

THE USE OF IMPULSE RESPONSE TRACER EXPERIMENTS IN HORIZONTAL SUBSURFACE FLOW CONSTRUCTED WETLAND DEVELOPMENT

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A research proposal submitted to the Faculty of Engineering and the Built Environment, University of the Witwatersrand, in fulfillment of the requirements for the degree of Master of Science in Engineering.

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DECLARATION

I declare that this research report is my own unaided work. It is being submitted to the Degree of Master of Science in Civil Engineering to the University of the Witwatersrand, Johannesburg. It has not been submitted before for any degree or examination to any other University.

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ABSTRACT

In the past three decades there has been an increased interest in constructed wetlands (CW) and their effectiveness in treating water. The hydraulic efficiency of a CW can be determined by using chemical reactor theory to develop residence time distribution (RTD) parameters such as effective volume (V_{eff}), normalized variance (σ^2) and mean residence time (τ_m). Five experiments were conducted to study the effects on these RTD parameters in a CW by using a glass pilot-scale laboratory rig and varying the inlet-outlet positions. The rig made use of a glass tank 250x250x500mm filled with clear superabsorbent polymer balls as a packing. The clear tank and balls made it possible for the flow to be observed when a FWT red impulse tracer dye was inserted into the system. The flow was photographed at specific time intervals for visual analysis and comparison. . The visual results showed the formation of a hull-shaped velocity profile in all the experiments. The RTD was obtained by collecting tracer samples at specific outlet positions during the course of each experiment. The five inlet-outlet configurations RTD parameters results showed; a straight flow path from a single inlet to outlet yielded the least desirable hydraulic performance with dead volumes contributing to up to 67% of the CW. An increase in the number of outlets and changing the direction of flow diagonally showed up to a 96% improvement to the effective volume of the system could be achieved when compared with single inline inlet-outlet flow. The best result was achieved by combining the visual and RTD data to make changes to the rigs geometry in order to eliminate dead zones and yielded up to a 148% improvement in the effective volume of the system when compared with single inline inlet-outlet flow. A well designed CW with respect to inlet-outlet position can result in reduced land requirements and construction costs by minimizing the dead volume and improving hydraulic efficiency.

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NOMENCLATURE

E_i is the exit age distribution at time i [T^{-1}]

t_i is time i [T]

τ is the ideal mean residence time [T]

Q is the volumetric flow rate [$L^3 T^{-1}$]

C_i is the concentration taken at time i [$M L^{-3}$]

Δt is the time interval between any time t_i and t_{i+1} [T]

t_m is the mean of the residence time distribution [T]

ϵ is the void fraction of a packed bed

V_V is the volume of voids [L^3]

M_V is the mass of the voids [M]

V_S is the volume of material [L^3]

M_S is the mass of a material [M]

V is the volume of a packed bed [L^3]

σ^2 is the second moment of the residence time distribution, the variance

σ_θ^2 is the normalized variance

D is the dispersivity [L]

N is the number of tanks in a tanks-in-series model

V_{eff} is the ratio derived from the ideal residence time to ideal residence time

λ is the hydraulic efficiency factor

P is the pressure in a model [$M L^{-1} T^{-2}$]

ρ is the density of the liquid [$M L^{-3}$]

μ is the dynamic viscosity of the liquid [$M L^{-1} T^{-1}$]

D_m is the mean particle diameter [L]

C_{in} is the inlet concentration [$M L^{-3}$]

C_{out} is the outlet concentration [$M L^{-3}$]

q is the hydraulic loading rate [$L T^{-1}$]

a , b and c is regression coefficients [1]

k_A is the areal decomposition constant [$L^2 T^{-1}$]

k_v is the volumetric decomposition constant [$L^3 T^{-1}$]

HRT is the hydraulic retention time [T]

r is the rate of biological degradation [$L T^{-1}$]

K_{HSC} is the half-saturation constant [$M L^{-3}$]

C is the contaminant concentration [$M L^{-3}$]

$k_{0,v}$ is the zero-order volumetric rate constant [$M L^{-3} T^{-1}$]

R_{TN} is the total nitrogen removal [$M L^{-3}$]

K_{TSRP} is the time of the removal [T]

n is the porosity

T is temperature in degrees celcius

ACRONYMS

PFR - Plug Flow Reactor

CSTR - Continuous Stirred Tank Reactor

TIS – Tanks in Series

RTD – Residence Time Distribution

CW - Constructed Wetlands

SSFCW- Subsurface Flow Constructed Wetlands

FSFCW- Free Surface Flow Constructed Wetlands

ANN- Artificial Neural Networks

CFD- Computational Fluid Dynamics

1. INTRODUCTION

The earth's population has exceeded 7 billion human beings (UNFPA, 2011). The economic, environmental and social impacts require that in order for life to continue into the foreseeable future the most sustainable practices and frameworks must be adopted and implemented. The goal of the work undertaken in this research aims towards expanding sustainable environmental practice development.

Water is one of the most valuable resources on earth; it serves to sustain almost all forms of life and is used for a myriad of purposes. Broadly water can be categorised by its use: potable (drinking quality), industrial and agricultural. After use water is expelled and becomes wastewater. Wastewater is any water that has had its quality affected by anthropogenic influence. Sewage forms part of wastewater and consists mainly of domestic, municipal or industrial liquid wastewater of which treatment most frequently occurs by septic tanks or wastewater treatment plants. The use of wastewater treatment plants can be costly as they require skilled personnel and frequent maintenance.

This research report aims to investigate and further develop an alternate form of wastewater treatment namely, constructed wetlands (CW). CW are an engineered system that is designed and constructed to make use of natural processes in order to treat wastewater. CW are can be classified according to the major macrophytic life form present in them namely; floating leaved, free floating, rooted emergent or submerged. Furthermore they may be classified according to the systems overriding hydrological make-up; free surface and subsurface flow and directionality of flow; vertical or horizontal (Vymazal, 2010).

Under controlled conditions, a CW has low maintenance requirements and can be less costly to operate than conventional methods of wastewater treatment depending on the scale of operations. The use of CW for wastewater treatment can be dated back to the 1950's in Europe and 1960's in Northern America but has

enjoyed less exposure in a South African context (Sheridan et al, 2006; Sheridan et al, 2011; Vymazal, 2011).

The development of CW for use within sub-Saharan Africa can lead to a more sustainable method of treating wastewater and thus helping to alleviate water scarcity. The benefits of making use of a CW include;

- Potential low capital costs in rural areas;
- Relatively simplistic operation;
- Minimal maintenance requirements; and
- Aesthetic nature of constructed wetlands.

CW have for the longest time been viewed as a black box. Little was known about the biological, chemical and physical processes occurring within them (Vymazal, 2010). The physical characteristics such as geometry and substrate composition play a pivotal role in ensuring optimal efficiency of such a constructed wetland system. The effect of changes to the physical characteristics is one of the areas in need of development and study. Many methods are available for the analysis of CW wetlands; however, none of these methods can fully replicate constructed wetland processes due to their complex nature. Furthermore, many of the methods focus solely on one of the processes at work in CW leaving results project specific (Kadlec, 2000). The research presented here aims to assist in the further development of a more general method or technique for analyzing and understanding flow within subsurface wetlands for practical application.

The research presented here made use of pilot-scale laboratory experiments consisting of a glass tank 250x250x500mm filled with clear superabsorbent polymer balls. The tanks had nine inlet and nine outlet positions that would make it possible to compare the effects on visual and RTD data when varying inlet-outlet configurations. In this research five different inlet-outlet combinations would be considered, namely:

- top centre inlet to top centre outlet;
- bottom centre inlet to top centre outlet;
- bottom centre inlet to all top outlets;
- bottom centre inlet to all top outlets but including a wedge in the geometry;
and
- bottom right inlet to top left outlet.

The use of a tracer dye injected into the steady state systems was proposed as the best method to observe flow patterns and make timed sample data available.

Samples from the experiments would then be processed in a Merck Spectrophotometer in order to determine concentration values and using this data combined with residence time distribution theory inferences would be drawn on the characteristic performance of each system.

Research Aims and Objectives:

1. To investigate the effect on the residence time distribution parameters and flow patterns when varying the inlet-outlet configurations of a horizontal subsurface flow constructed wetland.
2. To compare and discuss the effects of varying the inlet-outlet configuration on the residence time distribution parameters

The basis for the research objectives was to observe the flow patterns that occur in a packed bed such as a subsurface flow constructed wetland (SSFCW). The visualization of the flow patterns makes it possible to identify areas in which a system may not be performing optimally. Such areas within a system where short-circuiting, bypass or dead volumes occur can thus be address and the performance of a system altered.

The RTD data captured gives the systems characteristics a numerical value that can be weighed against the visual data and improvements tracked.

This research report is structured into 6 chapters with the first being this introduction chapter.

Chapter 2 provides a review of the literature available regarding Constructed Wetlands along with current methods and modeling approaches.

Chapter 3 presents the residence time distribution theory used in the research.

Chapter 4 outlines the methodology used in the experimental pilot laboratory scale setup.

Chapter 5 presents the results of the experiments and a discussion

Chapter 6 concludes the research.

2. LITERATURE REVIEW

2.1 History of Constructed Wetlands

Natural wetlands have been used for over a century to treat wastewater in the United Kingdom and in Northern America. The discharge of wastewater into many of these natural wetlands was mainly due to ease of disposal rather than for treatment purposes and resulted in the permanent degradation of many wetlands (Vymazal, 2011). The degradation of these natural wetlands led to the need for alternative means of treating wastewater.

Research into the use of wetland plants to treat wastewater began as early as the 1950's by Dr. K. Seidel of Germany and steered the development of constructed wetlands (CW) along with a series of related conferences throughout the 1970's and 1980's (Vymazal, 2011; Wood, 1995).

The increasing need for treated wastewater in the last five decades has resulted in a need to develop an understanding of the biological, chemical and physical processes at work in CW as well as their complex interactions (Somes, 2000; Vacca, 2005; Langergraber, 2007).

2.2 Classification and Uses of Constructed Wetlands

CW can be classified according to the major macrophytic life form present in them be it; floating leaved, free floating, rooted emergent or submerged macrophytes. Furthermore they may be classified according to the systems overall hydrological make-up, free surface and subsurface flow, as well as flow directionality; vertical or horizontal (Vymazal, 2010). A summary of CW classification can be found in Figure 2-1.

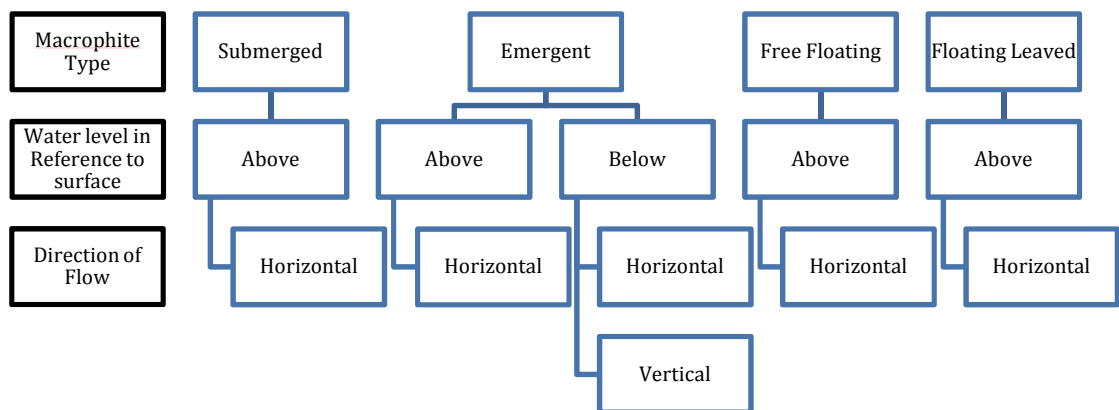


Figure 2-1 Classification of various types of Constructed Wetlands
 adapted from (Vymazal 2010)

Free surface flow constructed wetlands (FSFCW) typically consists of a channel with a barrier that prevents seepage, emergent vegetation and water at a shallow depth flowing through the system. The water surface is exposed to the atmosphere and the intended flow path through the system is horizontal. FSFCW can be more readily found in North America (Vymazal, 2011).

Subsurface flow constructed wetlands (SSFCW) also consists of a channel with a barrier to prevent seepage, but contains a suitable depth of porous media. Rock or gravel is the most commonly used media type and the media also supports the root structure of the emergent vegetation. The design of these systems assumes that the water level in the bed will remain below the top of the rock or gravel media i.e. no free surface is present. The SSFCW can also be found in a variation of horizontal or vertical subsurface flow. SSFCW can be more readily found in Europe (Vymazal, 2011).

The various types of CW are all predominantly used to treat domestic wastewater, agricultural wastewater, acid mine drainage, and stormwater runoff amongst others (Davis 1995, Vymazal 2010). A cross-sectional illustration of both a FSFCW and a SSFCW can be seen in Figure 2-2.

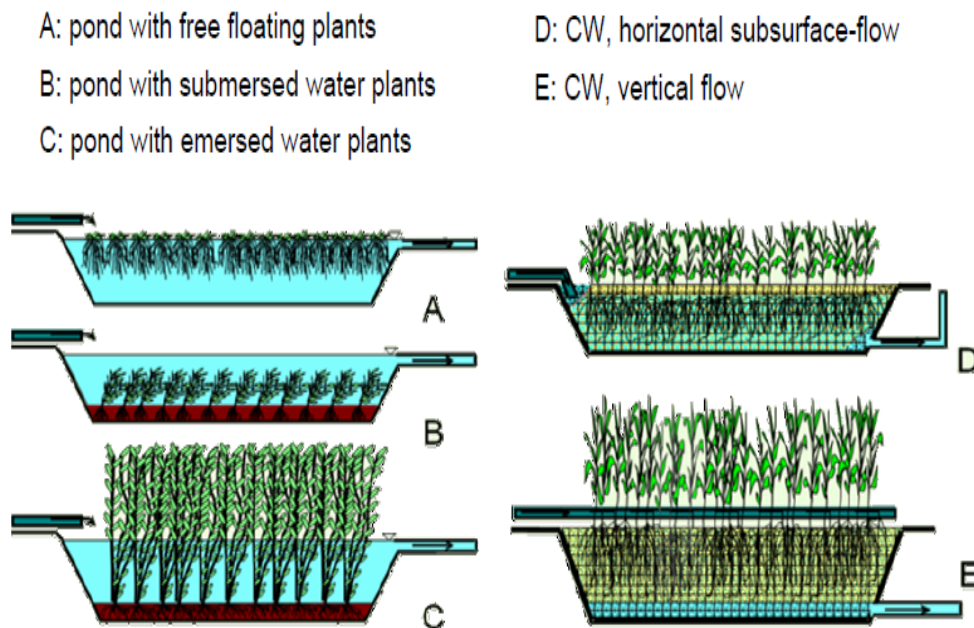


Figure 2-2 Illustration of wetland types and configurations.

