Chapter 13
Clogging Measurement, Dissolved Oxygen and Temperature Control in a Wetland Through the Development of an Autonomous Reed Bed Installation (ARBI)

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Abstract The suitability of different magnetic resonance sensor types, based on magnet arrangement, for the detection of different solids loadings in wetland sludges were explored. Unilateral and borehole design sensors were investigated. A development of the Helmholtz-style borehole design was selected due to its simplicity of design, low cost and large field of detection. The effect of aerating and heating a pilot wetland on organic matter and NH_4-N reduction was investigated. Aeration improved performance across a range of oxygen concentrations down to 0.5 ppm below which little benefit was seen. No significant improvement was seen with heating between control and experimental bed. This is thought to be due to seasonal effects raising the temperature of the control to within 10 °C of the experimental bed, a difference thought not to be significant at the measured temperature range, (15–25 °C). Temperature driven hydrolysis of embedded organics may also be causing increased soluble COD outlet loads. We have demonstrated a Helmholtz like NMR sensor can detect differences in solids loading when buried in a gravel mix. Aeration can significantly increase treatment performances by 56 % and 69 % for COD and NH_4-N reduction respectively at an oxygen tension of 5 ppm.

Keywords Aerated wetland • Clogging • Feedback • Sensor • Magnetic resonance • Temperature

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13.1 Introduction

13.1.1 General

The use of wetland waste water treatment systems is increasing as the demand for robust, low maintenance, sustainable technologies rises across both the municipal and industrial sectors. Concomitant end-user driven developments in the design and operation of the technology have been directed at key factors associated with performance and longevity including oxygen transfer rates and clogging.

Significant performance improvement has been seen with the introduction of direct aeration such as Forced Bed Aeration™, (Oullet-Plamondon et al. 2006; Nivala et al. 2007, 2013) though the addition of feedback control systems also linked to similar temperature control systems would help to optimise performance and minimise power consumption.

The relationship between areal organic load and clogging rates is becoming better understood (Nivala et al. 2013) and the use of different effluent delivery point aspects, horizontal/vertical, width/length and varying these with time is being explored generally. The ability to monitor clogging *in situ* would improve our understanding of the relationship between clogging and performance and enable improved prediction and control of the clogging process. This would allow operators to maximise the efficiency of their systems as well as budget for and control refurbishment cycles.

A consortium of research institutes and SMEs are involved in a 2 year study to develop and trial a modular wetland system ARBI (Autonomous Reed Bed Installation) capable of measuring and monitoring clogging factors, and controlling environmental conditions including, aeration, temperature and effluent delivery point.

The objective of the project is to construct and design a working wetland treatment system which offers treatment performance based feedback control of aeration and heating systems and a prototype magnetic resonance (MR) sensor which can detect differences in levels of clogging and generate a control signal to be interpreted by the heating and aeration systems.

Water quality monitoring sensors and MR clogging sensors will monitor the reed bed and adjust parameters including temperature, aeration and effluent delivery point to optimise treatment and minimise clogging. The development of algorithms to 'program' the operation of the clogging control system will be an important area of future work but is outside of this project scope. The modular nature of ARBI will allow easy extension of treatment capability and replacement of clogged sections as well as providing a vehicle to take the system to market.

13.1.2 MR Probes for Clogging

Magnetic resonance (MR) is a non-invasive technique best known for its application in medical imaging (Johnston et al. 2006). MR can be used to measure the properties of non-medical samples using a fixed magnetic field and radio frequency (RF) coil which transmits a sequence of high power pulses and collects a signal from the sample. This technique can be applied in a variety of ways, however this work focusses on MR relaxation measurements. The relaxation measurements probe the decay of the energy transferred to the sample which can provide information about the sample and its environment. One of the most basic sequences for obtaining a relaxation value (in our case T_2^{eff}) is a CPMG sequence (Meiboom and Gill 1958), which was employed in this work. Another relaxation parameter, T_1, can be recorded using a series of CPMG measurements as described elsewhere (Morris et al. 2011).

It has been demonstrated in a laboratory environment that the MR relaxation times, T_1 and T_2^{eff}, are sensitive to the levels of clogging in a water sample (Morris et al. 2011; Shamim et al. 2013). There is potential that, using MR probes, the relative proportions of free water, suspended solids, biofilms and plant matter can be detected in wetlands.

