Long Term Monitoring of Constructed Wetlands using an NMR Sensor

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Abstract— **Subsurface flow wetlands have become a popular technology for the treatment of waste water all over the world. These systems become clogged over time, and must be renovated at great expense. We present a nuclear magnetic resonance sensor which is sufficiently small and inexpensive that several of them could be embedded in a constructed wetland to allow spatially resolved long term continual monitoring of the clogging process. We demonstrate the suitability of this sensor by first measuring NMR of sludge from an operational wetland, and secondly by monitoring the evolution of the fluid's NMR spin lattice relaxation time (T_1) during clogging in a model wetland. Measurement of clogging rates in two locations are made and found to be 10.7x10-2min-1 and 4.9x10-3min-1 for regions near the inlet and the centre respectively.**

I. INTRODUCTION

Constructed wetlands are simple to operate and maintain, and relatively low-cost in comparison to conventional wastewater treatment technologies. They are proven to be effective for the removal of pollutants from a variety of industrial, agricultural and municipal wastewaters. These facets have seen them gain worldwide popularity over the past three decades and several variants now exist, such as horizontal subsurface flow constructed wetlands [1, 2]. Over 1200 horizontal subsurface flow constructed wetlands exist in the UK, predominantly used for the final treatment of waste water that has already undergone primary and secondary processes at a rendering plant [3]. They usually incorporate a gravel bed planted with reeds, through which the wastewater is passed for purification, ensuring that the water level is below the surface of the gravel [4] (see Fig. 1). Amongst other things, subsurface operation avoids odors and prevents insect breeding. They are popular with operators as they provide effluent which consistently achieves Environmental Agency discharge consents, even compensating for failing upstream processes [5].

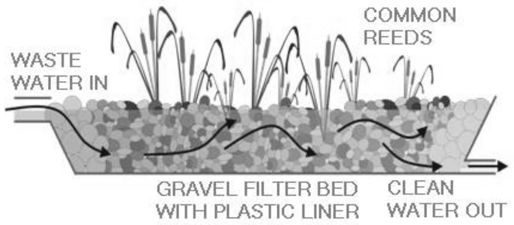

Figure 1. Cross-sectional view of a horizontal subsurface flow wetland as used in the UK for the tertiary treatment of municipal wastewaters

Treatment processes include filtration and settling of suspended solids, the assimilation of organic material and nutrients into bio-films and plant biomass in addition to precipitation of heavy metals and phosphates [6]. These factors cause the gradual clogging of the gravel pore space [7, 8], the effects of which include gravel surface sludge accumulation, surface flow, preferential flow-path formation, poor reed growth, weed establishment and in extreme cases detrimentally reduced treatment performance [9, 10]. Methods to renovate a clogged system include replacing some or all of the gravel with fresh media, washing the gravel *in situ* and applying chemical oxidants to volatilize organic matter accumulations [12]. Ultimately it is desirable to maximize the lifetime of the system by studying the nature and development of clogging such that design and operation guidelines can be refined.

Several methods exist to determine the extent of clogging by measuring hydraulic parameters at various points in the system. Recently, *in situ* methods to directly measure the loss in substrate hydraulic conductivity caused by clogging have been applied to wetlands [13, 14]. These are considered an improvement on previous methods, which estimated the system hydraulic conductivity from the gradient of the subsurface water-table and Darcy's Law [15], because they have elucidated the extreme variation in conductivity that is present within a system. For example, Knowles *et al.* [16] reported width averaged hydraulic conductivities at the inlet which were 2-3 orders of magnitude lower than elsewhere in the system.

Other investigations have considered the porosity and dry weight of accumulated solids that are present in an extracted gravel sample, although these have often correlated poorly with hydraulic conductivity measurements leading many authors to conclude that the form and density of the clog matter, and not solely the quantity, is highly influential on hydrology [8, 17-19]. Similarly inconclusive were *in situ* applications of Time Domain Reflectometry to explore the relationship between subsurface moisture content and how clogged the media had become. This measurement was found to be less useful as the saturated clog matter is usually 95% water by volume making variations hard to detect [8, 19].

