Executive Summary:
The ARBI Project has successfully demonstrated the suitability of skip lorry transportable wastewater constructed wetlands modules to treat two types of wastewater: Municipal taken directly from a mains sewage system and simulated air strip runoff. A comprehensive research and development plan was undertaken to achieve this goals. The modules work on the principle of providing optimal conditions for the treatment of wastewater by micro-organisms present in the pore-space of a gravel matrix. To determine the procedure needed to optimise the treatment system, water quality sensors produced by Oxyguard International in Denmark are used to measure the Dissolved Oxygen, Redox, pH and Temperature whilst purpose built magnetic resonance sensors measure the clog state of the wetlands. The experience of LabTools from the UK was invaluable in designing, constructing and testing the electronics system which is used to generate and acquire the signals from the MR probes. An industrial programmable logic controller produced in collaboration with TechnoSam from Romania is used to automate the system, making measurements and adjusting the bed conditions. Initial work on the project focused on determining the optimum design for the magnetic resonance probes by Nottingham Trent University (NTU) in the UK and determining the optimum design for the bed conditioning system by Universitat Politècnica de Catalunya in Spain. The housing for the modules was developed next in collaboration with LightMain in the UK and involved extensive material selection processes by NTU. Once the conditioning system and MR probes were completed and optimised, trial modules were constructed to begin to gather details on the behaviour of the systems with regard to adapting the environment. Sizing of the final modules was calculated based on knowledge from these prototypes and of larger systems from the experience of ARM ltd. from the UK who are leaders in wetland installations. Testing of the two types of wastewater have revealed that in contrast to traditional large scale constructed wetlands, a reduced footprint is needed for the automated system. It was beyond the scope of this project to determine if the lifetime of the systems is indeed extended as expected but the preliminary results are very promising in this regard. The project is continuing beyond the funding with initial work on commercialising the modules for sale across Europe in the coming years.

Project Context and Objectives:
Constructed wetlands are an important means of wastewater treatment with applications extending to both a domestic and industrial settings. A typical constructed wetland will incorporate a gravel matrix held within an impermeable container. Microbial life grows and
lives within the pour spaces between the gravel. Reeds are also normally planted leading to another commonly used name, reed beds. Wastewater is flown through these beds and through a series of biological, chemical, and physical processes the contaminants are removed.

One limitation is the operational lifetime of a constructed wetland. While original predictions estimated that wetlands may have a useful life of over fifty years [1], practical experience has seen significant impairment in operation occurring in as little as ten years [2]. This is due to occlusion of the macroscopic pores within the gravel matrix by microorganism biofilms. Clogging retards the motion of the wastewater moving through the wetland and reduces the treatment efficiency until such a point that the bed floods. On becoming critically clogged the bed must be taken offline and the gravel either cleaned or replaced. This is both a costly and time consuming exercise. In order to partially mitigate this problem, some wetlands are equipped with a step-feeding system. The point in the bed that typically becomes clogged first is where the wastewater enters the wetland, as this is where the microbes will have the greatest supply of nutrient (the wastewater). With step-feeding, the inlet is moved, this way biofilm growth across the bed is more consistent, reducing the chances of critical clogging.

As constructed wetland technology has grown in popularity, other new methods for improving treatment efficiency have been devised. Popular improvements include applying aeration, which feeds the microbes with oxygen allowing for greater growth. Heating is also employed as wetlands treatment efficiency is reduced significantly in colder climates.

The autonomous reed bed installation (ARBI) project is an EU FP7 project set up to design a modular reed bed solution incorporating technology to maximise treatment efficiency. Beyond this however, ARBI is an autonomous system where decisions on the aeration, heating, and step feeding are determined by a suite of sensors installed throughout the bed. Some of the sensor technology, such as thermocouples for controlling the heating, or dissolved oxygen sensors for controlling the aeration were off-the-shelf, and provided by one of the consortium members (OxyGuard®), the clog state sensor was not.

Typically when the clog state of a constructed wetland needs to be determined a method where tracer dyes are fed into one location of the bed, and are then monitored at another is used [3]. This is a time consuming process that requires two people over a few days, it also does not produce a result immediately. Magnetic resonance (MR), most commonly known due to magnetic resonance imaging (MRI), can be a powerful tool to determine the clog state of a system [4]. Magnetic resonance sensors comprise two main components, a magnet and a radio frequency (RF) coil as part of a resonant circuit. The sensor is controlled by a magnetic resonance spectrometer which is used to generate and interoperate RF signals.

In MR, a sample is placed within a magnetic field. Some samples, such as water, contain atoms with a property called a magnetic moment. When placed in the field some of the magnetic moments will align with the magnetic field, and some will align in the other direction, but ultimately there will be a net magnetisation. This can be manipulated using RF pulses. In a simple experiment, an RF pulse of the correct frequency and duration can be used to tip the net magnetisation perpendicular to the applied magnetic field. Here the magnetisation will rotate around the applied magnetic field, this motion of the magnetic field will induce a current in the RF coil which can be interrupted by the MR spectrometer and tell the user information about the sample.

Once the magnetisation has been tipped perpendicular to the applied magnetic field and begins to rotate it will slowly start to loose energy to the surrounding system. This is known as relaxation. For clog state measurements a longitudinal relaxation (sometimes known as T1 or spin-lattice relaxation) measurement is typically made [4] on the water and biofilm. This relaxation probes the time taken for the magnetisation to realign with the applied magnetic field.

Prior to the ARBI project a proof of concept of this technology had been developed [4] and additional research had been conducted looking at the use that MR could play in studying wetlands. One of the key goals in ARBI was to develop an optimised MR sensor, exploring different magnet geometries and coil types. Once designed, a series of these sensors were constructed and field tested in real wetlands. Further to this, the final design was incorporated into the final ARBI modules.

In order to operate the probes a low-cost MR spectrometer also needed to be developed. Typical MR spectrometers cost many thousands of pounds which was not ideal for ARBI as this would have taken up a significant portion of the modules overall cost. ARBI developed a lower-cost solution thanks to recent developments in technology.

As well as the sensor technology, it was highly important to understand the optimal operational settings for each module. This involved a study into the optimal dissolved oxygen concentration in constructed wetlands of this type, the optimal operating temperature, and
finally a study into the benefits that step-feeding can bring to treatment efficiency.

The constructed wetland modules also had to be designed. Initially this involved a detailed investigation into the potential materials that it could be constructed from as it was most desirable to have a light module that would still have the required sturdiness and endurance. Prototype modules were developed and evolved until a final optimal geometry was determined.

The final important constituent of the ARBI module was the automation system. This had to be designed, installed, tested, and ultimately optimised. Beyond this, a set of prototype modules of the final design were constructed and rigorously tested with both domestic and industrial wastewater to determine the treatment efficiency of this new system.

By the end of ARBI the goal was to have developed a complete modular wetland system that could operate autonomously for many years based on input from its sensor suite.


Project Results:
The scientific results derived from the ARBI project broadly fall into three categories. The first of these explored the optimal settings for the aeration and heating within horizontal sub-surface flow (HSSF) wetlands. The benefits of step-feeding were also explored during these studies. Some of this work has been disseminated to the scientific community [1-3].

Considerable work went into the development and testing of the ARBI magnetic resonance sensor. A plethora of sensor designs were investigated and some of the results from the testing of these has been disseminated [5 - 11]. After selecting the most promising design, a series of prototype probes were built for testing in established wetlands as well as the ARBI prototypes. To facilitate this, how measurements were effected by seasonal and environmental changes was fully explored.

Finally a section on the prototype ARBI prototypes has been presented. This section details the initial experimental findings and explores the treatment efficiencies of each bed.

1. Determination of optimal parameters for HSSF wetlands

The benefits of adding a forced aeration system to constructed wetlands has been suggested in the literature to reduce nitrogen species and improve the removal of organic matter [12, 13]. Recent studies have identified that removal rates can be improved almost ten-fold with the addition of an aeration system [14]. Most literature deals with continuous aeration, which consumes considerable amounts of energy. Here the dissolved oxygen level required for the optimal bed operation has been investigated in order to allow for a non-continuous aeration to be applied, preventing the bed from dropping below this threshold value.

Similarly the virtue of heating constructed wetlands has been identified in the literature. Work exists suggesting that an increase in temperature can enhance the oxidation of organic matter within a wetlands [15, 16] and increase the concentration of organic matter dissolved [17]. Both of these effects may reducing clogging within a wetland, which is desirable. Additionally, heating has been seen to increase the treatment efficiencies of some wetlands [18].

Finally the potential for implementing step-feeding was also investigated in line with the literature [19-21]. A pilot plant was used to conduct these studies.
The pilot plant consisted of two well-established HSSF wetlands fed in parallel from a 1.2 m³ plastic tank. This tank was fed from a municipal sewer and stored for five hours while being continuously stirred. Wastewater then travelled to a hydrolytic up flow bed-reactor (HUSB) for primary treatment for three hours before the wastewater reaches the two beds for secondary treatment to occur. Fig. 1 shows the set-up of the pilot plant.

FIGURE 1

Aeration experiments with the pilot plants were conducted in two steps. A short study was conducted with the two bed over two weeks. One bed was used as a control, and the other with forced aeration applied. As second, more comprehensive set of experiments was then undertaken. Here six beds were used with three as controls and three were aeration was applied. Experiments were carried out over four month, two months with the beds in a ‘cold’ climate, and two months where seasonal changes and the use of greenhouses exposed them to a warm climate.

