Evaluation of Baffles for Optimisation of Waste Stabilisation Pond Hydraulics

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Jill Helen Harrison

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ABSTRACT

Waste stabilisation ponds are a common form of treating wastewater throughout the world and they provide a reliable, low-cost, low-maintenance treatment system. A literature review undertaken highlighted the need for improved understanding of the hydraulics of such systems, and their upgrade. In particular, the application of baffles is not well understood beyond the use of longer, traditional baffles to increase the approximation to plug flow. The mechanisms and interactions behind baffles are not generally understood.

The work involved the use of CFD modelling to assess various pond designs. In addition to this, traditional tracer studies were carried out on a physical laboratory model, and on a full-scale field pond. These traditional studies highlighted the success of the computer modelling approach.

CFD modelling was used to model twenty pond designs, utilising various baffle lengths, number and position. These cases also studied inlet type and outlet position. In the second phase of the work, six of the CFD designs were tested in the laboratory setting. The final phase of work involved two tracer studies carried out on a field pond, utilising a modified inlet, then a combination of a modified inlet and the inclusion of a short (stub) baffle.

CFD modelling has shown to be an effective investigative and design tool. The addition of results from laboratory and field studies further emphasises the benefits of the CFD modelling. The work has also provided an understanding of key flow mechanisms and interactions that have previously been attributed to other factors.

Single baffles are not generally effective, and a minimum of two baffles will generally be required to achieve significant treatment improvements. The potential of short (stub) baffles has been shown, however they are sensitive to design changes and should be further researched.

Previous research has looked at the pond using a 'black-box' approach, this work seeks to open and explain the flow patterns within that 'black-box'.

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1. INTRODUCTION

This section will briefly introduce the need for the research, and the objectives and approach of the work.

1.1 The Need for the Research

Waste stabilisation ponds are a common technology used for treating domestic, agricultural and industrial wastewaters. They are common in New Zealand, but are also a low-cost, low-technology application for wastewater treatment in developing countries.

The overall efficiency of these systems is dependent on a number of factors. Watters (1971) cites biological factors as having been considered the most important, and hydraulic factors were given little attention. Over recent years, research has given more importance to hydraulic factors.

Hydraulic flow characteristics such as bulk flow patterns, short-circuiting, inlet and outlet positioning, presence of 'dead spaces' and the use of baffles are of significant importance to the overall efficiency of a pond system. Baffles can offer such improvements if properly designed. They can direct flow in such a way as to reduce hydraulic short-circuiting and the presence of dead spaces.

There are a great number of ponds used in New Zealand and throughout the world. These existing ponds are likely to be suffering from poor hydraulic, and therefore, treatment efficiency. This lack of efficiency can give ponds a bad reputation.

Despite the popularity of waste stabilisation ponds in New Zealand, and throughout the world, there is a clear lack of guidelines for engineers on the improvement of their hydraulic, and therefore, treatment efficiency. As they are in common usage, an improvement method that is efficient, and cost-effective, needs to be available.

1.2 Objectives and Approach

The aim of this research was to contribute to the improved understanding of baffle design and use in waste stabilisation ponds. The use of computational fluid dynamics (CFD) modelling as a design tool was also evaluated. The specific objectives of the thesis are given below:

- To investigate the use of baffles in waste stabilisation ponds in terms of:
  - Length of baffles
  - Number of baffles
  - Position of baffles
- To investigate the effect of inlet type, and outlet position
- To evaluate the use of CFD as a design tool to investigate various baffle configurations
- To apply the findings of the work into the field environment

To achieve the given objectives, the work was completed in three phases. In the first phase of work, a range of pond configurations was tested within the CFD environment. This produced an idea of the hydraulic and treatment efficiency of each configuration and allowed a large range of designs to be tested in a timely manner. The time and cost involved with laboratory models and field studies can often be prohibitive.

The second phase of the work involved taking some well-performing configurations from the CFD environment and testing them in a laboratory model pond. The use of CFD modelling as a design tool is relatively new to the field of waste stabilisation ponds, therefore the comparison between the CFD results and a traditional testing method was beneficial.

The final phase of work involved the implementation of two pond configurations in a full-scale field pond. The results were compared with those obtained from the CFD and laboratory modelling. The ultimate test of any design is how it performs in the field situation and therefore the field studies performed for this work offered the final test of the CFD modelling tool.

2. LITERATURE REVIEW

2.1 Waste Stabilisation Ponds

Waste stabilisation ponds (oxidation ponds, lagoons) are relatively shallow bodies of wastewater contained in an earthen basin (Metcalf & Eddy, 1991). The technology is well-used and the reasons for this are summarised by Shelef & Kanarek (1995), and Mara *et al.*, (1992a):

Advantages

- Low capital investment, especially with regard to construction cost
- Simple flow scheme, equipment and installation (minimum of piping, pumping, aeration, and reduced need for pre-treatment)
- Low energy and operating costs
- Simplicity of operation
- Relatively high and consistent level of treatment – due to long retention time, biological competition and settling
- Buffering of peak hydraulic loads
- Relative resistance to shock organic loads, therefore suited to summer tourist locations with higher temperatures providing raised treatment efficiency and the ability to allow increased loading
- Sludge digestion is incorporated into treatment, particularly with the use of anaerobic ponds
- Some 'ultimate disposal' due to evaporation and seepage (unlined ponds)
- Some nutrient removal
- Algal harvesting (high-rate ponds)
- Effluent storage for reuse by irrigation

Disadvantages

- High land area requirements
- Effluent can contain high suspended algal concentrations, the disposal of which to receiving bodies is controversial
- Performance is dependent to a large extent on climatic conditions such as wind, temperature, solar irradiance

- Overloading or abrupt climatic changes can cause odour nuisances and deterioration of effluent quality
- Possibility of groundwater contamination by seepage from ponds
- Water losses due to evaporation and seepage in situations where water for reuse is considered an important commodity

These lists are comprehensive, although to some extent, the disadvantages listed above can be reduced. For example, by lining a pond the problem of seepage and the possibility of groundwater contamination can be removed. Also the use of anaerobic ponds at the front end of a pond system can reduce the land area required.

Wood (1997) stated that the continued use of pond technology is being undermined by the inconsistent performance relative to current discharge requirements, particularly with respect to suspended solids, pathogen, and nutrien t removal. As the public grows more aware of the issues relating to the protection and sustainability of our natural environment, the regulations governing such issues become more stringent. Craggs (1998) also commented on the declining popularity of pond systems due to the demand for consistent and high quality discharges. Fritz *et al.*, (1979) reports that waste stabilisation ponds have "fallen into disfavour" (pg. 2724) due to high land requirements, high organic concentrations in effluent and dependence on environmental factors.

Fritz *et al.*, (1979) noted that many of the problems, as mentioned above, result from a lack of understanding of the basic biomechanical mechanisms involved in ponds, improper operation and system overloading. Wood (1997) commented on the apparent simplicity of ponds and how it can be deceiving, "...for their performance in removing pollutants is a complex function of fluid hydrodynamics, the contacting of biomass with pollutants, physico-chemical and biological mechanisms."(pg. 2).

As has been shown, waste stabilisation ponds have a large number of advantages relevant for many small to medium size communities, and for developing areas. However, their sometimes low treatment efficiency can put them into disfavour. This can lead to the implementation of 'higher technology' treatment systems in developing areas where the infrastructure and expertise is not available to support them.

Research needs to be carried out into the reasons for poor performance of existing ponds and into the development of new pond designs.

2.2 Types of Ponds

The classification of ponds is usually based on the nature of the biological activity within the pond - aerobic, anaerobic, or facultative. An anaerobic pond when used, is the first pond in a series and is termed a primary pond. Aerobic ponds can be termed primary or secondary ponds depending on whether it follows an anaerobic pond. Facultative ponds have an anaerobic zone on the bottom, with the aerobic zone near the surface. Maturation ponds and high rate algal ponds are also discussed.

2.2.1. Anaerobic

Anaerobic ponds when used, are the first ponds in a series. They receive the highest organic loading and their purpose is to remove the bulk of this organic load. Their depth is in the range of 2-5m in order to accommodate the accumulation of sludge. The depth also maintains anaerobic conditions by reducing the surface area to volume ratio (Mara *et al.*, 1992a).

The treatment performance of an anaerobic pond is highly dependent on temperature, with the critical temperature for methanogenesis about 10°C. Below this temperature minimal sludge digestion occurs and the pond acts more as a settlement pond. In warmer climates therefore, anaerobic ponds are particularly effective. Mara *et al.*, (1992a) mention that in temperatures above 20°C, 60% of the BOD (biochemical oxygen demand) can be removed in a pond with a one day retention time.

A typical problem with the existence and operation of anaerobic ponds is the potential for objectionable odours due to fermentation proc esses (hydrogen sulphide and other volatile by-products). Many district and regional councils in New Zealand make mention of "offensive or objectionable odours" within various rules and policies. Odour is therefore an important issue from an operator's point of view, as that of the public. According to Meiring *et al.*, 1968 (in Curtis and Mara, 1994), control of odour can be achieved by ensuring organic loads of less than 400g/m^{3}d as long as the incoming sewage has a sulphate concentration of less than 500mg/L. Normal domestic or municipal wastewaters contain less than 300mg sulphate/L (Mara & Pearson 1998).

A novel application of anaerobic pond technology is within the Advanced Integrated Wastewater Pond System (AIWPS) developed during more than 35 years of pond research at the University of California at Berkley by Oswald and co-workers (Craggs *et al.*, 1998). As part of the AIWPS system, Oswald *et al.*, (1994) investigated the use of fermentation pits within a primary facultative pond. These pits are semi-enclosed in the anaerobic bottom layer of a deep facultative pond. The semi-enclosed nature prevents oxygenated water from the aerobic layer entering the pit and helps prevent odour escaping.

2.2.2. Facultative

Facultative ponds are the most common type of pond in use throughout the world. There are two types: primary – which receive raw wastewater, and secondary – which receive settled wastewater, often from a front end anaerobic pond. Pelczar *et al.*, (1993) define facultative anaerobes as organisms that do not require oxygen for growth (but may use it if available), which grow well under both aerobic and anaerobic conditions, and for which oxygen is not toxic.

Facultative ponds are designed to remove BOD on a surface loading basis of 100-400 kg BOD/ha.d (Mara *et al.*, 1992a). The loading of a facultative pond is lower than that of an anaerobic pond. High removal of pathogens is also seen in facultative ponds (Mara *et al.*, 1992b).

The lower layer of a facultative pond acts in a manner similar to that of an anaerob ic pond, as shown in Figure 2-1. It has a sludge layer below an anoxic water layer. The upper reaches of the pond are aerobic due to diffusion of oxygen from the atmosphere and the presence of oxygen-producing algae. The presence of the algae in the facultative ponds gives them a characteristic dark green colour, however when the ponds become overloaded they may appear red or pink due to the presence of anaerobic purple sulphide-oxidising photosynthetic bacteria (Mara *et al.*, 1992a).

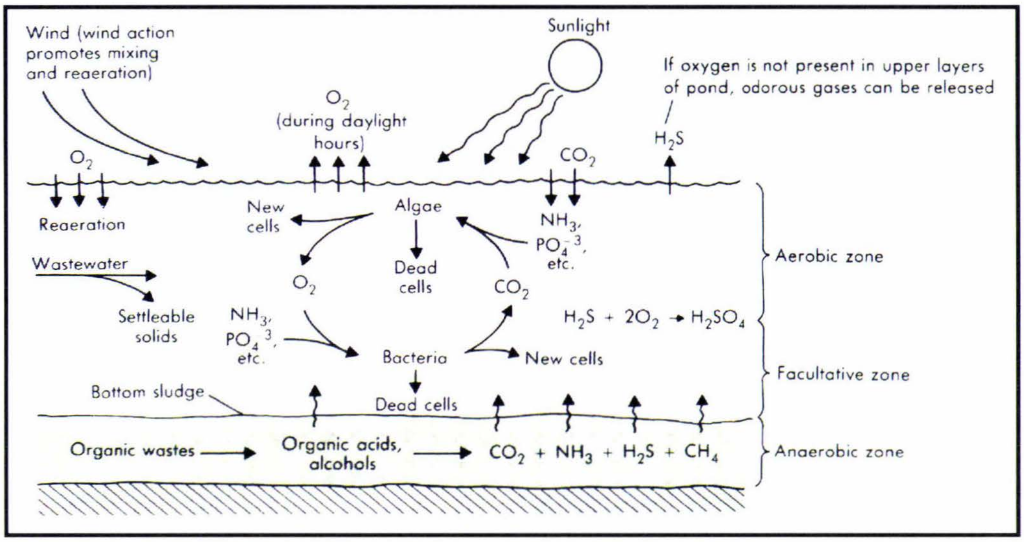


Figure 2-1 Facultative Pond (Tchobanoglous and Schroeder, 1985, pg 635)

2.2.3. Maturation Ponds

Maturation ponds are predominantly designed to achieve pathogen removal. They are typically aerobic throughout their depth (1-1.5m). Their BOD removal is quite small, but their contribution to nitrogen and phosphorus removal can be significant (Mara *et al.*, 1992a).

Pathogen die-off is promoted by the high pH levels generated in the ponds (Mara *et al.*, 1992b), with reductions of 4-6 log units of faecal coliforms, 2-4 log units for faecal viruses. Curtis and Mara (1994) categorises the mechanisms by which pathogens are removed from ponds: the dark mechanisms, pH, and light. Dark mechanisms are those of starvation (due to lack of nutrients), predation (by protozoa) and enteric bacteria binding to algae. In regard to pH, *Escherichia coli* are known to require a neutral pH, therefore an increase in pH can rapidly kill the bacterial cells. With respect to light – the energy in sunlight is transferred to bacterial and viral cells in such a manner as to cause parts of the cell or virus to be destroyed. Curtis and Mara (1994) discusses this mechanism in detail.

2.2.4. High-Rate Algal Ponds

High-rate algal ponds were developed at the University of California (USA) by Oswald and co-workers (Shelef and Azov, 1987). High-rate algal ponds are usually 'race track' shaped and are mixed with a paddle wheel. High-rate algal ponds are shallower than conventional facultative ponds, but require a much shorter retention time and produce far more dissolved oxygen (Green *et al.*, 1996). As reported by Green *et al.*, (1996) a well-designed high-rate algal pond will generate high amounts of dissolved oxygen per unit area.

Another advantage of such systems is the harvesting and processing of the algal-bacterial biomass to produce potentially valuable proteinaceous animal feed that may be needed where feed shortages may occur (Shelef and Azov 1987). This however is not an issue in New Zealand due to readily available protein sources.

These systems have been researched extensively in recent times, with a number of papers presented at the 5th IWA Specialist Conference on Waste Stabilisation Ponds held in Auckland, New Zealand, 2002. They included: Chen *et al.*, (2002); Craggs *et al.*, (2002a & 2002b); Cromar & Fallowfield (2002); da Costa *et al.*, (2002); El Hamouri *et al.*, (2002); and Jupsin *et al.*, (2002).

2.3 Pond Design

There are a number of alternative approaches to the design of waste stabilisation ponds, these include:

- Loading Rates
- Empirical Design Equations
- Rational Models
- Mechanistic Modelling

2.3.1. Loading Rates

In the loading rate approach, parameters such as flow, population, or BOD loading are used to determine the volume or area of a pond required. This sim plified process design approach has been very commonly used throughout the world. For example, a design guideline produced in New Zealand in 1974 gave a figure of 84 kg

BOD_5/ha.d as the design loading for raw sewage ponds and secondary ponds (MWD 1974). This type of approach ignores the effects of pond shape, wastewater characteristics, temperature and so on.

Recent design guidelines (Mara & Pearson 1998, Mara *et al.*, 1992b) provide design equations based on loading rates which take into account the effect of temperature on the performance of various pond types (anaerobic, facultative and maturation).

With respect to maturation ponds, Mara & Pearson (1998) suggest a minimum acceptable retention time of 3 days (4-5 days for temperatures below 20°C). The reason for this is to minimize hydraulic short-circuiting and prevent algal washout. The basis for this arbitrary value and the reasoning is not given.

The loading rate approach to pond design essentially treats a pond as a 'black box' and while temperature effects are taken into account, many other aspects of pond performance - shape for example - are largely ignored.

2.3.2. Empirical Design Equations

Empirical design equations are derived from regression of experimental pond performance data. Design approaches include areal loading, the McGarry and Pescod relationship, Bucksteeg recommendations, Gloyna equation and the Larson Relation (Wood 1997).

As this method involves the regression of data for one particular pond or a series of ponds the question is raised as to how applicable the equations will be in other locations. Prats and Llavador (1994) and Wood (1997) reported that as correlations are based on data collected from selected sites or locations, the validity of this method when applied to other different sites is debatable.

2.3.3. Rational Models

This design approach uses theory developed in the field of reactor engineering. First order reaction kinetics is typically assumed for removal rates. There are two flow regimes – ideal and non-ideal. Attempts have also been made to produce a combined model incorporating both flow regimes.

2.3.3.1. Ideal Flow

Ideal flow is a theoretical concept for which zero mixing (plug-flow) or infinite mixing (completely mixed flow) is assumed. Both types of ideal flows have been used to describe waste stabilisation pond systems.

