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Measurement Techniques for Wastewater Filtration Systems

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1. Introduction

Filter-based microbiological wastewater treatment systems (such as subsurface flow constructed wetlands, trickling filters and recirculating sand filters) require a thorough understanding of system hydraulics for their correct design and efficient operation. As part of the treatment process, the filter media will gradually become clogged through a combination of solids filtration and retention, biomass production and chemical precipitation. Eventually the media may become so clogged that hydraulic malfunctions ensue, such as untreated wastewater bypassing the system. To achieve good asset lifetime a balance must be struck between these essential treatment mechanisms and the hydraulic deterioration that they cause.
For many wastewater filtration systems the exact mechanism of clogging is not obvious, and few specialised techniques have been developed which allow the cause and extent of clogging to be measured in typical systems. The resultant lack of understanding regarding clogging hinders the ability of operators to maintain good hydraulic performance. In this chapter, for the first time, we compare three different families of standard hydraulic measurement techniques and discuss the information that they can provide: hydraulic conductivity measurements; clog matter characterisation and hydrodynamic visualisation. Each method is assessed on its applicability to typical wastewater filtration systems using horizontal subsurface flow constructed wetlands as a case study.
Furthermore, several new techniques will be considered which have been specifically developed to allow *in situ* determination of hydraulic health for subsurface flow constructed wetland wastewater filtration systems. These include *in situ* constant and falling head permeameter techniques and embeddable magnetic resonance probes.
Discussion is given to the ways in which different methods can be combined to gather detailed information about the hydraulics of wastewater filtration systems before exploring methods for condensing heterogeneous hydraulic conductivity survey results (that vary by several orders of magnitude) into a single representative value to describe the overall hydraulic health of the system.

2. Mechanisms of clogging

A typical subsurface flow wetland comprises a layered structure as seen in figure 1. Such a system usually comprises a gravel matrix in which Phragmites australis (the common reed) is grown. These systems are used as an environmentally friendly method for wastewater sanitisation before eventual discharge into a watercourse. The wastewater flows under gravity through the gravel (below the surface), where it encounters optimum conditions for purification: solids are removed by the gravel substrate and the root network of the reeds, which also provide a surface on which to trap particulates and promote biofilms. Removal of organic material, pathogens and nutrients is predominantly due to biofilms. Many chemical compounds are absorbed or precipitated depending on the physicochemical conditions of the wastewater constructed wetland (Brix, 1994). Over time this causes the pore spaces between gravel grains to become occluded. A small amount of clogging will occur due to biofilm growth which helps to improve the overall efficiency and functionality of the system, although over time, excessive biofilm growth and retention of solids may lead to bypass flow of untreated influent. The balance between these two dominant clogging mechanisms often requires a multi-modal assessment methodology to elucidate the complete nature and severity of the clogging.

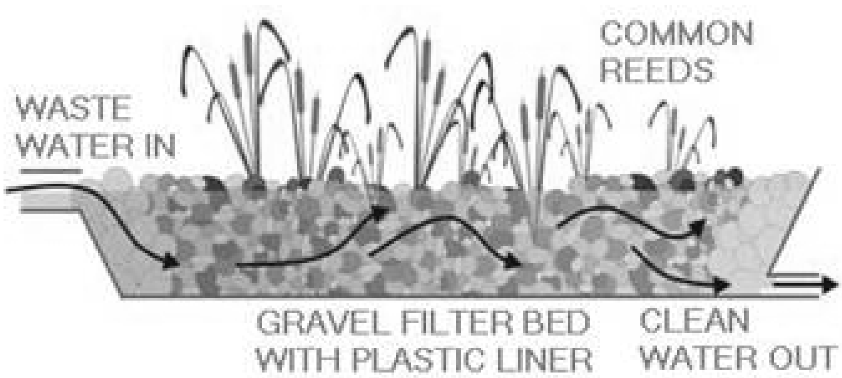


Fig. 1. Cross sectional view of a typical subsurface flow constructed wetland.

3. Traditional measurement strategies

There are a variety of measurement techniques available to determine the hydraulic conditions within the filter *in situ* (Knowles et al., 2009a; Lin et al, 2003), whilst determination of the composition and quantity of clog matter usually requires samples of the gravel matrix to be extracted prior to laboratory analysis. Each of these measurement techniques is discussed in this section along with the weaknesses and strengths of each strategy, which are summarised in Table 1. Whilst no individual technique is suitable for gaining a full insight into the true extent of clogging, they may be useful to understand individual contributions of system clogging or be used in combination for an understanding of the interplay between different factors.

3.1 Hydraulic conductivity measurements

Traditional measurements of hydraulic conductivity share two common elements. The first is that a test well or sample core must be made either *in situ* or remotely in a laboratory. The second is that the hydraulics of the system must be tested in some repeatable or measurable way to determine the hydraulic properties of the sample under test. In this section seven common hydraulic conductivity measurement techniques will be briefly discussed.

Test Family	Test	Description
Hydraulic Conductivity	Slug Test	A piezometer tube (devoid of media) is inserted into the media. The water level is rapidly changed by addition of water or a metal slug. The evolution of the water level back to equilibrium is used to calculate the permeability.
	Pumping Test	Water is pumped at a constant rate into or out of a well, and the resulting cone of depression in the filtration medium is monitored over time.
	Steady State Test	Flow through the filter medium results in a hydraulic gradient. Differences in the height of the water table are observed in different wells.
	Unlined Auger Hole	A borehole is made into the media and water is either added or removed. The recharge rate or flow rate into the media is measured.
	Infiltration Tests	A ring is impressed into the surface of the filtration medium and water is added to measure the infiltration rate through the surface.
	Laboratory Permeameter	A sample of the media is placed into a laboratory permeameter cell. A constant or variable head of water is then applied across the media. Manometer take off points allow the variation in resistivity across the sample to be determined.
	Modified Cube Method	A cubic sample of the filtration media is sealed in wax before removing single sets of opposing faces and passing flow through the media, the hydraulic conductivity in different planes can be determined.
Clog Matter Characterisation	Direct Porosity Measurements	Either saturated or drainable porosity of an extracted sample is measured in the laboratory. This approximates the ratios of free to interstitial water.
	Time Domain Reflectometry	A family of methods which rely on the dielectric constant of a medium being proportional to water saturation. Each method uses a different approach to measure this property. TDR and CP are inserted at various points and give readings in the immediate locality whilst the GPR is swept over the surface providing a subsurface image.
	Capacitance Probe	
	Ground Penetrating Radar	
	Solids Assays	Total and volatile solids of the interstitial clog matter are determined by drying the samples. Suspended fractions in interstitial water may also be measured.
Hydrodynamic Visualisation	Breakthrough Curve	The breakthrough of a pulse of tracer added to the system inlet is monitored at the outlet of the system
	Internal Tracing	The dynamics of an inlet injected tracer are monitored at different points in the system.

Table 1. Summary of available hydraulic measurement techniques separated into families.

3.1.1 Slug test

To perform a slug test, a hollow tube perforated at the lower end or a piezometer is inserted into the gravel substrate. A rapid and temporary change in water level, followed by return to the equilibrium state is used to determine the hydraulic conductivity of the substrate near the tube. This is achievable in one of two ways: the first (and the origin of its name) is shown in figure 2 and requires the introduction of a metal slug into the water which infiltrates the tube thus displacing some of it. The second is to add a known amount of water to the well. Measurements of the water level (or air pressure above the water) will show a sudden increase corresponding to the volume of the slug followed by an exponential decay back to the natural level of the water table. The hydraulic conductivity of the surrounding gravel can then be determined.

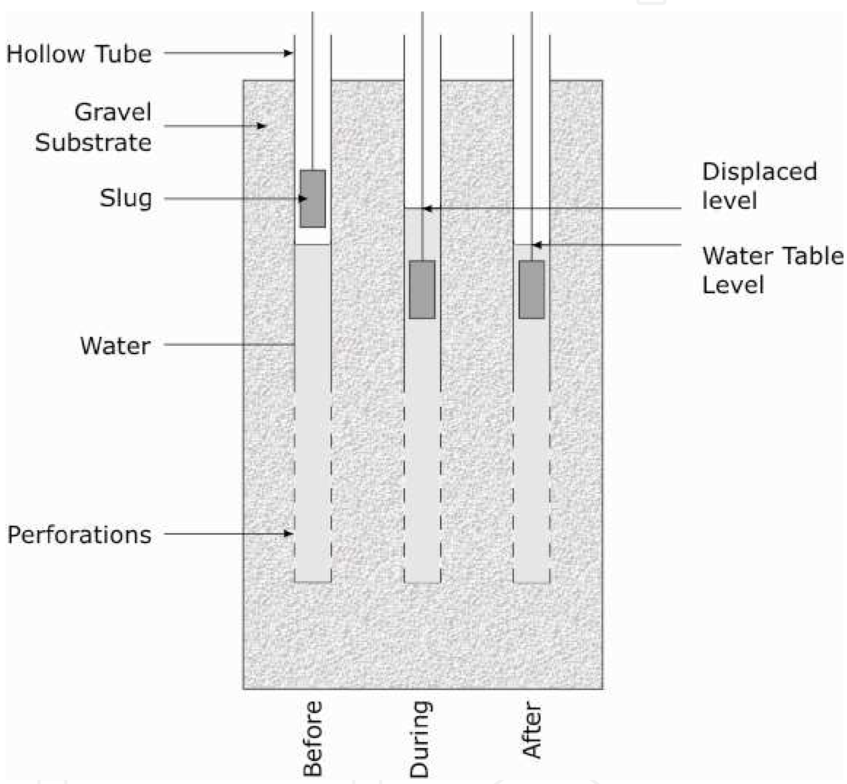


Fig. 2. Schematic representation of the measurement phases in the slug test used in a gravel substrate.