The advantages of employing a CW for treatment purposes include: reduced capital costs compared with chemical treatment options, minimal operation and maintenance costs, tolerance to flow fluctuations, natural habitats for animal life (Knight, 1997), reduced environmental impacts, the encouragement of water recycling, and pleasant aesthetics. However, there are also drawbacks to using CW: they have larger land needs than orthodox treatment plants (such as wastewater treatment plants) and their performance may vary seasonally, toxic wastewaters may kill off biological treatment components (Davis, 1995), and they are prone to subsurface clogging and subsequent surface flow (Vymazal, 2011).

CW have been identified to have great potential in developing countries; especially in rural communities where municipal wastewater treatment may not be available. The use of CW in developing countries is however limited due to lack of awareness and local expertise (Kivaisi, 2001).

2.3 Current Modelling Approaches

Techniques used in the design of CW range from rules of thumb (Wood, 1995; Davis, 1995; Kadlec et al, 2008) to a list of more recently developed numerical models such as first order transportation, Monod kinetics and other process based models (Langergraber et al, 2009a). The success of these approaches varies with each having their own advantages, disadvantages and limitations.

2.3.1 Simplified and empirical transport models

Rule of thumb models follow a simplified approach to designing CW, and are the easiest and quickest to apply; however, they have the highest measure of variability (Rousseau, 2004). These models are founded on observation, and attempt to suggest appropriate aspect ratios that will maximize the effectiveness of CW. The advantage to employing such an approach is that there is a large amount of literature available that allows the designer of a CW to quickly come up with a solution to apply (US EPA, 2000). The disadvantage of using such an approach is that there may be little to no understanding of the processes that are occurring within the CW. Should problems arise a solution may be difficult to come up with and further damage may be done to the system, as the design is not optimised. More land may be required than is truly required.

Regression equations originate from empirical analyses which attempt to identify relationships between parameters (Rousseau, 2004). Regression equations can be used to monitor the general performance of a CW and produce correlations between various parameters. Stone et al. (2002) used regression equations (Eq 1) to predict outlet concentration of the swine lagoon but found that the regression coefficients (r^2) were less than 0.6 suggesting that more factors than were considered influenced the outcome.

$$C_{out} = aC_{in}^b q^c \quad \text{Eq (1)}$$

Where: C_{in} is the inlet concentration
 C_{out} is the outlet concentration
 q is the hydraulic loading rate, and
 a , b and c are regression coefficients

A limitation of these kinds of empirical equations is that due to most equations combining a small number of parameters such as wetland sizes, effluent compositions, plant species and prevailing climate conditions other influential processes are neglected resulting in an over simplified result (Stone et al, 2002)

2.3.2 First-order transport models

First-order equations (Kadlec et al, 2008; Kadlec, 1997) function under the assumption of steady-state operating conditions such as inlet concentration, flow rate, and influent type and can be viewed as ideal plug-flow reactors. First-order models have been used to forecast removal of pollutants such as nitrogen, ammonia, phosphorus, suspended solids, and other forms of organic matter generally making use of either Eq (2) or (3) (Kumar et al, 2011).

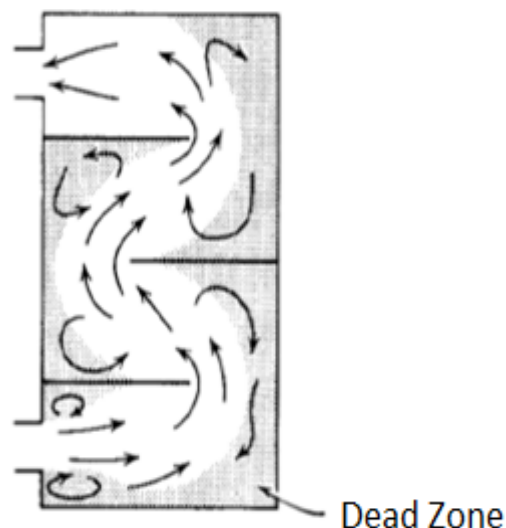


Figure 2-3 Illustration of dead zones and short-circuiting in reactors (Levenspiel, 1972).

$$\frac{C_{out}}{C_{in}} = e^{-\frac{k_A}{q}} \quad \text{Eq (2)}$$

Where: k_A is the areal decomposition constant, and

$$\frac{C_{out}}{C_{in}} = e^{-k_v HRT} \quad \text{Eq (3)}$$

Where: k_v is the volumetric decomposition constant, and
HRT is the hydraulic retention time

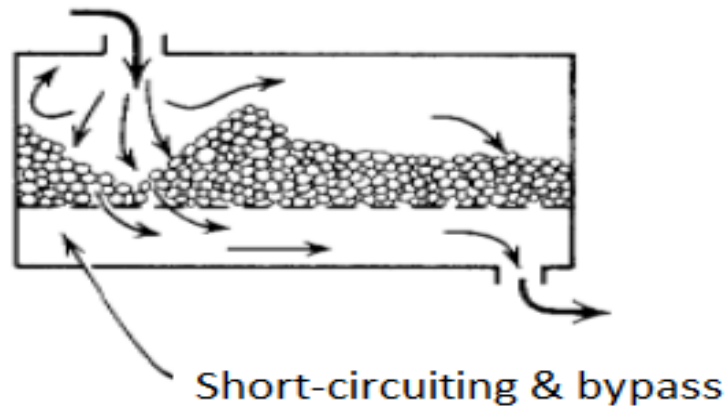


Figure 2-4 Illustration of short-circuiting and bypass in reactors (Levenspiel, 1972).

The use of first-order models is well documented and it has been noted that although they are commonly used in design they are based on input-output responses and say very little about the hydrodynamics and other internal processes at work in a system.

The fact that these models are based on ideal plug flow and steady state condition has its own drawbacks. In reality the formation of dead zones, occurrence of short-circuiting and bypass (illustrated in Figure 2-3 and 2-4) create non-ideal plug flow, variable inlet concentration and hydraulic loading that affect steady state conditions (Kadlec, 2000; Rousseau, 2004).

Furthermore, first order models show that removal rates continue to increase as loading rates increase which in practice is known not to be the case when compared with the zero-order models where the kinetics becomes independent of concentration (Mitchell et al, 2001). Attempts have also been made to incorporate background concentrations and the effects of precipitation and evapotranspiration with variable success (Rousseau, 2004).

A case study by Jamieson et al. (2007) reported that the efficiency of treating livestock wastewater in cold climates was higher when compared to studies done in warmer climates. The corresponding kA values for water quality parameters; biological oxygen demand, total phosphorus total, nitrogen, ammonium nitrogen, ammonia nitrogen and total suspended solids were lowered by at least 0.005 m d^{-1} compared with the kA values reported by Reed et al (1995) and Kadlec and Knight (1996) after adjusting the outlet concentration for dilution. Stone et al. (2004) reported considerably lower kA values for the marsh-pond-marsh wetland system, however, in comparison this was justified by lower reaction rate constants due to higher hydraulic loading in these systems.

2.3.3 Monod kinetic models and Neural Networks

Some of the limitations of first order models may be overcome by employing Monod kinetic equations such as Eq (4); these describe first-order rate laws for small concentrations (where $C \ll K_{HSC}$) and zero-order rate laws for large concentrations (Mitchell et al, 2001).

$$r = k_{0,v}V \frac{C}{K_{HSC} + C} \quad \text{Eq (4)}$$

Where: r is the rate of biological degradation

K_{HSC} is the half-saturation constant

C is the contaminant concentration

$k_{0,v}$ is the zero-order volumetric rate constant

Monod kinetics is based on viewing metabolism in terms of elementary modes representing various options for the utilization of external substrate. Each substrate contributes to the production of intracellular metabolites, extracellular products, and biomass.

Multi-Monod kinetics that account for more than one Monod relationship has been shown to more closely represent the complex biodegradation routes of nitrogen and organic pollutant removal in horizontal and vertical flow CW than first-order models (Saeed et al, 2011).

Kemp and George (1997) made use of a comparable model to represent ammonia removal in a pilot-scale SSFCW that treated wastewater. The coefficient of determination was $r^2=0.94$ for ammonium removal in the Monod type model, better described the variability of the data than previous first-order model.

Artificial neural networks (ANN), a computational model that mimics biological neural networks, has been used to successfully model the total nitrogen removal in CW as employed by Akrotos et al (2009) in Eq (5) and (6), with satisfactory performance. The design equation beneficially makes use of a Monod type expression that takes both first and zero order rate laws into account (Kumar et al, 2011).

$$R_{TN} = \frac{HRT}{K_{TSRP} + HRT} \quad \text{Eq (5)}$$

$$K_{TSRP} = \left(\frac{22.8}{T}\right) 45.5 \left(\frac{n}{1-n}\right)^3 \quad \text{Eq (6)}$$

Where: R_{TN} is the total nitrogen removal

K_{TSRP} is the time of the removal

n is the porosity

T is temperature

Naz et al. (2009) conducted an analysis of SSFCWs by modelling the system using an ANN–back propagation algorithm. The results demonstrated the successful use of ANN with r^2 values for predicting effluent total chemical oxygen demand = 0.90, soluble chemical oxygen demand = 0.90, and total biological oxygen demand = 0.94.

2.3.4 Process based models

Process based models attempt to assimilate processes occurring in a system into a single model. The more processes and process interactions a model can accurately capture that occurs within a system, the more rigorous that model becomes.

A two-dimensional mechanistic model has been used to determine the relative contribution of different microbial reactions to organic pollutant removal in horizontal SSFCW by coupling the Retraso reactive transport code with multiphase flow and heat code CodeBright. The results of the model were limited as it was only an initial attempt to integrate the microbial processes in organic matter removal in horizontal SSFCW by Ojeda et al (2008).

Structural thinking experiential learning laboratory with animation, known as STELLA, introduced in 1985 is a graphical programming language that can be used to model dynamic systems has also been successfully used in several CW studies (Wang et al, 2000; Ahn et al, 2002; Mayo, 2005) to model pollutant removal.

Pimpan and Jindal (2009) described the adsorption, desorption and plant uptake in the laboratory scale FSFCWs using the STELLA software. The simulated average cadmium removal efficiencies were in the range of 61.7- 99.6 % and the measured average values between 74.6 - 96.5 % showing a high level of correlation.

Constructed wetland two-dimensional model known as CW2D, developed by PC-Progress, is a multi-process reactive transport model for SSFCW as an extension of the HYDRUS, a variably saturated water flow and solute transport program.

CW2D has been used to focus on the hydraulic behaviour of CW (Langergraber et al, 2005) as well as pollutant removal in pilot scale CW with the results showing a good match with the measured data for water flow, tracer experiments and pollutant removal processes (Toscano et al, 2009).

Constructed wetland model known as CWM1 is a bio-kinetic process model that considers aerobic, anoxic and anaerobic processes for organic matter, nitrogen and Sulphur in SSFCW. CWM1 like CW2D works as an extension of HYDRUS and has been developed to deliver a generally accepted model for biochemical transformation and degradation processes in SSFCW (Langergraber et al, 2009b).

Computational fluid dynamics (CFD) is a division of fluid mechanics that uses numerical methods and processes to simulate fluid flow that has been shown to be capable of simulating flow in porous media such as SSFCW. The residence time distribution (RTD) of a SSFCW can be modeled using particle trajectory theory, which defines the key indicators such as, the normalized retention time, normalized variance and hydraulic efficiency. The key indicators give interpretable values of the SSFCW hydraulic performance (Fan et al, 2008).

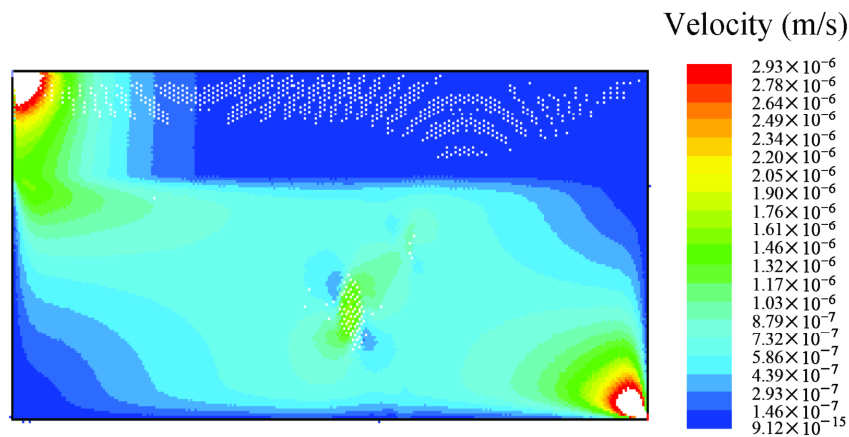


Figure 2-5 Illustration Velocity vectors figures in a SSFCW (Fan et al, 2008)

CFD has thus far been utilized to simulate flow patterns in porous media with stratified layers, as well as for varying inlet and outlet catchment areas as shown

in Figure 2-5. The hydraulic efficiency in the simulations were shown to be affected mainly by the selection of a specific porous media (Fan et al, 2008) which confirmed the results of prior work done on packing materials (García et al, 2004; Suliman et al, 2007). The effects of distribution and catchment area using CFD have also been investigated (Fan et al, 2009). The work done on horizontal SSFCW using CFD has however not been compared to any experimental data.

