Management and treatment of landfill leachate by a system of constructed wetlands and ponds in Singapore
C. H. Sim, B. S. Quek, R. B. E. Shutes and K. H. Goh

ABSTRACT
Lorong Halus, Singapore’s first landfill leachate treatment system, consists of a pre-treatment system (8,000 m²), five constructed reed beds (38,000 m²), five polishing ponds (13,000 m²), an education centre and a learning trail for visitors. Eight species of wetland plants (total 160,000 plants) were selected for their ability to uptake nutrients, tolerance to low phosphorus concentrations and resistance to pest infestations. The wetland was launched in March 2011 and water quality monitoring started in April 2011. The removal efficiencies of the pre-treatment system from April 2011 to August 2012 are biochemical oxygen demand (BOD₅) 57.4%; chemical oxygen demand (COD) 23.6%; total suspended solids (TSS) 55.1%; ammoniacal nitrogen (NH₄-N) 76.8%; total phosphorus (TP) 33.3% and total nitrogen (TN) 60.2%. Removal efficiencies of the reed beds are BOD₅ 47.0%; COD 42.2%; TSS 57.0%; NH₄-N 82.5%; TP 29.3% and TN 83.9%. Plant growth is generally satisfactory, but the lower than designed volume of leachate has adversely affected some sections of plants and resulted in uneven flow distribution in reed beds. The plant management programme includes improving plant regrowth by harvesting of alternate strips of plants and replanting. The treated effluent meets water quality limits for discharge to the public sewer and is subsequently treated by the NEWater treatment system, which recycles water for industrial and indirect potable use.

INTRODUCTION
There are relatively few reported studies of full-scale constructed wetland (CW) systems for the treatment of landfill leachate in comparison to studies of pilot-scale and experimental systems. Bulc (2006) reported that the performance of a pilot integrated CW system treating landfill leachate did not vary significantly with regard to temperature but varied with precipitation. Landfill leachate with high iron content required a pre-treatment chamber and a new CW aeration system to maintain effective operation (Nivala et al. 2007). Chemical oxygen demand (COD) removal was found to be more effective in a horizontal pilot-scale CW than in a combined vertical and horizontal CW system (Yalcuk & Ugurlu 2009). However, in a laboratory-scale vertical flow CW with a recirculation ratio of 1:3, removal efficiencies of 96% for COD in 8 d and 92% for biochemical oxygen demand (BOD₅) in 3 d were reported by Lavrova & Koumanova (2010). Compared to unplanted CWs, in planted recirculating subsurface horizontal flow CWs, plant-available radiation significantly increased the release of organic N and removal of ammonia after 9 d (Bialowiec et al. 2012). Kadlec & Zm thinner (2010), in a study of a wetland system treating leachate from a closed landfill in the USA with a high recirculation rate, reported a reduction of ammonia mass averaging 99.5% over 9 years.

A study in a tropical climate in Thailand by Sawattayothin & Polprasert (2007) of landfill leachate treatment by CW experimental systems with a hydraulic retention time of 8 d yielded the best treatment efficiencies with BOD₅ and total nitrogen (TN) of 91 and 96% respectively with an estimated 88% of the input TN taken up by the plant biomass. Chiemchaisri et al. (2009) found that high nitrogen in the stabilised leachate adversely affected the treatment performance and vegetation in a subsurface horizontal flow CW system planted with Typha angustifolia in Thailand. In Malaysia, Ujang et al. (2005) recorded more than 80% removal for total suspended solids (TSS), BOD, COD, Zn, Ni, Cu, Cr and Pb from landfill leachate in an experimental subsurface flow CW planted with Scirpus
**Methods**

**Site description**

Lorong Halus treatment wetland is Singapore's first and largest constructed treatment wetland (5.1 ha), transformed from a former landfill. It is situated adjacent to the eastern bank of the Serangoon Reservoir. Lorong Halus Remediation System is designed to preserve the water quality of the Serangoon Reservoir. The former landfill site occupied an area of 234 ha and received the solid waste of Singapore from 1970 to 1999. The construction of Lorong Halus wetland commenced in April 2009, was completed in July 2010 and officially launched in March 2011.