The aeration system was chosen based on a review of the literature, in particular work by Butterworth [22], where a pierced resin pipe with an orifice of 0.8 mm was selected. Laboratory experiments were conducted to further justify the chosen system. Pierced piping with orifices of five different sizes were examined to determine the effects that aperture size had on the diameter of bubbles produced, the distribution of these bubbles, the transfer rate of oxygen into the water, and finally how different oxygen flow rates effected the bubble distribution. For the bubble size and distribution studies, photographs of the bubbles were taken from the side of a clear box filled with water, with aeration strips at the bottom. The bubble size or distribution was then determined using Image J (National Institutes of Health, USA).

Fig. 2 shows the bubble size as a function of hole aperture.

FIGURE 2

The relationship observed in Fig. 2 was close to average bubble size = 10*hole diameter. From this it can be concluded that a hole size around 1/10 of the average pore diameter (0.6 mm hole) is most useful for the ARBI module as the bubbles will stand maximum chance of filling the pore spaces as they pass through.

Fig. 3 goes on to show the bubble distribution as a function of the aperture size.

FIGURE 3

The results show that, as would be expected, that the greater the hole size, the further across the bed the bubbles reached. These results were useful for determining the position of pipework in the final bed.

It was also important to see how the aperture size effected the oxygen transfer. For these experiments one of the small-scale ARBI prototypes was fitted with aeration pipes and was then filled with gravel and water. Nitrogen was bubbled through to the water (i.e. remove the oxygen from it) whilst the dissolved oxygen was monitored using an Extech Instruments Dissolved Oxygen Meter (Model: 407510A; Extech Instruments, Waltham, MA, USA). This was stopped when the oxygen level reached less than a given set point. The selected size was then connected to a compressor to bubble through air whilst the time-course of oxygenation was monitored. This process was repeated for each of the hole sizes to provide information regarding the rate of oxygenation each provided.

As is evidenced in Fig. 4, the data that was collected from the dissolved oxygen meter was processed to obtain a gradient (using the log of the time axis) related to the rate of oxygen transfer. The result for the 10 mm hole size presented significantly reduced oxygen transfer, with the other hole sizes given roughly equal oxygen transfer. This was most likely due to the fact that the pressure was insufficient to oxygenate the whole length of the strip reducing the oxygen transfer.

FIGURE 4

The final set of laboratory based validation experiments was to investigate how changing bubble flow rate changed the bubble cone diameter (i.e. the overall area that the aeration effected). For this study, the 1 mm hole aperture pipe was used. The cone diameter was measured 50 cm away from the aeration holes.
Here it was seen that by varying the flow rate between two values it is possible to fully aerate the system or to produce areas of alternating aerobic and anaerobic environments which may be desirable in certain circumstances.

The ultimate conclusion from these laboratory based studies was that the hole aperture size did not really matter providing that the aeration pump had an adequate flow rate, as even with a small aperture size the bubble cone could affect the desired size of area on the bed with an increase in the flow rate (as shown in Fig. 5).

For the studies in the established wetlands, the aeration pipe was located at the centre of the bed; this choice was made as its installation in that location would minimise the disruption to the gravel matrix, interfering with the biofilms. The aeration pipe was 50 cm long, and was rolled, occupying a 0.07 m² area (~18 % of the wetlands total area). Air was injected at 720 L/h. According to Butterworth [22], flow rate had an impact on bubble size in the systems without granular medium, but not on the systems with porous media. Dissolved oxygen within the ARBI and Control wetlands was 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). Water quality samples were taken from both the bed inlet and outlet biweekly for the first period of experimentation and three times per week for the second set of experiments. Chemical Oxygen Demand (COD), total nitrogen (only for the 2nd period), ammonium, nitrites and nitrates were measured according to the Standard Methods for Wastewater Treatment. In order to measure evapotranspiration, the water flow was measured at the outlet of each wetland by a flow meter device. Influent flow was known because it was pumped by peristaltic pumps.

Fig. 6 shows the dissolved oxygen concentrations in the control wetland and aerated wetland where the aeration has been applied constantly, for this bed the dissolved oxygen was about 5 ppm, compared to values near zero in the non-aerated bed.

Fig. 7 illustrates the aeration control. In this case the air pump was regulated in order to reach dissolved oxygen values of 3 ppm (Air 3), the signal variability was due to an electrical problem that was solved later. Similar patterns were recorded for the other configurations.

Water quality measurements for the different dissolved oxygen set-points were recorded and are shown in Fig. 8. Here it can be seen that for all dissolved oxygen concentrations except 0.2 mg/L aeration improved treatment efficiency.

During this period, the first 65 days refers to colder conditions (February-March), while from day 65 to 100 refers to warmer conditions (April-May with greenhouse). Overall effluent average concentrations were 220 ± 75 mgO₂/L and 184 ± 53 mgO₂/L for the control and aerated (ARBI) wetlands, respectively. Therefore, the average COD removal was increased by 17% in aerated (ARBI) wetlands, indicating the positive effect of aeration. Note that effluent values were high due to the very high surface organic loading rate (110 gCOD/m²•d) as a consequence of the influent water quality during this period. In fact, for the sake of comparison, during this period the flow was maintained the same as in period 1 (63 L/d) in spite of the increase in COD influent concentration.

Water temperatures oscillated between 11 ± 2.3 °C in cold period (February and March) and 18.1 ± 1.4 °C in the warm period (April and May with greenhouse). A detailed analysis of Fig. 9 indicated that the results for the same wetlands (control or aerated) were very similar in the cold and the warm periods, as what usually happens in this type of system.

Fig. 10 better illustrates the positive effects of aeration and shows the difference in the COD removal between the two types of bed. It is clear that the aerated system has a superior treatment efficiency with COD removal from 20 up to 80 mg/L greater than the control beds.

In period 2, the total nitrogen and ammonium were also determined. Ammonium nitrogen was not removed or it was poorly removed (Fig. 12) due to the high loads.
Fig. 13 shows the organic nitrogen content (calculated by the difference between total nitrogen and ammonium). In this case, concentrations of 28 ± 10 mg/L in the influent were reduced to 14 ± 6 and 12 ± 5 mg/L in the control and the aerated beds respectively, corresponding to a performance improvement of 11 %. This confirmed the observation from period 1, in the sense that ammonification was a reason for the higher effluent than influent concentrations in some of the samples. There was no indication that temperature had an effect on performance.

It should be noted that the evapotranspiration was monitored in period 2, and was seen to not have a great effect during the experiments.

Temperature experiments were conducted on the same wetlands as described earlier. Again, experiments were set over two periods where period 1 saw two beds (control and heated) examined over the space of two weeks and the second period saw three control beds and three heated beds investigated over a period of four months.

As before, a series of laboratory experiments were conducted in conjunction with the wetland studies to develop a system to heat the final ARBI modules (as mentioned earlier). This work was conducted using one of the small-scale ARBI prototypes. The in-lab experiments focused on the possibility of heating the wetland through hot air aeration, with heating in the bed monitored with both a thermocouple and a thermal imaging camera.

Two designs for this heating system were based around pushing compressed air past a heating element while the third one used a hot-air blower. This third design failed to provide a sufficient rate of air flow to visibly show aeration at the top of the bed and quickly overheated without inducing a temperature change.

The first compressor-based design used an air compressor. Air was passed through a 50 cm section of 22 mm diameter barrier pipe. The pipe was wrapped with 1 m of a commercial material with resistive heating elements woven into it. The voltage setting through the resistive filaments was set so that the temperature of the flowing air was 30°C (the heat of the actual pipe was much higher). After 15 minutes there was no change in the water temperature; however, the heat on the pipe had damaged the pipe integrity sufficiently as to result in a structural collapse, rendering it inoperable.

The final system used Nichrome wire heating element. The wire was wound giving coil 10 cm in length. The wire was installed inside of a 25 cm-section barrier pipe through which air was blown (Figure 4). The heating element did not touch the pipe, it also did not have to be as hot to heat the air to a higher level compared to the earlier design, thus putting less stress on the pipe itself. The second heating unit had an air temperature of 40 °C from the outlet. This allowed for a 1 °C increase in temperature in slightly over 15 minutes to the aerated part of the bed. A thermal image of the top of the bed is shown in Fig. 14.

Heating of the operational wetlands was by means of a commercial resistive heater set at 21°C located in the central zone of the bed (as was done with the aeration, to prevent disturbing the biofilms). With the implementation of greenhouses in the second period, the heated wetlands reached temperatures of around 25-26 °C. Temperature was monitored and controlled by means of a temperature probe located within the beds nearby the heating device connected to a data logger.

During period 1, the heating system was efficient and the temperature recorded nearby the heating device increased from 13.4 ± 1.4 °C in the control wetland to about 21.4 ± 4.5 °C in the heated (ARBI) wetland.

During period 2, temperatures oscillated slightly with the control wetland temperature increasing from 9-12 °C to about 18 °C when the greenhouse was installed. Similarly, in heated (ARBI) wetlands temperatures increased from 22-23 °C to around 26°C.

No clear differences between the two wetlands were observed during period 1. Chemical Oxygen Demand (COD) concentrations ranged between 350 and 520 mgO2/L in the influent and decreased to 150-180 mgO2/L in both beds.

Although differences were not clear, it was observed that during the 1st week of the experiment, the COD removal was slightly higher in the control wetland. This fact could be attributed to the hydrolysis and solubilisation of the organic matter present within the granular media of the ARBI wetland, which could have been favoured due to the higher temperature [23]. During the following week this trend changed, and better COD removal was observed within the ARBI wetland (12 %).
Solubilisation of a part of the retained organic matter in the ARBI wetland could have a positive effect on avoiding or delaying clogging. Thus, heating of a portion of the bed could be useful to remove part of the organic matter immobilized on the granular medium. COD concentrations for the second period are shown in Fig. 15.