The analysis of the relaxation curve from the slug test relies on two assumptions. The first is that the water and gravel in the area around the tube is incompressible, which is typically a reasonable assumption in an established water saturated wetland. The second is that the surrounding medium is completely homogeneous which unfortunately is rarely the case. The method for determining the hydraulic conductivity is based on a modified Thiem equation (equation 1)

$$K = \frac{R_W^2 \ln(h_0/h_t)}{Ft}, \tag{1}$$

where K is the hydraulic conductivity of the gravel substrate, R_W is the radius of the well, h_0 and h_t are the height of the water relative to the equilibrium level at the start and end of the experiment lasting time t and F is a shape factor determined by the dimensions of the well using one of several methods. The shape factor presented in equation 2 is valid only for a well which has a perforated section with a length, L_P, shorter than sixteen times its radius. The reader is referred to the work of Hvorslev (1951) for more unusual well geometries.

$$F = \frac{2\pi L_P}{\sqrt{L_P/\left(2R_W + 0.25\right)}}. \quad (2)$$

For gravel substrates which contain fractions of different gravel sizes, the hydraulic conductivity determined using the slug test is often not representative and an alternative technique is required.

3.1.2 Pumping test

The pumping test is typically performed on aquifers but is equally applicable (with careful consideration of error) to water saturated gravel substrates. The pumping test can be performed either by pumping water into or out of the gravel substrate. In a clogged system this can be quite disruptive if the flow rates are too high and in shallower systems, it may not be possible to withdraw a sufficiency of water to yield valid results in the case where the water is pumped out. The test is set up as in figure 3 with at least one test well, although the results are more reliable with several.

As water is withdrawn (or added) to the substrate, a cone of depression develops (for water withdrawal), the geometry of which corresponds to the flow rate out of (into) the well and hydraulic resistance to flow offered by the substrate. By measuring the height of the water table at several places along the radius of the cone it is possible to determine the hydraulic conductivity of the gravel substrate. Most often this test is performed with a constant pumping flow rate and the changing geometry of the cone of depression is plotted against time. It is also possible however to repeat this test several times in succession with increasing pump rates to improve the quality of the analysis. The hydraulic conductivity is again determined from the measurements using a steady state solution to the Thiem equation (eq. 3)

$$K = \frac{Q}{2\pi d(h - h_0)} \ln\left(\frac{r}{R}\right), \quad (3)$$

where Q is the flow rate of the pump, d is the depth of the substrate, h-h_0 is the drawdown (i.e. the difference between the depth of the water before and after the pump is started) measured at a distance r from the pumping well. R is the distance from the pumping well at which the water level is unaffected. In a small wastewater treatment system, where the cone of depression may quickly extend to the inlet, R can be assumed as the distance to the inlet of the system with a usually small experimental error.

The results from this test are only truly representative of the actual hydraulics of the system when it has undergone little clogging and is relatively deep in comparison to the depth of the wells and the depth of the cone of depression.

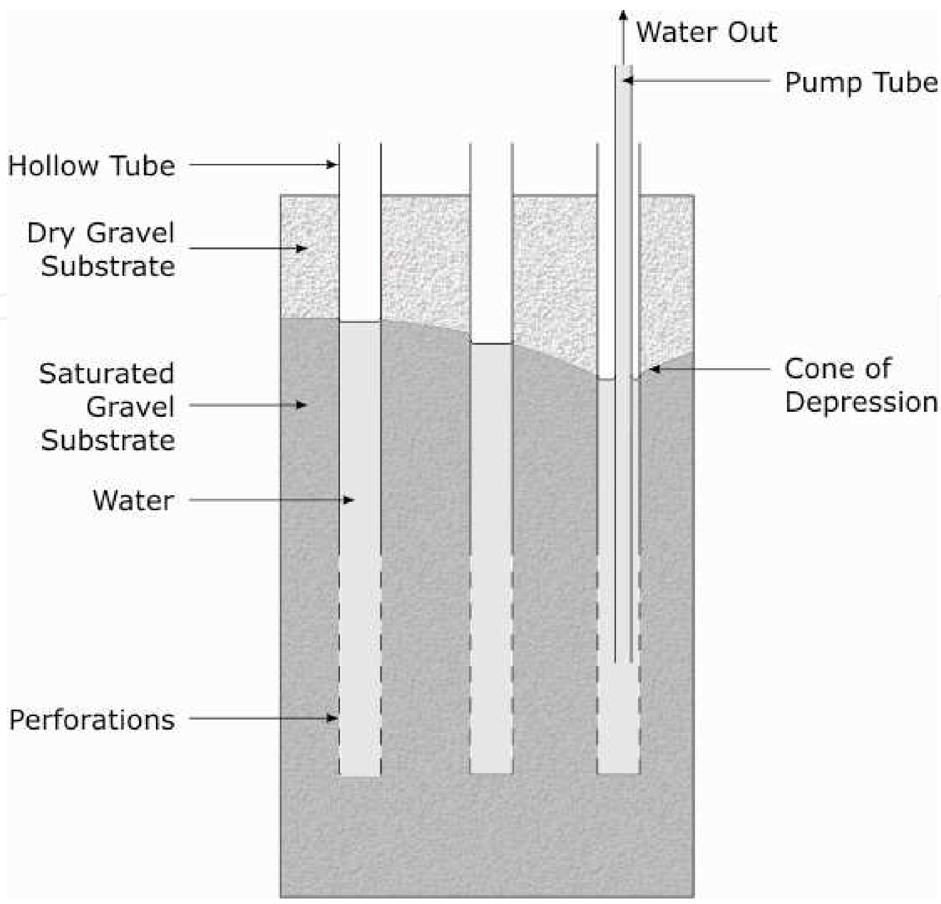


Fig. 3. Schematic of pump test set up. The right hand side is the pumping well whilst the left and centre are two test wells.

3.1.3 Steady state test

The steady state test is one of the least disruptive hydraulic conductivity tests. It requires only the insertion of several test wells (pipes with part perforation as used previously) at various lengths along the bed. The flow of water from one side of the bed to the other will result in a hydraulic gradient along its length, causing a variation in the height of the water table which can be measured in each test well. The determination of the hydraulic conductivity is then relatively simple using Darcy's law as in equation 4.

$$K = \frac{Qr}{Ah}, \tag{4}$$

where h is the difference in height between the water table in each well separated by distance r, and A is the cross sectional area through which the flow has taken place. This analysis relies on a homogeneous flow path between the wells and assumes that the flow uses the whole of the cross sectional area. Although the impact of these assumptions can be minimised by keeping the test wells relatively close together, the extra number of wells that are required may cause too great a disturbance to the substrate to be fully representative. This test is best performed in a system which has not undergone long term clogging to ensure that the results are as reliable as possible.

3.1.4 Unlined auger hole

The unlined auger test is a means of measuring the hydraulic conductivity in a constructed wetland which has undergone a sufficient degree of clogging that the gravel matrix has become stabilised by clog matter. This allows an unlined bore hole to be made without too great a risk of the walls collapsing into it. The three tests discussed so far can all be performed in an unlined auger hole with the benefit of complete confidence that the whole surface of the bore hole is participating in the method thus ensuring complete assessment of the local environment. The drawback of this method is however ensuring that the walls do not become weakened to the point of collapse and to avoid the build up of silt and sediment in the base of the well. This is particularly critical for the pumping test in which the large flow rates increase the likelihood of this occurring.

3.1.5 Infiltration test

The testing strategies discussed in the previous sections are primarily affected by horizontal hydraulic conductivity only. As this is the typical direction of fluid flow in a typical horizontal constructed wetland this is acceptable. In many situations, particularly clogged gravel beds, overland flow occurs which results in a dual flow regime with vertical and horizontal components. Additionally, vertical flow constructed wetlands are also becoming more popular thanks to their smaller footprint and thus methods for measuring the vertical hydraulic conductivity are required. In the infiltration test, the vertical infiltration rate of flow across the surface of the system is measured. This is normally performed by burying two concentric metal rings partially in the surface of the gravel (the rings are typically 60cm and 30cm in diameter and about 25cm in height buried 15cm into the gravel) as in figure 4. Both the central ring and the space between the two rings are filled with water. The drop in water level is monitored every few minutes. The water level is kept relatively constant and