Plug flow assumes no diffusion or mixing of the substrate occurs in the reactor, or pond in this application. Essentially, this means that the incoming wastewater travels as a slug from the inlet to the outlet. The integrated rate equation is as follows:

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

where C_e = effluent concentration (mg/L)

C_i = influent concentration (mg/L)

k = first order reaction rate constant (1/d)

t = time (d)

Middlebrooks (1987) conducted an investigation to evaluate the most frequently used design equations. He found that the first order plug flow model gave the best fit of all the rational models. As reported by Wood (1997), "while the plug flow is a simple model being applied to a complex system, it is often superior to a multi-parameter model with several undetermined coefficients." (pg. 25)

At the other extreme, completely mixed flow assumes the substrate is instantaneously mixed upon entering the reactor. For this mixing regime the CSTR (completely stirred tank reactor) equation can be derived:

$$C_e/C_i = 1/(1+kt)$$

The completely mixed model was used by Marais and Shaw (1961) using first order kinetics for the prediction of faecal bacteria reduction in ponds. Marais further expanded on this theory to incorporate the effect of anaerobic conditions on bacterial death rate and the influence of temperature (Marais 1966, 1970 and 1974, in Shilton 2001). Marais (1974) proposed the general CSTR requation as a method for designing pond systems:

$$C_e/C_i = 1/(1+kt)^n$$

where n = number of ponds in series

There are limitations to assuming 'ideal' conditions with regard to the flow within waste stabilisation ponds. "The accuracy of these equations may vary substantially with actual pond conditions and therefore their application is limited" (Preul and Wagner 1987, pg. 206).

2.3.3.2. Non-Ideal Flow

In reality, flow through reactors and waste stabilisation ponds will exist somewhere between the two extremes of plug flow and completely mixed flow. This is termed non-ideal flow.

Thirumurthi (1969) concluded from studies on design principles for waste stabilisation ponds, that the Wehner-Wilhem equation is a basic tool suitable for design.

Wehner and Wilhelm (1956) presented an analysis of the boundary conditions for a steady-state flow reactor with first order reaction kinetics and axial diffusion. The equation they derived is valid for reactors with any kind of entry or exit configurations. The common form of the equation is given below:

$$C_e/C_i = 4a\ .\ (\ e^{1/2d} / [(1+a)^2 . e^{a/2d} - (1-a)^2 e^{-a/2d}]\ )$$

where $d = D/uL$ (dispersion number)

$a = \sqrt{1 + 4k_t d}$

Ce, Ci = effluent and influent substrate concentrations

D = axial dispersion co-efficient (m^2/h)

u = fluid velocity (m/h)

L = characteristic length (m)

k = first order reaction constant (1/h)

t = detention time (h)

[Levenspiel, 1972, pg. 286]

Thirumurthi (1969) further simplified the equation by neglecting the second term in the denominator:

$$C_e/C_i = 4a. [e^{1-a/2d} / (1+a)^2]$$

The error involved in neglecting the second term of the equation is not significant until the value of the dispersion number exceeds two. After this point the error may be significant, however Thirumurthi (1969) noted that due to the low hydraulic loads the value of the dispersion number is unlikely to exceed one in waste stabilisation ponds.

In the conclusion to an investigation into the use of the Wehner-Wilhelm equation, Polpraset and Bhattarai (1985) stated "It was found that this equation could perform with a high degree of accuracy in the prediction of the total and faecal coliform die-off; and the results obtained had significantly higher correlation coefficient values than those of the completely mixed equations" (pg. 56).

2.3.3.3. Combined Pond Models

Models have been developed combining plug, completely mixed and dispersed flow. In these models the pond is considered as a number of separate hut interconnected flow regions with flow exchange hetween them.

Watters *et al.*, (1973) used one such method to model results of their field and laboratory experimental investigations. The model used was the Finite Stage Model. This model consists of a series of modules containing three flow units as shown in Figure 2-2 below: Completely Mixed Flow unit (F_a), Dead Flow unit (F_b), and a Plug Flow unit (F_c).

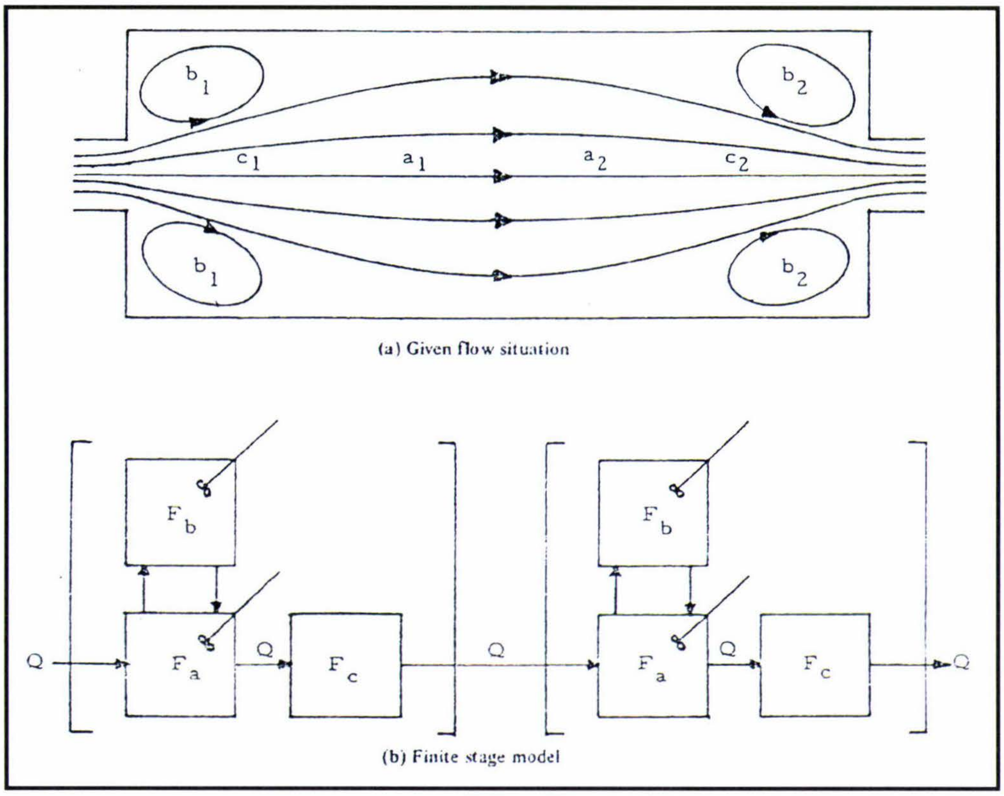


Figure 2-2 Finite Stage Model (Watters *et al.*, 1973, pg 16)

The use of combined pond models has produced good model fits, however, the method is not predictive. Parameters used in these models need to be calculated using experimental data. Ferrara and Harleman (1981) noted that the input parameter values needed by these models cannot be reliably predicted at this time.

2.3.4. Mechanistic Modelling

According to Colomer and Rico (1993), the application of a mechanistic model for a pond system consists of "considering a biological reactor and applying a complete material balance, including terms for substances produced or consumed, inflow, outflow, and accumulation for each component. Resolving simultaneously the system differential equations for all components, the evolution of each one with the time is obtained." (pg. 679). Two of the significant investigations on mechanistic modelling were carried out by Fritz *et al.*, (1979) and Colomer and Rico (1993).

Fritz *et al.*, (1979) proposed a mechanistic model for waste stabilisation ponds. Upon reviewing existing models describing the behaviour of pond systems the following comment was made: "There are no comprehensive models that can predict performance based on the variety of physical and biochemical factors that govern the quality of pond effluents." (pg. 2725). The authors go on to say that non-steady-state simulations of biomass and biochemical species whose kinetics are dependent on environmental factors have not previously been performed. The model proposed by Fritz *et al.*, (1979) consisted of twelve mass balance equations for biochemical and biomass components. Figure 2-3 below shows a schematic diagram of the processes occurring in a pond ecosystem.

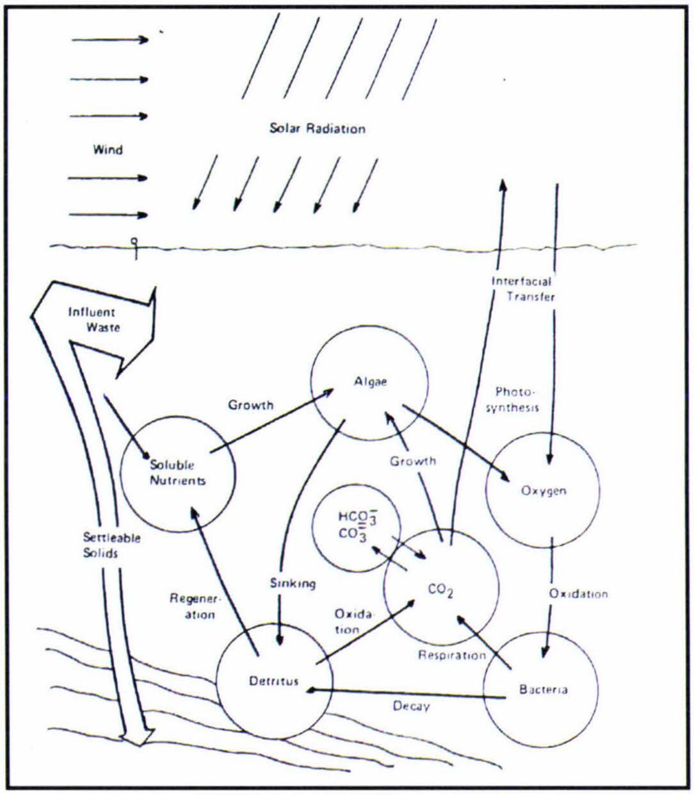


Figure 2-3 Schematic diagram of processes in a pond ecosystem (Fritz *et al.*, 1993, pg 2725)

The model as developed gave some reasonable results, however the authors listed a series of conclusions and recommendations highlighting areas for further development to improve the model.

Colomer and Rico (1993) proposed a revision to the Fritz *et al.*, (1979) model which was then tested against a set of field data. The authors concluded that the revised model "provides values in the same order of magnitude as real data, and it reproduces reasonably well the variations registered." (Colomer and Rico, 1993, pg. 683) They also concluded that the revised model was indeed an improvement on the

Fritz *et al.*, (1979) model and that the calculated concentrations of effluent depend significantly on the influent characteristics. The processes within the pond contribute less to the calculations.

2.4 Importance of Pond Hydraulics

The performance of ponds has been said to be largely dependent on climatic conditions. Kilani and Ogunrombi (1984) stated that hydraulic flow pattern in stabilisation ponds is one of the major factors influencing pond performance. A thorough knowledge of the hydraulic characterisations in ponds would seem important for efficient and more appropriate pond design.

Wood (1997) stated that the pond hydraulic s is often the limiting factor in achieving high pond performance, while Thirumurthi (1969) outlined that little attention had been given to pond shape, presence of dead spaces, inlet/outlet flow patterns.

Watters *et al.*, (1973) stated that little attention had been given in the past to the hydraulic characteristics of waste stabilisation ponds. Particular reference was given to the gross flow patterns within ponds which are affected by the shape of the lagoon, presence of dead spaces, existence of density differences, and the positioning of inlets and outlets. They concluded from their research that the pond hydraulics are important in determining the treatment efficiency of that pond. Hydraulic factors should be considered to maximise economy of construction and operation for maximum treatment.

Moreno (1990) made various conclusions relating to the hydraulics of a pond in her tracer study of the hydraulics of facultative stabilisation ponds. Hydraulics play a major role in the performance of ponds; dead volume within one pond studied was as high as 42%. This indicates the need for a thorough revision of the elements of design that influence the mixing of water inside ponds. Moreno (1990) proposed six factors that needed careful attention at the design stage of ponds to achieve good hydraulic performance:

- The main axis of flow should not be aligned with the prevailing wind direction.
- Ponds should be located a distance away from any element that may shield a pond from the mixing effect of wind.
- The simplest measure to avoid short-circuiting in ponds is to avoid locating inlet and outlets close together.
- Multiple inlets and outlets as well as the use of diffusers have proved useful in the prevention of short-circuiting.
- The shape of the ponds should be rectangular with rounded corners. Other shapes (branching, kidney, circular) have been shown to result in a higher degree of short-circuiting.
- The use of baffles improves performance. However, this measure results in a considerable increase in the cost of ponds.

Moreno (1990) commented that the performance of stabilisation ponds can be improved substantially through simple and economical measures to correct circulation patterns inside ponds. Also, while it would be far better to consider hydraulic implications during the design process, it is feasible to improve the hydraulics of existing ponds.

Wood (1997) in his doctorate thesis on the development of computational fluid dynamics models for the design of waste stabilisation ponds made some interesting comments. Mention was made that the factors which influence the hydraulics of ponds are well known, however the relative importance of these factors (wind, thermal energy, geometry, inlet design & baffles) is poorly quantified. This reduces pond design to an art form, relying more on experience than the application of the fundamental phenomena involved. Also, while small-scale experimental studies provide an economic evaluation of pond designs, scale-up issues are often a hindrance.

Shilton (2001) concluded that despite the research he reviewed, the insight into pond hydraulic behaviour is poor in the majority of the studies consisting of stimulus response tests – a black-box approach. Also, that the lack of mechanistic research has retarded efforts to improve and optimise hydraulic and treatment efficiency at a practical design level.

Hydraulic efficiency is usually expressed in terms of the approximation to plug-flow, the amount of the pond that is utilised – or volume of dead space, the time taken for a peak of tracer to reach the outlet, or mean hydraulic residence time. As mentioned by many pieces of research, dead spaces usually occur in the corners of rectangular ponds, where the major water flow bypasses these areas and back-eddies are often formed.

2.5 Factors Affecting Pond Hydraulics

In this section, the factors affecting the hydraulics of ponds will be discussed, in particular: inlet/outlet configuration, wind, and stratification. Baffles are also a significant factor that can affect pond hydraulics and form a major part of the research for this thesis, and will be discussed in detail in Section 2.6.

2.5.1. Inlets/Outlet Configuration

Mention has been made by several researchers about the influence of inlet/outlet configuration on the hydraulics of a pond, but there have been few significant bodies of work that have investigated different configurations. Mara and Pearson (1998) stated: "A single inlet and outlet are usually sufficient. These should be located in diagonally opposite corners of the pond (the inlet should *not* discharge centrally in the pond as this maximises hydraulic short-circuiting). The use of complicated multi-inlet and multi-outlet designs is unnecessary and not recommended." (pg. 59). The statement above appears to have been based on available knowledge at the time. It has been seen since noted in further research that the inlet/outlet positions require careful thought on a site-by-site basis.

Pearson *et al.*, (1995) made the following conclusion: "...the positioning and depths of the inlet and outlets may have a greater beneficial impact on treatment efficiency than pond shape." (pg. 137). Indeed the work of Watters *et al.*, (1973) and Shilton (2001) also shows that the position and design of the inlet can have a significant impact on the hydraulic and treatment efficiency of a pond.

Watters *et al.*, (1973) used a scale model pond in a laboratory to investigate the effect of nine different inlet/outlet positions and designs (including various diffusers) on hydraulic and treatment efficiency. They are shown in Figure 2-4 below.

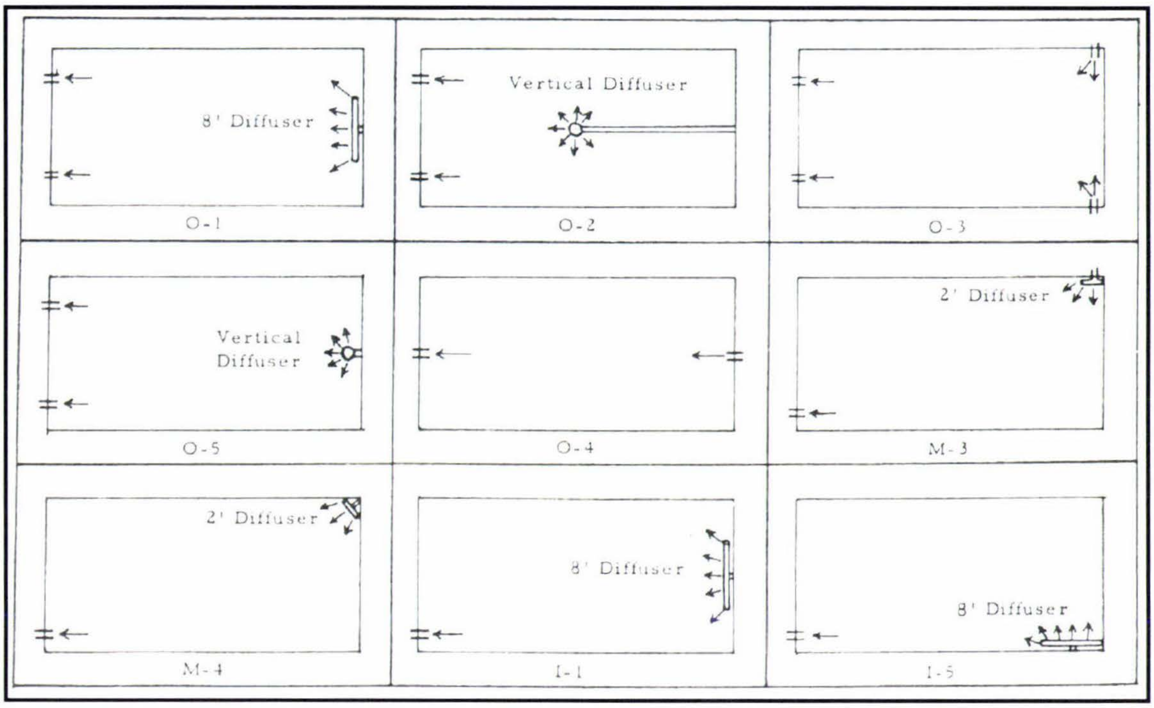


Figure 2-4 Inlet/Outlet Configuration tested by Watters *et al.*, (1973, pg 41)

Their research utilised tracer studies from which the concentration-versus-time curves could be used to calculate various hydraulic parameters. These curves were also combined with the first order reaction equation to determine treatment efficiency.