2.3.5 Model Verification and Validation

Verification and validation of computational simulations are fundamental to establishing and quantifying confidence in modeling. Verification can be taken as the evaluation of the accuracy of the solution to a computational model by comparison with known solutions. Validation on the other hand is the accuracy of a computational simulation by comparison with experimental data (Oberkampf et al, 2002).

3. Residence Time Distribution Theory

The content covered in this section details why the theory was selected to model packed beds such as SSFCW, the residence time distribution theory employed in the experiments, and assumptions made.

3.1 Introduction

Constructed wetlands can be regarded as chemical reactors and their treatment processes under controlled conditions as first-order biochemical reactions. The residence time distribution (RTD) of a chemical reactor is a probability distribution function that defines the amount of time that a fluid element might spend inside such a reactor. A fluid element can be viewed as a small volume of fluid where continuous properties such as concentration can be defined. The RTD measures the time fluid elements spend inside a reactor and typically characterizes the mixing and flow conditions. The behaviour of a real reactor can thus be compared with one of an ideal model.

The theory of residence time distribution has three main assumptions:

1. The reactor is taken to be in a steady state,
2. Transport at the inlet and outlet take place only by advection, and
3. The fluid is incompressible i.e. the density stays constant

For the first assumption of a steady state to hold true, the water balance of a CW must result in no accumulation with time. Zero accumulation is achieved when the summation of the flow rates in the system, namely; inflow, outflow, precipitation, infiltration and evapo-transpiration equals zero. This assumption was assumed to be valid for all experiments as they were performed in a controlled environment.

The second assumption refers to the transport mechanism of fluid occurring by bulk fluid motion. The assumption can be assumed reasonable for all the experiments performed.

The distribution of residence times is represented by an exit age distribution $E(t)$ and a fraction of fluid that spends a time, t , in the reactor is valued as $E(t)dt$

3.2 RTDs of ideal and non-ideal reactors

The residence time distribution of a packed bed such as a SSFCW can be compared to two ideal reactor models:

- plug flow reactor (PFR)
- continually stirred tank reactor (CSTR)

In an ideal PFR no mixing occurs and fluid elements are said to exit the system in the same order they arrived thus fluid entering the reactor at time, t will exit at time, $t + \tau$. The variance of an ideal PFR is zero.

In an ideal CSTR it is assumed that flow at the inlet is instantaneously mixed into the bulk of the reactor and thus the fluid at the outlet would have an identical composition at all instances. It is however not realistically possible to attain such rapid mixing and all real reactors will diverge from the ideal.

A mean residence time occurring before τ indicates that dead zones occur within the system where fluid is stagnant and thus the effective volume is less than the design value. Multiple peaks can be taken as an indication that one of the following or a combination of channeling, parallel paths to the exit or internal reticulation has occurred. Short-circuiting, bypass and hold up of the reactor fluid would be noted as a small initial pulse on the RTD curve as concentrated tracer reaches the outlet soon after injection.

3.3 Moments of the RTD for Pulse Input Experiments:

The theory presented here has been largely adapted from the work of Fogler (2005) and Levenspiel (1972) and are used together in the determination of hydraulic characteristics associated with RTD. The theory is presented in a step by step manner of each parameter.

In performing a pulse input experiment a small volume of concentrated non-reactive tracer is introduced at the inlet of the system. The concentration of the tracer changes based on a known function and response and the selected tracer should not alter any of the properties of the fluid nor affect the hydrodynamics of the system. Ideally the tracer should have a similar viscosity, diffusion coefficient and density to the flow medium. The injection of tracer should be over a relatively small time in comparison with the mean residence time of the reactor. A concentration vs. time curve, $C(t)$ is produced by measuring the concentration of tracer at the outlet. The $C(t)$ curve can then be converted into a residence time distribution in the following manner:

$$Q = \sum_{i=0}^{n \rightarrow \infty} C_i \Delta t \quad \text{Eq (7)}$$

Where: C_i is the concentration of sample i taken at time t_i and
 Δt is the time interval for the given C_i value

A corresponding E_i value can be determined for every C_i value as follows:

$$E_i = \frac{C_i}{Q} \quad \text{Eq (8)}$$

The following parameters are then calculated in order to determine the moments of the $E(t)$ distribution:

$$\text{a. } t_i \cdot E_i \cdot (t_i - t_{i-1}) \quad \text{Eq (9)}$$

$$\text{b. } t_i^2 \cdot E_i \cdot (t_i - t_{i-1}) \quad \text{Eq (10)}$$

The first moment (mean residence time) is defined as:

$$t_m = \sum_{i=1}^{n \rightarrow \infty} t_i \cdot E_i \cdot (t_i - t_{i-1}) \quad \text{Eq (11)}$$

The residence time (τ) for an ideal reactor is defined as:

$$\tau = \frac{V \cdot \varepsilon}{Q} \quad \text{Eq (12)}$$

Where: ε is the void fraction of the packed material and is defined as:

$$\varepsilon = \frac{V_V}{V_S} = \frac{M_V}{M_S} \quad \text{Eq (13)}$$

V_V and M_V are, respectively, the volume and mass of the voids

V_S and M_S are, respectively, the volume and mass of the materials

Q is the volumetric flow rate of the system

V is the volume of the model

The variance (σ^2) describes the degree of dispersion and is defined as:

$$\sigma^2 = \left(\sum_{i=1}^{n \rightarrow \infty} t_i^2 \cdot E_i \cdot (t_i - t_{i-1}) \right) - t_m^2 \quad \text{Eq (14)}$$

The variance has to be normalized so that the dispersion number, D , can be found.

The normalized second moment (σ_θ^2) is defined as:

$$\sigma_\theta^2 = \frac{\sigma^2}{t_m^2} \quad \text{Eq (15)}$$

The dispersion number, D , is then solved for iteratively using the following equation:

$$\sigma_{\theta}^2 = 2 \cdot D - 2 \cdot D^2 \cdot (1 - e^{-1/D}) \quad \text{Eq (16)}$$

The effective volume ratio as described in the literature presented by Perrson et al. (1999) is a parameter which is used to determine the efficiency of the system. It describes what ratio of the systems volume is active (i.e. what volume is not dead) the effective volume is defined as:

$$V_{eff} = t_m / \tau_{ideal} \quad \text{Eq (17)}$$

A mass balance can be carried out to determine the amount of tracer recovered from the system by taking the area under $C(t)$:

$$M = \int C(t) dt \quad \text{Eq (18)}$$

4. Methodology

4.1 Physical Experiment

Four phases were identified that need to be completed for every experiment to be run successfully, namely: mixing of the tracer, calibration of the Spectrophotometer, the running of the experiments themselves and testing of the samples in the Spectrophotometer.

A 1000mg/l concentration, using the FWT Red tracer powder (see Appendix F), was used for all the experiments. The 1000mg/l concentration was diluted to obtain varying concentrations in order to calibrate the Spectrophotometer. The experiments were run by injecting 20ml of the 1000mg/l concentration into the tank over a period of time no greater than ten seconds in order to create the impulse needed. Samples were taken at varying time intervals throughout each experiment and were analysed in the spectrometer to obtain the concentration.

The pilot laboratory scale inlet and outlet grid position as well as the apparatus set up can be seen in Figure 4-1 and 4-2 respectively.

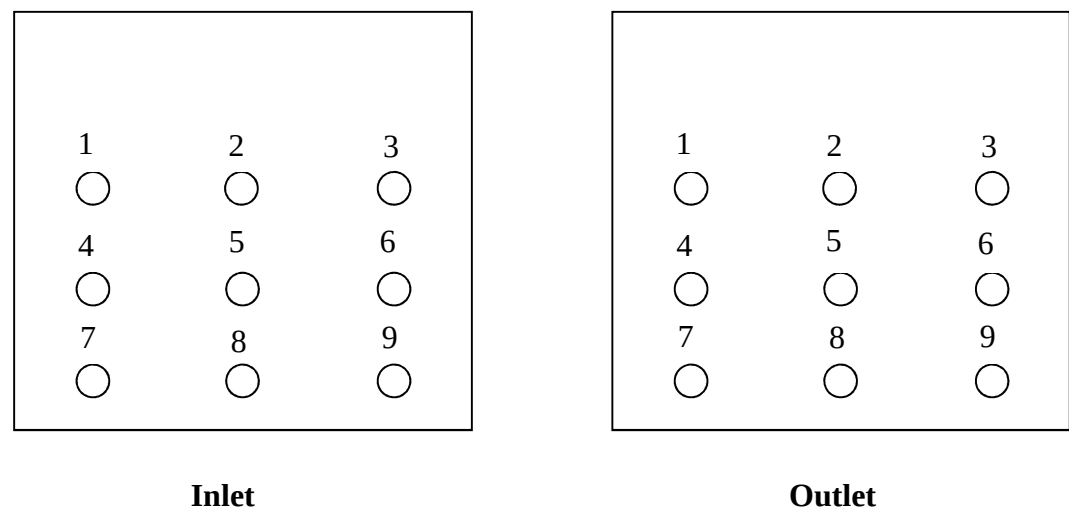


Figure 4-1 Inlet and Outlet Grid Position

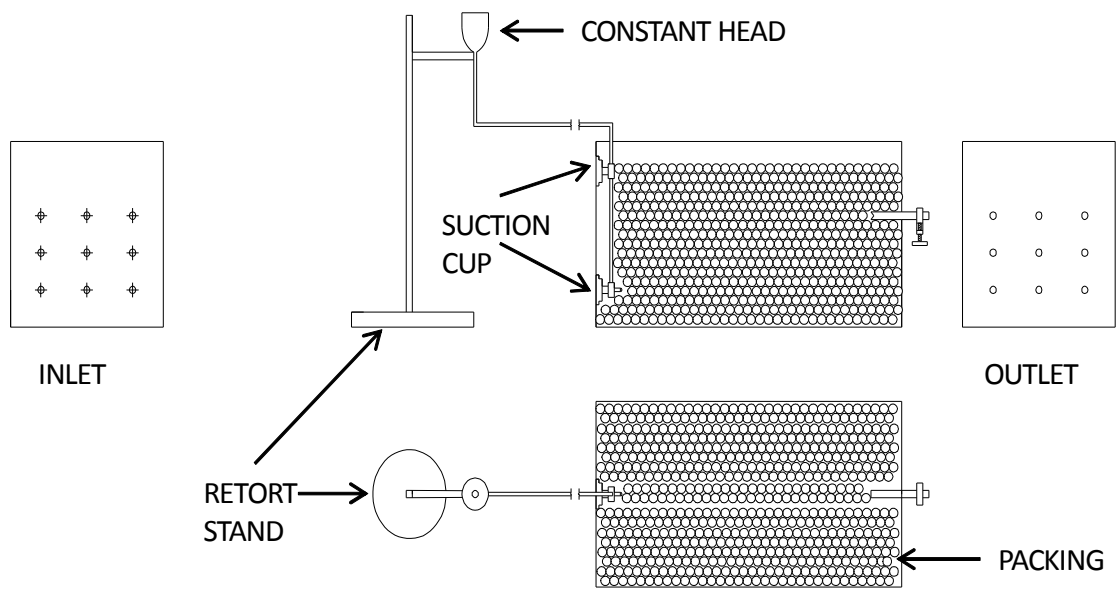


Figure 4-2 Apparatus Setup

The procedure to produce the replicable data is outlined below.

4.1.1 Tracer Mixing

- A clean measuring pan was placed on an electronic scale and the scale reset to zero.
- The measuring pan was then removed.
- FWT red dye was scooped into the measuring pan using a spatula and weighed on the scale, adding or removing dye until 0.1 grams was attained.
- The 0.1 grams was added to 100ml of distilled water in order that the concentration of the tracer would be 1000mg/l.
- The dye was then transferred into a 100ml volumetric flask by rinsing the measuring pan with distilled water into a funnel.
- The dye was rinsed out of the measuring pan until all the dye was cleared from it.
- The funnel was then rinsed until the dye was cleared from it as well.
- The remainder of volumetric flask was filled to the 100ml with distilled water, with the bottom of the meniscus touching the mark.

- The volumetric flask was then sealed and shaken in order to ensure thorough mixing.
- The volumetric flask was then unsealed and carefully poured into a measuring beaker.
- A syringe was inserted into the beaker and 20ml of dye extracted into it.
- The remained of the dye in the beaker was discarded.

4.1.2 Calibration

The spectrophotometer was calibrated in order that readings could be obtained from it accurately. In order to do this the process of tracer mixing has to be done as set out above in the previous section. Tracer concentrations of 0.1, 1, 10, 25, 50 and 100mg/l were made. The tracer concentrations were individually placed in the spectrophotometer, which recorded the absorbency value while the concentration is entered manually. The results of the absorbency values versus concentration curve are saved as a parameter, from which sample concentrations can be read off.

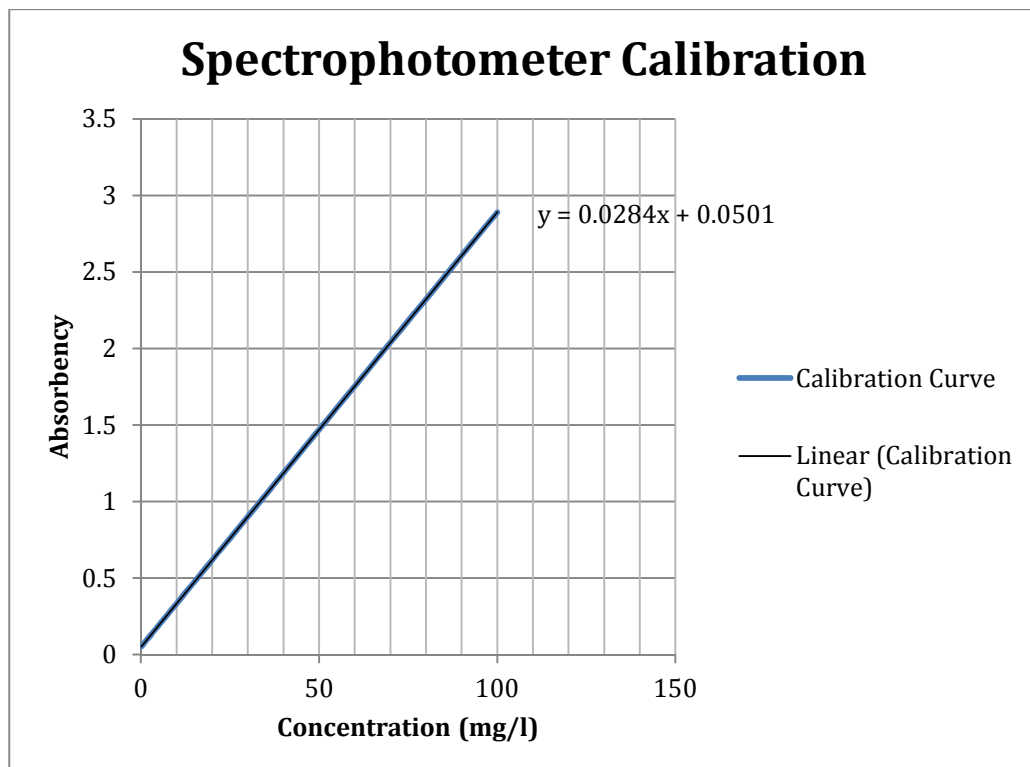


Figure 4-3 Spectrophotometer Calibration Curve and Equation

4.1.3 Experiment

- Clear superabsorbent polymer balls were prepared by soaking them over night in water in order that they may become fully saturated see Figure 4-4.



