, the pilot experiments results indicated that the unit head loss in cell A was 22.8 cm/100 m. Translating this to a full scale wetland with a total flow length of 450 m, the head loss over the system could reach 1.01 m at the maximum design flow of 36,000 m^3/day. This was an important factor when determining the elevation of the four full scale wetland cells.

In cell B, the unit head loss was 51.8 cm/100 m at a flow rate as low as 82.7 m^3/h, translating to 2.33 m over a 450 m long wetland system. Hence, with the high hydraulic design load for the FHS CW system, this filter media (diameter 40–60 mm) was deemed unsuitable. A too high head loss would lead to the need for a significantly increased elevation of the first ponds with substantially more earth work and an increase in the pump head. An alternative solution could be to decrease the flow velocity through the wetland cross sections, but this could only be done through an increase in the media depth or wetland cell area. Besides the possibly negative effect on plant growth and the biogeochemical conditions in the cells (more anaerobic conditions), this would increase the total media volume and/or required wetland area and lead to an increase in project costs.

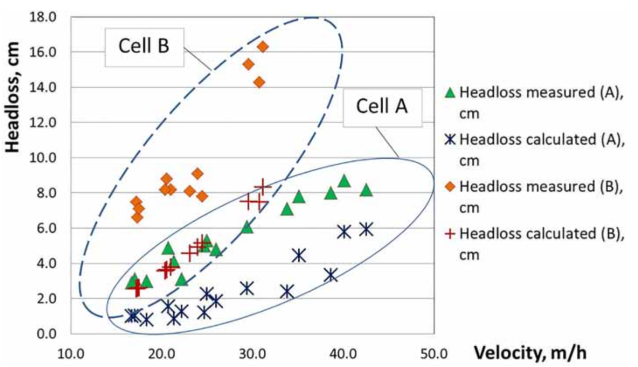

Figure 2 | Head loss versus flow velocity values, experimental and theoretical values in pilot wetland cell A and cell B at the Formosa Steel Company, Vietnam.

Treatment performance of the wetland cells

During the first year of operation, the effluent from the wastewater treatment system preceding the wetland system had a neutral pH, with little variation, and concentrations of potentially toxic compounds were, for several substances below the detection limit (Table 1). This effluent quality met the Vietnamese standards for industrial wastewater discharge to both inland waters (class A) and the sea (class B). Hence, the wetland system functioned as a polishing step during this monitoring period. As predicted, the hydraulic load was high, resulting in relatively high load of substances despite the low inflow concentrations. Concentrations were further reduced in the wetland system leading to very low levels of critical variables, such as NH_4^+-N, Fe and Mn, in the outflow from the system (Table 2). Concentrations of phenol, CN^- and Cr^{6+} were below the respective detection limits (10, 4 and 3 μg/l) also in the outflow from the system (values not shown).

The concentration reductions achieved agreed relatively well with the design model (Equation (2)) for BOD_5 and TN. There was a tendency to improved performance in the second period, when the observed concentrations of both BOD_5 and TN were lower than the predicted (Table 3). No effort was made to account for the possible influence of the approximately 20% lower hydraulic load on the removal rate constant in period 2, though a positive relation between hydraulic load and k-values has been observed when applying first order rate models to monitoring data (Kadlec 2000). Regarding NH_4^+-N, the wetland system performed better than predicted with the model (Table 3), and this is probably a result of the initial influence of plant uptake. The k_{20}-value used in the design model was conservatively set to the lower 0.2 percentile of the indicated range for lightly loaded 'agronomic' wetlands, i.e. wetlands with an annual NH_4-N load <0.33 g/(m^2*d) (Kadlec & Wallace 2009) similar to the load to the FHS wetland. If instead setting the k_{20}-value to 0.55 m/d (above the 0.8 percentile), the predicted outflow concentrations would have been 0.23 and 0.1 mg/l for period 1 and 2, respectively; this is still higher than the observed values. As the plants were in the establishment phase, they would have competed with nitrifying and heterotrophic bacteria for available nitrogen, resulting in the observed high NH_4^+-N removal efficiency