MR sensors can be produced in a near infinite number of designs depending on the arrangement of the magnets and therefore can be used to create magnetic fields of different strengths and orientations (between about 0.2 and 0.5 Tesla in this work). The magnets also required a tuned RF circuit that resonates at a frequency corresponding to the field strength of the magnet. The initial MR sensor work undertaken for ARBI, as outlined below, explored the suitability of different MR sensors for the application of being embedded into wetlands to monitor clog levels.

Multiple magnet configurations have been investigated for the MR probe. These have included an Earth's field NMR (EFNMR) system (Packard and Varian 1954) which uses the Earth's magnetic field instead of a permanent magnet, a four-magnet surface sensor (similar to a sensor using the stray field from a Halbach array (Chang et al. 2006), a Helmholtz-style permanent magnet arrangement (Morris et al. 2011), and a simple bar magnet design (Blümich et al. 2002). The use of the designs discussed above have either previously been disseminated in the literature or are about to be published in regards to their applications in reed beds (Morris et al. 2011; Hill-Casey et al. 2014; Hughes-Riley et al. 2014a, b, c, d, 2016). This work will briefly overview this enterprise.

13.1.3 Heating, Aeration and Step Feeding

The aeration of reed bed treatment systems to enhance performance has been studied widely as have the effects of temperature. Active heating to enhance performance has not received so much attention but the effects of both on clogging may be multifaceted and complex.

Aeration fuels aerobic microbial activity and biomass production potentially enhancing clogging but the physical action of aeration bubbles may scour solids/biofilms from media thus reducing clogging. Similarly, rising temperatures may enhance temperature sensitive microbial activity, creating biomass and increasing clogging, but may also enhance the hydrolysis of organic matter converting it from solid matter to soluble matter (García et al. 2010) effectively de-clogging systems.

Changing the point at which effluent is applied to a wetland treatment system should help in spreading the development of biomass across the whole of the system rather than just at the dosing point. We would expect this therefore to increase heterogeneity in terms of hydraulic conductivity through a wetland system reducing the tendency for effluent short circuiting. This could maximise the use of the whole bed for longer periods effectively extending its performance life.

The work outlined below was undertaken by the GEMMA-Group of Environmental Engineering and Microbiology, Universitat Politècnica de Catalunya-BarcelonaTech (UPC) and provides an initial investigation on the impact of aeration, heating and, to a limited extent, step feeding on treatment wetland performance.

13.2 Methods

13.2.1 Development of MR Sensor for Clog State Measurements

Details of the construction and design of the sensors have been discussed in full detail elsewhere (Hill-Casey et al. 2014; Hughes-Riley et al. 2014a, b, c, d, 2016), but for completeness a diagram showing the basic design of each sensor has been included below (Fig. 13.1). It can be seen that there are two principle configurations. A bore-hole design where reed bed material has to fill the inside of the sensor (the Helmholtz probe) whilst the other two are unilateral, or single-sided, devices which probe a volume some distance above the sensor surface (the four-magnet surface sensor, the bar-magnet sensor).

The data presented in this work was performed using three of the Helmholtz-style sensors (Fig. 13.1c). Each was built using two N42 neodymium magnets (diameter = 35 mm, height = 20 mm; HKCM Gmbh, Eckernfoerde, Germany), capped with steel disks, and separated by 20 mm to give central magnetic field strengths with corresponding proton resonant frequencies at 11.6 MHz, 11.4 MHz and 11.9 MHz. A parallel-series tuning board (using two 5.5–50 pF variable capacitors; Johanson Manufacturing, Boonton, USA) was attached to an enamelled wire solenoid (Rowan Cable Products Ltd., Potters Bar, UK) via an inductive tuning element to complete a resonant circuit for the transmission and receiving of RF signals.

