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TRACER STUDIES OF A SUBSURFACE FLOW WETLAND

A thesis submitted in partial fulfilment
of the requirements for the degree
of

MASTER OF TECHNOLOGY

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ABSTRACT

The use of constructed wetlands represents an innovative approach to wastewater treatment. However, the treatment performance of constructed wetlands has been variable due to an incomplete knowledge of the hydraulic characteristics. Current design methods idealise constructed wetlands as plug flow reactors ignoring the existence of longitudinal dispersion, short-circuiting and stagnant regions. The overall effect will be a reduction of treatment efficiency at the outlet.

This thesis investigates the hydraulic characteristics of a subsurface flow wetland using a fluorescence dye tracer so as to determine the difference between theoretical and actual retention times and their effect on treatment efficiency.

A thorough review of the literature is undertaken, firstly examining wetland systems and their treatment mechanisms, it then reviews their hydraulic characteristics and design considerations while finally discussing dye tracing studies.

A series of dye tracing trials were undertaken on a pilot scale gravel bed wetland with a theoretical retention time of four days. The results from this research are presented as plots of dye concentration versus time at the outlet. These results are analysed in terms of chemical reactor theory and their implications on performance of various treatment mechanisms is discussed.

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CHAPTER 1

INTRODUCTION

Natural wetlands have been used for many decades as a discharge site for wastewater. In recent years, their natural treatment processes has been recognised. Today there are numerous wetlands in use for waste treatment with a strong trend towards artificial wetlands specially designed for this application. The use of constructed wetlands which mimic natural marshlands, represents an innovative approach to wastewater treatment (*Bharidimarri et al., 1991*). Constructed wetlands have potential to provide low-cost and low-maintenance biological treatment of wastewater (*Fisher, 1990*). However, the treatment performance of constructed wetlands has been variable. This variability is due to an inadequate understanding of how to optimise the physical, chemical and biological processes providing treatment and an incomplete knowledge of the hydraulic characteristics that typify constructed wetlands (*Fisher, 1990*).

The efficiency of wastewater treatment in constructed wetlands is largely dependent on the effective duration of contact between the pollutants and the microbial populations. This concept is common to any reactor system. The degree of treatment being directly related to the residence time and efficiency of contact. To obtain maximum treatment efficiency, it is necessary to maximise contact between the wastewater contaminants, the wetland media and the plant roots/stems and minimise short circuiting (*Steiner & Freeman, 1989*). Current design methods idealise the constructed wetland as a plug flow reactor and use a "residence time" based solely on the volume of the wetland cell and the flow-rate (*Stairs, 1993*).

This idealisation ignores the existence of longitudinal dispersion, short-circuiting and stagnant regions within the wetland cells. The result of these phenomena is that the fluid elements are not retained in the wetland cell for the theoretical retention time, rather there is a distribution of residence time. If a system is designed as plug-flow ignoring the of distribution of residence time, the overall effect will be a reduction of treatment efficiency at the outlet.

An insufficiently understood aspect of constructed wetlands design is the hydraulic regime. Currently used hydraulic design criteria in the field of constructed wetlands are largely theoretical. An appreciation of the hydraulic regime and actual detention time in a wetland system is a prerequisite to the understanding of the treatment mechanisms and the effectiveness of the purification provided by such systems (*Fisher, 1990*). By injecting a fluorescent tracer into the system, an assessment of the hydraulic regime can be obtained. Tracer methods have been used extensively in chemical reactor analysis and have been employed frequently in more conventional wastewater treatment technologies, such as stabilisation ponds (*Slade, 1992; Stairs, 1993*).

This thesis investigates the hydraulic characteristics of a subsurface flow wetland using Rhodamine WT (fluorescent dye tracer) so as to firstly, determine the difference between theoretical and actual retention times and their effects on treatment efficiency. Secondly, to show through the calculation of the treatment efficiency that the current assumption of wetland being an ideal plug-flow reactor is not valid.

CHAPTER 2

LITERATURE REVIEW

This review is presented in three parts. The first part overviews wetland systems and their treatment mechanisms. The second part reviews the hydraulic characteristics and design considerations. The third part discusses dye tracing studies.

2.1 OVERVIEW OF CONSTRUCTED WETLAND SYSTEMS

2.1.1 Development History

Wetland treatment has been utilised in China for hundreds of years, in the United Kingdom and Europe for over one hundred years and in the USA since early this century (Venus, 1988). Other countries such as Australia (Spakota & Bavor, 1994), South Africa (Wood, 1994) and New Zealand (Tanner *et al.*, 1994) have made significant developments in the field of constructed wetlands as wastewater treatment systems. This decade, a significant amount of research has been carried out into constructed wetlands. The use of constructed wetlands which mimic natural marshlands, represents an innovative approach to wastewater treatment (Bhamidimarri *et al.*, 1991). The recent International Conference on Wetland systems for Water Pollution Control in China, reflects rapid advancement towards this innovative technology.

To date there are more than twenty-five constructed wetlands receiving wastewater in New Zealand (ARC, 1995).

Constructed wetland systems are commonly used for secondary or advanced treatment of domestic wastewater (*Metcalf & Eddy, 1991*). Recent studies have shown that constructed wetlands are currently being used in treating meat processing wastewater (*Van Oostrom, 1994*), agricultural non-point pollution (*Yin et al., 1994*), coal mining wastewater (*Tarutis & Unz, 1994*) and for river purification (*Green, et al., 1994*).

2.1.2 Constructed Wetlands

2.1.2.1 Definition

Constructed wetlands are natural wastewater treatment systems that combine biological, chemical and physical treatment processes (*Crites, 1994*). They have the potential to provide low-cost and low-maintenance treatment of wastewater (*Fisher, 1990*).

The use of constructed wetlands for wastewater treatment seeks to take advantage of many of the same principles that apply in a natural system, but does so within a more controlled environment (*USEPA, 1988*). Brix and Schelerup (1989) have categorised constructed wetlands as either being free water surface (FWS), subsurface flow (SF) or vertical flow (VF) types.

2.1.2.2 Free Water Surface Wetlands

Free surface flow wetland systems are densely vegetated overland flow channels (*Kadlec, 1994*). The main purpose of vegetation in this system is to create sites for bacteria which degrade pollutants. The degree of pollutant degradation is largely dependent on the duration of contact between the pollutant and the microbial population. Surface flow

wetlands generally have theoretical residence times of four to fifteen days (*Metcalf and Eddy, 1991*). During this time the effluent enters the wetland and comes into contact with the sediment, plant biomass, and plant litter surfaces which are covered in bacterial slim layers. This is where most of the microbial activities affecting the water quality occurs, including oxidation of organic matters and transformation of nutrients (*Wood, 1994*). Specific pollutant removal mechanisms are discussed in a later section. Principles of free surface flow is show in figure 2.1

2.1.2.3 Subsurface Flow Wetlands

A subsurface flow wetland system consists of channels or basins that contain gravel or sand media which supports the growth of emergent vegetation. This system has also been called "root zone" or "rock-reed filter" (*Metcalf & Eddy, 1991*). The flow is normally horizontal and there should be no free water surface above ground (*Venus, 1988*).

The fundamental treatment mechanism that facilitates biodegradation in subsurface flow systems is the diffusion of waste components into the biofilm of the root-zone (*Bhamidimarri et al., 1991*). This is a biological slim layer which covers the rhizome structure of the plants and the surrounding media. The rhizomes of the wetland plants transfer oxygen to the inside of the biofilm by leakage of oxygen through the root system encouraging the nitrification process. The outer layer of the biofilm around the roots are anoxic providing conditions for biological denitrification.

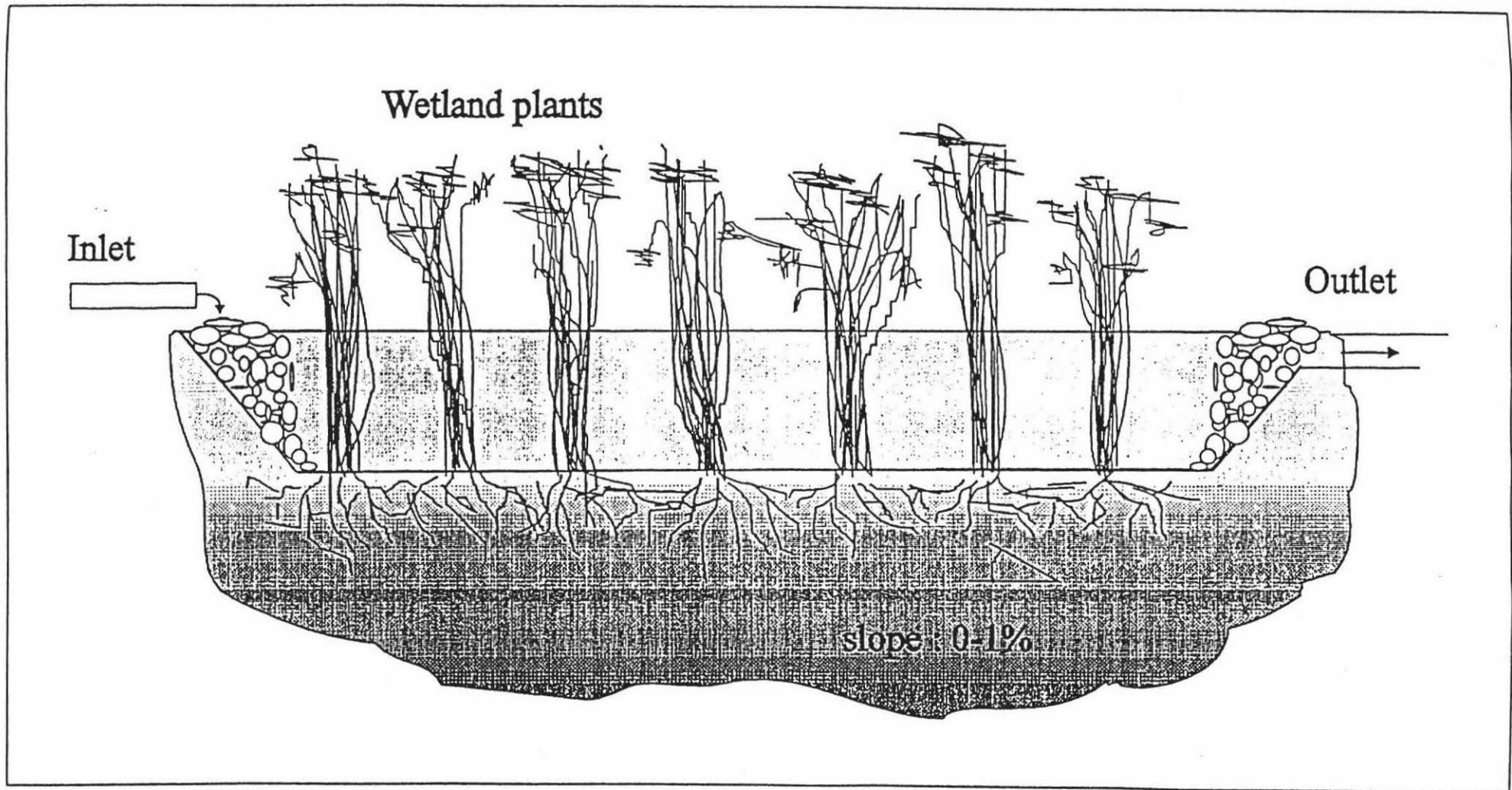


Figure 2.1 Typical Cross-Section of Free Surface Flow Wetland

As for free surface flow systems, the wastewater treatment mechanisms in subsurface flow wetlands are strongly related to the hydraulic retention time. For effective treatment, pollutants need to be in contact with the wetland media and plant roots for the duration of the design retention time (theoretical retention time) of the system. A cross-section of a typical subsurface flow system is shown in figure 2.2.

2.1.2.4 Vertical Flow Wetlands

A vertical flow wetland is the combination of free surface flow and subsurface flow wetlands. Treatment is achieved by maintaining a column of water on the surface resulting in a vertical trickling flow through the substratum into an underdrain (*Bhamidimarri et al., 1991*). Principles of vertical flow is shown in Figure 2.3. Vertical flow wetlands demonstrate similar treatment principals of both the free surface and subsurface flow wetlands.

2.1.3 Specific Pollutant Removal Mechanisms

Pollutant removal mechanisms of free surface flow and subsurface flow wetlands are summarised below.

2.1.3.1 BOD Removal

BOD (Biochemical Oxygen Demand) is a measure of the oxygen uptake in a given aquatic system principally as a result of the biochemical processes of the micro-organisms in that system (*Venus, 1988*). In wastewater wetlands, the BOD associated with settleable solids in the wastewater is reduced primarily by sedimentation and

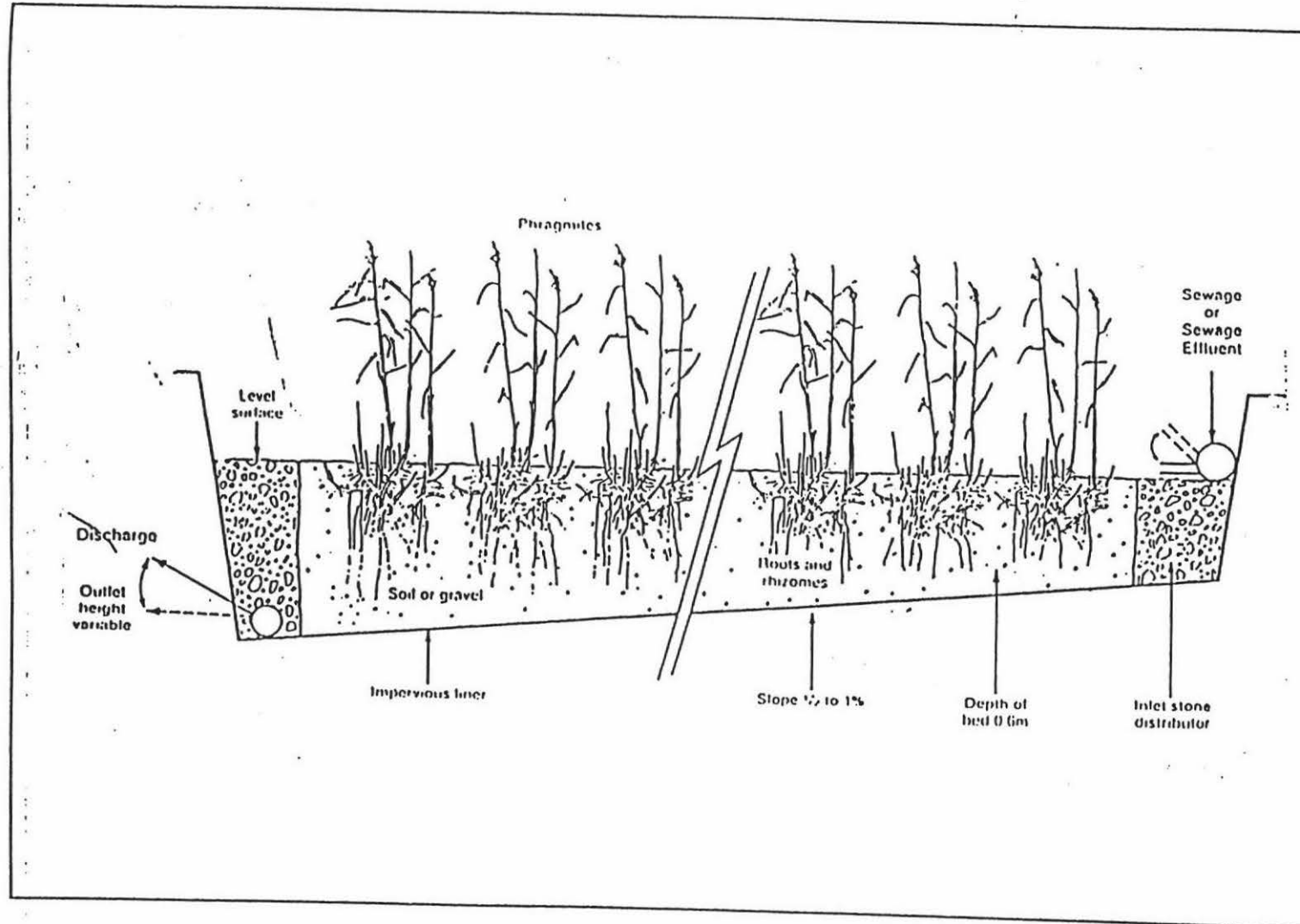


Figure 2.2 Typical Cross-Section of a Subsurface Flow Wetland

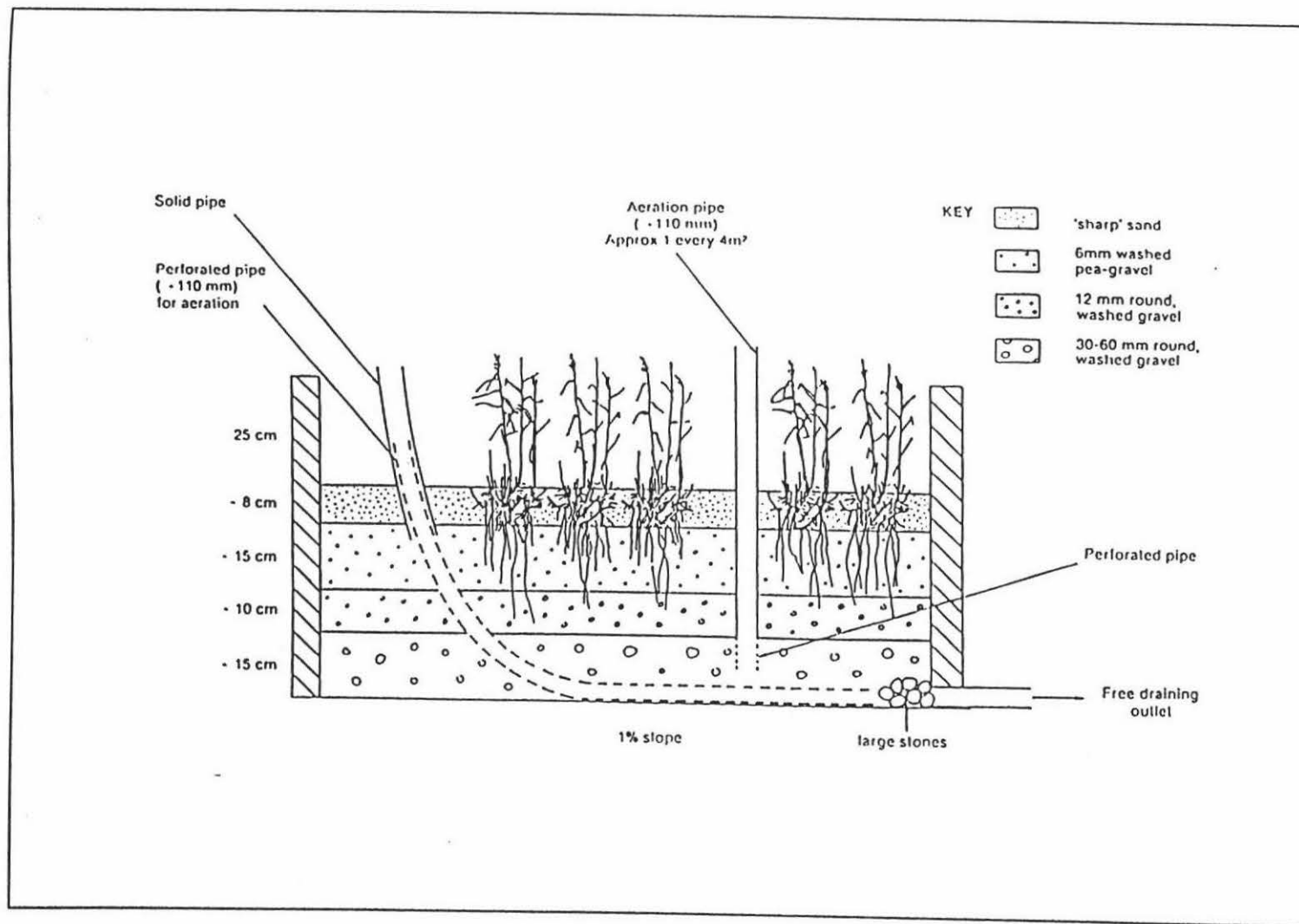


Figure 2.3 Typical Cross-Section of a Vertical Flow Wetland

secondarily by filtration (*Kloosterman and Griggs, 1989*). The colloidal soluble BOD remaining in solution is primarily removed as a result of metabolic activity by micro-organisms. *Watson et al., 1989* believes that in surface flow wetlands, the major oxygen source for these activities is wind-induced reaeration diffusion at the water surface.

The major oxygen source for subsurface flow systems is claimed to be from plants via its root zone (*Wood, 1994*). However, in practice, the amount of oxygen that can be expected to be released by the plants is now appreciated to be nominal in most subsurface flow wetlands. Hiley (1994) concluded from a recent study that there was no significant contribution of oxygen by the plants to the process of treating BOD in wetlands. Oxygen is needed for oxidation of the wastewater organic and nitrogen compounds passing through the system. Limited aeration around roots effectively limits the oxidative conditions. This implies that anoxic conditions will predominate unless the oxygen demand of the wastewater is lower than the available oxygen flux the plants and surface diffusion .

The general design procedure currently used for constructed wetlands for wastewater treatment is outlined in the USEPA Design Manual (*USEPA, 1988*). The design process is based on the assumption that BOD reduction are first-order and the hydraulics can be approximated by plug flow. Assuming a first-order removal model, hydraulic retention time becomes a principal parameter for predicting BOD removal. For surface flow wetlands designed to achieve BOD removal, required hydraulic retention time can be estimated by using the following first-order removal model:

$$C_e / C_o = A \exp [- 0.7 K_T (A_v)^{1.75} t] \quad (1)$$

where C_e = effluent BOD₅ concentration, mg / L
 C_o = influent BOD₅ concentration, mg / L
 A = empirically determined coefficient representing the fraction
of BOD₅ not removed by settling at the head of the system
0.7 = empirical constant
 K_T = temperature dependent first-order rate constant, d⁻¹
 A_v = specific surface area for microbiological activity, m² / m³
 t = hydraulic pore retention time, days

Reed et al. (1988) suggested that BOD₅ removal in subsurface flow wetland can be described using first-order plug flow kinetics:

$$C_e / C_o = \exp (-K_T t) \quad (2)$$

where C_e = effluent BOD₅ concentration, mg / L
 C_o = influent BOD₅ concentration, mg / L
 K_T = temperature dependent first-order reaction rate constant,
day⁻¹
 t = theoretical retention time, day

These first-order removal models appear in many of the key design manuals including the UsEpA Manual (UEPA, 1988), the text of Reed et al.(1988), WPCF Manual of Practice (WPCF, 1990) and Metcalf and Eddy (1991).

Equation (1) and (2) assume that as hydraulic residence time increases, effluent concentration of biodegradable contaminants decreases exponentially. Consequently, hydraulic residence time becomes a key design and operational parameter for optimising performance of wetland system. An underestimation of these times will lead to a higher effluent BOD₅ levels at the outlet.

2.1.3.2 Suspended Solids Removal

Both free surface and subsurface flow wetland systems effectively remove suspended solids (Watson, 1989). Successful removal of suspended solids depends on good contact with a large surface area of plants and bed media. In surface flow systems, wetland plants provide zones in which sedimentation of suspended solids can occur (Hiley, 1994). In subsurface flow wetlands, the gravel substratum in addition to providing physical support for plant growth and surfaces for sorption and biofilm growth, promotes the settling and filtration of suspended solids. Solids accumulation within the substratum of subsurface flow constructed wetlands has important implications for the maintenance of hydraulic conductivity and required wastewater retention times. Fisher (1990) showed major reduction in substratum permeability is at the head of the wetlands where the majority of solids removal was recorded. Tanner (1994) concluded that organic and inorganic solid accumulation during the first few years of operation can have significant

impacts on the hydraulic retention times. He showed through a tracer study that the mean hydraulic retention times in wetlands to be 10 to 25 percent below theoretical levels due to the wetland volume reduction from solid accumulation.

2.1.3.3 Nitrogen Removal

In wetlands, nitrogen is removed by a number of mechanisms:

1. Uptake and subsequent harvesting of wetland plants;
2. Volatilisation of Ammonia;
3. Bacterial Nitrification/Denitrification; and
4. Sedimentation.

Of these mechanisms, bacterial nitrification and denitrification is believed to be the primary removal mechanism of nitrogen (*Yang et al., 1994*).

Nitrogen in organic materials is transformed through a number of physical, chemical and biological processes (figure 2.4). Nitrogen enters the biological cycle through the assimilation of ammonia nitrogen (NH_4^+) and nitrate (NO_3^-) and through biological fixation of nitrogen gas (N_2) from the atmosphere into organic nitrogen (N) in the forms of proteins and amino acids (*Hamner and Knight, 1994*).

For nitrification process to occur, that is oxidation of ammonia nitrogen ($\text{NH}_3/\text{NH}_4^+$) to nitrate (NO_3^-), aerobic conditions are necessary. Anoxic conditions are required for

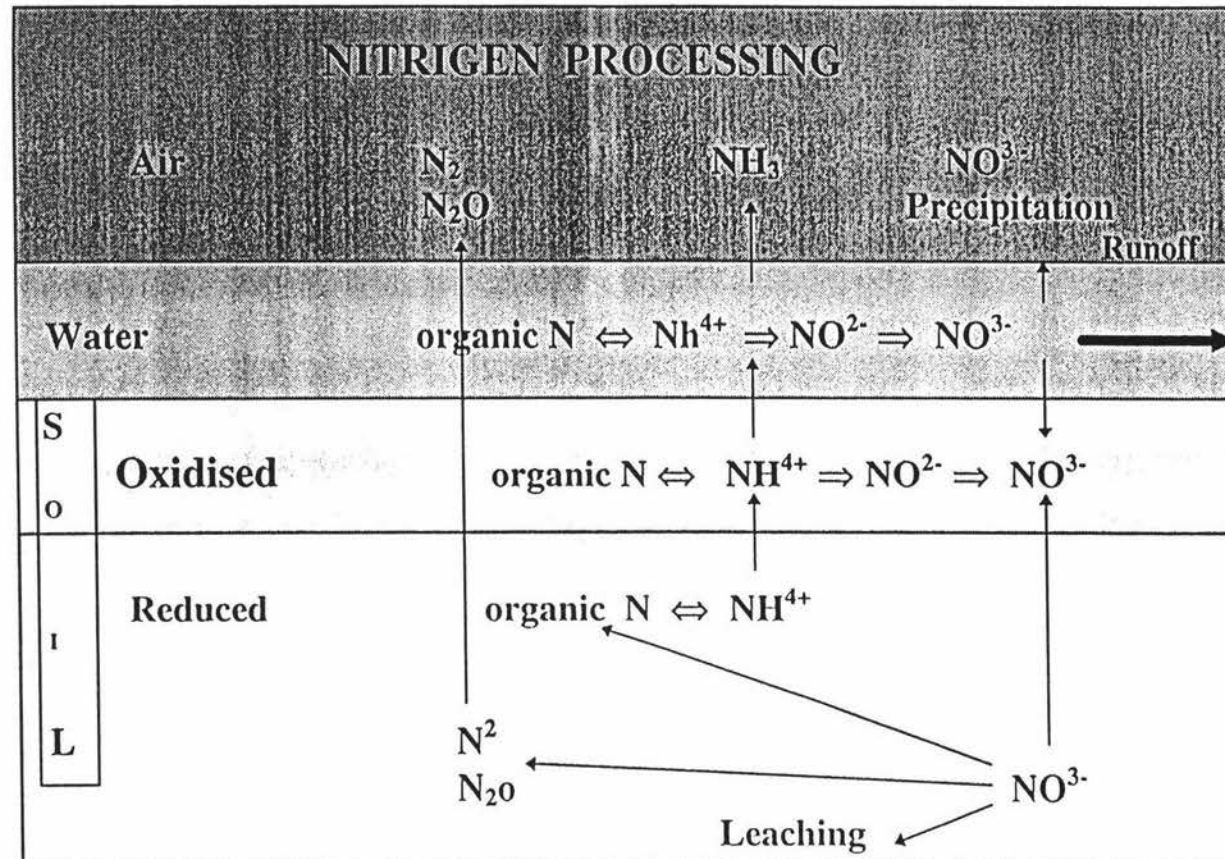
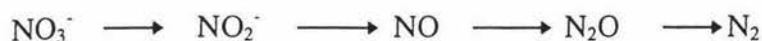


Figure 2.4 Nitrogen Removal In Wetlands

denitrification to occur whereby nitrate (NO_3^-) is reduced to nitrogen gas (N_2). The reaction for nitrate reduction are:



Free surface flow wetlands have a high potential for aerated zones, especially near the water surface due to oxygen from atmospheric diffusion. They may be limited in denitrification potential because of the lack of anoxic conditions, especially in younger systems with low internal organic matter storage (*Hamner and Knight, 1994*).

Subsurface flow wetlands frequently have the opposite limitations. Atmospheric oxygen diffusion is greatly reduced in subsurface flow wetlands and oxygen transport by plants through their roots may be insufficient to satisfy organic oxygen demands, resulting in anoxic conditions and severe limitations in nitrification (*Hamner and Knight, 1994*).

2.1.3.4 Phosphorus Removal

Phosphorus removal from wastewater in a wetland is by three methods:

1. sorption and precipitation with iron (Fe), aluminium (Al) and calcium (Ca) minerals;
2. plant uptake and subsequent harvesting; and
3. entrapment of solids.

Of these three methods the first, sorption and precipitation is believed to be the most effective. Sorption and precipitation reactions, unlike biomass (plant) harvesting and the

denitrification of nitrogen, do not remove phosphorus from wetlands. Rather they remove it from the wastewater flow and bind it in storage within the wetland system. This implies that the phosphorus removal is finite. Shikora et al. (1994) stated that phosphorus removal is dependent on the sorption capacity of the media used in a wetland. Kadlec (1994) also concluded that storage capacity of media in a wetland is finite. This implies that the phosphorus loading rate is proportional to the retention potential of the media.

2.1.3.5 Pathogen Removal

The wetland environment is hostile to most human enteric pathogens. Bacteria, viruses and parasites are reduced in wastewater passing through the wetland. The fate of bacterial pathogens and viruses in the subsurface environment is determined by their survival characteristics and their retention in the substrate matrix. Both survival and retention are largely determined by:

1. the climate;
2. the nature of the substrate; and
3. the nature of micro-organisms.

Temperature is an important climatic factor that will affect both viral and bacterial survival and movement. At higher temperatures, inactivation and natural die-off are rapid. The physical and chemical characteristics of the physical media also plays a major role in determining survival and retention of micro-organisms (*Metcalf and Eddy, 1991*). Bacteria are believed to be removed largely by filtration processes in the media, but adsorption is the major factor controlling virus retention.

Surface flow wetlands provide for the addition of enteric organisms via the warm blooded wildlife that may inhabit or use the wetland (*Kadlec, 1994*). This implies that the background level of faecal coliform are non-zero.

2.1.3.6 Heavy Metal removal

Metals are trapped by wetlands via a number of mechanisms, including plant uptake, cation exchange with the soils and particulate settling (*Kadlec, 1994*). Significant removals of about 50% for zinc and 60% for lead has been reported. Copper and other divalent metal cations are known to bind strongly to peats and therefore subsurface-flow wetlands are in use to trap these metals before they reach their receiving waters (*Kadlec, 1994*). Gersbert et al. (1983) reported subsurface flow wetland removal rates of 99% for zinc, 97% for copper and 99% for chromide.

2.2 HYDRAULIC CONSIDERATIONS AND SIZING

INTRODUCTION

It is widely presumed that simple first-order chemical rate laws apply for pollutant reduction and the constructed wetlands are approximately plug flow in their internal hydraulics. A wide variety of shape and depth distributions have been employed to accommodate such presumptions, usually with treatment efficiency that is limited due to the current incomplete knowledge of hydraulic characteristics within the wetland system. This section briefly discusses parameters that effect the hydraulic regime and outlines the current design procedure for constructed wetlands.

2.2.1 Hydraulic Retention Time

BOD removal is one of the principal parameters used in the design of wetlands by most of the design manuals. Based on the required effluent concentration, equations (1) and (2) can be used to determine the theoretical retention times for surface flow and subsurface flow wetlands respectively.

2.2.2 Water Depth

For free surface flow wetlands, the design water depth depends on the optimum depth for the selected vegetation. The design depth for subsurface flow wetlands should be determined in accordance with the type of vegetation indicated for the system. On the basis of experiments by Reed and Watson (1988), the relationship given in Table 1 is recommended.