Table 1 | Quality of the wastewater entering the CWs at the Formosa Steel plant, Vietnam, and concentration limits in the Vietnamese standards for industrial wastewater discharges to different recipients (class A and B; QCVN 40:2011/BTNMT)

Variable measured	Unit	Mean value ± SD (min-max)	Standard for industrial wastewater, class A	Standard for industrial wastewater, class B
pH	–	7.3 ± 0.18 (6.8–7.8)	6–9	5.5–9
Color	Pt/Co	27.8 ± 4.9 (20–39)	50	150
COD	mg/l	23.1 ± 2.6 (14–30)	75	150
BOD_5	mg/l	9.4 ± 2.3 (5 –15.8)	30	50
TSS	mg/l	17.4 ± 2.1 (14–26)	50	100
Mn	mg/l	0.43 ± 0.12 (0.08 –0.75)	0.5	1
Fe	mg/l	0.33 ± 0.18 (0.01 –0.86)	1	5
TN	mg/l	10.5 ± 2.8 (6.1 –19.2)	20	40
NH_4^+-N	mg/l	0.57 ± 0.19 (0.04 –2.1)	5	10
Cr (VI)	mg/l	<0.003	0.05	0.1
Cd	mg/l	<0.0007	0.05	0.1
Hg	mg/l	<0.0003	0.005	0.01
Phenol	mg/l	<0.01	0.1	0.5
CN^-	mg/l	<0.004	0.07	0.1
Grease and fats	mg/l	<0.3	5	10

Arithmetic means ± SD for the period September 2017–July 2018.

Table 2 | Mean ($n = 80$ per sampling site) water quality of the effluent from wetland cells CW1, 2, 3, 4 at Formosa Steel work, Vietnam, for the period September 2017 to July 2018. Arithmetic mean ± SD (min-max) are shown and units are as in Table 1

	Wetland cells			
Variables measured	CW1	CW2	CW3	CW4
Color	20.6 ± 4.5 (18–30)	19.6 ± 2.8 (17–28)	17.9 ± 2.9 (14–25)	16.7 ± 2.6 (12–21)
COD	20.2 ± 2.9 (15–29)	19.9 ± 2.0 (14–25)	17.4 ± 3.0 (11–23)	16.7 ± 3.3 (10–24)
BOD_5	7.7 ± 1.6 (6.0–11)	7.8 ± 1.1 (5.6–10.1)	6.7 ± 2.0 (4.9–9.1)	6.5 ± 0.9 (4.2–9.3)
TSS	15 ± 1.5 (10–22)	14.4 ± 2.5 (8–20)	13.0 ± 2.5 (5–17)	13.4 ± 2.4 (7–18)
Mn	0.27 ± 0.06 (0.22–0.61)	0.22 ± 0.05 (0.1–0.32)	0.17 ± 0.06 (0.03–0.41)	0.16 ± 0.08 (0.03–0.55)
Fe	0.22 ± 0.03 (0.06–0.49)	0.25 ± 0.16 (0.04–0.56)	0.18 ± 0.09 (0.03–0.71)	0.17 ± 0.10 (0.02–0.7)
TN	9.2 ± 1.5 (9.2–17)	9.5 ± 2.4 (8.3–16)	9.2 ± 2.1 (6.5–14.9)	8.9 ± 2.0 (6.1–15.8)
NH_4^+-N	0.29 ± 0.08 (0.13–0.67)	0.15 ± 0.03 (0.09–0.42)	0.08 ± 0.02 (0.02–0.69)	0.04 ± 0.01 (0.01–0.14)

(>90%; Figure 3). Those results corroborated well with previous studies on NH_4^+-N treatment efficiency from various industrial wastewaters: 84–94% (Vymazal 2014) and were higher than data reported by Xu *et al.* (2009) and Huang *et al.* (2011) studying wetlands treating steel wastewater.