Figure 4-4 Superabsorbent polymer balls in beaker (Purple balls instead of clear shown for clarity since the clear balls are almost invisible).

- The tank was prepared by placing a white neutral background behind and below it in order to make the dye clear in photographs and remove background noise.
- The inlet position of the specified experiment was noted and a sucker attached to that position.
- The inlet pipe was then attached to the sucker and aligned correctly.
- The outlet position was noted and prepared by inserting the necessary exit piping and sealing it correctly.
- The tank was filled with the superabsorbent polymer balls by scooping them from their storage container using a colander. This was done in order to ensure only the superabsorbent polymer balls enter the pilot laboratory scale rig and no water.
- Water was measured and added until a tight pack fill, at the specified level was achieved.

- The void ratio was thus determined by dividing the amount of water added by the amount of water that would have filled the container to the specified mark.
- The height of the water above the outlet position determined the discharge from the system and was measured by filling a measuring jug to 100ml whilst using a stopwatch to time this repeatedly. The division of the volume of water displaced by time was then converted to m^3/s .
- A continuous head tank was used for the inlet discharge and the height was set so that the inlet discharge would equal that of the outlet discharge.
- The system was then allowed to flow freely for 10 minutes in order to ensure that it was in a steady-state i.e. the water level of the system is neither rising nor falling.
- Once steady-state had been achieved the tracer was injected into the system.
- At specific times samples of the tracer were collected in glass tubes at the outlet.
- The entire process was photographed from a front and plan view perspective.
- The sampling continued until a specified elapse time occurred.
- After the completion of the experiment the samples were taken to the lab where they were analyzed in the spectrophotometer in order to attain their concentrations.

Five experiments were conducted with varying inlet and outlet configurations, namely (see Figure 4-1 for inlet-outlet grid positioning):

- Experiment 1: top centre inlet (2) to top centre outlet (2);
- Experiment 2: bottom centre inlet (8) to top centre outlet (2);
- Experiment 3: bottom centre inlet (8) to all top outlets (1, 2, & 3);
- Experiment 4: bottom centre inlet (9) to all top outlets (1, 2, & 3), including a wedge in the geometry; and
- Experiment 5: bottom right inlet (9) to top left outlet (1).

The wedge introduced in experiment 4 covered the breadth of the tank and was 100mm in length both in width and height (see Figure 4-5)

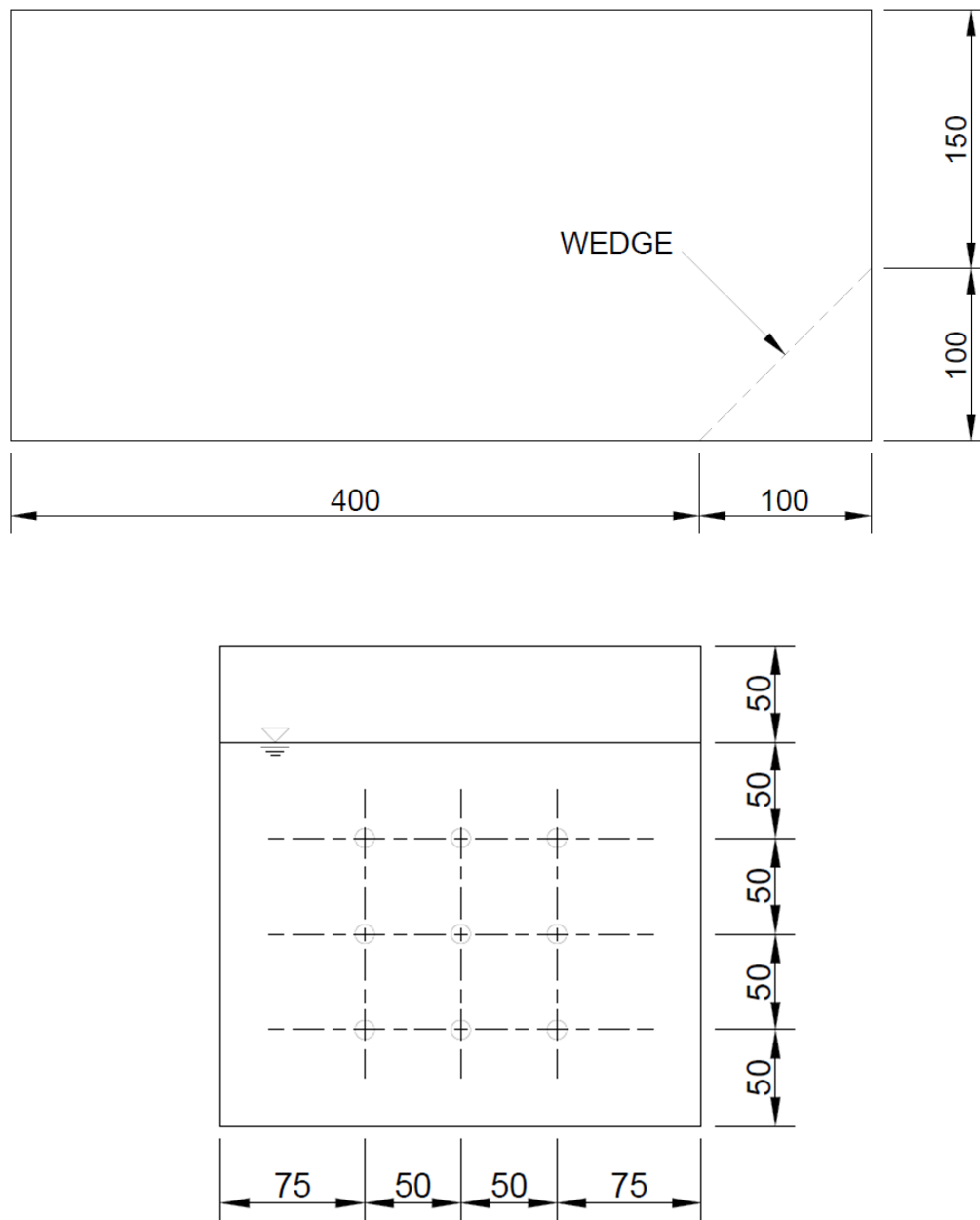


Figure 4-5 Elevation and Front view of rig geometry. Dimensions in millimeters (5mm holes oversized for clarity)

5. Results and Discussion

5.1 Introduction

In this section, the results are presented and discussed. To recap, the objective of this research was to:

1. To investigate the effect on the RTD parameters and flow patterns when varying the inlet-outlet configurations of a horizontal subsurface flow constructed wetland.
2. To compare and discuss the effects of varying the inlet-outlet configuration on the residence time distribution parameters.

The first research objective is discussed in chapter heading 5.2-5.6 and the second in 5.7. The data captured from experiment 1-5 can be found in Appendices A-E.

5.2 Experiment 1: Centre Top Inlet to Centre Top Outlet (2-2)

5.2.1 Residence time distribution Analysis

Experiment 1 focused on how the flow path would develop and affect the systems performance when the inlet-outlet positions were both centred at the top.

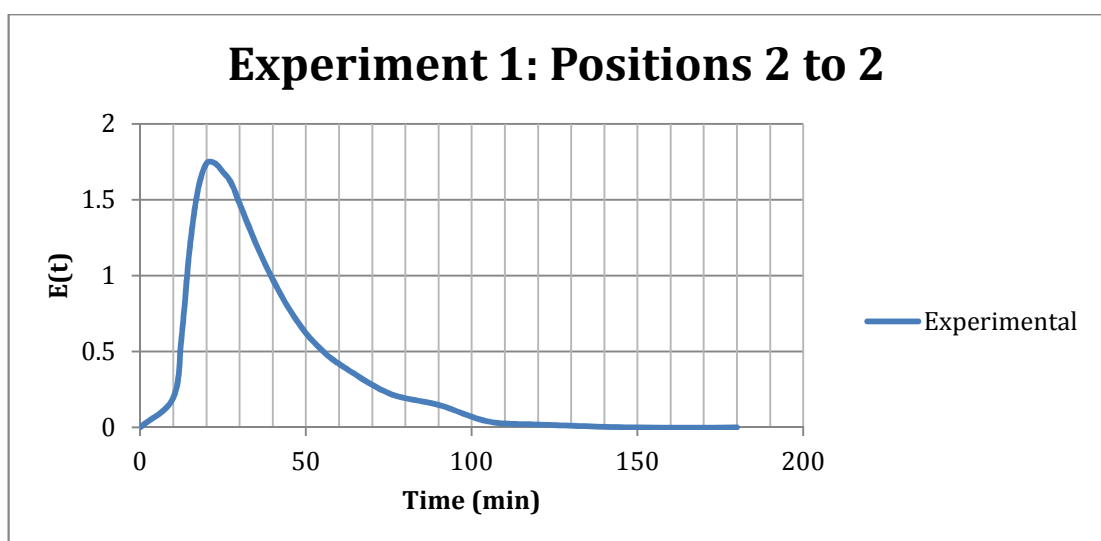


Figure 5-1 Experimental 1: Residence time distribution

Figure 5-1 depicts the characteristic age distribution for a packed bed reactor i.e. a single mode and a long tail. This confirms the findings of others Levenspiel (1972), Fogler (2005). A summary of the hydraulic parameters from the residence time distribution theory can be found in Table 5-1.

	t_m (min)	τ (min)	σ_0^2	V_{eff} (%)
Experimental	36.95	73.97	0.333	49.96

Table 5-1 Experiment 1: RTD Parameters

The data indicates that the system displays highly non-ideal behaviour as the mean residence time (t_m) is less than the theoretical residence time (τ) by 37.02 minutes. The cause of such a significant difference may be attributed to the flow occurring mostly at the top to middle of the system, the short length of the system not allowing for flow to form more fully towards the lower region and only 50% of the system volume being active.

5.2.2 Visual Analysis

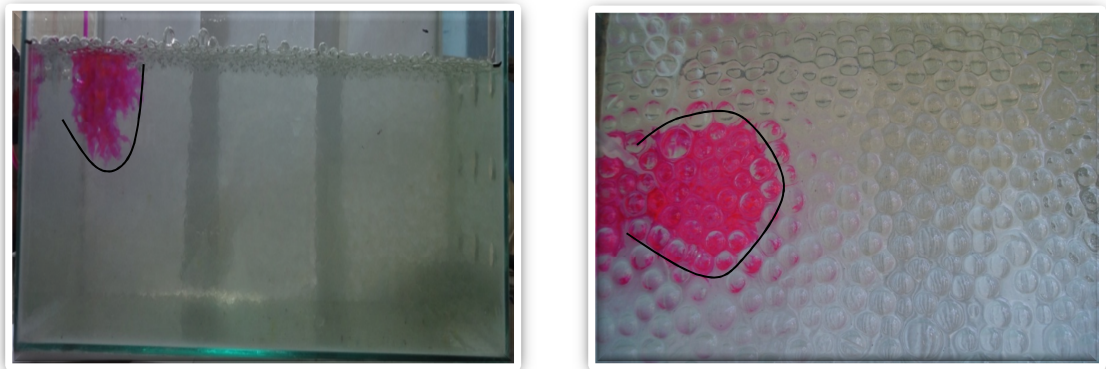


Figure 5-2 Experiment 1: Elevation and plan view ($t=10s$)

In Figure 5-2 the impulse injection of tracer is shown. The initial dispersion was seen to be radial in both views as the tracer impacted with the packing. The black line on the elevation and plan view depicts the approximate bounds of the tracer.

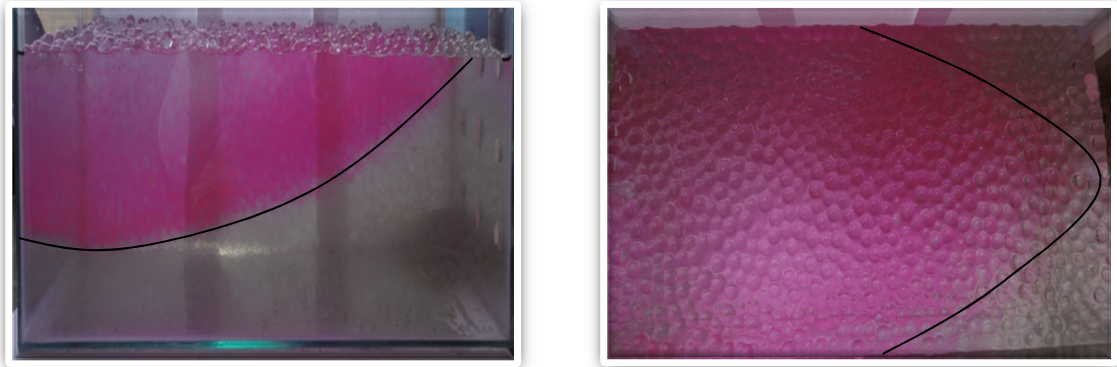


Figure 5-3 Experiment 1: Elevation and plan view (t=600s)

In Figure 5-3 the tracer was observed spreading downwards to the middle region of the system at the inlet and remained towards the top of the system as it approached the outlet. The flow pattern can be described as that of a hull-shape velocity profile (Sheridan, 2013). No tracer can be visibly seen towards the bottom of the system suggesting that the bottom region may be a dead volume.

