Reversing clogging in subsurface-flow constructed wetlands by hydrogen peroxide treatment: two case studies
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ABSTRACT
One of the most frequently encountered operational problems in subsurface-flow constructed wetlands is clogging. Traditionally, the restoration procedure is to remove the clogged gravel or sand and replace it with clean material. This method, while effective, is costly and may require sections of the facility to be taken offline for extended periods of time. Another common remediation strategy is to have a resting period for each wetland cell, although this is not an option for very small systems which often consist of only one treatment cell. Recently, a more radical approach has been tested on a number of lab-scale and pilot-scale setups which consists of an aggressive oxidation of organic matter by means of hydrogen peroxide (H2O2). Results indicate that after treatment, clogging was substantially reduced and that H2O2 did not appear to have a long-term negative effect on plants and biofilms. The outcomes of two full-scale tests are discussed in this paper.

Key words | clogging, dairy wastewater, HSSF wetland, hydrogen peroxide (H2O2), operations and maintenance (O&M), sludge removal, VF wetland

INTRODUCTION
Subsurface-flow (SSF) treatment wetlands are used widely across the world to treat many types of wastewaters. These treatment systems are quite robust, producing high-quality effluents with low operations and maintenance requirements (as compared to other wastewater treatment technologies). One of the major problems with SSF wetland systems is the tendency for solids to accumulate in the pore spaces as a result of organic and inorganic solids entrapment, biofilm growth, chemical precipitation and deposition and swelling of soil colloids. This issue is widely documented in the literature (see, for example, Kadlec & Watson 1993; Blazejewski & Murat-Blazejewska 1997; Langergraber et al. 2003; Davison et al. 2005; Caselles-Osorio et al. 2006). A recent study by Cooper et al. (2006) reported that in a survey of 255 SSF wetlands in the United Kingdom (median system age: ten years) 52% exhibited some degree of overland flow. Another study by Hanson (2002) in New Mexico, USA, indicated that all 21 SSF wetlands in the study experienced some degree of clogging at the influent end of the cell. Since clogging in SSF wetlands occurs below the surface of the gravel bed, assessment of the degree of clogging can be difficult. Methods to quantitatively determine the extent of clogging do exist (e.g., ground penetrating radar (Cooper et al. 2006) and in-situ measurement of hydraulic conductivity (Knowles et al. 2008)), but to date, these approaches have not been implemented outside of the United Kingdom. Wallace & Knight (2006) explain that a good field indicator of inlet zone clogging in HSSF wetlands is when a drop at the effluent water level control structure produces no noticeable drop in water level at the influent part of the bed.

From a design perspective, the extent and rate of clogging is influenced by both the organic loading rate on the influent cross-section of the wetland bed and the size of
the bed media. Design modifications that can help distribute the organic load over a larger area include increased pretreatment, the use of parallel or reciprocating beds, and consideration of wetland type (VF wetlands generally offer a much larger influent cross-sectional area per unit area than HSSF wetlands).

When subsurface-flow treatment wetlands experience bed clogging, the traditional restoration procedure is to remove the clogged bed media and replace it with clean media. This method, while relatively effective, is costly to the owners of the wastewater facility and may require sections of the facility to be taken offline for extended periods of time. *Kadlec & Wallace (2008)* report the cost of this method for two HSSF wetlands in Minnesota to be 10% and 19% of the initial construction cost of the treatment system. Gravel or sand replacement also requires disposal of the excavated material, which further adds to the costs of rehabilitation.

Another restoration option (for gravel-based systems) is to remove the clogged media, wash it, and return it to the wetland bed (*Cooper et al. 2006*), although this technology is still being developed. Extreme care must be taken to ensure that the liner is not damaged during the excavation and/or gravel replacement process. The cost for disposing the dirty gravel is saved, although there still remains a cost for disposal of the extracted biosolids.