In agreement with the model predictions, the reduction of TN was the lowest of all the variables (mean 14%). It is well known that the % removal is depending on the inflow concentrations as a first order rate removal model often describes the concentration reductions in CWs (Kadlec & Wallace 2009). Hence, a higher removal could have been expected in our study since the inflow contained around 10 mg/l TN, but the hydraulic load counteracted this as also confirmed by the predictions from the design model. Although nitrification-denitrification processes usually are the main nitrogen removal mechanisms in CWs (accounting for 60–96% of TN removal) (Chen *et al.* 2014), other authors have showed that macrophyte uptake can

Table 3 | Hydraulic load, observed inflow and outflow concentrations and outflow concentrations modelled using the Tanks-in-Series model ($P = 3$, $\Theta = 1.08$ for temp adjustment of k_{20})

Variable	Time period	Hydraulic load m/d	Inflow conc. mg/l	Load g/(m²*d)	Remov. rate, *k* m/d	C* mg/l	Predicted outflow conc mg/l	Observed outflow conc mg/l
BOD_5	Sept-Dec-17	0.58	7.5	4.3	0.235[a]	1[a]	5.4	6.6
	Feb-Jul-18	0.47	11.4	5.3	0.235[a]	1[a]	7.5	6.4
TN	Sept-Dec-17	0.58	10.5	6.1	0.089[b]	2	9.3	9.4
	Feb-Jul-18	0.47	10.4	4.9	0.089[b]	2	9.0	8.5
NH_4^+-N	Sept-Dec-17	0.58	0.72	0.42	0.056[b]	0	0.66	0.06
	Feb-Jul-18	0.47	0.40	0.18	0.056[b]	0	0.35	0.03

[a]For inflow concentrations 3–30 mg/l, 50% percentile, no temp adjustment of *k* (Kadlec & Wallace 2009).
[b]Adjusted *k*-value for 25 °C.

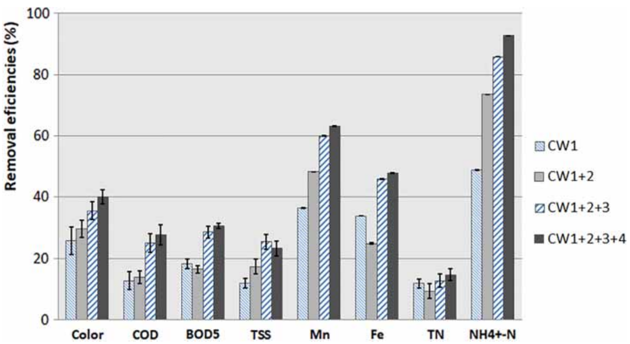

Figure 3 | Removal efficiencies (concentration reductions) of constructed wetland cells CW 1–4 at the Formosa Steel plant, Vietnam, during September 2017–July 2018.

account for a considerable TN reduction (14–52%) in wetlands receiving low loads of N (Wu *et al.* 2013). Uptake in *P. australis* and *T. orientalis* accounted for about 27 and 40% of TN removal in that study. In a systematic review of CWs receiving either non-point source water or secondary or tertiary treated wastewater, Land *et al.* (2016) found that the average removal efficiency was 39%. However, in a study by Bulc *et al.* (2006), TN removal efficiency in CWs treating textile wastewater was also only 5%, suggesting that the nitrogen was bound in recalcitrant compounds. This may also be the case in the FSH CW and, in that case, the plant uptake would play little role in the efficiency, though it was likely a significant process for the NH_4^+-N removal. However, when comparing the predicted outflow concentrations with those observed, it appeared that the TN removal improved as the plant and microbial community developed over time. Future monitoring data will shed more light on the N removal in this CW system.