In this period the COD concentrations in the influent was high and with a greater variability (610 ± 225 mg O₂/L). The first 65 days referred to cold conditions (February-March), while from day 65 to 100 refers to warm conditions (April-May with greenhouse). In general, the observed pattern was the same independently from when the greenhouses were placed above the beds on day 65. A certain positive effect of the heating system can be seen. In the cold period (from day 1 to 65), the average effluent concentrations of 211 ± 97 mgO₂/L and 171 ± 56 mgO₂/L were found in the control and the heated (ARBI) wetlands, respectively. During warm period (from day 65 to 100), the average effluent concentrations of 227 ± 36 mgO₂/L and 202 ± 35 mgO₂/L were found in the control and the heated (ARBI) wetlands respectively. COD removal in heated beds increased by 23 % during the cold period and by 12 % during the warm period. However, considering that effluents concentrations were similar throughout the whole experiment, it can only be concluded that differences in the COD removal between cold and warm seasons was due to the influent quality.

Concerning the ammonium nitrogen (NH₄⁺-N), during period 1 differences between systems with and without heating were not clearly observed. Effluent values were ranging between 27 and 32 mg NH₄⁺-N/L in both wetlands. The highly loaded influent was responsible for the high ammonium concentration in the effluent. Note that HSSF CWs were quite inefficient in N removal due to their prevailing anaerobic conditions, and effluent concentrations usually maintained rather constant independently of influent concentration [23]. Fig. 16 shows ammonium nitrogen concentrations along period 2. From day 30 a positive effect of heating on NH₄⁺-N removal can be observed, while no ammonium removal was obtained in the control wetlands. This was probably due to the positive effect of temperature on nitrification.

Concerning organic nitrogen, shown in Fig. 17, during the cold period average effluents concentrations were 15 ± 7 mg/L in the control and 12 ± 6 mg/L in heated (ARBI) wetland. In this case, organic nitrogen concentration in the heated (ARBI) wetlands was 15 % lower than in the control wetlands. During the warm period, effluent concentrations were the same in both the control wetlands and the heated (ARBI) wetlands (about 10 mg/L). These results confirm the strong effect that temperature had on nitrogen removal. The experiments highlighted that heating water can have a positive effect during the cold season, while warm air temperatures can already enhance nitrogen removal, without needing further water warming.

Experiments carried out during period 2 highlighted that heating water can have a positive effect during the cold season, reducing COD and organic nitrogen concentration by 23% and 15%, respectively. Nevertheless, warm air temperatures can already enhance nitrogen removal, without needing further water warming. On the whole, heating had a positive effect in the winter months, as expected. The final set of experiments regarding the optimal parameters for HSSF wetlands related to step-feeding. Experiments were conducted on (first) a pair of wetlands, one control and one where step feeding was implemented (ARBI) and then, in the second period on two sets of three beds (three control and three where step feeding was implemented). In the first period aeration (at a fixed set point) and heating (at 21°C) were in operation, whereas in the second period greenhouses were used to simulate a warm season for some of the experiment, but otherwise heating and aeration were not used. The feeding position was moved from the inlet (feeding position 1) to the middle part of the bed (feeding position 2) as shown in Fig. 17.

Fig. 18 shows the average COD concentration for the two feeding positions during period 1. Each feeding position was only used for three weeks. No clear differences of COD removal were detected between both wetlands. The average COD effluent concentration was around 100 mg/L in both wetlands. Moreover, no differences of COD removal were detected between the two feeding positions.

Period two saw each step-feeding position tested for close to a month. The COD concentrations are shown in Fig. 19. During the second period, the first 65 days refer to cold conditions (February-March), while from day 65 to 100 refers to warm conditions (April-May with greenhouses). In days 30 and 85 the feeding position were moved from the inlet (1) to the middle (2) part of the wetlands. As shown in the graph, the variability of the results indicated that no significant differences were detected during this experiment. Average effluents concentrations were 220 ± 75 mgO₂/L and 232 ± 65 mgO₂/L in the control and ARBI wetlands, respectively. The pattern was maintained when the greenhouse was placed above the beds on day 65 regardless of the feeding position.

Concerning ammonium nitrogen (NH₄⁺-N) during period 1, no differences were detected between the beds nor between feeding
positions. The effluent concentration was always between 24 and 31 mg/L.
Through the second period, the control and ARBI wetlands had similar efficiencies in term of ammonium nitrogen and organic nitrogen effluents concentrations (Fig. 20 and Fig. 21), showing no influence of feeding position in term of nitrogen removal. Average ammonium concentrations in the effluents were 25 ± 8 mg/L in the Control and 28 ± 7 mg/L in the ARBI wetland.
FIGURE 20
FIGURE 21
Ultimately this study did not show an improvement in treatment efficiency with step-feeding however this would be expected given the very short time scales that were explored compared to time scales that clogging occurs over. It is likely (based on the literature) that over a longer time scale an improvement with step feeding would have been observed. As such ARBI was still constructed with a basic step feeding system. The step feeding element had to be controllable in an automated fashion, so some kind of computer control was essential. A number of possible solutions were considered including using a linear actuator to physically move the inlet pipework. However, given that a simple two-step two-step-feeding system was chosen a three-way brass valve (designed for domestic central heating systems) was used to redirect wastewater to one feeding location or the other. The electronics that came with the valve body were not suitable for this application, so they were replaced with a servo which could then be computer controlled by the Technosam control system.
After this initial determination of optimal parameters for HSSF wetlands, specific values for the ARBI system were ultimately sort.
2. ARBI magnetic resonance sensor
The final ARBI modules required sensors to determine the clog state of the bed in a number of positions to both control the step feeding and to inform the operator of when the bed is about to become critically clogged so that it can be collected and replaced. Previously, work exploring MR sensors that could potentially be embedded has looked at a Helmholtz-style sensor [24]. This is a ‘bore-hole’ type of sensor where the explored sample has to be inside of the radio frequency coil. Another sensor design that can be used is a unilateral type where the sample to be explored sits on top of the sensor, allowing for very large samples to be investigated.
Selection of the ideal magnetic resonance sensor for monitoring a wetland environment required four major considerations. The principle consideration was the sensitivity to clog state as the final use of the device would be to make such a determination. Greater sensitivity to the clog state allows for an easier identification of the beds overall health and would be less prone to error. This parameter could only truly be determined through actual prototyping and testing.

The volume of the region interrogated by the MR probe was important as too small a volume may provide an unrepresentative analysis of the overall bed health. Also, on sensors where only a small volume was examined a large portion of this volume was in contact with the surface of the sensor itself. It was quite possible that this introduced edge effects. For example, in a wetland, biofilm might have used the sensor as a surface to grow on. This would bias results. Problems with adequate representation of the whole bed may have been mitigated somewhat by the inclusion of additional sensors. Similarly, if multiple sensors were used, edge effect could be minimised by introducing dissimilar sensor designs where the make-up of the bed itself would interact with the bed differently depending on the geometry. Computer simulations could go some of the way towards the selecting a geometry with a maximised sensitive volume, however the nuances of the construction itself and subtle differences in the magnets used for permanent magnet sensors would lead to variations from the computer model.

The cost of the sensors had to be considered, especially as a project like ARBI's terminal goal was to commercialise the module as a product. A number of commercially available MR systems, such as the NMR MOUSE® provide a very useful, small scale system for MR measurements in a laboratory setting for a fraction of the cost of a superconducting system such as a human imager. Even these systems are inappropriate for embedding into a wetland module long term as, despite alternatives, they still cost thousands to tens-of-thousands of euros. Bespoke constructed sensors should be possible for a fraction of the cost. Cheap sensors also allow for the possibility of multiple sensors to be embedded in a module, which was desirable for a more complete assessment of the overall bed health.

The final critical consideration was the signal-to-noise ratio (SNR) of the sensor while scanning material from a newly commissioned bed. Taking MR measurements on water is more technically challenging than a thickly clogged bed. While SNR can be improved by multiple repeat experiments, given spectrometer noise, as well as certain types of modulated noise from external sources, it was possible that a functional MR sensor might have been unable to detect water or thinly clogged wetland sludge as the signal may never meaningfully exceed the noise. This was obviously not desirable as a sensor near the bed outlet, or a sensors in a healthy bed would then not be operable. It was also desirable to not require very long experiments as the sensor and spectrometer required power to operate. The wealth of literature, coupled with computer simulations, could provide an indication of the designs that should have
yields the best signal intensity, but as with the other considerations a true gauge of the achievable SNR can only be achieved through prototype construction and testing.

Most of the sensor designs explored for ARBI consisted of permanent magnets (NdFeB were used as they were cheap), as other options such as electromagnets were not practical in a wetland setting, however an Earth's field nuclear magnetic resonance (EFNMR) probe was also considered [4] (but will not be discussed here).

Further to this, it was important to investigate how the sensors operation was affected by temperature changes (as NdFeB magnets are very temperature dependent [25]), such as those encountered in a wetland left outside. Ultimately the chosen probe design required testing in an operational wetland.

As discussed earlier many designs investigated for this application have previously been disseminated [4-11]. Different designs had divergent amounts of time spent on them depending on how promising the results were; some of these will be detailed below.

As explained earlier T1 is an effective gauge of clog state and therefore an important parameter to record during the testing of probes. T1 measurements were recorded by taking trains of echoes from a Carr Purcell Meiboom Gill (CPMG) sequence with different experimental repetition times. Echo integrals were summed to increase the overall signal strength and therefore reduce the required number of averages.

T2eff measurements were acquired using a Carr Purcell Meiboom Gill (CPMG) sequence where multiple collected echoes were fit as a function of time to extract this value.

Wetland samples explored during testing were either provided by ARM or taken from prototype wetlands at Nottingham Trent University.

