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ADVANCES IN AUTOMATED REED BED INSTALLATIONS

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Abstract
Constructed wetlands are a popular form of waste-water treatment that have proliferated across Europe and the rest of the world in recent years as an environmentally conscious alternative to chemical treatments. The ability to monitor the conditions in the bed and control input factors such as heating and aeration may extend the lifetime of the reed bed substantially beyond the ten year lifetime normally reached. The Autonomous Reed Bed Installation (ARBI) project is an EU FP7 initiative to develop such a bed. One critical parameter to observe is the clog state of the reed bed, as this can severely impact on the efficiency of water treatment. Magnetic resonance (MR) sensors can be a powerful tool in determining clogging levels (*Analyst 2011*, **136**, 2283-2286) and allow automated remedial action to be taken against the bed improving treatment efficiency, prolonging the life of the bed and avoiding the need to refurbish the bed, which is both time consuming and costly. This work details magnetic sensors suitable for long-term embedding into a constructed wetland.

Keywords: constructed wetlands, waste water, magnetic resonance, clogging, sensor, monitoring

1. INTRODUCTION

Constructed wetlands are an environmentally considerate means of water treatment, suitable for supplementing or replacing more environmentally invasive methods such as chemical treatment. As such these systems have gained popularity and have proliferated across the globe. The basic design is uncomplicated. A gravel matrix is used to create a porous structure for reeds to grow in. The reed root and rhizome network provides a substrate where microorganisms can live. Under optimal conditions these microorganisms remove approximately 90 % of pollutants from waste water, with the remaining pollutants being dealt with directly by the plants.

Effluent is then trickled through the reed bed and will come out the other side with a number of undesirable components removed, including ammonia and phosphorus (Fig. 1). Effluent is not exclusively domestic sewage, reed beds have also been employed to filter and purify water for wastewater in mines as well as landfill leachate and air strip run-off (Adeola *et al.* 2009; Cooper, 2007).

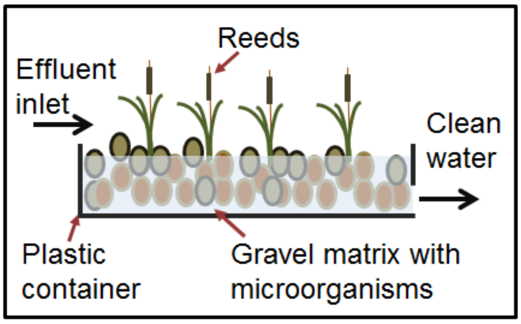

Fig. 1. Basic schematic of a sub-surface reed bed. A gravel matrix has reeds planted in it and effluent is flown through. A combination of the reeds and microorganisms remove unfavourable material from the effluent, resulting in clean water.

Once operational a reed bed ideally should require little maintenance. After effluent flow has begun, the simplest design can allow for a wetland to operate with no external interference for many years. A limiting factor is that over time the pores in the gravel matrix become clogged with microorganisms and particulate matter, severely reducing the reed beds efficiency to treat water, and ultimately rendering it inoperable. The process of reconditioning the bed after such a time (typically around ten years) involves removing the bed material (gravel) and either replacing or washing it. This is both time consuming and costly. Of course, this can only be acted upon in a timely and efficient manner if the internally clogging conditions of the reed bed can be monitored and understood. Work presented here will look at monitoring clogging levels in reed beds.

In a laboratory environment it has been shown that the magnetic resonance (MR) relaxation parameters T_1 and T_2^{eff} are sensitive to the level of clogging on extracted wetland samples (Morris *et al.* 2011; Hughes-Riley *et al.* 2014a under review; Hughes-Riley *et al.* 2014b). This was possible with a relatively cheap (~£150) Helmholtz configuration permanent magnet assembly.

MR utilises nuclear spin which is an intrinsic quantum property. Spins align in a magnetic field and are excited with a radio frequency coil, this both moves the spins into a plane perpendicular to the magnetic field, and results in the spins precessing. Precession of the spins within the coil induces a current; this is the signal that is collected (Rabi *et al.* 1938; Bloch, 1946). Diverse manipulation of spins allows for the collection of different information about a substance.

Relaxation deals with excited spins returning to a thermal equilibrium state; T_1 (spin-lattice) relaxation deals with spins returning to the same orientation as the magnetic field, and T_2 (spin-spin) relaxation regards precessing spins falling out of phase with one-another. T_2^{eff}, discussed in this work, regards spin dephasing where various factors are responsible, not just spin-spin interactions.