Regarding the variables BOD_5 and COD, the values in the inflow were close to what sometimes is considered background values for wastewater treatment wetlands receiving raw wastewater. However, for tertiary wastewater, Kadlec & Wallace (2009) suggested a C* (background) value of 1 mg/l in horizontal subsurface flow wetlands. The results from the first months of the FSH wetland system suggest that the wetland system was performing relatively well in view of the high hydraulic load (Table 3 and Figure 3). Earlier findings on COD removal rates by CWs treating steel wastewaters ranged from 31 to 77% (Xu *et al.* 2009; Huang *et al.* 2011). Baughman *et al.* (2003) investigated the performance of CWs treating textile wastewater and found a COD removal efficiency ranging from 20 to 34%. The mean BOD_5/COD ratio in the inflow to the FHS wetland system was 0.41, suggesting that the organic matter is not easily biodegradable. This could mean that a longer retention time than 1 day would be required for a substantial decomposition, or alternatively a finer media to allow for more filtration and sorption processes (Bulc *et al.* 2006). As discussed in the design section above, this was not a viable option for the FHS wetland system. These results correlated well with COD reduction rates recorded in other studies of steel wastewater and, therefore, it is plausible that the BOD_5 removal efficiencies may remain at the observed level.

Based on concentration reductions, the highest removal efficiencies were achieved for Mn (>60%) and Fe (>40%) (Figure 3). The observed Mn removal rate was consistent with the average Mn removal rate by wetland treatment systems previously reported by Lesley *et al.* (2008) (64.5%) despite the higher inflow concentrations in that study – 1.5 mg/l versus 0.43 mg/l. On the other hand, in other studies, Xu *et al.* (2009) and Huang *et al.* (2011) found that treatment efficiencies of Mn by CWs treating wastewater from steel enterprises reached 92.5–95% when influent concentrations were in the range of 0.53–2.23 mg/l. However, in those studies, the hydraulic loads have been lower with 1.5–2 days retention time compared to <1 day in the present study. Regarding Fe removal, the efficiency was 1.5 times lower than the results recorded by

Lesley *et al.* (2008), 48% as opposed to 70%. This could be due to the 10 times lower Fe concentrations in the influent in the FHS wetland system. Sedimentation, filtration and adsorption by surfaces could be important physical processes, which helps to decrease metal concentrations in CWs (Garcia *et al.* 2010). Metal remobilization can be favoured by oxidation in the rhizosphere due to oxygen released from roots of wetland plants (Garcia *et al.* 2010). The formation of iron plaque on the root surface of *P. australis* has been previously found in full scale HSSF CWs (Mantovi *et al.* 2003). The significance of metal uptake by plants is still a matter of debate. While several authors concluded that wetland plants play a significant role in metal uptake (Khan *et al.* 2009; Maine *et al.* 2009), other authors reported that plant uptake is negligible for total metal removal (Stottmeister *et al.* 2003). Some of that discrepancy can be related to load differences; plants have a limited uptake capacity and this will account for a larger proportion of the metal inflow in low loaded wetlands.

Colour removal is often an issue in treatment of steel works wastewater. There are studies showing that CWs can be effective in decolouration of some types of wastewater (mean removal of up to 90%) (Moshiri 1993). This depends strongly on the cause of the colour, and Bulc & Ojstršek (2008) found that CWs planted with *P. australis* removed 70 to 90% of the colour in textile wastewater, which was substantially higher than in the FHS wetland system (40%). Probably the short retention time and the relative recalcitrant organic compounds counteracted an efficient colour removal.

CWs are well known to remove TSS (Manios *et al.* 2003; Bulc & Ojstršek 2008), also from difficult wastewater such as textile wastewater (Bulc & Ojstršek 2008). In this study, removal efficiencies of TSS were only 23%, and this was equivalent to 13.35 mg/l in the effluent. This is lower than previous results on TSS removal in CWs treating petrochemical and refinery wastewaters (42–44%) (Vymazal 2014). Kadlec & Wallace (2009) summarized a large number of studies on gravel wetlands treating domestic wastewater, and the results suggest that a concentration around 5 mg/l TSS is achievable. It is possible that the TSS removal in the FHS wetland system will improve as the plant root system develops and covers a larger part of the filter media. This could improve the filtration effect and support the development of a viable microbial community. Filtration, followed by aerobic microbial degradation on the surface or anaerobic degradation within the media, could affect the effectiveness of organic solids removal (Manios *et al.* 2003).