More precisely, it is the ratio of free to associated (bound) interstitial water that will determine the hydraulic conductivity through the clog matter [19]. Comparing saturated and drainable porosity measurements will give a rough indication of this ratio [20] but it is difficult to non-destructively extract gravel samples from the wetland to allow these tests to be performed representatively [21]. Tracer tests can be used to deduce the relative active and stagnant wetland volumes, however, this is a bulk parameter not scalable to pore level due to the complications of dispersion and mixing [22-24]. All of the aforementioned methods either require expensive equipment, cannot continually monitor the clogging or cannot easily be adapted to investigate variations in hydraulic performance at different locations in the bed.

A new device was required that would meet the following specification:

- Measures the ratio of free to associated interstitial water so that direct correlation with hydraulic conductivity measurements could be attained
- Remain *in-situ* for extended periods of time but be minimally invasive so that the measurements are representative of an undisturbed system
- Be sufficiently low cost that monitoring the variation of clogging at different points in the system is achievable by employing numerous permanent sensors

Nuclear Magnetic Resonance or NMR is a technique which has found application in subsurface logging, particularly as a tool for oil industry site viability surveys [25]. More recently low cost NMR sensors have been used to study the drying process of Portland cement [26]. Small cylindrical sensors approximately 25mm in diameter and 20mm thick have been developed and embedded in Portland cement mixture. As the mixture dries the water content (to which NMR is intrinsically sensitive) will drop allowing its measurement over time with NMR. In addition to sensitivity to the water content of a sample, NMR can be used to determine the properties of the water, such as its local association. A system comprising of both free and bound water will present more than one NMR spin-lattice relaxation time (T_1). By measuring this relaxation time and the relative amplitudes of the two components, it is possible to determine the ratio of the two associated states. In this paper, we present an NMR sensor which is sufficiently small and low cost that it is viable as a permanent *in situ* probe for local constructed wetland clogging measurements. The probe is tested in a small model wetland in the lab to verify its suitability to field measurements.

II. SENSOR DESIGN

In order to generate and acquire an NMR signal, an instrument capable of producing a radio frequency field perpendicular to a static magnetic field must be created. To facilitate the low cost and small size requirements of the instrument for this purpose, the static magnetic field is produced using Neodymium-Iron-Boron ($Nd_2Fe_{14}B$) magnets which generate magnetic fields up to 1 Tesla at their surface. By arranging two such magnetic discs (50mm diameter, 10mm thick) with opposite poles facing, separated by 25mm, a field which has a 1cm^3 homogeneous volume in its centre can be produced. A 23mm diameter solenoid is placed so as to surround this volume. In order to deliver radio frequency pulses to the system and to measure the resulting signal, an iSpin (Spincore, Florida, USA) NMR console is used with a 400W RF pulse transmit amplifier (ACT, Aachen, Germany) and two ZFL-500 (Minicircuits, New York, USA) small signal receive amplifiers. A 6μs pulse length was used to tilt the magnetization into the transverse plane. A saturation recovery type sequence was used to estimate the value of T_1: If the spin system is saturated with RF by repeating a CPMG [27] sequence with insufficient time between each repetition, no signal is observed. As the time between each repetition is increased, signal will be observed. The relationship between the repetition time and the signal intensity is given by an exponential with time constant T_1.

III. MODEL WETLAND SETUP

A model wetland was constructed using a 500mm length of 200mm inner diameter clear acrylic pipe with 3mm wall thickness. A base plate of 5mm acrylic including two Speedfit (John Guest, Middlesex, UK) connectors was secured to one end. One outlet was closed with a tap to allow the system to be drained in the event of an overflow. A swivel arm flow regulator was connected to the other outlet to allow the volume of water in the system to be controlled (See figure 2). Diluted sludge is delivered to the system using a peristaltic pump from a continuously stirred reservoir.

The authors acknowledge the EPSRC for funding under platform grant EP/E063489/1.