Table 1 Recommended design depth for subsurface flow wetlands

Plant Species	Root Depth, cm
Bulrush	76
Reed	70
Rush	60
Sedges	60
Cattails	50

2.2.3 Aspect Ratio

Commonly referenced design guidelines stipulate a length to wide ratio of approximately 3 to 5 : 1 for free water surface wetlands (*Hammer, 1992*). Some suggestions range as high as 10 : 1 (*Watson and Hobson, 1989; Tchobanoglous, 1985*). The variation in treatment efficiencies experienced at different wetland sites suggest that there is a need to optimise the understanding of these geometric relationships. Studies have shown that a long narrow cell provides the greatest treatment efficiency. Listowel data (*Wile et al., 1985*) documented a long serpentine channel of length:width ratio 75:1 continually outperformed an equal area cell of 4 : 1 length : width. The short channel exhibited a high tendency for short-circuiting.

2.2.4 Area Estimation

2.2.4.1 Cross-sectional Area

The cross-sectional area (A_c) of subsurface flow wetlands is established by equation (3).

$$A_c = Q / k i \quad (3)$$

where A_c = cross-sectional area of the flow including the space occupied by porous media, m^2 ;

Q = average flow-rate of wastewater, m^3/d ;

k = hydraulic conductivity of the bed, m/s ; and

i = hydraulic gradient, m/m

2.2.4.2 Surface area

For free surface flow wetlands, the surface area is defined by the theoretical retention time and depth. As discussed above, guidelines for optimum length to width ratios have not been established firmly.

Surface area of subsurface flow wetlands can also be found by multiplying the length to width ($L \times W$). In this case, the width (W) is found by dividing the cross-sectional area (A_c) with the design depth (d):

$$W = A_c / d \quad (4)$$

where A_c can be found from equation 5 shown below

The required length may then be calculated using equation (5):

$$t = \frac{Lwd}{Q} \quad (5)$$

where L = basin length, m;
 d = basin depth, m
 W = basin width, m;
 n = porosity (fraction of cross-sectional area not occupied by plants or substrate); and
 Q = average flowrate through system ($Q_{in} + Q_{out}$)/2, m^3/day .

2.2.5 Flow in Subsurface Flow Systems

The hydraulic regime in subsurface flow wetlands is controlled by the permeability or the hydraulic conductivity of the media used and the hydraulic gradient of the system (Hu, 1994). Flow in a majority of subsurface flow systems is governed by Darcy's Law:

$$Q = kA_c i \quad (6)$$

in which Q = flow rate of fluid, m^3/day ;
 k = hydraulic conductivity or coefficient of permeability, $m^3 / m^2 \cdot day$;
 A_c = cross-sectional area, m^2 ; and
 i = hydraulic gradient, or headloss per length of the flow system, $\Delta h / \Delta L$, m/m.

This is due to laminar flow conditions of the wastewater flowing through the porous media. However, Fisher (1990) believes that in some cases where turbulent conditions are present, Darcy's Law may not be satisfactory in describing the system behaviour. Some experiments indicate that Ergun's equation may be more appropriate in this

situation. Ergun's equation is the linear combination of linear infiltration flow and quadratic open channel flow. It takes the form:

$$i = \frac{150 \mu}{\rho g} \left(\frac{1-n}{D_p n} \right)^2 v + 1.75 \frac{1-n}{D_p n g} v^2 \quad (7)$$

where i = hydraulic gradient, m/m;
 v = flow velocity, m/day;
 μ = viscosity, Pa.s;
 ρ = density, kg / L;
 g = gravitational acceleration, m² / s;
 n = medium porosity; and
 D_p = particle diameter, m

From Equation (7), the slope of the bed can be found by substituting v , for Q/bh :

$$i = \frac{150 \mu}{\rho g B h} \left(\frac{1-n}{D_p n} \right)^2 Q + \frac{1.75 (1-n)}{D_p n g B^2 h^2} Q^2 \quad (8)$$

where i = bed slope, $\Delta h / \Delta x$

2.2.6 Hydraulic Conductivity

In Equation (5), the hydraulic conductivity k , is a medium dependent parameter.

Hydraulic gradient in a subsurface flow wetland is dependent on the hydraulic

conductivity of the medium. Figure 2.5 represents the relationship between the water-level and hydraulic conductivity of a zero base slope subsurface flow wetland (Hobson, 1988). It has been stated that the hydraulic conductivity of a fully developed reed bed built in soil would be about $3 \times 10^{-3} \text{ m}^3/\text{m}^2.\text{s}$ (Boon, 1986, Hobson,1990). However, the validity of this value has been questioned as it is much higher that could be expected for soil (Bucksteeg, 1987). Research carried out by Herbert (1990) on a system for eight years has shown no evidence that the hydraulic conductivity has decreased over time. It has been strongly recommended not to use a design hydraulic conductivity of greater than the original media (Cooper, 1993). The site specific value for hydraulic conductivity can be measured on site but the data listed in Table 2 can be employed for initial design.

Table 2 Typical media hydraulic conductivity.

Media type	Maximum 10% grain size, mm	Porosity, n	Hydraulic conductivity, $k, \text{m}^3 / \text{m}^2.\text{d}$
Medium sand	1	0.42	420
Course sand	2	0.39	480
Gravely sand	3	0.35	500

USEPA (1988)

2.2.7 Organic Consideration

Organic loading must be limited such that the oxygen demand of the applied wastewater does not exceed the oxygen transfer capacity of the wetlands vegetation (Metcalf and Eddy, 1991). The overall BOD loading on subsurface flow wetlands should not exceed

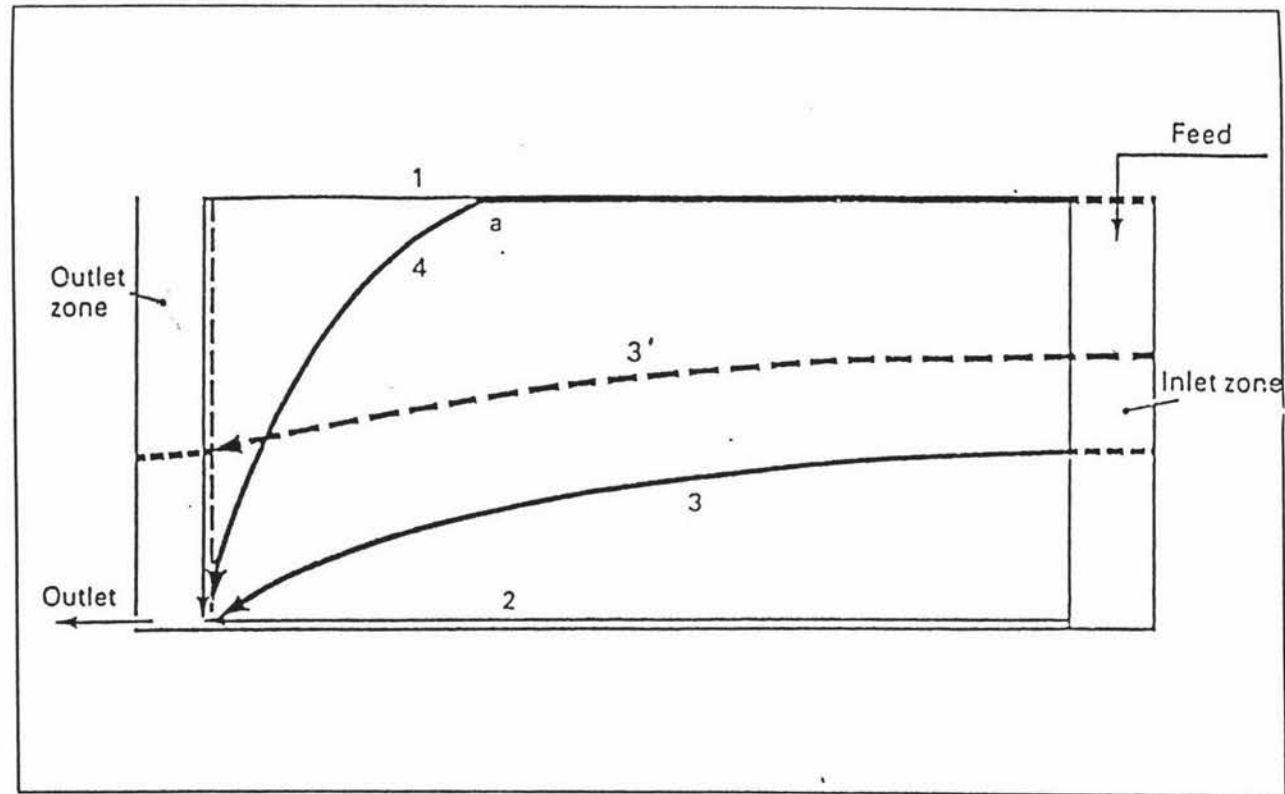


Figure 2.5 Water level curves for reed-bed treatment systems with different hydraulic conductivity (Hobson, 1988).

Curve 1 shows zero conductivity; curve 2 infinite conductivity; curve 3 low conductivity; curve 4 high conductivity; curve 3' the same conductivity as 3, but the outlet is artificially raised, and curve 4 represents a decreasing surface flow up to point a and drops to the outlet. In this case, the conductivity is too low to permit flow through the whole bed resulting in surface flow for the first part and dryness occurs for the second part.

about 7.5 kg/ha.day (*Crites, 1994*). Since actual organic loading is not applied uniformly but concentrated at the inlets, care must be exercised when using area loading criteria (mass/area.day). A major consideration in the design of a subsurface flow wetland is the effect of suspended solids. Subsurface flow wetlands have failed in the past when suspended solids caused a reduction in media permeability, resulting in surfacing and short-circuiting of the treatment process (*Lekven et al., 1993*). For systems treating wastewater with a significant fraction of settleable organic solids, the loading should be distributed along the length of the basin by step feeding to avoid anaerobic conditions at the head of the basin (*Metcalf and Eddy, 1991*).

2.2.8 Hydraulic loading Considerations

The hydraulic loading rate for wetland systems is not usually a primary design parameter but it is a convenient parameter to use in making preliminary estimate of the area of land required (*Metcalf and Eddy, 1991*). Hydraulic loading for constructed wetlands typically vary from 0.1 to 5.0 m³ m⁻².day (*Fisher, 1989*).

2.2.9 Actual Hydraulic Retention Time

Actual hydraulic retention time can be defined as the hydraulic retention time obtained by field experiments. It is also defined as the centroid of the residence time distribution (figure 2.6). Recent studies have shown that the actual residence times obtained via tracer studies were between 75 to 90% of the theoretical retention times (*Fisher, 1990; Pilgrim, 1992; Stairs, 1994*). Actual retention time is an important hydraulic factor in understanding the treatment efficiency of a wetland. If a system is designed using

theoretical retention time, then the assumption is that ideal plug flow conditions prevail.

In practice, this is not the case. Dye tracer studies are done to obtain the degree of deviation from ideal conditions via actual retention time and flow patterns. If a system is designed using the theoretical retention time, elements of the wastewater flow that experience treatment times less than the theoretical value are ignored (*Stairs and Moore, 1994*). This over simplification could be due to a limited knowledge of the hydraulic characteristics of wetlands and their effect on the treatment of wastewater.

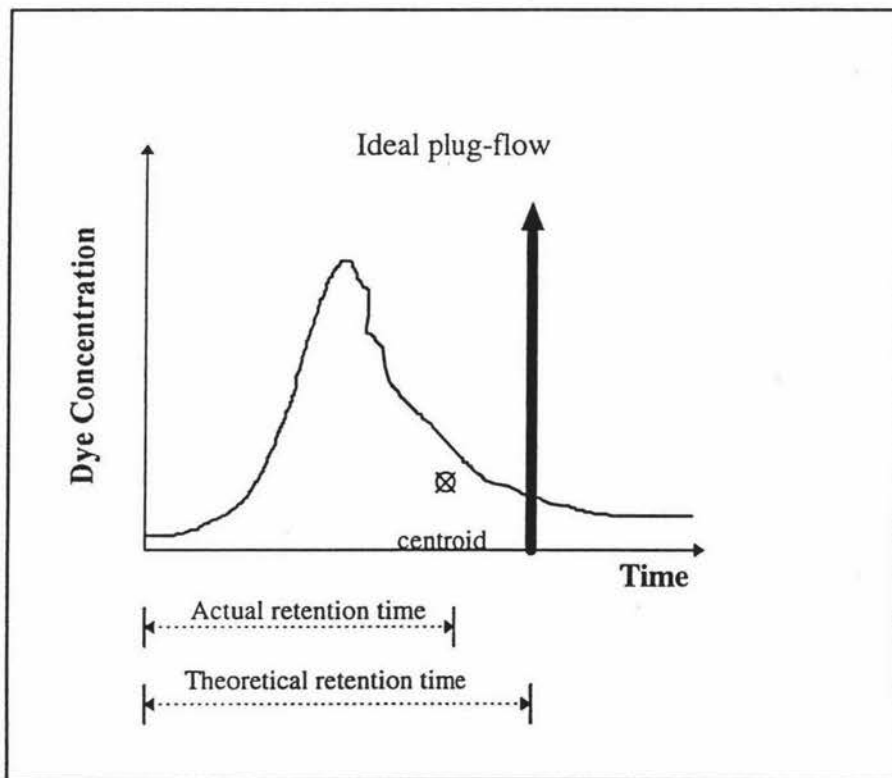


Figure 2.6 Mean and Theoretical Retention Times

2.3 DYE TRACING

2.3.1 Purposes of Tracer Studies

A tracer is defined as any substance, pre-existing or introduced to assess some characteristics of a system (*Stairs, 1994*). Tracer studies are commonly conducted for ground and surface water systems and have, for example, been used for hydraulic modelling of aerated lagoon systems (*Slade, 1992*). Hydraulic studies of artificial wetlands (*Bowmer, 1987; Pilgrim and Shulz, 1992; Fisher, 1990*) and flow characteristics of planted soil filter (*Netter, 1992*) have been conducted using dye tracers. For this research, Rhodamine WT (dye tracer) was used for hydraulic studies of a subsurface flow wetland.

2.3.2 General Description of Dye Tracer

2.3.2.1 Theory

Dye injection into a stream is assumed to behave in a similar manner as the water particles themselves. A measure of the movement of the tracer is considered a measure of the movement of the elements of fluid in the stream and of their dispersion characteristics (*Kilpatrick and Wilson, 1989*). The dispersion and the mixing of the tracer in the receiving stream takes place in all three dimensions of the channel (figure 2.7). Vertical mixing is normally completed first, and lateral mixing later, depending on stream characteristics and velocity variations. Longitudinal dispersion having no boundaries, continue indefinitely and is the dispersion component of primary interest (*Kilpatrick and Wilson 1989*). At any point downstream from an instantaneous dye

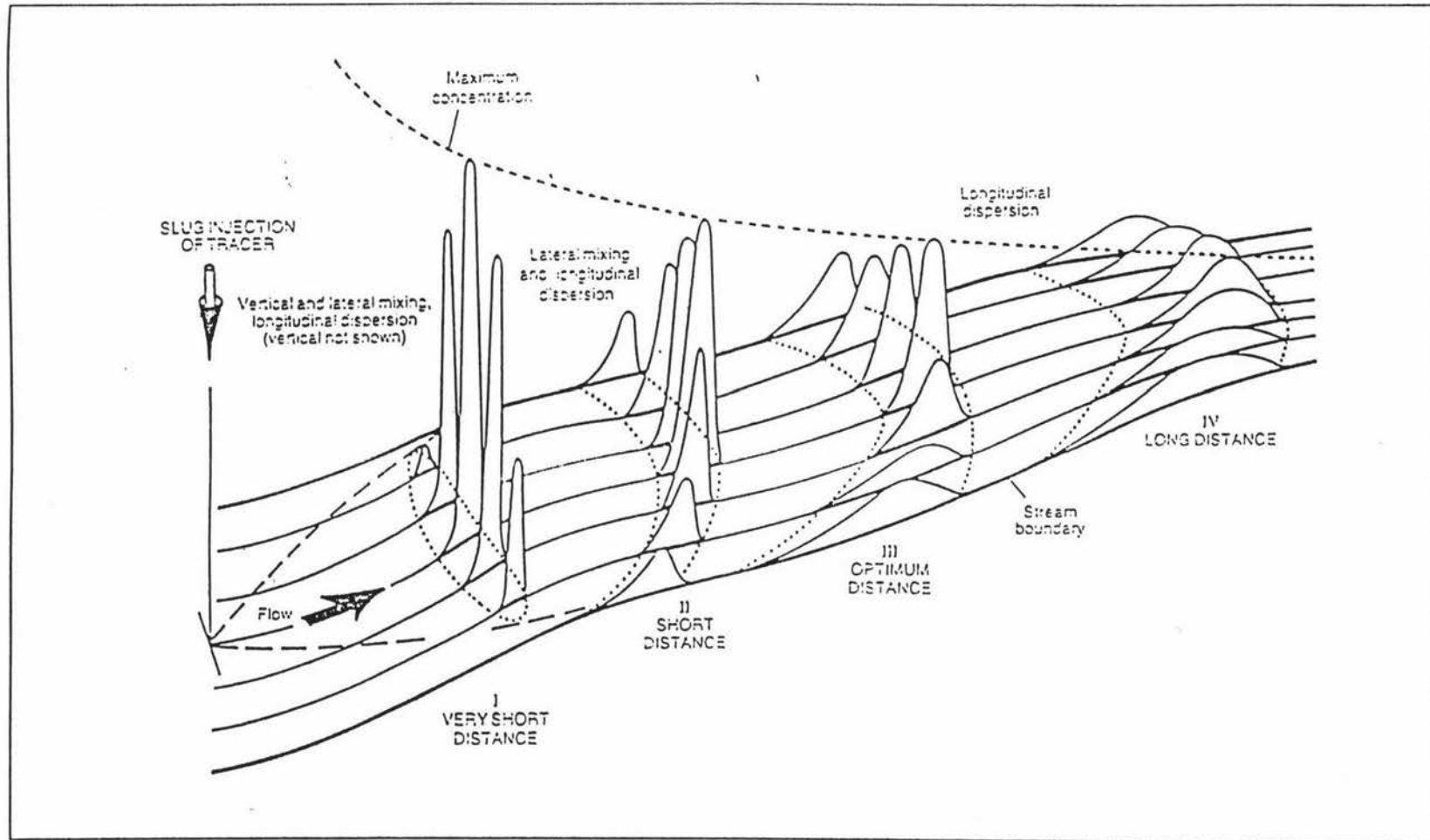


Figure 2.7 Lateral mixing and Longitudinal dispersion patterns and changes in distribution of concentration downstream from a single centre slug injection of tracer

injection, the response curve is normally represented by plotting concentration against elapsed time (figure 2.8).

The response curve is defined by the analysis of samples taken at selected time intervals during the dye cloud passage and is the basis for determining time of travel and dispersion characteristics (*Wilson, 1986*). The characteristics of the time-concentration curve along a streamline may be described in terms of elapsed time after an instantaneous dye injection. Characteristics pertinent to time of travel measurements are :

T_L , elapsed time to the arrival of the leading edge of the response curve at a sample point;

T_P , elapsed time to peak concentration, C_P , of the response curve;

T_C , elapsed time to the centroid of the response curve; and

T_t , elapsed time to the end of the tail of the response curve.

Refer to figure 2.8 over the page for further details.

2.3.3 Fluorescent Dyes

2.3.3.1 *Types Recommended for Tracing*

Hundreds of commercial dyes are available in a variety of colours. A great number are strongly fluorescent but only a few exhibit the combination of properties essential for water tracing. Two dyes, each a variation of the same basic organic structure (xanthene), have been used extensively as tracers; Rhodamine B and Rhodamine WT (*Wilson, 1986*) as their are:

1. water soluble (*Carter, 1974*);

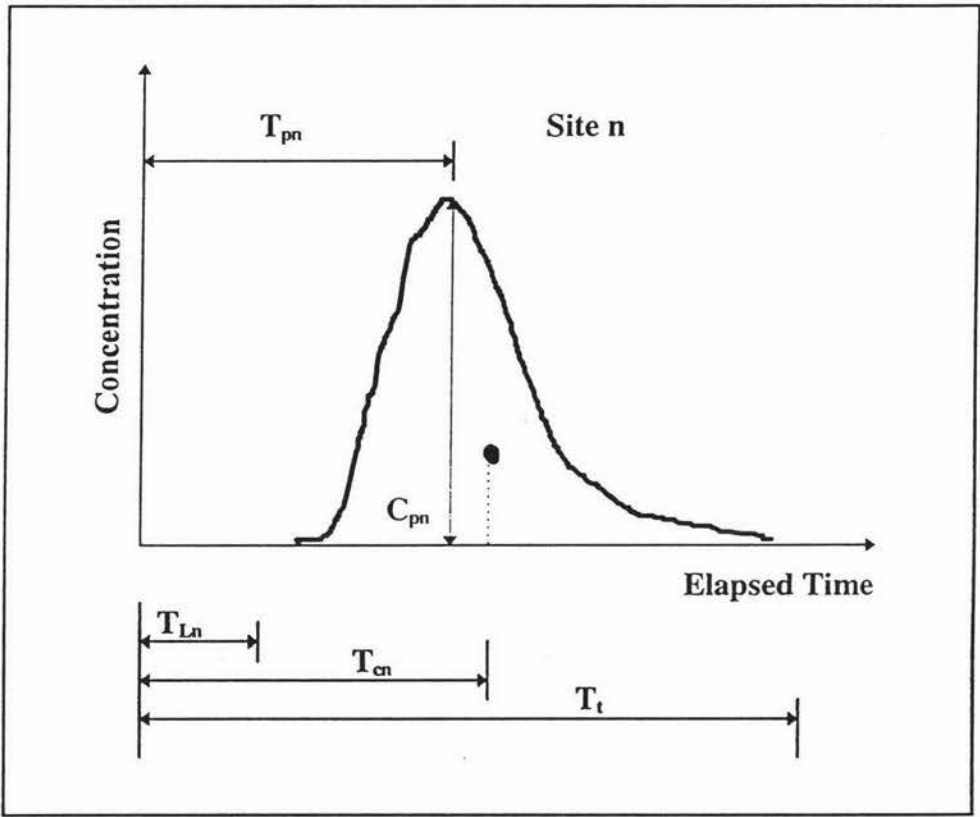


Figure 2.8 Typical graph for instantaneous dye injection

2. strongly fluorescent and easily isolated from background and instrumentally described at concentrations as low as 0.01 parts per billion (ppb) (*Brakes, (1992);*
3. inexpensive (*Wilson, 1986*); and
4. highly stable (*Denbigk and Turner, 1984*).

2.3.3.2 Rhodamine WT

Rhodamine WT has been praised by many sources as one of the more stable (non-reactive) water tracers (*Wilson, 1986; Smart C.C., 1988*). Among the advantages expounded by Smith and Laidlaw (1977) were its ease of detection, reasonable stability in a normal water environment and delectability at very low concentrations (*Stairs, 1994*). Wilson (1986) added that the dye was only "slightly susceptible to adsorption in most situations". Pilgrim et al. (1992) selected Rhodamine WT because of its adsorption resistance, an important characteristic in movement through gravel or crushed rock beds containing high contamination of plant roots and biological films. Steinback (1987) contented that Rhodamine WT was "developed to be particularly insensitive to sorption by suspended solids".

There have, however, been equally numerous studies demonstrating that Rhodamine WT is susceptible to adsorption and masking problems (*Stairs, 1994*). Masking effects occur in highly contaminated water where the dissolved organic compounds, which display fluorescence characteristics, mimic the actual dye concentrations. Smart (1985) recognised that dye tracers, notably rhodamines, adsorbed onto surfaces, particularly amorphous oxides and organic solids. Jones and Jung (1990) and Bencala (1983)

experimentally indicated appreciable capacity for sorption of rhodamine to stream bed sediments. Some researchers have even used rhodamine WT to mimic the sorption characteristics of pesticides in soluble transport studies (*Sabatini and Austin, 1991*).

Although the above evidence indicates the need for some caution when analysing fluorescent dye tracers, estimation of detention time and dispersion are still generally considered acceptable, provided the breakthrough signal is strong enough to be distinguished from the background (*Stairs, 1994*). Properties of Rhodamine WT are presented in Table 3

**Table 3 Properties of Rhodamine WT
Dye Tracer**

Appearance.....	clear very dark red aqueous solution, substantially free from insoluble matter
Specific gravity.....	approximately 1.15 at 20 %, 20°C
pH.....	10.8

2.3.4 Factors Which Affect Fluorescence

solution used buin hydraulic tracing, the effect is constant because the solvent is basically always water. Parameters of greatest concern through their effect on Rhodamine are temperature, suspended solids and chlorine (*Carter, 1974*).

2.3.4.1 Temperature

The most significant factor affecting fluorescence is sample temperature (*Wilson, 1986*). Fluorescence activity increases (resulting in higher readings) as temperature drops; lower

readings are obtained as temperature increases. Research conducted using Rhodamine WT have analysed samples held at a constant temperature (*Pilgrim and Schlz, 1992; Stairs, 1994*).

2.3.4.2 *Suspended Solids*

The presence of suspended solids decreases the amount of measured fluorescence. If the tracer is not appreciably adsorbed on the suspended solids, then scattering surfaces will deflect the fluorescence light away from the detector as well as deflecting the exciting radiation into the detector. The net effect is a decrease in the amount of measured fluorescence exponentially with increasing suspended solids concentration. This effect can be corrected by centrifuging or settling the sample (*Carter, 1974*).

2.3.4.3 *Chlorine*

The effect of free chlorine on rhodamine can be seen in Table 4. It can be observed that for the case when the diluent was sewage, the chlorine demand was satisfied by other substances and the tracer was not attacked (*Carter et. al, 1974*).

Table 4 The effect of free chlorine on Rhodamine

Dye	Diluent	Free Chlorine, ppm	Tracer concentration, ppb	Half life, min
Rhodamine WT	tap water	0.4	0.13	28.0
Rhodamine WT	sewage	0.8	0.18	∞
Rhodamine WT	sewage	1.0	1.32	∞

2.3.5 Stimulus-Response Techniques

In studying the flow in vessels, four stimulus-response techniques are commonly used. There are random input; cyclic input; step input and pulse input (*Levenspiel, 1972*).

The stimulus is the tracer input into a fluid entering the vessel. The response is a time record of the tracer leaving the vessel. Signals and their typical response are shown in figure 2.9.

For the study of flows in lagoons and wetlands (free surface and subsurface), instantaneous pulse input is most commonly used (*Slade, 1992; Pilgrim and Schlz, 1992; Stairs, 1994*).

Replicate experiments need to be exactly the same for all runs as reproducibility has been shown to be highly dependent on experimental technique (*Grobicki and Stuckey, 1992*).

2.3.6 Calibration Curves

Fluorescence varies linearly with concentration of the dye tracer. For most calibration, the curve passes through the origin, but as figure 2.10 illustrates, several possible shapes of curves have been observed (*Wilson, 1986*). Concentration quenching are observed at very high concentrations, usually above several hundred parts per billion (figure 2.10 B and 2.10 C). When such conditions are observed, standards can be diluted with the fluid under study.

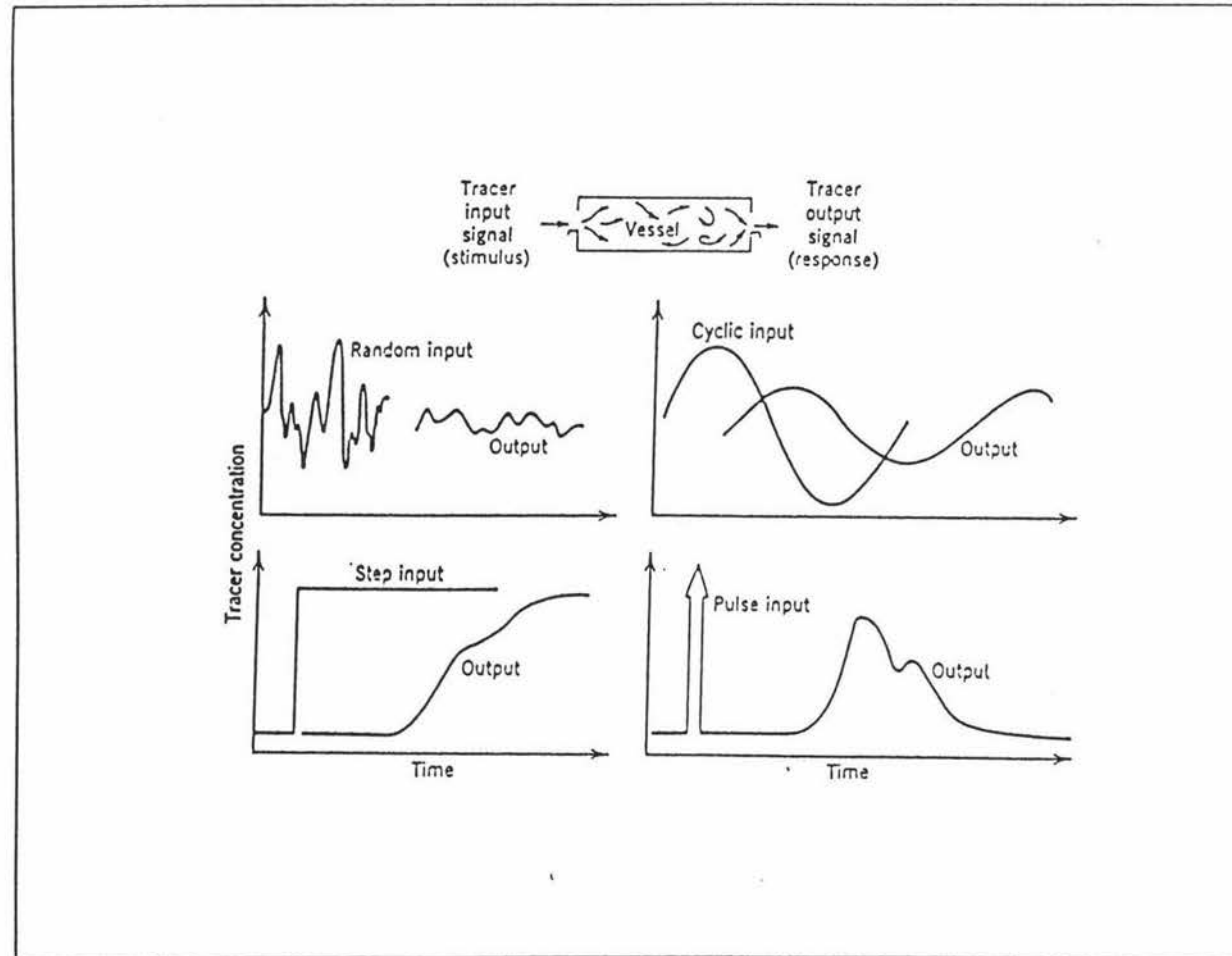


Figure 2.9 Stimulus-response techniques commonly used for flow in vessels

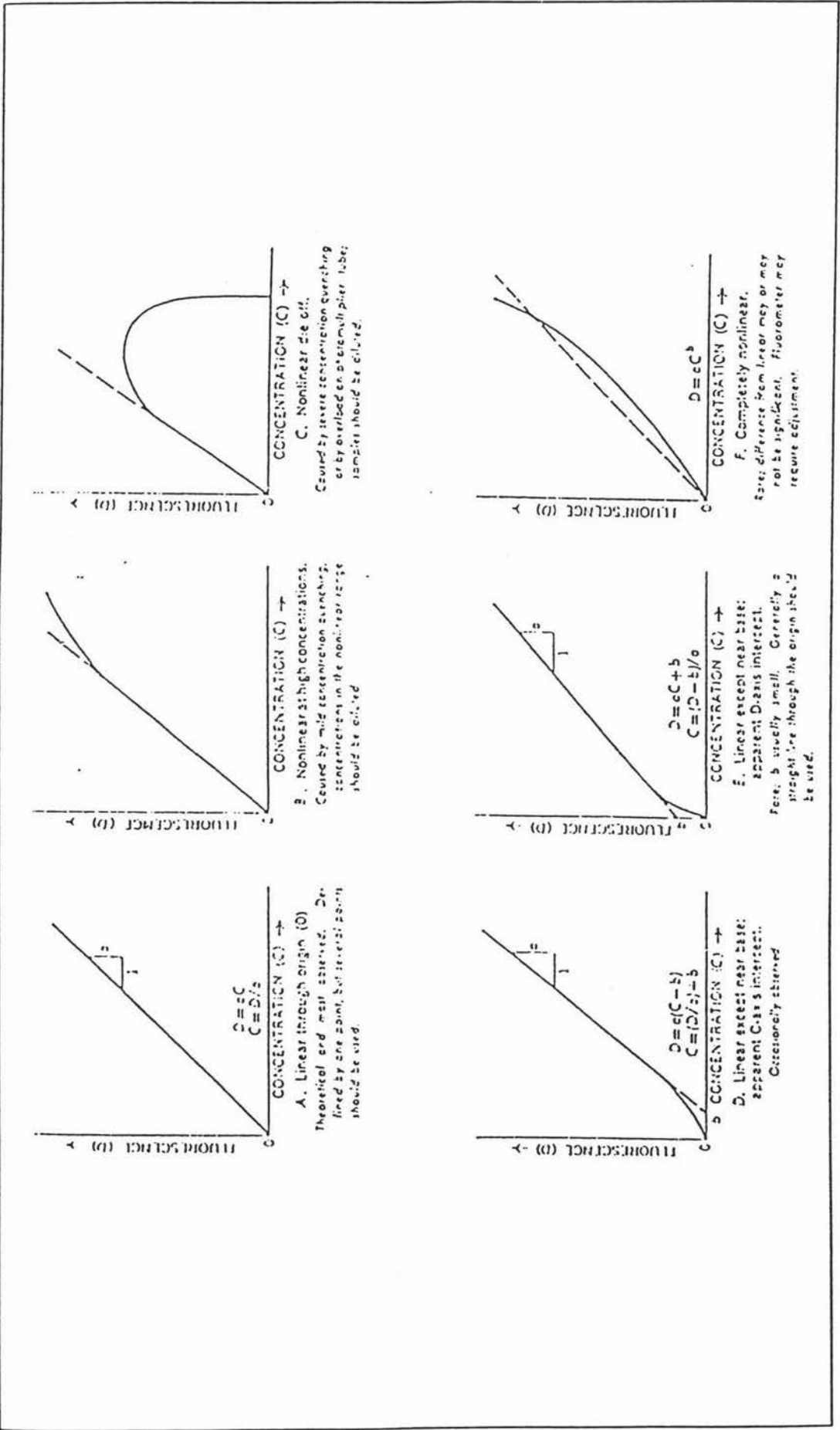


Figure 2.10 Types of calibration curves

Turner (1986) discovered that two types of curves (figure 2.10 D and 2.10 E) can result from incorrect alignment of the high-sensitivity kit installed on the fluorometer standard door. The problem can be corrected by factory adjustment or if the apparent intercept is small, a straight line through the origin should be drawn.