In their conclusions, they stated that the inlet and outlet types and configurations had a significant effect on the hydraulic characteristics and subsequent treatment efficiency determinations. A change of as much of 42% was indicated by the data for the important hydraulic parameters, while a change of 19% in treatment efficiency was indicated for the two extreme conditions of inlets and outlets.

The inlet/outlet configurations tested by Watters *et al.*, (1973) appear to have been arbitrarily chosen without taking into account the flow pattern that may form from the placing of the inlet. That is, they have not been chosen on the basis of what flow patterns may be created by the type and positioning of the inlet. For example, if the configuration of an existing pond was known to produce a slow circulation pattern with a significant dead space in one corner – then the best place for the outlet may be in that dead space.

Persson (2000) conducted a study using two-dimensional, vertically integrated numerical models to simulate hydraulic performance in 13 different pond layouts, including 5 with the same basic layout but differing inlets and outlets. The configurations tested are shown in Figure 2-5.

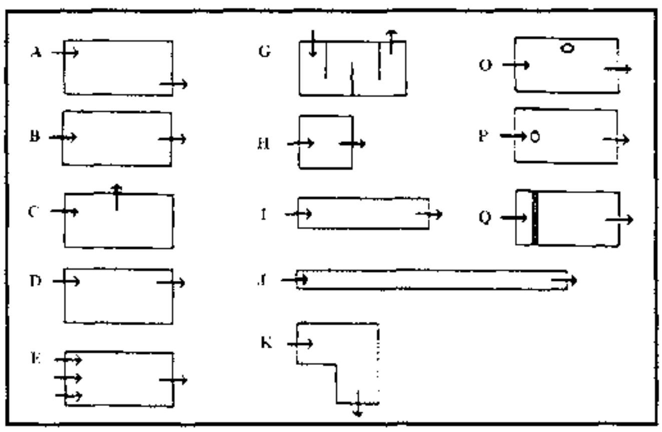


Figure 2-5 Configurations tested by Persson (2000)

Configuration 'E', with an inlet along the whole base of the pond, showed a close approximation to plug-flow and less short-circuiting. Persson (2000) concluded that the locations of inlets and outlets had a considerable impact on hydraulic performance. Configuration 'P', with an island placed in front of the inlet, showed an improved hydraulic performance. Figure 2-6 shows the HRT (hydraulic retention time) curves for the basic case (B), cases with either an island or sub-surface berm close to the inlet (P,Q), and the case with an inlet along the whole base (E). It can be seen that the addition of a blockage near the inlet, or type of inlet result in a significant improvement on the basic case.

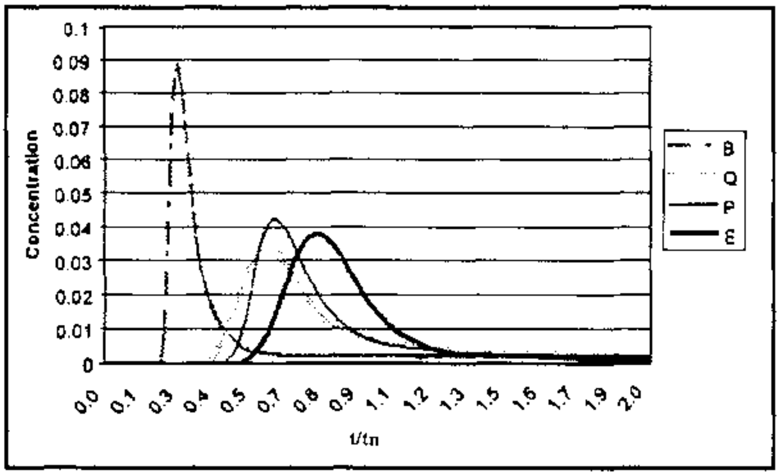


Figure 2-6 RTD Curves for Configurations B, Q, P, E (Persson, 2000, p246)

Shilton (2001) carried out investigations into the effect of outlet position, and into the effect of inlet type and position. With regard to the position of the outlet, it was observed that the outlet has minimal influence on the circulation pattern in the pond. The position of the outlet does change the overall flow pattern.

From his inlet investigations, Shilton (2001) also found the flow patterns of large and small horizontal inlets to be similar - except for the time lag due to the relative velocities produced by a large diameter inlet compared with a small diameter inlet. The most interesting result however was the investigation into an up-turned vertical inlet. When the pond had a horizontal inlet, a swirling pattern was produced in the pond - this led to short-circuiting. When the pond had an up-turned inlet, there was no swirling flow pattern produced and therefore short-circuiting was subsequently reduced.

Fares *et al.*, (1996) studied, as part of their investigations into hydrodynamic effects on ponds, the effects of changing the inlet/outlet arrangement of a waste stabilisation pond system in the Cayman Islands, British West Indies. Figure 2-7 shows the configurations tested.

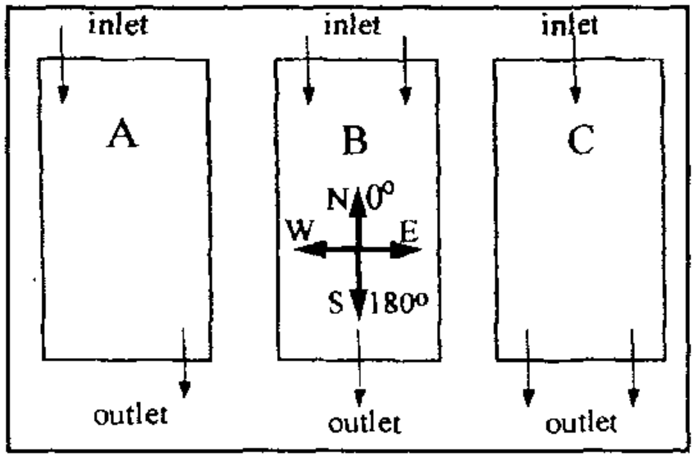


Figure 2-7 Inlet/Outlet Configurations tested by Fares *et al.*, (1996, Fig.2)

Fares *et al.*, (1996) concluded that the effect of the inlet/outlet arrangement only became significant at low wind speeds. A more thorough review of wind and its correlation with inlet influences can be found in Section 2.5.2 of this thesis.

Other authors have made mention of the importance of inlet/outlet position and design (Moreno, 1990) but have not specifically studied the effect of moving or redesigning inlets and outlets. This mention of the inlet/outlet importance is also often made without supporting data.

2.5.2. Wind

The effect of wind is often mentioned in literature as an influencing factor on pond hydraulics. For example, Thackston *et al.*, (1987) concluded that wind is an uncontrollable variable so basins should be designed for the worst-case scenario for wind speed and direction and geometry designed to resist wind effects. In particular, the outlet should be oriented towards the prevailing wind, and baffles should be used to force several changes in flow and direction. However there is an absence of extensive study exclusively on the effect of wind. As stated by Shilton (2001), despite being regarded as the dominant driving force of flow in ponds, the influence of wind has been poorly researched. Indeed, Marecos do Monte (1985) commented that the effect of wind, which influences mixing in ponds, is impossible to fully take into account.

Shilton (2001) included wind as a variable in a CFD model of a field pond. The results of the model were not far removed from the model without wind, and indeed the actual field results closely matched both models. He also performed an analysis of the power input by wind versus the power input from the inlet. Shilton (2001) concluded that the effect of wind may have been over-estimated and the effect of the inlet under-estimated and that under certain circumstances, the inlet could be sized to ensure that it dominates over wind as the driving factor for flow most of the time.

Other research has attempted to add the effect of wind into mathematical models: Fares & Lloyd (1995), Fares *et al.*, (1996) and Wood (1997). However this did not include extensive validation against field data.

A study was performed on quantifying wind effects by Watters *et al.*, (1973) at the Utah Water Research Laboratory. Their work involved the construction of a wind-water tunnel to simulate a wind over water situation, to evaluate diffusion coefficients as functions of wind shear for both stratified and un-stratified ponds. It is unclear from the work how the results found would then be applied to a field pond situation, with variable wind speed and direction.

2.5.3. Stratification

"Stratification is the temperature induced separation of the pond into layers." (Shilton 2001, pg. 45). The layers of a stratified pond will differ in temperature, dissolved oxygen concentration and redox measurements. The different dissolved oxygen levels will typically mean that the top layer is aerobic and the bottom layer is anoxic. Therefore, the biological and chemical characteristics of the two layers will be quite different.

Stratification in ponds may have a detrimental effect on the hydraulic behaviour of the system. An inflow to a pond could possibly travel in only the top or bottom layer of a stratified pond without mixing in to its full volume.

Watters *et al.*, (1973) carried out some work on the stratification of waste stabilisation ponds. Their work modelled three situations:

- Influent more dense than ambient fluid (summer time flows)
- Influent of the same density as ambient fluid
- Influent less dense than ambient fluid

Their conclusions were that the degree of stratification had an influence on the hydraulic performance. "For an increase in the degree of stratification…the influence on the hydraulic parameters and treatment efficiency depended on the type of stratification." (pg. 61). They found that when the density of the influent was *greater than* the density of the ambient fluid the hydraulic performance *improved*, when the density of the influent is *less than* the ambient fluid the hydraulic *efficiency decreased*.

Cavalcanti *et al.*, (2001) noted that the surprisingly high dead space volume in their polishing ponds was possibly due to a warmer and lighter upper layer on the surface over the cooler and denser bottom layer. Therefore, short-circuiting may have been occurring.

From their tracer studies, MacDonald & Ernst (1986) concluded that stratification was responsible for short-circuiting. This conclusion however, was based on the tracer output rather than actual measurements of tracer within the pond.

2.6 Baffles

Baffles are essentially obstacles placed in a flow-path to achieve better hydraulic, and in some applications, treatment efficiency. They have been used successfully in the water industry – chlorine contact tanks, water reservoirs, and stormwater detention ponds. Their benefits in nutrient removal and as attached growth systems is also recognised in the wastewater industry.

The use of baffles for the improvement of hydraulic and treatment efficiency in waste stabilisation ponds has formed a major part of the research for this thesis, therefore it has been discussed separately and in detail from the other factors influencing hydraulics.

In this section the application and benefits of baffles will be discussed, with specific regard to waste stabilisation ponds. Baffle use in water reservoirs, chlorine contact tanks and other uses will be included.

2.6.1. Hydraulic Investigations of Baffle Implementation

Baffles are commonly used as an attempt to improve the hydraulic and treatment efficiency of a waste stabilisation pond. Studies have been performed on a number of different baffle configurations with the general consensus being that the more baffles there are, the closer the approximation to plug-flow and the better the pond performance. As said by Reynolds *et al.*, (1975): "Baffles would also *(in addition to acting as attached growth systems)* affect the hydraulic flow pattern of the system and should reduce short circuiting and improve mixing conditions. Unfortunately, little research has been conducted in this area." (pg. 1005).

Watters *et al.*, (1973) performed 17 different tests on selected evenly spaced baffle arrangements. Tests were performed using four different lateral spacings, which corresponded to 2, 4, 6 & 8 baffles. These four spacings were tested using three lengths of baffles; they were 50%, 70% and 90% of the width of the pond. An example is shown below in Figure 2-8. This figure depicts a six-baffle case with the baffles extending 70% across the width of the pond.

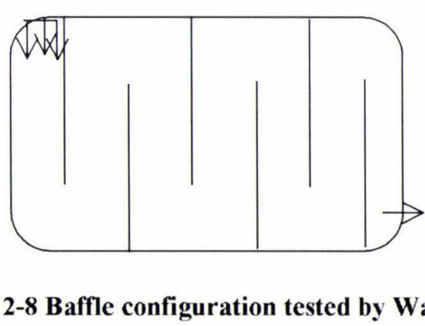


Figure 2-8 Baffle configuration tested by Watters *et al.*, 1973

The configuration shown in Figure 2-8 was found to be one of the best configuration of baffles. Surprisingly, the cases where baffles extended 90% across the width of the pond were less efficient than those only extending 70% across the width. This was explained as being due to higher velocity jets being created in the narrow flow path at the end of the baffles thus quickening the flow towards the outlet.

When the baffles extended 50% across the width of the pond, short-circuiting was discovered shown in Figure 2-9.

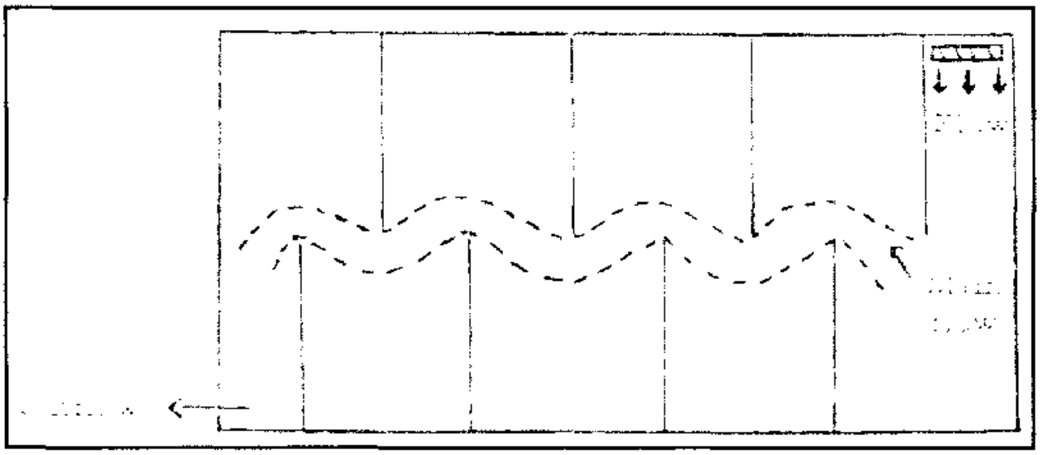


Figure 2-9 Short-circuiting caused by 50% width baffles - Watters *et al.*, 1973

The conclusion made was that the intermediate baffle size (70% of the pond width) gave the best results. The following figure (Figure 2-10) shows a graphical representation of their findings.

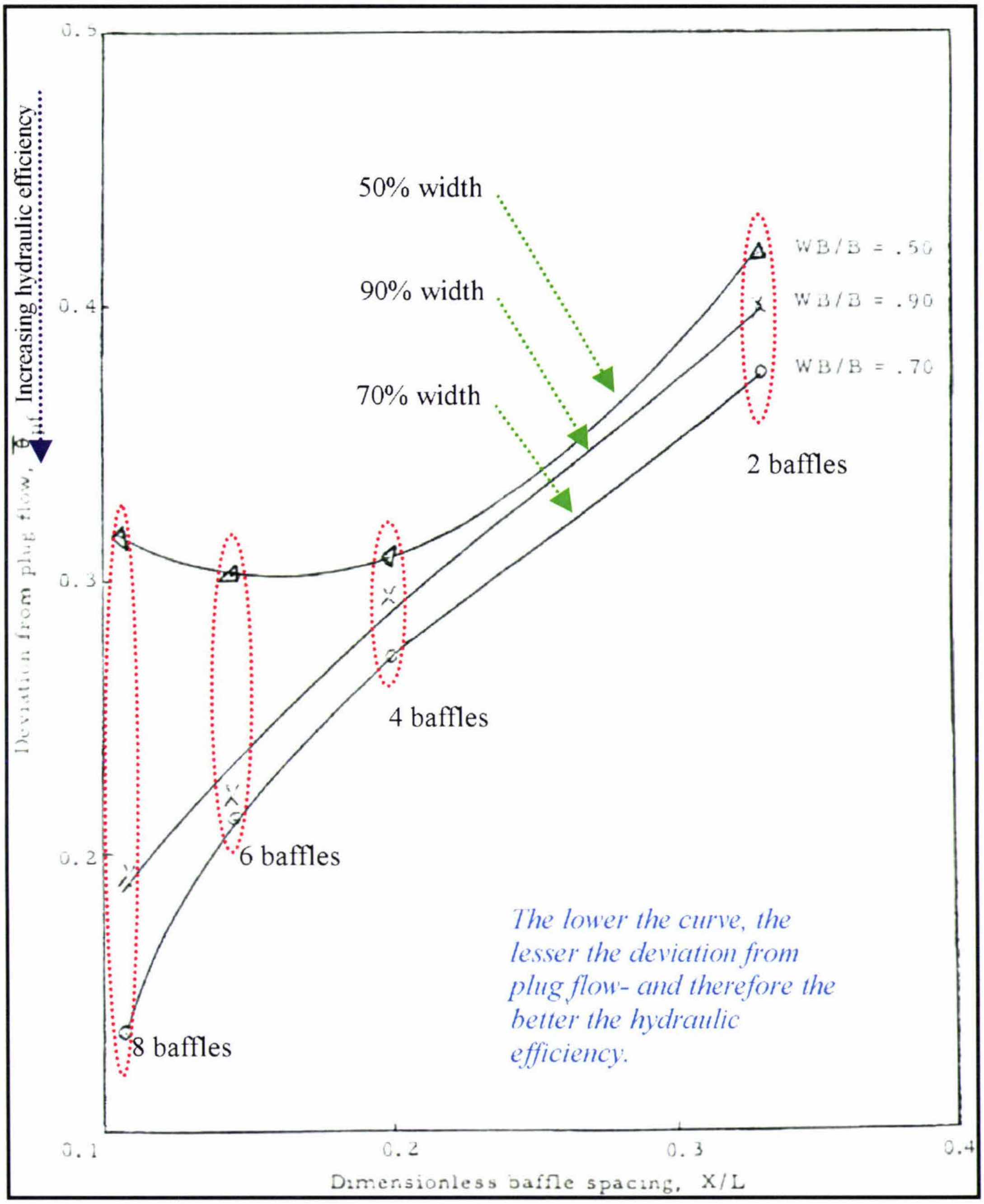


Figure 2-10 Plot of number of baffles versus hydraulic performance (adapted from Watters *et al.*, 1973, pg 47)

Tests were also performed on vertical baffling, where the flow takes an over-under path. A plan of the vertical baffles set-up is shown in Figure 2-11. It is probable that the vertical baffles were tested due to an expectation that fluid would mix well in each compartment prior to moving to the next. However, the results from these tests were not as good as for the horizontal lateral baffling. Reynolds *et al.*, (1975) also found similar results when comparing the performance of vertical baffling with horizontal baffling. The conclusion can be made that the short-circuiting due to the horizontal baffles also applies to the vertical baffling.