**Design of Lorong Halus remediation system**

The system helps to prevent the flow of leachate into the reservoir and treats the leachate that is collected. It consists of three components comprising a cut-off wall, a leachate collection system, and a treatment wetland.

A cut-off wall runs below the surface along the bank of the reservoir fronting the landfill site. The wall is composed of an impermeable mixture of cement and bentonite of about 18 m depth and 800 mm thick, stretching over 6.4 km. This impermeable mixture helps to effectively contain the leachate within the landfill and prevents it from flowing into the reservoir. The leachate collection system is designed to extract the trapped leachate for treatment. It comprises 125 pumping wells of 12 m depth which are linked by pipes running behind the cut-off wall, with submersible pumps installed to extract leachate from the wells.

The pre-treatment components consist of an equalisation tank (volume: 2,650 m$^3$), two aeration lagoons (total area: 2,453 m$^2$) and a sedimentation tank (volume: 7,350 m$^3$). The wetland is designed to treat leachate at capacity 3,000 m$^3$/d from the old landfill site. The equalisation tank equalises the leachate flow and it also functions as an initial sedimentation of solids. The two aeration lagoons function to breakdown the organic and nitrogen loads for better plant uptake in the reed beds. The sedimentation tank facilitates the settling of bacterial flocs carried over from the aeration lagoons.

The extracted leachate is pumped to the treatment wetland, which consists of five sub-surface flow reed beds and five lined polishing ponds with edge planting (Figure 1).

The sub-surface reed beds are filled with gravel size 70–100 mm at the inlet zone and 30–50 mm in the gravel bed. The porosity of the substrate is 0.35 and design hydraulic conductivity is 13,000 m/d. The media depth is 0.8 m with bottom liner and a length:width aspect ratio of 4:1. Water flows horizontally through the root zone (200–400 mm deep) at 150 mm below the substrate surface. The design total retention time is approximately 10.2 d, which includes 0.3 d for equalisation tank, 3.4 d for aeration lagoon, 1.3 d for sedimentation tank, 5.2 d for reed beds and 2 d for polishing ponds.

**Wetland plants**

A total of 160,000 plants of eight different wetland species was introduced. These include three species – cattail *Typha angustifolia*, vetiver grass *Chrysopogon zizanioides* and papyrus *Cyperus papyrus* – in the sub-surface wetlands, and an additional five species – spike rush *Eleocharis dulcis*, tube sedge *Lepironia articulata*, common reed *Phragmites karka*, umbrella sedge *Cyperus alternifolius* and water lily *Nymphaea* sp. – in the polishing ponds. The planting density in the reed beds is 4 per m$^2$. Wetland plants, which consist of both local and exotic species, were selected for their ability to uptake nutrients, tolerance of low phosphorus concentrations and resistance to pest infestations.

globulosus* and *Eriocaulon sexangulare*. In pilot-scale studies in Malaysia, Sim et al. (2008) studied nutrient removal in *Phragmites karka* and *Lepironia articulata* and Akinbile et al. (2012) treated landfill leachate in a subsurface flow CW planted with *Cyperus haspan* with variable removal of parameters (e.g. 33.8–67.0% of TN) in 3 weeks of treatment.
Education

Under the ABC Waters Programme, the reservoir became more vibrant, opening up opportunities for recreation, community spaces, research and education, while preserving a part of Singapore’s natural heritage. An education kiosk with information exhibits on the wetland was set up in the wetland to promote awareness of wetland systems, and a trail was established for visitors to walk through the wetland for nature appreciation. To make the park more accessible to the public, a pedestrian footbridge connecting the park to the activity cluster of Punggol New Town on the opposite bank was constructed.