2.4 NON-IDEAL CHEMICAL REACTOR THEORY AND TRACER STUDIES

The theory of non-ideal flow patterns in chemical reactors is well understood and the subject has been in the textbooks for twenty years (*Levenspiel, 1972; Fogler, 1991*). Levenspiel introduces the subject as follows "Thus far, we have restricted ourselves to two idealised flow patterns, plug flow and mixed flow....But deviation from ideally can be considerable. This deviation can be caused by channelling of fluid, by recycling of fluid or by creation of stagnant region in the vessel....Ignoring these factors can lead to gross errors in design ".

As mentioned, there are two ideal types of reactor systems; the plug flow reactor (PFR) and the continuous stirred tank reactor (CSTR). Fluid, in a plug flow reactor moves in the chosen spatial direction with no attempt to induce mixing between the elements in the direction of flow (*Denbigh and Turner, 1984*). In plug flow reactors, all fluid elements entering the reactor will experience the same residence times which is often referred to as " piston flow " (*Danckwerts, 1953*).

It is widely presumed that wetlands are approximately plug flow in their internal hydraulics. This presumptions appear in many key design manuals (*USEPA, 1988, Reed et al., 1988; and Metcalf and Eddy, 1991*). Several recent studies have shown that constructed free-water surface and subsurface flow wetlands are not plug flow devices (*Fisher, 1990; Pilgram, 1992; Stairs 1994*). In a completely mixed reactor, the fluid properties are uniform throughout the reactor, and everywhere identical to the outgoing

elements. The assumption used for the ideal case is that at time $t = 0$, the fluid is instantly dispersed throughout the reactor (*Stairs, 1994*).

2.4.1 Non-ideal Flow and Residence Time Distribution

Non-ideal systems deviate from either extremes of the two ideal reactors. This deviation can be caused by dispersion (the longitudinal transport of material due to turbulence and molecular diffusion); dead volume; short-circuiting; and density stratification (*Levenspiel, 1972; Tchnobanoglous and Schnoeder, 1985*). This results in lower than anticipated performance of the systems.

The degree of deviation from ideal flow can be measured by the dispersion number of the system. The larger the dispersion number, the greater the residence time distribution. This concept is illustrated in figure 2.11 with various magnitudes of longitudinal dispersion. Injection of a dye pulse input experimentally can be used to determine the residence time distribution. This is done by measuring and plotting the concentration of dye versus elapsed time (called the C-diagram) at the outlet. If the tracer used is considered stable and non-reactive, the graph of dye concentration versus elapsed time provides an accurate representation of the system (*Grobicki and Stuckey, 1992*). The area under the C-diagram should be equivalent to the mass of dye input into the system divided by the volumetric flow-rate, or,

$$\text{Area} = M / v \quad (9)$$

Where M = mass of dye input
 v = volumetric flow-rate

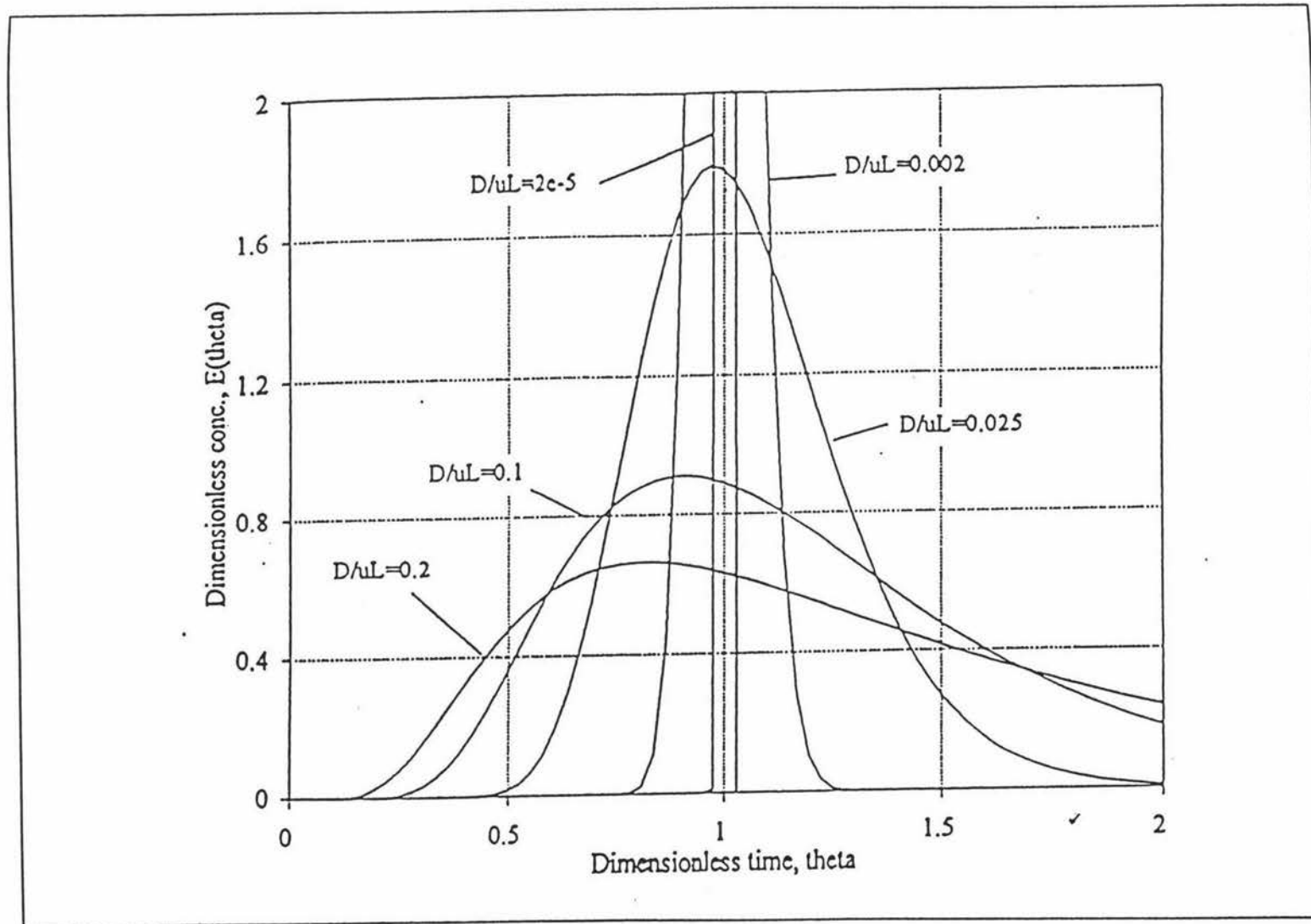


Figure 2.11 Dispersed plug flow for varying dispersion number

2.4.2 Dimensionless Residence Time Distribution

It is evident that elements of fluid taking different routes through the reactor may require different lengths of time to pass through the vessel. The time distribution of this fluid leaving the vessel is called the exit age distribution. It can be represented graphically by a normalised plot of the C-diagram, referred to as the E-diagram as shown in figure 2.12 (*Levenspeil, 1972*).

To normalise the concentration readings, C_i , (concentrations obtained by dye tracer study) are divided by the initial concentration of dye added, C_o , or

$$C_o = M_t / V \quad (10)$$

where M_t = mass of the dye added to the reactor

V = volume of the reactor

That is, the new concentration scale is given as $E_\theta = C_i / C_o$. The normalised time scale, θ , is calculated by dividing the residence time of each fluid element, t_i , with the theoretical residence time, t , or t_i / t . The area beneath the plot of E_θ versus θ should be equal to unity (*Denckwerts, 1953*).

2.4.3 Mean Residence Time and Variance

Mean residence time is also defined as the actual retention time (as described in section 2.2.9). The mean residence time, \bar{t} , and the variance, σ^2 , can be evaluated from the concentration versus time curve (figure 2.13).

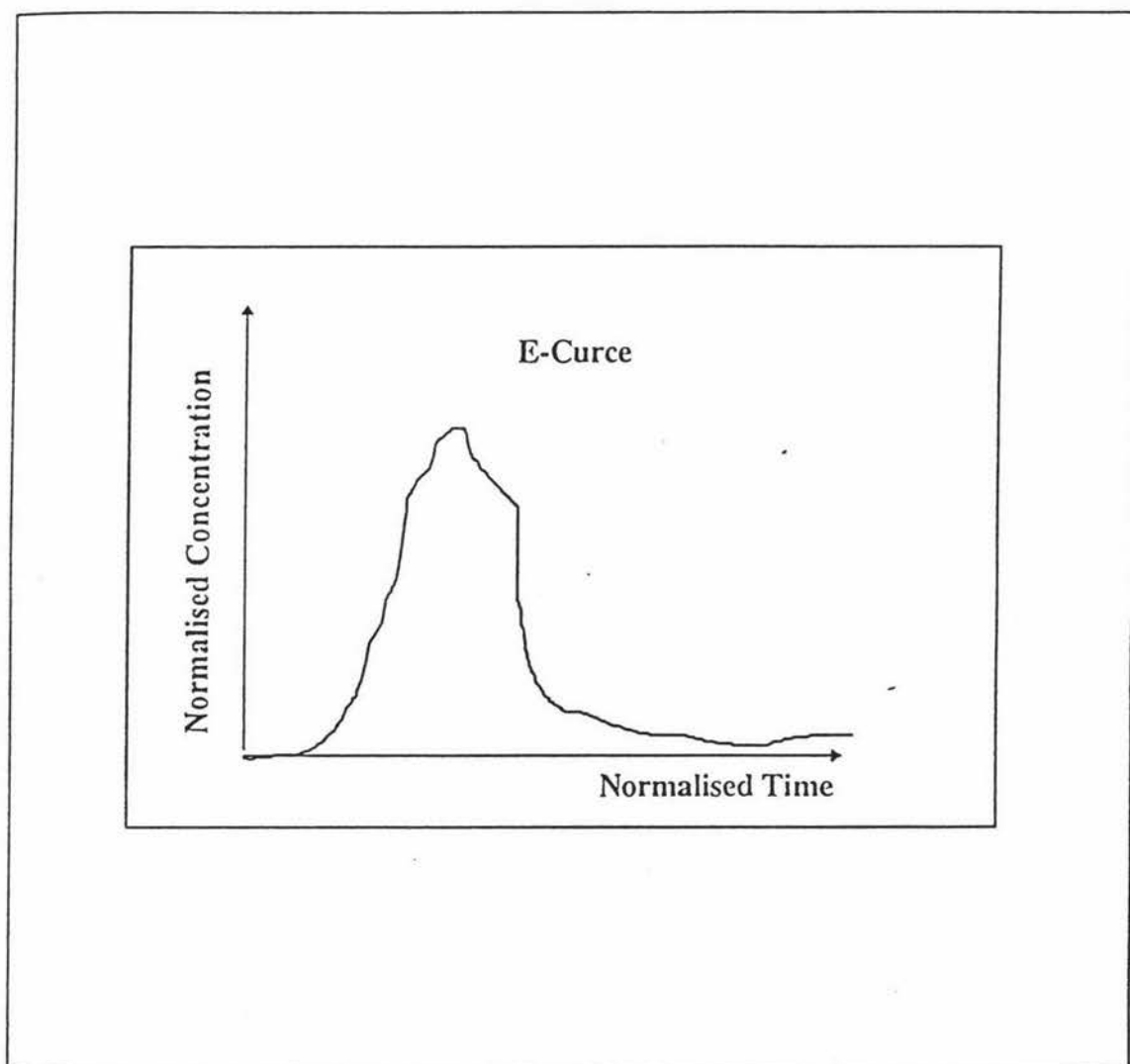


Figure 2.12 Normalised plot of C-curve called E-curve

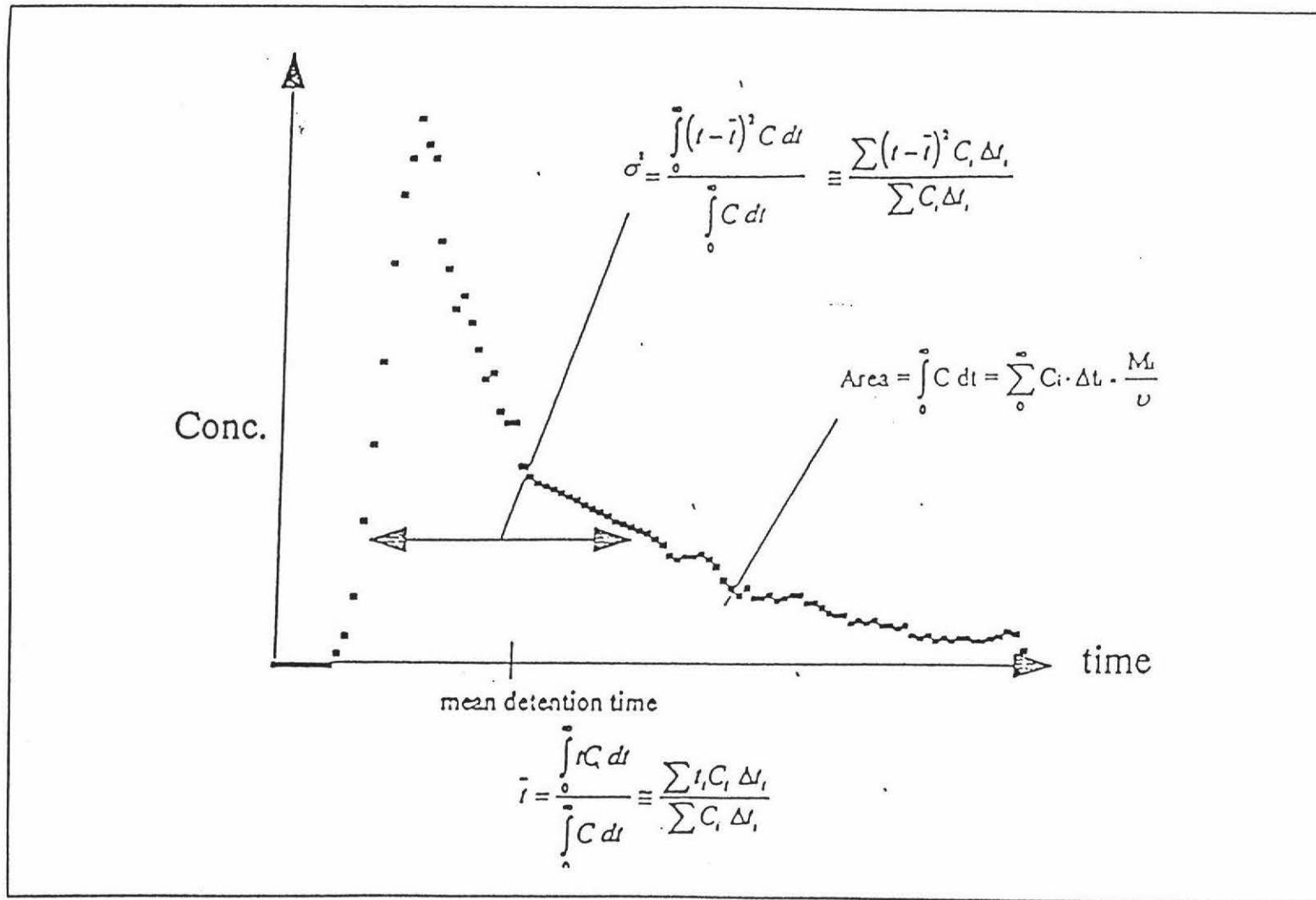


Figure 2.13 Determining Parameters of Residence Time Distribution

The mean residence time is a location parameter describing the centroid of the distribution. For a concentration versus time curve, the mean value is given by:

$$\bar{t} = \frac{\int_0^{\infty} tC \, dt}{\int_0^{\infty} C \, dt} \equiv \frac{\sum t_i C_i \Delta t_i}{\sum C_i \Delta t_i} \quad (11)$$

The spread of the distribution is commonly measured by the variance, σ^2 , defined as:

$$\sigma^2 = \frac{\int_0^{\infty} (t - \bar{t})^2 C \, dt}{\int_0^{\infty} C \, dt} = \frac{\int_0^{\infty} t^2 C \, dt}{\int_0^{\infty} C \, dt} - \bar{t}^2 \quad (12)$$

or in discrete form,

$$\sigma^2 \equiv \frac{\sum (t - \bar{t})^2 C_i \Delta t_i}{\sum C_i \Delta t_i} \equiv \frac{\sum t_i^2 C_i \Delta t_i}{\sum C_i \Delta t_i} - \bar{t}^2 \quad (13)$$

The variance represents the square or the spread of the distribution and has units of (time)².

2.4.4 Dead Space

The existence of stagnant regions in a reactor reduces the active volume of a treatment system. In a subsurface flow wetland, stagnant regions can occur throughout the system.

The net result is that the total volume of the system is not utilised. To calculate the

volume being utilised (which is called the effective or active volume), the mean retention time, \bar{t} , is multiplied by the actual average flow-rate, Q :

$$V_a = \bar{t} \cdot Q \quad (14)$$

where V_a = effective or active volume

This relationship calculates the reduction due to volumes occupied by plant matter (biological dead space), media and the volume attributed to stagnant regions.

2.4.5 Treatment Efficiency

Treatment efficiency of a reactor depends on two factors: the reaction kinetics (the rate) and the residence time. In the ideal reactors, all fluid elements experience the same residence time. In the non-ideal case, there is a distribution of residence time. Some elements are detained in the reactor longer than expected and some move through faster than expected. The effect of a distribution of residence time is a decrease in overall treatment efficiency. In almost all cases, deviations from ideal flow patterns results in decreased efficiency (*Levenspiel, 1972*).

To quantify this decrease in treatment efficiency, we can combine an expression for the kinetics of the reactor with the residence time distribution. If the conversion of the material is assumed to be first-order, then their extent of the reaction is directly dependent on the time that the material spends in the reactor. The exist age distribution, or E-curve, provides an estimate of the time that each portion of the total flow spends in

$$\left(\begin{array}{c} \text{mean concentration} \\ \text{of reactant} \\ \text{in exit stream} \end{array} \right) = \sum_{\text{all elements of exit stream}} \left(\begin{array}{c} \text{concentration of} \\ \text{reactant remaining} \\ \text{in element of age} \\ \text{between } t \text{ and} \\ t + dt \end{array} \right) \cdot \left(\begin{array}{c} \text{fraction of} \\ \text{exit stream} \\ \text{of age between} \\ t \text{ and } t + dt \end{array} \right) \quad (15)$$

or, in symbols,

$$\overline{C_A} = \int_{t=0}^{\infty} C_{A,\text{element}} E dt \quad (16)$$

in which,

$C_{A,\text{elements}}$ = concentration of reactant as a function of time;

C_A = mean concentration of material leaving the reactor unreacted; and

E = exit age density function.

An estimate of the conversion of a substance in the reactor is obtained from a kinetic expression. If the reaction were assumed to be irreversible and first-order .

The expression is,

$$C_{A,\text{element}} = C_{A0} e^{-kt} \quad (17)$$

where C_{A0} = Initial concentration

Substituting this rate expression in the above equation (16), we have the unconverted fraction,

$$\frac{\overline{C_A}}{C_{A0}} = \int_{t=0}^{\infty} e^{-kt} E dt \quad (18)$$

This expression gives the fraction of material that has not undergone reaction at $t = \infty$.

The extent of conversion can be related as:

$$\% \text{ treatment efficiency} = 100 \left[1 - \frac{\bar{C}_A}{C_{A_0}} \right] \quad (19)$$

When modelling the treatment kinetics with the first-order reaction usually suggested (*Kadlec, 1988*), a good estimate of the actual residence time of the system is required.

The conversion of BOD_5 can be used as an example.

2.5 FLOW MODELS

Levenspiel (1972) introduces two types of non-ideal flow models. By examining these different types of reactor models, we can improve our understanding of the flow in wetland systems. Although these models provide some flexibility compared to the ideal assumptions, they are still simplified representations of what is actually occurring in the systems (*Stairs, 1994*). The interactions of dispersion and mixing are too complex to describe mathematically and velocity patterns are difficult to quantify because of spatial nonuniformity (*Weber and Tehebanolous, 1985*). Due to channelling of fluid and preferential flow paths, localised velocities can greatly exceed those predicted. Nevertheless, the dispersed plug flow and the tank-in-series models have been used to provide reasonable approximations of the varying degrees of mixing characteristics of non-ideal flow.

2.5.1 Dispersed Plug Flow

Consider a plug of fluid on which is superimposed some degree of backmixing or intermixing, the magnitude of which is independent of position within the vessel. This model ensures no stagnant pockets or gross short-circuiting of fluid exists in the vessel. This is called the dispersed plug flow model (*Levenspiel, 1972*). In a tracer study, a pulse input into the reactor will appear as a spike at the outlet end for an ideal plug flow system and as the amount of dispersion increases, the spike will begin to flatten, as already illustrated in figure 2.11. The dispersion equation is derived by considering dispersion in the flow direction (x-direction). Since the dispersion process is primarily a function of concentration gradient, then:

$$F_{Ax} = -D_x \frac{\partial C_A}{\partial x} \quad (20)$$

where F_A = mass flux of material A in the x-direction;

D_x = coefficient of dispersion in x-direction; and

C_A = concentration of material A.

As figure 2.7 indicates, dispersion typically is three dimensional and the dispersion coefficient varies with direction and degree of turbulence. However, for simplicity, a simple one dimensional dispersion model can be considered. Taking a mass balance:

$$\text{Accumulation} = \text{inflow} - \text{outflow} + \text{generation}$$

then from figure 2.14, a mathematical translation can be obtained:

$$\frac{\partial C_A}{\partial t} A \Delta x = \left(u A_x C_A - A_x D_x \frac{\partial C_A}{\partial x} \right) \Big|_x - \left(u A_x C_A - A_x D_x \frac{\partial C_A}{\partial x} \right) \Big|_{x+\Delta x} + r_A A_x \Delta x \quad (21)$$

where A_x = cross-sectional area in x-direction;

V = average velocity in x-direction; and

r_A = rate of reaction of material A.

By taking the limit of the above equation as Δx approaches zero, and assuming that material is non-reactive (a conservative tracer), equation (21) becomes:

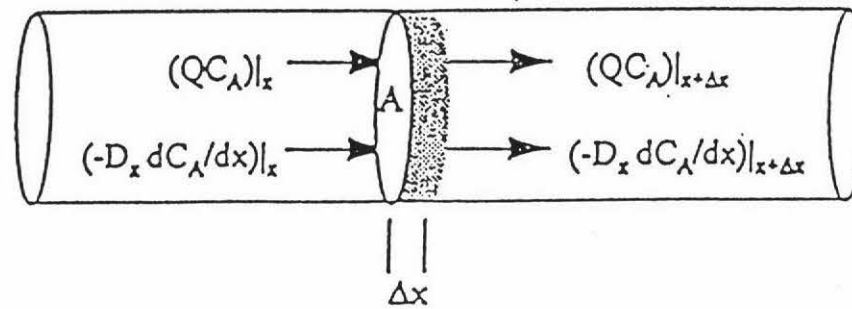


Figure 2.14 One dimensional mass balance for dispersed plug flow model

$$\frac{\partial C_A}{\partial t} = D \frac{\partial^2 C_A}{\partial x^2} - \frac{\partial C_A}{\partial \theta_H} \quad (22)$$

where θ_H = hydraulic retention time

2.5.1.1 Boundary Conditions and the Dispersion Model

Tchobanoglous (1985) propose that dispersion can be considered small when the dispersion number, D/uL is less than 0.2. If the dispersion in the system is small, Levenspiel (1972) provides an analytical solution for the dispersed plug flow model as:

$$E_{t_o} = \frac{u}{\sqrt{4\pi Dt}} \exp \left[-\frac{(L - ut)^2}{4Dt} \right] \quad (23)$$

where u = average velocity;
 D = dispersion coefficient; and
 L = length of travel path.

When dispersion in a system is large, outlet concentration curves become increasingly non-symmetrical and particularly sensitive to boundary conditions (*Levenspiel, 1972*). This fact has been a topic of discussion in the engineering field since Danckwerts paper in 1953. The inlet and outlet boundary conditions can be qualified as either open or closed (figure 2.15). A number of mathematical problems arise when attempting to provide analytical solutions when the boundary condition are considered (*Denbigh and Turner, 1984*). If the flow characteristics do not change drastically at a boundary, it is said to be open. In this case, it is assumed that backmixing occurs at the boundary,

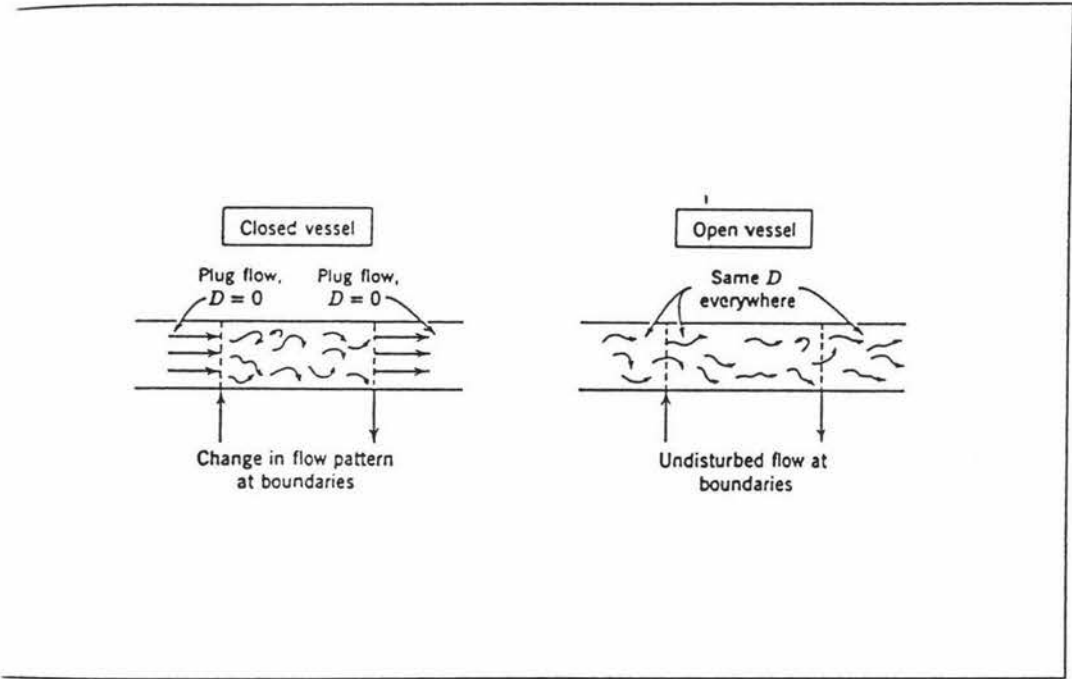


Figure 2.15 Open and Closed Vessels

which in turn distorts the residence time distribution. Conversely, if a boundary is considered to be closed, then no backmixing occurs, and the residence time distribution obtained is correct. Unfortunately, there has been no analytical solution for the case of a closed reactor to date (Levensiel, 1993). The partial differential dispersion equation above is interpreted to represent the fluid patterns in the reactor, but does not account for the possibility of a particle crossing and recrossing a boundary throughout its life in the reactor (Newman, 1981). The subsurface flow wetland used in this study is classed as an open vessel.

2.5.1.2 Determining Dispersion from Tracer Studies

The most accurate method of determining the dispersion present in a system is by a method analogous to the flood routing procedure used in hydrology (Fischer, 1968). A pulse of dye is released upstream at two sample points located at some distance apart from one another. As the pulse of dye passes the initial sampling point, it will have a characteristic residence time distribution. As it passes the second sampling point further downstream, the distribution will indicate an attenuated peak and larger variance characteristic of longitudinal dispersion. By comparing the change in the residence time distribution via the variance, an estimate of the dispersion in the stream can be made. The advantage of this routing technique is its insensitivity to the method of tracer injection. For this reason, it is commonly used in studies of dispersion in rivers. Fischer, 1968 gives the dispersion as:

$$D = \left(\frac{1}{2} \right) \cdot \bar{u}^2 \frac{\sigma_{t_1}^2 - \sigma_{t_0}^2}{t_1 - t_0} \quad (24)$$

where u = the mean velocity of the fluid;

σ_1^2, σ_2^2 = variance of distribution at upstream and downstream locations respectively; and

\bar{t}_1, \bar{t}_2 = mean time of passage of tracer cloud at each station.

2.5.4 Tank-in-Series

An approximation of the dispersed plug flow model is encompassed in the tank-in-series model as given below. A truly complete mixed reactor would be modelled with one tank ($N=1$), and plug flow would be modelled with an infinite number of complete mixed reactors ($N=\infty$). By matching the actual concentration versus time curve generated using field data with one of the curves produced by the theoretical tank-in-series model, an analogous number of tank-in-series is obtained to describe the residence time distribution

The theoretical tank-in-series model for N reactor in series is given as:

$$E_{\theta} = (N\bar{t}_i)^N E = \frac{N(N\theta)^{N-1}}{(N-1)!} e^{-N\theta} \quad (25)$$

where

E_{θ} = dimensionless concentration;

—

\bar{t}_i = mean residence time of one tank;

—

$\theta_i = \bar{t}_i / \bar{t}$ = dimensionless residence time of the reactor; and

N = number of tanks.

The theoretical tank-in-series model yields identical results as the theoretical dispersed plug flow model for small amounts of longitudinal dispersion. The use of one model over the other is usually described as a matter of convenience to the designer, although the tank-in-series model, unlike the dispersed plug flow model, has the advantage of insensitivity to boundary and method of injection and sampling (*Levenspiel, 1993*). To determine the number of analogous reactors in series from an experimental residence time distribution, *Levenspiel (1993)* suggests several approximations, the most reliable being:

$$\sigma_{\theta}^2 = 1/ N \quad (26)$$

The value of N represents the flow of fluid through N series of equal size ideal stirred tanks. The expression, σ_{θ}^2 , in the above equation represents the variance of the normalised curve of the actual residence time distribution.

CHAPTER 3

MATERIALS AND METHODS

3.1 THE WETLAND SYSTEM

The wetland system used in this study was a subsurface flow (SF) wetland located at Paraparaumu Sewage Treatment Plant which is operated by the Kapiti District Council. The treatment plant is designed to cater for a population of 25,000 people and has a peak flowrate of 7800 m³/day.

The subsurface flow wetland is not part of the treatment process at the Paraparaumu Sewage Treatment Plant. It is a pilot plant that was used for research purposes during the investigation of the 1993 upgrading of the treatment plant from 12,500 to 25,000 people.

The field samples for all the three runs were collected using a ISCO 3700 automatic sampler.

3.2 CONFIGURATION

The subsurface flow wetland experimental unit consists of one rectangular cell: 22 metres long, 6 metres wide and an average depth of 0.775 metres. The wetland has a slope of 0.74% and is lined throughout by low density polythene (figures 3.1 and 3.2).