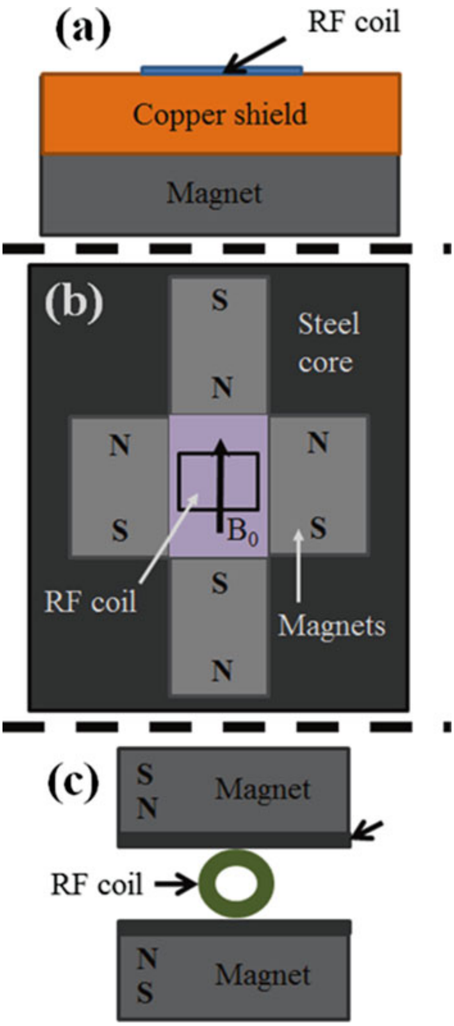

Fig. 13.1 Schematics, (not to scale) of the sensors explored in this work. (**a**) A simple bar magnet sensor: A pair of 75 mm diameter neodymium magnets was combined to provide the magnetic field. The coil is placed atop the magnet. A copper shield is used to minimize external RF interference. (**b**) Four-magnet surface sensor: Neodymium magnets are arranged as shown to produce a uniform field across the surface of the magnet gap. The RF coil was placed in this gap. Steel was used as a base to the magnet arrangement to improve the magnetic field homogeneity. (**c**) Helmholtz sensor: Two magnets are separated by a gap generating a uniform magnetic field where an RF coil is placed

Magnetic resonance experiments were conducted using a CPMG sequence where 128 echoes (echo time = 150 μs) were summed to provide a signal intensity for each repetition time explored. Different repetition times between 25 ms and 15 s were used and were plotted against the signal intensity. This was monoexponentially fit using IGOR Pro (Wavematrics, OR, USA) allowing for the relaxation time T_1 to be extracted. All experiments were carried out using a Kea^2 spectrometer (Magritek, Wellington, New Zealand).

The three MR probes were embedded into wetlands maintained by ARM Ltd (Rugeley, UK). Probes were embedded at locations that were believed to have different levels of clogging.

Table 13.1 Technical specifications of the experimental pilot plant at UPC

Parameter	Value
Dimensions (W × L × H)	55.2 cm × 70.5 cm × 35 cm
Water level	30 cm
Surface	0.39 m^2
Loading rate (design)	63 l/d
Hydraulic retention time	0.8 d
Organic loading rate	60 g COD/m^2•d
Ammonium loading rate	5 g NH_4^+-N/m^2•d

13.2.2 Effects of Aeration and Heating on Treatment Wetland Performance

Aeration and heating experiments were carried out in a pilot scale reed beds consisting of two horizontal subsurface flows constructed wetlands with the specifications outlined in Table 13.1.

One of the beds (the experimental wetland) was used to investigate aeration, heating and step feeding, the other wetland (control wetland) operated under normal saturated conditions.

13.2.3 Aeration

To test aeration effects the experimental wetland was equipped with an aeration system consisting of a pierced resin pipe of approximately 50 cm rolled at the bottom of the wetland at its central zone. The aeration roll occupied a surface of 0.07 m^2, which was about 20 % of the total bed surface. Air was injected by means of an air pump at a flow rate of 720 l/h. Dissolved oxygen within the aerated and non-aerated bed were continuously monitored by means of a dissolved oxygen probe (CS512 Oxyguard Type III, Campbell Scientific Inc., USA) connected to a data logger (CR1000, Campbell Scientific Inc., USA).

At the beginning of the experiment air was continuously injected (24 h/d), reaching oxygen concentrations within the bulk liquid of approximately 5 mg/L. After 9 days the oxygen concentration within the bed was set at 3 mg/L by means of a control program in the data logger (control Deadbond version 2.5).

The oxygen concentration within the bed was successively reduced to 1.5, 0.5 and 0.2 mg O_2/L in order to test the treatment performances at different aeration rates. Each configuration was tested for 2 weeks and power consumption for each set point calculated. Water samples were collected twice a week from the inlet and from the outlet of the two beds and immediately analysed for Chemical Oxygen Demand (COD) and ammonium according to the *Standard Methods for Wastewater*

Treatment, (APHA-AWWA-WPCF 2001 APHA-AWWA-WPCF Standard Methods for the Examination of Water and Wastewater (twentieth ed.) American Public Health Association, Washington DC (2001).