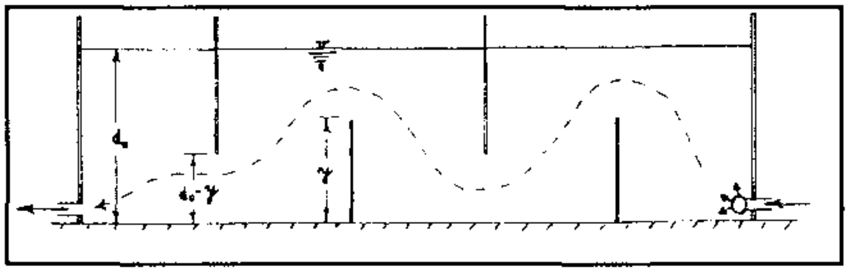


Figure 2-11 Vertical Baffle Configuration - Watters *et al.*, 1973

Nemerow (1969) investigated the use of a vertically baffled biological basin for the treatment of poultry plant wastes. The treatment system involved screening followed by a two-stage oxidation pond system, with final treatment by chlorination. The first stage of the pond system was a baffled, high rate, deep pond. With this baffle arrangement, some frequent scum removal was required, however on the whole the system worked very well with BOD removals of 85% to 95%. The baffles also provided extra biological surface area for BOD reduction. Unfortunately, no information was given as to the degree of improvement from the existing situation, so the effect of the baffle cannot be assessed.

Watters *et al.*, (1973) also tested longitudinal horizontal baffles, these baffles are positioned lengthways down the pond, as shown in Figure 2-12. The probable intention of the longitudinal baffles is to allow a large mixing area for the fluid prior to moving to the next compartment of the pond. However, the longitudinal baffles were found to be as effective as the transverse horizontal baffles with a similar length of flow path. The conclusion to be drawn from these results is that the fluid path within each compartment of the pond is the same regardless of the compartment size.

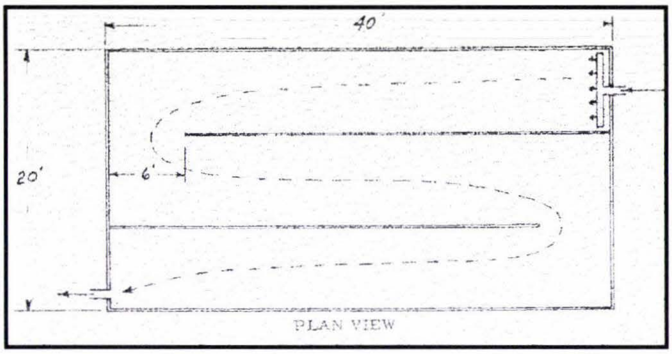


Figure 2-12 Longitudinal baffle configuration - Watters *et al.*, 1973

The baffle configurations chosen to be tested in the work of Watters *et* al., (1973) appear to have been systematically decided upon in terms of number and length. However, the flow patterns that may be set-up with the inclusion of baffles, do not appear to be taken into account.

Shilton (2001) tested the effect of adding a baffle to a pond combined with three different inlet types – small horizontal, large horizontal, and vertical upturned. With respect to the two horizontal inlets, an improvement on short-circuiting of a factor of approximately five was found. However, in the case of the vertical upturned inlet, a similar, and significant improvement was found both with and without the use of the baffle. The observation made here was that in some cases the installation of a baffle does not necessarily improve pond hydraulics by default.

Reynolds *et al.*,(1975) tested the performance of three baffle configurations in scale-model ponds in a laboratory setting. The purpose of the investigation was to assess the use of the Marais-Shaw model for describing the reduction of soluble organic matter occurring in a waste stabilisation pond (assumed to be a completely mixed reactor). The conclusions made in this study were:

- The Marais-Shaw model indicates that the biological degradation rates were significantly higher in the baffled ponds than in the control pond;
- If the kinetic constants determined for the Marais -Shaw model are applicable to full-scale systems, a conventional pond without baffles would require almost twice the land area as a longitudinally baffled pond to produce effluent of similar quality.

Bors and Robinson (1980) experimented with the addition of a baffle curtain extending the full width of a pulp and paper mill oxidation pond, which had one-foot square openings at two-foot intervals across the curtain. The tracer studies performed before and after the installation of the curtain showed hydraulic improvement. That is the volume of the pond utilized improved from 12% to 54% achieving a reduction in the amount of dead space. Also, the time taken for the first tracer peak to reach the outlet increased from 18 hours to 87 hours. Their conclusion was that the addition of one baffle curtain produced almost a five-fold increase in pond retention time.

In a study on the influence of pond geometry and configuration on pond performance and efficiency, Pearson *et al.*, (1995) concluded that a baffled pond (baffle configuration not given) was the most efficient of the tertiary maturation ponds in terms of pathogen and organic removal. They also concluded that more work was needed in this area to determine the performance of baffled ponds when receiving higher influent pathogen concentrations than in the tertiary maturation pond, that is in a primary or secondary treatment pond. The detail and discussion as to the reasoning for the better performance of the baffled pond are somewhat lacking. Interestingly, the comment was made that "the apparent lack of impact of pond shape on facultative pond performance within a realistic range of length:breadth ratios allows the designer more freedom in shaping the ponds." (pg. 137).

Von Sperling *et al.*, (2002) evaluated and modelled the removal of helminth eggs in baffled and un-baffled ponds treating anaerobic effluent. The work is focussed towards helminth eggs, rather than the benefits of baffles, however they concluded that helminth egg counts in the sludge decreased along the length of the baffled pond. [1]

Pena *et al.*, (2002) studied the improvement of mixing patterns in pilot-scale anaerobic ponds. Their experiments involved the use of horizontal and vertical baffling, ponds fitted with cross-sectional nets (stretching across the width of the pond) and a pond with a mixing pit. They determined that all modifications made to

[1] Helminth eggs are from a parasite that can infect the intestinal tract of humans, known to settle easily.

the anaerobic ponds improved the performance. From their results, it appears that the horizontal baffles produced the greatest efficiencies in total suspended solids removal.

Lloyd *et al.*, (2002) investigated the use of channelling (essentially long baffles), top baffles (vertical baffles), and the removal of wind effects on the hydraulic short-circuiting and pathogen removal of maturation ponds. They found that the channelling improved the removal efficiency from 90% to 96%. The addition of the top baffles actually reduced performance, and they were removed. The addition of wind-breaks to the channelled pond improved the removal to 98.13%. This work shows that while baffles can improve the performance of a pond system, they cannot be considered as the only option. A range of modifications may produce the best improvement.

Pedahzur *et al.*,(1993) investigated the effect of baffle installation on the performance of a single-cell stabilisation in the field. Contrary to other work carried out, the conclusion was made that the installation of up to four baffles did not improve pond hydraulic flow patterns nor the efficiency of removing microorganisms or BOD reduction. The explanation proposed for this lack of improvement was due to the other studies having been limited to model ponds that are not exposed to solar radiation and remaining unstratified. The indication of this work is that any trials involving the field application of baffles needs to be carefully considered.

2.6.2. Baffles & Wind

Thackston *et al.*,(1987) concluded that baffles reduce the influence of wind on short-circuiting. The wind is unable to establish surface currents that move directly from the inlet to outlet as it is forced to blow across or against the flow over a portion of the flow path. While wind-induced circulation patterns may still establish, they do not take the form of large currents over the entire pond.

2.6.3. Baffles & Attached Growth Systems

Middlebrooks *et al.*,(1982) made mention of the use of attached microbial growth in waste stabilisation ponds as an apparent practical solution for maintaining biological populations, while still obtaining desired treatment. While baffles are often considered useful in ensuring good mixing and to eliminate short-circuiting, they can also provide substrate on which bacteria, algae and other micro -organisms can grow. Experiments performed in the US showed that the presence of attached growth to the baffles gave higher efficiency of treatment than non-baffled cases (Middlebrooks *et al.*, 1982).

2.6.4. Nutrient Removal in Baffled WSP

A study conducted by Muttamara & Puetpaiboon (1996) evaluated the removal of nitrogen in baffled waste stabilisation ponds comprising laboratory and pilot-scale ponds with different numbers of baffles. The conclusion was made that compared with normal waste stabilisation ponds, the inclusion of baffles gave higher nitrogen and organic carbon efficiencies. In this case the baffles served as part of the driving mechanism for ammonia removal due to the attached growth of bacteria and algae.

Costa *et al.*, (2002) analysed the efficiency of baffles in ponds in relation to nutrient removal through mathematical modelling. The study was undertaken in facultative ponds treating piggery wastes. They concluded that the introduction of baffles in facultative ponds resulted in an improved removal of total solids and consequently of COD (chemical oxygen demand) and total phosphorus. There is little discussion as to the removal efficiency of nitrogen.

2.6.5. Baffles in Tanks & Reservoirs

In an investigation into models to study a water reservoir, Grayman *et al.*, (1996) looked at the addition of barriers (or baffles) to improve the performance of the reservoir. The purpose of the study was to compare different types of models (computational, physical etc), and the addition of baffles and inlet races (a curved baffle forming a channel from the inlet). Improvements in performance were found using inlet races combined with central outflows, and in the case of a dividing wall extending across the tank. Figure 2-13 below shows the four experiments run on tanks with baffles or inlet races added to enhance performance.

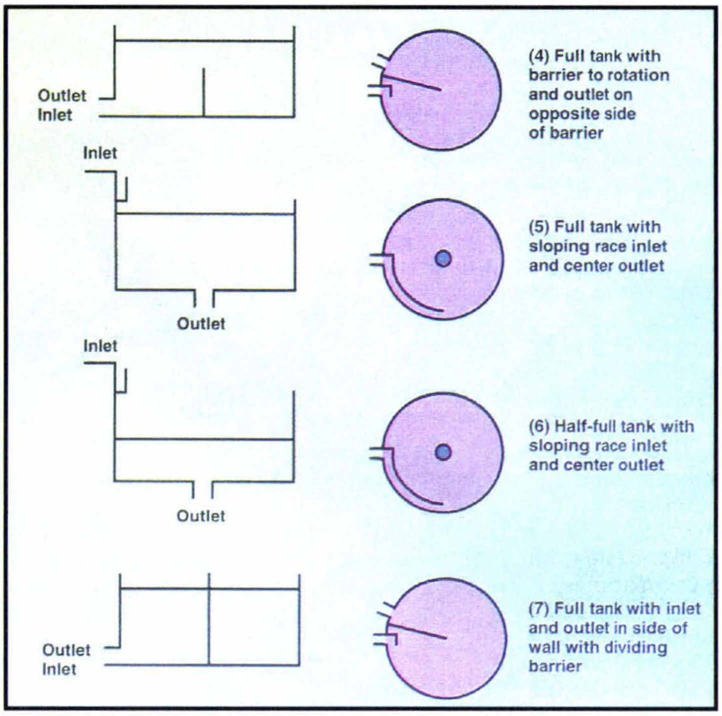


Figure 2-13 Experimental Set-ups for water reservoir study (Grayman *et al.*, 1996, pg. 66)

Figure 2-14 shows the dye patterns for the run performed on the full reservoir with a dividing barrier (Run 7 as shown in Figure 2-13). The figures show the fluid flow that is formed by the addition of a baffle. This visual assessment of the fluid flow allows the investigator to find the best position for an outlet. This set of figures suggests that to lengthen the time spent by the fluid in the tank, the outlet should be located next to the inlet but on the other side of the baffle.

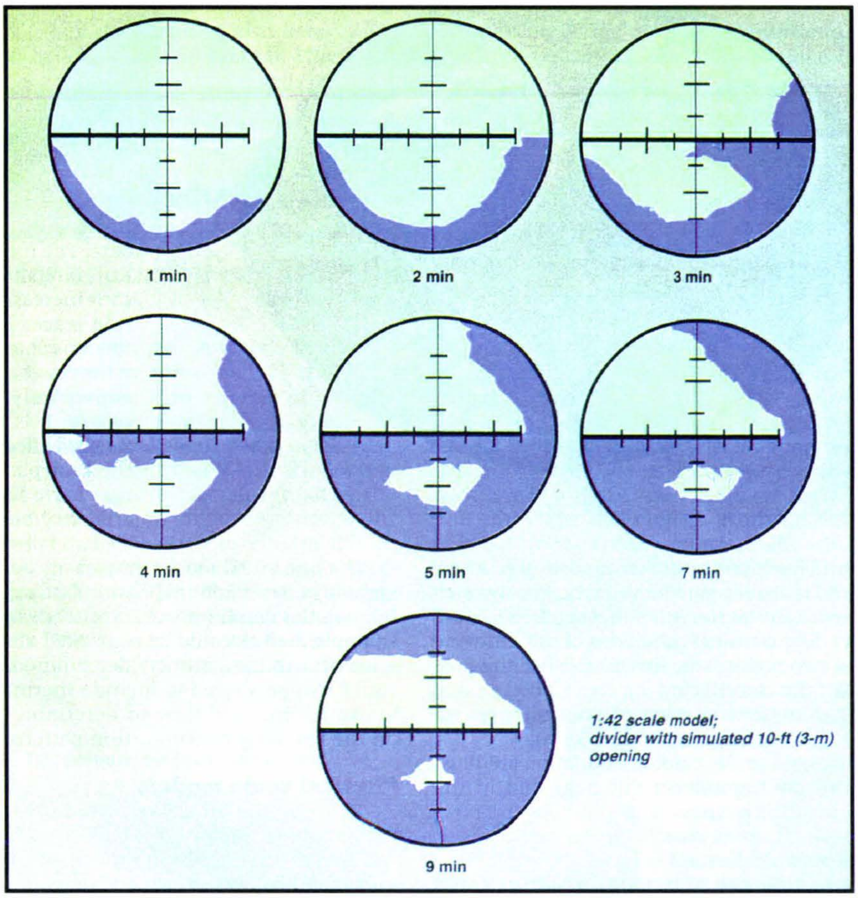


Figure 2-14 Dye patterns for water reservoir with dividing wall (Grayman *et al.*, 1996, pg. 70)

This work combines the use of inlets, outlets and baffles to improve the hydraulic efficiency of the tank systems. It shows that the position and type of baffles can be used to channel fluid in a more appropriate direction suitable for the application in question.

2.6.6. Chlorine Contact Tanks

As mentioned in Middlebrooks *et al*., (1982), a common practice for improving plug-flow conditions in a contact tank is to add baffles. The idea behind the addition of baffles is to increase the length-to-width ratio of the flow and therefore approximate plug-flow conditions and lengthen the time spent by the flow in the tank. The length–to-width ratio is considered to be the most important design consideration for chlorine contact tanks. Middlebrooks *et* al., (1982) gives a length-to-width ratio of 40:1 as being effective, although results have been obtained in similar experiments showing 25:1 as being very effective.

Hydraulic performance has also been improved by placing baffles near the inlet of tanks to dissipate the kinetic energy from inlet jetting. The use of 'T' shapes at baffle tips to reduce short-circuiting and flow separation, and corner fillers (rounded corners, or filling in corners) to eliminate dead spaces and to decrease solids build-up have been tried. The corner fillers have shown to have little impact on flow patterns, probably as they only fill in a dead space rather than affecting the major flow path.

2.6.7. Stormwater Detention Ponds

A study by Van Buren *et al.*, (1996) investigated the enhancement of removal of pollutants by an on-stream stormwater pond. On-stream ponds are located along existing urban areas and receive, as well as stormflow, a continuous baseflow of stormwater.

In this investigation, the performance of the existing pond was assessed and its remediation discussed. The remediation method discussed and tested was the addition of internal pond baffles. Simulations at a variety of flows were performed using PHOENICS software to investigate the effect of adding three internal baffles on hydraulic residence time. The baffles used were made of plastic curtains attached to posts and driven into the pond bottom. The simulated time taken for tracer to reach the pond outlet with no baffles was approximately 1 hour. When the simulation was run with the baffles in place, this time was increased to 15 hours. The concentration of the peak when it reached the outlet was also greatly reduced (1.5 ppb to 0.15 ppb). Figure 2-15 shows the results of the simulation both with and without baffles.