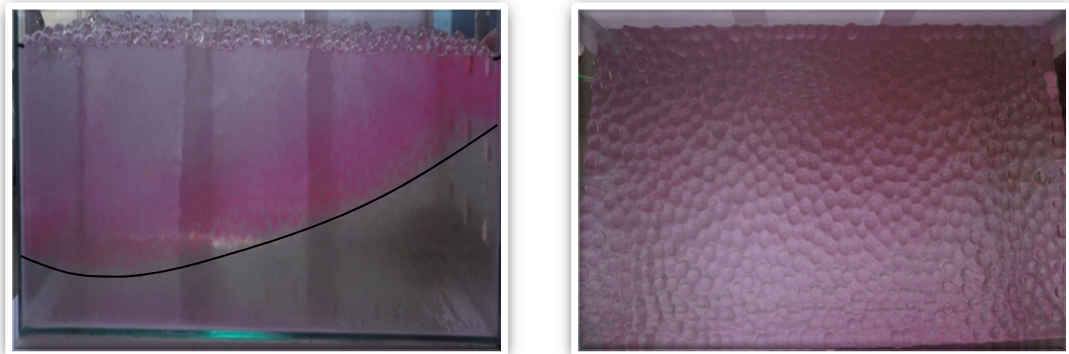


Figure 5-4 Experiment 1: Elevation and plan view (t=3600s)

In Figure 5-4 the tracer was seen to be clearing out towards the surface where the flow was greater than in the middle region of more visible tracer. The flow path remains similar to that of Figure 5-3 with the lower region of the system showing

no visible tracer. The black line on the elevation view shows the approximate divide between the region of visible tracer and none.

5.3 Experiment 2: Centre bottom to Centre top (8-2)

5.3.1 Residence time distribution analysis

Experiment 2 focused on how the system would perform with the flow occurring against gravity from the centre bottom inlet to the centre top outlet

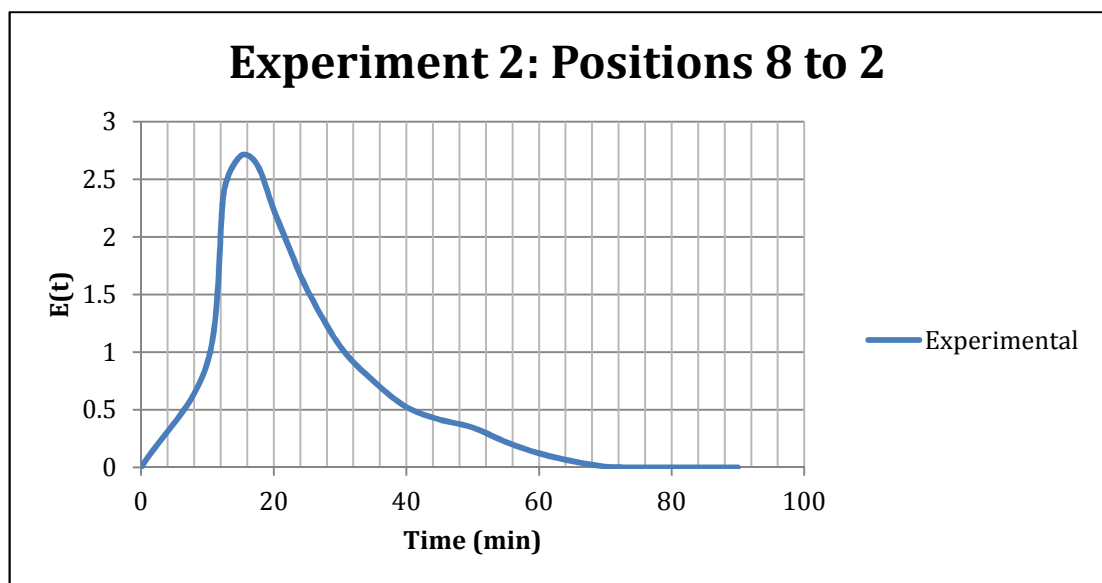


Figure 5-5 Experimental 2: Residence time distribution

Figure 5-5 depicts the characteristic age distribution for a packed bed reactor i.e. a single mode and a long tail. A summary of the hydraulic parameters from the residence time distribution theory can be found in Table 5-2.

	t_m (min)	τ (min)	σ_θ^2	V_{eff} (%)
Experimental	23.1	72	0.288	32.09

Table 5-2 Experiment 2: RTD parameters

The system, as in experiment 1, displays highly non-ideal behaviour as the mean residence time (t_m) is less than the theoretical residence time (τ) by 48.9 minutes. The cause of such a significant difference may be attributed to dead zones within the reactor.. The majority of the flow followed the path of least resistance diagonally between inlet position 8 and outlet position 2. Two thirds of the volume was noted to be dead and the inlet-outlet combination results in poor performance of the system.

5.3.2 Visual Analysis

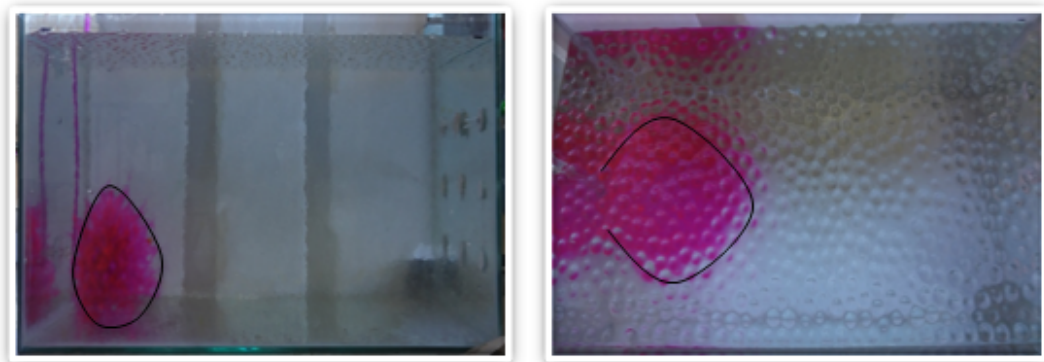


Figure 5-6 Experiment 2: Elevation and plan view (t=10s)

In Figure 5-6, the impulse tracer injection was captured 10 seconds into the experiment with the initial dispersion seen to be radial in both views.

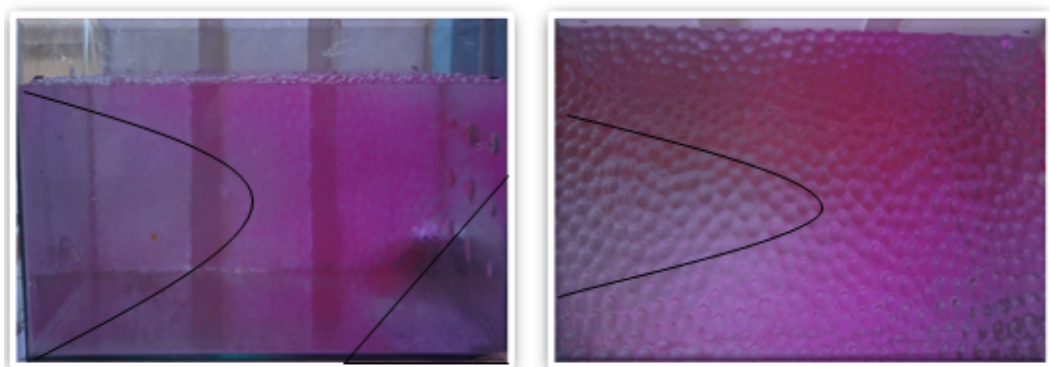


Figure 5-7 Experiment 2: Elevation and plan view (t=1800s)

In Figure 5-7 the tracer was observed flowing from the bottom left hand corner toward the top right of the system. The flow at 1800 seconds, from the left hand half of the system can be seen clearing out in a parabolic shape in both views suggesting the formation of a hull-shape velocity profile. On the right hand side at the top the tracer could be seen exiting the system and at the bottom a region free of visible tracer can be seen indicated by a black triangle.

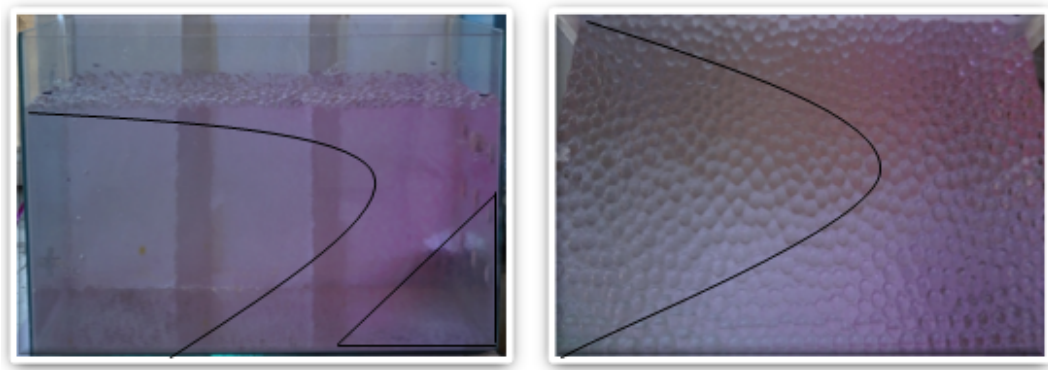


Figure 5-8 Experiment 2: Elevation and plan view (t=3600s)

In Figure 5-8, at 3600 seconds in the elevation view tracer was only visible in the band between the black triangle and parabola. In the plan view the tracer was only slightly visible in the region in front of the parabolic black line. This indicates that similarly to the other experiments, if flow enters the reactor from a single point, that it does not reach all parts of the reactor and that there are significant dead zones.

5.4 Experiment 3: Centre bottom to all top (8-1,2,3)

5.4.1 Residence time distribution analysis

Experiment 3 focused on how the system would perform with the flow occurring against gravity from the centre bottom inlet the top 3 outlets.

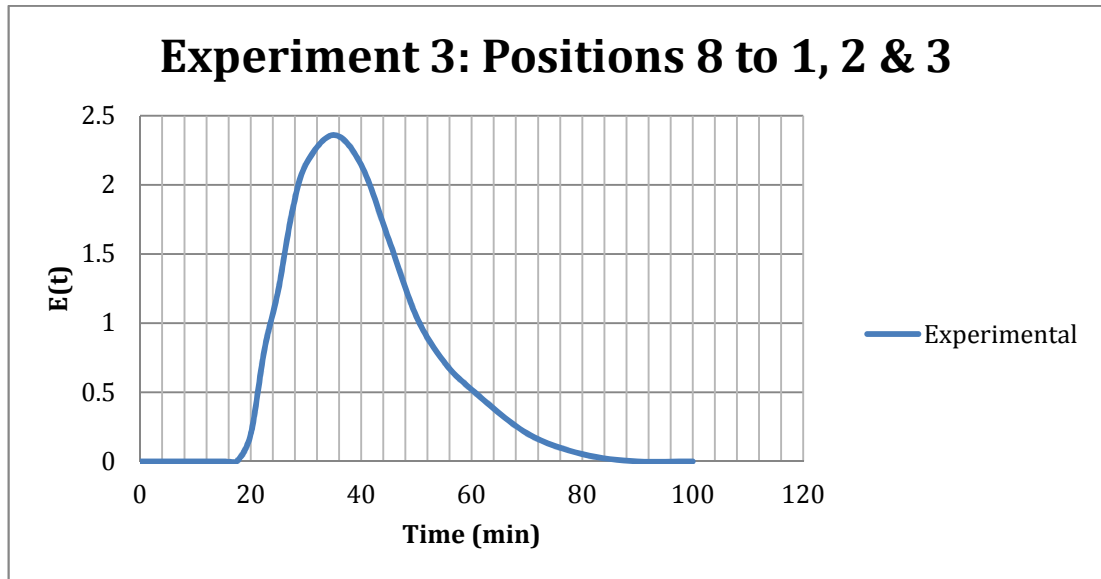


Figure 5-9 Experiment 3: Residence time distribution

Figure 5-9 depicts the characteristic age distribution for a packed bed reactor i.e. a single mode and a long tail, a notable flat line is present prior to 15 minutes as no tracer was sampled prior to this time period. A summary of the hydraulic parameters from the residence time distribution theory can be found in Table 5-3.

	t_m (min)	τ (min)	σ_θ^2	V_{eff} (%)
Experimental	40.32	72	0.085	56.0

Table 5-3 Experiment 3: RTD parameters

The system still displayed highly non-ideal behaviour as the mean residence time (t_m) was less than the theoretical residence time (τ) by 31.68 minutes. Again, the reason for such a significant difference may be attributed to the dead space within the reactor as was the case in experiment 2. The dispersion of the system improved when compared with that of experiment 2 as the flow is drawn towards the three separate outlets versus only one previously. The effective volume was measured at 56% indicating that under half of the system was not operating efficiently. This was an improvement on all experiments conducted thus far.

5.4.2 Visual Analysis



Figure 5-10 Experiment 3: Elevation and plan view (t=10s)

In Figure 5-10, the impulse tracer injection was captured 10 seconds into the experiment with the initial dispersion seen to be radial in both views.