As well as determining clog state MR can be used to analyse components of clogging and therefore better understand the problems being experienced in the reed bed (Bencsik *et al.* 2013). MR sensors used in these studies are designed to detect ^1H and therefore most MR measurements taken on wetland sludge will be on the water component. However the MR relaxation behaviour of water will be different depending on other factors, such as the water containing particulate matter.

For example, pure water is unrestricted to diffuse within the gradient of the magnetic field; dephasing of the proton spins as a result of this motion reduces signal intensity. Restricted water, such as water with particulate matter in it, cannot diffuse as freely meaning that the spins do not dephase as rapidly (Carr&Purcell, 1954). This will change the relaxation rate of the water.

A similar situation is true for biofilms. Water that is part of biofilm material will also experience relaxation at a very different rate to free-water. When both, or multiple conditions, are present the resultant relaxation data will contain a combination of components. This can have a multi-exponential fitting applied. The weighting of each exponential can provide an indicator of the quantity of spins in different states. Fig. 2 shows a mock T_2^{eff} curve illustrating how separate exponential data can be extracted.

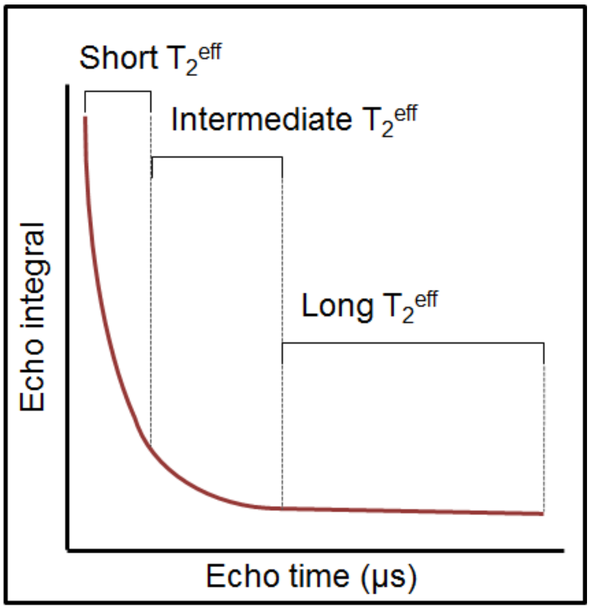

Fig. 2. Mock T_2^{eff} curve. Three different exponential components can be extracted. The short T_2^{eff} component would likely represent ^1H in the biofilm, the intermediate T_2^{eff} would correspond to water with particulate in it. The long T_2^{eff} component would represent free water.

T_1 behaves in a similar way, where different exponential components can be extracted and related to water under different conditions (i.e. in biofilm, containing particulate matter etc.). As a result measurements on wetland samples using a permanent magnet system have allowed for the collection of preliminary bi-exponential data. A thickly clogged sample containing biofilm was scanned with a Halbach magnet (discussed later) has previously been presented (Hughes-Riley *et al.* 2014c), and a similar curve is shown in Fig. 3. While two T_1 values can be extracted, the errors shown are great and additional refinement will be necessary before this can be used as a valuable indicator.

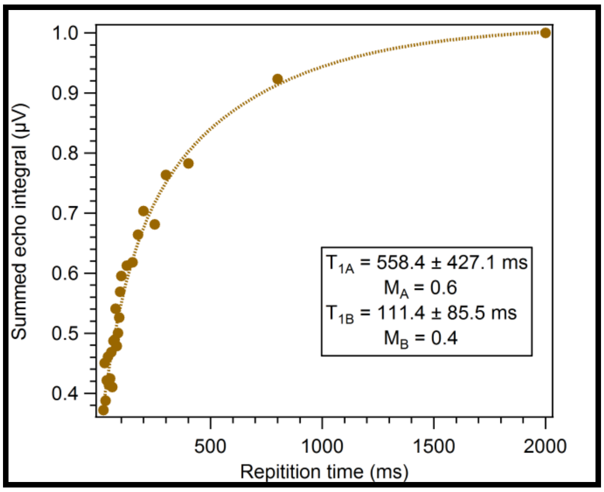

Fig. 3. T_1 curve collected using a Halbach magnet on a thickly clogged sample containing biofilm. A short and long T_1 can be extracted, although there are very large errors on both values. Additional repetition time values may allow for a superior fitting in future studies.