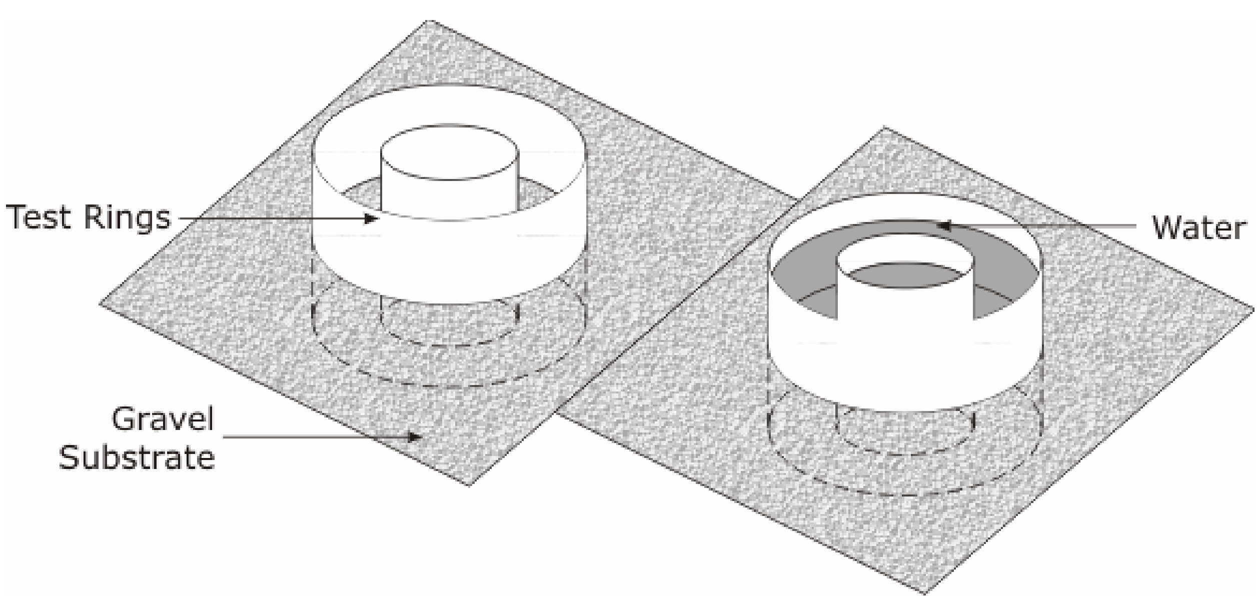


Fig. 4. Schematic representation of equipment used for infiltration testing before and after filling with water (left and right).

measurements are made frequently. Once the water is seen to be falling at a constant rate the value is noted as the basic infiltration rate. The time that this takes is also of some relevance, particularly on dry samples as it allows the tester to determine the wetability.
This test only indicates the infiltration rate through the surface of the substrate and does not indicate the hydraulic conductivity of the bulk substrate. It is worth noting that the test is only valid so long as the water between the two rings is at a similar level as that inside the inner ring, as it is used to prevent horizontal motion of the water from the centre.

3.1.6 Laboratory permeameter

The laboratory permeameter is often considered the most accurate means of assessing gravel permeability. However, to use a traditional permeameter, a sample of the gravel substrate must be extracted, in tact with the surrounding clog matter and transported to a laboratory. The sample is then loaded into the permeameter system and, using one of two techniques, the permeability is assessed. The standard setup for a laboratory permeameter is as shown in figure 5. A constant head of water is produced by using a top reservoir with a connection to the permeameter and a much larger overflow drain. Water is fed into the device at a rate that the overflow drain is utilised to a small degree, such that a constant flow rate into the permeameter is maintained. A bottom reservoir is used to create a water-lock and ensure that the sample remains saturated. The height difference between the water level in the top and bottom reservoir forces flow through the sample, with a flow-rate that corresponds to the hydraulic conductivity of the media. By measuring the outlet flow-rate, Darcy's law can be used to determine the hydraulic conductivity of the sample as in equation 5.

$$K = \frac{QL}{A\Delta h}, \tag{5}$$

where Δh is the distance between the bottom of the reservoir overflow and the bottom of the sample overflow and L is the vertical length of the sample with cross sectional area A. In this experiment Q is calculated using the volume of water collected per unit time.
The accuracy of this method can be somewhat improved by varying the value of Δh and measuring Q. If Q is then plotted against $(A\Delta h)/L$, a linear relationship with gradient K is found.
An alternative set up which allows a similar measurement accuracy in a shorter time is known as a falling head permeameter. The equipment is the same as in the static head permeameter only instead of keeping the level of the cup constant, it is allowed to drop with time from a height h_0 to a height of h_t at time t. Typically the cup is narrower than the sample in this experiment to allow the height of the liquid to be measured easily. The experimental protocol is to monitor the height of the liquid in the reservoir over time. A rearrangement of Darcy's law can then be used to determine the value of the hydraulic conductivity. If $ln(h_0/h_t)$ is plotted against t, the slope will be KA/aL, where a is the cross sectional area of the cup.
The main drawback of this technique is that the samples must be extracted from the wetland. Careful measurements do however give reliable assessment of the hydraulic conductivity using both protocols which are often used as benchmarks for alternative testing strategies.

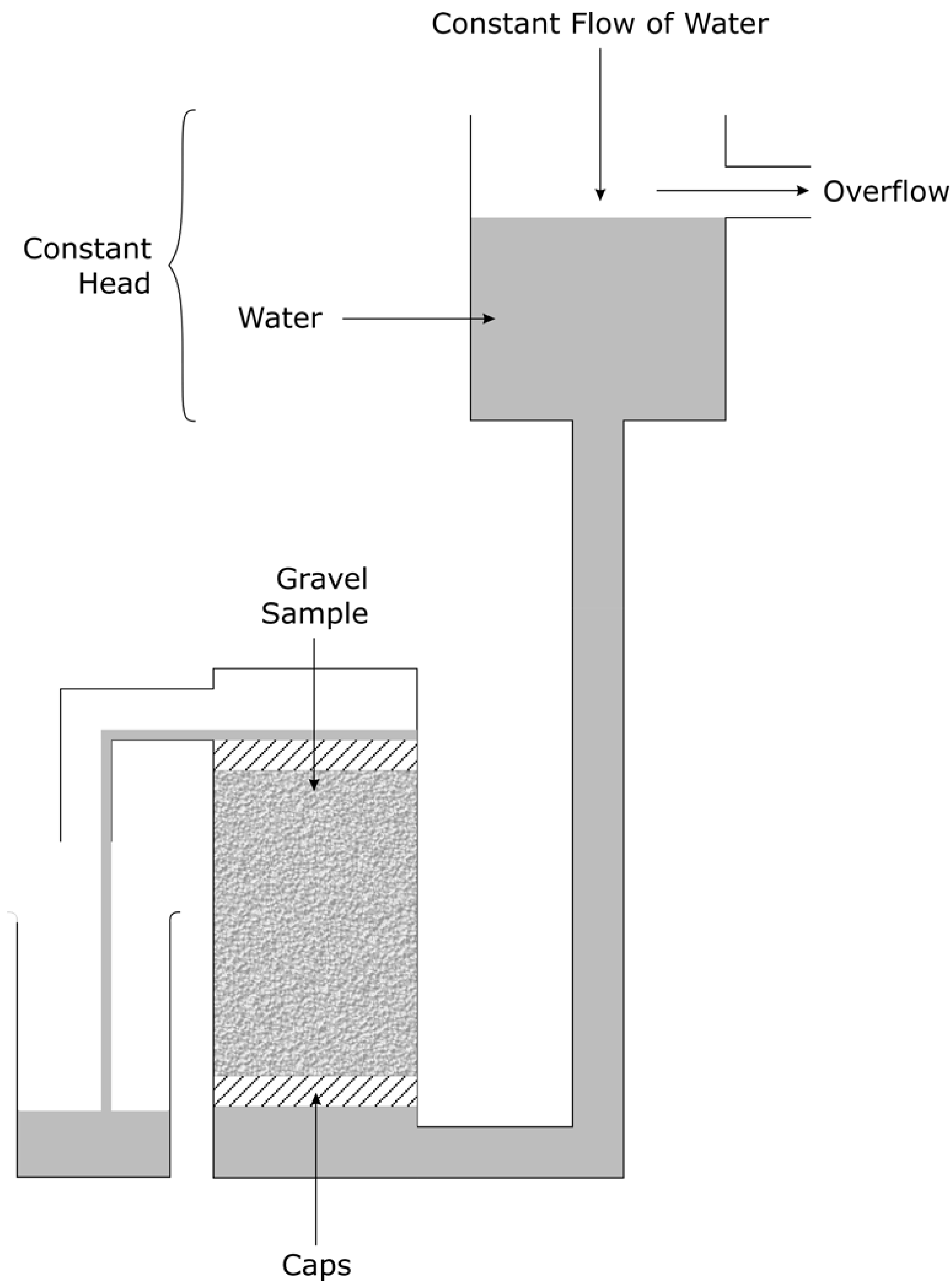


Fig. 5. Schematic representation of laboratory permeameter setup.

3.1.7 Measurements of anisotropic hydraulic conductivity

Hydraulic conductivity is a tensor with three nodes that represent hydraulic conductivity in different directions of flow. In an anisotropic medium, hydraulic conductivity at a point may vary depending on the flow direction. A simple example of this is whereby particle size stratification has created horizontal layers that encourage horizontal flow channelling, and do not encourage vertical flow across the layers. The previously discussed methods are axial tests which only allow measurement of hydraulic conductivity in one direction. Recent laboratory methods have been developed to allow anisotropic hydraulic conductivity to be evaluated in extracted soil samples (Renard et al., 2001). One such method called the Modified Cube Method has been applied to measure anisotropy in natural wetland peat samples (Beckwith et al.; 2003, Kruse et al.; 2008, Rosa and Larocque, 2008). The test involves cutting a cube of material from an extracted core and coating it in paraffin wax. One set of opposing sides of the wax case are removed and the sample subjected to an axial hydraulic conductivity test, such as the constant head laboratory permeameter test. After measurement the wax case is restored and a different set of opposing sides is removed, and the test repeated across this flow direction. This is performed for all three flow directions such that the hydraulic conductivity tensor can be ascertained.