In recent years, research has also been conducted on the use of in-situ application of concentrated hydrogen peroxide (H$_2$O$_2$) to restore hydraulic conductivity to clogged gravel beds (*Hanson 2002; Behrends et al. 2006, 2007*). Concentrated H$_2$O$_2$ is a very strong oxidant, capable of oxidizing even the recalcitrant (non-biodegradable) component of biofilms, which can account for up to 60–75% of biomass, by weight (*Behrends et al. 2007*). While concentrated H$_2$O$_2$ has been used to treat contaminated groundwater in pump-and-treat applications (*Scullion 2006*), it is generally not used for *in-situ* applications because it causes irreparable damage to the soil structure (*U.S. EPA 2000*). Use of concentrated H$_2$O$_2$ for reclamation of SSF wetlands is more promising, since gravel and sand are not prone to losing their structure when subjected to *in-situ* application of a concentrated hydrogen peroxide solution. Lower doses of peroxide have been used to provide sufficient oxygen for *in-situ* degradation by indigenous microorganisms (e.g. *Menendez-Vega et al. 2007*). Careful dosage is however necessary as iron and other soil minerals can catalyze Fenton-type like reactions which result in the production of hydroxyl radicals which can damage the cell integrity (*Watts et al. 1999*).

This paper presents two case studies of hydrogen peroxide remediation of full-scale subsurface-flow treatment wetlands; a HSSF wetland in Minnesota (domestic wastewater), and a VF wetland in Belgium (dairy wastewater).

### MATERIALS AND METHODS

#### Lake Elmo, Minnesota site

The Tamarack Farms HSSF wetland is located in Lake Elmo, Minnesota (USA) and treats wastewater from a small residential development. The treatment system is owned by the neighborhood Homeowners Association, and is permitted at the local (city) level; as a result, flow measurements are estimated from pump run times to the soil infiltration field. Average daily flow at the site is approximately 8.0 m$^3$/d. The wetland was built in 2000. The wetland cell dimensions are 33.5 m (long) by 20 m (wide) by 0.6 m (deep). The wetland cell is covered by wetland vegetation (mainly *Sagittaria latifolia*, *Scirpus acutus*, and *Scirpus fluviatilis*), and 15 cm of peat mulch. The wetland cell is lined with a 30-mil PVC liner and filled with gravel ($d_{10} = 5.3$ mm; uniformity coefficient = 2.0). The wastewater from the development enters an influent manhole via one 20-cm Ø gravity-flow and two 5-mm Ø sewage force mains. Wastewater gravity flows out of the manhole into a 10-cm Ø pipe and into the 10-cm Ø influent header. There are 10-cm Ø cleanout standpipes on either side of the influent and effluent headers. Effluent is collected by a 10-cm Ø pipe and flows into an 11.4 m$^3$ concrete tank. Water is pumped from the tank to four soil infiltration cells for final disposal. Figure 1 shows a schematic of the Tamarack Farms site. Discharge limits (prior to soil infiltration) were 25 mg/L BOD$_5$ and 30 mg/L TSS. While the system was meeting these treatment requirements, ponding of untreated effluent was viewed as a potential threat to human health, so corrective action was required.
The Tamarack Farms wetland started to experience seasonal (springtime) ponding near the influent header of the wetland in 2004. In following years, the area and duration of the ponding increased, to the extent that there was a permanently flooded section in the wetland. In 2006, the site operator dug two trenches into the gravel bed (perpendicular to the influent header) in an attempt to dissipate the ponded wastewater. The two hand-dug trenches were about 30 cm in width, 30 cm deep, and about 5 meters long. This effort provided temporary relief from ponding, but by 2007, the ponding persisted, even throughout the summer months. The site operator presented the Howeowners Association with process descriptions and cost information for excavation and replacement of gravel and for the experimental procedure using H2O2. Since gravel replacement (≈ $25,000 USD) was cost-prohibitive, the owners decided to pursue the experimental H2O2 procedure (≈ $5,000 USD).