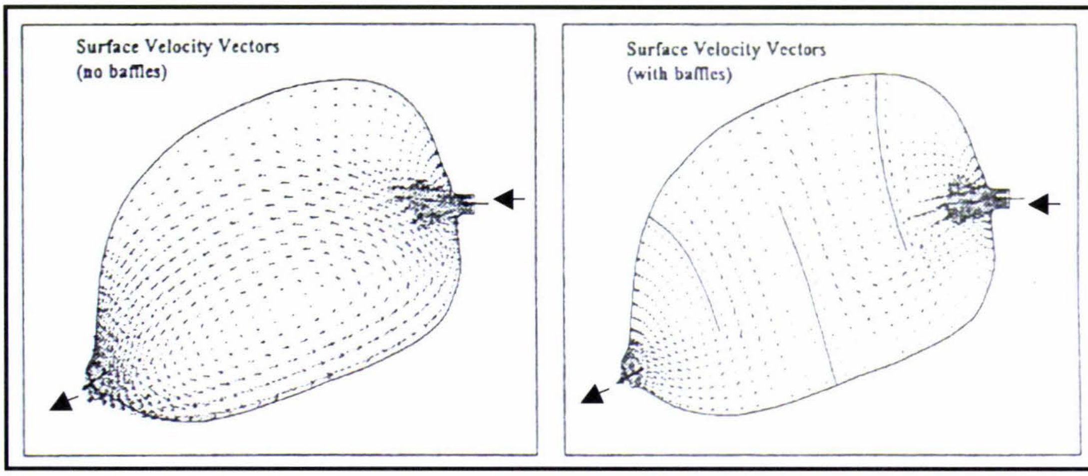


Figure 2-15 Simulation results of on-stream stormwater pond without and with baffles (Van Buren *et al.*, 1996, pg. 330)

2.6.8. Baffles Summary

In their journal article, Kilani and Ogunrumbi (1984) made a particularly relevant comment. "Since the installation of baffles in pond will involve additional construction cost, the expected improvement in the performance of large scale ponds has to be closely related to the additional cost involved."

Previous work follows along similar lines; baffles are added and the performance of the system assessed. However, this approach does not advance the design of pond systems or attempt to investigate the possible mechanisms by which the improvement is achieved. In addition, previous work on the most optimum configuration for baffles appears to be fairly similar. Most of the work conducted has dealt with evenly spaced baffles which extend the majority of the width of the pond. There appears to be a gap of information relating to innovative baffle arrangements – that is, the possibility of un-even baffles i.e. not evenly spaced, curved baffles to follow and control flow patterns, and the possibility of very short baffles to deflect flow away from outlets.

While the benefits of adding baffles to pond performance seem to be clear, the practicalities on a large-scale need to be considered. A compromise needs to be reached between cost and efficiency of a baffle configuration. Can a significantly improved level of performance be reached with a minimum number of flow-pattern based baffle designs?

2.7 Techniques for Assessing Pond Hydraulics

There are a number of techniques for assessing pond hydraulics. They include tracer studies, laboratory modelling, drogue tracking and CFD modelling. While tracer studies and laboratory studies have been used extensively, the fields of drogue tracking and CFD modelling are relatively new techniques in waste stabilisation pond research.

2.7.1. Tracer Studies

The tracer study is a stimulus-response technique. The most common form of this technique involves the pulse input of a tracer e.g. fluorescent dye, and the monitoring of the resulting tracer concentration at the outlet over time.

The tracer can be monitored and its concentration plotted against time to produce a hydraulic retention time distribution curve (HRT curve). The shape of the HRT curve has been used to characterise flow regimes. For example, Figure 2-16 shows the HRT curves for plug, mixed and dispersed flow. Time and concentration are dimensionless in the plots. The HRT curve allows the time to short-circuiting to be seen, i.e. the time before the tracer is detected at the outlet. The mean retention time can also be determined from the tracer study data.

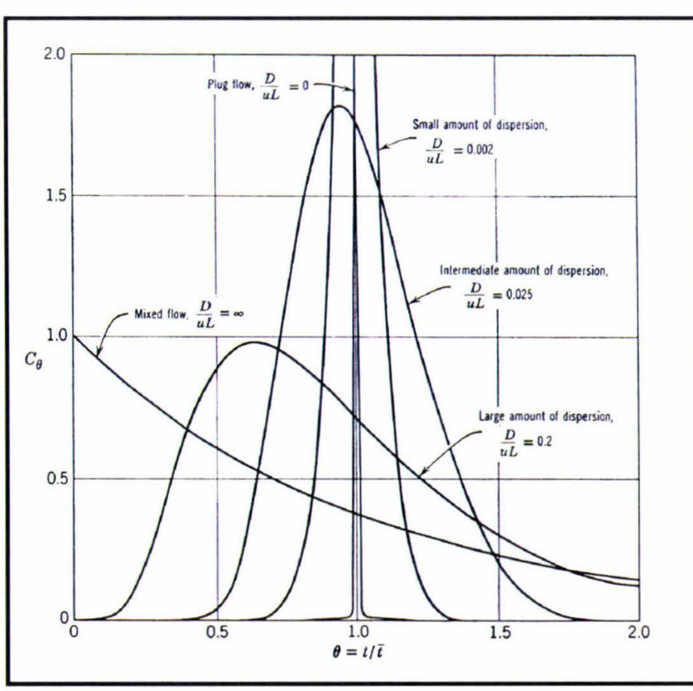


Figure 2-16 HRT curves for plug, mixed and dispersed flow (Levenspiel, 1972, pg. 277)

A large portion of hydraulic studies performed on waste stabilisation ponds, have been performed using tracer studies. They include: Watters *et al.*, (1973); MacDonald & Ernst (1986); Moreno (1990); Pedahzur *et al.*, (1993); Wood (1997); Salter (1999); Shilton *et al.*, (2000); Cavalcanti *et al.*, (2001); Barter (2002); Shilton & Harrison (2002); and Shilton (2001).

Watters *et al.*, (1973) conducted some of the earliest and most extensive previous work using tracer studies. Their work involved a series of tracer studies in field ponds and in a laboratory model. The work contributed significantly in the field of inlets, outlets, and baffles (as discussed in Section 2.5.1 & 2.6.1), but little discussion is made about the tracer technique. The tracer used was rhodamine WT dye.

Salter (1999) carried out tracer studies on two field ponds using sodium fluoride as the tracer. Figure 2-17 shows the results of three tracer studies undertaken on the Chesham pond. It shows that despite three replicate studies being carried out on the same pond, variation between the three HRT curves is quite noticeable. This highlights the difficulties of field investigations where the conditions such as inlet and weather are variable. Salter (1999) also carried out investigations into the use of CFD modelling (see Section 2.7.2) and the addition of baffles (see Section 2.6.1) into the model.

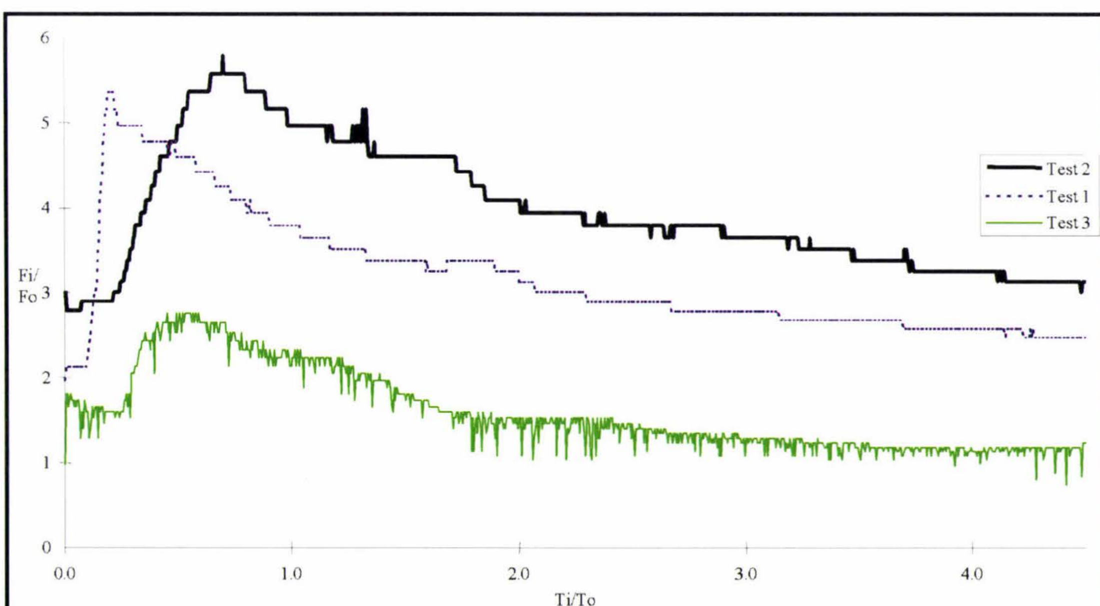


Figure 2-17 Tracer Results on Chesham Pond (Salter, 1999)

2.7.2. CFD Modelling

"Computational fluid dynamics has moved from mainframes to PCs and laptops. Newer and better software lets you conduct analyses not possible before. Regular engineers, not just experts, can now carry out CFD" (Bakker *et al.*, 2001, pg. 45).

CFD is a method of predicting processes such as fluid flow, heat transfer, mass transfer, chemical reactions, and related phenomena. It is a computer-based method of solving the partial-differential equations for energy, momentum and mass conservation within fluid flow. CFD programs were first developed in the 1960's. But due to the limited access to computers that could handle the processing of such programs at that time, CFD technology was not widely used. The advances in computer technology have allowed CFD to be readily available to the average design engineer.

Many areas of CFD modelling have come together to enable the modelling of waste stabilisation ponds. Such areas include river, lake and ocean modelling, modelling of settlers/clarifiers, and bioreactor modelling (Wood 1997).

As reported by Wood (1997), modelling using CFD is an important tool where predictions are required where existing data does not exist, or where physical experiments cannot be performed due to their difficulty or cost factors. Wood (1997) goes on to discuss the potential for CFD modelling as a design tool for investigating alternative geometries for waste stabilisation ponds. Models once developed can be easily adapted to evaluate a number of situations.

CFD modelling for pond systems has only been used by a few researchers in recent times. Wood (1997), Salter (1999), and Shilton (2001) have made preliminary investigations into the application of CFD modelling for pond systems. Ta (1999) carried out similar work on raw water reservoirs. However, its use is growing considerably. At the 5th IWA Specialist Conference on Waste Stabilisation Ponds 2002, a number of papers were presented entailing work on CFD modelling. They include; Guganesharajah *et al.*, (2002); Lloyd *et al.*, (2002); Shilton & Harrison

(2002a); Shilton & Harrison (2002b); Vega *et al.*, (2002). This contrasts with two at the previous conference, and only one from all of the ones before that.

The major focus of CFD modelling of waste stabilisation ponds to date is to assess the hydraulics of the pond.

Sweeney *et al.*, (2002) made the following conclusion: "Non-ideal flow behaviour in ponds may occur through regions of varying biological efficiency. Current hydraulic modelling approaches are focussed on predicting the *quantity* of hydraulic deviation, but not the associated biological *quality*. Integrated physical and biological models will provide a method of considering this problem." (pg. 509).

CFD modelling provides the ability to integrate reaction equations into every cell of a pond as it has been developed on a mass balance basis. Previously, an assessment of treatment efficiency of a pond involved the assumption of either plug-flow or completely mixed conditions, therefore applying the appropriate reaction rate equation to tracer curve data. The treatment efficiency of a pond modelled with CFD attempts to reflect the actual conditions within the pond without the need to make an overall assumption about the type of flow that may be occurring. Such work was first published by Shilton and Harrison (2002b).

2.7.2.1. CFD Modelling by Wood (1997)

The work of Wood (1997) can be considered the pioneering work for the application of CFD to waste stabilisation ponds. The objectives of his research were to: "...improve current understanding of pond hydraulics...validate hydraulic CFD models on appropriate systems...demonstrate the models are capable of providing predictive information for novel pond designs." (pg. 179).

Wood (1997) found that three-dimensional CFD could successfully predict experimental residence time distributions with a reasonable degree of success. He highlighted the potential of CFD models, in conjunction with pond reaction models to better understand pond flows and therefore provide a tool for overall pond optimisation. The visual assessment of flow patterns predicted by CFD modelling also allow insight into improved design of pond element (eg. outlet position).

2.7.2.2. CFD Modelling by Salter (1999)

Salter (1999) carried out CFD modelling of a pond system in Thailand and found significant short-circuiting. The author also concluded that thermal stratification made the situation worse, and the inclusion of baffles into the model improved the situation.

The grid density used in the modelling was quite low. This calls into question the accuracy of the solutions gained. Another concern regarding this work is that it was not validated against any experimental data from the pond modelled.

2.7.2.3. CFD Modelling by Shilton (2001)

The work of Shilton (2001) undertook to investigate the hydraulics in a scale, physical model of a pond using a range of different pond configurations. The data obtained was then compared against mathematical simulations of the same ponds undertaken using a commercial CFD package (PHOENICS). An evaluation was also made of a field pond using the same techniques. One of the more significant outcomes of the work, was the close match of the field data and the predictions of the CFD model.

In his conclusions, Shilton (2001) states that "…CFD modelling can not always be expected to provide an exact fit of experimental data. What is critical, however, is that CFD modelling appears to be effective at assessing 'step-changes' in pond hydraulics…". (pg. 187)

This work makes a significant contribution to the use of CFD as a design tool for the engineering profession. It does not aim to exactly model individual ponds and pond designs, but allows a timely assessment of designs that may be implemented in the field.

2.7.2.4. Other Work on CFD Modelling of WSP's

Vega *et al.*, (2002) applied CFD modelling to determine improvements from a series of modifications to an anaerobic pond. The modifications included inlet-outlet positioning, baffling and pond geometry. They concluded that CFD is a powerful tool to predict the effects of modifications on waste stabilisation ponds. They also concluded that baffles and better inlet-outlet positioning are simple interventions to improve pond performance.

Recently, a 3D computational hydraulic model was developed for assessing and designing waste stabilisation ponds by Guganesharajah *et al.*, (2002). The model (HYDRO-3D) was developed and calibrated to simulate field data from waste stabilisation ponds in Colombia and Mexico and simulates wind induced currents, inlet and outlet flows, and model faecal coliforms. However, as the model is calibrated against field data, its applicability is brought into question – can the model be successfully applied to other waste stabilisation ponds?

2.7.3. Laboratory Modelling

The difficulty of performing field studies, with their inconsistent conditions and flow-rates, and high-cost, mean that the modelling of ponds on physical scale models in the laboratory is an attractive option. Antonini *et al.*, (1983) noted that effective studies of retention time distributions could only be performed effectively under controlled conditions in the laboratory.

Research using physical models varies due to confusion as to how the models should be built. A study by Thirumurthi and Nashashibi (1967) involved the use of a model in which the depth was equal to the actual pond depth - in a sense a large fish tank type arrangement. The dimensions of the model do not represent a typical waste stabilisation pond.

To better represent full-scale systems, it has been suggested that dimensional analysis should be employed. It is generally accepted that the Froude number should be maintained in free surface systems although the effect this has on the Reynolds number should also be considered.

Watters *et al.*, (1973) produced the first research using a well designed scale model. They emphasised that correct modelling of the inflow is important if the model is to represent full-scale behaviour. The work of Watters *et al.*, (1973) used the scale model to investigate inlet and outlet types and arrangement, the effect of baffles, the degree of stratification, and the length-to-width ratio.

The conclusions made by Watters *et al.*, (1973) are still relevant today, and are a testament to the benefits of a well-designed investigation using a suitably designed laboratory model.

2.7.4. Drogue Studies

Drogue studies essentially involve placing an object in the pond, and tracking its movement to build up the velocity profile within a pond. They have been used before in oceanic studies, but are relatively new to the waste stabilisation pond arena.

Two drogue studies that have been performed were by Shilton and Kerr (1999) and Barter (2002).

The work by Shilton and Kerr (1999) is the first published using techniques to determine the actual velocities within a waste stabilisation pond. They used drogues, as seen in Figure 2-18, that were of two different lengths. This gave an indication of the fluid velocities present at different depths. The drogues were tracked by two surveyors using theodolites, fixing the drogue position at pre-determined intervals. The angles were then triangulated and velocities could be determined.

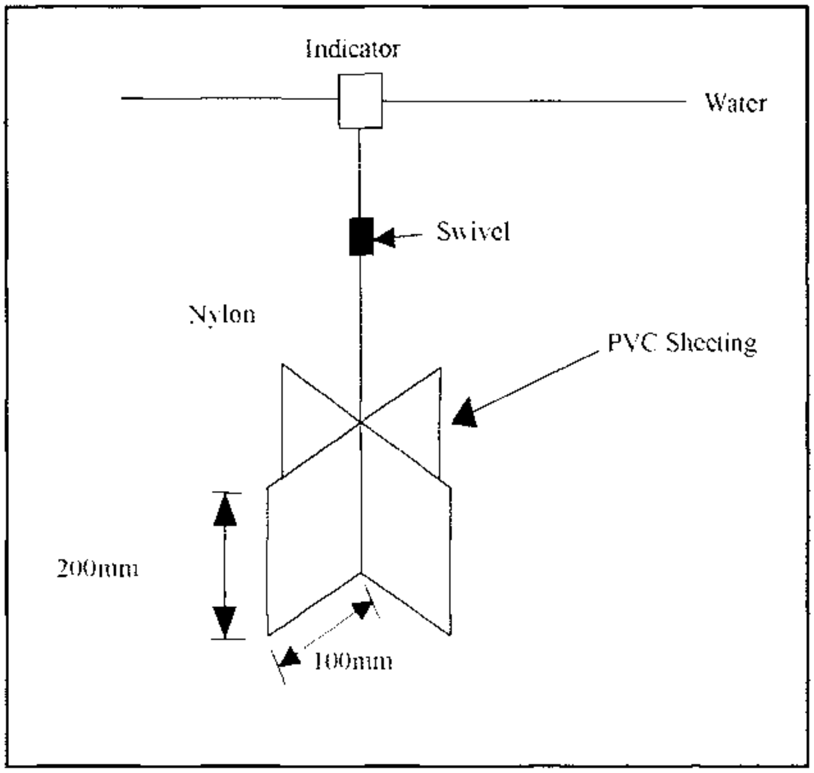


Figure 2-18 Drogue used by Shilton and Kerr (1999)

The drogues were dropped at a position in the pond, tracked, then picked up and placed at another position manually. A boat was used to manoeuvre around the pond.