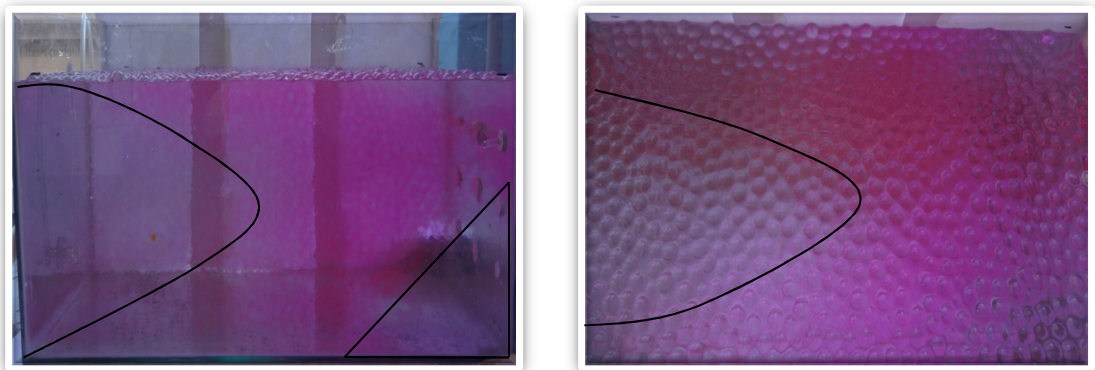


Figure 5-11 Experiment 3: Elevation and plan view (t=1800s)

In Figure 5-11 as in Figure 5-7, tracer can be seen flowing from the bottom left hand corner toward the top right of the system. In the elevation view a band of visible tracer could be seen between the parabolic black line and triangle. A tracer free dead volume appears at the bottom right hand corner of the system enclosed by a black triangle. In the plan view the tracer could be seen in front parabolic black line with the tip approximately halfway in the system.

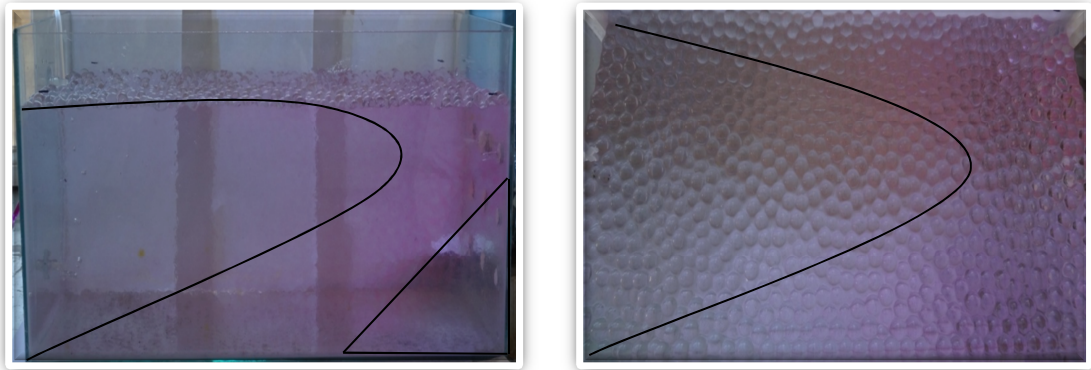


Figure 5-12 Experiment 3: Elevation and plan view (t=3600s)

In Figure 5-12, tracer could only just be seen flowing from the mid bottom region toward the top right of the system. In the elevation view the band of tracer had become narrower between the parabolic black line and triangle than seen in Figure 5-11. A visibly tracer free dead volume appeared at the bottom right hand corner of the system enclosed by a black triangle. In the plan view the parabolic black line with the tip approximately three quarters of the way in the system showed lightly colored tracer towards the outlet.

5.5 Experiment 4: Centre bottom to All top (8-1,2,3+Wedge)

5.5.1 Residence Time Distribution Analysis

Experiment 4 focused on how the system would perform with the flow occurring against gravity from the center bottom inlet to the top 3 outlets with the inclusion of a wedge within the reactor. This wedge physically reduced the volume of the reactor and essentially occupied the dead volume which had been observed in the experiments conducted prior to this point.

Figure 5-13 depicts the characteristic age distribution for a packed bed reactor i.e. a single mode and a long tail. A summary of the hydraulic parameters from the residence time distribution theory can be found in Table 5-4.

The discussion of the comparison with experiment 2 and 3 is done in Chapter 5.7 but it can be noted that the introduction of the wedge to the geometry made a notable difference to experiment 4's RTD parameters. The system still displayed non-ideal behaviour as the mean residence time (t_m) was less than the theoretical residence time (τ) by 13.62 minutes. However, the effective volume was found to be 79.8% which would represent a significant improvement.

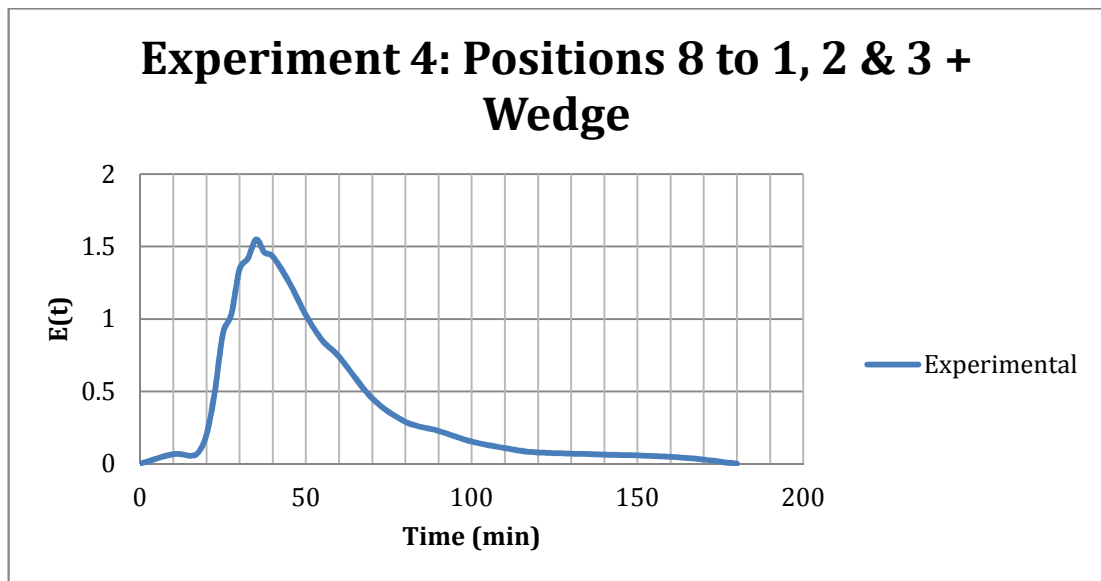


Figure 5-13 Experiment 4: Residence time distribution

	t_m (min)	τ (min)	σ_θ^2	V_{eff} (%)
Experimental	53.76	67.38	0.301	79.8

Table 5-4 Experiment 4: RTD parameters

5.5.2 Visual Analysis

In Figure 5-14, the dispersion of tracer in both the elevation and plan view could be seen as radial.

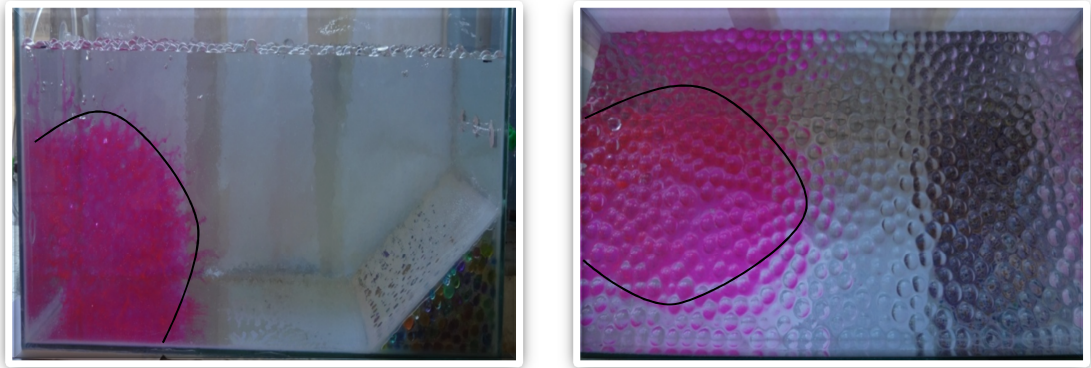


Figure 5-14 Experiment 4: Elevation and plan view (t=60s)

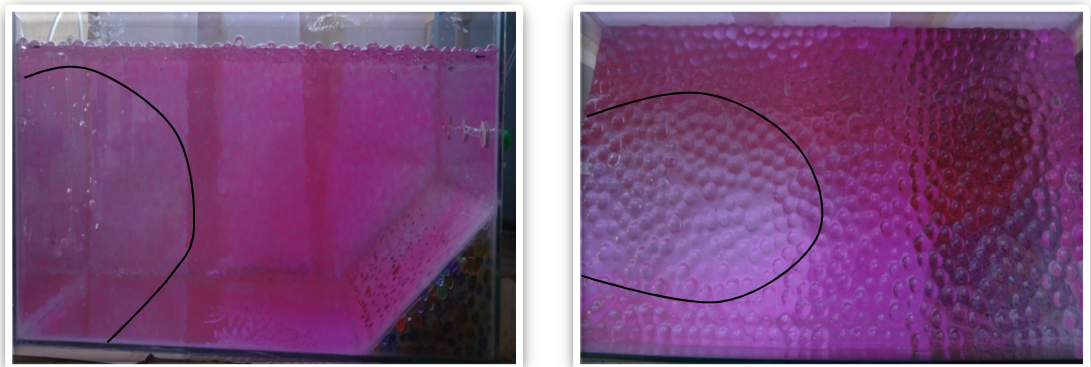


Figure 5-15 Experiment 4: Elevation and plan view (t=1800s)

In Figure 5-15, in the elevation view, visible tracer could be seen flowing throughout most of the system with only a small amount of clearing out occurring behind the black parabolic line. The black triangular dead volume seen in experiment 2 and 3 was replaced with the wedge and in this picture, it is noticeable that the clear dead volume seen in earlier experiments no longer exists. In the plan view the visible tracer could be seen in front parabolic black line with the tip approximately halfway in the system.

In Figure 5-16, in the elevation view, the visible tracer was seen in a band between the black line and the right hand side of the system. In the plan view, the visible tracer could be seen in the predominately towards the right side of the system.



Figure 5-16 Experiment 4: Elevation and plan view (t=3600s)

5.6 Experiment 5: Bottom Right to Top Left

5.6.1 Residence Time Distribution Analysis

Experiment 5 focused on how the system would perform with the flow occurring against gravity from the bottom right inlet to the top left outlet. This experiment was conducted to determine if a diagonal path would make any notable improvement to the system when compared to previous experiments.

Figure 5-17 depicts the characteristic age distribution for a packed bed reactor i.e. a single mode and a long tail. A summary of the hydraulic parameters from the residence time distribution theory can be found in Table 5-5.

The system once again displayed highly non-ideal behaviour as the mean residence time (t_m) was less than the theoretical residence time (τ) by 35.58 minutes. The cause of such a significant difference may be attributed to dead volumes as was the case in experiment 2 and 3. The effective volume was measured at 62.9% indicating that approximately one third of the system was not operating efficiently. It is postulated that this improved effective volume is due to there being a slightly longer path which resulted in more time for diffusion of the dye within the system.

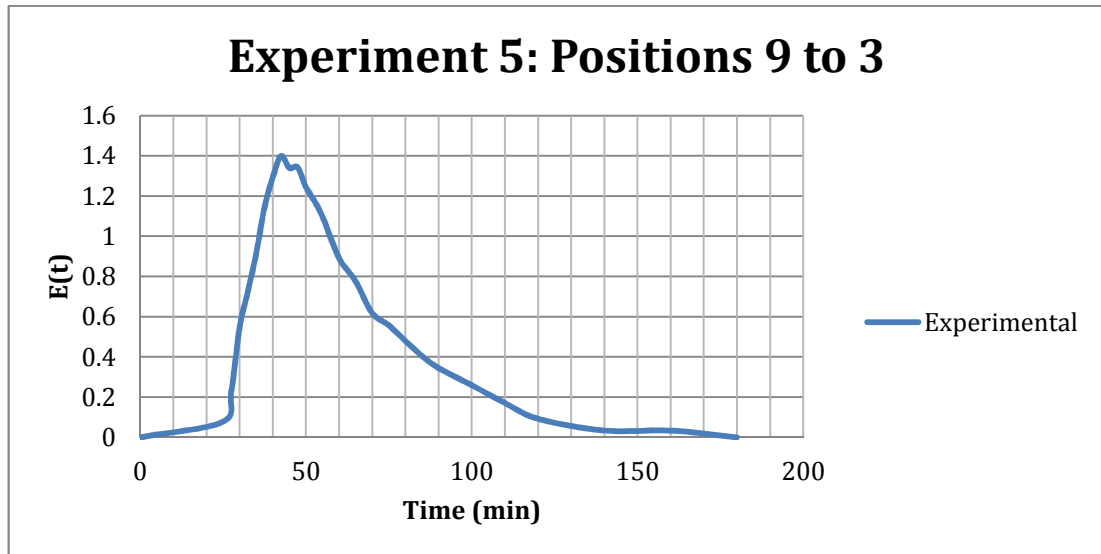


Figure 5-17 Experiment 5: Residence time distribution

	t_m (min)	τ (min)	σ_θ^2	V_{eff} (%)
Experimental	60.42	96	0.184	62.9

Table 5-5 Experiment 5: RTD parameters

5.6.2 Visual Analysis

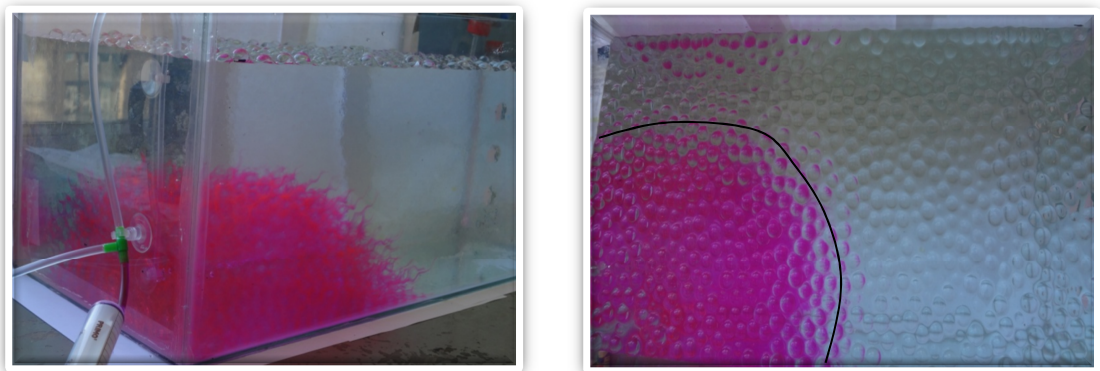


Figure 5-18 Experiment 5: Elevation and plan view (t=60s)

In Figure 5-18 the angled elevation view showed the dispersion of tracer from the bottom right hand corner. In the plan view the tracer could be seen dispersing radially forward.