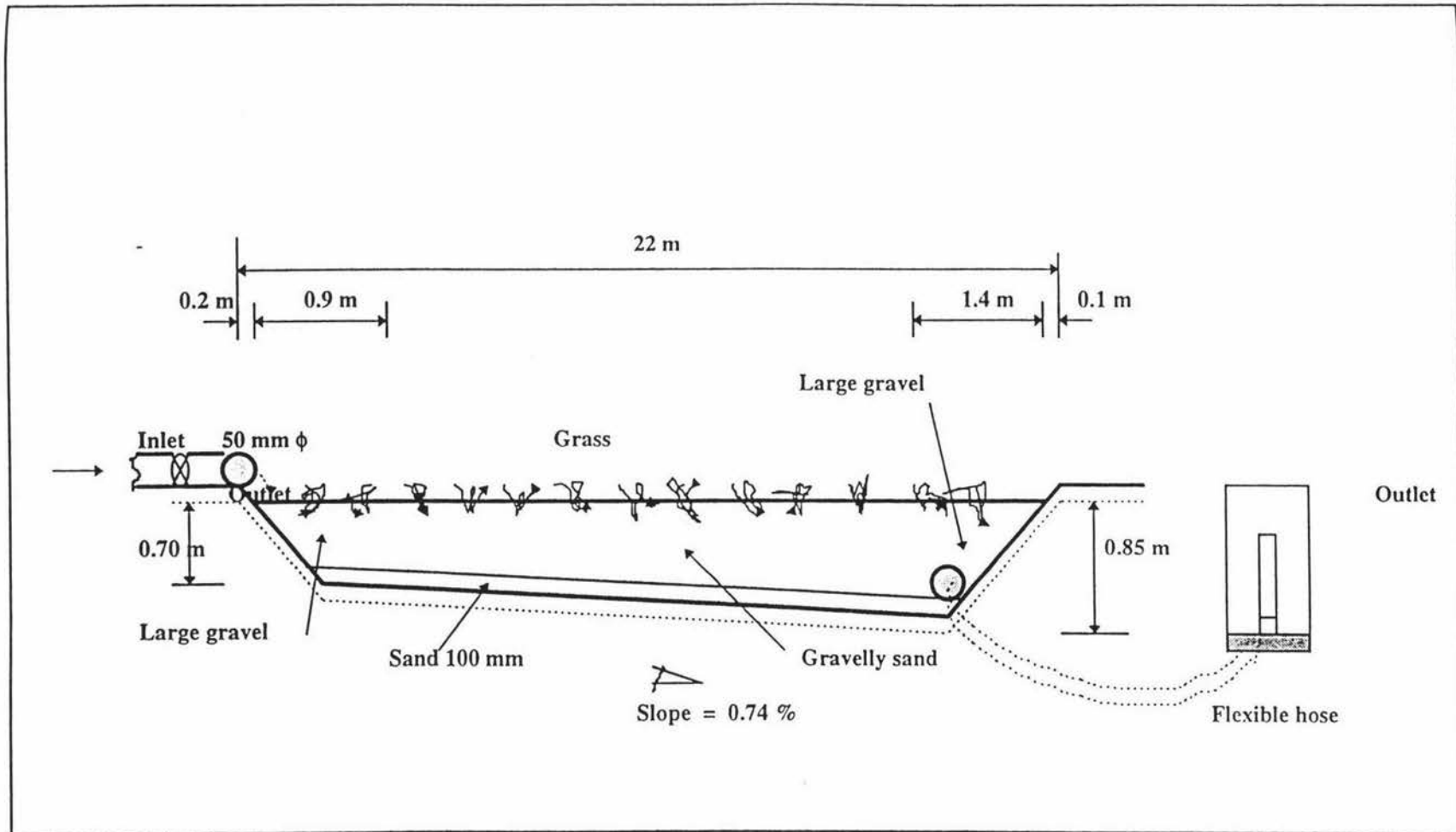


Figure 3.1 Longitudinal Cross-section of the Subsurface Flow Wetland

The wetland has been in use for three years for trial purposes. During these years, it has been fully planted but was harvested prior to this research leaving only a grass cover. The subsurface flow wetland consisted of three media: large gravel, gravelly sand and medium sand.

3.3 EFFLUENT SUPPLY

The effluent to the wetland is secondary treated sewage effluent from two clarifiers which is passed through a ultra violet system. A portion of the effluent flow is then diverted to the wetland via separate distribution pipes. Effluent enters the wetland through a manifold few centimetres off the ground. The flowrate into the wetland is controlled by a ball valve. Flow is along the length of the wetland, with a manifold inlet and outlet at opposite ends (figure 3.2).

3.4 DYE STUDIES

This section is presented in three parts: laboratory work, field work and sample analysis.

3.4.1 Laboratory Work

Before any laboratory work was undertaken, selection of a suitable dye tracer was made. The tracer finally chosen was a fluorescent dye, Rhodamine WT. This is a bright fluorescent red dye with a minimum delectability of 0.1 ppb (parts per billion). The choice was made due to the properties and characteristics as described earlier in the literature review.

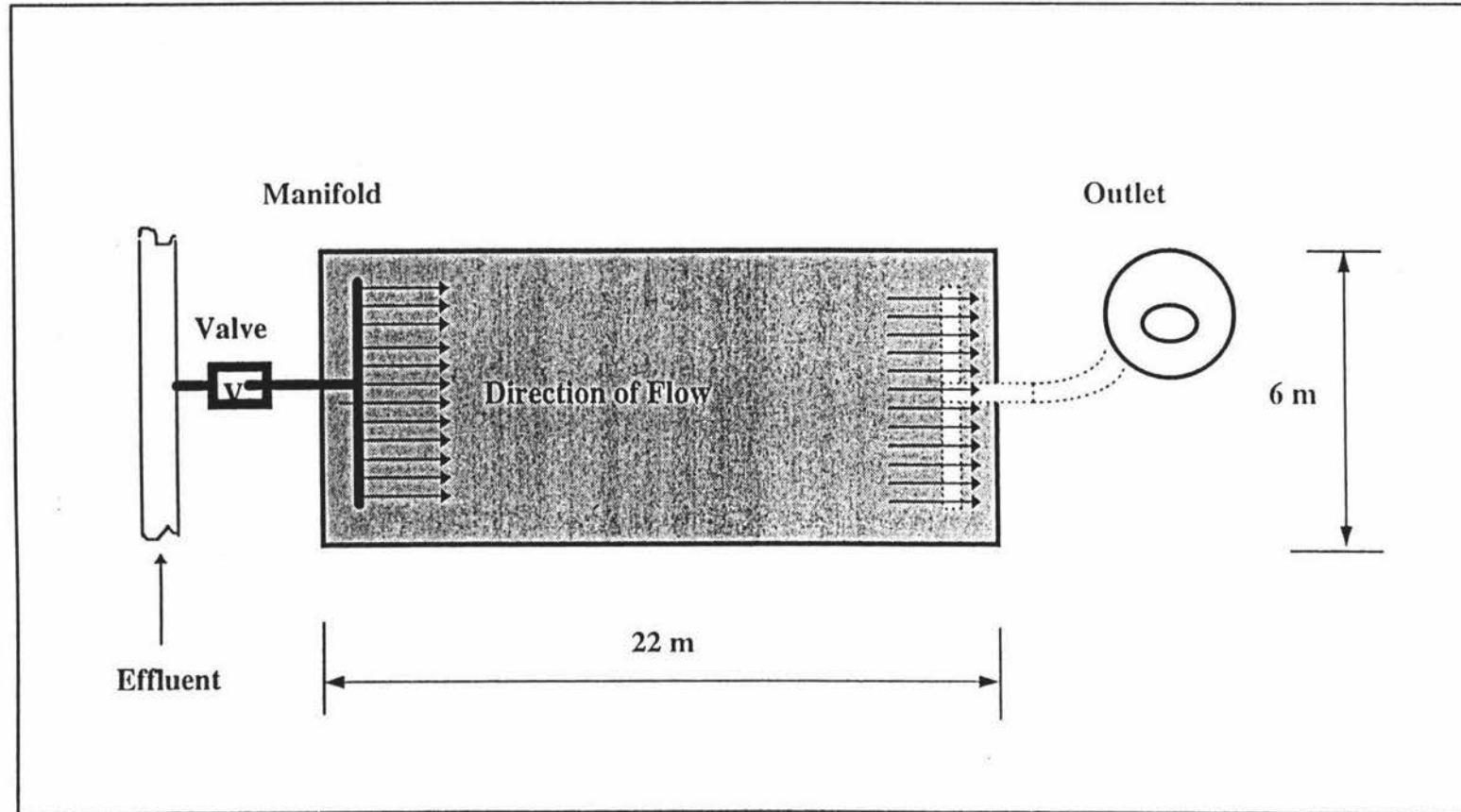


Figure 3.2 Dimensions of the Subsurface Flow Wetland

3.4.1.1 Calibration Curves

Two calibration curves were obtained from standards prepared with distilled water and with effluent from the treatment plant. This was done to compare and compensate the effects of suspended solids, chlorine and pH (Carter, 1974; Wilson, 1986; Stairs, 1994). Effluent and distilled water calibration curves were determined using standards prepared according to procedures outlined in Wilson (1986). Standards were made with rhodamine dye serially diluted ranging from 0.23 $\mu\text{g/L}$ to 2300 $\mu\text{g/L}$ in both distilled water and effluent. Because Rhodamine dye fluorescence is particularly sensitive to temperature (Carter, 1974), the standards were held in a bath of constant temperature of 20 °C.

Numerous readings were taken at low concentrations ($< 50 \mu\text{g/L}$) as it was assumed that most of the sample collected at the outlet would be in this range. The results established were plotted (refer to chapter 4) and a linear relationship of the fluorescent readings versus the concentration of the standards serially prepared. This could then be used to link the fluorescence of field samples back to dye concentrations.

3.4.1.2 Temperature Effect

Due to some doubts about the stability of the Rhodamine WT at varying temperatures, standards were measured at 18°C, 20°C and 25°C and their comparison graphically represented. This is discussed in section 4.1.1.

3.4.1.3 Time Delay Effect

Questions of decay of the fluorescence over time were also raised. Standards were measured for their fluorescence on day one and after seven days at a constant temperature of 20 °C.

3.4.1.4 Theoretical Hydraulic Retention Time/ Porosities/Flowrate Calculations

A theoretical hydraulic retention time (HRT) of four days was selected for use in all three runs. This was then set by adjustment of the flowrate as discussed below.

Porosities of the wetland were obtained experimentally. The media were thoroughly washed, oven dried, and a known volume (V_m) placed into a two litre beaker. A known volume of water (V_w) was then poured to the top level of the media. Porosity was then found by using the following equation:

$$n = V_w/V_m \quad (27)$$

where n = porosity

The required flow-rate was calculated by the equation:

$$Q = nV_m / \text{HRT} \quad (28)$$

where Q = flow-rate (m^3/day)

The flow-rate needed for a chosen theoretical retention time of four days was calculated using the media porosities and their volumes, yielding a value of 6.28 litres/minute. This flow-rate was held constant throughout the three runs and periodically checked to ensure constant flow.

3.4.1.5 Tracer Volume Calculation

By using the volume of the wetland (accounting for porosity) and the maximum detectable dye concentration in the effluent of 805 $\mu\text{g/L}$, the theoretical volume of dye to be added to the wetland was calculated to be approximately 130 ml. However, a set volume of 300 ml of dye was used in tracer studies. The basis of using this volume over the theoretical volume was to counter the effects of adsorption/desorption and suspended solids. However, using the higher dye volume did result in some of the outlet samples having concentrations beyond the maximum detectable range of 805 $\mu\text{g/L}$. This was simply remedied by diluting the samples with distilled water.

Calculations for the required flow-rate and dye volume can be found in appendix D

3.4.2 Field Work

Refer to figure 3.3 for positions of sample injection and collection for all the three runs.

3.4.2.1 First Run

The wetland was subjected to a constant flow-rate of 6.28 L/min for three weeks before any dye injection. Three hundred millilitres of Rhodamine WT was mixed with effluent

in two twenty litre containers and added as an instantaneous pulse at the centre of the inlet. The duration of the injection of the dye was fifty minutes. An automatic sampler, containing twenty-four sample bottles was used to collect samples at the outlet at three hour intervals. A total of eighty-eight samples were collected from the outlet over three hundred and ninety hours. The duration of this run was from the period of 6 March to 20 March, 1995.

3.4.2.2 Second Run

After the first run, the flow-rate was increased for a week to allow the flushing out of the remaining dye tracer. The flow-rate was then adjusted back to 6.28 L/min for a week before the start of the second run.

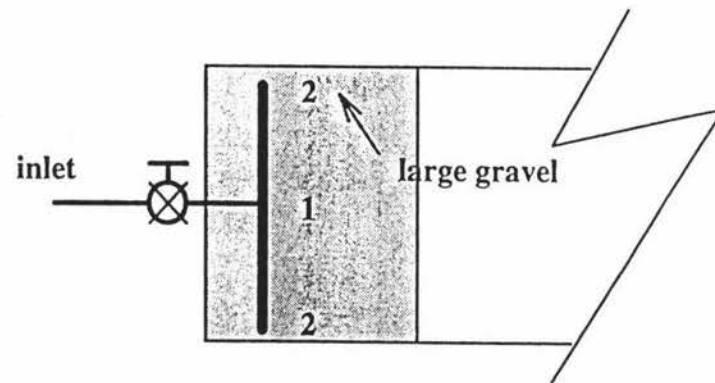
Again, three hundred millilitres of Rhodamine WT dye was mixed with effluent in two twenty litre containers and added as an instantaneous pulse. The mixture was poured manually but evenly along the large gravel under the inlet manifold. The duration of dye injection was thirty minutes. Ninety-six samples were collected at three hour intervals by the automatic sampler at the outlet over a period of four hundred and six hours. The duration of this run was from the period of 4 April to 21 April, 1995.

3.4.2.3 Third Run

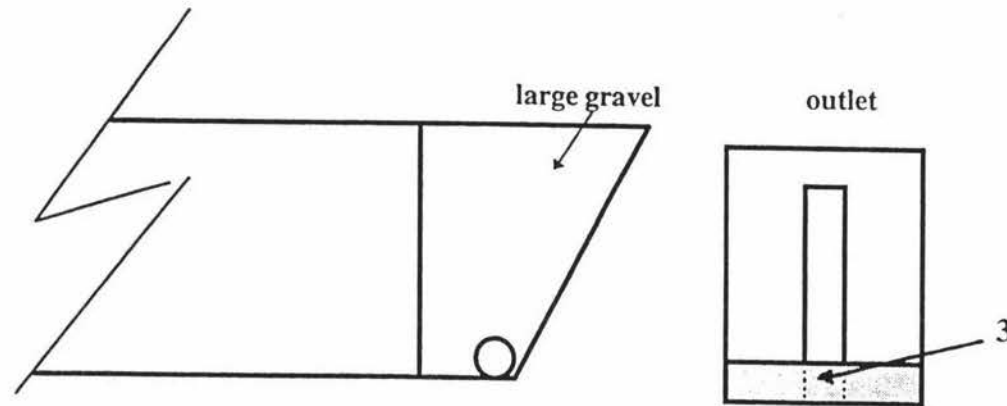
Similar procedures as the second run were followed. The duration of this run was for thirteen days starting on 10 July and ending on the 23 July, 1995.

3.4.3 Sample Analysis

Samples collected in the field were analysed on the same day. As Rhodamine Wt dye is particularly sensitive to temperature, the samples were stored in a bath at 20 °C prior to analysis. Three fluorescent readings were taken for each sample and the average used for calculation purposes. A number of samples from both runs had to be diluted by a factor of half, that is, 3 ml of sample to 3 ml of effluent, to obtain values within the linear range of the effluent calibration curve.



1. For the first run, dye was injected at position 1
2. For the second and the third run, dye was evenly distributed along position 2-2



3. outlet samples were taken from position 3

Figure 3.3 Positions for sample injection and collection

CHAPTER 4

RESULTS AND DISCUSSION

4.1 CALIBRATION CURVES

Fluorescence readings versus dye concentrations are shown in figure 4.1. Linear representation of figure 4.1 is depicted in figure 4.2. Data pertaining to both figures are given in appendices A and B.

Calibration curves with the dye diluted in effluent demonstrated reduced fluorescence from the distilled water samples (figure 4.1). An interesting observation from the comparison of the linear calibration curves (figure 4.2) was that their slopes were approximately equal suggesting a linear damping of fluorescence rather than a total divergence. The lower readings can be attributed to the effects of suspended solids and chemicals such as chlorine in the effluent. To compensate the effect of the effluent on the dye concentrations, the effluent calibration curve was used to determine the field sample concentrations.

From figure 4.1, it was determined that the maximum detectable dye concentration is 805 $\mu\text{g/L}$.

4.1.1 Temperature Effect

As discussed earlier in section 2.3.4.1, temperature can be a significant factor affecting fluorescence. To investigate this, standards prepared with distilled water were measured for their fluorescence at temperatures of , 18°C, 20°C and 25°C.

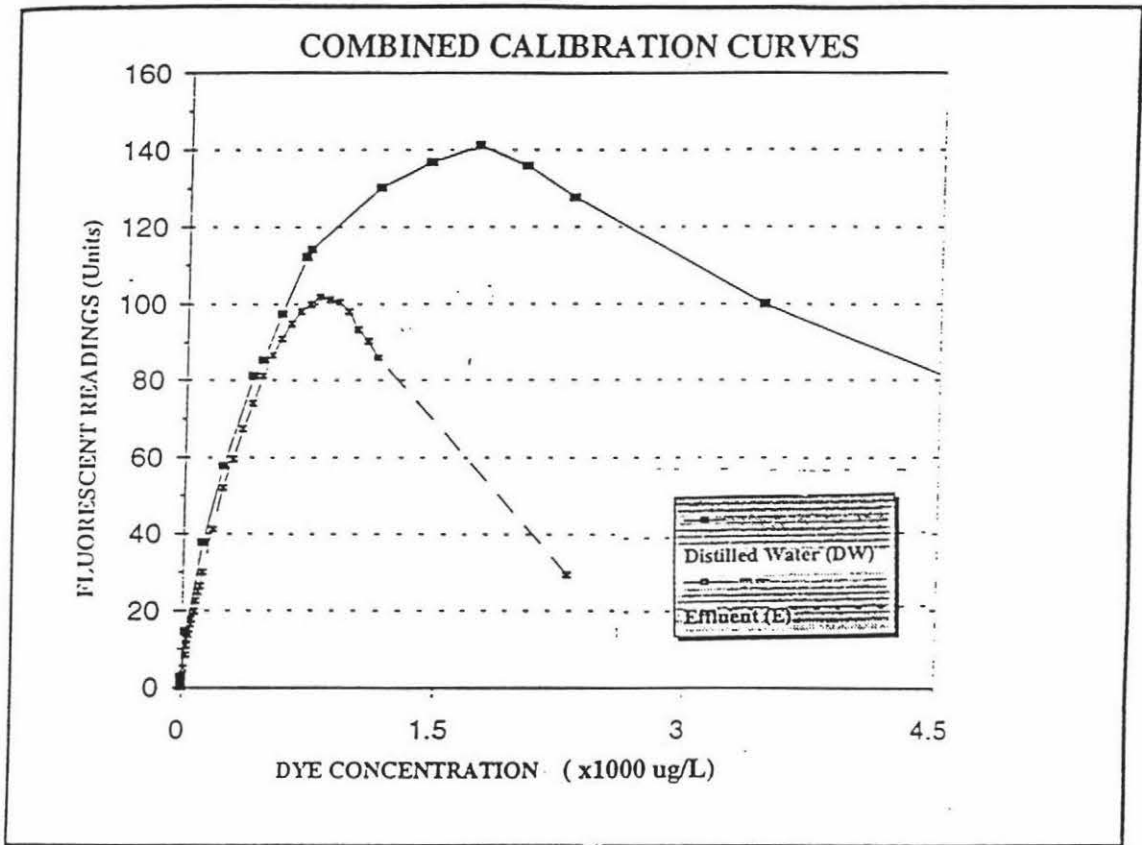


Figure 4.1 Calibration Curves

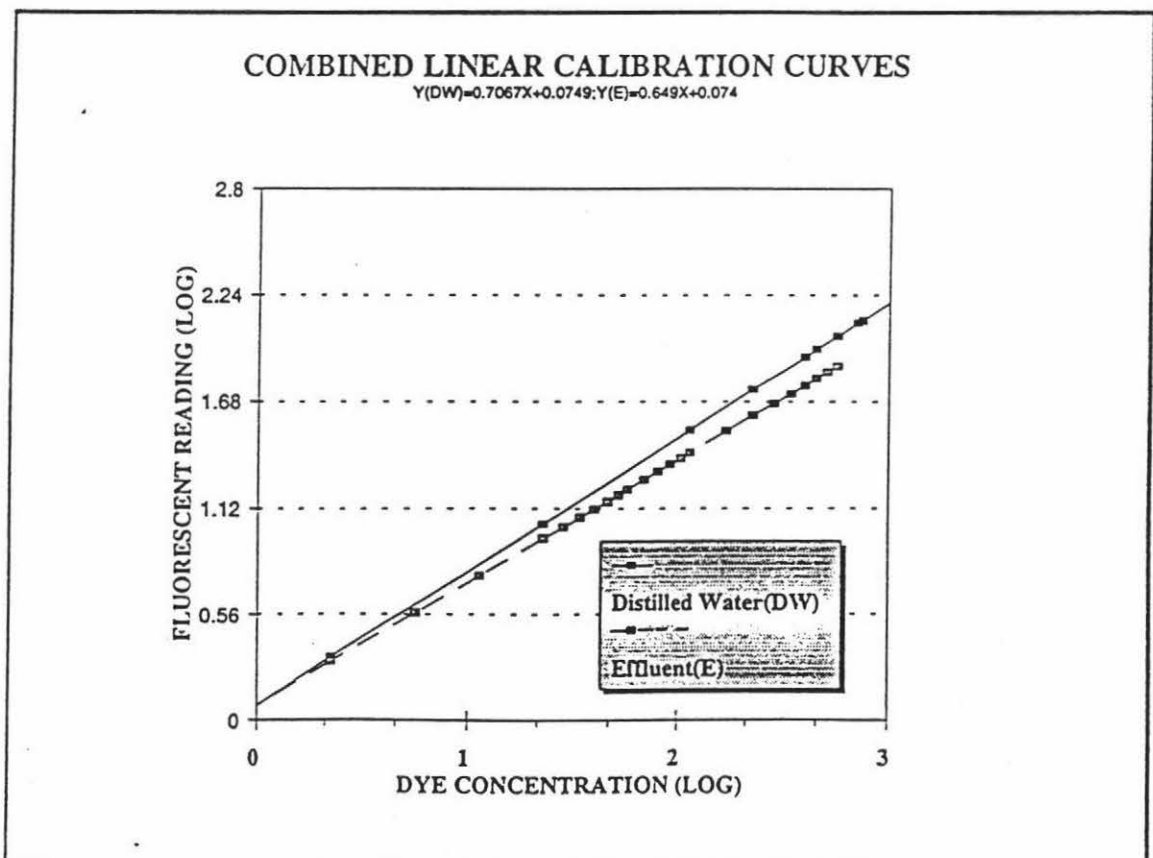


Figure 4.2 Linear Calibration Curves

Reduced temperatures demonstrated higher fluorescence readings as shown in figure 4.3. A temperature of 20°C was used for effluent calibration and field samples by placing the standards and the samples in a bath of constant temperature of 20°C.

Data pertaining figure 4.3 is presented in appendix C.

4.1.2 Time Delay Effect

Fluorescence activity seems to decrease over time resulting in lower readings. This is shown in figure 4.4 where readings were taken at a separation period of seven days. The lower readings could be attributed to standards being exposed to sunlight. Care and effort was made to minimise exposure to sunlight.

Data for figure 4.4 is given in appendix C.

4.2 RESIDENCE TIME DISTRIBUTION

The residence time distribution of tracer and hence effluent of the three runs are graphically illustrated in figure 4.5. A summary of the key parameters from this figure are given in Table 5.

Table 5 Summary of Retention Times of the Three Runs

Run #	Shortest retention time, (days)	Longest retention time, (days)	Time to peak (days)	Mean retention time, (days)	Peak concentration (µg / L)
1	0.88	≈ 14	1.88	2.71	1172
2	0.88	≈ 14	2.63	3.47	1841
3	0.83	≈ 14	1.83	3.41	1821