Before the H2O2 procedure could be arranged, it was necessary to obtain approval from the local permitting authority. Unforeseen challenges made it difficult to obtain support and approval for experimental procedure (e.g., staff turnover at the local (City) authority, unfamiliarity with wetland treatment technology, and resistance from the City’s designated civil/wastewater engineers). Even though the owners of the Tamarack Farms system (the Howeowners Association) fully accepted the risks associated with the procedure, it took nearly six months of meeting with various groups at the state, county, and city levels to obtain approval to move forward. It is extremely important to involve local authorities early on in the process for any remediation efforts on full-scale treatment wetland systems.

Safety

Safety was a significant concern when preparing for the Tamarack Farms H2O2 procedure. Since concentrated hydrogen peroxide (35%) is an extremely potent oxidant, great care must be exercised before, during, and after the procedure. Although the wetland system is relatively small, we decided to have two people fully suited in safety gear (see Figure 3a) on site during the chemical application; one to apply the chemical, and the other to stand by in case there were any problems with transporting or applying the chemical to the gravel bed. Safety gear included chemical-resistant full body suits with hoods, chemical-resistant boots and gloves, safety goggles, and full face shields. Boots and gloves were sealed to the body suit so that chemical could not seep in and come in contact with skin. On the day of the experiment, a safety meeting was held at the site, where...
potential risks were identified and emergency procedures reviewed. While Hanson (2002) reports adding diluted (5%) H$_2$O$_2$ to the influent header (after scouring the header with a brush to remove excess organic matter), the magnitude of the exothermic reaction between concentrated (35%) H$_2$O$_2$ and organic matter is not predictable. Besides rapid formation of gas bubbles that could pressurize the pipe, the heat associated with the reaction may melt the inside of the pipe. For these reasons, we chose not to apply any H$_2$O$_2$ directly into the influent header.

**Preparation**

The area of significant ponding at the Tamarack Farms site (along the influent header, and extending into the middle of the wetland cell, refer to Figure 2) was estimated to be 160 m$^2$. With a 45-cm gravel depth, the volume of gravel in this area is 72 m$^3$ (160 m$^2 \times 0.45$ m). Behrends et al. (2006) used 9.3 L H$_2$O$_2$ per m$^3$ of gravel in a VF wetland bed. We based our calculation on this number, plus a factor of safety of 2.5, for a total H$_2$O$_2$ volume of approximately 1,660 L (72 m$^3 \times 9.3$ L/m$^3 \times 2.5$).

As is common in small wastewater treatment systems, the Tamarack Farms wetland is not equipped with flow meters. The hydraulic residence time ($t$), as calculated from pump run times to the drainfield dosing tank, was approximately 10 days. Average flow through the system was approximately 8 m$^3$/d. Analytical monitoring of the wetland effluent was scheduled for the day of the experiment ($t = 0$), and 1.0, 1.5, and 2.0 t. Analytical results were to be reviewed as soon as the results became available. One of the stipulations from the permitting authority was that if the analytical results indicate that the system had become non-compliant with the system permit (e.g., excessive loads of BOD or TSS to the soil infiltration system), precautionary actions would be implemented. These actions were identified as pumping the drainfield dosing tank, recirculating wetland effluent back to the front of the treatment system, and/or increased analytical monitoring of the wetland effluent.

Prior to the experiment, visual inspection of the drainfield dosing tank was noted (e.g., effluent color, water level in the tank); sludge and scum buildup in the tank were minimal. About a week before the experiment, a trail was mowed from the road to the wetland site to facilitate access to and exit from the site. The vegetation in the influent section of the wetland was also mowed.

**Geel, Belgium site**

At the Hooibekhoeve, an experimental and demonstration farm of the Province of Antwerp (Belgium), a vertical-flow constructed wetland (CW) was built in 1996 to treat the domestic wastewater from the farmers’ family and the meeting room as well as the dairy wastewater generated by rinsing the milking machine and milk storage tank. The treatment plant is permitted in accordance with the Flemish Environmental Legislation (VLAREM) and has to fulfill the common effluent standards for small-scale wastewater treatment plants (being 25 mg/L BOD and at least 90% reduction; 125 mg/L COD and at least 75% reduction; 60 mg/L SS and at least 70% reduction).