A pilot study has also been conducted using Earth's field nuclear magnetic resonance (EFNMR; Hill-Casey *et al.* 2014 under review). T_1 and T_2^{eff} measured using EFNMR was sensitive to clog state, and the probe could be successfully embedded into a gravel matrix filled with water. However when attempts were made to embed the probe into a wetland module interference of the surrounding ferrous cage introduced inhomogeneity to the localised Earth's field, making measurements impossible. Building the outer case of a wetland module from another material (not metal) is impractical at the size needed for sufficient treatment, making the use of EFNMR for the desired application non-ideal.

Unilateral magnet arrangements have been explored for this application in the laboratory including using the stray field of a Halbach array and bar magnet (Hughes-Riley *et al.* 2014a under review; Hughes-Riley *et al.* 2014c). Unilateral designs are preferred over an internal volume design as they are less disruptive to the flow-path of effluent and cannot become physically clogged by gravel. The Halbach design showed promise in a lab environment, however further development (unpublished) to deploy the sensor into a reed bed has been problematic. Signal intensity is not sufficient to take T_2^{eff} measurements in a timely manner. Another issue is that in its current configuration only about 2 mm above the probe can be explored. This small volume (~1000 mm^3) is not ideal as it may not be representative of the health of the reed bed overall.

Subsequently this work re-examines the use of a Helmholtz magnet assembly which probes a far larger volume. The sensor used in this work was small (sensitive region of ~10 cm^3), however up-scaling should not provide a significant challenge and is only limited by the size of available magnets. Previous reports have either used mock systems constructed in a laboratory or samples extracted from an actual wetland and taken to a laboratory for investigation, here for first time MR measurements taken in situ from a reed bed are presented.

This research was conducted as part of the Automated Reed Bed Installation (ARBI) project, an EU FP 7 funded initiative to design an automated constructed wetland module. The ability to control the environment in the reed bed may extend lifetime, and possibly increase efficiency. For example, reed bed efficiency decreases in the winter months as it is a less favourable environment for the microorganisms and reeds (Kadlec&Wallace, 2009). Advanced sensors will be fitted to each module to monitor the clogging level, oxygenation, and temperature of each bed. This information will be fed into a control system which will determine where and when action is needed.

2. METHODS

2.1 Prototype constructed wetland for MR testing

A static wetland module was constructed at Nottingham Trent University with the express purpose of testing MR sensors (previously described elsewhere; Hill-Casey *et al.* 2014 under review). An intermediately bulk container (1.02 m x 0.92 m x 0.90 m; DV Containers Ltd, Wrexham, UK) was used as the basis of the module. The container was filled with non-magnetic gravel (average length = 9.6 mm; Travis Perkins Trading, Bulwell, UK), water, and had common reeds (*Phragmites australis*) planted in it, making the module a close representation of a real operational wetland (Fig. 4). The wetland did have an outlet pipe to allow for liquid to flow through; however this was not utilized during these experiments.

Fig. 4. An overhead photo of the prototype wetland at the Nottingham Trent University. The basis of the module was an IBC container.

2.2 MR sensor design

A Helmholtz MR sensor, first presented elsewhere (Hughes-Riley *et al.* 2014d) and very similar to a design by Morris *et al.* 2011, was used in this study. The magnet arrangement comprised a pair of neodymium magnets (Fig. 5; height = 20, radius = 17 mm; Magnet Monster, Flensburg, Germany). The magnets were separated by 20 mm (slightly over half the magnet radius) and arranged with anti-parallel polarization. This created a region of homogeneous magnetic field where an eight-turn solenoid coil was installed.

The solenoid was attached to a tuning board; this had three capacitors, a 12 – 100 pF variable capacitor for matching (Johanson Manufacturing, New Jersey, USA) and a 12 – 100 pF variable capacitor and a single 55 pF fixed capacitor for tuning the resonant circuit to 13.87 MHz, the required frequency for the field generated.

The sensor had to be water-tightened so that it could be embedded into a wetland. Therefore the sensor was coated a silicon elastomer potting compound (RS Components Ltd., Northhants, UK). Laboratory tests confirmed that this sufficiently water-tightens the sensor to allow for operation, however the viability of this method for long term embedding is currently untested.

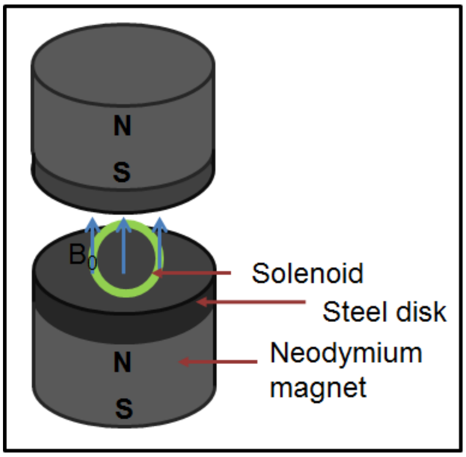

Fig. 5. Helmholtz sensor design. Magnets are separated by 20 mm, in the gap there is a homogeneous magnetic field in which the solenoid coil is installed. Steel disks are place on each magnet to reduce the field gradient.