Water quality monitoring

PUB commenced water quality monitoring in the reed beds and ponds following 8 months of operation of the system in April 2011. Water quality was monitored over 16 months on a monthly basis to assess the performance of the pre-treatment system, five reed beds and four ponds and quantify the extent of nutrient removal by the wetland plants.

A total of 13 water quality sampling points were monitored with one point at each of the three pre-treatment system components: equalisation tank, aeration lagoons and sedimentation tank; reed beds 1–5; and ponds 1, 2, 3 and 5, except pond 4. Pond 4 was not monitored as it receives water from the other polishing ponds. Raw leachate quality samples were taken from the inlet pipe to the equalisation tank.

Water quality parameters monitored include pH, BOD5, COD, total organic carbon (TOC), TSS, TN, ammoniacal nitrogen (NH4-N) and total phosphorus (TP). Samples were analysed by an accredited laboratory in accordance with Standard Methods (APHA et al. 2005; JIS 2008; HACH 2012).

Plant growth and nutrient content in plant biomass

Plants were randomly selected and marked at each reed bed and plant height based on the longest leaf was measured. Plant samples of emergent species were selected randomly from each site, and above-ground biomass (leaves and stems) was harvested in August 2011 and March 2012 for analysis of nitrogen and phosphorus content.

All harvested plant material was weighed on site and washed before the plant sample was sent to the laboratory. About 300–500 g of plant material was used for each analysis. The plant materials were ground into fine powder for nutrient analysis. TN was determined using the Kjeldahl method, whereas TP involved a total digestion and ascorbic acid reduction method for colorimetric determination (APHA et al. 2005).

The mass of plants harvested during wetland maintenance was recorded monthly, and the mass of nutrients removed by plant harvesting was calculated using the following:

\[
\text{Mass of nutrients removed (kg)} = \frac{\text{mass of plants harvested (g wet wt)} \times \text{nutrient content of the harvested species (mg/g wet wt)}}{10^6}
\]
RESULTS AND DISCUSSION

Raw leachate quality

The quality of raw leachate in the equalisation tank is highly variable for all parameters (Table 1). TP levels were low for plant establishment. Essential elements for plant growth include iron, manganese, zinc and copper were also low.

The salinity levels of the raw leachate were high, in the range of 9.1–19.3 ppt with an average of 13 ppt. The high salinity levels in the leachate were due to saline water being trapped in the soil. Water from Serangoon Reservoir is used to dilute the leachate at a ratio of 1:3 to an average salinity of 4 ppt.

Water quality monitoring and removal efficiency

Following pre-treatment of the landfill leachate, there is a reduction in the average concentrations of all parameters in reed beds 2–5. Reed bed 1 shows high concentrations of all parameters (except TSS), which are probably due to underground leachate seepage from the surrounding high ground. More vetiver grass has been planted along the edge of the reed bed to treat the seepage. Pond 1 following reed bed 1 also shows high concentrations of all parameters in comparison to ponds 2, 3 and 5 (Figure 2).

The removal efficiencies of key parameters were calculated for the pre-treatment system and reed beds, excluding reed bed 1. Removal efficiencies were calculated by comparing the difference between the inlet and outlet concentrations against inlet concentrations at each stage.

The removal efficiencies of TSS by the pre-treatment system and reed beds are 55.1 and 57.0% respectively. Average TSS concentrations increased in the four monitored ponds following the reed beds (Figure 2(a)). This increase is probably caused by re-suspension of sediment particles from inlet flows and intense rainfall events and the feeding of fish by visitors.

Average TOC concentrations are similar for reed beds 2–5 and are lower in ponds 2, 3 and 5 (Figure 2(b)). Carbon is required for the growth and maintenance of populations of bacteria and should not be lowered further in the reed beds.