An early design explored was the horseshoe arrangement (Fig. 22), which was successful for the NMR MOUSE® [26, 27]. This was a unilateral type of sensor. Initially a small unit was constructed from two N42 neodymium magnets (19 x 40 x 15 mm3) polarised in the 40 mm axis and separated by 7.5 mm (half the width of the magnets). The magnets were mounted on a ~ 5 mm ferrous (iron) base to improve the homogeneity of the field lines. The produced a 410 mT field between the magnets, with a gradient of 13.3 T/m in the B0 direction.

![FIGURE 22](image)

Coils were milled from PCB board with a number of simple hoop designs attempted; hand-wound coils from enamelled copper wire of an appropriate size were not attempted as fabricating coils of this size proved too difficult. While PCB board coils have been shown to work in the literature, and designs built for this project did operate correctly in a very homogeneous field (inside of a commercial Halbach magnet), attempts to make them work on any of the unilateral systems described in this work were unsuccessful. The exact reason of this is unclear but may be down to inadequate inductance in the coil region for these systems.

The small horseshoe system was unable to produce an adequate signal however the field profile suggested that the basic design was viable. This resulted in the construction of a larger unit where larger coils could be fabricated. This unit was built from two large N42 neodymium magnets (30 x 30 x 55 mm3) polarised in the 55 mm axis. The magnets were separated by 15 mm and held apart by acrylic spacers on one facing. The other three facings were built of acrylic and had the magnets glued to them using a strong two-part adhesive. Copper tape was attached on top of each magnet to shield the magnets from stray RF which can interfere with MR measurements. A layer of electrical tape was placed on top of this to protect the copper.

An iron base (~5 mm thick) was again used, however it was 5 mm away from the magnets due to the way that the arrangement was fabricated (Fig. 23). The field (B0) just above the magnets was 420 mT with an 8.1 T/m gradient in the B0 direction.

![FIGURE 23](image)

Initially the construction and use of PCB coils were attempted, included a double-sided butterfly design. Eventually a simpler design...
was attempted using a simple two-turn loop surface coil wound from 1 mm enamelled copper wire. Using this system signal was successfully collected from a rubber sample, however the SNR was prohibitively poor. Subsequently the design was abandoned. These experiments did ultimately validated a design of an in-house RF coil and associated circuitry that could function in an inhomogeneous magnetic field and this coil design was subsequently reused for the four magnet surface sensor.

Inspired by work by Chang et al. [28] a Halbach magnet (Fig. 24) was constructed from eight N42 neodymium magnets, where the homogenous stray field was intended to be used for MR measurements. The magnets were spaced using an acrylic former such that a 70 mm diameter was left. The magnetic field was 105 mT at the centre of the magnet gap just below (~5 mm) the top of the magnets, with a gradient of 1.6 T/m 25 mm away from the centre.

FIGURE 24
This high uniformity was favourable for successful MR signal collection however this was never achieved on this particular magnet. This was likely due to two reasons; the first and most likely was that the PCB board RF coils never performed well. These RF coils were not viable on other bespoke magnet arrangements (other than the highly homogenous field inside of a commercial Halbach) and there use on this magnet may have led to the failure of the sensor.

The second reason for poor SNR was the low operating frequency when compared to other systems explored. There is a square relationship between signal-intensity and the operating field strength which may have led to prohibitively low SNR in this case. As a consequence the next sensor design (the Halbach-derived four-magnet surface sensor) was built to have a much higher operating field strength.

Given the issues later discovered with the PCB board coils it was evident that the Halbach design may have proven viable.

A four-magnet (Halbach inspired) surface sensor was next attempted. Inspire by the low cost Halbach array by Hills et al. [29] four 30 x 40 x 40 mm3 N42 neodymium magnets polarised along the 30 mm axis were placed with a 30 x 40 gap in the centre, as shown by Fig. 25. Magnets were mounted on five 1.5 mm thick steel to reduce the overall field gradient. Three prototypes of this design were built. One version worked significantly better than the other two, however this unit became damaged at some point and after repairs were made never worked as well as the other magnets (these measurements have not been presented in this report).

FIGURE 25
Once the sensors correct operation was confirmed T1 measurements were explored. T1 was recorded as described above where were recorded by taking trains of CPMG echoes with different experimental repetition times using the Kea spectrometer. The data below (Fig. 26) represented a very thick sample compared to a very thin one and has previously been published [5].

FIGURE 26
The T1 values showed a significant difference for the two samples, with T1 = 127 ± 27 ms for the thick sample and T1 = 915 ± 212 ms for the thin sample. This made the four magnet surface sensor a suitable choice for testing in wetland.

Additional laboratory tests included ensuring that the sensor would not behave differently when embedded in gravel and water, as the change in the surrounding conditions on the system may have made measurements prohibitive. For this experiment a bottle containing a thick wetland sludge was attached to the surface of the sensor and the entire assemble was surrounded in a plastic bag and buried in a gravel-water mix kept in the laboratory. This allowed for successful measurements.

Other experiments investigated how far away a sample could be from the sensor and still be detected. For this glass slides (1 – 1.5 mm) were placed between the sample bottle and sensor and MR measurements were attempted. It was seen that MR was consistently possible with only a single slide. Given the sample container thickness this showed a sensitive region of ~2 mm.

With appropriate evaluation for the MR sensors suitability conducted a unit was water-tightened by coating it in a silicon elastomer potting compound. Laboratory tests saw a portion of the elastomer of about 1 mm thickness placed on the RF coil. Once the compound was confirmed to not be MR active, the experiment was repeated with the sample on top, and allowed for successful measurements also. This method of water-tightening was likely unsuitable for long term embedding due to impairment that might occur to the silicon coating over time or physical damage from motion during transport. Minor damage was experienced in field testing and the modelling putty (was used to re-enforce edges and the electronics were the elastomer was more prone to breaking.
The MR sensor was buried in a Nottingham Trent University test wetland and the Kea spectrometer used to perform experiments. Unfortunately the SNR collected with the sensor was extremely poor and completely prohibitive to taking relaxation measurements. This was partly due to the inability to re-tune the probe (in the configuration presented) when it was embedded due to the proximity of the tuning board to the coil. This resulted in poor tuning and matching of the RLC circuit once the system was buried.

Despite the initial failed attempt a second try at field testing was attempted. For this unit the cabling between the coil and RLC circuit was extended allowing for easy retuning. Additionally a diluted ABS mixture was used to water-tighten the probe. This probe was embedded into a wetland at an ARM site. Unfortunately to date this has not managed to produce acceptable enough signal to carry out relaxation measurements.

The simplest unilateral magnet arrangement is a single bar magnet, as proposed by Blümich et al. [30]. Two large cylindrical magnets were attached together by their own magnetic force to provide an approximately 0.5 T polarising field at the surface of the magnet (Fig. 27). This was covered with copper tape to reduce RF loading of the magnets.

FIGURE 27
While able to collect signal adequately, recorded T1 measurements were not able to distinguish between different clog states, as shown in Fig. 28.

FIGURE 28
The lack of sensitivity to clog state shown by the prototypes made the design unviable as a clog sensor and therefore exploration of the design was discontinued. Additional work was conducted allowing for the for the reason for this lack of sensitivity to be determined, this being an unacceptably large magnetic field gradient. More details are available in the previously mentioned manuscript [5].

Due to the issues found with the four magnet surface sensor when embedded in a wetland, the Helmholtz-like magnet arrangement was re-examined. Multiple Helmholtz designs were constructed for this work, however they largely fall into categories of size. Most of the sensors used a pair of cylindrical neodymium magnets (height = 20 mm, radius = 17 mm) like the example shown in Fig. 29.

FIGURE 29
Figure 29 shows a sensor of the final design used in ARBI. Here the magnets were separated by 20 mm by a 3D printed ABS housing. Many of the earlier prototypes used laser cut casings as seen on the larger probe in Fig. 30 where larger N35 neodymium magnets (diameter = 75 mm, height = 20 mm) where utilised, allowing for a larger central solenoid.

FIGURE 30
Despite the larger sensitive volume the larger Helmholtz-style sensor had a significantly poorer SNR than the smaller sensors, so was abandoned.

A probe similar to type shown in Fig. 29 used to collect a T1 measurement while embedded in a wetland. This measurement, along with additional laboratory measurements on wetland samples from ARM, is shown in Fig. 31 (previously published elsewhere [6, 10]).

FIGURE 31
Samples were dried out in the laboratory to determine the percentage of dry solids. From this a relationship between the percentages of dry solids in a sample to the T1 relaxation time could be found. As expected a higher percentage of solid material in the sample led to shorter T1 times.

As this type of sensor was able to make clear distinctions between different clog states, and was able to operate correctly while embedded in a wetland it was chosen to be used for the final ARBI probe. Subsequently a number of these probes were constructed and embedded in both the final ARBI modules as well as already mature beds managed by ARM. Prior to this however, a series of final optimisations had to be made to the design to optimise its operation.

Further improvements were possible when the prototypes were built as a significant number of magnets had to be purchased. Due to the nuanced differences in field strength between magnets, and the desire to create MR probes with as small as possible a field...
gradient to achieve the greatest possible signal intensity, it was important to match the magnets to one-another carefully. The magnets were therefore separated from their shipping container, numbered and each had their magnetic field measured.

The magnets were then matched to one another using a piece of Matlab code written specifically for this purpose. Given the large volume of magnets required this allowed for the construction of probes with very well matched magnets (far better than the earlier prototype sensors), hence yielding far superior signal intensity.

The sensors operation as a function of temperature was explored for both the Helmholtz-style sensor and the four magnet surface sensor [9]. Ultimately for the four magnet surface sensor the position of the invested ROI changed with temperature as the magnetic field corresponding to the RF coils resonant frequency changed. Early results for the Helmholtz-style sensor saw large reductions in signal intensity at the upper and lower limits of what was requires (broadly speaking 0 °C up to 45 °C, the largest temperature range that was likely to be encountered while the probe was embedded in a wetland). The early results differed somewhat from later studies due to the superior magnet matching of the final probes (and hence the favourably lower field gradient).