2.3 Magnetic resonance protocol

For this study Prospa v3.12 software was used to drive a Kea 2 spectrometer (Magritek, Wellington, New Zealand) to collect magnetic resonance measurements. All measurements were taken using CPMG sequences (Meiboom & Gill, 1958). For T_2^{eff} measurements a CPMG was taken with a single parameter set, and echo integrals were re-fit using Igor Pro v6.3 (WaveMatrics, Oregon, USA). For T_1 measurements CPMG sequences were run with different repetition times. A CPMG was used so that the echo train could be summed, reducing the number of repeat experiments needed. Summed echo integrals were normalised and then fit to a mono-exponential curve. All errors specified for T_1 and T_2^{eff} values are given as the error on the fitting provided by Igor Pro.

2.4 Sample preparation

Samples for additional laboratory validation experiments (ARM, Rugeley, UK) were stored in a 50 mm section of acrylic pipe (i.d. = 10 mm, o.d. = 12 mm) filling most of the coil region of the sensor. To calculate the mass of the dry solids in each sample samples were weighed, dried in a convection oven (Binder, Tuttlingen, Germany) and re-weighed.

3. RESULTS

Fig. 6 shows a T_2^{eff} measurement taken in the Nottingham Trent University prototype reed bed. Four sets of experiments with of 512 averages each were taken in sequence so that a standard deviation could be taken, giving an estimate for the error on each point. Overall these measurements took approximately 35 minutes. Due to the slow moving nature of the sludge in the reed bed, measurements taking several hours are possible. Therefore additional signal averages are possible, which would reduce the errors for each averaged echo integral and therefore the accuracy of the exponential fitting. A longer experimental time would also allow for a slower repetition between experiments (a repetition time of 1s was used, later experiments showed that a time exceeding 5s would yield far superior results).

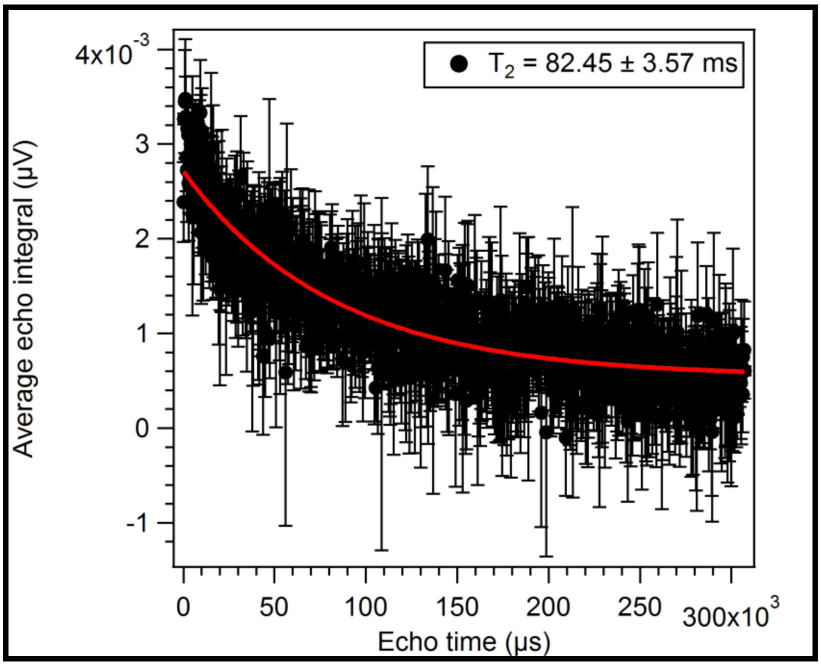

Fig. 6. T_2^{eff} measurement taken using the embedded sensor. Echo time = 300 μs, repetition time = 1000 ms, 2048 averages.

With the successful collection of a T_2^{eff} measurement validating the use of the sensor in a reed bed, a T_1 measurement was recorded, as shown in Fig. 7 (black markers). Also displayed in Fig. 7 are measurements of two other samples recorded in the laboratory environment on the same sensor. Analysis of the reed bed material showed that 0.15 % of its mass was dry solids. This would be expected as the effluent has not been run through this bed. The percentages of dry solids for other samples are shown on the graph.