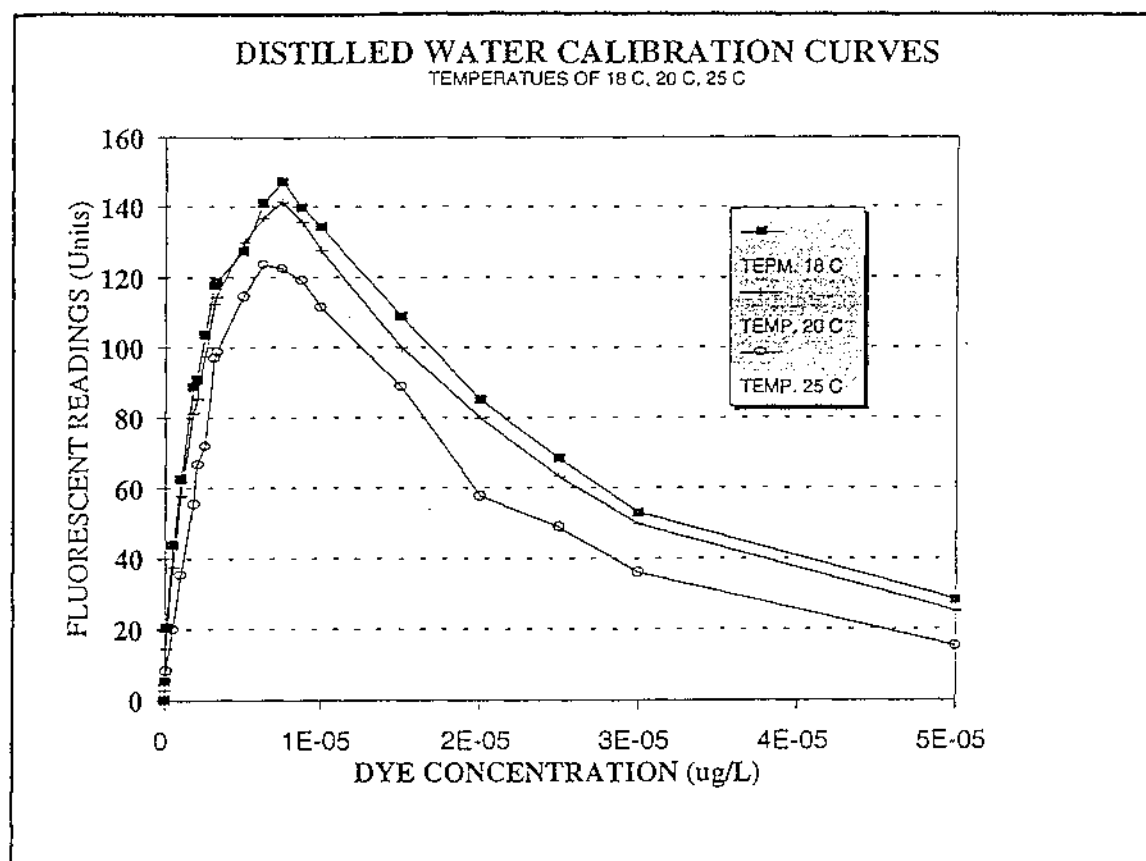


Figure 4.3 Calibration Curves at varying Temperatures

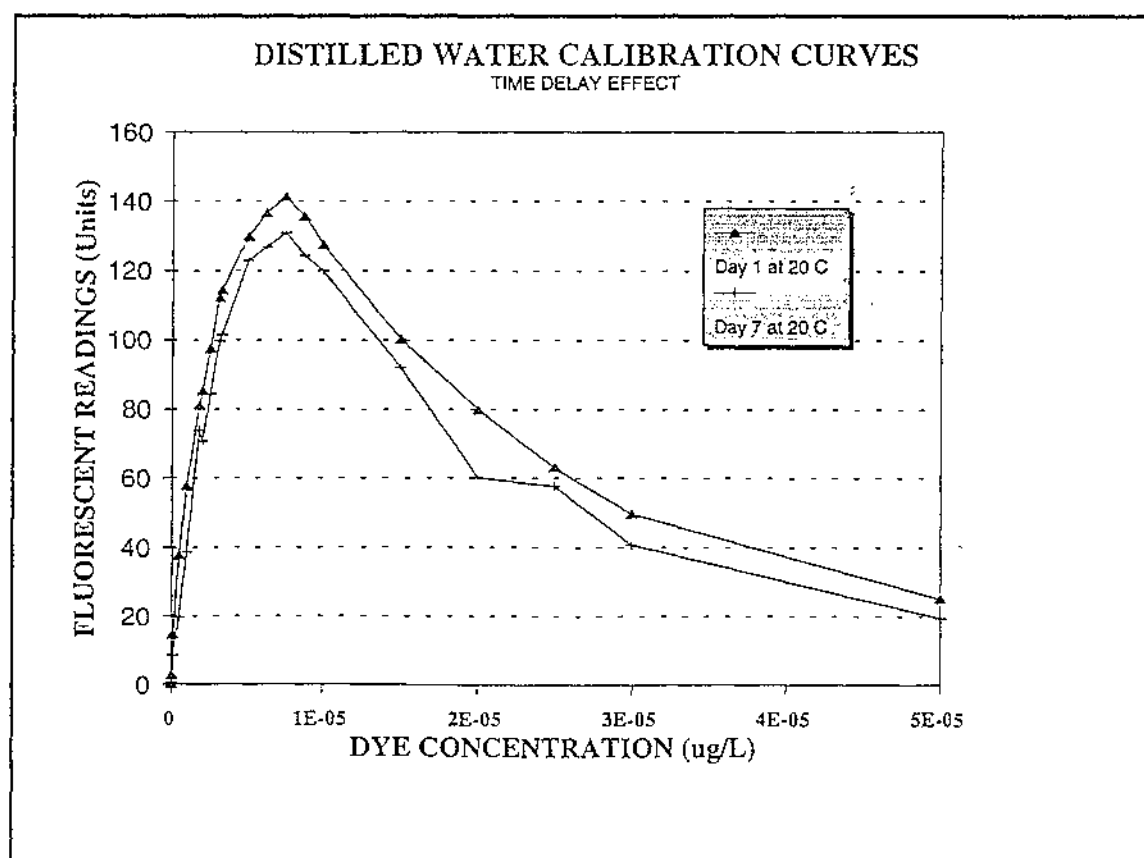


Figure 4.4 Time Delay on Fluorescence

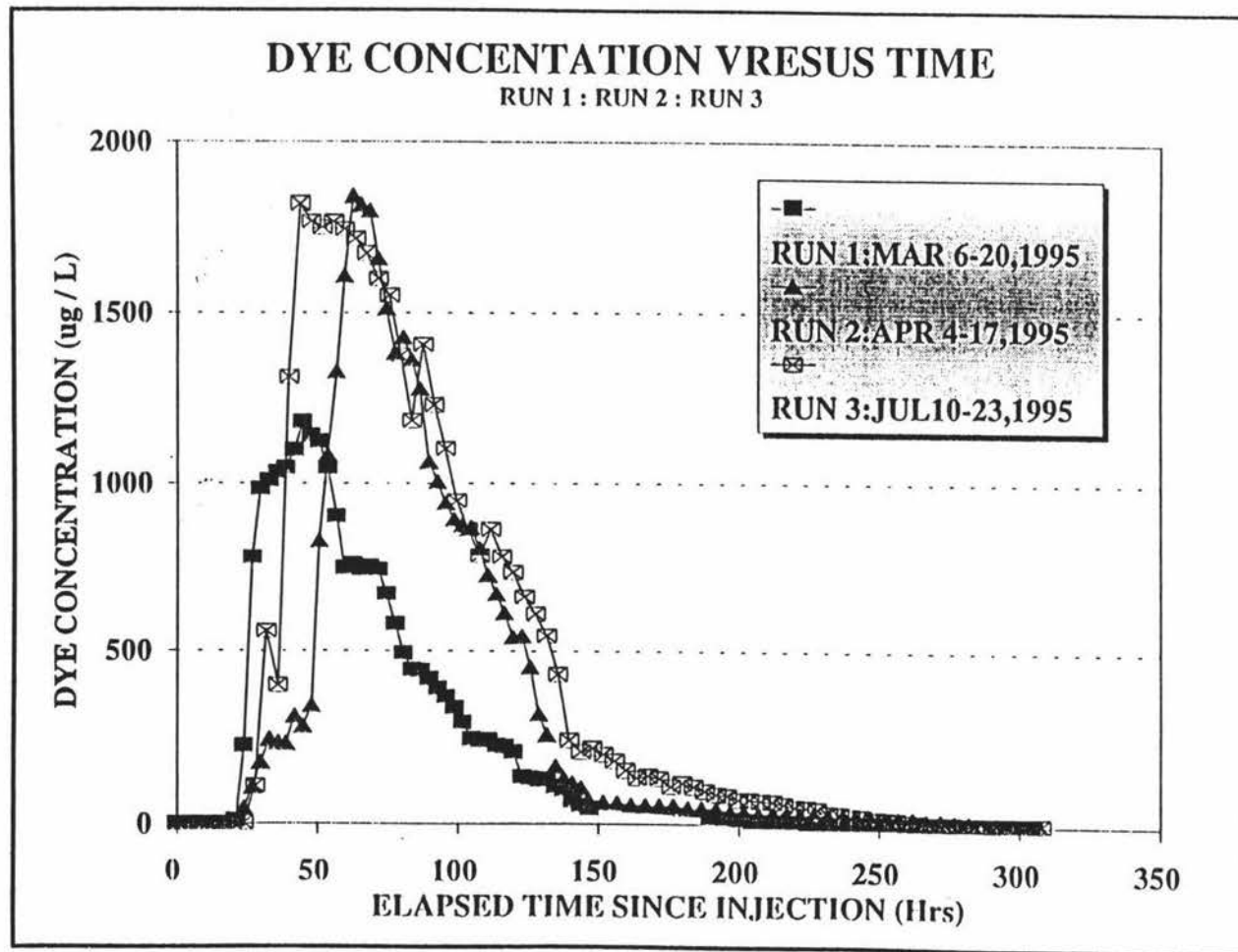


Figure 4.5 Dye Concentration versus Time for the Three Runs

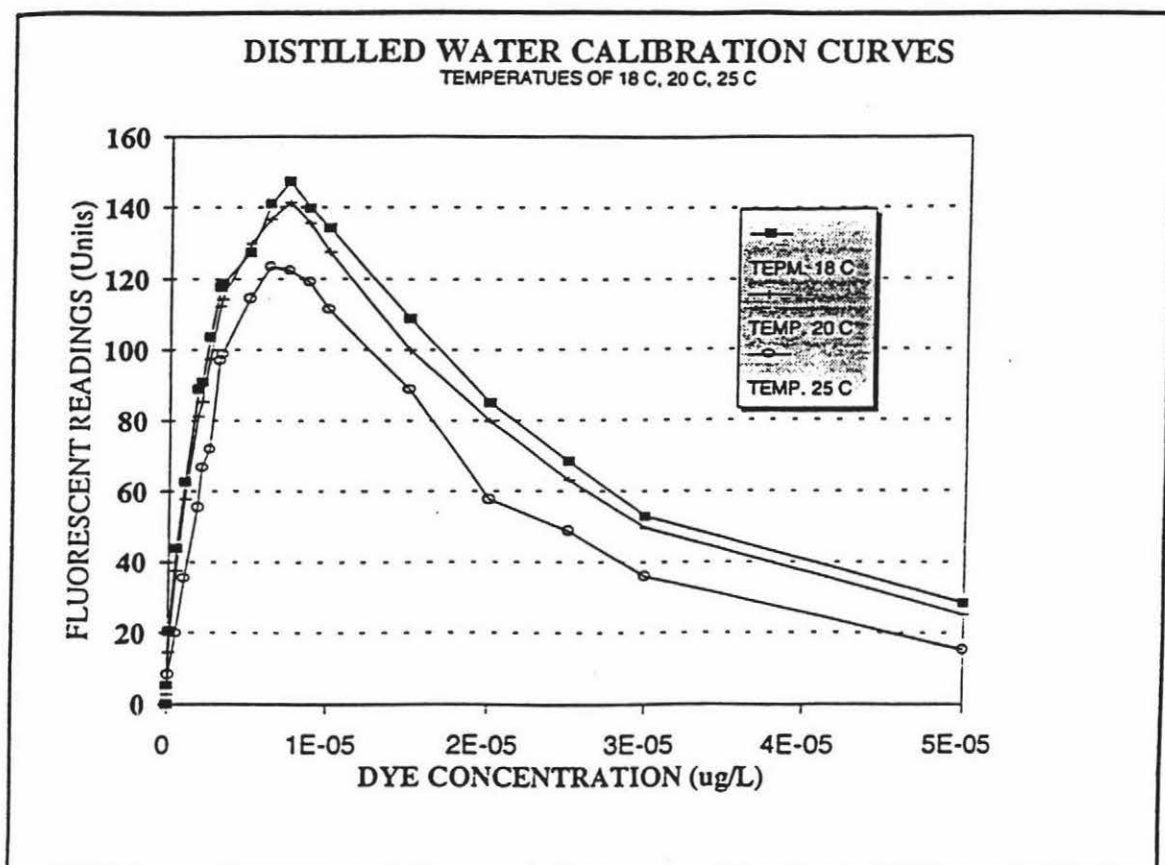


Figure 4.3 Calibration Curves at varying Temperatures

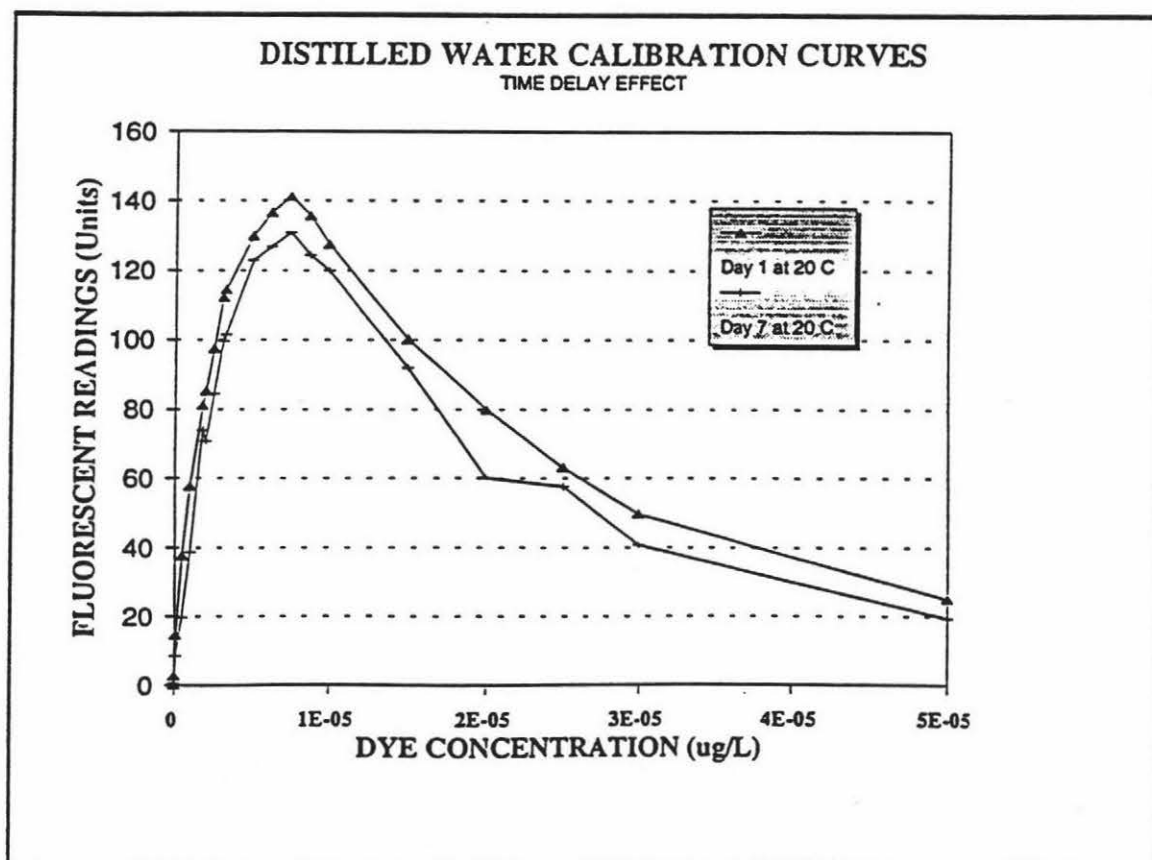


Figure 4.4 Time Delay on Fluorescence

All three runs displayed sharp rise to early peak followed by exponentially falling portion and long-tailing. The early sharp peaks are an indication of short-circuiting within the reactor while the long-tailing indicates some fluid elements being retained by backmixing and adsorption/desorption reactions.

Although the mean retention times of runs 1, 2 and 3 were 2.71, 3.47 and 3.41 days respectively, some tracer remained in the wetland for only 0.88 days while the longest retention time was approximately 14 days. Ideal plug flow in current wetland design process assumes a theoretical retention time that is experienced by all the fluid elements. This implies that the treatment of each fluid element is the same. Clearly, this is not the case as illustrated by the hydraulic residence time distribution shown in figure 4.5 where some portions of the wastewater are under-treated while other portions are overtreated. Given that the mean retention times are shorter than the theoretical, it is clear that the overall treatment achieved would be less than normally predicted. As a number of the treatment mechanisms (including BOD removal) are not linear functions of time, an integration of the treatment over time is needed to determine the actual reduction in treatment efficiency. This is discussed in section 4.4.2.

Data for figure 4.5 is given in appendix E.

4.3 HYDRAULIC RETENTION TIMES

A summary of the retention times from the three trials are given in Table 6 and full graphically represented results of tracer concentration versus hydraulic retention time are shown in figures 4.6-4.8 on the following pages 72-74.

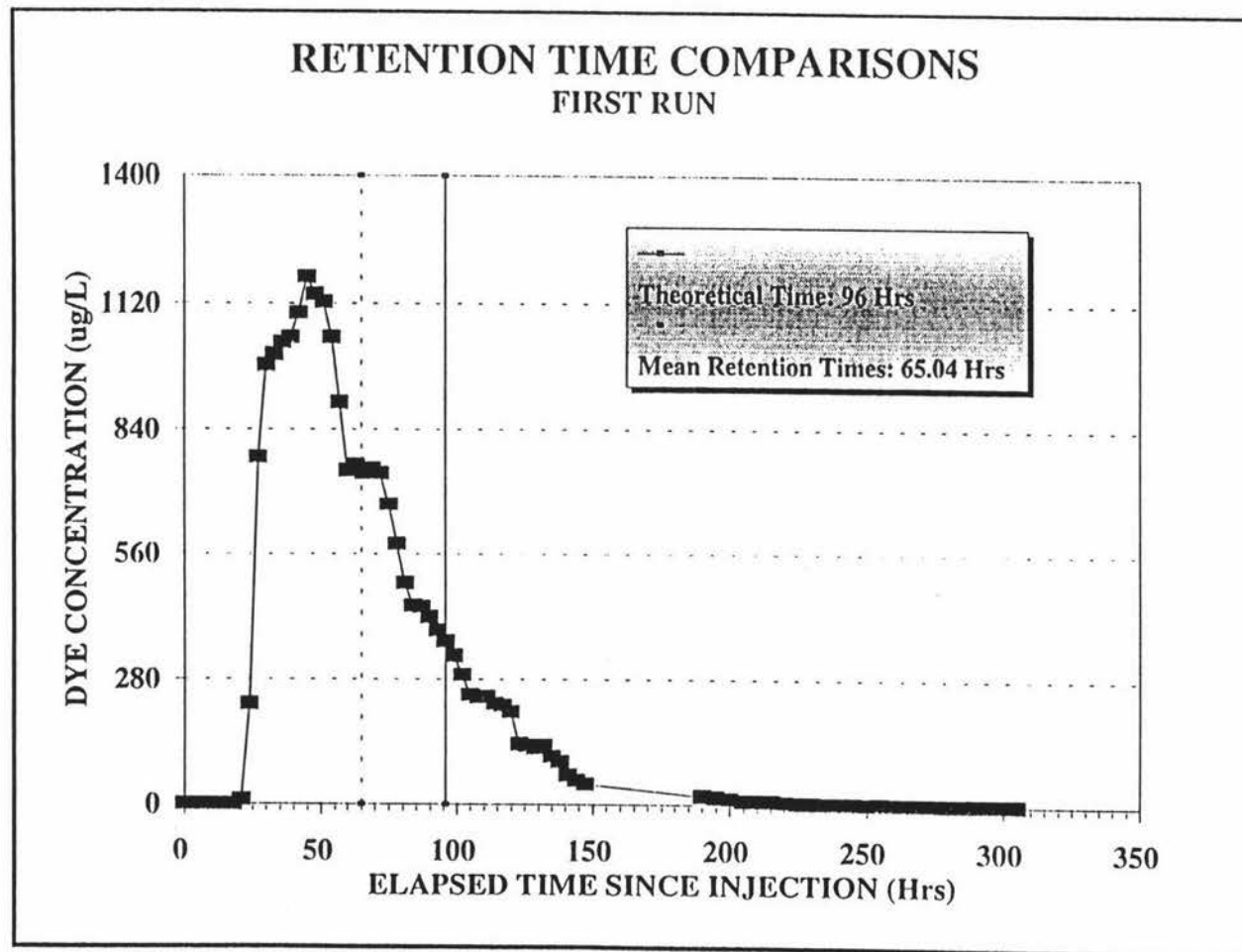


Figure 4.6 Run 1 Retention Time Comparison

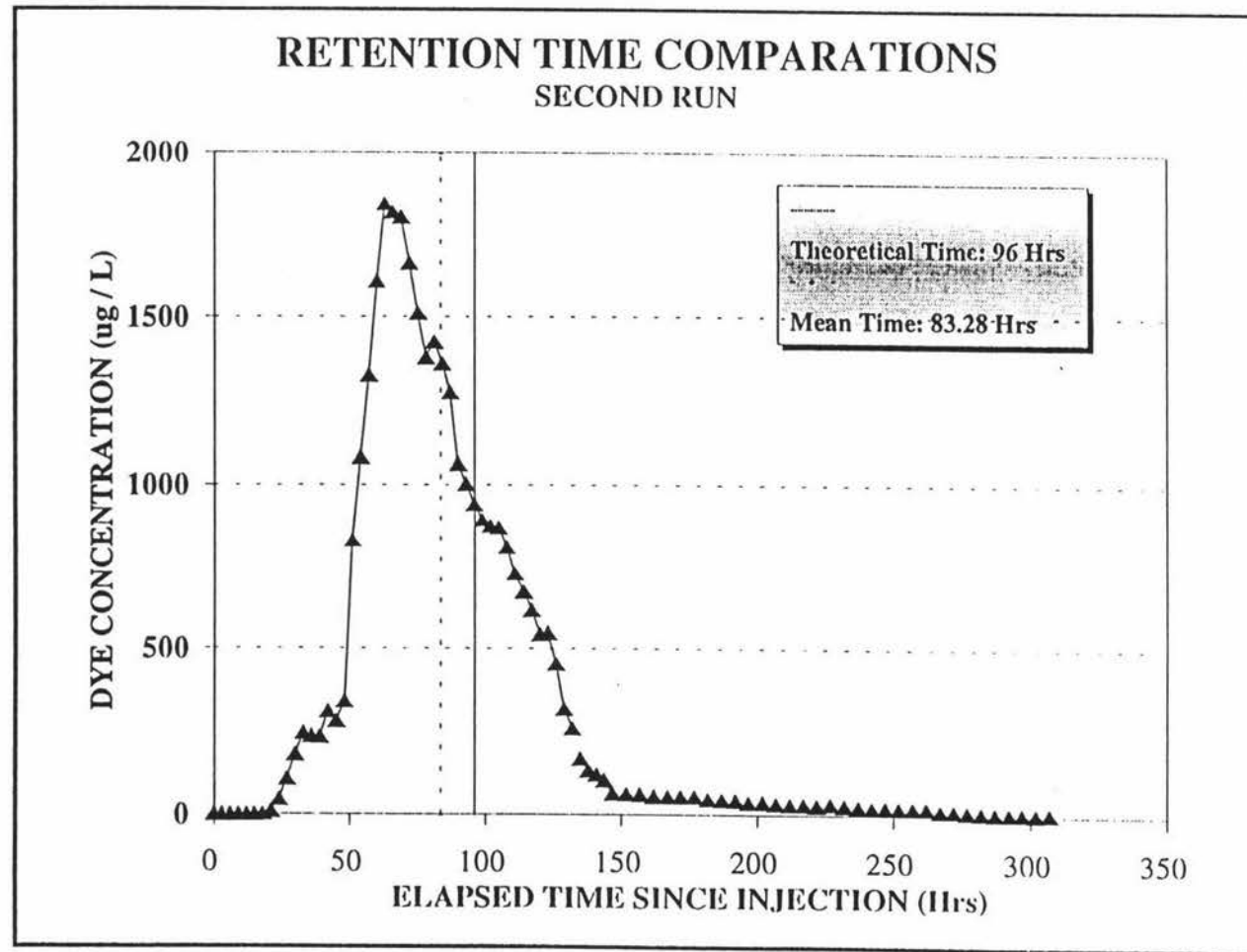


Figure 4.7 Run 2 Retention Time Comparison

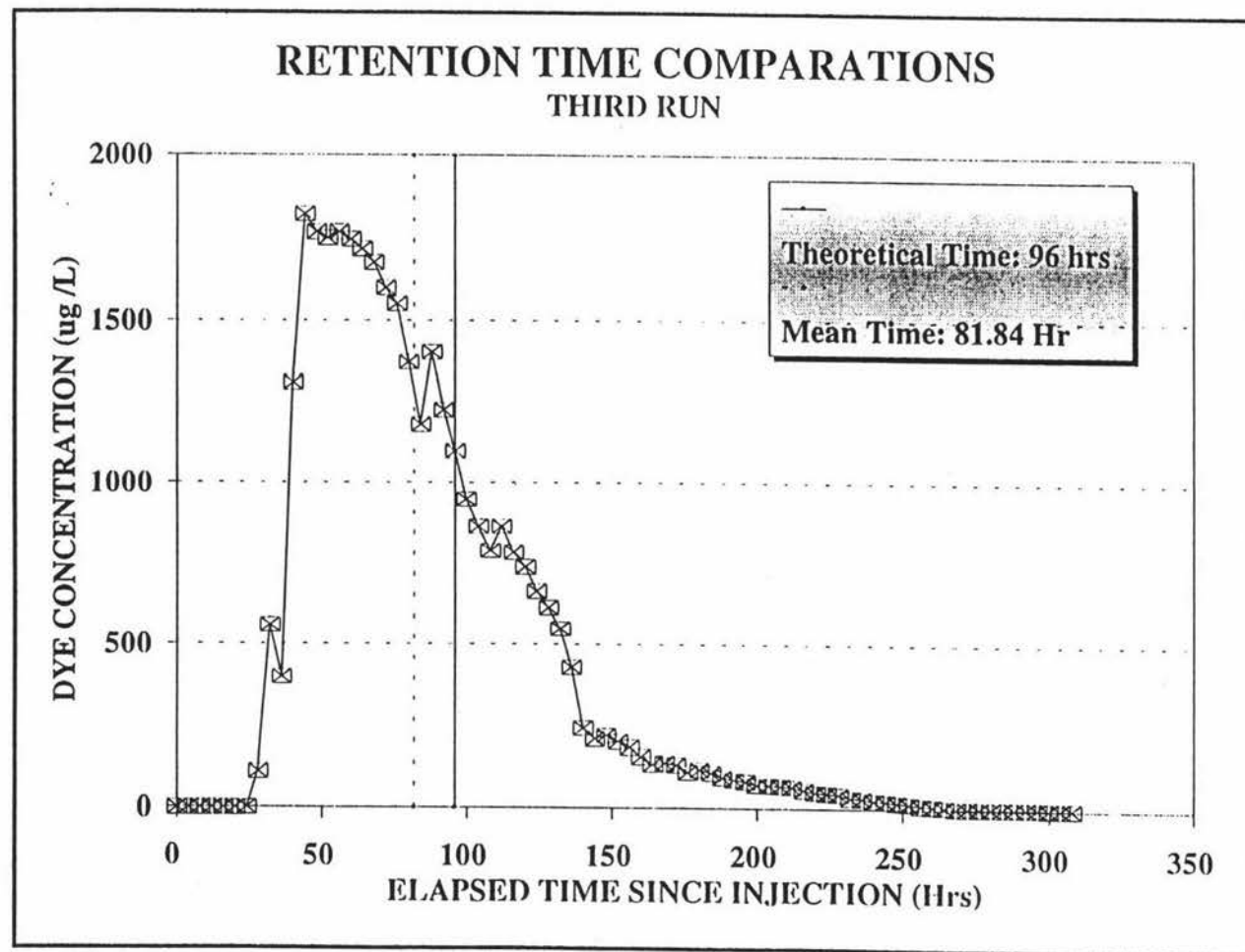


Figure 4.8 Run 3 Retention Time Comparison

Table 6 Summary of Mean Retention Times

Run #	Theoretical (days)	Mean * (days)	Difference %
1	4	2.71	32
2	4	3.47	13
3	4	3.41	15

* refer to Appendix F for data and calculations

The mean retention times of all three runs were 13% to 32% lower than the theoretical hydraulic time. This appears to correspond with other published dye tracer studies of gravel bed wetland that hydraulic retention times of between 75 and 90% of the theoretical retention times (*Fisher, 1990; Pilgrim et al., 1992; Stairs and Moore, 1994*). The implications of the differences in the hydraulic retention times are discussed in sections 4.4.2.

4.3.1 Inlet Flow Distribution

Noticeably, run 1 had the lowest mean retention time in comparison to runs 2 and 3. This can be related to the dye injection technique and the type of flow distribution as discussed in materials and method section. An inlet distribution pipe manifold over the width of the wetland was used for runs 2 and 3 giving mean retention times of 3.47 days and 3.41 days respectively, compared to the theoretical retention time of 4 days. However, run 1 consisting of a single midpoint entry to the front of the wetland without inlet manifolds, consequently demonstrated the lowest mean retention time of 2.71 days.

By using an inlet distribution pipe with manifolds, the potential for uniform flow and contact with the entire volume of the wetland is maximised. The results suggest that the type of flow distribution structure at the inlet can have a significant effect on the flow distribution and hence the treatment efficiency.

4.3.2 Treatment Efficiency

As mentioned earlier in the literature review, a number of key treatment mechanisms are time dependent reactions. For example, it is assumed that BOD reduction follows a first-order reaction. The actual retention time within the system is therefore a critical parameter to the treatment efficiency of the wetland system.

To best illustrate the variation of treatment efficiencies between the three runs and the theoretical case, a hypothetical BOD conversion can be calculated based on the residence time distributions and the first-order kinetic equation given in section 2.4.5. A typical kinetic coefficient, k , of 0.23 days^{-1} and an initial BOD value of 45 mg/L was assumed in the calculation. The resulting treatment efficiency was compared to the value that would have been obtained if using normal plug flow assumption and the theoretical retention time. Since the subsurface flow wetland is a non ideal flow reactor, each fluid elements experience different retention times. To determine the treatment efficiency of a nonideal system, it is necessary to use an integration residence time distribution rather than the mean retention time. To achieve this, tracer information was directly converted using linear process as discussed in the literature review. The example over the page was followed to obtain the results summarised in Table 7.

Example:

The concentration readings in Table E1 was obtained using an instantaneous pulse injection into a subsurface flow wetland.

Table E1

Time t , min	Tracer output Concentration, C gm/L
0	0
5	3
10	5
15	5
20	4
25	2
30	1
36	0

1. Draw the E-curve

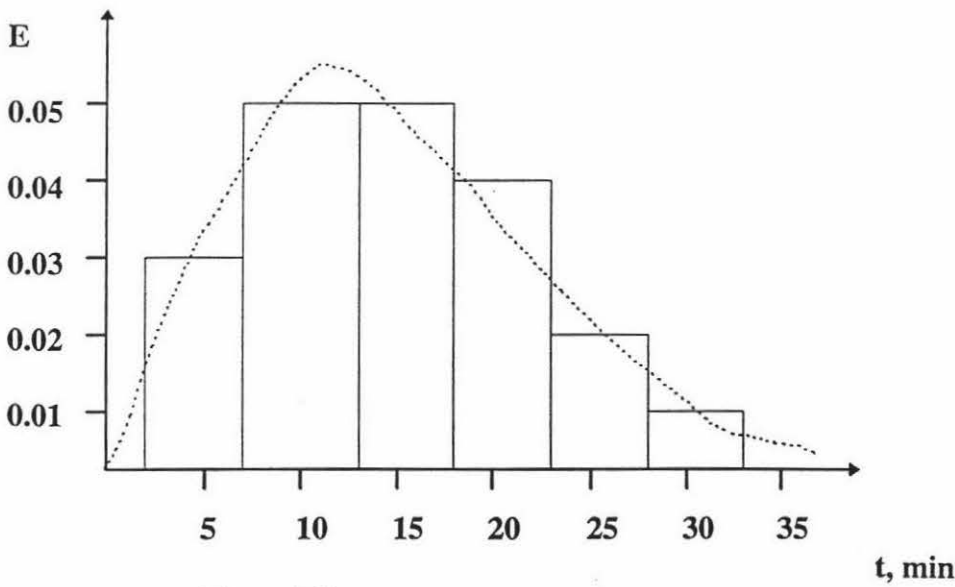


Figure E1

To find E , the area under this curve must be equal to unity: that is, the concentration reading must each be divided by Q , giving:

$E = C / Q$ Where $Q = \Sigma C \Delta t$
 $= (3+5+5+ 4+2+1) 5$
 $= 100 \text{ gm.min/L}$

Thus we have

t, min	0	5	10	15	20	25	30
E, L/min	0	0.03	0.05	0.05	0.04	0.02	0.01

Figure E1 is a plot of this distribution.

2. Find the fraction of reactant unconverted in the wetland.

The fraction unconverted , given by :

$C_e / C_o = e^{-kt}$

and is found as shown in Table E2.

Table E2

t	E	kt	e^{-kt}	$e^{-kt} E \Delta t$
5	0.03	1.53	0.2154	0.0323
10	0.05	3.07	0.0464	0.0116
15	0.05	4.60	0.0100	0.0025
20	0.04	6.14	0.0021	0.0004
25	0.02	7.68	0.0005	0.0001
30	0.01	9.21	0.0001	0
				$\Sigma = 0.0469$

The fraction of reactant unconverted in the wetland, C_e / C_o , equals 4.7 %. Assuming an initial effluent concentration, C_o , the final effluent concentration, C_e , can be found.

Table 7 Treatment Efficiency Comparison (assuming $k = 0.23\text{ d}^{-1}$ and initial BOD = 45 mg/L)

	Factor of Reactant Unconverted $C_e/C_o = C_A/C_{AO}$	Effluent Concentration C_e (mg/L)	% Treatment efficiency	% Actual Treatment Efficiency compared to Plug Flow
Wetland				
Run 1	0.55	24.8	45	73
Run 2	0.46	20.7	54	87
Run 3	0.47	21.2	53	85
Plug Flow	0.40	18	60	

- refer to appendix G for calculations

The fraction of reactant unconverted in the wetland ranges from 46% to 55%. This resulted in actual treatment efficiency of only 73% to 87% of what would have been predicted using the theoretical retention time in the plug flow equation.

From appendix G, it is evident that the majority of this unconverted material comes from the early portion of the E-curve. This is due to the early arrival of the dye tracer indicated by sharp rises to early peaks by all three runs. As discussed in section 4.3, this illustrates that channelling and short-circuiting significantly reduces pollutant treatment in wetlands. If the basis of the example wetland system design was to have obtained a desired effluent concentration, C_e , then the actual residence times from the three runs would have yielded significantly higher C_e values than calculated using the theoretical retention time. This means that the effluent discharge would have had water quality concentrations significantly higher than designed for, effectively resulting in a design failure.

The use of the theoretical retention time in the plug flow equation in current wetland design process ignores this reduction in treatment efficiency which compromises the effectiveness and reliability of wetland treatment systems.

4.4 DEAD VOLUME

Dead space was calculated by considering the volume of a reactor that would produce a mean retention time obtained from the analysis of the tracer concentration versus time graphs. The resultant reduced and dead volumes in Table 8 was obtained by subtracting this quantity from the actual reactor volume.

Table 8 Effective volume and dead space of the wetland

Run #	Actual volume without porosity, m ³	Mean retention time, days	Flow-rate, m ³ / day	Effective volume, m ³	Dead space %	Media porosity	Effective porosity
1	83.74	2.71	9.05	25.34	69	0.43	0.30
2	83.74	3.47	9.05	31.86	62	0.43	0.38
3	83.74	3.41	9.05	32.58	61	0.43	0.39

The dead space percentage represents the percentage of the wetland volume occupied by the media and hydraulic dead space (stagnant regions). By comparing the effective and the media porosities in Table 8, a large portion of dead space can be attributed to the volume obtained using the media porosity. Some dead space will also exist from the

concentration of plant roots in the media pores and the wetland media above the level of the hydraulic profile. However, the extent of dead space depends on the hydraulic features of the system being studied.

4.5 DISPERSION NUMBER

Deviation from plug flow can be interpreted by the extent of the longitudinal dispersion. In a wetland, large dispersion is undesirable in terms of effectiveness in treating wastewater, as it implies a large variation in contact time of the wastewater and the plant root mass and supporting media. The extent of longitudinal dispersion is measured by the dispersion number, D/uL . A summary of the dispersion number from the three runs are given in Table 9.

Table 9 Dispersion Number and Coefficient

Run #	Dispersion No. (D / uL)	Average Velocity of Wastewater, u (m / s)	Length, L (m)	Dispersion coefficient, D (m^2 / s)
1	0.115	$9.09 \text{ e-}4$	22	$1.09 \text{ e-}6$
2	0.055	$7.34 \text{ e-}4$	22	$4.04 \text{ e-}6$
3	0.085	$7.47 \text{ e-}4$	22	$6.35 \text{ e-}6$

- refer to Appendix H for calculations

As mentioned, design manuals often assume wetland as ideal plug flow reactors and that the reactor has negligible dispersion, that is, $D/uL = 0$. These assumptions are invalid for wetlands as it is clearly a non-ideal reactor and there will always be a certain degree of dispersion present in this system. The distribution of the effluent is governed by two

types of flow; connective and diffusion. If the flow is connective, spread of material is mainly a result of velocity gradients, whereas if a flow is due to diffusion, spread of material results mainly from molecular properties as governed by the Fick’s Law.

Pure convective flow occurs if the flow path is so short as to prohibit the effects of molecular diffusion from being significant. If the flow path is very long diffusion distorts the velocity profile. It is likely that the flow regime of the subsurface flow wetland falls between the two extremes. However, this does not imply that the only deviation from plug flow is solely due to diffusion. Backmixing and adsorption/desorption reactions could in fact be more likely to cause this deviation from plug flow.

4.6 DYE RECOVERY

The mass of dye recovered from each run was calculated by integrating the normalised residence time distribution curves. Dye recovery percentage of runs 1, 2 and 3 are summarised in Table 10 with noticeably reduced dye recoveries for all three runs.

Lower dye recovery in run 1 of 38% could be attributed to dye adsorption onto the wetland media. This is demonstrated by increased dye recoveries in run 2 of 56% while replicate run 3 was reasonably good at 77%.

Table 10 Dye Tracer Recovery

RUN #	DYE % RECOVERED
1	38
2	56
3	77

- Refer to appendix I for calculations

Lower peak of the residence time distribution of run 1 (figure 4.5) may be due to the initial adsorption onto the wetland media. This implies that the effect on treatment could be worse as first lot of dye is absorbed. Due to this initial dye adsorption, dye recovery from run 2 is assumed to be okay even though only 56% of the dye was recovered.

The current assumption that a wetland can be approximated as an ideal plug flow reactor, implies that there are no adsorption/desorption reactions, backmixing or short-circuiting within the reactor. This would assume that the exact amount of the dye tracer injected would subsequently be recovered.

4.7 MODELS

In approximating the models, the residence time distributions of runs 2 and 3 were normalised so that the area under the curves were equal to unity and fit with the dispersed plug-flow equation:

$$E_{t_o} = \frac{u}{\sqrt{4\pi Dt}} \exp \left[-\frac{(L - ut)^2}{4Dt} \right]$$

and the tank-in-series equation:

$$E_{\theta} = (N\bar{t}_i)^{-1} E = \frac{N(N\theta)^{N-1}}{(N-1)!} e^{-N\theta}$$

Levenspeil (1972), in approximating models for non-ideal flow reactors, also assumes that all the dye is recovered and that the area under the E-curve is equal to unity

Therefore, the models obtained using the equations given by Levenspeil (1972), can not truly reflect what is actually happening within a subsurface flow wetland.