13.2.4 Heating

The experimental wetland was heated by means of a heat pipe embedded in the aeration system, set at 21 °C. Temperature was monitored by means of a temperature probe (Model 107, Campbell Scientific Inc., USA) located within both reed beds. Water samples were collected twice a week from the inlet and outlet of the two beds and analysed for Chemical Oxygen Demand (COD) and ammonium according to the *Standard Methods for Wastewater Treatment.*

13.2.5 Step Feeding

The feeding position was moved from the inlet front (feeding position 1) to the middle part of the bed (feeding position 2). Water samples were collected twice a week from the inlet and outlet of the two beds. During part of this period heating and aeration were run simultaneously in the experimental bed. Aeration was controlled to hold an oxygen tension of 0.5 mg/l determined from optimisation in the earlier aeration studies. The temperature in the experimental and control beds were 25 °C and 15–20 °C respectively.

13.3 Results

13.3.1 Magnetic Resonance Sensors

As outlined earlier, various MR sensors have been developed for use with the ARBI unit. An intention of the project was to select the most successful design after a trial period and bring this forward for implementation into an active reed bed.

13.3.2 Unilateral Surface Sensors

Unilateral surface sensors have one main advantage over a bore-hole design sensor which is that they cannot become completely clogged with material (such as a reed rhizomes) making the sensor inoperable as might happen with an enclosed design. Unfortunately, these sensors are only capable of interrogating a small region above the coil surface. This becomes increasingly problematic when the sensor is waterproofed as this process will remove part of the already small sensitive region.

A simple bar-magnet design (Blümich et al. 2002) was investigated as this was the most simple magnet arrangement available for a sensor design. Unfortunately, while providing a strong signal, an extremely short T_2^{eff} (309 ± 60 μs on a thin wetland sample) led to a T_1 insensitivity to the clog state. This study was covered in more detail elsewhere (Hughes-Riley et al. 2014c).

The four-magnet surface sensor proved more promising. A sensor of this configuration showed differences in the T_2^{eff} as well as T_1 sensitivity (Hughes-Riley et al. 2014b, c).

13.3.3 Helmholtz-Style Permanent Magnet Arrangement

The Helmholtz-style permanent magnet arrangement was the first design used for this application (Morris et al. 2011). For ARBI two variations on this design have been explored. A small unit (using 35 mm diameter magnets) similar to Morris et al.'s earlier design and a larger unit (using 75 mm diameter magnets), allowing for a larger sample volume to be explored. The later design was able to collect signal however the signal intensity was inferior to that of the smaller unit. Additionally, under normal laboratory conditions (~20 °C) the entire region within the solenoid of the larger sensor was not able to collect MR data. Given the favourable signal intensity of the smaller Helmholtz-style sensor further effort has been expended to ascertain the viability of the design for long term deployment into a wetland. One important area that has been explored was how temperature variations effected the probes operation. This was an important factor as magnetic field strength is known to change with temperature significantly (Clegg et al. 1991) and large temperature changes may have significantly affected the signal strength acquired from the sensor. Preliminary work showed a major reduction in the signal intensity collected by the probe as it became warmer or cooler than standard laboratory temperature (Hughes-Riley et al. 2014a). Later work, with a slightly improved sensor, has shown a far less extreme effect, with the signal intensity only reducing by a factor of two at the extremes of the temperature range that the probe would likely encounter while in a wetland in Europe Hughes-Riley et al. (2016).

A water-tightened sensor of this design has been used to collect T_1 measurements in a test wetland (Hughes-Riley et al. 2014d). Further to this, probes have been embedded into operational wetlands as part of a study into how the probes operate with seasonal variation and how the deviation in environmental factors over many months affect the T_1 values recorded from the probes, as well as the probes general operability. Figure 13.2 shows T_1 values collected from three operational probes after they had been embedded for 62 days.