As the reduction in the signal at non-optimal temperatures was believed to be due to the region between the magnets with a field relating to the pulsed RF signal moving up or down as the magnet field strength changed, any alteration in the field gradient could have a major effect on the sensors operation at different temperatures. In a worst case scenario, the reduced field gradient may have resulted in non-operation at extreme temperatures.

This also led the way to other vital research that had to be conducted in the lab. In order to understand the data collected by the probes, it was very important that the relaxation parameters T1 at different temperatures.

While T1 was determined to be the parameter that needed to be collected, it was still vital that another parameter, T2eff, was understood to some extent. T2eff can be collected using a CPMG sequence and is a measure of the dephasing of precessing spins. This sequence was also used to collect T1 which took advantage of summing multiple echoes resulting from a series of refocusing pulses. In order to do this correctly the summed echoes must not show any significant decay in signal (shown by T2eff) or the T1 would become T2eff weighted, which would skew the recorded values.

T2eff is partially dependant on diffusion of the spins within a magnetic field gradient. As the gradient of these sensors will change slightly with temperature, so would the T2eff value recorded. Other factors that might affect T2eff include clogging and the temperature of the sample. Clogging was previously seen to have a minimal effect on T2eff for sensors of this design [6] so can be discounted. T2eff as a function of temperature is not well reported in the literature, but as temperature will affect the diffusion of the spins within a field gradient, may have a significant effect: A short study was therefore conducted to investigate.

This understanding allowed for the correct number of echoes over the relevant temperature range to be collected. A future version of ARBI could use this information to automatically optimise the number of echoes to keep the number of experimental averages to a bare minimum and therefore minimise the time that the spectrometer is kept on.

The most vital set of laboratory experiments was an investigation into the T1 values as a function of temperature, especially for clogged samples, so that clog state could be more easily extracted in a system where the temperature was high or low. The effect of temperature on the T1 relaxation time in water is well known and reported in the literature [31-33].

The central magnetic field strength of the Helmholtz-style sensor was known to change with changes in temperature. This has been shown in Fig. 32.

FIGURE 32

The graph showed a close to linear relationship, in keeping with the theory, with the linearity breaking down slightly at the extremes of the temperature range explored. The relationship shows a change of 0.0003 T/°C. It was also important to know the gradient of the magnetic field within the coil region of the sensor was measured at room temperature (22 ± 1 °C). With the orientation shown in Fig. 9 the gradients were found to be Gx = 0.29 ± 0.03 Tm⁻¹, Gy = 0.15 ± 0.06 Tm⁻¹, Gz = 0.46 ± 0.06 Tm⁻¹. A network analyser was used to find out the maximum bandwidth of the coil, which was determined to be 0.5 MHz. Given these gradients and the range of frequencies that the coil was able to excite, it was apparent that at no time would the entire volume of
Given this consideration, it was possible that a frequency corresponding to the centre field of the probe would not in-fact yield the highest MR signal at a given temperature, so instead a range of frequencies, from 10.2 MHz up to 11.5 MHz were investigated. Initially the probe was kept at room temperature (18 ± 1 °C). A frequency would be set, the probe would be tuned and matched as best as possible (this varied slightly, with the value of the absorption of energy at the desired frequency being recorded each time). A pulse calibration would then be run to acquire the optimal pulse length. The probe would be re-tuned if necessary and CPMG sequence (τE = 150 μs, 64 echoes, 16 scans, 15 000 ms repetition time) was run; the echoes would be summed and this would be used to obtain an integral. For each frequency this process was repeated three times (four measurements in total). Experiments were then repeated at the high and low ends of the temperature range of interest, with results displayed in Fig. 33.

FIGURE 33

It was observed from Fig. 33 that at higher and lower temperatures that the signal intensity was generally less than at room temperature. This was also true for when the probe was tuned to its optimal frequency at a given temperature, however it appeared that when colder an overall higher signal intensity could be achieved compared to when warmer. In both cases, the probe did not perform as well as it did at room temperature.

There were many contributing factors to why this might have been the case; primarily at warmer temperatures the field strength of the sensor would decrease. Field strength was known to have a square dependence with respect to the signal intensity collected [34] so a reduction of signal would be reasonable. An increase in signal intensity was not seen at lower temperatures, however other contributing factors may have had influence such as the magnetic field gradients that may have increased as the temperature reduced. This would have led to a signal reduction as a result of additional dephasing. T2eff measurements taken later in this study seem to support this theory. It was interesting to note that the optimal operating frequencies at each temperature did not correspond directly to the center frequencies presented in Fig. 32, with all of the frequencies shifted slightly higher. This suggested that a higher portion of the sensors sensitive volume was at a higher field strength than at the center.

It is also important to recognize that at different frequencies, different pulse durations were used, altering the bandwidth of the excitation. This would have an effect on areas within the solenoid that could be detected.

A graph of signal intensity as a function of temperature was produced (Fig. 34). Different devices were used to bring the probe and sample to a given temperature and then maintain the temperature throughout these were a domestic refrigerator, leaving the probe outside, lab temperature, and a convection oven set to two different temperatures (usually 40 °C or 50 °C). Each scan was conducted with the B1 frequency set to 10.7 MHz (a compromise between the centre frequency, and frequency of the highest signal at room temperature), with a repetition time between experiments of 15 000 ms to allow for full T1 relaxation of the water. Measurements were taken using a CPMG sequence with 64 echoes (τE = 150 μs) summed; 16 experimental averages were used for each measurement.

FIGURE 34

It was observed that the drop in intensity between the peak and high or low temperatures was roughly a factor of two and a half. Most importantly the sensor was seen to work over the entire temperature range of interest.

A cause of the drop in signal intensity could plausibly be due to off-resonance effects. In a system such as this (where there is a large static magnetic field gradient) multiple coherence pathways contribute to each overall echo amplitude. These effects have been investigated thoroughly in the literature [35] partly due to their importance for well-logging applications [36]. In a sample where the diffusion in the stray field gradient is not negligible, contributions from the coherence pathways that are off-resonance will decay rapidly compared to the on-resonance contributions [35]. As the on-resonance region within the RF coil moves with temperature changes, the contribution from off-resonance coherence pathways will increase. The more rapid decay of these pathways will therefore lead to a smaller overall signal intensity in these cases.

Changes in the optimal pulse length at high and low temperatures were not believed to be a major cause of signal loss. This was supported by running a pulse length calibration at various temperatures, where no major difference in the pulse length was observed.
As the drop-off in signal intensity was believed to be due to the region within the coil where MR was possible (i.e. where the field matched the frequency of the RF excitation) moving as the strengths of the constituent magnets changing it would stand to reason that at high or low temperatures regions within the coil would no longer allow for MR detection, or would produces a poorer SNR as the spins would be excited off-resonance. To understand this better a 1.15 ± 0.05 mm ID capillary tube was filled with water and magnetic resonance measurements were taken with it at different locations in the at the extreme edges of the coil as well as the centre. At room temperature (20 °C) the signal intensity was independent of the location of the capillary tube within the coil. The entire system was heated (to 52 ± 1 °C) and the experiment was repeated. This showed little difference in the overall signal intensity integral depending on the capillary tubes location, however some change in the SNR was noticed. This may have been due to a change in the background noise between experiments given the relatively poor signal intensity when the very sample capillary tube sample was used. Finally the system was reduced in temperature (to 9 ± 1 °C) and again the capillary tube of water was scanned at the five different locations with minimal differences observed.

This is a very important feature to know as it validates the measurements taken by the probes over the temperature range of interest. Changes in the magnetic field gradient over the sensor caused by the field altering with temperature would affect the recorded T2eff value. T2eff is the relaxation time recorded where the decay in signal intensity due to diffusion within a field gradient is also accounted for as is known by the theory [35]. Hence, changing the temperature would change both the gradient and diffusion components of the T2eff value.

Four T2eff measurements were taken at six different temperatures in a situation where the probe was submerged into the water sample. In all cases the probe and sample were kept at the relevant temperature for at least one hours to ensure that the magnet assembly was at the desired temperature. Temperature readings were taken with the k-type thermocouple submerged into the water. These results are shown in Fig. 35.

FIGURE 35

T2eff is seen to increase with a decrease in temperature until 5 °C. It has been observed here that where the graph gradient has been significantly reduced, the diffusion of the water within the gradient seems to dominate. Literature values were sought to better understand this important relationship, however the information was not forthcoming. Given this important omission in the literature a brief study into understanding T2eff of water as a function of temperature was therefore conducted. Here a straight linear relationship was observed, with the T2eff increasing with decreasing temperature. This implied that the drop seen in Fig. 35 was due to an increase of the field gradient at lower temperatures.

T1 is known to change with temperature (first shown by Bloembergen et al. [33]) which is now well understood and in the literature. Generally speaking the relationship between T1 and temperature is linear over a small range of temperatures depending on the exact nature of the sample.

Four T1 measurements were taken at five different temperatures in a situation where the probe was submerged into the water sample. As before the temperature readings used a submerged k-type thermocouple and used the general heating and cooling protocol described before.

The exact nature of what was occurring in this system can be better understood when literature values are examined. Simpson and Carr have published a comprehensive study of T1 as a function of temperature for oxygen-free water [31]. They are not the only people to record this type of relaxation data and a comprehensive review of work conducted by their contemporaries has been provided by Krynicki [32]. While these experiments did not use deoxygenated water, Simpson and Carr’s work should still provide a reasonable approximation for the ARBI data and is presented below (Fig. 36).