The above equations used to approximate the models are based on the assumption that no stagnant regions or any adsorption/sorption reactions are present within the reactor. Implying that all of the dye tracer injected into the reactor is recovered. In reality, no constructed reactor is an ideal one and that there will always be some percentage of dye losses within a reactor.

The actual residence time distribution of the three runs were matched up the theoretical distributions obtained by using the equations mentioned previously. Although the models can be fitted to the data, as was done here by equating the area under the normalised curve to unity, the fundamental assumptions in the model do not conform to what is intuitively occurring in the system. A better approximation of the models is given by Wakao (1990), however, a thorough analysis of these models are considered outside the scope of this research.

It is clear that the subsurface flow wetland is not a plug flow reactor and a better model for the wetland system suggested by the shape of the residence time distribution might be a combination of the dispersed plug flow reactor and eight to nine completely mixed tank-in-series. The models are summarised in figure 4.9 and calculations are shown in appendix K.

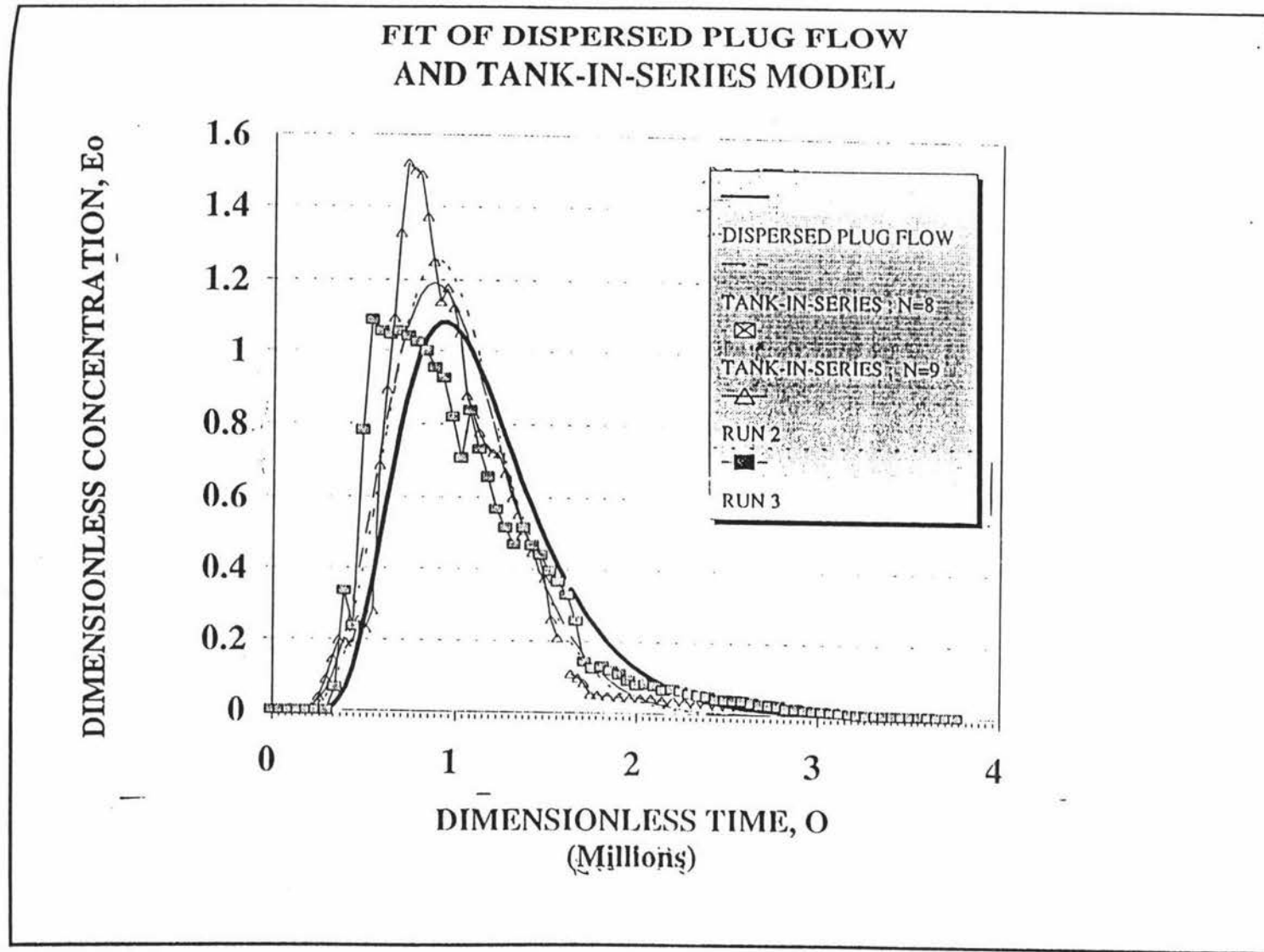


Figure 4.9 Fit of the Dispersed Plug Flow and Tank-in-series Models to tracer study data for the Three Run

CHAPTER 5

CONCLUSION

Tracer studies were undertaken to determine the actual hydraulic residence time distributions in a wetland wastewater treatment system.

All three tracer runs displayed a sharp rise to early peak, followed by an exponential decrease with a long tail. In evaluating the plots of dye concentration versus time graphs, it was clear that the wastewater experiences a distribution in residence time that deviates significantly from the plug flow assumption used in most design manuals.

Actual mean residence times of the subsurface flow wetland for runs one (that had a single point injection) was 2.71 days. Tracer runs two and three (which had the influent distributed across the inlet to the wetland) had mean retention times of 3.47 days and 3.41 days respectively. These values were significantly less than the theoretical retention time of four days. The actual mean retention times were 13 % to 32 % lower than the theoretical retention time. In the use of the theoretical retention time, current wetland design process ignores this reduction.

By using an inlet distribution pipe with manifolds, the potential for uniform flow and contact with the entire volume of the wetland is maximised. The actual mean retention times given above suggest that the type of flow distribution structure at the inlet can have a significant effect on the hydraulics and hence the treatment efficiency.

The distribution of the residence time combined with the non-linear reduction of parameters such as BOD following first order kinetics results in calculation of treatment efficiencies less than those predicted using the theoretical retention time in the plug flow equation.

Two chemical engineering models; dispersed plug-flow and tank-in-series, were fitted against the field data. Model for the subsurface flow wetland suggested by the shape of the residence time distribution could include a combination of the dispersed plug-flow model and $N = 8$ to $N = 9$ tank-in-series.

Clearly, the use of the theoretical retention time in the plug flow equation has the potential to compromise the treatment efficiency of wetlands. This area of wetland hydraulics deserve further consideration in future research.

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APPENDIX A

Data for Distilled Water Calibration Curve

Fluorometer Reading (Y) units	Dye Conc. (X) ug/L	Log (x)	Log of (Y)	Reg Value
0	230000	5.361728	ERR	
8.4	23000	4.361728	0.9242792861	
25.1	11500	4.060698	1.3996737215	
49.8	6900	3.838849	1.6972293428	
63.2	5750	3.759668	1.8007170783	
79.9	4600	3.662758	1.9025467793	
100.1	3450	3.537819	2.0004340775	
127.6	2300	3.361728	2.1058506744	
135.7	2012.5	3.303736	2.1325798477	
141.3	1725	3.236789	2.1501421618	
136.8	1437.5	3.157608	2.1360860974	
130.1	1150	3.060698	2.1142772966	2.23785516
114.4	747.5	2.873611	2.0584260245	2.10564103
112.3	717.6	2.855882	2.0503797563	2.09311211
97.5	575	2.759668	1.9890046157	2.02511727
85.4	460	2.662758	1.9314578707	1.95663096
81.2	402.5	2.604766	1.9095560292	1.91564805
57.9	230	2.361728	1.7626785637	1.74389306
37.7	115	2.060698	1.5763413502	1.53115516
14.5	23	1.361728	1.1613680022	1.03719306
2.8	2.3	0.361728	0.4471580313	0.33049306
0.3	0.23	-0.63827	-0.522878745	-0.3762069

Regression Output:	
Constant	0.07486022
Std Err of Y Est	0.08585422
R Squared	0.9910073
No. of Observations	10
Degrees of Freedom	8
X Coefficient(s)	0.7067421738
Std Err of Coef.	0.0238024979

APPENDIX A

CALIBRATION

1 gram of powder dissolved into 1 billion ml of distilled water

$$= 1 \text{ ppb}$$

$$= 1 \mu\text{g} / \text{L}$$

1 ml of Rhodamine WT solution dissolved into 1 billion ml of distilled water

$$= \frac{1 \text{ ml} * 0.2 \text{ g per g} * 1.15}{1 \times 10^{-9}}$$

$$= 0.23 \mu\text{g} / \text{L}$$

Rhodamine Wt solution : 20% by weight, specific gravity of 1.15

therefore initial concentration of Rhodamine Wt (C_A)

$$= 0.2 \text{ g} / \text{ml} * 1.15$$

$$= 200 \text{ g} / \text{L} * 1.15$$

$$= 230 \text{ g} / \text{L}$$

$$= 230 \times 10^6 \mu\text{g} / \text{L}$$

$$= 2.3 \times 10^8 \text{ ppb}$$

DILUTION

From page 22 of Wilson Jr., 1986.

$$1. C_A = 2.3 \times 10^8 \text{ ppb}$$

$$\begin{aligned}
 2, C_B &= C_A * \frac{10 \text{ ml sol. A}}{1000 \text{ ml sol. B}} \\
 &= \frac{2.3 \times 10^8}{10^9} * \frac{10 \text{ ml}}{1000 \text{ ml}} \\
 &= 2.3 \times 10^6 \text{ ppb}
 \end{aligned}$$

3. The other concentrations can be found by using the equation given below

The above calculations uses the following equation :

$$C_f = C_i V_i / V_f$$

where $V_f = V_i + V_a$

and V_a = distilled water volume

C_i = Initial concentration

V_i = initial volume

C_f = final concentration

APPENDIX B

Data for Effluent Calibration Curve

Fluorometer Reading (Y) units	Dye Conc. (X) ug/L	Log of (X)	LOG(Y)	REG VALUES
29.4	2300	3.361727836	1.46834733	
86	1150	3.06069784	1.93449845	
90.4	1092.5	3.038421446	1.95616843	
93.5	1035	3.01494035	1.97081161	
98.2	977.5	2.990116766	1.99211149	
100.6	920	2.963787827	2.00259798	
101.2	862.5	2.935759104	2.00518051	
102	805	2.90579588	2.00860017	
100	747.5	2.873611197	2	
98.2	690	2.838849091	1.99211149	
94.9	632.5	2.80106053	1.97726621	
91	575	2.759667845	1.95904139	1.866632301189
86.7	517.5	2.713910354	1.9380191	1.836923289536
81.2	460	2.662757832	1.90955603	1.803711440134
74.2	402.5	2.604765885	1.87040391	1.766058950728
67.6	345	2.537819095	1.8299467	1.722592341677
59.8	287.5	2.458637849	1.77670118	1.671182254875
52.1	230	2.361727836	1.71683772	1.608261393819
41.3	172.5	2.236789099	1.61595005	1.527142295363
30.1	115	2.06069784	1.4785665	1.412811347504
26.5	103.5	2.01494035	1.42324587	1.38310233585
25	92	1.963787827	1.39794001	1.349890486448
22.6	80.5	1.90579588	1.35410844	1.312237997042
19.9	69	1.838849091	1.29885308	1.268771387992
17.6	57.5	1.759667845	1.24551267	1.217361301189
16.6	51.75	1.713910354	1.22010809	1.187652289536
15.2	46	1.662757832	1.18184359	1.154440440134
13.7	40.25	1.604765885	1.13672057	1.116787950728
12.5	34.5	1.537819095	1.09691001	1.073321341677
10.9	28.75	1.458637849	1.0374265	1.021911254875
8.5	23	1.361727836	0.92941893	0.958990393819
5	11.5	1.06069784	0.69897	0.763540347504
3.3	5.75	0.759667845	0.51851394	0.568090301189
1.7	2.3	0.361727836	0.23044892	0.309719393819
0.3	0.23	-0.63827216	-0.5228787	-0.33955160618

Regression Output:	
Constant	0.074249599641
Std Err of Y Est	0.15724246291
R Squared	0.930538391961
No. of Observations	35
Degrees of Freedom	33
X Coefficient(s)	0.64927076
Std Err of Coef.	0.03087978

APPENDIX C

TEMPERATURE AND TIME DELAYEFFECT

DATA FOR FIGURE 4.3 and FIGURE 4.4

DYE CONC. ug/L	FLUORO. READING at temp. 20 C(Units)	FLUORO. READING at Temp. 25 C(Units)	FLUORO. READING at Temp. 18 C(Units)	FLUORO. READING After 7 Days at 20 C
230000	0	0	0	0
23000	8.4	2.3	9.2	5.2
11500	25.1	15.4	28.4	19.4
6900	49.8	36.1	53.1	40.8
5750	63.2	48.9	68.5	57.7
4600	79.9	57.7	85	60.1
3450	100.1	88.9	108.9	92
2300	127.6	111.3	134.2	119.9
2012.5	135.7	119.2	139.9	124.3
1725	141.3	122.5	147.3	131
1437.5	136.8	123.6	141.1	126.8
1150	130.1	114.7	127.5	123
747.5	114.4	98.8	118.8	101.4
717.6	112.3	97.1	117.7	99.7
575	97.5	72	103.8	84.4
460	85.4	66.9	91	70.9
402.5	81.2	55.5	88.9	74
230	57.9	35.4	62.7	38.7
115	37.7	20	44	19.6
23	14.5	8.4	20.5	8.5
2.3	2.8	1.2	5.3	0.6
0.23	0.3	0.1	0.5	0

APPENDIX D

FLOW- RATE AND DYE VOLUME CALCULATIONS

FLOW-RATE, Q

The wetland consist of three media :

1. large gravel at the inlet and outlet (8 mm ϕ)
2. small sandy gravel in the middle section (2 mm ϕ)
3. medium sand on the bottom of the wetland (1 mm ϕ)

Their volumes are 6.89, 66.49, 10.36 m³ respectively

Their volume with porosity were calculated as follows :

Large gravel

$$\begin{aligned} nV &= 0.47 * 6.89 \\ &= 3.24 \text{ m}^3 \end{aligned} \quad \text{where porosity, } n = 0.47$$

Sandy gravel

$$\begin{aligned} nV &= 0.43 * 66.49 \\ &= 28.59 \text{ m}^3 \end{aligned} \quad \text{where } n = 0.43$$

Medium sand

$$\begin{aligned} nV &= 0.42 * 10.36 \\ &= 4.35 \text{ m}^3 \end{aligned} \quad \text{where } n = 0.42$$

Total volume, $V_T = 36.18 \text{ m}^3$

Using the equation :

$$\text{HRT (days)} = nV / Q$$

$$= V_T / Q$$

$$Q = 36.18 \text{ m}^3 / 4 \text{ days}$$

$$= 9.05 \text{ m}^3 / \text{day}$$

$$= 6.28 \text{ L} / \text{minute}$$

Where HRT = theoretical retention time
of 4 days

DYE VOLUME

Maximum detectable concentration of Rhodamine WT dye tracer is $805 \mu\text{g} / \text{L}$

Using equation :

$$C_o = M_d / V_R$$

Where C_o = initial concentration

M_d = mass of dye added

V_R = volume of the reactor

$$M_d = 805 \mu\text{g} / \text{L} * 36.18 \times 10^3 \text{ L}$$

Since 1 ml of Rhodamine = $0.23 \mu\text{g} / \text{L}$. **Dye Tracer volume $\approx 130 \text{ ml}$**

APPENDIX E

FIRST RUN DATA
INJECTION TIME : 12.26 pm
DURATION TIME : 50 MINUTES
DILUTION FACTOR : 1:2
DYE VOLUME = 300 ml

A	B	C	D	E		G	H	I
DATE	TIME	HOURS	BOTTLE	FLUORO	LOG OF	LOG OF CONC	CONC.	CONC. x2
				READING (Y)	READINGS(Y)	(X)	ug / L	ug / L
MARCH 6	12.26	0	0	0	0	0	0	0
	15.26	3	1	0	0	0	0	0
	18.26	6	2	0		0	0	0
MARCH 7	21.26	9	3	0	0	0	0	0
	0.26	12	4	0	0	0	0	0
	3.26	15	5	0	0	0	0	0
	6.26	18	6	0	0	0	0	0
	9.26	21	7	3.5	0.5441	0.724	5.29	10.59
MARCH 8	12.26	24	8	25.4	1.4048	2.049	112.05	224.11
	15.26	27	9	57	1.7559	2.590	389.14	778.27
	18.26	30	10	66.4	1.8222	2.692	492.27	984.54
	21.26	33	11	67.4	1.8287	2.702	503.74	1007.47
	0.26	36	12	68.5	1.8357	2.713	516.45	1032.91
	3.26	39	13	69	1.8388	2.718	522.27	1044.55
	6.26	42	14	71.3	1.8531	2.740	549.33	1098.65
	9.26	45	15	74.6	1.8727	2.770	588.97	1177.94
	12.26	48	16	73	1.8633	2.756	569.63	1139.26
	15.26	51	17	72.3	1.8591	2.749	561.24	1122.47
MARCH 9	18.26	54	18	69	1.8388	2.718	522.27	1044.55
	21.26	57	19	62.7	1.7973	2.654	450.66	901.33
	0.26	60	20	55.6	1.7451	2.573	374.51	749.03
	3.26	63	21	56.2	1.7497	2.581	380.76	761.51
	6.26	66	22	55.3	1.7427	2.570	371.41	742.81
	9.26	69	23	55.8	1.7466	2.576	376.59	753.18
	12.26	72	24	55.3	1.7427	2.570	371.41	742.81
	15.26	75	0	51.8	1.7143	2.526	335.83	671.65
	18.26	78	1	47.2	1.6739	2.464	291.01	582.02
	21.26	81	2	42.4	1.6274	2.392	246.70	493.40
MARCH 10	0.26	84	3	39.6	1.5977	2.346	222.06	444.12
	3.26	87	4	39.4	1.5955	2.343	220.34	440.67
	6.26	90	5	38.1	1.5809	2.321	209.24	418.48
	9.26	93	6	36.4	1.5611	2.290	195.04	390.07
	12.26	96	7	34.9	1.5428	2.262	182.79	365.59
	15.26	99	8	32.9	1.5172	2.222	166.91	333.83
	18.26	102	9	30	1.4771	2.161	144.80	289.60
	21.26	105	10	26.9	1.4298	2.088	122.41	244.82
	0.26	108	11	26.5	1.4232	2.078	119.62	239.23
	3.26	111	12	26.6	1.4249	2.080	120.31	240.62
MARCH 11	6.26	114	13	25.5	1.4065	2.052	112.73	225.47
	9.26	117	14	25.2	1.4014	2.044	110.70	221.40
	12.26	120	15	24.1	1.3820	2.014	103.34	206.69
	15.26	123	16	18.3	1.2625	1.830	67.63	135.26
	18.26	126	17	18	1.2553	1.819	65.93	131.86
	21.26	129	18	17.5	1.2430	1.800	63.13	126.26

MARCH 12	0.26	132	19	17.9	1.2529	1.815	65.37	130.73
	3.26	135	20	15.8	1.1987	1.732	53.94	107.87
	6.26	138	21	14.7	1.1673	1.684	48.26	96.52
	9.26	141	22	11.5	1.0607	1.519	33.07	66.13
	12.26	144	23	10.2	1.0086	1.439	27.49	54.98
MARCH 15	15.26	147	24	9.1	0.9590	1.363	23.06	46.12
	10.26	190	1	5.3	0.7243	1.001	10.03	20.06
	15.26	195	2	4.8	0.6812	0.935	8.61	17.22
	20.26	200	3	4.3	0.6335	0.861	7.27	14.53
MARCH 16	1.26	205	4	3.2	0.5051	0.664	4.61	9.22
	6.26	210	5	3.1	0.4914	0.643	4.39	8.78
	11.26	215	6	3.1	0.4914	0.643	4.39	8.78
	16.26	220	7	2.7	0.4314	0.550	3.55	7.10
MARCH 17	21.26	225	8	2.2	0.3424	0.413	2.59	5.18
	2.26	230	9	2.1	0.3222	0.382	2.41	4.82
	7.26	235	10	1.8	0.2553	0.279	1.90	3.80
	12.26	240	11	1.9	0.2788	0.315	2.07	4.13
	17.26	245	12	1.6	0.2041	0.200	1.59	3.17
MARCH 18	22.26	250	13	1.5	0.1761	0.157	1.44	2.87
	3.36	255	14	1.6	0.2041	0.200	1.59	3.17
	8.26	260	15	1.3	0.1139	0.061	1.15	2.30
	13.26	265	16	1.3	0.1139	0.061	1.15	2.30
	18.26	270	17	1.4	0.1461	0.111	1.29	2.58
MARCH 19	23.26	275	18	1.3	0.1139	0.061	1.15	2.30
	4.26	280	19	1.2	0.0792	0.008	1.02	2.04
	9.26	285	20	1.1	0.0414	-0.051	0.89	1.78
	14.26	290	21	0.9	-0.0458	-0.185	0.65	1.31
	19.26	295	22	1	0.0000	-0.114	0.77	1.54
MARCH 20	0.26	300	23	1	0.0000	-0.114	0.77	1.54
	5.26	305	24	0.9	-0.0458	-0.185	0.65	1.31

Column E : the dye sample was diluted by a ratio of 1;2
This readings were than obtained using a fluorometer

Column G : X can be found : $x = (Y - 0.0742)/0.64927$

Column H : X = concentration of dye tracer. This is found by taking inverse log X
Refer to the effluent calibration curve for clarity

Column i : since the dilution rate is 1:2, the true concentration twice that of column H

APPENDIX E

SECOND RUN

Start Date: April 4, 1995

Injection Time: 12.00 pm

Duration of Injection: 30 minutes

Dye Volume: 300 ml

Dilution Ratio: 1/2

DATE	TIME	ELAPSED TIME(HRS)	BOTTLES	FLUORO. READINGS (Y)	Log of Y	Log of X	Dye Conc. ug/L
APRIL 4	12.00	0	0	0.0			0
	15.00	3	0	0.0			0
	18.00	6	0	0.0			0
	21.00	9	0	0.0			0
	24.00	12	0	0.0			0
APRIL 5	3.00	15	0	0.0			0
	6.00	18	1	0.0	0.00	-0.1143	0.77
	9.00	21	2	3.4	0.53	0.7043	5.06
	12.00	24	3	9.1	0.96	1.3628	23.06
	15.00	27	4	15.6	1.19	1.7234	52.89
APRIL 6	18.00	30	5	21.8	1.34	1.9472	88.55
	21.00	33	6	26.7	1.43	2.0828	121.01
	24.00	36	7	26.0	1.41	2.0650	116.16
	3.00	39	8	25.9	1.41	2.0625	115.47
	6.00	42	9	31.2	1.49	2.1870	153.82
APRIL 7	9.00	45	10	29.3	1.47	2.1450	139.63
	12.00	48	11	33.3	1.52	2.2306	170.05
	15.00	51	12	59.4	1.77	2.6177	414.66
	18.00	54	13	70.6	1.85	2.7332	541.04
	21.00	57	14	80.5	1.91	2.8210	662.23
APRIL 8	24.00	60	15	91.3	1.96	2.9052	803.93
	3.00	63	16	99.7	2.00	2.9641	920.64
	6.00	66	17	98.8	1.99	2.9580	907.87
	9.00	69	18	98.3	1.99	2.9546	900.81
	12.00	72	19	93.2	1.97	2.9190	829.84
APRIL 9	15.00	75	20	87.7	1.94	2.8783	755.63
	18.00	78	21	82.6	1.92	2.8382	689.02
	21.00	81	22	84.4	1.93	2.8527	712.28
	24.00	84	23	81.9	1.91	2.8325	680.05
	3.00	87	24	78.5	1.89	2.8042	637.06
APRIL 9	6.00	90	1	69.8	1.84	2.7256	531.63
	9.00	93	2	67.2	1.83	2.7002	501.44
	12.00	96	3	64.5	1.81	2.6728	470.75
	15.00	99	4	62.3	1.79	2.6496	446.24
	18.00	102	5	61.5	1.79	2.6409	437.45
APRIL 9	21.00	105	6	61.2	1.79	2.6377	434.17
	24.00	108	7	58.4	1.77	2.6063	403.95
	3.00	111	8	54.5	1.74	2.5601	363.16
	6.00	114	9	51.7	1.71	2.5248	334.83
	9.00	117	10	48.9	1.69	2.4876	307.31
APRIL 9	12.00	120	11	45.1	1.65	2.4335	271.31
	15.00	123	12	45.3	1.66	2.4364	273.17
	18.00	126	13	40.1	1.60	2.3549	226.39
	21.00	129	14	31.7	1.50	2.1976	157.63
	24.00	132	15	27.7	1.44	2.1074	128.06

DATE	TIME	ELAPSED TIME(HRS)	BOTTLES	FLUORO. READINGS (Y)	Log of Y	Log of X	Dye Conc. ug/L
APRIL 10	3.00	135	16	20.8	1.32	1.9158	82.37
	6.00	138	17	18.0	1.26	1.8191	65.93
	9.00	141	18	16.9	1.23	1.7769	59.83
	12.00	144	19	15.3	1.18	1.7104	51.33
	15.00	147	***20	11.2	1.05	1.5017	31.75
APRIL 11	20.00	152	21	11.0	1.04	1.4897	30.88
	1.00	157	22	10.8	1.03	1.4774	30.02
	6.00	162	23	10.1	1.00	1.4326	27.07
	11.00	167	24	10.0	1.00	1.4259	26.66
	16.00	172	1	9.9	1.00	1.4192	26.25
APRIL 12	21.00	177	2	9.9	1.00	1.4192	26.25
	1.00	182	3	9.1	0.96	1.3628	23.06
	6.00	187	4	9.0	0.95	1.3554	22.67
	11.00	192	5	8.7	0.94	1.3328	21.52
	16.00	197	6	7.8	0.89	1.2597	18.19
APRIL 13	21.00	202	7	7.9	0.90	1.2682	18.55
	1.00	207	8	7.1	0.85	1.1968	15.73
	6.00	212	9	7.0	0.85	1.1873	15.39
	11.00	217	10	7.0	0.85	1.1873	15.39
	16.00	222	11	6.5	0.81	1.1378	13.73
APRIL 14	21.00	227	12	7.1	0.85	1.1968	15.73
	1.00	232	13	6.5	0.81	1.1378	13.73
	6.00	237	14	6.0	0.78	1.0842	12.14
	11.00	242	15	5.5	0.74	1.0260	10.62
	16.00	247	16	5.7	0.76	1.0499	11.22
APRIL 15	21.00	252	17	5.3	0.72	1.0012	10.03
	1.00	257	18	5.4	0.73	1.0137	10.32
	6.00	262	19	5.3	0.72	1.0012	10.03
	11.00	267	20	4.1	0.61	0.8295	6.75
	16.00	272	21	4.1	0.61	0.8295	6.75
APRIL 16	21.00	277	22	3.3	0.52	0.6843	4.83
	1.00	282	23	3.0	0.48	0.6206	4.17
	6.00	287	24	2.5	0.40	0.4986	3.15
	11.00	292	1	2.3	0.36	0.4428	2.77
	16.00	297	2	2.0	0.30	0.3494	2.24
APRIL 17	21.00	302	3	1.5	0.18	0.1569	1.44
	1.00	307	4	2.2	0.34	0.4131	2.59

APPENDIX E

THIRD RUN

Start Date: JULY 10, 1995

Injection Time: 12.00 pm

Duration of Injection: 30 minutes

Dye Volume: 300 ml

Dilution Ratio: 1/2

DATE	TIME	ELAPSED TIME(HRS)	BOTTLES	FLUORO. READINGS (Y)	Log of Y	Log of X	Dye Conc. ug/L
JULY 10	12.00	0	1	0.0			0
	16.00	4	2	0.0			0
	20.00	8	3	0.0			0
	24.00	12	4	0.0			0
JULY 11	4.00	16	5	0.0			0
	8.00	20	6	0.8			0
	12.00	24	7	3.4	0.00	-0.1143	0.77
	16.00	28	8	16.0	1.20	1.7403	54.99
JULY 12	20.00	32	9	46.0	1.66	2.4467	279.69
	24.00	36	10	36.9	1.57	2.2992	199.18
	4.00	40	11	79.9	1.90	2.8160	654.64
	8.00	44	12	99.0	2.00	2.9594	910.71
JULY 13	12.00	48	13	97.1	1.99	2.9464	883.93
	16.00	52	14	96.5	1.98	2.9423	875.53
	20.00	56	15	97.1	1.99	2.9464	883.93
	24.00	60	16	96.3	1.98	2.9409	872.73
JULY 14	4.00	64	17	95.3	1.98	2.9339	858.81
	8.00	68	18	93.8	1.97	2.9233	838.08
	12.00	72	19	91.0	1.96	2.9030	799.86
	16.00	76	20	89.2	1.95	2.8897	775.63
JULY 15	20.00	80	21	82.4	1.92	2.8366	686.46
	24.00	84	22	74.8	1.87	2.7719	591.40
	4.00	88	23	83.6	1.92	2.8463	701.91
	8.00	92	24	76.6	1.88	2.7878	613.47
JULY 16	12.00	96	1	71.4	1.85	2.7408	550.51
	16.00	100	2	64.8	1.81	2.6759	474.12
	20.00	104	3	61.0	1.79	2.6355	431.98
	24.00	108	4	57.4	1.76	2.5948	393.35
JULY 17	4.00	112	5	61.0	1.79	2.6355	431.98
	8.00	116	6	57.2	1.76	2.5924	391.24
	12.00	120	7	55.0	1.74	2.5662	368.31
	16.00	124	8	51.4	1.71	2.5209	331.84
JULY 18	20.00	128	9	48.8	1.69	2.4862	306.34
	24.00	132	10	45.4	1.66	2.4379	274.09
	4.00	136	11	38.8	1.59	2.3328	215.19
	8.00	140	12	26.6	1.42	2.0803	120.31
JULY 19	12.00	144	13	24.2	1.38	2.0171	104.01
	16.00	148	14	25.0	1.40	2.0388	109.35
	20.00	152	15	23.6	1.37	2.0003	100.06
	24.00	156	16	22.2	1.35	1.9594	91.07
JULY 20	4.00	160	17	20.0	1.30	1.8896	77.54
	8.00	164	18	18.2	1.26	1.8265	67.06
	12.00	168	19	18.6	1.27	1.8410	69.34
	16.00	172	20	18.0	1.26	1.8191	65.93
JULY 21	20.00	176	21	16.0	1.20	1.7403	54.99

DATE	TIME	ELAPSED TIME(HRS)	BOTTLES	FLUORO. READINGS (Y)	Log of Y	Log of X	Dye Conc. ug/L
JULY 16	24.00	180	22	16.8	1.23	1.7729	59.28
	4.00	184	23	15.8	1.20	1.7319	53.94
	8.00	188	24	14.6	1.16	1.6790	47.76
	12.00	192	1	13.8	1.14	1.6413	43.79
	16.00	196	2	13.4	1.13	1.6217	41.85
JULY 19	20.00	200	3	12.2	1.09	1.5589	36.22
	24.00	204	4	12.0	1.08	1.5479	35.31
	4.00	208	5	11.8	1.07	1.5366	34.40
	8.00	212	6	11.6	1.06	1.5252	33.51
	12.00	216	7	10.6	1.03	1.4649	29.17
JULY 20	16.00	220	8	9.6	0.98	1.3986	25.04
	20.00	224	9	9.4	0.97	1.3845	24.24
	24.00	228	10	9.0	0.95	1.3554	22.67
	4.00	232	11	7.4	0.87	1.2245	16.77
	8.00	236	12	7.2	0.86	1.2062	16.08
JULY 21	12.00	240	13	6.4	0.81	1.1274	13.41
	16.00	244	14	6.2	0.79	1.1062	12.77
	20.00	248	15	5.4	0.73	1.0137	10.32
	24.00	252	16	4.8	0.68	0.9350	8.61
	4.00	256	17	4.2	0.62	0.8456	7.01
JULY 22	8.00	260	18	3.6	0.56	0.7425	5.53
	12.00	264	19	3.0	0.48	0.6206	4.17
	16.00	268	20	2.3	0.36	0.4428	2.77
	20.00	272	21	2.2	0.34	0.4131	2.59
	24.00	276	22	2.3	0.36	0.4428	2.77
JULY 23	4.00	280	23	2.1	0.32	0.3820	2.41
	8.00	284	24	2.1	0.32	0.3820	2.41
	12.00	288	1	2.1	0.32	0.3820	2.41
	16.00	292	2	2.0	0.30	0.3494	2.24
	20.00	296	3	2.0	0.30	0.3494	2.24
JULY 23	24.00	300	4	1.9	0.28	0.3151	2.07
	4.00	304	5	1.8	0.26	0.2789	1.90
	8.00	308	6	1.7	0.23	0.2407	1.74