Figure 13.2 shows a very clear distinction between clog levels where Probe A recorded a long T_1 time, Probe B a shorter T_1 time, and Probe C collected a short T_1

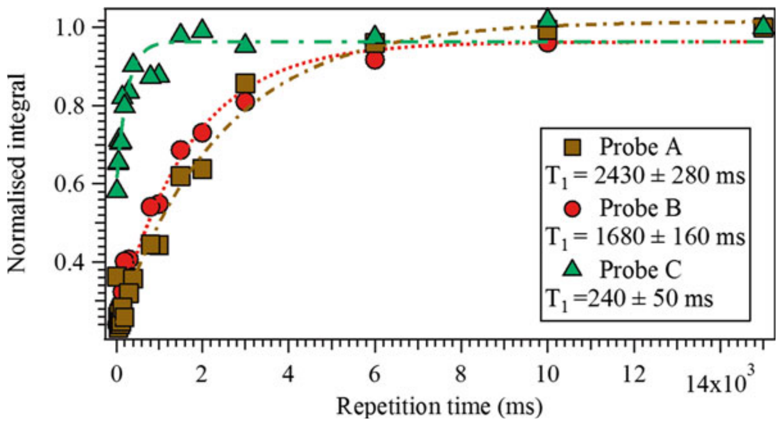

Fig. 13.2 T_1 measurements taken using Helmholtz-style MR sensors embedded into operational constructed wetlands. Each shows a very different clog level, with the short T_1 time recorded by Probe C representing a greater clogging than the long T_1 time recorded using Probe A

time; where a short T_1 corresponds to a greater level of clogging (Morris et al. 2011). Ultimately, it would be desirable to correlate T_1 times to the hydraulic conductivity within wetland samples, and this will be the focus of future work.

Long term monitoring of the embedded probes is on-going with preliminary results showing little change in the T_1 values over time. This would be expected for these already well-established beds where a change in clog level should only occur over a very long time scale.

The Helmholtz design was the simplest of all the MR sensor designs explored, it was the least expensive and had the largest sensitive volume of all the permanent magnet geometries considered. As a result, this made it the primary contender for use in the final ARBI unit.

13.3.4 Aerated System

The organic matter removal significantly increased in the aerated bed ($p < 0.05$). The COD inlet concentrations of about 400–300 mgO_2/L decreased to 160–140 mgO_2/L in the control bed, whereas lower values (about 70 mg O_2/L) were reached in the aerated bed, however the COD concentration in the outlet of the two beds were similar when the aeration set point was 0.2 ppm, shown in Fig. 13.3. The percentage increase in COD removal seen across the set point oxygen concentrations of 5, 3, 1.5, 0.5 and 0.2 mgO_2/L was 56 %, 46 %, 40 %, 35 %, and 3 % respectively.

Differences between systems with and without aeration were more evident when looking at ammonium nitrogen (NH_4+−N) (Fig. 13.4). Ammonium nitrogen concentrations in the inlet ranged between 14 and 32 mgNH_4+−N/L due to variation in the wastewater quality. The concentrations in the outlet were generally higher in the

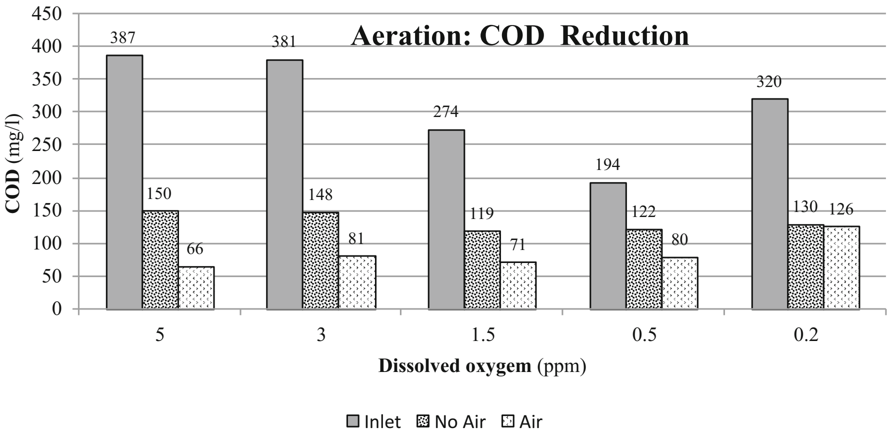

Fig. 13.3 COD concentration in the aerated and control beds at five different set point oxygen concentration levels