3.2 Clog matter characterisation

The techniques described in the previous section are used to assess the hydraulic properties of the clogged porous media flow system. However, these tests cannot reveal information about the cause of clogging and the nature of the clog matter, which is often key in determining the health of a system. In this section we will consider the range of common tools available to determine the properties of the clog matter fraction in the system.

3.2.1 Direct porosity measurements

There are numerous methods for measuring the porosity of a sample directly. In this section we will discuss the two most commonly used for samples collected from constructed wetlands. This is a highly invasive technique and requires the extraction of sample cores from the gravel substrate. Once these cores are extracted, they are analysed in the laboratory using two tests to determine the amount of water which is free and the amount that is associated, that is to say the amount that is associated with the surface of the grains in biofilms for example. The first test is relatively straightforward and relies on taking a known volume of the core sample which is allowed to drain of water for a few minutes, possibly during gentle agitation, whilst preventing the loss of any clog matter. The sample is placed in a container and the amount of water needed to fill the sample (again with or without agitation) divided by the total apparent volume of the sample is the free water porosity. This measure is reliable in samples with well connected pores so that all of the free water is able to drain unhindered from the sample. The water is then drained again from the sample in preparation for the second test. Collection and determination of the volume of this second drain of water is advisable as a means to check the reliability of the first measurement.
Determination of the remaining, and hence associated, water in the sample can be achieved using one of two methods. The longer of the two methods allows the remaining water to drain slowly from the sample in a sealed vessel (as evaporation will result in much of the loss) until it is completely dry, the volume of the collected water then represents the pore space occupied by interstitial water in the sample. This is a lengthy process and requires a careful set up to avoid disrupting the sample. The alternative technique, which is often

combined with a solids assay as described in section 3.2.5 is to weigh the sample before and after gentle heating to evaporate the interstitial water fraction. The mass change is then used to determine the volume of water lost. This method may give unpredictable results in a sample which contains volatile solids which will contribute to the mass of the sample. Although these techniques both offer useful results, the need to collect a core of the gravel substrate often makes them less attractive than their *in situ* counterparts.

3.2.2 Time domain reflectometry

Time domain reflectometry is a technique which relies on the relationship between the dielectric properties of different materials and their water content. The principal for measuring clogging using Time Domain Reflectometry and the next two techniques to be reviewed; Capacitance Probes and Ground Penetrating Radar; is that they all measure properties that will vary depending on the amount of interstitial water in a sample. Therefore, it would be possible to detect where accumulation of clog matter has reduced the interstitial water volume compared to a calibrated clean sample. This, in itself, is an inherent limitation of these techniques as clog matter is typically well hydrated (often above 95% water by volume) and as such very small variations in water volume must be measured. The complexity of the system used to perform the measurements is such that a detailed description is beyond the scope of this chapter. Instead, the basic operating principles of the technology will be provided along with the relationship between the results and the physical properties of the sample. The technique is particularly difficult to use in a gravel substrate as the grains disrupt its underlying mechanism. Its use in heavily clogged media is however still valuable as a method for assessing water content.

The underlying principle of time domain reflectometry is similar to that of radar. An electromagnetic wave pulse is produced and transmitted into the gravel substrate, often using metal electrodes. The wave will propagate through the medium at a speed which is determined by the dielectric constant of the medium which is dependent on the water content. The wave will be reflected and picked up by the same electrodes as were used to deliver it into the medium. The time between the emission and absorption of this pulse is used to determine the speed with which it travelled through the medium. This is then converted to water content using a calibration produced from samples with known water content. Whilst the technique may offer very accurate results, it is heavily influenced by spurious reflections caused by local heterogeneities, may be affected by changes in electrical conductivity (such as those caused by salinity) and relies on calibration in similar samples to those under test to be representative. An alternative technique which relies on the same underlying principle is known as time domain transmissometry. In this technique, instead of using the same electrodes to generate and measure the pulse, separate electrodes are used. In this way it is possible to somewhat reduce the influence of local inhomogeneity on the results although this is often of little benefit in a filtration system containing gravel which is still highly reflective to the wave.

3.2.3 Capacitance probe

The operation of the capacitance sensor is similar in some respects to time domain reflectometry in that electrodes are used to determine the dielectric properties of the gravel substrate. In this technique however, the two electrodes are commonly metallic plates wrapped around a cylinder (see Figure 6). In combination with the surrounding gravel substrate, clog matter and water, a capacitor is formed. The capacitance of this arrangement is dependent on the size and spacing of the plates and the dielectric permittivity of the surrounding medium. The dielectric permittivity is in turn dependent predominantly on the water content and salinity. Several of these probes are often included on a single plastic cylinder to maximise the measurements that can be made for a single insertion.

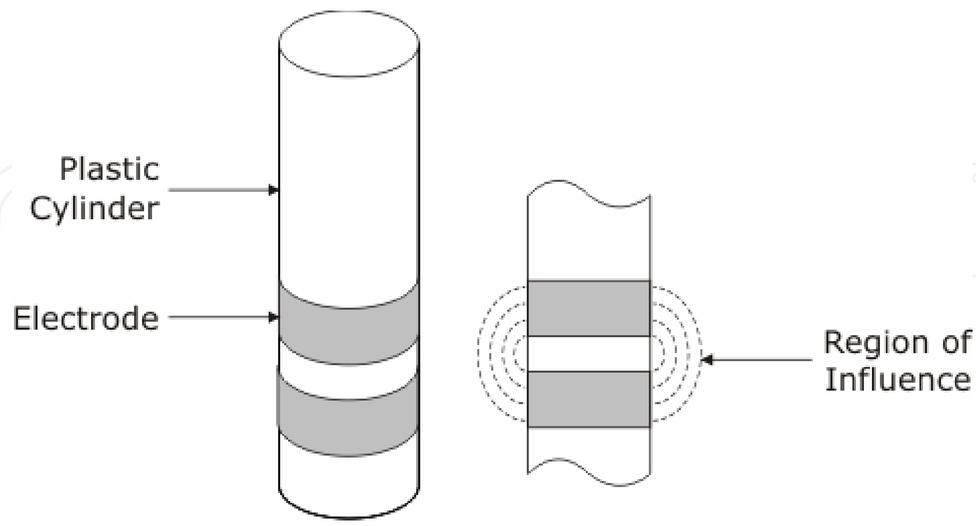


Fig. 6. Schematic of capacitance sensor. Right hand figure is front view of left hand figure showing the area in which measurements are made.

The measurement of the capacitance is typically made by including the capacitance probe as an element of a resonant circuit. The frequency at which the circuit resonates is determined by the value of the capacitor and thus may be used to determine the dielectric permittivity in the region of influence (see figure 6). The size of, and spacing between the plates may be adjusted to optimise the penetration distance from the cylinder into the medium based on the intended usage. For example, the plates would ideally be separated by a greater distance for measurements in gravel where the particle size is large in comparison to a measurement in a sand filter. As with time domain reflectometry, the capacitance probe must be calibrated. Owing to its considerably lower cost however, it is quite practical to have several probes along the bed including one in the influent, thus compensating for the effect of salinity.

3.2.4 Ground penetrating radar

Ground penetrating radar is a technique which uses pulses of microwaves to determine the properties of a sample non-destructively. The instruments are relatively expensive and complex but offer an unprecedented measure of the dielectric properties of a sample without requiring its extraction. In a typical setup, a unit is moved along the surface of a bed whilst the measurement is made. Microwave pulses are transmitted by a coil in contact with the surface of the ground. At changes in dielectric constant (such as different media or different water content) the microwaves are reflected back and picked up by the instrument. The use of ground penetrating radar in a typical constructed wetland is very challenging given the reed growth above ground making it difficult to place the equipment on the surface and the propensity for gravel to cause a great number of reflections before any measurements have been made. For this reason it is not usually practical for the majority of situations.

3.2.5 Solids assays

In order to assess the quantity of clog matter in an extracted sample from a wetland, solids assays may be used. The typical procedure is to extract a known volume or mass of sample from a wetland and collect the water which drains from it. This sample is then dried and the remaining solids are weighed to determine the free particulates in the sample. In the case of a gravel substrate, the sample is washed to allow the clean gravel to be sieved out and removed. The accumulated solids fraction is then dried (often in an oven at a low temperature) and the remaining solid fraction weighed to determine the quantity of the clog matter. Whilst this method offers a good measure of the total quantity of solids in the sample, as a single measurement it may not offer much insight into the actual clogging process. This is because a large contribution of the clogging comes from biofilms which may contain up to 80% water by volume. When this water is removed, the volume occupied by the biofilm will be greatly reduced thus giving a misleading result in terms of the extent of the clogging. This test is best performed with the direct porosity measurements detailed in section 3.2.1 to provide a fuller understanding. If desired, ignition tests above 550°C can then be used to calculate the volatile fraction of the sample (BS-EN-872, 2005).

3.3 Hydrodynamic visualisation

All of the techniques presented thus far in this chapter have been localised measurements which rely on studying the material directly around a probe or the extraction of samples for laboratory analysis. In systems in which the flow path is in some way defined (as it is in constructed wetlands) hydrodynamic visualisation techniques are useful for determining how flow responds to clogging. Two strategies are discussed in this section both of which rely on injecting a tracer (for example rhodamine dye) near the inlet and then monitoring for its presence at one or more locations in the bed.