APPENDIX F

FIRST RUN

MEAN RESIDENCE TIME AND VARIANCE CALCULATIONS

A	B	C	D	E	F	G
TIME ti (hours)	CONCENTRATION Ci (Ug / L)	TIME INTERVAL ti(hours)	A*B*C	B*C	TIME ^ 2 ti ^ 2	F * E
0	0	0	0	0	0	0
3	0	3	0	0	9	0
6	0	3	0	0	36	0
9	0	3	0	0	81	0
12	0	3	0	0	144	0
15	0	3	0	0	225	0
18	0	3	0	0	324	0
21	10.59	3	667	31.75689	441	14004.79
24	224.11	3	16136	672.3288	576	387261.4
27	778.27	3	63040	2334.814	729	1702079
30	984.54	3	88609	2953.633	900	2658269
33	1007.47	3	99740	3022.422	1089	3291418
36	1032.91	3	111554	3098.73	1296	4015954
39	1044.55	3	122212	3133.635	1521	4766259
42	1098.65	3	138430	3295.956	1764	5814066
45	1177.94	3	159022	3533.825	2025	7155996
48	1139.26	3	164053	3417.769	2304	7874540
51	1122.47	3	171739	3367.423	2601	8758667
54	1044.55	3	169216	3133.635	2916	9137680
57	901.33	3	154127	2703.989	3249	8785259
60	749.03	3	134825	2247.078	3600	8089479
63	761.51	3	143926	2284.534	3969	9067317
66	742.81	3	147076	2228.431	4356	9707044
69	753.18	3	155908	2259.539	4761	1.1E+07
72	742.81	3	160447	2228.431	5184	1.2E+07
75	671.65	3	151121	2014.953	5625	1.1E+07
78	582.02	3	136193	1746.063	6084	1.1E+07
81	493.40	3	119897	1480.212	6561	9711668
84	444.12	3	111919	1332.371	7056	9401212
87	440.67	3	115016	1322.021	7569	1E+07
90	418.48	3	112990	1255.44	8100	1E+07
93	390.07	3	108830	1170.21	8649	1E+07
96	365.59	3	105290	1096.769	9216	1E+07
99	333.83	3	99146	1001.477	9801	9815476
102	289.60	3	88617	868.7971	10404	9038965
105	244.82	3	77117	734.448	11025	8097289
108	239.23	3	77511	717.6951	11664	8371195
111	240.62	3	80128	721.8706	12321	8894167
114	225.47	3	77111	676.41	12996	8790624
117	221.40	3	77711	664.1925	13689	9092131
120	206.69	3	74408	620.0685	14400	8928986
123	135.26	3	49910	405.7749	15129	6138969
126	131.86	3	49842	395.575	15876	6280149
129	126.26	3	48862	378.7786	16641	6303255
132	130.73	3	51770	392.1953	17424	6833611
135	107.87	3	43688	323.6162	18225	5897905
138	96.52	3	39961	289.575	19044	5514666

APPENDIX F

SECOND RUN MEAN RESIDENCE TIME AND VARIANCE CALCULATIONS

A	B	C	D	E	F	G
TIME ti (hours)	CONCENTRATION Ci (Ug / L)	TIME INTERVAL ti(hours)	A*B*C	B*C	TIME ^ 2 ti ^2	F * E
0	0	0	0	0	0	0
3	0	3	0	0	9	0
6	0	3	0	0	36	0
9	0	3	0	0	81	0
12	0	3	0	0	144	0
15	0	3	0	0	225	0
18	1.54	3	83.01	4.61	324	1.49E+03
21	10.12	3	637.78	30.37	441	1.34E+04
24	46.12	3	3320.38	138.35	576	7.97E+04
27	105.78	3	8567.87	317.33	729	2.31E+05
30	177.10	3	15939.30	531.31	900	4.78E+05
33	242.02	3	23959.80	726.05	1089	7.91E+05
36	232.32	3	25090.03	696.95	1296	9.03E+05
39	230.94	3	27020.02	692.82	1521	1.05E+06
42	307.63	3	38761.65	922.90	1764	1.63E+06
45	279.26	3	37699.74	837.77	2025	1.70E+06
48	340.10	3	48974.01	1020.29	2304	2.35E+06
51	829.31	3	126884.82	2487.94	2601	6.47E+06
54	1082.08	3	175297.50	3246.25	2916	9.47E+06
57	1324.46	3	226482.23	3973.37	3249	1.29E+07
60	1607.86	3	289414.53	4823.58	3600	1.74E+07
63	1841.28	3	348002.60	5523.85	3969	2.19E+07
66	1815.75	3	359517.69	5447.24	4356	2.37E+07
69	1801.61	3	372933.78	5404.84	4761	2.57E+07
72	1659.68	3	358491.44	4979.05	5184	2.58E+07
75	1511.26	3	340033.24	4533.78	5625	2.55E+07
78	1378.05	3	322462.81	4134.14	6084	2.52E+07
81	1424.57	3	346170.41	4273.71	6561	2.80E+07
84	1360.10	3	342745.33	4080.30	7056	2.88E+07
87	1274.12	3	332544.72	3822.35	7569	2.89E+07
90	1063.26	3	287079.14	3189.77	8100	2.58E+07
93	1002.87	3	279801.63	3008.62	8649	2.60E+07
96	941.49	3	271149.25	2824.47	9216	2.60E+07
99	892.49	3	265069.11	2677.47	9801	2.62E+07
102	874.90	3	267718.94	2624.70	10404	2.73E+07
105	868.33	3	273525.20	2605.00	11025	2.87E+07
108	807.91	3	261761.94	2423.72	11664	2.83E+07
111	726.32	3	241865.99	2178.97	12321	2.68E+07
114	669.65	3	229021.96	2008.96	12996	2.61E+07
117	614.62	3	215731.57	1843.86	13689	2.52E+07
120	542.62	3	195343.34	1627.86	14400	2.34E+07
123	546.33	3	201596.13	1638.99	15129	2.48E+07
126	452.79	3	171154.61	1358.37	15876	2.16E+07
129	315.26	3	122004.87	945.77	16641	1.57E+07
132	256.12	3	101423.31	768.36	17424	1.34E+07

APPENDIX F

THIRD RUN

MEAN RETENTION TIME AND VARIANCE CALCULATIONS

A	B	C	D	E	F	G
TIME ti (hours)	CONCENTRATION Ci (Ug / L)	TIME INTERVAL ti(hours)	A*B*C	B*C	TIME ^ 2 ti ^2	F * E
0	0	0	0	0	0	0
4	0	4	0	0	16	0
8	0	4	0	0	64	0
12	0	4	0	0	144	0
16	0	4	0	0	256	0
20	0	4	0	0	400	0
24	1.54	4	1.48E+02	6.14905	576	3.54E+03
28	109.98	4	1.23E+04	439.929	784	3.45E+05
32	559.39	4	7.16E+04	2237.55	1024	2.29E+06
36	398.35	4	5.74E+04	1593.41	1296	2.07E+06
40	1309.28	4	2.09E+05	5237.14	1600	8.38E+06
44	1821.41	4	3.21E+05	7285.64	1936	1.41E+07
48	1767.85	4	3.39E+05	7071.4	2304	1.63E+07
52	1751.05	4	3.64E+05	7004.22	2704	1.89E+07
56	1767.85	4	3.96E+05	7071.4	3136	2.22E+07
60	1745.47	4	4.19E+05	6981.87	3600	2.51E+07
64	1717.63	4	4.40E+05	6870.52	4096	2.81E+07
68	1676.17	4	4.56E+05	6704.67	4624	3.10E+07
72	1599.73	4	4.61E+05	6398.91	5184	3.32E+07
76	1551.25	4	4.72E+05	6205.01	5776	3.58E+07
80	1372.91	4	4.39E+05	5491.64	6400	3.51E+07
84	1182.81	4	3.97E+05	4731.24	7056	3.34E+07
88	1403.83	4	4.94E+05	5615.3	7744	4.35E+07
92	1226.93	4	4.52E+05	4907.73	8464	4.15E+07
96	1101.03	4	4.23E+05	4404.1	9216	4.06E+07
100	948.24	4	3.79E+05	3792.97	10000	3.79E+07
104	863.97	4	3.59E+05	3455.87	10816	3.74E+07
108	786.70	4	3.40E+05	3146.8	11664	3.67E+07
112	863.97	4	3.87E+05	3455.87	12544	4.34E+07
116	782.48	4	3.63E+05	3129.92	13456	4.21E+07
120	736.61	4	3.54E+05	2946.45	14400	4.24E+07
124	663.68	4	3.29E+05	2654.72	15376	4.08E+07
128	612.69	4	3.14E+05	2450.74	16384	4.02E+07
132	548.19	4	2.89E+05	2192.76	17424	3.82E+07
136	430.38	4	2.34E+05	1721.52	18496	3.18E+07
140	240.62	4	1.35E+05	962.494	19600	1.89E+07
144	208.01	4	1.20E+05	832.048	20736	1.73E+07
148	218.70	4	1.29E+05	874.788	21904	1.92E+07
152	200.12	4	1.22E+05	800.488	23104	1.85E+07
156	182.13	4	1.14E+05	728.532	24336	1.77E+07
160	155.09	4	9.93E+04	620.359	25600	1.59E+07
164	134.12	4	8.80E+04	536.486	26896	1.44E+07
168	138.69	4	9.32E+04	554.754	28224	1.57E+07
172	131.86	4	9.07E+04	527.433	29584	1.56E+07
176	109.98	4	7.74E+04	439.929	30976	1.36E+07

APPENDIX F

Mean Retention Times and Variance Calculations

$$\bar{t} = \text{mean retention time} = \frac{\sum t_i C_i \Delta t_i}{\sum C_i \Delta t_i}$$

$$\sigma^2 = \text{variance} = \frac{\sum t_i^2 C_i \Delta t_i}{\sum C_i \Delta t_i} - \bar{t}^2 = \text{hours}^2$$

$$\sigma_\theta^2 = \text{dimensionless variance} = \sigma^2 / \bar{t}^2$$

$$\text{Column D} = t_i C_i \Delta t_i$$

$$\text{Column E} = C_i \Delta t_i$$

$$\text{Column G} = t_i^2 C_i \Delta t_i$$

APPENDIX G

RUN 1 TREATMENT EFFICIENCY

t	delta t	E	exp(-kt)	exp(-kt) * E * delta t
0	0	0	1.00E+00	0.00E+00
3	3	0	9.72E-01	0.00E+00
6	3	0	9.44E-01	0.00E+00
9	3	0	9.17E-01	0.00E+00
12	3	0	8.91E-01	0.00E+00
15	3	0	8.66E-01	0.00E+00
18	3	0	8.41E-01	0.00E+00
21	3	0.00016	8.17E-01	3.85E-04
24	3	0.00332	7.94E-01	7.91E-03
27	3	0.01153	7.72E-01	2.67E-02
30	3	0.01459	7.50E-01	3.28E-02
33	3	0.01493	7.28E-01	3.26E-02
36	3	0.01531	7.08E-01	3.25E-02
39	3	0.01548	6.88E-01	3.19E-02
42	3	0.01628	6.68E-01	3.26E-02
45	3	0.01746	6.49E-01	3.40E-02
48	3	0.01688	6.31E-01	3.19E-02
51	3	0.01663	6.13E-01	3.06E-02
54	3	0.01548	5.95E-01	2.77E-02
57	3	0.01336	5.79E-01	2.32E-02
60	3	0.0111	5.62E-01	1.87E-02
63	3	0.01129	5.46E-01	1.85E-02
66	3	0.01101	5.31E-01	1.75E-02
69	3	0.01116	5.16E-01	1.73E-02
72	3	0.01101	5.01E-01	1.65E-02
75	3	0.00995	4.87E-01	1.45E-02
78	3	0.00863	4.73E-01	1.22E-02
81	3	0.00731	4.60E-01	1.01E-02
84	3	0.00658	4.46E-01	8.82E-03
87	3	0.00653	4.34E-01	8.50E-03
90	3	0.0062	4.21E-01	7.84E-03
93	3	0.00578	4.10E-01	7.10E-03
96	3	0.00542	3.98E-01	6.47E-03
99	3	0.00495	3.87E-01	5.74E-03
102	3	0.00429	3.76E-01	4.84E-03
105	3	0.00363	3.65E-01	3.97E-03
108	3	0.00355	3.55E-01	3.77E-03
111	3	0.00357	3.45E-01	3.69E-03
114	3	0.00334	3.35E-01	3.36E-03
117	3	0.00328	3.25E-01	3.20E-03
120	3	0.00306	3.16E-01	2.90E-03
123	3	0.002	3.07E-01	1.85E-03
126	3	0.00195	2.98E-01	1.75E-03
129	3	0.00187	2.90E-01	1.63E-03

132	3	0.00194	2.82E-01	1.64E-03
135	3	0.0016	2.74E-01	1.31E-03
138	3	0.00143	2.66E-01	1.14E-03
141	3	0.00098	2.58E-01	7.59E-04
144	3	0.00081	2.51E-01	6.13E-04
147	3	0.00068	2.44E-01	5.00E-04
190	43	0.0003	1.61E-01	2.06E-03
195	5	0.00026	1.54E-01	1.96E-04
200	5	0.00022	1.47E-01	1.58E-04
205	5	0.00014	1.40E-01	9.55E-05
210	5	0.00013	1.33E-01	8.67E-05
215	5	0.00013	1.27E-01	8.26E-05
220	5	0.00011	1.21E-01	6.36E-05
225	5	7.7E-05	1.15E-01	4.42E-05
230	5	7.1E-05	1.10E-01	3.93E-05
235	5	5.6E-05	1.05E-01	2.95E-05
240	5	6.1E-05	9.99E-02	3.06E-05
245	5	4.7E-05	9.52E-02	2.24E-05
250	5	4.3E-05	9.07E-02	1.93E-05
255	5	4.7E-05	8.65E-02	2.03E-05
260	5	3.4E-05	8.24E-02	1.41E-05
265	5	3.4E-05	7.86E-02	1.34E-05
270	5	3.8E-05	7.49E-02	1.43E-05
275	5	3.4E-05	7.14E-02	1.22E-05
280	5	3E-05	6.80E-02	1.03E-05
285	5	2.6E-05	6.48E-02	8.55E-06
290	5	1.9E-05	6.18E-02	5.98E-06
295	5	2.3E-05	5.89E-02	6.71E-06
300	5	2.3E-05	5.61E-02	6.39E-06
305	5	1.9E-05	5.35E-02	5.18E-06
TOTAL				5.55E-01

RUN 2

TREATMENT EFFICIENCY

t	delta t	E	exp(-kt)	exp(-kt) * E * delta t
0	0	0	1.00E+00	0.00E+00
3	3	0	9.72E-01	0.00E+00
6	3	0	9.44E-01	0.00E+00
9	3	0	9.17E-01	0.00E+00
12	3	0	8.91E-01	0.00E+00
15	3	0	8.66E-01	0.00E+00
18	3	1.5E-05	8.41E-01	3.85E-05
21	3	0.0001	8.17E-01	2.46E-04
24	3	0.00046	7.94E-01	1.09E-03
27	3	0.00105	7.72E-01	2.43E-03
30	3	0.00176	7.50E-01	3.96E-03
33	3	0.0024	7.28E-01	5.25E-03
36	3	0.00231	7.08E-01	4.90E-03
39	3	0.00229	6.88E-01	4.73E-03
42	3	0.00305	6.68E-01	6.12E-03
45	3	0.00277	6.49E-01	5.40E-03
48	3	0.00338	6.31E-01	6.39E-03
51	3	0.00823	6.13E-01	1.51E-02
54	3	0.01074	5.95E-01	1.92E-02
57	3	0.01315	5.79E-01	2.28E-02
60	3	0.01596	5.62E-01	2.69E-02
63	3	0.01828	5.46E-01	3.00E-02
66	3	0.01803	5.31E-01	2.87E-02
69	3	0.01789	5.16E-01	2.77E-02
72	3	0.01648	5.01E-01	2.48E-02
75	3	0.015	4.87E-01	2.19E-02
78	3	0.01368	4.73E-01	1.94E-02
81	3	0.01414	4.60E-01	1.95E-02
84	3	0.0135	4.46E-01	1.81E-02
87	3	0.01265	4.34E-01	1.65E-02
90	3	0.01056	4.21E-01	1.33E-02
93	3	0.00996	4.10E-01	1.22E-02
96	3	0.00935	3.98E-01	1.12E-02
99	3	0.00886	3.87E-01	1.03E-02
102	3	0.00869	3.76E-01	9.79E-03
105	3	0.00862	3.65E-01	9.44E-03
108	3	0.00802	3.55E-01	8.53E-03
111	3	0.00721	3.45E-01	7.45E-03
114	3	0.00665	3.35E-01	6.68E-03
117	3	0.0061	3.25E-01	5.95E-03
120	3	0.00539	3.16E-01	5.11E-03
123	3	0.00542	3.07E-01	5.00E-03
126	3	0.0045	2.98E-01	4.02E-03
129	3	0.00313	2.90E-01	2.72E-03
132	3	0.00254	2.82E-01	2.15E-03

135	3	0.00164	2.74E-01	1.34E-03
138	3	0.00131	2.66E-01	1.04E-03
141	3	0.00119	2.58E-01	9.21E-04
144	3	0.00102	2.51E-01	7.67E-04
147	3	0.00063	2.44E-01	4.61E-04
152	5	0.00061	2.32E-01	7.13E-04
157	5	0.0006	2.22E-01	6.60E-04
162	5	0.00054	2.11E-01	5.68E-04
167	5	0.00053	2.01E-01	5.33E-04
172	5	0.00052	1.92E-01	5.00E-04
177	5	0.00052	1.83E-01	4.77E-04
182	5	0.00046	1.74E-01	3.99E-04
187	5	0.00045	1.66E-01	3.74E-04
192	5	0.00043	1.58E-01	3.38E-04
197	5	0.00036	1.51E-01	2.72E-04
202	5	0.00037	1.44E-01	2.65E-04
207	5	0.00031	1.37E-01	2.14E-04
212	5	0.00031	1.31E-01	2.00E-04
217	5	0.00031	1.25E-01	1.90E-04
222	5	0.00027	1.19E-01	1.62E-04
227	5	0.00031	1.13E-01	1.77E-04
232	5	0.00027	1.08E-01	1.47E-04
237	5	0.00024	1.03E-01	1.24E-04
242	5	0.00021	9.80E-02	1.03E-04
247	5	0.00022	9.34E-02	1.04E-04
252	5	0.0002	8.90E-02	8.86E-05
257	5	0.0002	8.48E-02	8.69E-05
262	5	0.0002	8.08E-02	8.05E-05
267	5	0.00013	7.71E-02	5.17E-05
272	5	0.00013	7.34E-02	4.92E-05
277	5	9.6E-05	7.00E-02	3.36E-05
282	5	8.3E-05	6.67E-02	2.77E-05
287	5	6.3E-05	6.36E-02	1.99E-05
292	5	5.5E-05	6.06E-02	1.67E-05
297	5	4.4E-05	5.78E-02	1.28E-05
302	5	2.9E-05	5.51E-02	7.85E-06
307	5	5.1E-05	5.25E-02	1.35E-05
TOTAL				4.56E-01

RUN 3 TREATMENT EFFICIENCY

t	delta t	E	exp(-kt)	exp(-kt) * E * delta t
0	0	0	1	0
4	4	0	0.96232793272161	0
8	4	0	0.92607505009625	0
12	4	0	0.89118788850418	0
16	4	0	0.85761499841077	0
20	4	0	0.82530686849168	0
24	4	1.122566278E-05	0.79421585261655	3.5662397338118E-05
28	4	0.0008031323199	0.76429609958321	0.0024553235982337
32	4	0.0040848595093	0.7355034854991	0.012017713627369
36	4	0.0029089238665	0.70779554870989	0.0082356934570489
40	4	0.0095608823355	0.68113142717955	0.02604886972108
44	4	0.01330062166	0.65547179822941	0.03487272958825
48	4	0.0129095095899	0.63077882054743	0.03257218093188
52	4	0.0127868531635	0.60701607838198	0.031047301848501
56	4	0.0129095095899	0.58414852783811	0.030164284088235
60	4	0.0127460590248	0.56214244519682	0.028660403147323
64	4	0.0125427753236	0.54096537718133	0.027140828735325
68	4	0.0122400059525	0.52058609309687	0.025487907513092
72	4	0.0116818193088	0.50097453877354	0.023409176161038
76	4	0.0113278360881	0.4821017922441	0.021844680321222
80	4	0.0100255082535	0.46394002109165	0.018604938042354
84	4	0.0086373181014	0.44646244140394	0.015424952506891
88	4	0.0102512626597	0.4296432782741	0.017617544382325
92	4	0.0089595198177	0.41345772778925	0.014817530823696
96	4	0.0080401071219	0.3978819204512	0.012796053049208
100	4	0.0069244301736	0.38289288597511	0.010605260211559
104	4	0.0063090134978	0.36846851941424	0.0092986914500488
108	4	0.0057447716617	0.3545875485609	0.0081480980022872
112	4	0.0063090134978	0.34122950257543	0.0086112861504335
116	4	0.0057139712578	0.32837468179704	0.0075052939742507
120	4	0.0053790236112	0.31600412869186	0.006799174677881
124	4	0.0048464360687	0.30409959989553	0.0058951970776298
128	4	0.0044740568525	0.29264353930894	0.0052372153295475
132	4	0.0040030866079	0.28161905220751	0.004509381825662
136	4	0.0031428002541	0.27100988032587	0.0034069196830299
140	4	0.0017571234724	0.26080037788112	0.0018330338623807
144	4	0.0015189810919	0.25097548849936	0.0015249080862251
148	4	0.0015970077346	0.24152072301138	0.0015428418508818
152	4	0.0014613663507	0.23242213808497	0.0013586155669857
156	4	0.0013300045253	0.22366631566205	0.0011899088479452
160	4	0.00113252308	0.21524034317052	0.00097505862558588
164	4	0.0009794064742	0.20713179448157	0.0008114648821237
168	4	0.0010127558797	0.19932871158437	0.00080748529859366
172	4	0.0009628791283	0.19181958695105	0.00073879630671831
176	4	0.0008031323199	0.18459334656612	0.00059301153067231

180	4		0.0008658101588	0.17763933359514	0.00061520775848119
184	4		0.0007877224063	0.17094729266865	0.00053863605091987
188	4		0.0006974902173	0.16450735475818	0.00045896908248496
192	4		0.0006395048379	0.15831002262194	0.00040496010141553
196	4		0.0006111797931	0.15234615679888	0.00037244357036043
200	4		0.0005289491733	0.14660696213035	0.00031019052565845
204	4		0.0005156530005	0.1410839747895	0.00029100149967041
208	4		0.0005024760023	0.13576904979932	0.00027288275754381
212	4		0.0004894191035	0.13065434902096	0.00025577893748994
216	4		0.0004259701402	0.12573232959443	0.00021423287225111
220	4		0.0003656769543	0.12099573281488	0.00017698140421433
224	4		0.0003540095986	0.11643757342788	0.0001648800745304
228	4		0.0003310762253	0.11205112932797	0.00014838985975096
232	4		0.0002449035706	0.10782993164531	0.00010563174110792
236	4		0.0002347837511	0.10376775520574	9.7451931222792E-05
240	4		0.0001958318683	0.099858609350303	7.8221992145712E-05
244	4		0.000186486231	0.096096729100532	7.168286726903E-05
248	4		0.0001507434612	0.092476566656624	5.576095094449E-05
252	4		0.000125734313	0.088992783215861	4.4757785834389E-05
256	4		0.0001023611418	0.085640241099262	3.5064931434937E-05
260	4		8.072801224E-05	0.082413996174833	2.6612472368478E-05
264	4		6.096351416E-05	0.079309290566254	1.9339892234512E-05
268	4		4.048946653E-05	0.07632154563624	1.2360874671143E-05
272	4		3.781015196E-05	0.073446355234241	1.1108071410673E-05
276	4		4.048946653E-05	0.070679479198505	1.1447097630312E-05
280	4		3.519584071E-05	0.068016837102937	9.5756390582088E-06
284	4		3.519584071E-05	0.065454502239532	9.2149049393744E-06
288	4		3.519584071E-05	0.062988695827491	8.8677604205344E-06
292	4		3.264793895E-05	0.060615781440499	7.9159213271749E-06
296	4		3.264793895E-05	0.058332259643941	7.6177122063671E-06
300	4		3.016795423E-05	0.056134762834134	6.7738838234896E-06
304	4		2.775750848E-05	0.05402005027199	5.9978480137802E-06
308	4		2.541835341E-05	0.051985003303761	5.2854927432727E-06
TOTAL					0.46950066144643

APPENDIX G

Treatment Efficiency Calculations

$$k = 0.23 \text{ days}^{-1}$$

$$\text{BOD initial} = 45 \text{ mg / L}$$

Wastewater is decomposing at a rate :

$$-r_A = kC_A, \quad \text{where } k = 0.23 \text{ d}^{-1}$$

For plug flow reactor, the theoretical retention time = 4 days

For Run 1, $t = 2.71$ days

Run 2, $t = 3.47$ days

Run 3, $t = 3.41$ days

for plug flow reactor then

$$\frac{C_A}{C_{ao}} = e^{-kt}$$

$$= e^{-0.23 * 4}$$

$$= 0.40$$

that is, the fraction of reactant unconverted in a plug flow reactor equals 40%

Effluent concentration, C_e

$$C_e / C_o = 0.40 \quad \text{where } C_o = 45 \text{ mg / L}$$

$$C_e = 0.40 * 45 = 18 \text{ mg/L}$$

$$\% \text{ treatment efficiency} = 100\% * [1 - C_e / C_o]$$

$$= 100 * (1 - 0.40)$$

$$= 60\%$$

WETLAND

RUN 1

From spreadsheet $C_e/C_o = 0.55$
 $C_e = 24.8 \text{ mg/L}$

% treatment efficiency = 45

Reduced efficiency % = 60 % - 45 % = 15% where 60% is the plug flow treatment efficiency

RUN 2

From spreadsheet $C_e/C_o = 0.46$
 $C_e = 20.7 \text{ mg/L}$

% treatment efficiency = 54

Reduced efficiency % = 60 % - 54 % = 6% where 60% is the plug flow treatment efficiency

RUN 3

From spreadsheet $C_e/C_o = 0.47$
 $C_e = 21.2 \text{ mg/L}$

% treatment efficiency = 53

Reduced efficiency % = 60 % - 53 % = 7% where 60% is the plug flow treatment efficiency

APPENDIX H

Calculation of the Dispersion Number and the DISPERSION coefficient

Using equation $\sigma_\theta^2 = 2 (D / uL)$ for small extend of dispersion

Run1

$$\sigma_\theta^2 = 0.23$$

$$D / uL = 0.115$$

$$\text{where } L = 22 \text{ m}$$

$$= \text{Dispersion number}$$

$$u = L / \bar{t}$$

$$= 22 / 2.71 \text{ days}$$

$$= 9.04 \times 10^{-5} \text{ m/s}$$

therefore $D = 1.09 \times 10^{-6} \text{ m}^2 / \text{s}$ which is the dispersion coefficient

Run 2

$$\sigma_\theta^2 = 0.11$$

$$D / uL = 0.055$$

where

$$L = 22 \text{ m}$$

$$\text{therefore } D = 4.04 \times 10^{-6} \text{ m}^2 / \text{s}$$

$$u = 7.34 \times 10^{-5} \text{ m/s}$$

Run 3

$$\sigma_\theta^2 = 0.17$$

$$D / uL = 0.085$$

where

$$L = 22 \text{ m}$$

$$\text{therefore } D = 6.35 \times 10^{-6} \text{ m}^2 / \text{s}$$

$$u = 7.47 \times 10^{-5} \text{ m/s}$$

APPENDIX I

DYE RECOVERY % : RUN 1

A	B	C	D
Ci / Co Dimensionless	t/ theoretical Dimensionless	Mean Dimensionless concentration	Column C * Column B Dimensionless time
0	0	0	0
0	0	0	0
0	0.03125	0	0
0	0.03125	0	0
0	0.03125	0	0
0	0.03125	0	0
0	0.03125	0	0
5.70E-03	0.03125	0.003	8.90E-05
1.21E-01	0.03125	0.063	1.97E-03
4.19E-01	0.03125	0.270	8.43E-03
5.30E-01	0.03125	0.474	1.48E-02
5.42E-01	0.03125	0.536	1.68E-02
5.56E-01	0.03125	0.549	1.72E-02
5.62E-01	0.03125	0.559	1.75E-02
5.91E-01	0.03125	0.577	1.80E-02
6.34E-01	0.03125	0.613	1.91E-02
6.13E-01	0.03125	0.624	1.95E-02
6.04E-01	0.03125	0.609	1.90E-02
5.62E-01	0.03125	0.583	1.82E-02
4.85E-01	0.03125	0.524	1.64E-02
4.03E-01	0.03125	0.444	1.39E-02
4.10E-01	0.03125	0.407	1.27E-02
4.00E-01	0.03125	0.405	1.27E-02
4.05E-01	0.03125	0.403	1.26E-02
4.00E-01	0.03125	0.403	1.26E-02
3.62E-01	0.03125	0.381	1.19E-02
3.13E-01	0.03125	0.337	1.05E-02
2.66E-01	0.03125	0.289	9.05E-03
2.39E-01	0.03125	0.252	7.89E-03
2.37E-01	0.03125	0.238	7.44E-03
2.25E-01	0.03125	0.231	7.23E-03
2.10E-01	0.03125	0.218	6.80E-03
1.97E-01	0.03125	0.203	6.36E-03
1.80E-01	0.03125	0.188	5.88E-03
1.56E-01	0.03125	0.168	5.24E-03
1.32E-01	0.03125	0.144	4.49E-03
1.29E-01	0.03125	0.130	4.07E-03
1.30E-01	0.03125	0.129	4.04E-03
1.21E-01	0.03125	0.125	3.92E-03
1.19E-01	0.03125	0.120	3.76E-03
1.11E-01	0.03125	0.115	3.60E-03
7.28E-02	0.03125	0.092	2.88E-03
7.10E-02	0.03125	0.072	2.25E-03
6.80E-02	0.03125	0.069	2.17E-03

7.04E-02	0.03125	0.035	1.10E-03
5.81E-02	0.03125	0.064	2.01E-03
5.20E-02	0.03125	0.055	1.72E-03
3.56E-02	0.03125	0.044	1.37E-03
2.96E-02	0.03125	0.033	1.02E-03
2.48E-02	0.03125	0.027	8.50E-04
1.08E-02	0.4479	0.018	7.98E-03
9.27E-03	0.0521	0.010	5.23E-04
7.82E-03	0.0521	0.009	4.45E-04
4.96E-03	0.0521	0.006	3.33E-04
4.73E-03	0.0521	0.005	2.52E-04
4.73E-03	0.0521	0.005	2.46E-04
3.82E-03	0.0521	0.004	2.23E-04
2.79E-03	0.0521	0.003	1.72E-04
2.59E-03	0.0521	0.003	1.40E-04
2.05E-03	0.0521	0.002	1.21E-04
2.22E-03	0.0521	0.002	1.11E-04
1.71E-03	0.0521	0.002	1.02E-04
1.55E-03	0.0521	0.002	8.47E-05
1.71E-03	0.0521	0.002	8.47E-05
1.24E-03	0.0521	0.001	7.67E-05
1.24E-03	0.0521	0.001	6.46E-05
1.39E-03	0.0521	0.001	6.85E-05
1.24E-03	0.0521	0.001	6.85E-05
1.10E-03	0.0521	0.001	6.08E-05
9.58E-04	0.0521	0.001	5.35E-05
7.04E-04	0.0521	0.001	4.33E-05
8.28E-04	0.0521	0.001	3.99E-05
8.28E-04	0.0521	0.001	4.31E-05
7.04E-04	0.0521	0.001	3.99E-05
			0.380