Figure 2-19 shows the drogue used by Barter (2002) in his investigation into the hydraulics of the waste stabilisation pond in Nelson, New Zealand. The study involved the combined use of a tracer study using dye and drogue tracking.

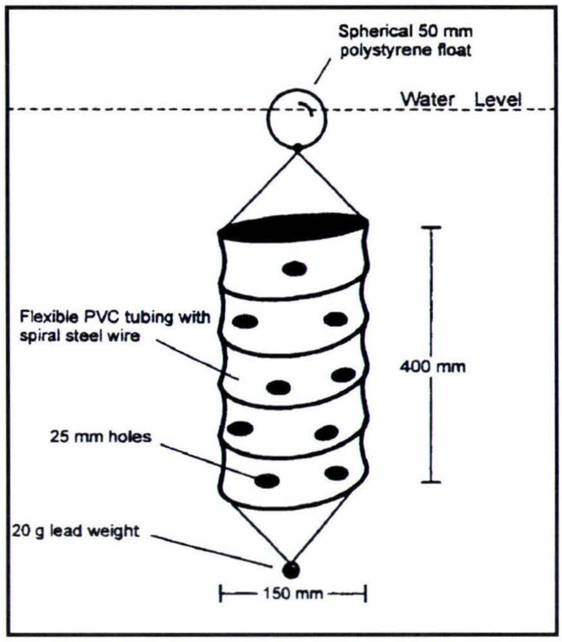


Figure 2-19" Holey-sock" drogue (Barter 2002)

A series of drogues were placed near the inlet of the pond and tracked using a camera that was mounted in a blimp that took photos at a pre-determined interval, allowing the velocity to be determined. Barter (2002) concluded that the combination of tracer study and drogue tracking techniques provided a relatively low-cost and effective means of determining pond velocities. The use of the low-level photography is a particularly inventive method of determining the velocities.

Drogue tracking is a very useful m ethod of determining the actual velocities present in a pond. The techniques used by Shilton and Kerr (1999) and Barter (2002) provide practical and low-cost methods of measuring fluid velocities in a pond.

2.8 Summary and Conclusions

Waste stabilisation ponds provide a low-cost, low-technology method for treating wastewater. This relative simplicity hides what is recognised as both a hydraulically and biologically complex process. Traditional methods of assessing waste stabilisation pond performance rely on assumptions about the flow characteristics within a pond.

The design manuals that are in use today, Mara and Pearson (1998) and Mara (1992a), provide engineers with a safe and reliable design methodology based on a loading rate approach. While these form the basis for sizing waste stabilisation ponds, they take no account of the hydraulic design.

As has been discussed in this review, the hydraulics of waste stabilisation ponds have a direct impact on treatment efficiency. However, the elements impacting on hydraulic efficiency, such as inlets, outlets and baffles, while previously researched, still require more investigation. As mentioned by Wood *et al.*, (1995, pg. 112), "it is currently impossible to reliably predict how various modifications of pond design, such as placement and number of inlets, use of baffles, etc, might affect pond performance".

Baffles offer the opportunity to achieve significant improvements in the hydraulic, and therefore treatment, efficiency of waste stabilisation ponds. However, research that goes beyond a simple performance assessment is lacking, as is the investigation of innovative baffle arrangements. In addition to this, there appears to be a lack of understanding of the flow mechanisms and interactions caused by baffles.

The assessment of the hydraulics of waste stabilisation ponds can be undertaken using tracer studies on laboratory scale models or field ponds, drogue studies, and using computation fluid dynamics (CFD) modelling. CFD modelling has shown the potential to produce accurate predictions of pond hydraulic behaviour in a timely manner, reducing the need for costly and time-consuming field trials.

The integration of reaction kinetics within a CFD model of a waste stabilisation pond allows a prediction of the improvement in treatment efficiency of various pond designs.

In summary, a significant amount of work is still required on the hydraulics of pond systems, and the influence of different elements within such systems. The work needs to use a combination of investigative methods to ensure a comprehensive understanding. These methods, CFD modelling, laboratory modelling and field studies are used in this thesis. The methodology of these processes is discussed in Section 3.

3. METHODOLOGY

3.1 Experimental Overview

The objectives of this work were to investigate baffles, inlets and outlets in waste stabilisation ponds, to evaluate the use of CFD as a design tool, and To apply the findings of the work into the field environment. The e xperimental work was carried out in three stages.

1) Stage 1 - CFD Modelling

   A pond was sized according to modern design manuals and then modelled using the PHOENICS CFD software package. A range of baffle configurations were applied to the model pond and tested for their hydraulic and treatment efficiency.

2) Stage 2 – Laboratory Studies

   A range of the more efficient configurations modelled using CFD were investigated on a laboratory-scale model pond.

3) Stage 3 – Field Studies

   Two field trials were performed, one using a modified inlet, and the other a innovative baffle configuration to assess their influence on hydraulic and treatment efficiency under field conditions.

3.2 CFD Modelling

3.2.1. Introduction to PHOENICS

The PHOENICS CFD software was developed by Concentration, Heat and Momentum Limited (CHAM), an engineering-consultancy and software company, founded in 1974, located in Wimbledon, England, and operating world-wide.

"PHOENICS is a software embodiment of the laws of physics and chemistry which govern the motion of fluids, the stresses and strains in solids, and heat flow, diffusion and chemical reaction."

(http://www.cham.co.uk/phoenics/d_polis/d_docs/tr326/cadimprt.htm)

The generalised form of the equation solved by PHOENICS can be written as:

$$\frac{\partial(\rho\phi)}{\partial t}+\frac{\partial}{\partial x_k}\left(\rho U\phi - \Gamma_\phi \frac{\partial\phi}{\partial x_k}\right)=S_\phi$$

where: ϕ - the variable in question
ρ - density
U - vector velocity
Γ_ϕ - the diffusive exchange coefficient for ϕ
S_ϕ - the source term

The balance equation cannot be solved numerically in differential form. Hence, PHOENICS solves a finite-volume formulation of the balance equation. The finite volume equations are obtained by integrating the differential equation over the cell volume. Therefore the division of the object in question into a grid of cells over which the equation is solved (the pond in this case) is very important.

3.2.2. Development of the Computer Model

A pond was developed within the computer modelling software. The pond was designed in accordance with Mara & Pearson (1998), a well-used design manual for waste stabilisation ponds.

The model design was based upon an average daily flow (ADF) of 10,000m^3/day (0.116m^3/s). The pond was a primary facultative pond, i.e. the effluent has not undergone any form of treatment prior to entering the pond. The pond was 640 metres long, 320 metres wide, 1.5 metres deep with sloped sides. The inlet and outlet were initially located in diagonally opposite corners in accordance with the recommendations made by Mara & Pearson (1998). The concentration of faecal coliforms at the inlet was set at 1×10^8 cfu/100mL as used by Mara & Pearson (198) in their design examples. The pond is depicted in Figure 3-1.

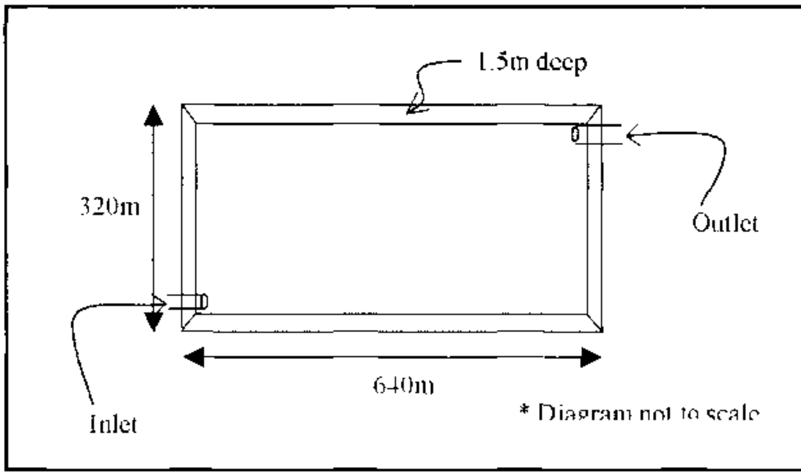


Figure 3-1 Schematic diagram of computer model

The inlet was located 10 metres away from the long side of the pond, and 4 metres out into the pond. The outlet was also located 10 metres from the long side of the pond and 4 metres out into the pond.

3.2.3. Simulations Undertaken

The simulations of different pond configurations using the computer model were undertaken in three parts: a steady state simulation, followed by the addition of faecal coliforms for assessment of treatment efficiency, and finally a non-steady state (transient) simulation.

3.2.3.1. Obtaining a Solution

Steady-State runs were performed on the pond. This involved setting up the model, setting up the grid within PHOENICS, and solving for momentum (which allows the calculation of velocity) throughout the pond. The following figure (Figure 3-2) depicts a typical output from such a simulation. The arrows indicate the size and direction of the velocity of the fluid.

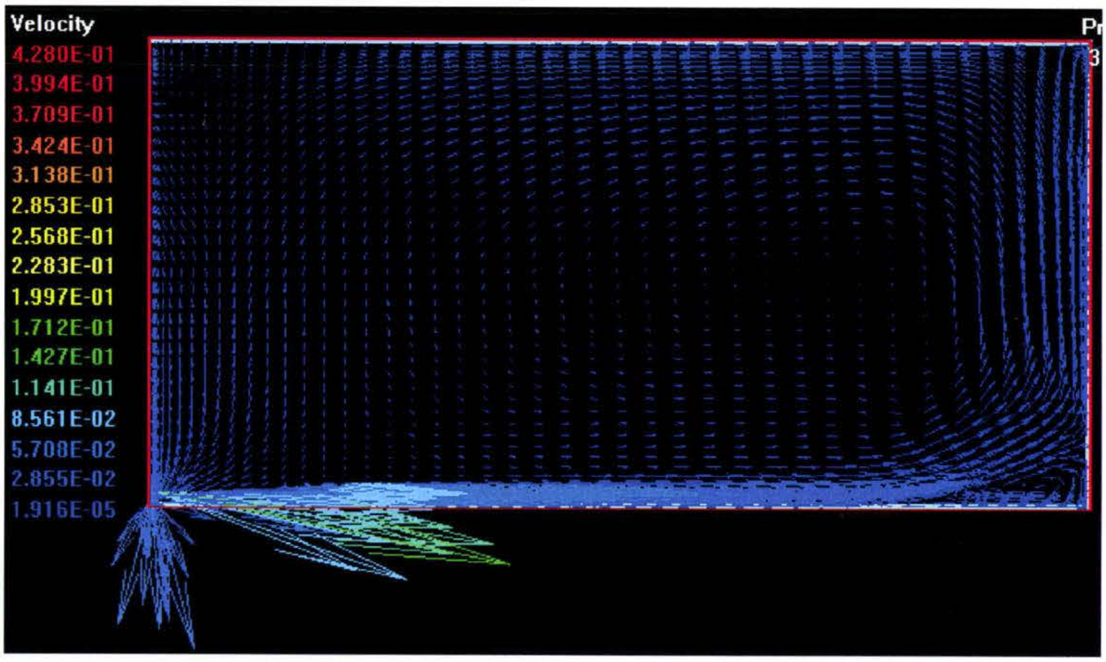


Figure 3-2 Example Output from PHOENICS - Steady-state Simulation

The accuracy of the output was checked by assessing the mass-balance and the residuals. For example, the following figure (Figure 3-3) is gained upon running a simulation. It shows the calculation performed to check the error value, and the mass balance check.

```
Whole-field residuals before solution
with resref values determined by EARTH
& resfac= 1.000000E-03
variable  resref (res sum)/resref
  P1   1.580E-02  2.156E+01
  U1   2.560E-04  4.463E+03
  V1   8.880E-05  7.018E+03
  W1   4.244E-06  4.547E+04
  KE   5.777E-07  4.371E+04
  EP   4.158E-08  7.031E+05

!! Zero nett sources are not printed !!!

Nett source of U1  at patch named: OB6   (INLET     ) = 1.679E+02
Nett source of U1  at patch named: OB7   (OUTLET    ) = -7.511E-01
Nett source of U1  at patch named: OB1   (FLOOR     ) = -2.389E+01
pos. sum= 1.678871E+02 neg. sum=-2.464453E+01
nett sum= 1.432426E+02

Nett source of V1  at patch named: OB7   (OUTLET    ) =-4.163E-01
Nett source of V1  at patch named: OB1   (FLOOR     ) = -4.840E+00
pos. sum= 0.000000E+00 neg. sum=-5.256243E+00
nett sum=-5.256243E+00

Nett source of W1  at patch named: OB7   (OUTLET    ) = 1.675E+00
pos. sum= 1.675164E+00 neg. sum= 0.000000E+00
nett sum= 1.675164E+00

Nett source of R1  at patch named: OB6   (INLET     ) = 1.158E+02
Nett source of R1  at patch named: OB7   (OUTLET    ) = -1.158E+02
pos. sum= 1.157824E+02 neg. sum=-1.157830E+02
nett sum=-5.950928E-04

Nett source of KE  at patch named: OB6   (INLET     ) = 1.521E -01
Nett source of KE  at patch named: OB7   (OUTLET    ) = -2.042E-03
Nett source of KE  at patch named: KESOURCE =-4.684E+00
pos. sum= 1.521453E-01 neg. sum=-4.685922E+00
nett sum=-4.533776E+00

Nett source of EP  at patch named: OB6   (INLET     ) = 4.523E -02
Nett source of EP  at patch named: OB7   (OUTLET    ) = -4.110E-05
Nett source of EP  at patch named: KESO URCE =-5.489E-01
pos. sum= 4.522517E-02 neg. sum=-5.489389E-01
nett sum=-5.037137E-01
```

Error Check

$$\text{Error} = \frac{(2.560\text{E-04} * 4.463\text{E+03})}{1.679\text{E+02}} \times 100 = 0.68\% \checkmark\checkmark$$

Mass Balance Check – is there a mass balance of R1? ✓✓

Figure 3-3 PHOENICS Result file from a steady-state simulation

3.2.3.2. Non-Steady State Runs

After a solution had been obtained using the steady state simulation, a non-steady state simulation could be undertaken. This involves stopping the solvers for pressure, momentum and turbulence, while maintaining their stored steady state values. 'Patches' could then be added to simulate the insertion of a tracer in the inlet of the pond, and to monitor the concentration of the tracer at the outlet. Therefore simulating the experimental tracer studies.

3.2.4. Integrating Reaction Kinetics

To integrate bacterial kinetics into the CFD model, first order kinetics have been assumed. This assumes a first order reaction rate constant (k) value for the whole pond. The k value incorporates temperature, substrate, biodegradability, algae etc.

$$dC/dT = -kC$$

In most pond equations, a flow regime and therefore boundary conditions are assumed. The rate equation is integrated using these boundary conditions to give:

If plug flow: $1/1+kt$

If completely mixed: e^{-kt}

The coliform results that are produced by the model appear very accurate, however, they are still based on an assumption – that the kinetics is first order. Therefore, the results still need to be used with care. An assessment of the improvement in the pond can still be assessed by the log reduction of coliforms.

Despite the exact conditions in each part of the pond being used to calculate decay, there are still limitations. The value of k is still based around some questionable assumptions. They are gained from back-calculating field data, plots and therefore equations that assume that the BOD going out of a pond is proportional to the BOD coming in. It also makes assumptions about temperature and time.

The steady-state simulation, as discussed previously, will show the resulting flow patterns from a given pond configuration – thus, an indication of the hydraulic efficiency. To gain a measure of treatment efficiency, a scalar is added to the model incorporating reaction kinetics. This involves inserting a 'patch'. A patch is an area or volume over which a boundary condition or source is applied. In this instance, PHOENICS applies first order reaction kinetics to every cell in the pond. A source is the variable in question, for example, momentum, pressure or a quantity of coliforms.

ϕ is the source term in PHOENICS, all 'sources' in PHOENICS are defined by the following general equation:

$\phi = c(V - \phi N)$

where c = coefficient
V = value
ϕN = value at node N

by defining $c = k$, $\phi N = C$, $V = 0$

$\phi = k(0 - C)$
$= -kC$ ← 1^{st} order reaction rate

The first step in applying reaction kinetics to the PHOENICS model is inserting a new 'user-defined' object to which the "patch" is applied. This object 'volume', has the same dimensions as the pond. A new 'decay' patch is applied and values for the coefficient and value defined. In this application the coefficient (or k value) was 1.1×10^{-5}, and the value = 0. There are a number of reaction rate determining equations in literature. For the purposes of this work, the equation proposed by Marais (1974) has been used ($k_T = 2.6\ (1.19)^{T-20}$).

In this instance, the value of 'k' is kept constant, and is influenced by temperature, which is also chosen as a single value that applies over the whole pond. While this work makes the jump in considering actual hydraulic conditions in bacterial decay, further work is needed to improve on integrating appropriate equations and models for decay, once they are better understood.

3.2.5. Grid Refinement

When the model is formed, the pond is divided into a three-dimensional grid of cells. The density of this grid affects the accuracy of the solution. If a grid is too coarse, then it will produce errors in the solution. However, as the grid gets too fine, there are no further significant improvements in accuracy – the grid has reached independence.

Therefore as a part of this work, two cases were run at varying grid densities and their results (velocity, and coliform concentration) from one slice of the pond were plotted.

The following two figures (Figure 3-4 and Figure 3-5) show the grid comparison for Case 1, the basic pond case with no baffles. A slice was taken through the pond and the velocities and coliform concentration compared for five different grid densities.