FIGURE 36

It was clear that the general trend was the same, and the intercept for both datasets were within the error of one another, the gradient was different. There were a number of potential reasons for the discrepancy in the gradient, the use of non-deoxygenated water being the most likely candidate. As highlighted by Krynicki [32], earlier work often disregarded the important role that dissolved oxygen (which is highly paramagnetic) might cause on the relaxation values.
It was an interesting comparison to look at the T1 value taken for water at 20 °C recorded by Bloembergen et al. [33] who did not use deoxygenated water (a close approximation to these experiments) saw a T1 time of 2.3 s. This value agrees closely with the results of this study where T1 at 20 ± 1 °C was found to be 2.5 s.

With the methodology to obtain T1 at different temperatures established, and the validation the sensor is operable at multiple temperatures, a study into the spin-lattice relaxation as a function of temperature was conducted on a variety of wetland samples at different clog states. This vitally important study allowed for an in-lab determination of different clog states over the temperatures experienced over a seasonal cycle. This allowed for an accurate understanding of how seasonal variation would affect the probes where random parameters could be more easily controlled, and the measurements could be repeated multiple times under exact repeat conditions.

Shown in Fig. 37 are three different samples. A sample taken from the Nottingham Trent wetlands before being filled with propylene glycol (essentially gravel and water) representing a newly commissioned bed, a sample from a fairly newly commissioned bed at ARM (using ~20 mm gravel), and a sample from a mature bed from ARM (this bed was not close to becoming non-functional).

T1 relaxation times were collected using the same method described for the water T1 experiments with the probes embedded in the sample. It is important to note that due to the different specific heat capacity of gravel compared to water that the samples were required to be kept at temperature for approximately 5 hours (this information was gained from a series of preliminary experiments not shown here).

For the samples comprised of 10 mm gravel it was observed that the relationship seen was largely unaffected by temperature with the exception of being at the extremes of the probes operating temperatures (this was not strictly true for the -1 °C value, however this was below the operational temperature of both the probe and the ARBI module). Changes seen at the edges of the operating temperatures are likely due to the regions of the sample that the MR probe was collecting data from, as this would change depending on the temperature of the magnets as discussed earlier. To fully understand the relationship however this study would need to be repeated with only the temperatures of the samples being changed. Interestingly, for the sample where larger gravel was used the relationship between temperature and T1 time was linearly dependant, like for water. 20 mm gravel could not easily fit inside of the probes coil aperture where 10 mm gravel easily fit inside. The presence of gravel in the coil was presumably the cause of the different relaxation relationship observed.

For ARBI however, where only a ‘clogged’ or ‘not clogged’ status was really required, the apparent temperature independence would still allow for a reasonable estimate of clog level.

For the testing phase of ARBI, the beds constructed at Nottingham Trent University were earmarked for treating industrial wastewater. It was decided that propylene glycol would be used for this task as this is used as a type of aviation antifreeze [36], with a typical aviation antifreeze containing about 70 % propylene glycol diluted by water. The use of this type of wastewater introduced a new parameter that would influence T1 measurements as propylene glycol is a proton containing compound, and hence was directly detectable by NMR.

A brief literature review did not reveal any information regarding relaxation times and concentration of propylene glycol in mixed solutions with water as those that would be present in the ARBI test wetlands. A study of this type was conducted in the lab. Eight different samples were prepared with varying concentrations of propylene glycol in solutions with water. A water sample was also investigated. T1 measurements of the protons in the bulk solution were taken as previously described and plotted against the propylene glycol concentration as determined by a HI 96832 Digital Propylene Glycol Refractometer (Hanna Instruments, Woonsocket, RI, USA) as shown in Fig. 37.

FIGURE 36

The trend is approximately linear allowing the use of refractometry to correct for the shift in the MR measurements of clogging. This work was previously presented elsewhere [11]. It was important to note however that the propylene glycol concentration may only limit the maximum T1 relaxation time that was recordable, with the clog state still being the dominating factor. Given that low concentrations of propylene glycol still allow for long T1 relaxation times, in practice propylene glycol concentration may not have a significant effect on recorded values in an actual wetland. The maximum concentration of hydrocarbon glycols comprising the influent at Heathrow airport would be around 1.5 % providing a very long T1 time, far longer than the T1 times that clogging would allow.
It was also highly important to understand how the probes would operate in active wetlands, and how seasonal developments might change the recorded T1 values. The main seasonal change was known to be temperature, which was why the laboratory work focussed so heavily on the understanding of temperature effects. The long term observation of the probes covered two locations, the ARM facilities in Staffordshire were used to monitor a domestic wastewater influent system, and the prototype ARBI modules at Nottingham Trent University were used to monitor an industrial wastewater situation, in this case an influent containing propylene glycol.

An example of the wealth of T1 relaxation data taken at the ARM facilities has been shown in Fig. 37.

**FIGURE 37**

It was clear that different probes were detecting different clog conditions depending on their location. Of more interest was the season change. In line with laboratory results with temperature, clog state measurements were seen to change very little over the course of a matter of months as shown in Fig. 38.

**FIGURE 38**

Broadly speaking, when the factors above are considered, the data shows little to no difference with seasonal change. This was further supported by the temperature dependence measurements taken in the laboratory which showed that temperature change should make no difference to recorded T1 times.

Each of the Nottingham Trent prototype wetlands had four probes installed, giving a total of twelve probes. After initial testing six of these probes were measured regularly. The recorded MR measurements have been included here however to give an example of the variation seen in a system using propylene glycol (Fig. 39), which was not possible at ARM’s facilities. The T1 measurements for these experiments went out to a repetition time of 4.5 s, which was long enough for all of the T1 values recorded in the data presented.

**FIGURE 39**

It should be noted that the presented results here were all taken before significant biofilm growth was believed to have occurred in the Nottingham Trent wetlands.

With the notable exception of Probe 42, the T1 values recorded for all of the probes does not appear to change significantly over the time frame shown above. This was an interesting and useful result as over the time frame of these experiments the average propylene glycol concentration in the beds dropped from 19.1 % to 14.6 %. Based on laboratory experiments this would have been a $T_1 \approx 1200 \text{ s}$ increasing to $T_1 \approx 1450 \text{ s}$. Except for probes in Bed 1, all of the values collected are below 1250 s (within the error of 1190 s), with most lower than this value. This seems to suggest that something other than the propylene glycol concentration is the limiting factor for the T1 relaxation. The most likely limiting factor being particulate content.

Ultimately an understanding of how seasonal variation (primarily temperature) effects the operation of the probes and the values that they record has been obtained. Ultimately the laboratory work showed that the T1 measurements were reasonably insensitive to temperature changes, which was unexpected given the sensitivity of the T1 of water to temperature changes. In situ monitoring at ARM saw little change in the recorded T1 values over the course of three months. This would be expected given that monitoring occurred in mature wetlands so little change was expected in the clog state. It has been concluded that although propylene glycol concentration does effect T1 relaxation time, it appears to only limit the maximum time and therefore should not require additional consideration for the ARBI modules.

Further MR work explored the construction of a cheap spectrometer to use with the ARBI probes. Ultimately it was demonstrated that through a lengthy evolutionary process it was possible to construct an MR console using off the shelf components and software development. The total cost of the console was around EUR 500. The console was benchmarked this against a commercial console and found that the values for T1 measurements are within experimental error. Fig. 40 shows T1 experiments using the red Pitaya based system compared to a commercial system (the Apollo) showing similar results for a sample of oil.

**FIGURE 40**

3. ARBI prototype testing
Ultimately seven prototype ARBI modules were constructed based on design decisions made through a careful review of the literature, laboratory based material testing, and prototyping. The final module was designed to ensure that the module was capable of withstanding the stresses imparted to it, through the treatment media and external environment whilst being suitable for transport on a skip lorry. ~10 mm gravel was chosen as the bed treatment medium. The bed dimensions were 120 x 220 x 103 cm³. The modules comprised a steal outer cage with lightweight composite panels inside and a welded EDPM membrane. The prototypes used for testing the domestic and industrial wastewater had bolted-together steel cages; the final prototype design had a welded cage compatible with a skip lorry.

For the prototype testing the prototypes can be split into two sets. Each set included three beds: a bed lacking aeration, heating, and step feeding, a bed with aeration applied constantly, and a bed with aeration controlled such that a given set point was maintained. Of the two sets of beds UPC dealt with domestic wastewater treatment while Nottingham Trent explored the viability of using the beds to treat industrial effluent (in this case propylene glycol).

A picture of the construction of the experimental plant at UPC (Barcelona, Spain) for the treatment of domestic waste is shown in Fig. 41, and a picture of the experimental plant at Nottingham Trent University (Nottingham, England) is shown in Fig. 42.

FIGURE 41

FIGURE 42

For both experimental plants aeration was provided by means of aeration pipes (outer diameter of 15 mm) as described in deliverable 5.3 and were located on the bottom of two of the beds. The system of pipes was connected to an air compressor. Dissolved oxygen within the three wetlands 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).

One bed was continuously aerated (24h per day), while the aeration of the second one was controlled, setting oxygen concentration at a given set point by means of a control program of the data logger (control Deadbond version 2.5). This value was chosen in accordance with the previous experiments carried out within the ARBI project.

In addition, pH (K01TVPLD, Oxyguard, Denmark) and RedOx (K01TVRLD, Oxyguard, Denmark) probes were installed in the influent and in the 3 beds. Data gathered was monitored by the Pacific control unit, which was a measuring, monitoring and control system developed by Oxyguard.

For the domestic wastewater situation raw wastewater came from a building hosting around 50 people was treated in a septic tank. From there it was stored in a stirred tank until it was fed to the 3 beds constituting the experimental plant. Beds were automatically fed by means of peristaltic pumps regulating the flow at 190 L/d in each bed. Step feeding effects were tested by moving the feeding pipe from one side of the bed to the opposite side (long side). Each feeding position was tested during 22 days. Position 1 was tested from the 15th of May until the 22nd of June, while position 2 was tested from the 23th of June to the 29th of July.