DYE RECOVERY % : RUN 2

A	B	C	D
Ci / Co Dimensionless	t / theoretical Dimensionless	Mean Dimensionless concentration	Column C * Column B Dimensionless time
0	0	0	0
0	0.03125	0	0
0	0.03125	0	0
0	0.03125	0	0
0	0.03125	0	0
0	0.03125	0	0
0.00082750804	0.03125	0.000413754018742	1.2929813085701E-05
0.00544943429	0.03125	0.003138471165811	9.8077223931605E-05
0.02482443779	0.03125	0.015136936041685	0.00047302925130266
0.05693932797	0.03125	0.040881882881765	0.0012775588400552
0.09533475538	0.03125	0.076137041679174	0.0023792825524742
0.13027840806	0.03125	0.11280658172396	0.0035252056788737
0.12505522713	0.03125	0.12766681759654	0.0039895880498918
0.12431519341	0.03125	0.12468521027184	0.003896412820995
0.16559839185	0.03125	0.14495679263092	0.0045298997697164
0.15032421885	0.03125	0.15796130535026	0.0049362907921956
0.18307437971	0.03125	0.16669929928388	0.0052093531026213
0.44641898605	0.03125	0.31474668288009	0.0098358338400029
0.58248550354	0.03125	0.51445224479331	0.016076632649791
0.71295552604	0.03125	0.64772051478812	0.020241266087129
0.86551029893	0.03125	0.78923291248144	0.024663528515045
0.99116303862	0.03125	0.92833666877291	0.029010520899154
0.97741611687	0.03125	0.98428957774376	0.030759049304493
0.96980807801	0.03125	0.97361209743723	0.030425378044913
0.89340722187	0.03125	0.9316076499377	0.029112739060553
0.81351070896	0.03125	0.85345896541319	0.026670592669162
0.74180233506	0.03125	0.77765652200782	0.024301766312744
0.76684586826	0.03125	0.75432410166164	0.023572628176926
0.73214217465	0.03125	0.74949402145711	0.023421688170535
0.68585761521	0.03125	0.70899989492923	0.022156246716538
0.57235078908	0.03125	0.62910420214476	0.019659506317024
0.53984671362	0.03125	0.55609875135325	0.017378085979789
0.50680435146	0.03125	0.52332553254453	0.016353922892017
0.48042664222	0.03125	0.49361549684343	0.015425484276357
0.47095791061	0.03125	0.47569227641842	0.014865383638076
0.46742420886	0.03125	0.46919105973772	0.014662220616804
0.43489649296	0.03125	0.4511603509088	0.0140987609659
0.39098040538	0.03125	0.41293844916737	0.01290432653648
0.36047523506	0.03125	0.37572782022048	0.01174149438189
0.33084990527	0.03125	0.34566257016597	0.010801955317687
0.29209258052	0.03125	0.31147124289597	0.0097334763404991
0.29408999485	0.03125	0.29309128768703	0.0091591027402198
0.24373686614	0.03125	0.2689134304936	0.008403544702925
0.16970343178	0.03125	0.20672014895669	0.0064600046548964
0.13786911873	0.03125	0.15378627525606	0.0048058211017517

A	B	C	D
Ci / Co Dimensionless	t/ theoretical Dimensionless	Mean Dimensionless concentration	Column C * Column B Dimensionless time
0.08868330937	0.03125	0.044341654687461	0.0013856767089832
0.07097934737	0.03125	0.079831328373757	0.0024947290116799
0.06440990082	0.03125	0.067694624097103	0.0021154570030345
0.05526162429	0.03125	0.059835762556779	0.0018698675798993
0.0341797343	0.03125	0.044720679297128	0.0013975212280352
0.03324422138	0.052083333333	0.033711977841022	0.0017558321792199
0.03231785214	0.052083333333	0.032781036758882	0.0017073456645251
0.02914870431	0.052083333333	0.030733278225982	0.0016006915742699
0.02870539402	0.052083333333	0.028927049165573	0.0015066171440403
0.02826447202	0.052083333333	0.028484933016943	0.0014835902612991
0.02826447202	0.052083333333	0.028264472016674	0.0014721079175351
0.02482443779	0.052083333333	0.026544454902953	0.0013825236928621
0.02440552891	0.052083333333	0.024614983348918	0.0012820303827562
0.02316389523	0.052083333333	0.023784712071512	0.0012387870870579
0.0195780106	0.052083333333	0.021370952914896	0.0011130704643175
0.01996593486	0.052083333333	0.019771972730003	0.0010297902463543
0.01693842075	0.052083333333	0.018452177805786	0.00096105092738471
0.01657237922	0.052083333333	0.016755399984996	0.00087267708255185
0.01657237922	0.052083333333	0.016572379223052	0.00086314475120061
0.01478476049	0.052083333333	0.015678569858789	0.00081659218014528
0.01693842075	0.052083333333	0.015861590620733	0.00082612451149652
0.01478476049	0.052083333333	0.015861590620733	0.00082612451149652
0.01306995223	0.052083333333	0.013927356361812	0.00072538314384436
0.01143068845	0.052083333333	0.012250320337623	0.00063803751758452
0.01207713973	0.052083333333	0.011753914088868	0.00061218302546189
0.01079681371	0.052083333333	0.011436976719039	0.00059567587078326
0.01111216578	0.052083333333	0.010954489740838	0.00057054634066864
0.01079681371	0.052083333333	0.010954489740838	0.00057054634066864
0.00727070595	0.052083333333	0.009033759826491	0.00047050832429639
0.00727070595	0.052083333333	0.007270705946491	0.00037868260137975
0.00520454629	0.052083333333	0.006237626118273	0.00032487636032672
0.00449397055	0.052083333333	0.004849258421511	0.00025256554278705
0.0033937196	0.052083333333	0.003943845076702	0.00020540859774492
0.00298471098	0.052083333333	0.003189215291904	0.00016610496311999
0.00240666698	0.052083333333	0.002695688979482	0.00014040046768137
0.00154520621	0.052083333333	0.001975936592114	0.00010291336417259
0.00278720333	0.052083333333	0.002166204768101	0.00011282316500526
			0.563

DYE RECOVERY % = 56.30 %

DYE RECOVERY % : RUN 3

A	B	C	D
Ci / Co	t/ theoretical	Mean Dimensionless	Column C * Column B
Dimensionless	Dimensionless	concentration	Dimensionless time
0	0	0	0
0	0.04166666667	0	0
0	0.04166666667	0	0
0	0.04166666667	0	0
0	0.04166666667	0	0
0	0.04166666667	0	0
0.000827508	0.04166666667	0.000413754018742	1.723975078093E-05
0.0592034932	0.04166666667	0.03001550061608	0.0012506458590033
0.3011184411	0.04166666667	0.18016096714059	0.0075067069641911
0.2144334751	0.04166666667	0.2577759581005	0.010740664920854
0.7047875154	0.04166666667	0.45961049525462	0.019150437302276
0.9804651667	0.04166666667	0.84262634105276	0.035109430877198
0.9516340511	0.04166666667	0.96604960889613	0.040252067037339
0.9425923419	0.04166666667	0.94711319646694	0.039463049852789
0.9516340511	0.04166666667	0.94711319646694	0.039463049852789
0.9395851717	0.04166666667	0.94560961141033	0.03940040047543
0.9245999633	0.04166666667	0.93209256751758	0.038837190313232
0.9022810951	0.04166666667	0.91344052919064	0.03806002204961
0.8611339536	0.04166666667	0.88170752436717	0.036737813515299
0.8350398186	0.04166666667	0.84808688613619	0.035336953589008
0.7390377587	0.04166666667	0.78703878866924	0.032793282861218
0.6367062945	0.04166666667	0.68787202662643	0.028661334442768
0.7556794118	0.04166666667	0.69619285317126	0.029008035548803
0.6604576325	0.04166666667	0.70806852212948	0.029502855088728
0.5926824453	0.04166666667	0.62657003888433	0.026107084953514
0.5104394936	0.04166666667	0.5515609694496	0.0229817070604
0.465073598	0.04166666667	0.48775654578764	0.020323189407818
0.4234800936	0.04166666667	0.44427684577653	0.018511535240689
0.465073598	0.04166666667	0.44427684577653	0.018511535240689
0.421209619	0.04166666667	0.44314160849283	0.018464233687201
0.3965187054	0.04166666667	0.40886416219944	0.01703600675831
0.3572586206	0.04166666667	0.37688866302664	0.015703694292777
0.3298084112	0.04166666667	0.34353351592862	0.014313896497026
0.2950904912	0.04166666667	0.31244945118248	0.013018727132603
0.2316738461	0.04166666667	0.2633821686135	0.010974257025562
0.1295276569	0.04166666667	0.18060075146224	0.0075250313109267
0.1119728151	0.04166666667	0.12075023596345	0.0050312598318102
0.1177246068	0.04166666667	0.11484871092263	0.0047853629551097
0.1077257018	0.04166666667	0.11272515428377	0.0046968814284903
0.0980422676	0.04166666667	0.10288398471902	0.004286832696626
0.0834847768	0.04166666667	0.090763522217592	0.003781813425733
0.0721976729	0.04166666667	0.077841224847345	0.0032433843686394
0.074656049	0.04166666667	0.073426860952999	0.0030594525397083
0.0709793474	0.04166666667	0.072817698187732	0.0030340707578222
0.0592034932	0.04166666667	0.065091420283634	0.0027121425118181

A	B	C	D
Ci / Co	t/ theoretical	Mean Dimensionless	Column C * Column B
Dimensionless	Dimensionless	concentration	Dimensionless time
0.0638238365	0.04166666667	0.031911918229757	0.0013296632595732
0.05806754	0.04166666667	0.060945688234957	0.0025394036764565
0.0514160074	0.04166666667	0.054741773724331	0.0022809072385138
0.0471415723	0.04166666667	0.049278789864529	0.002053282911022
0.0450535707	0.04166666667	0.046097571473095	0.0019207321447123
0.0389918797	0.04166666667	0.042022725164536	0.0017509468818557
0.0380117425	0.04166666667	0.038501811065574	0.0016042421277322
0.0370403903	0.04166666667	0.037526066374674	0.0015635860989448
0.0360778913	0.04166666667	0.036559140813946	0.0015232975339144
0.0314007041	0.04166666667	0.033739297696025	0.0014058040706677
0.0269561472	0.04166666667	0.029178425650453	0.0012157677354356
0.0260960795	0.04166666667	0.026526113367976	0.0011052547236657
0.0244055289	0.04166666667	0.025250804199843	0.0010521168416601
0.0180532479	0.04166666667	0.021229388408788	0.00088455785036616
0.0173072579	0.04166666667	0.017680252916448	0.00073667720485202
0.0144358911	0.04166666667	0.015871574495746	0.00066131560398941
0.0137469705	0.04166666667	0.014091430781249	0.00058714294921871
0.0111121658	0.04166666667	0.012429568135059	0.00051789867229413
0.0092685979	0.04166666667	0.010190381843568	0.00042459924348202
0.0075456273	0.04166666667	0.008407112606223	0.00035029635859263
0.0059509252	0.04166666667	0.006748276226522	0.00028117817610508
0.0044939706	0.04166666667	0.005222447852758	0.00021760199386492
0.002984711	0.04166666667	0.003739340768169	0.00015580586534037
0.0027872033	0.04166666667	0.002885957155469	0.00012024821481123
0.002984711	0.04166666667	0.002885957155469	0.00012024821481123
0.0025944874	0.04166666667	0.002789599211391	0.00011623330047461
0.0025944874	0.04166666667	0.002594487439411	0.0001081036433088
0.0025944874	0.04166666667	0.002594487439411	0.0001081036433088
0.002406667	0.04166666667	0.002500577207503	0.00010419071697928
0.002406667	0.04166666667	0.002406666975594	0.00010027779064976
0.0022238531	0.04166666667	0.002315260021352	9.646916755633E-05
0.0020461653	0.04166666667	0.002135009171108	8.895871546282E-05
0.0018737327	0.04166666667	0.001959949001673	8.166454173637E-05
TOTAL			0.7666

% DYE RECOVERY = 76.66 %

APPENDIX I

DYE RECOVERY CALCULATIONS

The area under the normalised curve of concentration versus time is the amount of dye recovered. Spreadsheet were set-up in appendix I and their calculations explained below.

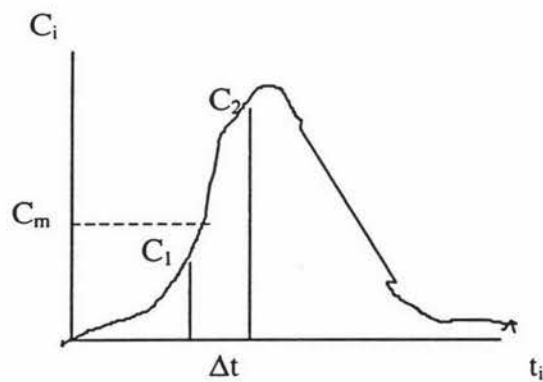
1. Column A : C_i / C_o where C_i = dye concentrations obtained by tracer study

C_o = initial concentration of dye added to wetland (1857.7 $\mu\text{g} / \text{L}$)

2. Column B : Δt / theoretical retention time (96 hours)

where Δt = time intervals (hours)

3. Column C :using the least square approximation method, the mean concentration, $C_m = (C_2 + C_1) / 2$. This is graphically represented below.



4. Column D : area under the normalised curve

APPENDIX J

DISPERSED PULG-FLOW AND TANK-IN-SERIES MODEL

* O Dimensionless	** DISPERSION NUMBER D / uL Dimensionless	*** DISPERSED PLUG-FLOW MODEL			**** TANK-IN-SERIES MODEL	
		PART 1	PART 2	Eo = Co	Eo for N=8	Eo for n=9
0	0.07	ERR	ERR	ERR	0	0
0.04		5.59	2.295E-40	1.3E-39	2.082E-07	2.106E-08
0.07		3.95	4.435E-19	1.8E-18	1.993E-05	3.887E-06
0.11		3.23	5.066E-12	1.6E-11	0.0002546	7.184E-05
0.15		2.80	1.605E-08	4.5E-08	0.0014262	0.00051741
0.18		2.50	1.92E-06	4.8E-06	0.0050851	0.00222376
0.22		2.28	4.465E-05	0.0001	0.0136244	0.00689458
0.25		2.11	0.00040713	0.00086	0.0299708	0.0170629
0.29		1.98	0.00206823	0.00409	0.0570681	0.03580626
0.33		1.86	0.00711351	0.01326	0.0973223	0.06624448
0.36		1.77	0.01862088	0.03293	0.1521481	0.11096351
0.40		1.69	0.03996541	0.0674	0.2217006	0.17151109
0.44		1.61	0.07390846	0.11933	0.3048164	0.24806829
0.47		1.55	0.12188624	0.18907	0.3991395	0.33934281
0.51		1.49	0.18370731	0.2746	0.5013824	0.44267671
0.55		1.44	0.25764824	0.37207	0.6076636	0.55432315
0.58		1.40	0.3408162	0.47654	0.7138647	0.6698281
0.62		1.36	0.42962473	0.58278	0.8159623	0.78445028
0.65		1.32	0.52026147	0.68585	0.9103047	0.89356191
0.69		1.28	0.60907468	0.78151	0.9938161	0.99298793
0.73		1.25	0.69284877	0.86649	1.0641244	1.07925901
0.76		1.22	0.7689682	0.93851	1.119616	1.14976909
0.80		1.19	0.83548593	0.99625	1.1594297	1.20284114
0.84		1.17	0.89111929	1.03924	1.1834015	1.23771333
0.87		1.14	0.93519624	1.06768	1.1919761	1.25446304
0.91		1.12	0.96757231	1.08232	1.1860978	1.25388746
0.94		1.10	0.98853417	1.08429	1.1670931	1.23735931
0.98		1.08	0.99870116	1.07497	1.1365538	1.20667333
1.02		1.06	0.9989327	1.05584	1.0962295	1.16389661
1.05		1.04	0.99024579	1.02846	1.0479314	1.11123188
1.09		1.02	0.97374506	0.99432	0.9934528	1.05089978
1.13		1.00	0.95056575	0.95487	0.9345057	0.98504341
1.16		0.99	0.92182918	0.91142	0.872673	0.91565569
1.20		0.97	0.88860941	0.86516	0.809377	0.84452876
1.24		0.96	0.85190984	0.81714	0.74586	0.7732231
1.27		0.95	0.81264795	0.76826	0.6831763	0.70305353
1.31		0.93	0.77164668	0.7193	0.6221937	0.63508901
1.34		0.92	0.72963113	0.67088	0.563601	0.57016288
1.38		0.91	0.68722919	0.62352	0.5079214	0.50889065
1.42		0.90	0.64497512	0.57763	0.4555281	0.45169274
1.45		0.88	0.60331513	0.53353	0.4066628	0.39881983
1.49		0.87	0.56261425	0.49143	0.3614541	0.35037912
1.53		0.86	0.52316399	0.4515	0.3199357	0.30636013
1.56		0.85	0.48519021	0.41383	0.2820646	0.26665892
1.60		0.84	0.44886102	0.37847	0.2477363	0.23110026

* O	** DISPERSION NUMBER D / uL	*** DISPERSED PLUG-FLOW MODEL			**** TANK-IN-SERIES MODEL	
		PART 1	PART 2	Eo = Co	Eo for N=8	Eo for n=9
Dimensionless	Dimensionless					
1.64	0.07	0.83	0.41429439	0.34542	0.2168004	0.19945719
1.67		0.82	0.38156533	0.31465	0.1890728	0.17146788
1.71		0.82	0.35071253	0.28612	0.1643466	0.14684987
1.74		0.81	0.32174442	0.25974	0.142402	0.12531156
1.78		0.80	0.2946446	0.23542	0.1230131	0.10656153
1.84		0.79	0.25352394	0.1992	0.0957682	0.08074111
1.90		0.77	0.21722724	0.16795	0.0739946	0.06064954
1.96		0.76	0.18541865	0.14112	0.0567667	0.0451892
2.02		0.75	0.1577194	0.11823	0.0432603	0.03341416
2.08		0.74	0.1337337	0.09878	0.0327612	0.02453074
2.14		0.73	0.11306736	0.08233	0.0246637	0.01788766
2.20		0.72	0.09534064	0.06846	0.0184643	0.01296053
2.27		0.71	0.08019662	0.05681	0.0137502	0.00933402
2.33		0.70	0.06730606	0.04706	0.0101886	0.0066839
2.39		0.69	0.05636988	0.03891	0.0075137	0.0047603
2.45		0.68	0.04711964	0.03212	0.0055161	0.00337287
2.51		0.67	0.03931693	0.02647	0.0040323	0.00237813
2.57		0.67	0.03275178	0.02179	0.0029356	0.00166895
2.63		0.66	0.02724068	0.01791	0.0021289	0.00116606
2.69		0.65	0.02262424	0.01471	0.0015381	0.00081124
2.75		0.64	0.01876482	0.01207	0.0011074	0.0005621
2.81		0.64	0.01554416	0.00989	0.0007945	0.00038797
2.87		0.63	0.01286108	0.00809	0.0005682	0.00026679
2.93		0.62	0.01062933	0.00662	0.0004051	0.0001828
2.99		0.62	0.00877572	0.00541	0.000288	0.00012483
3.05		0.61	0.00723827	0.00442	0.0002041	8.496E-05
3.11		0.60	0.00596466	0.0036	0.0001443	5.765E-05
3.17		0.60	0.00491089	0.00294	0.0001017	3.9E-05
3.23		0.59	0.00403997	0.0024	7.151E-05	2.63E-05
3.29		0.59	0.00332093	0.00195	5.016E-05	1.769E-05
3.36		0.58	0.00272786	0.00159	3.51E-05	1.187E-05
3.42		0.58	0.00223916	0.00129	2.451E-05	7.938E-06
3.48		0.57	0.0018368	0.00105	1.707E-05	5.298E-06
3.54		0.57	0.0015058	0.00085	1.187E-05	3.527E-06
3.60		0.56	0.00123371	0.00069	8.234E-06	2.342E-06
3.66		0.56	0.00101022	0.00056	5.701E-06	1.552E-06
3.72		0.55	0.00082678	0.00046	3.94E-06	1.026E-06

*, **, ***, **** Refer to appendix J for clarification

NORMALISED CURVE DATA FOR RUN 2

** O Dimensionless time	** Ci * ti	*** E = Ci / Q	**** Eo = E * t
0	0	0	
0.04	0	0	0
0.07	0	0	0
0.11	0	0	0
0.15	0	0	0
0.18	0	0	0
0.22	4.61	1.53E-05	0.00127108
0.25	30.37	1.01E-04	0.0083705
0.29	138.35	4.58E-04	0.0381311
0.33	317.33	1.05E-03	0.08746055
0.36	531.31	1.76E-03	0.14643711
0.40	726.05	2.40E-03	0.20011163
0.44	696.95	2.31E-03	0.19208867
0.47	692.82	2.29E-03	0.19095195
0.51	922.90	3.05E-03	0.25436421
0.55	837.77	2.77E-03	0.23090261
0.58	1020.29	3.38E-03	0.28120786
0.62	2487.94	8.23E-03	0.68571326
0.65	3246.25	1.07E-02	0.8947156
0.69	3973.37	1.31E-02	1.09512156
0.73	4823.58	1.60E-02	1.32945037
0.76	5523.85	1.83E-02	1.52245684
0.80	5447.24	1.80E-02	1.50134114
0.84	5404.84	1.79E-02	1.48965496
0.87	4979.05	1.65E-02	1.3723009
0.91	4533.78	1.50E-02	1.24957741
0.94	4134.14	1.37E-02	1.13943115
0.98	4273.71	1.41E-02	1.17789878
1.02	4080.30	1.35E-02	1.12459284
1.05	3822.35	1.27E-02	1.05349834
1.09	3189.77	1.06E-02	0.87914837
1.13	3008.62	9.96E-03	0.82922112
1.16	2824.47	9.35E-03	0.77846703
1.20	2677.47	8.86E-03	0.73795006
1.24	2624.70	8.69E-03	0.7234058
1.27	2605.00	8.62E-03	0.71797793
1.31	2423.72	8.02E-03	0.66801436
1.34	2178.97	7.21E-03	0.6005579
1.38	2008.96	6.65E-03	0.55370102
1.42	1843.86	6.10E-03	0.50819561
1.45	1627.86	5.39E-03	0.44866317
1.49	1638.99	5.42E-03	0.45173126
1.53	1358.37	4.50E-03	0.3743873
1.56	945.77	3.13E-03	0.26066968
1.60	768.36	2.54E-03	0.2117712

** O Dimensionless time	** Ci * ti	*** E = Ci / Q	*** Eo = E * t
1.64	494.24	1.64E-03	0.13622028
1.67	395.58	1.31E-03	0.10902646
1.71	358.96	1.19E-03	0.09893558
1.74	307.98	1.02E-03	0.08488355
1.78	190.49	6.30E-04	0.05250112
1.84	308.79	6.13E-04	0.05106414
1.90	300.18	5.96E-04	0.04964121
1.96	270.75	5.38E-04	0.0447733
2.02	266.63	5.29E-04	0.04409237
2.08	262.53	5.21E-04	0.0434151
2.14	262.53	5.21E-04	0.0434151
2.20	230.58	4.58E-04	0.0381311
2.27	226.69	4.50E-04	0.03748764
2.33	215.16	4.27E-04	0.03558045
2.39	181.85	3.61E-04	0.03007242
2.45	185.45	3.68E-04	0.03066829
2.51	157.33	3.12E-04	0.02601793
2.57	153.93	3.06E-04	0.02545568
2.63	153.93	3.06E-04	0.02545568
2.69	137.33	2.73E-04	0.02270985
2.75	157.33	3.12E-04	0.02601793
2.81	137.33	2.73E-04	0.02270985
2.87	121.40	2.41E-04	0.02007585
2.93	106.17	2.11E-04	0.01755789
2.99	112.18	2.23E-04	0.01855086
3.05	100.29	1.99E-04	0.01658424
3.11	103.22	2.05E-04	0.01706863
3.17	100.29	1.99E-04	0.01658424
3.23	67.53	1.34E-04	0.01116803
3.29	67.53	1.34E-04	0.01116803
3.36	48.34	9.60E-05	0.00799434
3.42	41.74	8.29E-05	0.00690288
3.48	31.52	6.26E-05	0.00521286
3.54	27.72	5.51E-05	0.00458461
3.60	22.35	4.44E-05	0.00369671
3.66	14.35	2.85E-05	0.00237348
3.72	25.89	5.14E-05	0.00428123
TOTAL		100720.16	

*, **, ***, **** Refer to appendix J for clarification

NORMALISED CURVE DATA FOR RUN 3

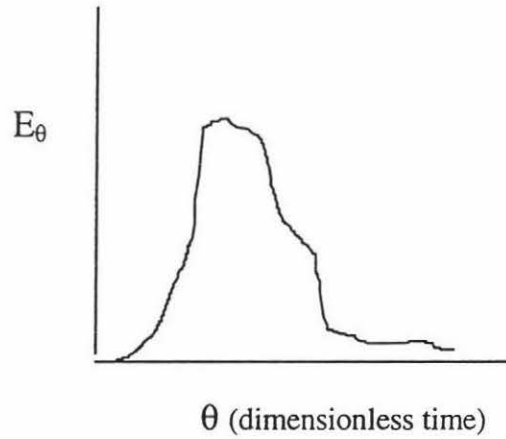
** O Dimensionless time	** Ci * ti	*** E = Ci / Q	**** Eo = E * t
0	0	0	0
0.048875855327468	0	0	0
0.097751710654936	0	0	0
0.1466275659824	0	0	0
0.19550342130987	0	0	0
0.24437927663734	0	0	0
0.29325513196481	6.14904672494	1.1226E-05	0.00091871
0.34213098729228	439.929317231	0.00080313	0.06572835
0.39100684261975	2237.55091203	0.00408486	0.3343049
0.43988269794721	1593.41226688	0.00290892	0.23806633
0.48875855327468	5237.1350694	0.00956088	0.78246261
0.53763440860215	7285.64056079	0.01330062	1.08852288
0.58651026392962	7071.40230678	0.01290951	1.05651426
0.63538611925709	7004.21517384	0.01278685	1.04647606
0.68426197458456	7071.40230678	0.01290951	1.05651426
0.73313782991202	6981.86949416	0.01274606	1.04313747
0.78201368523949	6870.51740726	0.01254278	1.02650073
0.83088954056696	6704.67036136	0.01224001	1.00172209
0.87976539589443	6398.91418278	0.01168182	0.95604009
0.9286412512219	6205.01388423	0.01132784	0.92707011
0.97751710654936	5491.64177746	0.01002551	0.8204876
1.0263929618768	4731.23713345	0.00863732	0.70687811
1.0752688172043	5615.30257324	0.01025126	0.83896334
1.1241446725318	4907.72857524	0.00895952	0.7332471
1.1730205278592	4404.10471464	0.00804011	0.65800237
1.2218963831867	3792.97378893	0.00692443	0.56669537
1.2707722385142	3455.86889195	0.00630901	0.51632966
1.3196480938416	3146.79587924	0.00574477	0.47015211
1.3685239491691	3455.86889195	0.00630901	0.51632966
1.4173998044966	3129.92443683	0.00571397	0.46763141
1.466275659824	2946.45119611	0.00537902	0.44021929
1.5151515151515	2654.71735832	0.00484644	0.39663233
1.564027370479	2450.740342	0.00447406	0.36615681
1.6129032258065	2192.75842169	0.00400309	0.32761261
1.6617790811339	1721.52201538	0.0031428	0.25720677
1.7106549364614	962.494112556	0.00175712	0.14380298
1.7595307917889	832.047594238	0.00151898	0.12431341
1.8084066471163	874.78800801	0.00159701	0.13069911
1.8572825024438	800.488144894	0.00146137	0.11959822
1.9061583577713	728.532482406	0.00133	0.10884757
1.9550342130987	620.358679383	0.00113252	0.09268569
2.0039100684262	536.486467809	0.00097941	0.08015463
2.0527859237537	554.754168931	0.00101276	0.08288394
2.1016617790811	527.433334456	0.00096288	0.07880203
2.1505376344086	439.929317231	0.00080313	0.06572835

* O Dimensionless time	** Ci * ti		*** Eo = E * t
2.1994134897361	474.262163963	0.00086581	0.0708579
2.2482893450635	431.488276309	0.00078772	0.0644672
2.297165200391	382.062068072	0.00069749	0.0570826
2.3460410557185	350.299595378	0.0006395	0.05233708
2.3949169110459	334.784072826	0.00061118	0.05001895
2.4437927663734	289.740859479	0.00052895	0.0432892
2.4926686217009	282.457655853	0.00051565	0.04220104
2.5415444770283	275.239732181	0.00050248	0.04112264
2.5904203323558	268.08759494	0.00048942	0.04005406
2.6392961876833	233.3323517	0.00042597	0.0348614
2.6881720430108	200.305738947	0.00036568	0.029927
2.7370478983382	193.914747482	0.00035401	0.02897215
2.7859237536657	181.352604214	0.00033108	0.02709528
2.8347996089932	134.150074562	0.0002449	0.02004291
2.8836754643206	128.606772181	0.00023478	0.0192147
2.9325513196481	107.270219345	0.00019583	0.01602688
2.9814271749756	102.150988354	0.00018649	0.01526203
3.030303030303	82.5722814422	0.00015074	0.01233684
3.0791788856305	68.8730973641	0.00012573	0.0102901
3.128054740958	56.0700473445	0.00010236	0.00837724
3.1769305962854	44.2201346236	8.0728E-05	0.00660678
3.2258064516129	33.393796385	6.0964E-05	0.00498925
3.2746823069404	22.1787903752	4.0489E-05	0.00331366
3.3235581622678	20.7111504865	3.781E-05	0.00309438
3.3724340175953	22.1787903752	4.0489E-05	0.00331366
3.4213098729228	19.2791172648	3.5196E-05	0.00288043
3.4701857282502	19.2791172648	3.5196E-05	0.00288043
3.5190615835777	19.2791172648	3.5196E-05	0.00288043
3.5679374389052	17.8834609622	3.2648E-05	0.00267191
3.6168132942326	17.8834609622	3.2648E-05	0.00267191
3.6656891495601	16.5250073711	3.0168E-05	0.00246895
3.7145650048876	15.2046449263	2.7758E-05	0.00227167
3.7634408602151	13.923333157	2.5418E-05	0.00208024
TOTAL	136941.73146		

APPENDIX J

CALCULATIONS

In fitting the models for nonideal flow, it is convenient to normalise the concentration versus time diagram (that is, the C-diagram). The normalised graph is sketched below and has dimensionless axis (Levenspeil, p271, 1979)



where θ = dimensionless time units
 $= t_i / \bar{t}$ and \bar{t} = mean retention time

also $E_\theta = \bar{t} E = C_\theta$
 $=$ dimensionless concentration units

$$\begin{aligned} \text{and } E &= C_i / Q \\ &= C_i / \sum C_i \Delta t_i \end{aligned}$$

Dispersed Plug Flow Model

Levenspeil (1979) suggest using the following equation for small extends of dispersion

$$C_\theta = \frac{1}{2 [\pi (D/uL)]^{0.5}} \exp [- (1-\theta) / 4\theta(D/uL)]$$

Tank - in - Series Model

Levenspiel (1979) also suggest the following equation for Tank-in-series model;

$$E_{\theta} = \frac{N(N\theta)^{N-1}}{(N-1)!} e^{(-N\theta)}$$

Where N = number of reactors

APPENDIX J

FLOW MODEL CALCULATIONS

DISPERSED PLUG-FLOW

For small extents of dispersion :

$$E_{\theta} = C_{\theta} = \frac{1}{2 \left(\pi \theta \frac{D}{uL} \right)^{0.5}} \exp \left[- (1 - \theta)^2 / \left(4 \theta \frac{D}{uL} \right) \right]$$

where C_{θ} = dimensionless concentration

$$\theta = t_i / \bar{t} \quad \text{and} \quad \bar{t} = \text{average of the mean retention times (days)}$$

$$\begin{aligned} & \text{i.e. } (\bar{t}_2 + \bar{t}_3) / 2 \\ &= (83.28 + 81.84) / 2 \\ &= 82.56 \text{ hours} \\ &= 3.44 \text{ days} \end{aligned}$$

D/uL = average dispersion number of runs 2 and 3
now for small extents of dispersion :

$$\sigma_{\theta}^2 = 2 D/uL$$

to estimate D/uL for the subsurface wetland, take the average of runs 2 and 3

$$\begin{aligned} \text{that is, } (D/uL)_{\text{average}} &= \frac{(D/uL)_2 + (D/uL)_3}{2} \\ &= (0.055 + 0.085) / 2 \\ &= 0.07 \end{aligned}$$

TANK-IN-SERIES

$$E_{\theta} = C_{\theta} = \frac{N (N \theta)^{N-1} \exp(-N \theta)}{(N-1)!}$$

Where N = number of reactors

$$= 1 / \sigma_{\theta}^2$$

also σ_{θ}^2 = average of runs 2 and 3

$$\text{that is, } (\sigma_{\theta}^2)_{\text{average}} = \frac{(\sigma_{\theta}^2)_2 + (\sigma_{\theta}^2)_3}{2}$$

$$= (0.11 + 0.17) / 2$$

$$= 0.14$$

therefore, $N = 1 / 0.14$

$$= 7.14$$

so the number of mixed reactors is between $N = 8$ to $N = 9$