3.3.1 Breakthrough curve

The basic measurement using a tracer method is the breakthrough curve. In this technique, a tracer such as rhodamine dye is injected at the inlet of the bed. A specific sensor for the dye to be used (an optical fluorescence detector in the case of rhodamine dye) is installed at a location in the bed (typically the outlet in the case of breakthrough) and is monitored from the time of injection, through detection of the dye, when it passes through the sensor, until the detection level returns to that at the start of the test. A plot of the detected dye from injection to end is known as the breakthrough curve and will typically have a single peak of given amplitude and breadth. The integral of this curve should equal the amount of dye injected. Should this not be the case, it is likely that there are features of the flow path that result in stagnant water. Occasionally distinct peaks will be picked up other than the main peak which indicates flow short-circuiting along multiple preferential flow-paths and resulting in multiple peaks. The treatment performance of the system is directly linked to the hydraulic performance. Ideally, the system behaves as a Plug Flow Reactor which means that all of the fluid remains in the system for the same duration, the design retention time; which would correspond to a sharp pulse of tracer being detected at the outlet. The broader the breakthrough curve, the greater the extent of mixing and short-circuiting within the system, and the more likely that some flow will prematurely discharge before sufficient time for treatment has elapsed (Figure 7). It is always wise to repeat the measurement with the sensor at several outlet locations on several different occasions as there are many factors which affect the flow path including temperature, humidity and precipitation. The reader is referred to Appendix B in Kadlec and Wallace (2009) for more information on such an analysis in constructed wetlands.

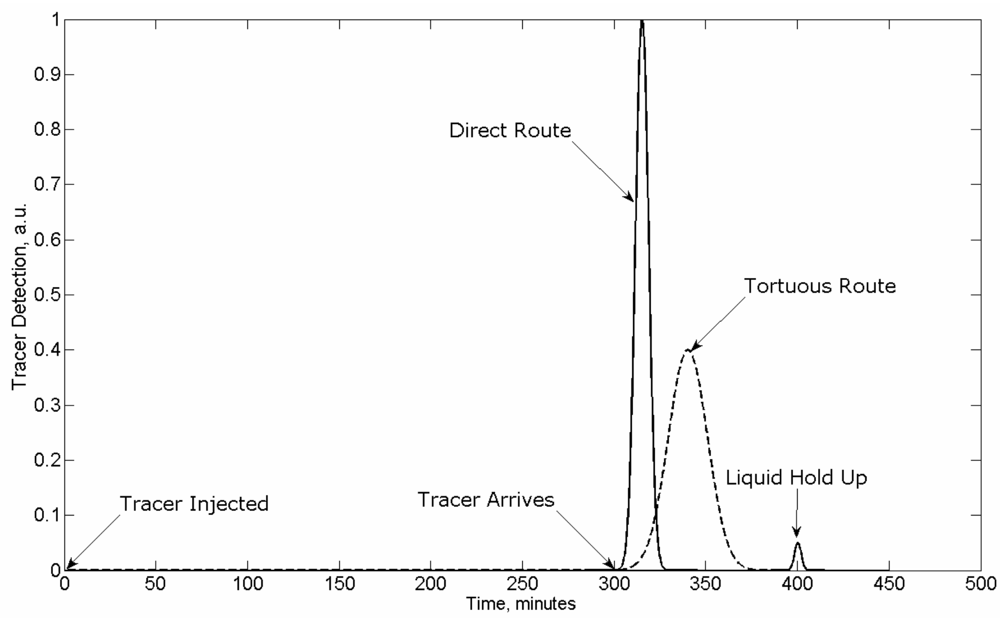


Fig. 7. Breakthrough curves from a direct (solid line) and tortuous (dashed line) system.

3.3.2 Internal tracing

If repeatedly monitored over the lifetime of the bed, the breakthrough curve method can be a good indicator of bed health. For a single or short term measurement, it can be beneficial to use a setup with several sensors to gain a better understanding of the local variations in the flow path. Such a setup is known as internal tracing. The same equipment is used as in the breakthrough curve system with a single injection of dye which is monitored over a grid or line of sensors. Typically at least three will be used in a line or nine in a grid. The analysis is very similar to that used for the breakthrough curve method only this time the dye front can be followed along the bed. As can be seen in the example in figure 8, it is common for the dye to arrive first at the detector nearest the injection with a sharp peak, as there has been little diffusion on the flow path. With high short circuiting a broader peak may then picked up on the next in line before the other two on the same row (detector 5 before 1 and 3 on figure 8) as the dye is carried primarily along the bed rather than across it. Ideally, the flow will be detected simultaneously across the width of the bed (detectors 1, 2 and 3) before advancing to the next row, which indicates good volumetric efficiency. In older, more clogged systems, this test often reveals areas of subsurface stagnation, bypass flows and blockages which core sampling using other techniques would not have found. The equipment is however quite costly and the analysis of many probes to achieve an in depth understanding is often challenging.

4. New Techniques for *in situ* measurements

Measurements made using more than one traditional method are often poorly correlated. This has lead scientists to conclude that it is the form and not the quantity of the clogging that is of primary importance (Caselles-Osorio et al., 2007). To improve the reliability of the measurements made and ensure that the information collected is as useful as possible, two new techniques have been developed. The first of these is the *in situ* permeameter which allows localised measurements of hydraulic conductivity to be performed at several bed locations. The second uses embeddable magnetic resonance probes to determine localised relative ratios of biofilm and particulate clogging. Combination of these two techniques shows good promise as a method for fully determining the clog state of a constructed wetland and indeed any other large scale waste water filtration system.

4.1 *In situ* Permeameter tests

By using an adaptation of the Hvorslev Test, as proposed in the Naval Facilities Soil Mechanics Design Manual (NAVFAC, 1986), it has been possible to directly determine gravel conductivity in Horizontal Subsurface Flow Constructed Wetlands (Caselles-Osorio and García, 2007, Caselles-Osorio et al., 2007, Pedescoll et al., 2009). Here an open ended tube is used such that the piezometer encases the sample to be tested. In this way, the ability to easily delineate variations in vertical conductivity is sacrificed as the test measures the vertical conductivity of the entire gravel core. Regardless, these authors consider the method introduced by Caselles-Osorio and García (2007) to be highly preferable to laboratory based hydraulic conductivity studies, as direct measurements of substrate conductivity are made, thus removing the discussed uncertainties associated with sample extraction and transportation.

Recently, a novel method has been devised to allow the three dimensional hydraulic conductivity of HSSF TWs to be determined in situ. The method recreates the laboratory constant head permeameter test in situ by using a submersible permeameter cell that encapsulates a test specimen of media, and a Mariotte Siphon actuated recharge reservoir to maintain constant head conditions in the cell (figure 9). The apparatus is designed for use by one person in remote locations, weighing approximately 10 kg and utilising 10 L of water for one test, and is sized to be appropriate for the range of media hydraulic conductivities typically encountered in mature subsurface flow wetlands (from 0 to 10,000 m/d, Pedescoll et al., 2009). Manometer take off tubes are immersed to different depths within the permeameter cell so that the vertical variation of hydraulic conductivity can be found. By repeating the test at different locations over the surface of the bed and interpolating between results it is possible to generate a three-dimensional hydraulic conductivity profile for the wetland. The apparatus design and methodology are elaborated upon in Knowles and Davies (2009b).

4.2 Magnetic resonance probes

Magnetic resonance is a technique which is most often found in a medical setting. It is however also useful as a tool for making measurements in any aqueous environment. Its use for the study of porous media is well published in the literature although this usually involves the extraction of a sample core (typically under 10cm diameter and 70cm long) from the system of interest and measurement in a laboratory. An alternative system is used when prospecting for oil which involves an inside out magnetic resonance device that interrogates the physical properties of the rocks surrounding a trial bore hole. More recently a device has been produced (Morris, et al. 2009) which allows *in situ* determination of the relative ratios of particulate anvd biological clogging in porous filtration systems. The principles of operation and its benefits are discussed in this section.