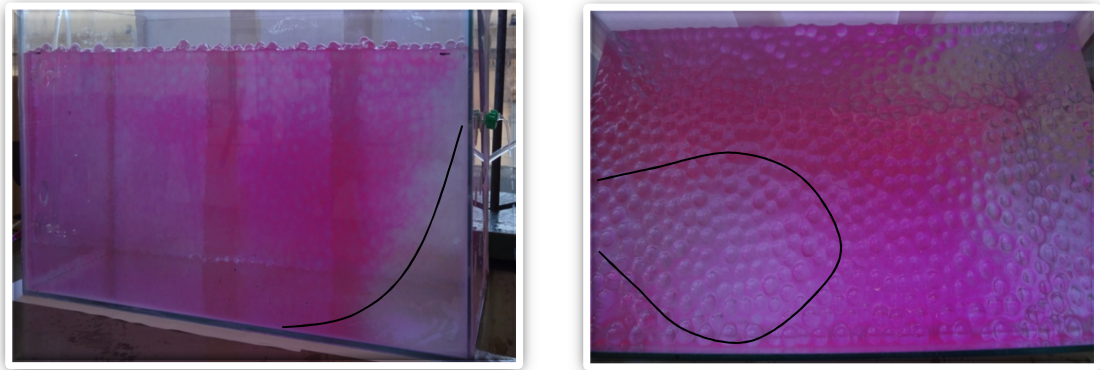


Figure 5-19 Experiment 5: Elevation and plan view (t=1800s)

In Figure 5-19 in the elevation view, the visible tracer was observed moving forward with a hull-shape velocity profile as it traveled from the right to left hand side of the system. In the plan view the visible tracer was seen clearing out in the region enclosed by the black line. Notably in the plan view is the tracer that remained in the bottom corner by the outlet.

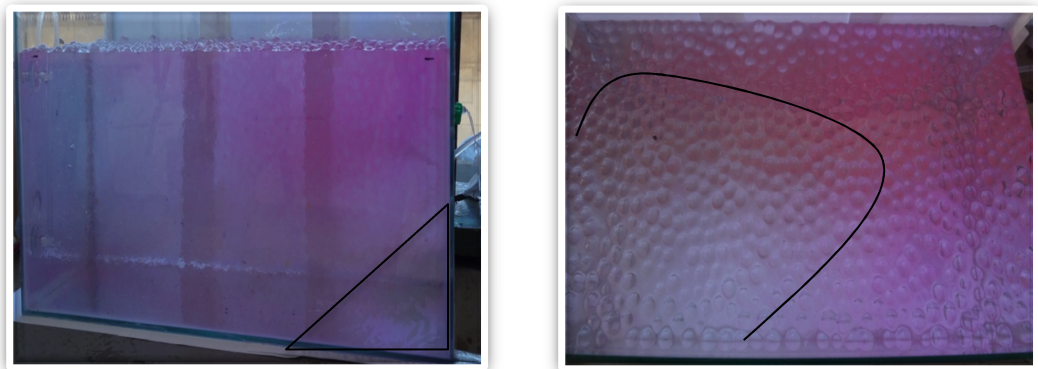


Figure 5-20 Experiment 5: Elevation and plan view (t=5400s)

In Figure 5-20, the elevation view, the tracer was visible predominately above the black triangle enclosing the dead zone. In the plan view the flow could be seen moving from the inlet at the bottom right toward the outlet at the top left.

5.7 RTD parameter and flow pattern comparison

The RTD parameters of all five experiments are presented in Table 5-6. The moments of the RTD obtained are compared and give an indication of the hydraulic efficiency of the system. The data shows that all the experiments displayed highly non-ideal behaviour as the mean residence times varied largely from those of their ideal. The effective volume of all the experiments except 4 and 5 are significantly lower than 100%.

	t_m (min)	τ (min)	σ_0^2	V_{eff} (%)
Experiment 1: Centre Top-Centre Top	36.95	73.97	0.333	49.96
Experiment 2: Centre Bottom-Centre Top	23.1	72	0.288	32.09
Experiment 3: Centre Bottom-All Top	40.32	72	0.085	56
Experiment 4: Centre Bottom-All Top + Wedge	53.76	67.38	0.301	79.8
Experiment 5: Bottom Right-Top Left	60.42	96	0.184	62.9

Table 5-6 Experimental RTD parameter comparison

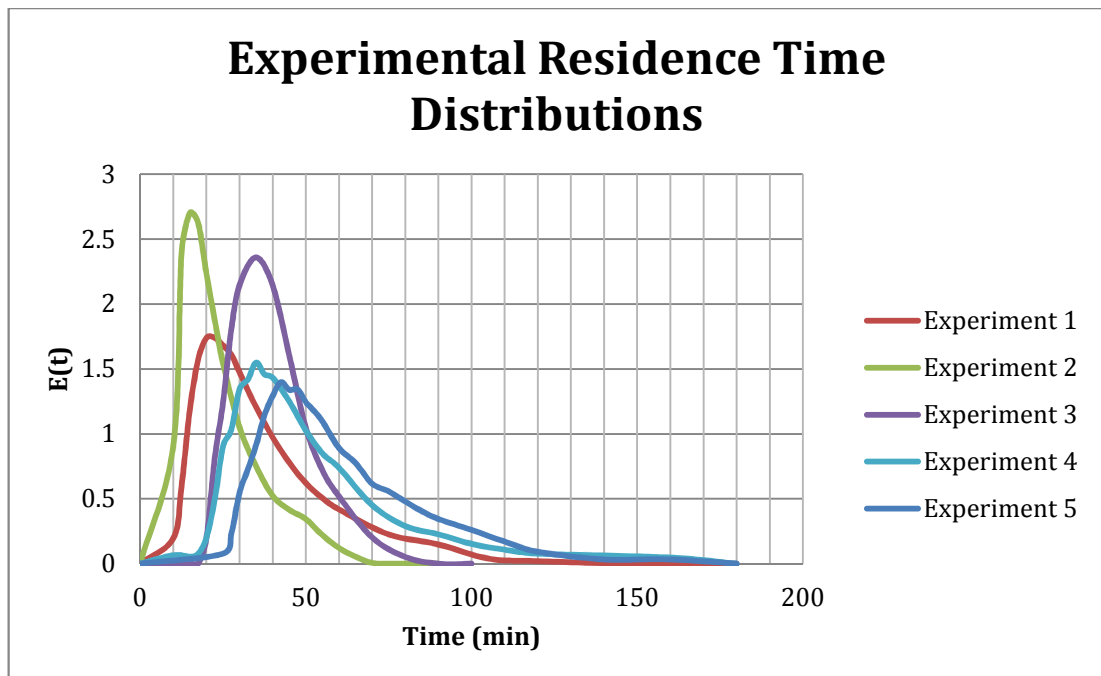


Figure 5-21 Experimental residence time distribution comparisons

The characteristic age distribution of all five experiments is presented in Figure 6-1. Notably the median of the residence time distributions changes between experiments and all display a single mode with a long tail.

5.7.1 Comparison 1: Experiment 1 vs Experiment 2

The comparison of these two experiments focuses on the effect of a change in elevation when using a single inlet and outlet port and how it affects the systems performance. Experiment 2's inlet utilized the bottom center port of the system as opposed to that of experiment 1, where it utilized the top center port, and in both experiments the center top outlet was utilized.

It was expected that by changing the inlet port to the bottom the RTD parameters would improve as the flow would be occurring against gravity but this was not the case.

Experiment 2 showed a 37.5% decrease in mean residence time, a 13.5% decrease in normalized variance and a 35.7% decrease in effective volume over that of experiment 1. Although both experiments perform poorly in terms of the RTD parameters, Experiment 2's performance was significantly more inefficient.

The results indicate that utilizing experiment 2's inlet-outlet configuration produce the least desirable performance of all the experiments.

5.7.2 Comparison 2: Experiment 1 vs Experiment 3

As in comparison 1 these two experiments focus again on the effect of a change in elevation of the inlet port and how it affects the system performance, except in this instance, by utilizing more than one outlet position.

The expected improvement in RTD parameters when the flow occurs against gravity was this time realized as the flow towards the outlet was dispersed.

Experiment 3 showed a 9.12% increase in mean residence time, a 74.5% decrease in normalized variance and a 12.1% increase in effective volume over experiment 1. It is noted that utilizing more outlets makes a marginal improvement in the RTD parameters when comparing a top-to-top and bottom-to-top flow regime.

5.7.3 Comparison 3: Experiment 2 vs Experiment 3

Comparison 3 focuses on the effect of utilizing more outlet ports and how it affects the systems performance. Experiment 2 saw the inlet utilizing the bottom center port and outlet the top center port whereas, experiment 3 made use of the same configuration except utilized all 3 top outlet ports.

Experiment 3 showed a 74.54% increase in mean residence time, a 70.5% decrease in normalized variance and a 74.51% increase in effective volume over experiment 2. It is noted that utilizing more outlets makes a significant improvement when comparing the bottom-to-top flow regime experiments.

5.7.4 Comparison 4: Experiment 3 vs Experiment 4

Comparison 4 highlights the improvements that can be made to a system by using visual data to make changes to geometry. In experiment 2 and 3 a dead zone was visibly apparent under the outlet of the system and in experiment 4 that volume was removed from the system.

Experiment 4 showed a 33.3% increase in mean residence time, a 254% increase in normalized variance and a 42.5% increase in effective volume over that of experiment 3. The comparison shows the success of combining visual and RTD data to effect efficient changes within a system.

5.7.5 Comparison 5: Experiment 2 vs Experiment 5

The comparison of these two experiments focuses on the effect of a change in direction of flow when using a single inlet and outlet port and how it affects the systems performance. Experiment 5 saw the inlet utilizing the bottom right port and the outlet the top right port.

It was expected that by changing direction of flow across the system that the RTD parameters would improve as the distance and hence time taken for the tracer to travel from the inlet to the outlet was increased due to there being additional length (and hence time) for diffusion of the tracer to occur.

Experiment 5 showed a 161% increase in mean residence time, a 36.1% decrease in normalized variance and a 96% increase in effective volume over that of experiment 2.

The results indicate that by making use of a diagonal flow path, significant improvements can be made to the hydraulic efficiency of the system between similar flow regimes.

6. CONCLUSION

The following objectives were considered for this study:

1. To investigate the effect on the residence time distribution parameters and flow patterns when varying the inlet-outlet configurations of a horizontal subsurface flow constructed wetland.

It can be concluded that varying the inlet-outlet configuration of a CW can make a significant difference to the performance of such a system. Notably making use of a single inlet and outlet that fall in a straight path produces the worst performance of a CW as, large dead volumes and the short-circuiting of flow occur. When the flow path occurs diagonally or is distributed to numerous outlets the hydraulic efficiency is greatly improved which can be attributed to the dispersion of flow as well as the flow path increasing. It is also of great benefit to make use of visual data such as in the pilot laboratory-scale experiments that allow for changes to be made to the systems geometry in order to eliminate dead volumes. The change in geometry along with the flow distribution to multiple outlets yielded the best performing hydraulic efficiency in a system.

2. To compare and discuss the effects of varying the inlet-outlet configuration on the residence time distribution parameters

All the experiments showed a highly non-ideal behaviour as the mean residence time varied significantly from that of the ideal indicating that dead zones occur within the system where fluid is stagnant and thus the effective volume is less than the design value. Experiment 4 indicated a marked improvement on the behaviour.

It can therefore be concluded that the location of inlet and outlet ports can have a significant effect of the hydraulic performance of a constructed wetland. This has significant ramifications for design. If the CW is poorly designed with respect to

inlet-outlet port location, it will need to be significantly larger than the conceptual design since it may be that more than 50% of the volume is inactive, this is especially important in locations where construction costs or land costs are high. Through careful design, however, a lot of the dead volume can be removed and the active volume of the CW would be much greater as a percentage of the total volume.

This research also has its own limitations which could impact design. The superabsorbent polymer balls are spherical, which is different to the shape of quarried aggregate normally used in CWs in South Africa. The experimental data was captured by conducting one run for each experiment and thus the repeatability would need to be confirmed. The dye may behave differently to the contaminants of concern which the CW is used to treat. There is also no guarantee that FWT is a conservative tracer; some of it may have sorbed to the gel beads. And finally, the glass laboratory reactors are much smaller than real CWs, this implies that edge effects may be magnified. Notwithstanding these limitations, the results can be used to guide CW design.

Some recommendations for future research include:

- Experiments can be conducted comparing the use of a single inlet to multiple outlets in order to determine if the improvement to a system can be related to the number of outlets used.
- Experiments can be performed utilizing a number of other possible inlet-outlet configurations.
- The variables used in this research can be expanded on; system geometry, inlet-outlet size, flow rates etc.