The removal efficiencies of BOD$_5$ and COD are 57.4 and 23.6% respectively by the pre-treatment system, and 47.0 and 42.2% respectively by the reed beds. The reduction in BOD$_5$ and COD is maintained in the ponds except in pond 1, as previously mentioned (Figures 2(c) and 2(d)).

Average TP concentrations in reed beds and ponds were 0.04 and 0.05 mg/L (Figure 2(e)). The removal efficiency of the pre-treatment system is 33.3% and that of the reed beds is 29.3%. The reduction in comparison with sedimentation tank concentrations is lower than expected, but the removal efficiency of the reed beds may increase or possibly decrease with time.

The removal efficiencies for TN and NH$_4$-N are 60.2 and 76.8% respectively for the pre-treatment system, and 83.9 and 82.5% for the reed beds. Average TN and NH$_4$-N concentrations showed a marked decrease in reed beds 2–5 and ponds 2, 3 and 5 (Figures 2(f) and 2(g)).

The removal of NH$_4$-N and TN increased by 47.1 and 39.8% in polishing ponds 2, 3 and 5 compared to the reed bed effluent, although the removal of TSS decreased by 155.1%. The overall removal efficiencies of pre-treatment, reed beds and polishing ponds are presented in Table 2.

The good performance of the reed beds suggests that both nitrification and denitrification are taking place in the aerobic and anaerobic zones of the subsurface flow beds and that the populations of bacteria controlling these processes have been established. Although the polishing ponds have not yet shown a marked final stage treatment performance in addition to their ultraviolet disinfection and water column mixing functions, their monitoring and assessment continues.

Water quality monitoring is continuing and removal efficiencies will be calculated over a longer period when the data are available.

As the leachate passes through the wetland, the high rates of evaporation and evapo-transpiration may result in higher concentrations at the outlet compared to the inlet. The surface temperature of the gravel substrate in the reed beds can reach 50 °C at or near midday.

Monthly rainfall data from January 2011 to July 2012 showed maximum rainfall in January 2011 and minimum

---

Table 1 | Water quality of raw leachate from April 2011 to August 2012

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Range</th>
<th>Average</th>
</tr>
</thead>
<tbody>
<tr>
<td>pH</td>
<td>6.5–7.9</td>
<td>7.03</td>
</tr>
<tr>
<td>BOD$_5$ (mg/L)</td>
<td>2–32</td>
<td>15.5</td>
</tr>
<tr>
<td>COD (mg/L)</td>
<td>56–129</td>
<td>88.6</td>
</tr>
<tr>
<td>TSS (mg/L)</td>
<td>1.2–149</td>
<td>25.4</td>
</tr>
<tr>
<td>TOC (mg/L)</td>
<td>4.4–33.4</td>
<td>20.3</td>
</tr>
<tr>
<td>NH$_4$-N (mg/L)</td>
<td>5.6–7.5</td>
<td>41.9</td>
</tr>
<tr>
<td>TP (mg/L)</td>
<td>0.01–0.33</td>
<td>0.09</td>
</tr>
<tr>
<td>TN (mg/L)</td>
<td>5.8–77.7</td>
<td>43.5</td>
</tr>
</tbody>
</table>
Average concentrations (with ±S.E.) of TSS, TOC, BOD$_5$, COD, TP, TN and NH$_4$-N measured at different stages of Lorong Halus wetland: pre-treatment system consisting of incoming leachate (S1), equalisation tank (S2), aeration lagoon (S3) and sedimentation tank (S4); reed beds 1 to 5 (S5 to S9); and polishing ponds 1, 2, 3, 5 (S10 to S13).

Figure 2
rainfall in February and June in 2011 and 2012 respectively at Serangoon reservoir adjacent to Lorong Halus. The annual average rainfall for Singapore is 2,358 mm (Figure 3). Analysis of correlations between rainfall and all parameters showed that TN and BOD$_5$ have the highest correlations (0.714 in reed bed 2 and 0.767 in reed bed 4 outlets respectively) with daily rainfall in reed beds 2–5. These positive correlations suggest that organic and nitrogen compounds within the reed beds are flushed out by intense rainfall. There are no strong negative or positive correlations between other parameters and daily rainfall.