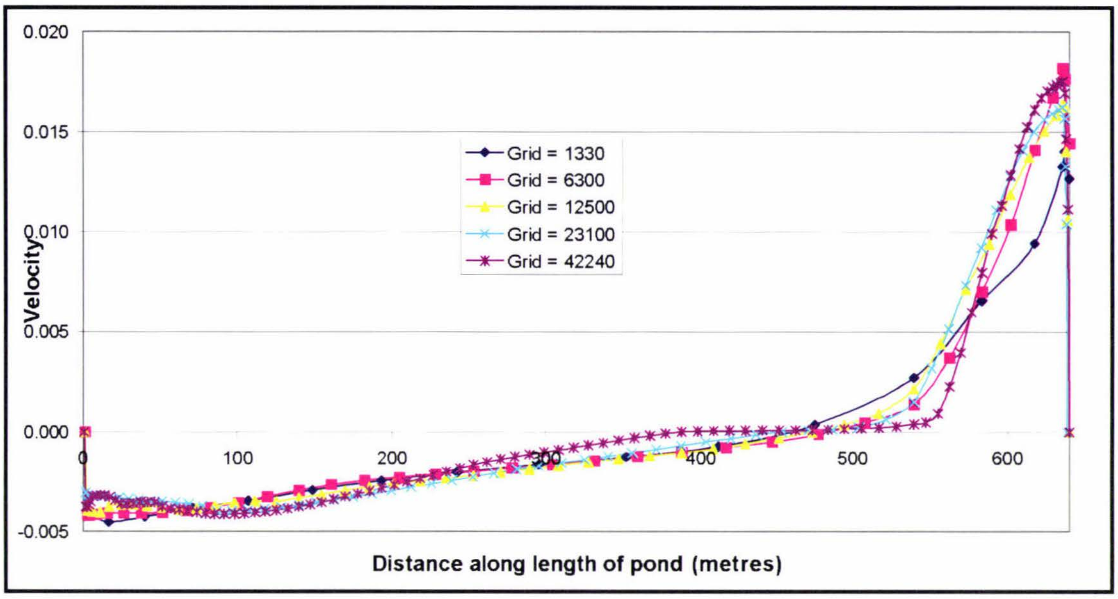


Figure 3-4 Grid Comparison, Velocity Plot, Case 1

The velocities all follow the same general pattern, however, the higher grid densities show the effect of the end wall, that is, the slowing of the flow in the cells closest to the boundary. It is not present in the lower grid densities.

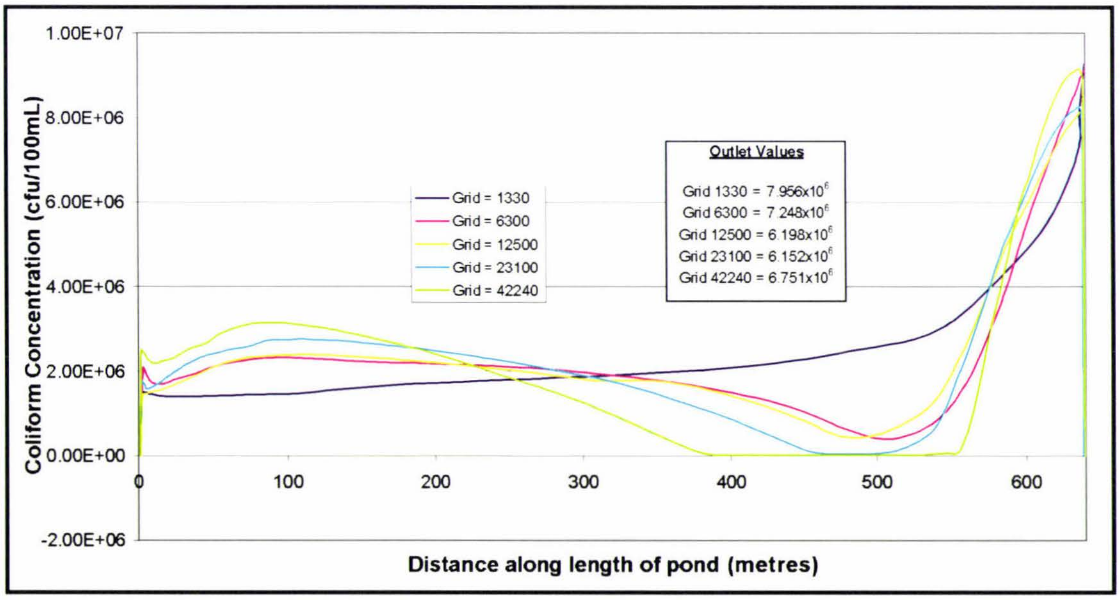


Figure 3-5 Grid Comparison, Coliform Plot, Case 1

As can be seen in Figure 3.5, all the grid densities give a coliform level at the outlet in the same order of magnitude. The plots show a general trend, with the lowest grid density showing the most inaccurate representation, as was expected.

The next two figures show the same comparison for Case 2, the traditional two baffle (see Table 1) case as tested by Watters *et al.*, 1973.

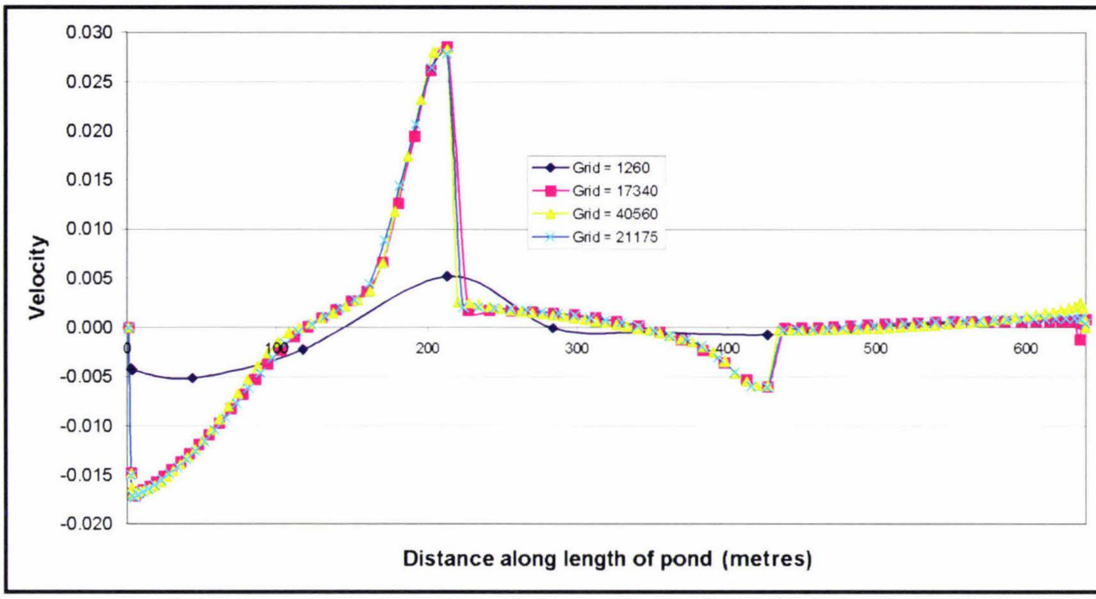


Figure 3-6 Grid Comparison, Velocity Plot, Case 2

As seen in Figure 3.6, the three denser grids show a very close relationship in the velocity profile. The lower grid density shows a very inaccurate solution.

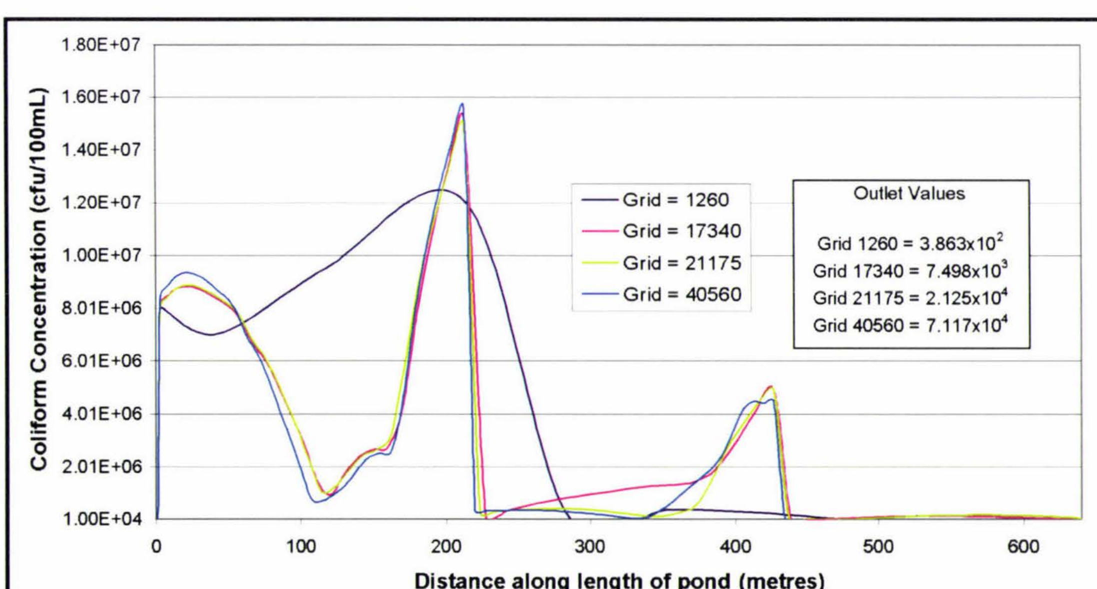


Figure 3-7 Grid Comparison, Coliform Plot, Case 2

As seen in the above figure (Figure 3-7), the lowest grid density sh ows an inaccurate solution. The outlet coliform values however, show only the highest two grid densities giving the same order of magnitude concentration. The coliforms concentration at the outlet does not change in magnitude when increasing from 20,000 cells to 40,000 cells, therefore the grid has reached independence.

The plots presented above clearly show the effect of grid density on the accuracy of the solution. As a result of the above two cases, a minimum grid density of 20000 cells was used for the CFD models.

3.2.6. Turbulence

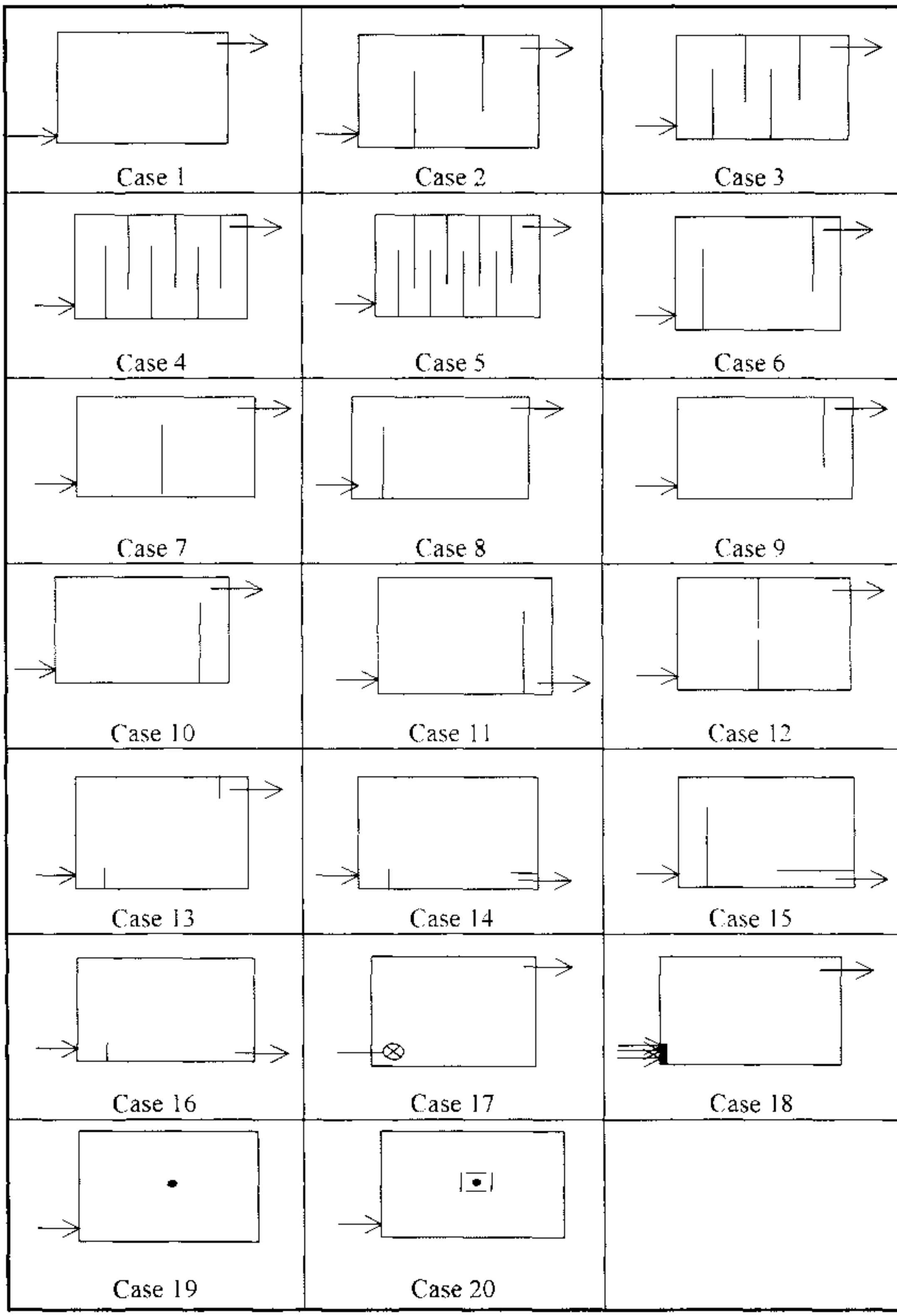
"Turbulence is a fluid motion that is unsteady and irregular in both space and time." (Shilton, 2001, p94) The resulting mass and momentum transfer within the fluid is different to that in laminar flow. This fluctuation is simplified by models that use average values of turbulence variables.

Shilton (2001) conducted an investigation into the various recommended models, such as k-epsilon and Chen-Kim k-epsilon, and found there to be little or negligible effect on the resulting solution.

3.3 Configurations tested using CFD

The range of cases tested using the CFD model is shown in Table 1. Traditional pond designs were tested to show that the CFD model could predict similar improvements as found by previous researchers, and to improve on the understanding of the mechanisms behind their success. Innovative designs were also tested to expand on existing knowledge.

Table 1 - Configurations tested using CFD (diagrams not to scale)



3.4 Laboratory Studies

3.4.1. Development of Lab Models

Many previous researchers have used laboratory models, however the design of the models has varied widely. In this work, the pond was designed in the same manner as Watters *et al.*, (1973) and Shilton (2001).

The development of the scale models to accurately model the performance of the full-scale pond needs to be considered carefully. The flow-rates cannot be scaled straight down. The flow-rates used in the lab-scale pond need to retain the same fluid properties as in the field pond.

The model used was a 1:12 model of a typical, theoretical pond, as shown in Figure 3-8.

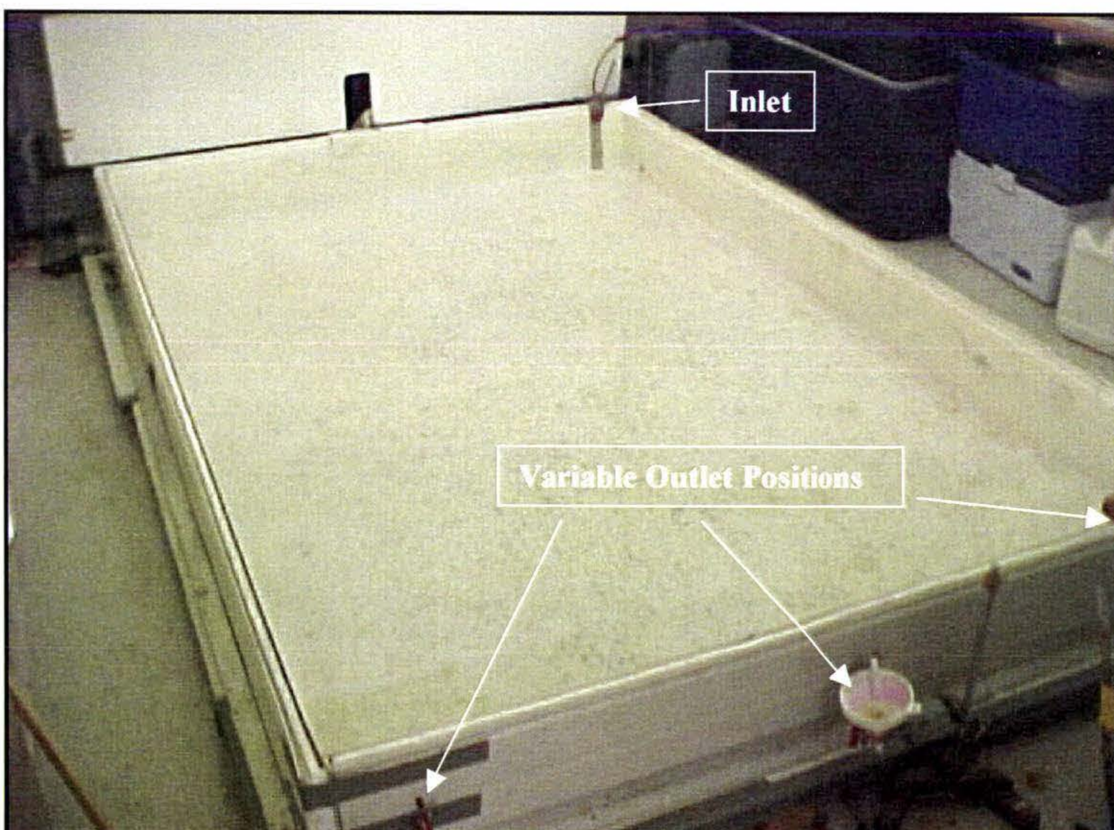


Figure 3-8 Laboratory model

3.4.1.1. Reynolds Number versus Froude Number Design

Two fundamental expressions of the forces that govern flow behaviour are the Reynolds number and the Froude number. The Reynolds number and Froude number cannot both be satisfied when developing a scale model. The Reynolds number is generally used when dealing with closed pipe applications. The Froude number is widely used in open channel flow situations. Therefore, it has been generally considered appropriate in developing scale models of waste stabilisation ponds to maintain the Froude number at the expense of the Reynolds number.