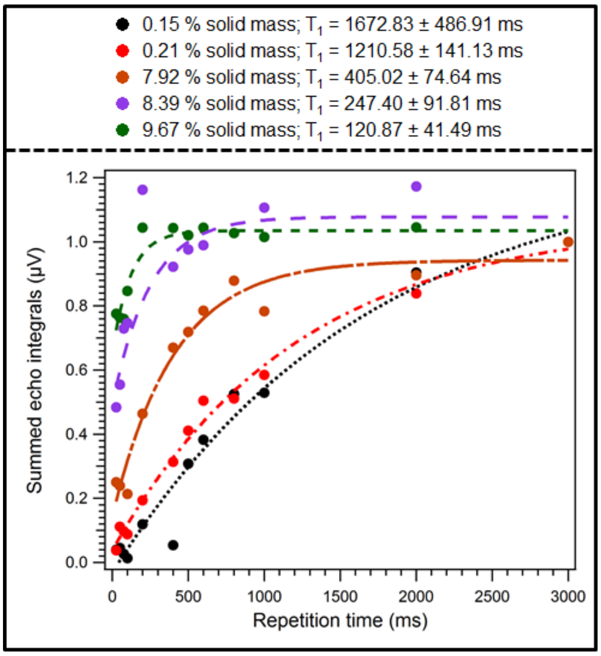

Fig. 7. T_1 measurements taken using the embedded sensor, with additional laboratory measurements. Echo time = 300 µs, 512 averages. Errors in the normalised integral sum are small, and therefore have not been included in the graph. A systematic error occurred for the final two points of the 8.39 % solid mass curve at 200 ms (shown) and 800 ms (not shown). These points have not been included in the fitting. The 75 ms point is omitted from 7.92 % solid point due to an equipment failure.

As expected, additional solid material (i.e. clogging) results in a shorter T_1. The relationship between the T_1 measurement and percentage of solid material in the sludge has been plotted (Fig. 8). A linear relationship is observed. This is expected based on the work of Morris *et al.* 2011, where hydraulic conductivity had a linear relationship compared to T_1 relaxation. Hydraulic conductivity should be proportional to the percentage of solid material, and this work appears to confirm that.

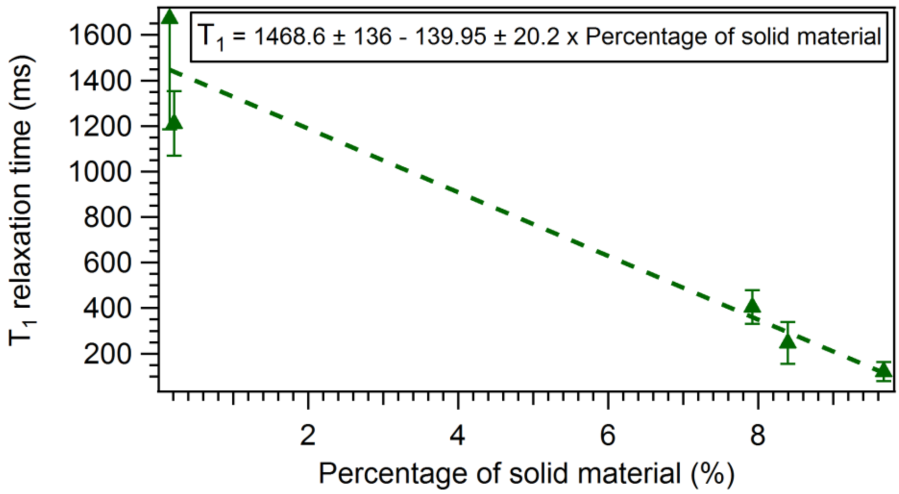

Fig. 8. T_1 plotted against the percentage of solid material in the sludge sample. A linear relationship is observed. Errors in the percentage of the solid material due to weight are minimal, and therefore error bars are too small to plot.

4. CONCLUSION

An automated reed bed module will allow for real-time optimisation of environmental parameters. This should lead to an increased bed lifetime, and superior water treatment. Additionally, we have shown for the first time that an MR probe can be used to probe an actual reed bed *in situ*.

A short study exploring a comparison between T_1 relaxation and quantity of solids in samples has been conducted. As seen from previous studies increasing particulate matter results in shortening T_1 values (Morris *et al.* 2011).

Further development of MR sensors is desirable. A large Helmholtz sensor or a unilateral magnet assembly would be less likely to become physically clogged and therefore inoperable, or unrepresentative, than the small internal volume design presented here.

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