### Plant nutrient content and removal

The nutrient content of the above-ground biomass of cattail, vetiver grass and papyrus in the reed beds were 1.33–2.18 mg N/g and 0.06–0.27 mg P/g of wet weight. After accounting for moisture content (cattail: 67.1%, vetiver grass: 53.6%, papyrus: 73.7%), nutrient content ranged from 4.29 to 6.63 mg N/g and 0.26 to 0.58 mg P/g of dry weight. This is higher in comparison to the 1.03–1.73 mg N/g and 0.18–0.4 mg P/g measured in the leaf tissue of five wetland species in a previous study in Singapore (Sim et al. 2011). The much higher nitrogen content is probably due to the higher concentrations of nitrogen in the incoming leachate (average: 43.5 mg/L) compared to those in the ponds (0.39–2.02 mg/L) in the previous study.

For the reed beds, cattail had the highest average TN content while vetiver grass had the highest average TP content. For the polishing ponds, common reed was found to have the highest average nutrient content for both TP and TN (Table 3). The sequences of nutrient uptake by the plant species were:

**Reed beds**

TP – vetiver grass > cattail > papyrus
TN – cattail > vetiver grass > papyrus

**Polishing ponds**

TP – common reed > spike rush > cattail > tube sedge
TN – common reed > cattail > spike rush > tube sedge

An estimated total of 94.3 kg of TN and 6.9 kg of TP were removed from Lorong Halus wetland by plant harvesting over 16 months, from April 2011 to August 2012 (Table 4). This translates to an average of 70.7 kg of TN and 5.2 kg of TP removed per year or 13.9 kg/ha TN and 1.0 kg/ha TP per year. The harvested plant material is sent

### Table 2 | Removal efficiency of pre-treatment, reed beds and polishing ponds

<table>
<thead>
<tr>
<th></th>
<th>Pre-treatment system (%)</th>
<th>Reed beds (%)</th>
<th>Polishing ponds (%)</th>
<th>Combined pre-treatment and reed beds (%)</th>
<th>Combined pre-treatment, reed beds and ponds (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>BOD$_5$</td>
<td>57.4</td>
<td>47.0</td>
<td>0.0</td>
<td>77.4</td>
<td>77.4</td>
</tr>
<tr>
<td>COD</td>
<td>23.6</td>
<td>42.2</td>
<td>0.8</td>
<td>55.9</td>
<td>56.2</td>
</tr>
<tr>
<td>TSS</td>
<td>55.1</td>
<td>57.0</td>
<td>−155.1</td>
<td>80.7</td>
<td>50.8</td>
</tr>
<tr>
<td>NH$_4$N</td>
<td>76.8</td>
<td>82.5</td>
<td>47.1</td>
<td>95.9</td>
<td>97.9</td>
</tr>
<tr>
<td>TP</td>
<td>33.3</td>
<td>29.3</td>
<td>−19.5</td>
<td>52.9</td>
<td>43.7</td>
</tr>
<tr>
<td>TN</td>
<td>60.2</td>
<td>83.9</td>
<td>39.8</td>
<td>93.6</td>
<td>96.1</td>
</tr>
</tbody>
</table>