Water samples were collected firstly twice and then three times per week from the influent and from the effluent of the wetlands and immediately analysed for Chemical Oxygen Demand (COD), total nitrogen (TKN), ammonium, nitrites and nitrates according to the Standard Methods for Wastewater Treatment.

For the industrial wastewater monitoring all three beds were fed with a propylene glycol solution through gravity using industrial wastewater 1000 L IBC was raised above the height of the influent position. The flow was controlled through taps that were manually adjusted to a position to acquire the optimal flow rate. For the industrial wastewater treatment testing propylene glycol measurements were also taken (using a Propylene Glycol Refractometer). It is highly important to note that for much of its operating time the propylene glycol concentration was far higher than that that would have been found in a typical industrial effluent (~1.5 % or less). Literature seemed to indicate that the biodegradation of propylene glycol should have produced a significant build-up of biomass [37] and it had been hoped that at this higher feeding-rate would induce rapid clogging, however MR probes measurements indicate that this was not the case. Therefore, while the industrial wastewater beds were capable of step-feeding, step-feeding was not at any point employed on these beds.

A determination of the treatment efficiency for the industrial wastewater was only attempted after the beds had been established for a number of months to allow for a build-up of biofilm but also so that the comparison could be made at a stable (lower) propylene glycol
concentration.

Fig. 43 shows the dissolved oxygen concentration recorded in the 3 beds used to treat domestic wastewater. Data clearly shows the effect of aeration. In the bed without air injection, oxygen concentration was always near to zero. In the bed with intermittent air injection oxygen concentrations ranged between 0.5 and 2 mg/L. This pattern was due to the high power of the compressor used for air injection, in fact when oxygen concentration decreased to the set point a valve opened and air was injected, reaching values up to 2 mg/L. On the other hand, when air was injected over 24h, oxygen concentrations were more stable, oscillating between 7 and 8 mg/L.

FIGURE 43

Similarly, oxygen concentrations for the three prototypes used to treat industrial effluent as well as the storage tank were also recorded over the course of the wetlands operation (Fig. 44). It can be seen that most of the time the dissolved oxygen level is high for all of the beds (including at times where the tank readings were zero – this was likely due to the tank being empty at these times).

FIGURE 44

It was of interest that clearly the industrial wastewater typically had a far higher dissolved oxygen concentration to start with than for the domestic wastewater beds. It is quite possible that this was due to the fact that the industrial wastewater beds were situated in the United Kingdom, whereas the domestic wastewater beds were located in Spain. The UK is subject to more rainfall than Spain, especially in the summer months, so the domestic wastewater beds may not have been exposed to signicant quantities of rain. Due to this it was difficult to extract useful information about the efficiencies of the aeration system from the beds processing industrial wastewater.

In accordance with the summer season in Spain, water temperatures for the domestic wastewater wetlands oscillated between 21°C and 32°C, for this reason heating was not tested in this system.

FIGURE 45

Similarly temperature measurements from the wetlands for industrial waste water treatment were also monitored over the course of their operation and these results have been shown in Fig. 46 below. It can be seen from the graph that despite the relatively high temperatures during the English summer the temperatures recording in the beds were surprisingly low, in particular for the constantly aerated bed.

FIGURE 46

Based on the known ambient temperatures it was understood that the temperature values acquired from the OxyGuard probes was not representative of the temperature values within the beds. Therefore the manually recorded temperature measurements taken during magnetic resonance experiments were plotted, as shown in Fig. 47.

FIGURE 47

Here the temperatures are all above 14 °C (but were typically above 15 °C) making the need for heating unnecessary. This also allowed for a better comparison with the beds in Spain, which were also not heated during this series of experiments. The discrepancy in the recorded values was slightly concerning, however can be explained by the placement of the probes. A 'sample' box was used to record measurements, with the Oxyguard® probes installed. These boxes were typically shaded by the bulk of the wetland, additionally the smaller volume compared to the beds would result in more rapid equilibration with the ambient temperature. This is further supported by the fact that the 'Air 24h' bed having consonantly lower temperatures in Fig. 46, as this bed was in the most shaded (and therefore cooler) location.

Redox values were similar in the 3 beds used to treat domestic wastewater and in the storage tank for the whole experiment, ranging between 250 and 300mV.

Redox values for the non-aerated industrial wastewater bed varied between 0 and 150 mV throughout the study, while the redox values observed for the other two beds varied between roughly 150 and 300 mV for the beds until late July when the readings took a sudden drop and typically stayed between 0 and 150 mV (see Fig. 48). The reason for this sudden shift is not forthcoming.

It is of interest to note that the non-aerated bed appeared to have microbial growth far earlier in the study than the other two beds (biofilm could be clearly seen in this bed). Hence, it is possible that the drop in redox in late July for the other two beds was an indication of when significant microbial activity and growth started, as a reduction in the redox activity does imply an increase in microbial activity.

FIGURE 48
The establishment of biofilm in the non-aerated bed earlier than the others may be due to the more hostile environment for the initial establishment of biofilms that an aerated bed provides. This was also coupled with the high propylene glycol concentrations observed, and a combination of these two factors may have prevented a significant establishment of biofilm in the aerated beds until the propylene glycol concentration had decreased significantly. Measurements here also taken for the pH in both the three beds and tank for the domestic wastewater (Fig. 49), and for the three beds treating industrial wastewater (Fig. 50).

FIGURE 49

FIGURE 50

From Fig. 49 (for the domestic wastewater) pH was seen to range between 7 and 8 in all the of beds; while pH values for the tank ranged between around 7.5 and 8.5. This was similar to the values observed in the industrial wastewater beds, however the general trend observed in these beds was a gradual decrease over the course of the experiments. This was likely due to the slightly alkaline nature of propylene glycol, as seen later, the propylene glycol concentration dropped significantly over the course of the experiments.

It was of great interest during the study of the prototype wetlands to determine the absolute maximum concentration of propylene glycol that could be processed by the wetlands. While glycol-based wastewater, such as airstrip runoff would typically be mixed with storm water, this would not always be the case, especially in the summer months leading to very high propylene glycol concentrations in the wastewater. Additionally other industrial processes produce wastewater and having an indication of the limitations would be useful to identify ARBI's viability for these other applications.

While literature exists on the degradation of glycols, little of it has focussed on the maximum level that can be treated. Castro et al. [38] identify that Beaumont et al. [39] have demonstrated that soil based treatment could effectively treat solutions with up to 20 % propylene glycol, which was far higher than the percentages typically investigated. A study at an airport by Wallace and Liner have employed concentrations of exceeding 5 % which was successfully treated with a vertical subsurface ow constructed wetland [40].

Based on the literature the ARBI constructed wetlands earmarked for industrial waste treatment were initially intended to run at 20 %, with the concentration being diluted over time. Obviously, it was important to monitor the propylene glycol concentration for the industrial wastewater treating beds as the concentration had the potential to have knock on effects on pH reading MR measurements, and the bed treatment efficiency. The concentration as a function of date has been shown below (Fig. 51).

FIGURE 51

The general trend has been a reduction in the concentration over time. Day 31 corresponds to 8th June, where most of the other data for the industrial wastewater bed in this report was recorded from.

When compared to the redox potential, it was observed that for the two aerated beds microbial activity appeared to increase significantly on the 12th July for the continuously aerated bed, and the 17th July for the automated bed, corresponding to propylene glycol concentrations of approximately 8.1 % and 8.5 % respectively.

Obviously, a very important set of results were those taken monitoring water quality. Fig. 52 shows COD concentrations in the inuent and in the 3 beds in the domestic wastewater testing plant. The mean inuent concentration was 118 ± 62 mg/L, with some pick up to 300 mg/L. COD removal was observed in the 3 beds, where the mean concentrations were 68 ± 14 mg/L and 53 ± 12 mg/L in the aerated beds (continuous and partial, respectively) and 61±14 mg/L in the non-aerated bed. Such values correspond to removals between 45 % (partial aeration) and 57 % (continuous aeration). The results from the 3 beds were significantly different (p<0.05).

Aeration seems to have a slightly positive effect on COD removal only when intermittent aeration was applied. No differences were detected between feeding positions.

FIGURE 52

Concerning Total Kjeldhal Nitrogen (TKN) (Figure 23), inuent concentrations ranging between 10 and 40mg/L were reduced to 10-15 mg/L in the bed without aeration. On the other hand, when air was injected, concentrations were reduced to about 3 mg/L. In this sense, the difference between the two aerated beds was not significant (t=0.76; p>0.05). However, both beds were significantly different from the one that was not aerated (t= 3.11 p<0.05 between Air 24h and No air; t=6.64 p<0.05 between Air 0.at set point and No air). Results
indicated similar removal for continuous and intermittent aeration. This suggested that the set point was already sufficient to remove TKN, thus continuous aeration was not necessary to improve TKN removal. Also in this case, no differences were detected between feeding positions.

Similar results were obtained for ammonium (Figure 24) and organic nitrogen (Figure 25) that were calculated by subtracting ammonium from the TKN. In both cases the aerated beds showed significant lower concentration than the bed without aeration and the influent (p<0.05). In the case of ammonium, concentrations of 15±11 mg/L present in the influent were reduced to 7±3 mg/L in the bed without aeration. Values near to zero were obtained with both partial and continuous aeration. For organic nitrogen, influent concentrations of 9±4 mg/L were reduced to 6±3 mg/L in the bed without aeration, while significant lower values were found in the aerated beds (4±2 mg/L) (p<0.05).