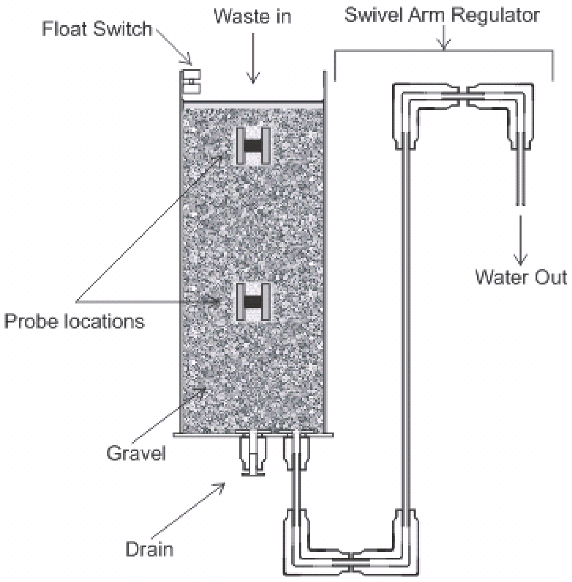

Figure 2. *Schematic of model wetland setup.*

Twenty liters of sludge are retrieved from an active constructed wetland site (Moreton, Morrell, South Warwickshire, UK, Severn Trent Water Ltd.). The sludge is filtered to remove large items of debris which could clog the pumping system. It is subsequently diluted with water to a final concentration of 10mg·ml^{-1} to facilitate delivery. The peristaltic pump delivers the waste to the top of the column at a flow rate of 200ml·min^{-1}. As the gravel becomes clogged with the solids in the waste the outlet rate decreases and water begins to pool at the inlet. Once the water level has reached 20mm from the top of the column a float switch shuts off the pump and the gravel is assumed to be completely clogged. In two separate experiments, the NMR probe is buried at two locations in the column to observe two different clogging rates, one 20mm from the surface (inlet) and one 300mm from the surface (centre).

IV. RESULTS

To facilitate comparison between a real constructed wetland and our model system, the T_1 of undiluted sludge is measured in the NMR probe. The saturation recovery curve is shown in Fig. 3.

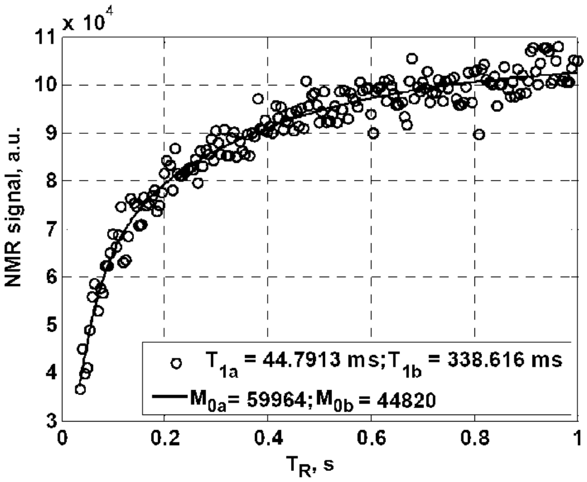

Figure 3. *Saturation recovery curve from sludge in the NMR sensor. The fit is biexponential indicating the presence of both free and associated water. Each point represents 32 averages.*

Saturation recovery experiments in the model wetland are repeated every 15 minutes for each probe location. The resulting saturation recovery curves are used to perform a least squares exponential recovery curve fit and hence estimate the value of T_1 for each experiment.

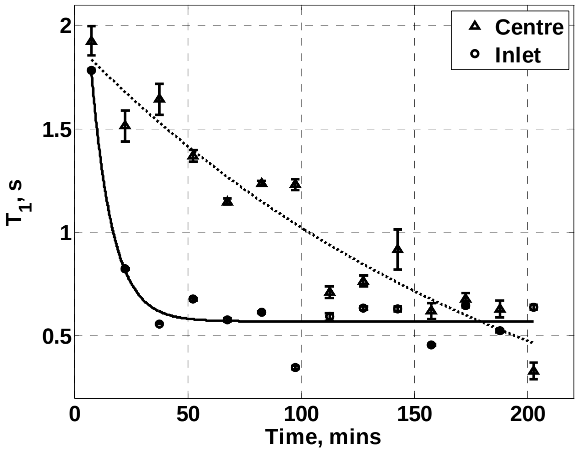

Figure 4. *Time course of T_1 for the two separate sensor locations. The exponential fits demonstrate the considerably faster clogging seen at the inlet in comparison to the centrally positioned sensor as is confirmed visually through the acrylic tube.*

The time-courses of T_1 for both locations are plotted in Fig. 4. A least squares exponential fit is performed to estimate the clogging rate for both sensor locations. These are found to be 107x10^{-3}min^{-1} and 4.9x10^{-3}min^{-1} for the inlet and the centre locations respectively.