The wetland was designed based on a daily load of 2,280 gCOD/day (800 g/day from domestic wastewater; 580 g/day from rinsing the milking machine; 170 g/day from rinsing the milk storage tank and 730 g/day from rinsing the dairy parlor). For treating dairy wastewater in a vertical-flow wetland, a load of 35 gCOD/m$^2$.day and a safety margin of 10% is used by the company (Rietland). In this case a wetland of 75 m$^2$ was thus constructed (5.4 × 16.3 m surface area and an internal slope of 2:1). The main body of the filter consists of three layers of sand: (top) 10 cm coarse sand; (middle) 40 cm fine sand mixed with steel slag and (bottom) 50 cm fine sand mixed
with limestone. On top and below of that main layer are two gravel (Ø 8–16 mm) layers of 10 cm each, for distributing the influent and collecting the effluent respectively. Drainage pipes (Ø 80 mm) were placed at 2 m interspace and are separated from the main filter body by a geotextile. Influent distribution pipes in the top gravel layer were put at 1 m interspace. The filter was planted with *Phragmites australis*.

Toilet wastewater flows to a septic tank; other domestic wastewater passes a degreaser and dairy wastewater passes a settling tank before are all three flows are combined in a pump well. Then twice a day approximately 1,500 liters of water is pumped on top of the wetland cell. Under normal operating conditions about half of the effluent is recycled for enhanced denitrification; the other half is either used for cleaning purposes or discharged into a nearby ditch.

A first clogging problem occurred soon after start-up because Ca(OH)₂ from the steel slag was reacting with the sand thereby forming an impenetrable layer. After 6 months of operation this layer was mechanically destroyed (implying a disturbance of the upper layers) and since then the filter has operated many years without significant problems. Later on, expanding livestock at the farm has continuously resulted in an increased wastewater load leading to a thick layer of sludge which is hindering water flow and is causing deterioration in effluent water quality. The provincial government thus decided to replace the system by a much bigger wetland which made this CW an ideal site for experimenting with H₂O₂.

Because the wetland was to be decommissioned soon, it did not take much convincing to obtain permission to carry out the experiment. A decrease in effluent quality was hardly of concern given the already very bad performance of this wetland.

**Preparation**

In the preparatory phase, the wetland was visited to estimate the extent of the problem (i.e. sludge layer thickness and sludge organic matter content). Sludge layer thicknesses at nine locations were simply measured by sticking a ruler in the sludge until hitting the solid gravel layer and were found to vary between 2 and 8 cm. Having at least 2 cm of sludge in any location clearly explains the observed ponding and the bad odors. The observed uneven distribution of the sludge layer points to uneven distribution of wastewater across the surface of the VF bed.

At the same locations, samples were collected for subsequent analysis of organic matter contents. After drying the samples at 70°C, gravel and plant parts were removed manually. Samples were then ground and sieved over 1 mm mesh to remove remaining plant fibers. The initial idea was that H₂O₂ would rather react with “simple” organic matter (from the dairy wastewater) rather than with “complex” organic matter from the plant fibers. Triplicate samples were put in Al cups, dried at 105°C, weighed, ashed for one hour at 520°C and then weighed again. Organic matter content was expressed as a percentage with reference to dry matter and varied between 10–65% (average 27%).

The required volume of peroxide was calculated as follows:

1. \( M_{\text{wet,i}} \) (kg sludge wet weight/m²) = sludge thickness (m)/density (estimated at 1,450 kg/m³)
2. \( M_{\text{dry,i}} \) (kg sludge dry weight/m²) = \( M_{\text{wet,i}} \) * 0.25 (water content estimated at 75%)
3. \( M_{\text{org,i}} \) (kg OM/m²) = \( M_{\text{dry,i}} \) * fraction_OMi (measured data)
4. \( M_{\text{org,total}} = \sum (M_{\text{org,i}} * 75/9) \) (assuming each location is representative for 1/9th of the area).