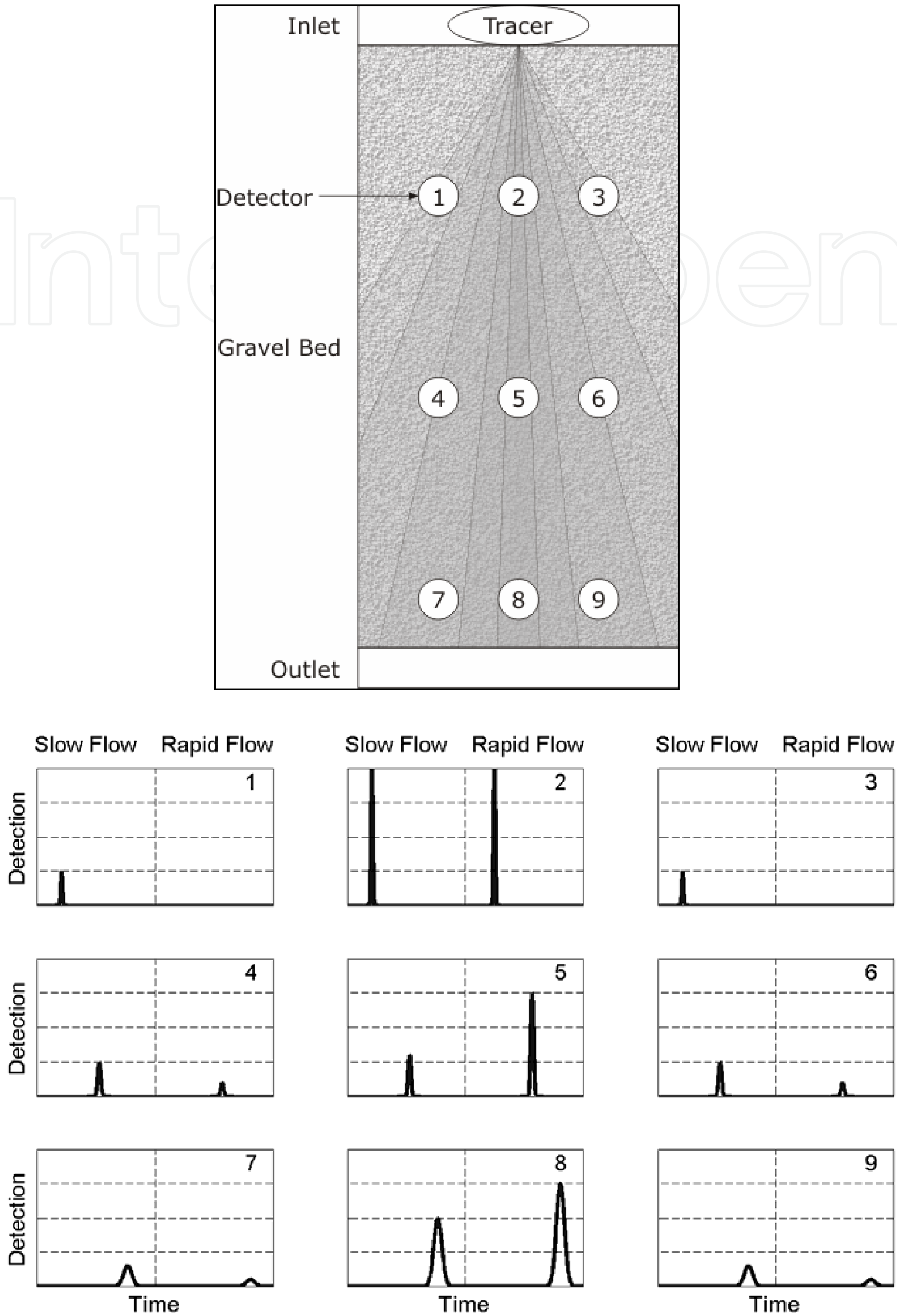


Fig. 8. Top: nine probe internal tracing setup. The grey shaded areas are flow paths, the darker the shade, the faster the flow it represents. Bottom: simulated results for each probe.

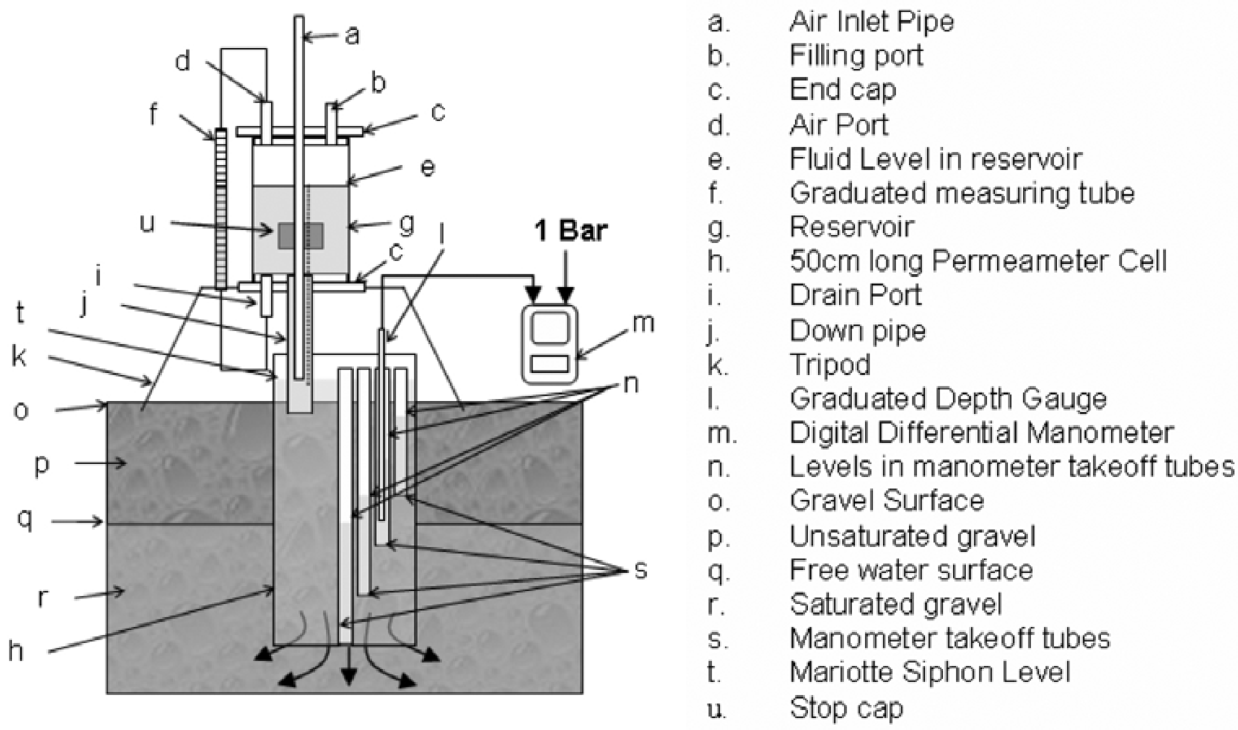


Fig. 9. Experimental set-up for the in situ determination of the vertical hydraulic conductivity profile of high porous media (not to scale). Reproduced from Knowles and Davies (2009b).

4.2.1 Theory

Magnetic resonance is a measurement technique which relies on the intrinsic properties of water molecules [9]. When in a magnetic field, the nuclei of hydrogen molecules align with the field in a process known as diamagnetism. This alignment can be perturbed by applying a time varying magnetic field. By applying such a field at an appropriate frequency, the nuclei can be made to rotate. Once the nuclei have been rotated away from the static magnetic field, they will attempt to realign. As this occurs, a process known as precession takes place in which the nuclei rotate about the axis of the static field much like a spinning top. Because each of the nuclei behaves like a tiny magnet, a very small current can be induced in a conducting coil placed around the sample. In combination, these effects can provide information about the properties of the molecules in the sample. The magnetic resonance probe developed for determining the ratios of biological and particulate clogging uses a series of applied time varying magnetic fields known as a spin echo sequence. This allows averaging of the signal before the system has returned to equilibrium. If the delay between repeating this sequence is not longer than the time it takes for the system to return to equilibrium, there will be a loss in signal. This characteristic is used to measure the 'spin lattice relaxation time' or T_1. By systematic variation of this delay (a process known as saturation recovery) an exponential relationship is found with time constant T_1 [11]. This time constant is dependent on the molecular environment and hence can be used to determine the local association of water. In the presence of several different water associations, the resulting data will be multi-exponential allowing the ratios of each environment to be determined.

4.2.2 Practical implementation

The magnetic resonance probes are produced with permanent magnets to generate the static magnetic field. This allows the probes to be sufficiently small that they can be embedded in the filtration system. Within these magnets is an insulated copper coil which is used to apply the time varying magnetic field to the sample and is also used to collect the resulting signal. This probe is attached to an electronic system which generates the required time varying fields, averages the resulting signals and processes the results to determine the ratios of the clogging components. The clog state of the medium under interrogation is then provided to the user. Probes have been produced which can be used to make individual localised measurements or to make several measurements at different heights (Figure 9) thus limiting the disturbance to the filter medium.

4.2.3 Data collection

For a typical subsurface flow constructed wetland, at least six of these probes would be placed at various locations across the bed (see figure 10). The relative ratios of biological and particulate clogging are determined at each of these locations over time from the saturation recovery curves. The ratios (R_{BP}) are determined from the curves automatically using the relationship in equations 5 and 6.

$$R_{BP} = \frac{M_{0B}}{M_{0P}}, \tag{5}$$

$$S = M_0\left[1 - \exp\left(1/T_1\right)\right], \tag{6}$$

where M_0 is proportional to the number of protons contributing to the signal, S, from that environment, T_1 is the spin lattice relaxation time and subscripts B and P represent the contributions from biological and particulate clogging respectively. Curves representative of the situations of dominant particulate clogging, dominant biological clogging and an equal ratio of the two are shown in figure 11. Although in established systems these are almost never seen as there are often as many as four water environments in the pore spaces of the gravel, the simple curves are presented here to give the reader a fundamental understanding of the process.