CONCLUSIONS

Experiments in pilot scale horizontal subsurface flow wetlands receiving treated wastewater from a steel industry showed that theoretically calculated values of head loss at different hydraulic loading rates can substantially underestimate the observed values. Hence, field testing is warranted when designing large scale wetlands for high hydraulic loads. The study showed that filter media of 50–100 mm diameter had an observed unit head loss of 22.8 cm/100 m at a flow rate 122 m^3/h, equal to a total head loss of 1.01 m over the total length of the planned full scale wetland system, with a design flow rate of 36,000 m^3/day. The discrepancy from the theoretical values was probably explained by the heterogeneity of the gravel, which was neither sieved nor washed. In case media with such non-uniform size ranges must be used, a safety factor for head loss increase should be included in the design.

During the first operational year, the four full scale CW cells, with a mean retention time of 0.9 days, received a wastewater that met the discharge standards. The inflow concentrations were further reduced in the CW system, and in the second half of the observation period they were lower than predicted from the design model for BOD_5 and TN, suggesting that the system improved as the plant and microbial communities developed. Highest removal efficiencies were observed for NH_4^+-N (>90%), Mn (>60%), and Fe (48%). The removal of TN was lower at 15%, for BOD_5 31% and for COD 28%, corresponding to 8.9, 6,5 and 16.7 mg/l, respectively, in the effluent. Those relatively

Figure 4 | Hybrid pond – wetland system for Formosa Steel plant wastewater polishing treatment, Vietnam (design flow 36,000 m^3/day, total area 10 ha). (1) Waste stabilization pond cells; (2) subsurface flow constructed wetland cell CW1; (3) subsurface flow constructed wetland cell CW2; (4) subsurface flow constructed wetland cell CW3; (5) free water surface flow constructed wetland cell CW4.

low removal rates are explained by the high hydraulic load and short retention time. Despite this, the removal of colour amounted to 40%, whereas TSS was removed by 23%. The results confirm that a hybrid pond and CW system can serve as a polishing step for wastewater from the steel industry, reducing the risk for discharge of potentially toxic substances to the environment. A further benefit is the 'green element' created in the industrial landscape (Figure 4).

REFERENCES

APHA, AWWA, WEF 2012 *Standard Methods for the Examination of Water and Wastewater*, 22nd edn. American Public Health Association, Washington, p. 1360.

Baughman, G. L., Perkins, W. S., Lasier, P. J. & Winger, P. V. 2003 Effect of treatment in a constructed wetland on toxicity of textile wastewater. *AATCC Review* **3**, 28–30.

Borst, M., Riscassi, A. L., Estime, L. & Fassman, E. L. 2002 Free-water depth as a management tool for constructed wetlands. *Journal of Aquatic Plant Management* **40**, 43–45.

Bulc, T. G. & Ojstršek, A. 2008 The use of constructed wetland for dye-rich textile wastewater treatment. *Journal of Hazardous Materials* **155**, 76–82.

Bulc, T. G., Ojstrsek, A. & Vrhovšek, D. 2006 The use of constructed wetland for textile wastewater treatment. In: *Proc. 10th Internat. Conf. Wetland Systems for Water Pollution Control*. MAOTDR, Lisbon, Portugal, pp. 1667–1675.

Chen, Y., Wen, Y., Zhou, Q. & Vymazal, J. 2014 Effects of plant biomass on nitrogen transformation in subsurface-batch constructed wetlands: a stable isotope and mass balance assessment. *Water Research* **63**, 158–167.

Davis, L. 2000 *A Handbook of Constructed Wetlands. A Guide to Creating Wetlands for: Agricultural Wastewater, Domestic Wastewater, Coal Mine Drainage, Stormwater in the Mid-Atlantic Region*. USDA-Natural Resources Conservation Service and the US Environmental Protection Agency-Region III, Harrisburg, PA.

Garcia, J., Rousseau, D. P. L., Morató, J., Lesage, E. L. S., Matamoros, V. & Bayona, J. M. 2010 Contaminant removal processes in subsurface-flow constructed wetlands: a review. *Critical Reviews in Environmental Science and Technology* **40**, 561–661.

Grace, J. B. 1989 Effects of water depth on Typha latifolia and Typha domingensis. *American Journal of Botany* **76**, 762–768.