**Behrends et al. (2006)** suggest 20 to 25 mL 30% H₂O₂ per 50 g sludge (about 0.4 L 30% H₂O₂/kg VSS). In this case we used 35% H₂O₂, which translates in 118 liters of peroxide needed. It was decided to apply 100 L during the experiment in order not to “over-oxidize” the wetland, with the thought that severe oxidation could be detrimental to the plants and subsurface microbial community. Total cost was 570 Euro. The reader should be aware of the fact that organic matter accumulated in the pores (and not on top of the bed) was not taken into account during this whole calculation.

Water quality data of influent and effluent from the past years were kindly provided by PIH (Provincial Institute for Hygiene, Antwerpen). In the weeks after the experiment, regular influent and effluent samples were taken to monitor the (expected) change in water quality. Analyses were also carried out in the accredited lab of PIH.
As a means of further verification, a second set of sludge samples was collected before the experiment was initiated.

RESULTS AND DISCUSSION

Lake Elmo, Minnesota site

The H$_2$O$_2$ procedure was conducted on 26 September 2007. The chemical was ordered from Hawkins, Inc. (Minneapolis, Minnesota), and arrived on a truck at the site. The chemical company provided a submersible pump and valves, connections, and hosing to transport the H$_2$O$_2$ from the truck to the wetland. The tubing used to transport the chemical from the truck to the wetland was food-grade flexible PVC tubing (Finger Lakes Extrusion, Union Springs NY). The chemical delivery person oversaw the pump controls at the truck, while two people were in the wetland cell applying the H$_2$O$_2$.

The H$_2$O$_2$ was injected into the gravel bed using a tree jettter (Figure 3a). The tree jettter was inserted into the gravel, and a queue (verbal and visual) was given to the chemical delivery person to start or stop the chemical pump. The rate of chemical pumping varied between 4 and 8 L/min, depending on the location, degree of clogging, and water level in the gravel bed. The reaction between the wetland bed and the H$_2$O$_2$ was extremely exothermic. Steam was produced during H$_2$O$_2$ injection, and the wetland surface bubbled (Figure 3a,b). Injection of hydrogen peroxide into the ponded area resulted in a foamy residue that migrated in the downstream direction.

The steam clouds produced from the reaction had a distinct odor, which was extremely pungent at the site of the chemical injection. Approximately 1,660 L of 35% hydrogen peroxide was applied in 40-L increments directly into the gravel media along the inlet header.

Prior to H$_2$O$_2$ application, there was about 60 cm of standing water in the influent header cleanout (refer to Figure 1). The standing water in the cleanout subsided immediately upon application of peroxide to the gravel surrounding the influent header. The sewer manhole just upstream of the wetland cell had experienced standing water (~1 m depth) for many months. In only two hours after the H$_2$O$_2$ application, the standing water in the manhole also subsided, and remained low, even during pumping events from upstream sewer lines.

The amount of analytical data for the Tamarack Farms is somewhat limited. Since the wetland system is permitted at the local level (as opposed to the state level), monitoring requirements for onsite wastewater treatment systems vary by local jurisdiction. For the Tamarack Farms site, water quality samples are only required for the wetland effluent, twice yearly. As a result, the local authority requested follow-up sampling that could provide direct comparison of treatment performance before and after the H$_2$O$_2$ application. In this fashion, the follow-up sampling mirrors the requirements of the operating permit.

Analytical results before and after the H$_2$O$_2$ application are presented in Table 1. The sample obtained on September 26 was collected approximately six hours after the first injections of H$_2$O$_2$ into the gravel bed, and is thus
categorized as being “after” H2O2 application. We speculate that the observed change in nitrogen speciation was due to liberation of organic nitrogen that had been previously bound up in interstitial biomass, which was disrupted during the application.

The system operator noted that during the October 10 and October 18 sampling events, the effluent had a slight brown-orange color, which was in contrast to the crystal-clear effluent that was sampled on the day of the experiment. The discoloration was likely a result of oxidized material passing through the wetland system. We speculate that the increase in effluent TSS concentration is likely a result of the liberation of particulate biomass, not only through chemical oxidation, but also due to the physical processes from heat and bubbling that occurred during the H2O2 application.