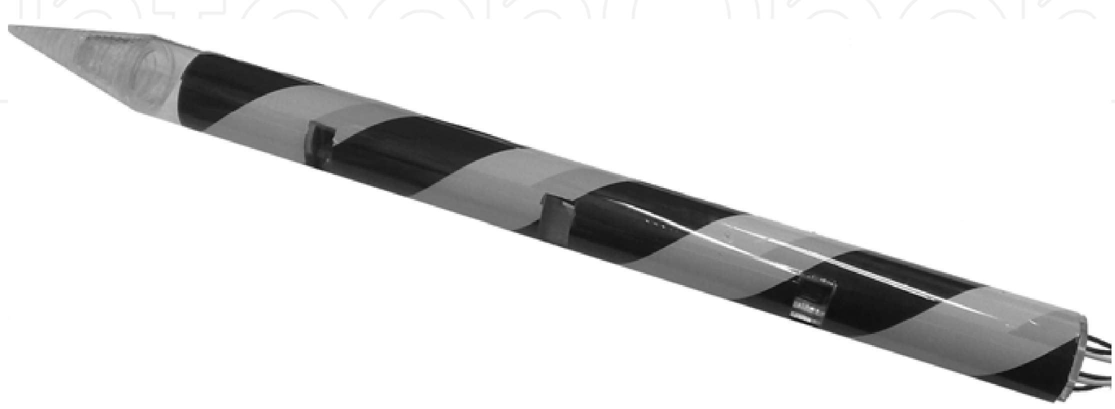


Fig. 9. Magnetic resonance probe used to determine the ratios of particulate and biological clogging. This version has three sensors spaced along its length.

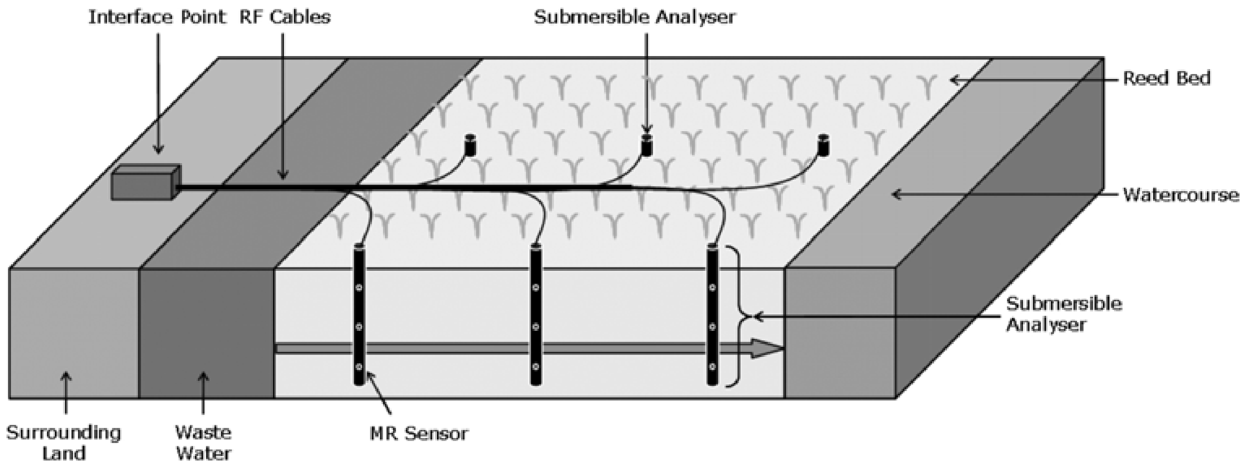


Fig. 10. Cross sectional view of subsurface flow wetland showing six submersible analysers each with three probes at different heights.

The time evolution of the clogging ratios and individual values should be monitored to provide an indication of the bed health. Typically the inlet plots will show a more rapid increase in biological clogging than those near the outlet of the system. A typical monitoring plot which would be obtained from a six probe system is shown in figure 12.

4.2.4 Limitations

The technique is intrinsically limited to dealing with filtration of aqueous systems which are free from magnetic compounds. Although this is not a concern in municipal waste water treatment, it may be an issue for the treatment of industrial run off, particularly ochre rich mine water. As the probes are embedded into the actual filter medium which is typically outdoors, temperature correction is a key issue which must be compensated for regularly. The current system relies on experiencing temperature changes less than 5K about the average for the system into which it is installed. A second generation probe system which automatically corrects for changes in temperature up to 20K about the average is currently under development.

5. Dealing with heterogeneous survey results

One of the challenges when performing measurements on several porous media filtration systems is the comparison of filters with different construction. It is often the case, particularly with industrial waste water treatment, that there will be several stages of filtration utilising different filter media, to remove a range of undesirable content to meet preset consents.

Recently a method has been introduced which allows several factors of a given filtration system to be considered and, in combination with measured parameters permits the determination of a clog factor. This numerical value provides a means of comparing the clog state of several diverse treatment stages thus allowing hydraulic health to be monitored over time. This information can then be fed back into the design of a new system which will last longer or operate more effectively. In this section we consider how the clog factor can be applied to wetlands for the measurement techniques discussed in the previous sections.

5.1 Clog factor

Due to the vide variation in hydraulic conductivity which occurs in clogged filters, the arithmetic mean of measurements may not provide a very representative indication of the hydraulic health of the system. A common practice in hydrology is to use the geometrical mean of the dataset as a more representative improvement on either the arithmetic or harmonic means (Binley et al., 1989). Representative homogeneous values for hydraulic conductivity are however generally misleading, as in actuality hydraulic conductivity spans several orders of magnitude. A single value model cannot capture the influence of varying hydraulic conductivity on the subsurface water table profile: a function that is imperative for determining wetted volume and hence predicting treatment performance (Persson et al., 1999). In response, the Clog Factor (CF) has recently been developed.

The CF is a novel metric that converts hydraulic conductivity, an intensive physical property, into an extensive bulk property that can be representatively averaged for subsequent analysis. It can be used to describe the state of clogging in any porous media flow system but has been derived intentionally to explore clogging dynamics in subsurface flow wetlands. The CF is based on the Kozeny-Carman equation (equation 7) which describes the theoretical hydraulic conductivity of porous media, based on the assumption of ideal spherical media of homogeneous diameter d and porosity θ. The fluid density ρ, dynamic viscosity μ and gravity g are also included in the Kozeny Carman equation. Applying this formulation in reverse, experimentally measured values of hydraulic conductivity and the median particle diameter of the sampled gravel are used to calculate corresponding theoretical clogged porosities θ_E.

$$k = \frac{\rho g d^2 \theta^3}{150\mu(1-\theta)^2} \tag{7}$$

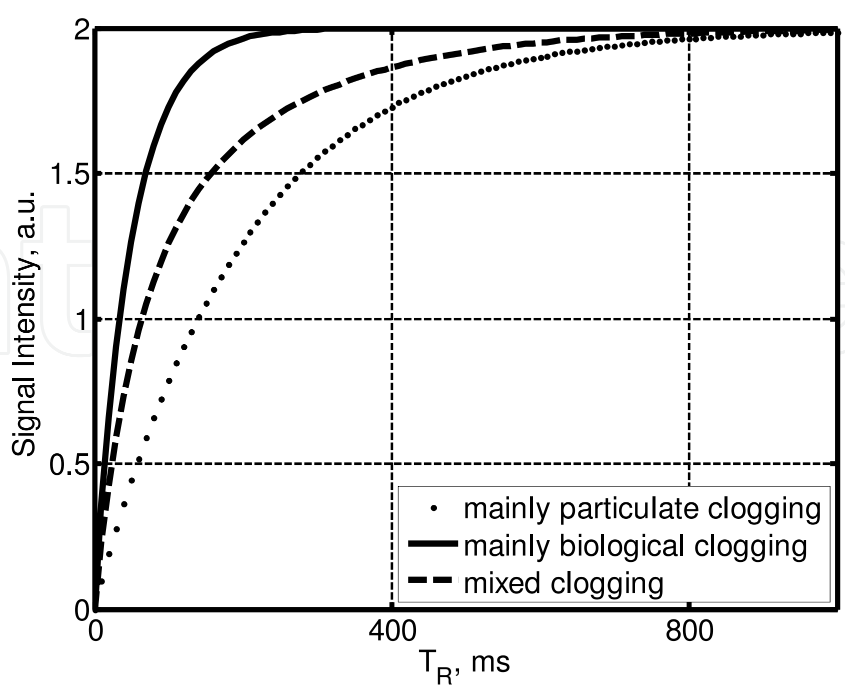


Fig. 11. Typical saturation recovery curves for three different clogging cases.

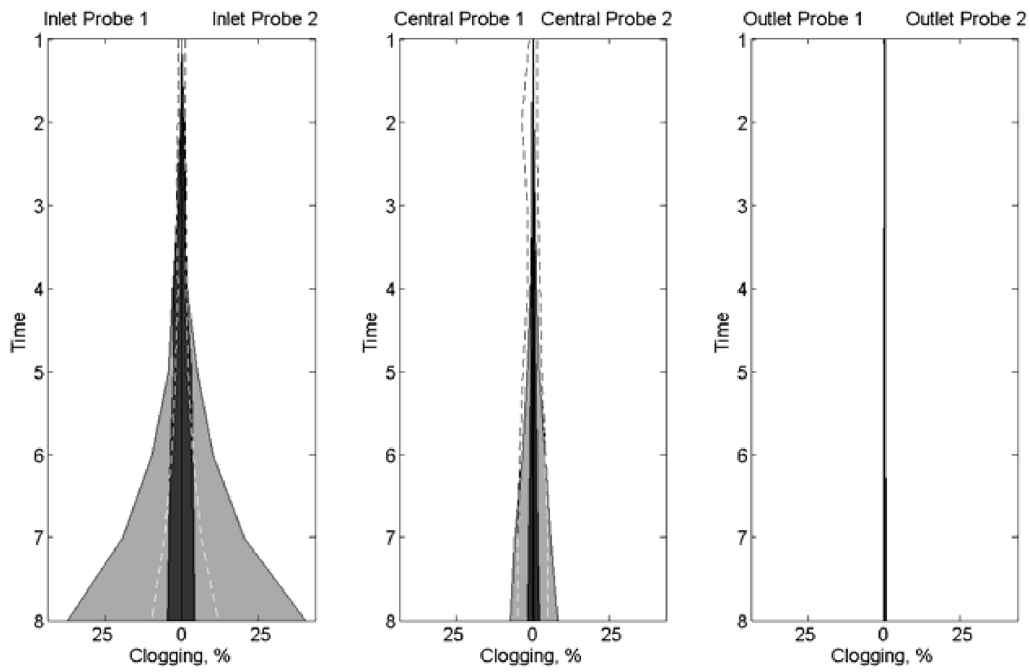


Fig. 12. Simulated results of typical monitored output for six probe system. Grey is biological clogging whilst black represents particulate clogging. The dashed line is 10 times the ratio between them.