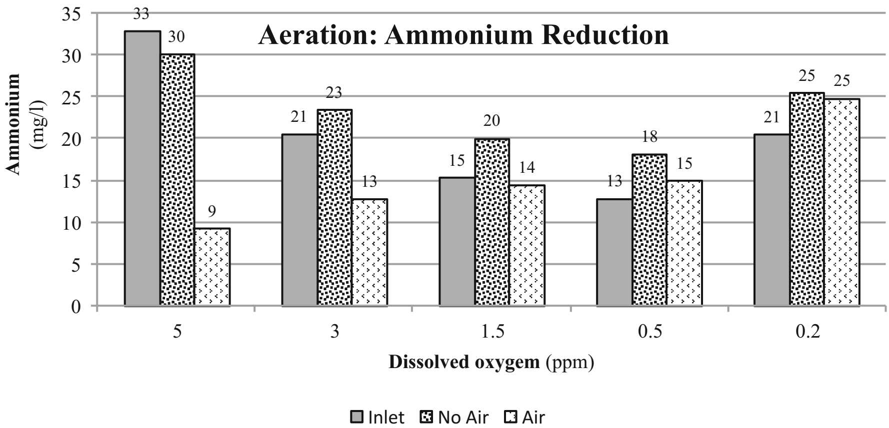

Fig. 13.4 Ammonium concentration in the aerated and control beds at five different set point oxygen concentration levels

control (18–29 mg NH4+−N/L) than in the experimental beds (9–24 mgNH_4+−N/L) and on a percentage basis, aeration increased ammonium removal by 69 %, 45 %, 28 %, 18 % and 2 % for the 5, 3, 1.5, 0.5 and 0.2 mgO_2/L set points respectively. As for COD, the difference between the aerated and the non-aerated bed was visible down to 0.5 ppm, whilst no differences (2 %) were observed at 0.2 ppm mgO_2/L.

The optimal aeration rate, balancing performance effect and power consumption is 0.5 mgO_2/L, which provides a 35 % and 18 % increase in COD and NH_4+−N removal respectively at a power consumption rate of 0.2 kWhr/m^3 water treated.

13.3.5 Heated System

Chemical Oxygen Demand (COD) concentrations ranging between 350 and 520 mgO_2/l in the inlet decreased to 150–180 mgO_2/l in both beds with the application of heating to the bed. The similar performance indicates that the difference in temperature between the two beds is not great enough to affect microbial degradation significantly at this particular temperature range.

Even if differences were not significant it was observed that initially (during the first week) that the COD removal was slightly higher in the control. This may be attributed to the hydrolysis of the embedded organic matter present within the granular media (García et al. 2010) which occurred to a greater extent in the higher temperature bed, effectively increasing the soluble COD load in the effluent indicating a decrease in the performance of the wetland. During the following week the tendency was changing and slightly better COD removal was observed within the experimental bed. This temperature based hydrolysis could have a positive effect through reduction of solids and hence de-clogging: as the clogging phenomenon is mostly attributed to the organic matter retention within the granular media.

13.3.6 Step Feeding

The impact of different feeding positions or changing the position of the influent flow can only realistically be seen with long term comparisons; thus no significant differences in COD removal were detected between the outlet concentrations of the two beds when the feeding position was changed. Moreover, no significant differences ($p>0.05$) of COD removal were detected between the two feeding positions. Similarly with respect to ammonium nitrogen (NH_4+-N), no significant differences ($p>0.05$) were detected between beds nor between feeding positions.

The COD reduction results obtained whilst both heating and aeration were operated simultaneously indicated a good overall reduction but little difference in performance against the control this is likely to be due to the relatively low aeration level (0.5 mgO_2/L) and also suggests, when compared to the previous aeration results, that the impact of aeration on aerobic microbial degradation is greater at lower temperatures.

13.4 Conclusions

We have demonstrated in this work that a Helmholtz-like sensor with a comparably large sensitive volume can be used to monitor T_1 when buried in operational, established wetlands. Furthermore we have again demonstrated the sensitivity of this parameter to clogging. The large sensitive volume makes it most representative of the bed health on the whole which is highly desirable.

Aeration can significantly increase treatment performance, by 69 % for ammonia reduction and 56 % for COD reduction based on a dissolved oxygen level of 5 ppm. A balance of performance and electric consumption indicated the oxygen set point at 0.5 ppm as the best configuration. This configuration increased COD and ammonium removal by 35 % and 18 % respectively. The positive effects on treatment performance seen with aeration may be better in colder climates through offsetting of low temperature effects. Considering that the control already achieves the regulation thresholds, results suggest that wetland surface could be reduced by 18 % without affecting performances. Heating did not show a significant effect on COD and ammonium removal but this could be due to the already high temperature in the control bed (10–15 °C) which will be confirmed with further work in a cooler climate. However, the hydrolysis of organic matter caused by heating suggests that it could be applied to delay or reduce the level of particulate organic matter in the medium and, consequently, reduce the clogging phenomenon.

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