### Table 3 | Nutrient content in plant biomass of selected species in Lorong Halus wetland

<table>
<thead>
<tr>
<th>Plant species</th>
<th>Average TP (mg/g wet wt)</th>
<th>Average TN (mg/g wet wt)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Reed beds</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Vetiver grass <em>Chrysopogon vизаниoides</em></td>
<td>0.27</td>
<td>1.99</td>
</tr>
<tr>
<td>Papyrus <em>Cyperus papyrus</em></td>
<td>0.06</td>
<td>1.33</td>
</tr>
<tr>
<td>Cattail <em>Typha angustifolia</em></td>
<td>0.13</td>
<td>2.18</td>
</tr>
<tr>
<td><strong>Polishing ponds</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Spike rush <em>Eleocharis dulcis</em></td>
<td>0.17</td>
<td>2.14</td>
</tr>
<tr>
<td>Tube sedge <em>Lepironia articulata</em></td>
<td>0.08</td>
<td>1.76</td>
</tr>
<tr>
<td>Common reed <em>Phragmites karka</em></td>
<td>0.30</td>
<td>4.73</td>
</tr>
<tr>
<td>Cattail <em>Typha angustifolia</em></td>
<td>0.14</td>
<td>2.29</td>
</tr>
</tbody>
</table>
for composting by the wetland maintenance contractor. However, the compost is not applied to soils planted with edible crops.

**Management of low leachate volume**

The current diluted leachate inflow volume to the reed beds is low, at about 500 m³/d (designed maximum flow at 3,000 m³/d). As a result, the hydraulic retention time in reed beds 1, 4 and 5 (6,000 m²) and reed beds 2 and 3 (10,000 m²) are 13.65 and 22.75 d respectively, much longer than the designed rate of 3.2 d. If the volume of leachate continues to be low, there may be a need to install one or more additional pumps to draw water from the Serangoon reservoir.

The low leachate volume may cause poor plant growth. To investigate if increasing leachate volume improves plant growth, the penstocks controlling the inlet flow to reed beds 1 and 2 were closed in May and June 2012 and the flow diverted to reed beds 3–5. Following increase in flow to reed beds 3–5, there is no significant improvement to the growth of papyrus and vetiver grass in these three reed beds. It was observed that cattail generally thrives very well, either with (in reed beds 4 and 5) or without (reed beds 1 and 2) leachate flow.

The reed beds were designed to have a 14 cm difference in level between the inlet and outlet. The uneven distribution of water across the wetland cells may be partially caused by low flow of leachate. Differential volumes of leachate discharged from the holes along and below the inlet pipes indicated that the holes may be too big for the low volume of leachate, resulting in uneven distribution of flow. Monthly pipe inspection and cleaning is carried out to ensure that there is no blockage. It is recommended that the level of the lateral pipes to both left and right of the point of entry of the inlet pipe be monitored for settlement.

**Plant growth and maintenance**

Plant growth is generally satisfactory. The high growth rate and maximum height of cattail, papyrus and vetiver grass of 2.7 m, 2.4 and 1.4 m respectively, has resulted in high plant biomass production. A large of labour is required to maintain the plant stand in a neat condition.

The lower volume of leachate than the design flow has adversely affected some sections of plants in reed beds. The cause of the poor growth of some sections of plants in the reed beds was investigated by raising the water level in each reed bed to just below the surface, by raising the adjustable outlet structure, and monitoring plant growth and colour. The investigation ceased after 10 d as surface ponding occurred following high rainfall events and the possible colonisation by mosquitoes. In order to reduce ponding near the reed bed inlets, removal of the plants, raising the level of the granite stones and the use of smaller gravel/stones to fill the gaps between the larger-sized gravel were carried out.

The removal of leaf litter should be minimised as it provides a carbon source for microbes and shade for the substrate and lowers the surface temperature. However, there may be a problem with fungus growth in the tropical climate. Vetiver grass in reed bed 1 and 2 showed slow growth rate and fungus infestation. Treating the fungus with dormant oils has effectively controlled the disease.

**Plant trimming and replacement**

A replanting trial with vetiver grass sourced from one supplier from each of two neighbouring countries, Malaysia and Thailand, was introduced to part of reed bed 4. However, as growth of the plants was poor, possibly due to low phosphorus concentrations in the leachate, foliar spray fertiliser, NPK (21:21:21), was applied to the replanted vetiver grass in reed bed 4 in the evening at intervals of 2 weeks in May and June 2012. Green regrowth was observed in plants from both sources but at different rates (Figure 4).