V. DISCUSSION

The model wetland clogged to the point that no flow was observed in approximately 4 hours. The NMR results show a clear trend in the value of T_1 with time as the gravel becomes clogged. Unlike samples collected from constructed wetlands which typically present two T_1 components for free and associated water (see Fig. 3), the recovery curves collected in the model wetland have only a single component relating to the extent to which the water has been restricted in the pore volume. This is most likely due to the considerably shorter residence time in the model system which prevents the build up of bacterial films allowing water association and hence a shorter T_1 component. We have still however measured a clear reduction (2s to 600ms) in T_1 as the system becomes clogged. The expected clogging distribution for the wetland shown in

Fig. 5 is seen in our system after approximately 100 minutes. If the residence time in our system was similar to that in a constructed wetland, this would most likely have been the point at which the bacterial films would prevent further clogging.

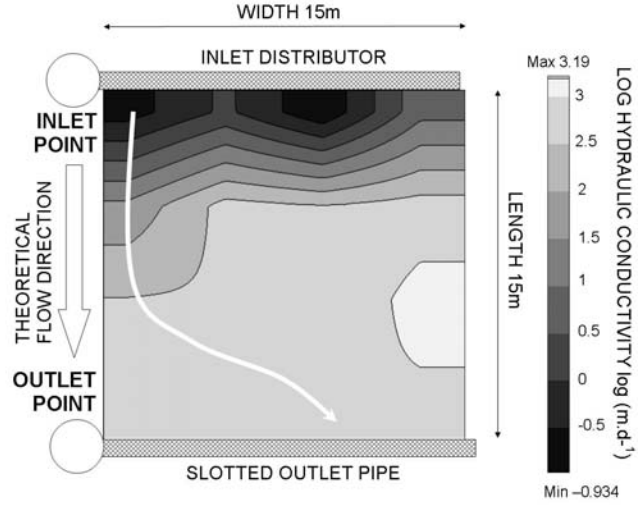

Figure 5. Plan view of a mature constructed wetland showing the variation in clogging across the surface of the bed. Darker shaded areas are more heavilly clogged. Adapted from [16]

The sensor presented allows for a large signal to be rapidly acquired for laboratory testing. The time scales of the clogging process in a real constructed wetland are far longer and in consequence the signal can be averaged for a greater amount of time with no loss of information. Hence, for an embeddable probe, a smaller unilateral design could be produced which would generate less disturbance to the gravel bed.

VI. CONCLUSION

We have demonstrated the suitability of NMR measurements to determine the extent of clogging in a model wetland system. By using T_1 measurements, the time course of clogging has been observed at two locations reproducing in part the expected pattern from work in the literature. Although the residence time in the system was insufficiently long to form conclusions on bacterial film clogging processes, optical observation of solids induced clogging has been seen to correspond well to our NMR measurements. We have demonstrated that NMR may be a useful tool for long term *in situ* monitoring of constructed wetlands, yielding important information about clogging processes.

VII. FURTHER WORK

The model wetland system has been shown to exhibit the same clogging behavior for solids as is seen in operational constructed wetlands. By increasing the residence time and reducing the concentration of the diluted sludge, it may be possible to promote generation of bio-film layers on the pore surfaces thus further representing a genuine system, allowing localized pore clogging to be studied. The effect of temperature changes on the model system could also be investigated in terms of the effect which this has on the clogging and the NMR signal. The NMR results could then be compared to local hydraulic conductivity measurements to determine their correlation. Having fully characterized the model wetland system, these NMR probes could be buried in several locations across an operational constructed wetland, allowing spatially resolved determination of clogging processes.

ACKNOWLEDGMENT

The authors gratefully acknowledge the help of Nicassio Geraldi, Nicola Doy, Christophe Trabi and David Parker who have been instrumental in setting up and maintaining the model wetland setup.

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