The ratio of clogged to experimental clean porosity allows the CF to be calculated (equation 8), whereby a value of 0 indicates zero clogging and a value of 1 indicates complete clogging. It is important to emphasise that the CF may not represent the practical clogged porosity, as it has been shown that reductions in hydraulic conductivity often do not correspond to reductions in porosity, and rather it is the form and nature of clogging that are important (Caselles-Osorio et al., 2007; Platzer and Mauch, 1997; Tanner et al., 1998). In this way the CF actually represents the effective or relative reactor volume that has been lost to clogging.

$$CF = 1 - \frac{\theta_E}{\theta_I} \tag{8}$$

The advantages of the Clog Factor are:

- It is an extensive bulk property so it can be applied to any scale porous media flow system
- Removes dimensions from the data so that comparisons can be performed between systems with different physical and media sizes
- Highlights deviations from theoretical clean conductivity due to both clogging and media non-ideality
- Allows reasonable statistical comparisons where orders of magnitude changes in hydraulic conductivity would skew a data set
- Allows single-parameter values to be published to indicate health of bed at a point in time

The Clog Factor provides a useful tool with which the inter- and intra-system variations of filter system hydraulic health can be objectively compared.

6. Conclusion

In this chapter we have detailed the various methods currently available to determine the extent to which a large scale porous media based filtration system has become clogged. By considering the traditional methods available to measure the clogging it has been shown that any single technique cannot provide a sufficiently detailed picture of the state of the system. We have presented two recent developments for *in situ* measurements of the clogging and have shown that they both provide more relevant information than their laboratory based counterparts. By combining these two techniques, the full nature of the clogging can be elucidated and used to inform remedial action leading to a life extension.

7. References

Binley, A., Beven, K. & Elgy, J. (1989). Physically Based Model of Heterogeneous Hillslopes: 2. Effective Hydraulic Conductivities. *Water Resources Research,* 25 (6), 1227-1233.

Brix, H. (1994) Functions of Macrophytes in Constructed Wetlands. *Water Science and Technology.* 29, 71.

Caselles-Osorio, A., Puigagut, J., Segu, E., Vaello, N., Granés, F., García, D. & García, J. (2007). Solids accumulation in six full-scale subsurface flow constructed wetlands. *Water Research,* 41 (6), 1388-1398.

Cooper, D., Griffin, P. & Cooper, P. (2005). Factors affecting the longevity of sub-surface horizontal flow systems operating as tertiary treatment for sewage effluent. *Water Science and Technology,* 51 (9), 127-135.

Cooper, P. F., Job, G. D. & Green, M. B. (1996). *Reed beds and constructed wetlands for wastewater treatment*. Water Research Centre.

EC/EWPCA (1990). *European Design and Operations Guidelines for Reed Bed Treatment Systems*. Swindon, UK: WRc.

García, J., Ojeda, E., Sales, E., Chico, F., Píriz, T., Aguirre, P. & Mujeriego, R. (2003). Spatial variations of temperature, redox potential, and contaminants in horizontal flow reed beds. *Ecological Engineering,* 21 (2-3), 129-142.

Green, M. B. & Upton, J. (1995). Constructed reed beds: Appropriate technology for small communities. *Water Science and Technology,* 32 (3), 339-348.

Griffin, P., Wilson, L. & Cooper, D. (2008). Changes in the use, operation and design of sub-surface flow constructed wetlands in a major UK water utility. *11th International Conference on Wetland Systems for Water Pollution Control,* Indore, India, 419-426.

Hvorslev, M.J. (1951). Time Lag and Soil Permeability in Ground-Water Observations, Bulletin Number 36, Waterways Experimental Station Corps of Engineers.

Kadlec, R. H. & Watson, J. T. (1993). Hydraulics and Solids Accumulation in a Gravel Bed Treatment Wetland. In: MOSHIRI, G. A. E. (ed.). *Constructed wetlands for water quality improvement : Conference : Selected papers.* Boca Raton: Lewis Pub, pp 227-235.

Knowles, P. R. (2010). Clogging and Hydraulics in Horizontal Subsurface Flow Constructed Wetlands. Doctorate in Mechanical Engineering and Design Thesis, Aston University.

Knowles, P. R., Griffin, P. & Davies, P.A. (2009a). Complementary methods to investigate the development of clogging within a horizontal sub-surface flow tertiary treatment wetland. *Water Research*. 44, 320.

Knowles, P. R. & Davies, P. A. (2009b). A method for the in-situ determination of the hydraulic conductivity of gravels as used in constructed wetlands for wastewater treatment. *Desalination and Water Treatment,* 1 (5), 257–266.

Knowles, P. R. & Davies, P. A. (2010). A Finite Element Approach to Modelling the Hydrological Regime in Horizontal Subsurface Flow Constructed Wetlands for Wastewater Treatment In: VYMAZAL, J. (ed.). *Water and Nutrient Management in Natural and Constructed Wetlands.* Dordrecht: Springer Science+Business Media B.V.

Knowles, P. R., Dotro, G. C., Nivala, J. & García, J. (2010a). Clogging in subsurface-flow treatment wetlands: Occurrence, contributing factors, and management strategies. *Ecololgical Engineering,* Submitted.

Knowles, P. R., Griffin, P. & Davies, P. A. (2010b). Complementary methods to investigate the development of clogging within a horizontal sub-surface flow tertiary treatment wetland. *Water Research,* 44 (1), 320-330.

Lin, A., Debroux, J., Cunningham, J. & Reinhard, M. (2003). Comparison of rhodamine WT and bromide in the determination of hydraulic characteristics of constructed wetlands. *Ecological Engineering*

Madigan, M. T., Martinko, J. M. & Brock, T. D. B. O. M. (2006). *Brock biology of microorganisms*. 11th ed. ed. Upper Saddle River, NJ: Pearson Prentice Hall.

Morris, R.H., Newton, M.I., Bencsik, M., Knowles, P.R., Davies, P.A. & Griffin, P. (2009). Long term monitoring of constructed wetlands using an NMR sensor. *IEEE Sensors.* 1733-1737.

Murphy, C. & Cooper, D. (2010). The Evolution of Horizontal Sub-Surface Flow Reed Bed Design for Tertiary Treatment of Sewage Effluents in the UK. In: VYMAZAL, J. (ed.). *Water and Nutrient Management in Natural and Constructed Wetlands.* Dordrecht: Springer.

Pedescoll, A., Uggetti, E., Llorens, E., Granés, F., García, D. & García, J. (2009). Practical method based on saturated hydraulic conductivity used to assess clogging in subsurface flow constructed wetlands. *Ecological Engineering,* 35 (8), 1216-1224.

Persson, J., Somes, N. L. G. & Wong, T. H. F. (1999). Hydraulic efficiency of constructed wetlands and ponds. *Water Science and Technology,* 40 (3), 291-300.

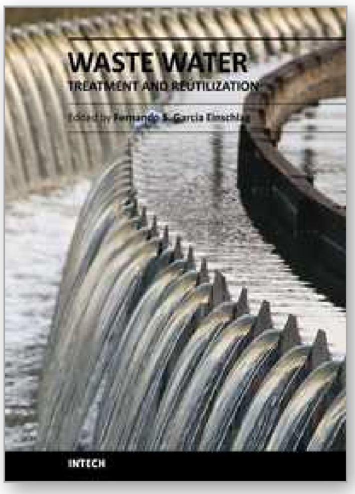
Platzer, C. & Mauch, K. (1997). Soil clogging in vertical flow reed beds - Mechanisms, parameters, consequences and.....solutions? *Water Science and Technology,* 35 (5), 175-181.

Speer, S., Champagne, P., Crolla, A. & Kinsley, C. (2004). Hydrodynamic Pathways in a Maturing Constructed Wetland. *8th International Conference on Wetland Systems for Water Pollution Control,* Avignon, France.

Suliman, F., Futsaether, C., Oxaal, U., Haugen, L. E. & Jenssen, P. (2006). Effect of the inlet-outlet positions on the hydraulic performance of horizontal subsurface-flow wetlands constructed with heterogeneous porous media. *Journal of Contaminant Hydrology,* 87 (1-2), 22-36.

Tanner, C. C., Sukias, J. P. S. & Upsdell, M. P. (1998). Organic matter accumulation during maturation of gravel-bed constructed wetlands treating farm dairy wastewaters. *Water Research,* 32 (10), 3046-3054.

USEPA (2000). Constructed wetlands treatment of municipal wastewaters. U.S. EPA Office of Research and Development: Washington, D.C., United States.



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