Treatment performance does not appear to have been significantly compromised in the months following the experiment. Field observations from the system operator indicate that at the time of this writing, standing water in the wetland cell and influent structures has not returned. The total cost for the Tamarack Farms hydrogen peroxide application was $4,600 USD, which included the chemical (and delivery to the site), safety equipment, labor (two hours of the delivery man’s time plus about 8 hours of field work at $75/hr), and follow-up sampling. Efforts that fell outside of this scope (e.g., proposal writing, corresponding and meeting with local authorities and site owners) took considerable effort (upwards of 50 hours).

### Geel, Belgium site

The experiment took place on 30 January 2008 after feeding had been stopped for a day or two. Because of warnings for strongly exothermic reactions, the peroxide was at first

| Table 1 | Wetland effluent analytical results before and after the H2O2 application at the Tamarack Farms HSSF wetland in Lake Elmo, Minnesota |
|-----------------------------------------------|
| Parameter | Before H2O2 application | After H2O2 application |
|-----------------------------------------------|
| CBOD (mg/L) | 3 | 4.4 | < 4 | 11.6 | 4.2 | 4.5 | 5.7 | 9.1 | 2.2 |
| NH4-N (mg/L as N) | 17.1 | 19.6 | < 0.1 | 0.18 | 0.17 | 23.6 | 25.4 | 26.6 | 17.0 |
| NO3 + NO2 (mg/L as N) | 4.45 | 6.59 | 3.04 | 1 | 2 | 1.3 | 0.1 | 0.42 | 2.41 |
| TN (mg/L as N) | 19.8 | 24.0 | 17.3 | 31.8 | 27.4 | 28 | 29.6 | 29.6 | 23.2 |
| TKN (mg/L as N) | 15.3 | 17.4 | 14.3 | 30.8 | 25.4 | 26.7 | 29.6 | 29.2 | 20.8 |
| pH (SU) | NS | NS | 7.2 | 7.2 | 7.6 | NS | NS | NS | NS |
| TSS (mg/L) | < 1 | 13 | 2.4 | 13 | 28 | 5.6 | 8 | 6 | 2.6 |

*Quarterly monitoring as required by operating permit.
NS = Not Sampled.

| Table 2 | Effluent quality data for different periods (average ± standard deviation) |
|-----------------------------------------------|
| Parameter | Normal operation (N = 33) | Overloaded/Clogged (N = 10) | After peroxide dosing (N = 7) |
|-----------------------------------------------|
| CBOD (mg/L) | 4.7 ± 4.1 | 864.5 ± 817.3 | 395.0 ± 598.6 |
| COD (mg/L) | 40.7 ± 27.6 | 1242.5 ± 1002.4 | 680.0 ± 820.6 |
| TSS (mg/L) | 5.9 ± 11.0 | 105.5 ± 88.7 | 159.1 ± 167.7 |
| NH4 (mg/L as N) | 1.0 ± 1.8 | 61.6 ± 38.5 | 63.9 ± 6.8 |
| NO3 (mg/L as N) | 42.0 ± 16.5 | 0.6 ± 0.0 | 0.6 ± 0.0 |
| TN (mg/L as N) | 45.4 ± 15.8 | 80.0 ± 52.6 | 80.3 ± 17.3 |
| TP (mg/L as P) | 18.2 ± 4.1 | 20.3 ± 20.0 | 12.5 ± 15.1 |
| pH (SU) | 7.1 ± 0.2 | 7.0 ± 0.6 | 7.0 ± 0.4 |
strongly diluted with tap water before being applied onto the bed surface. Since the scale of the wetland was quite small, manual application of the peroxide was done by means of a simple garden sprinkling can. In a later stage, because the reaction of the sludge with the peroxide seemed not too violent, pure 35% peroxide was applied onto the surface, which again did not result in overly strong reactions. Obviously normal safety precautions were taken: gloves, fully covering clothes, and safety goggles and with a garden hose as a makeshift emergency shower. As observed at the Minnesota site, peroxide application resulted in steam production and bubbling as a result of the strongly exothermic reactions.