Huang, X. F., Ling, J., Xu, J. C., Feng, Y. & Li, G. M. 2011 Advanced treatment of wastewater from an iron and steel enterprise by a constructed wetland/ultrafiltration/reverse osmosis process. *Desalination* **269**, 41–49.

Kadlec, R. H. 2000 The inadequacy of first-order treatment models. *Ecological Engineering* **15**, 105–119.

Kadlec, R. H. & Wallace, S. 2009 *Treatment Wetlands*, 2nd edn. CRC Press, Taylor and Francis Group, Boca Raton, FL.

Khan, S., Ahmad, I., Shah, M. T., Rehman, S. & Khaliq, A. 2009 Use of constructed wetland for the removal of heavy metals from industrial wastewater. *Journal of Environmental Management* **90**, 3451–3457.

Land, M., Granéli, W., Grimvall, A., Hoffmann, C. C., Mitsch, W. J. & Tonderski, K. S. 2016 How effective are created or restored freshwater wetlands for nitrogen and phosphorus removal? A systematic review. *Environmental Evidence* **5**, 5–9.

Lesley, B., Daniel, H. & Paul, Y. 2008 Iron and manganese removal in wetland treatment systems: rates, processes and implications for management. *Science of The Total Environment* **394**, 1–8.

Maine, M. A., Suñe, N., Hadad, H., Sánchez, G. & Bonetto, C. 2009 Influence of vegetation on the removal of heavy metals and nutrients in a constructed wetland. *Journal of Environmental Management* **90**, 355–363.

Manios, T., Stentiford, E. I. & Millner, P. 2003 Removal of total suspended solids from wastewater in constructed horizontal flow subsurface wetlands. *Journal of Environmental Science and Health, Part A: Toxic/Hazardous Substances and Environmental Engineering* **38**, 1073–1085.

Mantovi, P., Marmiroli, M., Maestri, E., Tagliavini, S., Piccinini, S. & Marmiroli, N. 2003 Application of a horizontal subsurface flow constructed wetland on treatment of dairy parlor wastewater. *Bioresource Technology* **88**, 85–94.

Moshiri, G. A. 1993 *Constructed Wetlands for Water Quality Improvement*. Taylor & Francis, Boca Raton, FL.

Quasim, S., Motley, E. & Zhu, G. 2000 *Water Works Engineering: Planning, Design and Operation*. Prentice Hall, Upper Saddle River, NJ, pp. 373–400.

Schöpke, R. 2007 Multicomponent systems in water treatment – Data compilation and use for dimensioning treatment plants. Heft 14, Schriftenreihe Siedlungswasserwirtschaft und Umwelt. Dep Water Technology and Urban Water Engineering, Brandenburg Technical University, Cottbus, Germany (in German).

Stottmeister, U., Wießner, A., Kuschk, P., Kappelmeyer, U., Kästner, M. & Bederski, O. 2003 Effects of plants and microorganisms in constructed wetlands for wastewater treatment. *Biotechnology Advances* **22**, 93–117.

Vymazal, J. 2009 The use constructed wetlands with horizontal sub-surface flow for various types of wastewater. *Ecological Engineering* **35**, 1–17.

Vymazal, J. 2014 Constructed wetlands for treatment of industrial wastewaters: a review. *Ecological Engineering* **73**, 724–751.

Wu, H., Zhang, J., Wei, R., Liang, S., Li, C. & Xie, H. 2013 Nitrogen transformations and balance in constructed wetlands for slightly polluted river water treatment using different macrophytes. *Environmental Science and Pollution Research* **20**, 443–451.

Xu, J. C., Chen, G., Huang, X. F., Li, G. M., Liu, J. & Yang, N. 2009 Iron and manganese removal by using manganese ore constructed wetlands in the reclamation of steel wastewater. *Journal of Hazardous Materials* **169**, 309–317.

Yang, L. & Hu, C. C. 2005 Treatments of oil-refinery and steel-mill wastewaters by mesocosm constructed wetland systems. *Water Science and Technology* **51**, 157–164.

First received 15 November 2018; accepted in revised form 9 July 2019. Available online 22 July 2019