From Fig. 56 and Fig. 57 it was evident how the aeration influenced the nitrification/denitrification phenomenon. A quite high amount of nitrite and nitrate was present in the influent (4±2 mg/L and 8±4 mg/L, respectively). Similar values were found in the bed without aeration. Concerning the aerated beds, the higher amount of nitrate (21±9 mg/L) was found in the continuous aerated bed than in the partial aerated one (12±7 mg/L). In this sense, partial aeration can be useful to reduce the amount of both nitrate and nitrite. In fact, considering the total nitrogen as the sum of TKN, nitrite and nitrate (Fig. 58), intermittent aeration can achieve significantly (p<0.05) lower concentrations (18±7 mg/L) than that of continuous aeration (27±6 mg/L). This could be due to the fact that intermittent aeration provided alternate aerobic/anoxic conditions for the simultaneously occurring of nitrification and denitrification.

Measurements of the evapotranspiration were taken for the wetlands that processed the domestic wastewater. Values recorded from the flow meter device indicated that evapotranspiration was similar in the 3 beds, accounting for about 20 L/m²•d. Such high values were related with the high temperatures (up to 32°C) and solar radiation present during the period of the experiment.

Taking into account the evapotranspiration, Fig. 59 and 60 show the efficiency of COD and total nitrogen removal, respectively. As it can be observed in Fig. 56, COD removal efficiency ranged between 30 and 80%. More specifically, average removals were 37% in the continuously aerated, 46% in the partially aerated and 44% in the not aerated bed. As mentioned above, intermittent aeration had a slight positive effect on COD removal.

Total nitrogen removal performances (Fig. 60) ranged between 20 and 80%. Average removals were 50% in the continuously aerated, 66% in the partially aerated and 65% in the not aerated bed. The lower removal found in the bed that was continuously aerated can be attributed to the high concentration of nitrite found in this bed, which were a consequence of the aerobic conditions present in the bed.

Industrial wastewater testing saw the bed with no aeration have a COD removal efficiency of 40.9 %, the automated aeration bed with a removal efficiency of 42.0 %, and the constantly aerated bed with a removal efficiency of 44.2%. Unfortunately the flow rates into each bed varied slightly (between 2160 and 2680 L/day). In particular the flow rate into the bed with no aeration was notably higher. The exact reason for the flow rate difference was not identified. The difference in flow rate may have contributed to the lower COD removal efficiency of the non-aerated bed. Clearly treatment efficiencies varied only very slightly between the beds, with the constantly aerated bed giving a slightly superior treatment efficiency than the other two, and the non-aerated bed producing the poorest treatment efficiency. This was expected, as aeration was known to improve treatment from both the literature and the earlier work package. It is
possible that over time the two aerated beds might show a greater treatment efficiency as the biofilm growth in these two beds was thought to have been hindered early in the beds operation as discussed earlier.

Due to the discrepancy in the flow rates COD removal rate (in kg) per unit area were also calculated with the non-aerated bed having a treatment efficiency of 22.6 kg/m², the automated bed having a 18.7 kg/m² treatment efficiency, and the constantly aerated bed with a treatment efficiency of 20.5 kg/m².

COD removal rate in kg per unit area per day gives a clearer indication of the industrial wastewater treating beds actual treatment efficiency given the discrepancy in the flow rate into each bed. Here it was seen that the bed without aeration had the highest removal efficiency (where the flow rate has been accounted for).

The constantly aerated bed provided a slightly higher removal efficiency in kg/m² per day than the bed where the aeration was automated. From the dissolved oxygen measurements it seems unlikely that this difference was due to the dissolved oxygen concentrations in each bed, as the values for the automated aeration and constant aeration beds were similar throughout the study, whereas the dissolved oxygen in the bed with no aeration changed dramatically (and was often lower than in the other two beds).

The most likely reason for the higher COD removal efficiency (in kg per meter squared per day) was due to the superior biofilm growth in the non-aerated bed as discussed earlier. Further to the argument provided earlier, an assessment the quantity of biomass in each bed was estimated by weighing the dry mass of a sample from each of the wetlands. From this it was clear that the two aerated beds had 66.2 % (automated) and 62.5 % (constant) of the biomass compared the non-aerated bed. This was significantly less and explains the superior treatment efficiency of the non-automated bed. In time the biofilm growth in the aerated beds should increase and with more growth treatment efficiency would be expected to be higher.

References


Potential Impact:
The impact of the project thus far is measured predominantly in terms of the publication outputs in scientific journals and trade journals and through conference presentations. Several announcements have been made in the industrial press which have reached a good audience, resulting in several invited presentations and publications. The outputs of this nature are summarised at the end of this section.

The next phase of the project, after the funding has finished, is to commercialise the results of the project generating impact in terms of revenue for the beneficiaries. The route forward with this, discussed in deliverable 7.5 – Final Plan for Dissemination and Use of the Foreground will ensure that the consortium moves forward as a whole and that all partners are capable of equal benefit from the project results.

Although it is yet to generate any socio-economic impact, it is clear that there is good scope for significant impact in this area. The modules themselves increase the environmentally friendliness of water treatment and can be retrofitted easily to existing septic tank installations, providing a green solution for personal households. The plan to commercialise the units, will lead to the generation of jobs in the areas local to manufacture as well as many more for delivery and installation teams. This is a particularly positive outcome as it represents much sought after labour positions.

The modules are also suitable for treatment of difficult wastewaters such as airstrip runoff and industrial process waste. The ability to quickly and easily install systems to deal with such waste will minimise environmental pollution and allow companies to more easily comply with consents.

Dissemination of the existence of the project
Following the kick off meeting and subsequent press release, a number of articles about ARBI appeared in the press:
http://wwtonline.edie.net/news/researchers-launch-study-into-novel-wetland-treatment#.U6E9m_IdWSp
http://www.waterbriefing.org/home/technology-focus/item/8676-%C2%A311m-eu-study-underway-to-develop-modular-wetland-treatment-system

Dissemination of the knowledge generated by the project
Scientific conferences and journal articles are the main ways in which the knowledge generated by the project has been disseminated and where possible these outputs are included on the public facing website for the ARBI project (www.arbi-eu.com).

Conference presentations:
Wetpol, Nantes, Oct 2013 Presentation included discussion about ARBI
Magnetic Resonance in Porous Media conference (MRPM 2014) in New Zealand P53 Magnetic resonance relaxation measurements using open-geometry sensors to assess the clog state of constructed wetlands
Magnetic Resonance in Porous Media conference (MRPM 2014) in New Zealand P69 Determining the clog state of constructed wetlands using an embeddable Earth’s Field Nuclear Magnetic Resonance probe
NTU Star Conference 2014 An Earth’s Field Nuclear Magnetic Resonance Probe For In Situ Monitoring Of Constructed Wetlands
NTU Star conference 2014 Magnetic resonance relaxation measurements using open geometry sensors to assess the clog state of constructed wetlands
BRSG AGM presentation 2014 Online monitoring of constructed wetlands using NMR sensors
Numerous (3 at different offices Warrington, Nottingham, Birmingham) general presentations to the Environment Agency which made reference to The ARBI project.
IWA Wetland Systems for Water Pollution Control conference in Shanghai 12th-16th Oct 2014 Clogging measurement, dissolved oxygen and temperature control in a wetland through the development of an Autonomous Reed Bed Installation (ARBI)
Water Research and Wetlands Conference Romania 2014 Advances in automated reed bed installations
NTU Star conference 2015, A Low Cost NMR Console: Who Said NMR Has to Be Expensive?
NTU Star conference 2015, Prototype construction of an Automated Reed Bed Installation (ARBI)
NTU Star conference 2015, Demonstration of the Temperature Dependence of T2eff of Water Performed Using Two Common Nuclear Magnetic Resonance Systems

International Conference in Magnetic Resonance Microscopy (ICMRM 2015), 2nd – 6th August 2015, Munich, Germany. Demonstration of the temperature dependence of T2eff of water performed using common nuclear magnetic resonance systems

International Conference in Magnetic Resonance Microscopy (ICMRM 2015), 2nd – 6th August 2015, Munich, Germany. Further investigation of constructed wetland clog state using spin-lattice relaxation measurements

9th WORKSHOP on Nutrient Cycling and Retention in Natural and Constructed Wetlands, 26-29 March 2015, Trebon, Czech Republic, Clogging modelling and smart subsurface flow constructed wetlands

Journal Articles:
Magnetic resonance relaxation measurements using open-geometry sensors to assess the clog state of constructed wetlands. T. Hughes-Riley, J.B. Webber, M.I. Newton, R.H. Morris submitted to Diffusion fundamentals 30/04/2014

Trade Journals
Uggetti, E., Puigagut, J., García, J., Hughes-Riley, T., Newton, M.I., Morris, R.H. Webber, J.B. 2014, Sensores de resonancia magnética para mejorar la operación de humedales construidos para el tratamiento de agua residual. Automática e Instrumentación, 459
Pending journal articles include:
Hughes-Riley, T., Dye, E.R. Newton, M.I. Morris, R.H. Temperature dependence of magnetic resonance probes for use as embedded sensors in constructed wetlands, Measurement Science and Technology; submitted
F. Hill-Casey, T. Hughes-Riley, J.B.W. Webber, M.I. Newton, R.H. Morris, Demonstration of the temperature dependence of the T2eff of water performed using three common nuclear magnetic resonance systems, Scientific Reports, in preparation (http://www.nature.com/srep/ is high impact factor multidisciplinary journal and open access to improve the dissemination).
Pending books chapter

Future publications
A paper on the material from WP3, discussing the viability of the use of novel treatment media for the systems.
Performance of the ARBI modules for various influents.

List of Websites:
http://ARBI-EU.com

Related documents
final1-arbi_final_report_figures.pdf