**Sludge reduction**

After surface application of 100 L of 35% peroxide, only a slight decrease in sludge layer thickness was observed, in the order of 1–2 cm, leaving plenty of sludge still on the wetland surface. This indicated that the amount of peroxide dosed was too low. As a consequence, water was still ponding on the surface after the experiment. Given in addition the fact that the wetland had subsided under its own weight in the course of time, a lot of influent spilled over the wetland boundaries.

**Water quality data**

Data of the effluent quality are summarized in Table 2. “Normal operation” are data from June 2002 until the overloading of the system in December 2005, “Overloaded/ clogged” are data from March 2006 until March 2007 and “After peroxide dosing” are data taken in the four weeks after the experiment. In general there is neither clear improvement nor decrease of the effluent quality after application of the H$_2$O$_2$.

**Post-experiment verification**

Because of the clear underestimation of the required peroxide dose, further experiments were done with a second set of sludge samples collected just before the experiment took place. The procedure was similar as for the first experiment, be it that this time only intact large plant parts such as stems and leaves were removed. This obviously resulted in higher organic matter contents of 51.9 ± 21.3% as compared to the first analysis of 27.4 ± 18.3% organic material on average.

Jar tests were then conducted to assess the degradability of the sludge by peroxide. An aliquot of wet sludge (2–10 g) was mixed with 10 mL 30% H$_2$O$_2$. Results showed that on average 4.57 ± 1.91 g organic material was oxidized, or in other words 2.2 L 30% H$_2$O$_2$/kg VSS would be required as compared to the 0.4 L 50% H$_2$O$_2$/kg VSS as suggested by the laboratory-scale experiments reported by Behrends et al. (2006). It became clear that the plant detritus was also strongly affected so certainly for VF constructed wetlands it is recommendable to remove as much plants and plant detritus as possible before the peroxide application.

**CONCLUSIONS**

Hydrogen peroxide remediation appears to be a promising method to remediate clogging in subsurface-flow treatment wetlands. This paper presented two case studies of H$_2$O$_2$ remediation of SSF wetland systems. The Minnesota case study was approached from the standpoint of a consulting engineer, where a factor-of-safety was applied to the calculated H$_2$O$_2$ requirement, to ensure a high level of oxidation and bubbling in the clogged area of the bed. While the Minnesota case study was successful, it is possible that a similar result could have been obtained by using a smaller amount of H$_2$O$_2$. The Belgium case study was approached in a more academic way, performing jar tests first to determine H$_2$O$_2$ requirements. The findings of the Belgium study accentuate the importance of accounting for the potential oxidation of aboveground plant biomass when determining the amount of H$_2$O$_2$ to use, as the peroxide will preferentially oxidize whatever material it first contacts. Future research in this area should focus on optimizing the amount of H$_2$O$_2$ dose required for effective treatment of clogged subsurface-flow wetlands.

While every case will require special points of attention, it is crucial to gain public approval and appropriate permits for any full-scale remediation of this kind. Safety is also a crucial consideration when dealing with large volumes of
concentrated H$_2$O$_2$. Mowing or removing tall vegetation in the ponded area of the wetland is recommended, for safety and accessibility reasons.

It is extremely important to assess and document the extent of clogging in the wetland bed (for VF wetlands, how thick is the sludge layer, and what is the organic matter content; for HSSF wetlands, what is the aerial and volumetric extent of clogged bed media). Laboratory jar experiments with sludge and/or clogged gravel can be used to calculate the amount of peroxide required for remediation at a specific site. For VF wetland systems where the H$_2$O$_2$ is surface-applied, plant detritus should not be removed from jar test samples, as the organic content of the plants adds to the overall organic content of the sludge layer.

Prior to H$_2$O$_2$ application, arrangements should be made so that any disruption in treatment performance can be quickly identified (e.g., extra analytical monitoring) and addressed (e.g., storage of dirty effluent, or a recycle loop back to the wetland influent for further treatment). Post-experiment monitoring should include water quality monitoring and visual inspections of the wetland bed. For extensive clogging problems, follow-up application of H$_2$O$_2$ may be required.

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