Vetiver grass in reed bed 5 was trimmed and cut low to 30 cm height above the gravel bed. Green growth was observed nearer to the inlet, and browning further away from the inlet pipe. A low percentage of regrowth was

### Table 4: Total mass (kg) of nutrient removed from plant biomass (April 2011 to Aug 2012)

<table>
<thead>
<tr>
<th>Mass of plants harvested (kg)</th>
<th>Plant species</th>
<th>TN removed (kg)</th>
<th>TP removed (kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reed beds</td>
<td>Cattail, vetiver grass, papyrus</td>
<td>56.5</td>
<td>3.6</td>
</tr>
<tr>
<td>Polishing ponds</td>
<td>Mix of species, mainly cattail</td>
<td>37.8</td>
<td>3.3</td>
</tr>
<tr>
<td>Total</td>
<td></td>
<td>94.3</td>
<td>6.9</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Total mass (kg) of nutrient removed from plant biomass (April 2011 to Aug 2012)</th>
<th>Mass of plants harvested (kg)</th>
<th>Plant species</th>
<th>TN removed (kg)</th>
<th>TP removed (kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reed beds</td>
<td>24,625</td>
<td>Cattail, vetiver grass, papyrus</td>
<td>56.5</td>
<td>3.6</td>
</tr>
<tr>
<td>Polishing ponds</td>
<td>18,730</td>
<td>Mix of species, mainly cattail</td>
<td>37.8</td>
<td>3.3</td>
</tr>
<tr>
<td>Total</td>
<td>43,355</td>
<td></td>
<td>94.3</td>
<td>6.9</td>
</tr>
</tbody>
</table>
recorded in December 2011. Trimming of papyrus also showed no significant regrowth.

Plant replacement started in March 2012. Dead papyrus was replaced with new papyrus in reed bed 3 and dead vetiver grass with cattail in reed beds 1 and 2. Vetiver grass replacement with Cattail in sections of reed bed 1 was completed in early June and showed good growth.

**CONCLUSIONS**

The combined removal efficiency of the pre-treatment system and reed beds is BOD$_5$ 77.4%, COD 55.9%, TSS 80.7%, NH$_4$-N 95.9%, TP 52.9% and TN 93.6%. The performance of TN removal is higher than the expected range, and BOD and COD removal is within the expected range. Removal performance of TP is still low.

The plant nutrient content recorded for the three plant species, cattail, vetiver grass and papyrus ranged from 0.08 to 0.32% TN and 0.006 to 0.026% TP. The average removal of TN and NH$_4$-N was highest in the reed beds at 83.9% TN and 82.5% NH$_4$-N.

The average treated effluent quality of BOD$_5$ 3.5 mg/L, COD 39.1 mg/L, TOC 8.4 mg/L, NH$_4$-N 1.7 mg/L, TN 2.79 mg/L and TP 0.041 mg/L met the water quality limits for discharge to PUB’s sewer line and was subsequently treated by the NEWater treatment system, which recycles water for industrial and indirect potable use.

The wetland system has achieved its potential in terms of water quality improvement and serves as a demonstration showcase in Singapore. The access and resources allow visitors to gain an understanding of CWs and wildlife.

**ACKNOWLEDGEMENTS**

Many thanks to Lorong Halus wetland management team and especially Gao Ruoming. Jennifer Yip is thanked for providing information on the planting and replanting methods and monitoring at Lorong Halus. Zoe Ong, an intern with PUB, is also thanked for her contribution on the monitoring work at the wetland. We are also grateful to CPG Corporation for the design of the system and Ever-shine for the operation and maintenance of the wetland.

**REFERENCES**


First received 24 February 2013; accepted in revised form 23 April 2013