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8. APPENDICES

Appendix A- Experiment 1 Laboratory RTD

Inlet: Centre Top
Outlet: Centre Top

Container	Time (min)	ABS	Concentration (mg/l)	Cumulative Concentration (mg/l)	Qi	Ei	ti.Ei.Δt	t ² .Ei.Δt
0	0	0	0	0	0	0	0	0
1	10	0.0669	0.5927	0.5927	0.099	0.196	0.005	0.001
2	12.5	0.1013	1.8041	2.3968	0.075	0.596	0.005	0.001
3	15	0.1522	3.5954	5.9922	0.150	1.188	0.012	0.003
4	17.5	0.1852	4.7553	10.7475	0.198	1.571	0.019	0.006
5	20	0.1996	5.2622	16.0097	0.219	1.739	0.024	0.008
6	22.5	0.1997	5.2665	21.2762	0.219	1.740	0.027	0.010
7	25	0.1947	5.0903	26.3665	0.212	1.682	0.029	0.012
8	27.5	0.1885	4.8713	31.2378	0.203	1.610	0.031	0.014
9	30	0.1769	4.4632	35.701	0.186	1.475	0.031	0.015
10	35	0.1538	3.6513	39.3523	0.304	1.206	0.059	0.034
11	40	0.1338	2.9468	42.2991	0.246	0.974	0.054	0.036
12	45	0.1171	2.3583	44.6574	0.197	0.779	0.049	0.037
13	50	0.1035	1.8814	46.5388	0.157	0.622	0.043	0.036
14	55	0.0935	1.5292	48.068	0.127	0.505	0.039	0.035
15	60	0.0861	1.2672	49.3352	0.106	0.419	0.035	0.035
16	75	0.0695	0.6829	50.0181	0.171	0.226	0.071	0.088
17	90	0.0629	0.451	50.4691	0.113	0.149	0.056	0.084
18	105	0.0535	0.1202	50.5893	0.030	0.040	0.017	0.030
19	120	0.0518	0.0601	50.6494	0.015	0.020	0.010	0.020
20	150	0.0482	0	50.6494	0.000	0.000	0.000	0.000
21	180	0.0463	0	50.6494	0.000	0.000	0.000	0.000
ΣQi 3.026 τ_m (hr) 0.616 τ (ideal) 1.233 V_{eff} 0.500 σ^2 0.126 $\sigma\theta^2$ 0.333 $\sigma\theta^2=2D-2D^{2*}(1-e^{-(1/D)})$ D 0.2104 λ 0.333 N 3.000 $N(\text{check})$ 3.000								

Appendix B- Experiment 2: Laboratory RTD

Inlet: Centre Bottom
Outlet: Centre Top

Container	Time (min)	ABS	Concentration (mg/l)	Cummulative Concentration (mg/l)	Qi	Ei	ti.Ei.Δt	ti ² .Ei.Δt
0	0	0	0	0	0	0	0	0
1	10	0.0848	1.2242	1.2242	0.204	0.910	0.025	0.004
1.5	12.5	0.1416	3.2217	4.4459	0.134	2.395	0.021	0.004
2	15	0.1533	3.6341	8.08	0.151	2.702	0.028	0.007
2.5	17.5	0.1504	3.531	11.611	0.147	2.625	0.032	0.009
3	20	0.1355	3.0069	14.6179	0.125	2.236	0.031	0.010
3.5	22.5	0.1219	2.5301	17.148	0.105	1.881	0.029	0.011
4	25	0.1091	2.079	19.227	0.087	1.546	0.027	0.011
5	30	0.0902	1.4132	20.6402	0.118	1.051	0.044	0.022
6	35	0.0787	1.0094	21.6496	0.084	0.750	0.036	0.021
7	40	0.0701	0.7044	22.354	0.059	0.524	0.029	0.019
8	45	0.0659	0.5584	22.9124	0.047	0.415	0.026	0.019
9	50	0.0632	0.4639	23.3763	0.039	0.345	0.024	0.020
10	55	0.0585	0.2963	23.6726	0.025	0.220	0.017	0.015
11	60	0.0547	0.1632	23.8358	0.014	0.121	0.010	0.010
12	65	0.0521	0.073	23.9088	0.006	0.054	0.005	0.005
13	70	0.0503	0.0085	23.9173	0.001	0.006	0.001	0.001
14	75	0.05	0	23.9173	0.000	0.000	0.000	0.000
15	90	0.0488	0	23.9173	0.000	0.000	0.000	0.000

ΣQi	1.345
τm (hr)	0.385
τ(ideal)	1.200
Veff	0.321
σ ²	0.043
σθ ²	0.288
σθ ² =2D-2D ² *(1-e ^{-1/D}))	
D	0.174
λ	0.229
N	3.475
N(check)	3.475

Appendix C- Experiment 3: Laboratory RTD

Inlet: Centre Bottom
Outlet: All Top

Container	Time (min)	ABS	Concentration (mg/l)	Cummulative Concentration (mg/l)	Qi	Ei	ti.Ei.Δt	ti².Ei.Δt
0	0	0	0	0	0	0	0	0
1	15	0.047	0	0	0.000	0.000	0.000	0.000
2	17.5	0.0471	0	0	0.000	0.000	0.000	0.000
3	20	0.0599	0.3479	0.3479	0.014	0.194	0.003	0.001
4	22.5	0.0913	1.4519	1.7998	0.060	0.808	0.013	0.005
5	25	0.1133	2.2252	4.025	0.093	1.238	0.022	0.009
6	27.5	0.1421	3.2389	7.2639	0.135	1.803	0.034	0.016
7	30	0.1597	3.8575	11.1214	0.161	2.147	0.045	0.022
8	35	0.1705	4.2398	15.3612	0.353	2.360	0.115	0.067
9	40	0.1595	3.8532	19.2144	0.321	2.144	0.119	0.079
10	45	0.132	2.8823	22.0967	0.240	1.604	0.100	0.075
11	50	0.1035	1.8814	23.9781	0.157	1.047	0.073	0.061
12	55	0.0868	1.2929	25.271	0.108	0.720	0.055	0.050
13	60	0.0765	0.9321	26.2031	0.078	0.519	0.043	0.043
14	70	0.0604	0.3651	26.5682	0.061	0.203	0.040	0.046
15	80	0.0527	0.0944	26.6626	0.016	0.053	0.012	0.016
16	90	0.0463	0	26.6626	0.000	0.000	0.000	0.000
17	100	0.0468	0	26.6626	0.000	0.000	0.000	0.000

ΣQi	1.797
τ_m (hr)	0.672
τ_{ideal}	1.200
V_{eff}	0.560
σ^2	0.038
$\sigma\theta^2$	0.085
$\sigma\theta^2=2D-2D^{*2}(1-e^{-(1/D)})$	
D	0.045
λ	0.513
N	11.788
N(check)	11.788

Appendix D- Experiment 4: Laboratory RTD

Container	Time (min)	ABS	Concentration (mg/l)	Cumulative Concentration (mg/l)	Qi	Ei	ti.Ei.Δt	ti².Ei.Δt				
									ΣQi	τm (hr)	τ(ideal)	σ²
0	0	0	0	0	0	0	0	0				3.260
1	10	0.0562	0.2147	0.2147	0.036	0.066	0.002	0.000				0.896
2	15	0.0552	0.1803	0.395	0.015	0.055	0.001	0.000				1.123
3	17.5	0.0571	0.2491	0.6441	0.010	0.076	0.001	0.000				0.798
4	20	0.0686	0.6529	1.297	0.027	0.200	0.003	0.001				0.242
5	22.5	0.0956	1.6022	2.8992	0.067	0.492	0.008	0.003				0.301
6	25	0.1335	2.9382	5.8374	0.122	0.901	0.016	0.007				σθ²=2D-2D²*(1-e^(-1/D))
7	27.5	0.1456	3.3635	9.2009	0.140	1.032	0.020	0.009				D
8	30	0.1747	4.3858	13.5867	0.183	1.345	0.028	0.014				λ
9	32.5	0.1814	4.6221	18.2088	0.193	1.418	0.032	0.017				N
10	35	0.1936	5.0517	23.2605	0.210	1.550	0.038	0.022				N(check)
11	37.5	0.1852	4.7553	28.0158	0.198	1.459	0.038	0.024				
12	40	0.1827	4.6694	32.6852	0.195	1.432	0.040	0.027				
13	45	0.1659	4.0765	36.7617	0.340	1.251	0.078	0.059				
14	50	0.1451	3.3463	40.108	0.279	1.027	0.071	0.059				
15	55	0.1288	2.7707	42.8787	0.231	0.850	0.065	0.060				
16	60	0.1185	2.4098	45.2885	0.201	0.739	0.062	0.062				
17	70	0.0919	1.4733	46.7618	0.246	0.452	0.088	0.103				
18	80	0.0769	0.945	47.7068	0.158	0.290	0.064	0.086				
19	90	0.071	0.7388	48.4456	0.123	0.227	0.057	0.085				
20	100	0.0642	0.4982	48.9438	0.083	0.153	0.042	0.071				
21	110	0.0601	0.3522	49.296	0.059	0.108	0.033	0.061				
22	120	0.0573	0.2534	49.5494	0.042	0.078	0.026	0.052				
23	160	0.0544	0.1546	49.704	0.103	0.047	0.084	0.225				
24	180	0.0466	0	49.704	0.000	0.000	0.000	0.000				

Appendix E- Experiment 5: Laboratory RTD

Inlet: Left Bottom
Outlet: Right Top

Container	Time (min)	ABS	Concentration (mg/l)	Cummulative Concentration (mg/l)	Qi	Ei	ti.Ei.Δt	ti².Ei.Δt
0	0	0	0	0	0	0	0	0
1	25	0.0585	0.2963	0.2963	0.123	0.078	0.013	0.006
2	27.5	0.0748	0.872	1.1683	0.036	0.228	0.004	0.002
3	30	0.1094	2.0876	3.2559	0.087	0.546	0.011	0.006
4	32.5	0.1288	2.7707	6.0266	0.115	0.725	0.016	0.009
5	35	0.1493	3.4923	9.5189	0.146	0.914	0.022	0.013
6	37.5	0.1741	4.3644	13.8833	0.182	1.142	0.030	0.019
7	40	0.1904	4.94	18.8233	0.206	1.293	0.036	0.024
8	42.5	0.2019	5.3438	24.1671	0.223	1.399	0.041	0.029
9	45	0.1954	5.1161	29.2832	0.213	1.339	0.042	0.031
10	47.5	0.1958	5.129	34.4122	0.214	1.343	0.044	0.035
11	50	0.1852	4.7553	39.1675	0.198	1.245	0.043	0.036
12	52.5	0.1777	4.4932	43.6607	0.187	1.176	0.043	0.038
13	55	0.1692	4.1925	47.8532	0.175	1.097	0.042	0.038
14	60	0.1469	3.4064	51.2596	0.284	0.892	0.074	0.074
15	65	0.1343	2.964	54.2236	0.247	0.776	0.070	0.076
16	70	0.1171	2.3583	56.5819	0.197	0.617	0.060	0.070
17	75	0.1106	2.1306	58.7125	0.178	0.558	0.058	0.073
18	80	0.1022	1.8342	60.5467	0.153	0.480	0.053	0.071
19	85	0.094	1.5464	62.0931	0.129	0.405	0.048	0.068
20	90	0.0875	1.3187	63.4118	0.110	0.345	0.043	0.065
21	100	0.0782	0.9922	64.404	0.165	0.260	0.072	0.120
22	110	0.0686	0.6529	65.0569	0.109	0.171	0.052	0.096
23	120	0.0601	0.3522	65.4091	0.059	0.092	0.031	0.061
24	140	0.0537	0.1288	65.5379	0.043	0.034	0.026	0.061
25	160	0.0537	0.1288	65.6667	0.043	0.034	0.030	0.080
26	180	0.0494	0	65.6667	0.000	0.000	0.000	0.000
ΣQi 3.820 τ_m (hr) 1.007 τ (ideal) 1.600 V_{eff} 0.629 σ^2 0.186 $\sigma\theta^2$ 0.184 $\sigma\theta^2 = 2D \cdot 2D^2 \cdot (1 - e^{-1/D})$ D 0.103 λ 0.514 N 5.442 $N(\text{check})$ 5.442								

Appendix F- Tracer Information



WATER TRACING DYE FWT RED PRODUCTS

TECHNICAL DATA BULLETIN

Bright Dyes FWT Red products are specially formulated versions of Rhodamine WT dye for convenient use in water tracing and leak detection studies. This bright, fluorescent red dye is certified by NSF International to ANSI/NSF Standard 60 for use in drinking water. It may be detected visually, by ultraviolet light and by appropriate fluorometric equipment. Today it is most often used visually. Visually the dye appears bright pink to red, depending on its concentration and under ultraviolet light as bright orange.

The dye is resistant to absorption on most suspended matter in fresh and salt water. Compared to Bright Dyes FLT Yellow/Green products it is significantly more resistant to degradation by sunlight and when used in fluorometry, stands out much more clearly against background fluorescence. As always the use and suitability of these products for any specific application should be evaluated by a qualified hydrologist or other industry professional.

General Properties	Tablets	FWT Red 25 Liquid	Powders
Detectability of active ingredient ¹	Visual <100 ppb	Visual <100 ppb	Visual <100 ppb
Maximum absorbance wavelength ²	550/588 nm	550/588 nm	550/588 nm
Appearance	Dark red convex 1.6cm diameter	Clear dark red aqueous solution	Dark red fine powder
NSF (Max use level in potable water)	0.3 ppb	0.8 ppb	0.1 ppb
Weight	1.05 gms ± 0.05		
Dissolution Time ³	50% < 3 minutes 95% < 6 minutes		50% < 3 minutes 95% < 6 minutes
Specific Gravity		1.03 ± 0.05 @ 25° C	
Viscosity ⁴		1.3 cps	
pH		8.7 ± 0.5 @ 25° C	

Coverage of Products	One Tablet	One Pint Liquid	One Pound Powder
Light Visual	604 gallons	31,250 gallons	604,000 gallons
Strong Visual	60 gallons	3,125 gallons	60,400 gallons

Caution: These products may cause irritation and/or staining if allowed to come in contact with the skin. The use of gloves and goggles is recommended when handling this product, as with any other dye or chemical.

To our best knowledge the information and recommendations contained herein are accurate and reliable. However, this information and our recommendations are furnished without warranty, representation, inducement, or license of any kind, including, but not limited to the implied warranties and fitness for a particular use or purpose. Customers are encouraged to conduct their own tests and to read the material safety data sheet carefully before using.

¹ In deionized water in 100 ml flask. Actual detectability and coverage in the field will vary with specific water conditions.

² No significant change in fluorescence between 6 and 11 pH.

³ (One tablet, 1 gram of powder), in flowing deionized water in a 10 gallon tank.

⁴ Measured on a Brookfield viscometer, Model LV, UL adapter, 60 rpm @ 25° C.

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