Watters *et al.*, (1973) made mention of the importance of the correct modelling of the inlet to ensure the model behaviour duplicates the prototype behaviour. They also found that variations in the Reynolds number do not make much difference but turbulent inlet jets need to be maintained.

The development of the scale model for this study used a retention time of 1.5 days, giving an inlet Reynolds number of 4050 which is just inside the turbulent region. Therefore while the Froude number has been maintained in this work, care has also been taken to ensure that turbulent conditions exist in the inlet jets of both the scale model and the full-scale system.

3.4.2. Froude Number Based Design

The Froude Number represents the ratio of inertial to gravitation forces.

$$Fr = \frac{\upsilon}{\sqrt{gy}}$$

where Fr = Froude number

υ = fluid velocity (m/s)

g = gravity (m^2/s)

y = depth of fluid (m)

To design the lab pond on the basis of Froude number it must be the same in the laboratory as it is in the field. Using the subscripts f for the field pond, and m for the model pond:

$Fr_f = Fr_m$

$$\frac{v_f}{\sqrt{gy_f}} = \frac{v_m}{\sqrt{gy_m}}$$

$$\frac{\sqrt{y_m}}{\sqrt{y_f}} = \frac{v_m}{v_f}$$

$$\frac{y_m}{y_f} = \frac{v_m^2}{v_f^2}$$

y_m/y_f = scale factor for length $= S_L$
v_m^2/v_f^2 = scale factor for velocity $= S_V$

$$S_L = S_V^2$$

Using the continuity equation for flow: $Q = Av$

$Q = L \times L \times v$ $(A = L \times L)$
$S_Q = S_L \times S_L \times S_V$
and $S_V = \sqrt{S_L}$
$= S_L^{0.5}$

$\Rightarrow$ $$S_Q = S_L^{2.5}$$

The same process can be followed through to give a scale factor for time.

3.4.3. Laboratory Pond Set-up

The laboratory pond model had physical dimensions as follows:

Length = 2.715m

Width = 1.75m

Depth = 125mm

The pond was located in a temperature-controlled room, and the inflow was regulated via a variable speed pump from a water bath. The inflow was set at a field retention time of 1.5 days, equating to 10.4 hours in the laboratory model. The inlet and outlet positions were adjustable (as seen in Figure 3-8). The experimental set-up is shown in Figure 3-9.

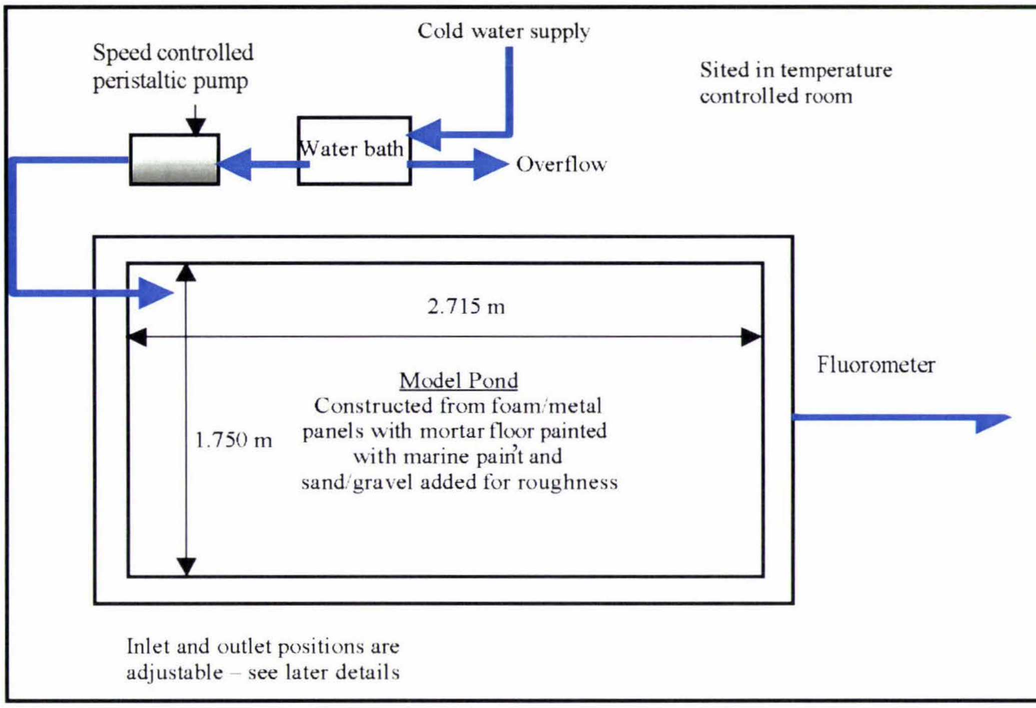


Figure 3-9 Experimental Set-up – Laboratory Pond (Shilton 2001, pg 78)

The set-up of the pond also included a camera mounted above the pond to allow photos to be taken at a pre-determined interval. These photos provided a visual record of the flow pattern occurring in the pond.

3.4.4. Tracer Studies

The stimulus response tracer technique was used in this work. A tracer was inserted into the system, and the outlet was monitored for the concentration of tracer exiting the system. A plot of the tracer concentration leaving the system over a period of time, after the pulse input of the tracer, characterised the retention of fluid within the system. This plot is commonly referred to as the hydraulic retention time distribution (HRT) curve.

The tracer used for this work was rhodamine WT. This dye is capable of being measured accurately at low concentrations. The concentration of tracer at the outlet was measured using a Sequoia-Turner 450 fluorometer, and a Shimadzu RF-1501 Spectrofluorophotometer. The Sequoia-Turner fluorometer suffered some problems towards the end of the laboratory work and the Shimadzu was then used. The following figure (Figure 3-10) shows the set-up of the laboratory tracer study.

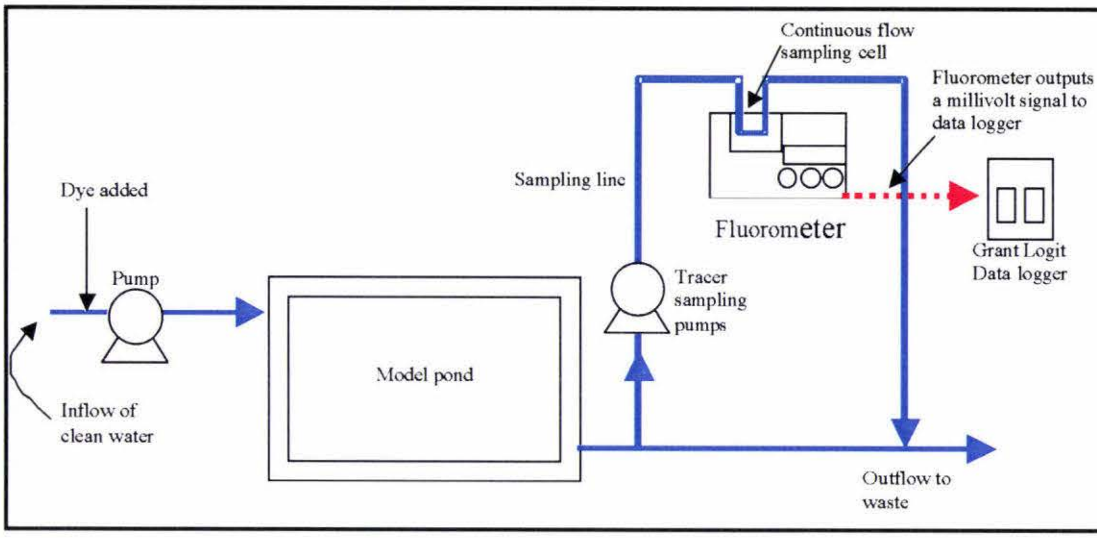


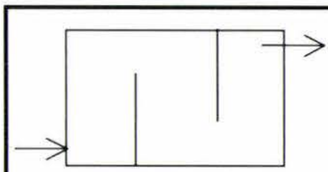
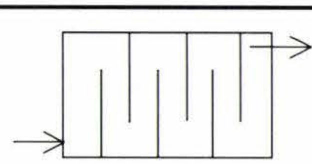
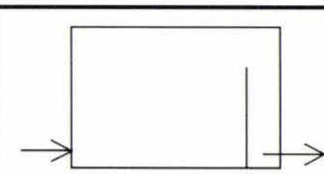
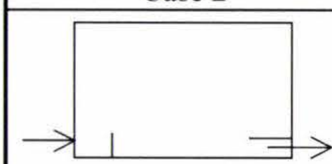
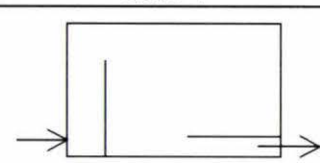
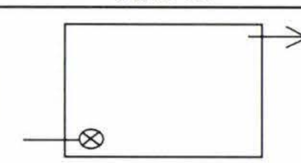
Figure 3-10 Set-up of Tracer Study on Laboratory pond

As varying amounts of tracer were used for different runs, the results could not directly be compared until the tracer outputs were 'normalised'. This involves making the concentration dimensionless, so that the area under the hydraulic retention time (HRT, concentration versus time) curve equal to 1. By making the tracer concentration dimensionless then different tracer studies could be compared directly. It was not necessary to make the time scale dimensionless as the inflow to the pond was set at a constant rate.

3.4.5. Configurations tested in the Laboratory

The following table (Table 2) depic ts the configurations tested in the laboratory. Six cases that were tested on the CFD model were then tested in the laboratory model. The six cases were chosen based on the performance in the CFD model, they are numbered according to the number given to them at the CFD modelling stage.

Table 2 - Configurations tested in the Laboratory (diagrams not to scale)

 Case 2	 Case 4	 Case 11
 Case 14	 Case 15	 Case 17

3.5 Field Studies

Two tracer studies were performed on the Ashhurst pond. Ashhurst is a small community with a population of approximately 3000 people, located some 20km east of Palmerston North, New Zealand. The tracer studies were undertaken in the same manner as for the laboratory modelling, however, the outlet was sampled by an auto-sampler, the samples collected and analysed back at the laboratory. The limiting factor when performing field studies is time. It can take over 2 months to complete one tracer study in the field. Therefore only 2 configurations were tested. The following figures show a map of the Ashhurst area (Figure 3-11), and the secondary pond at Ashhurst (Figure 3-12).

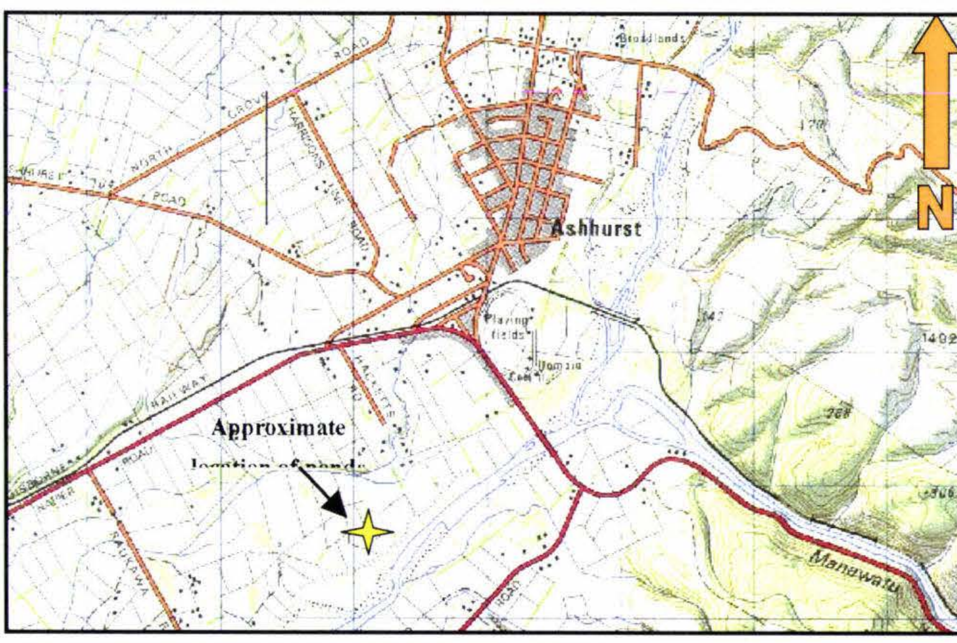


Figure 3-11 Map of Ashhurst showing pond location

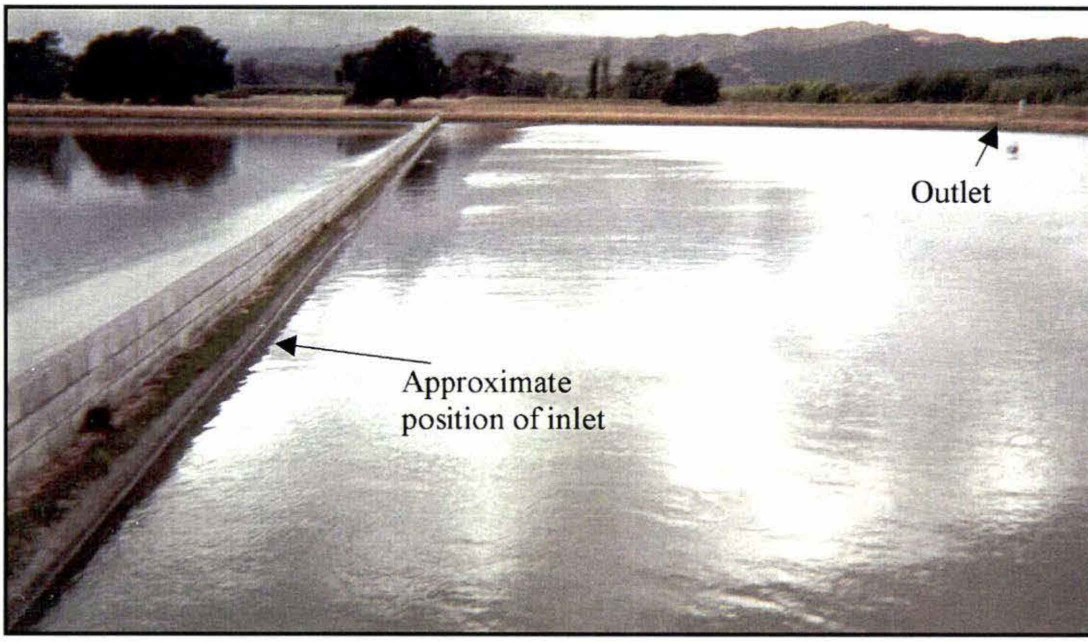


Figure 3-12 Ashhurst secondary pond

The existing pond is approximately 60 metres wide by 120 metres long, and is roughly rectangular in shape. The inlet is located approximately 18 metres along the partition that separates the primary and secondary ponds and is 300mm in diameter. The outlet is located in the opposite corner, and is via a submerged pipe exiting to a weir arrangement with final discharge to the Manawatu River. The figure below (Figure 3-13) depicts the existing pond.

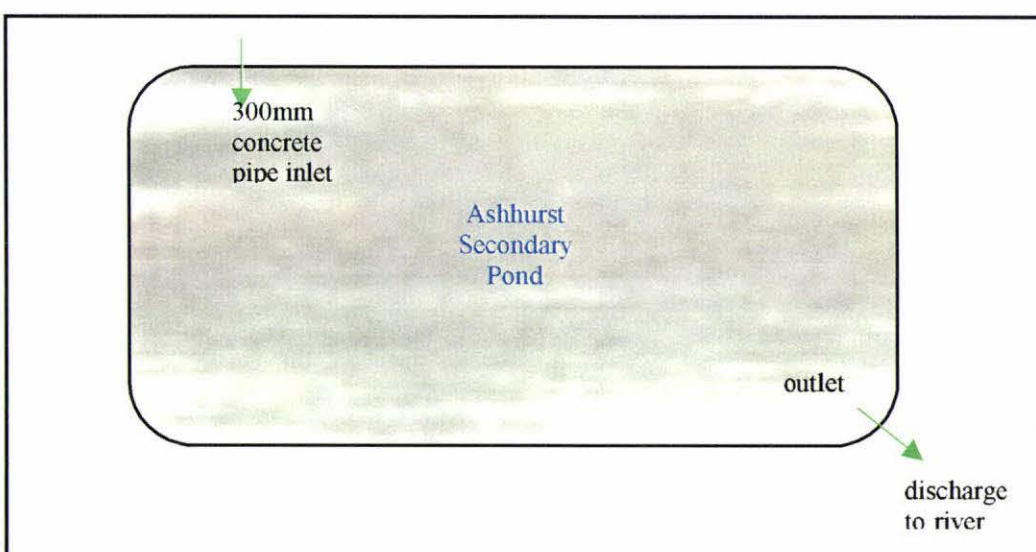


Figure 3-13 Schematic diagram of existing Ashhurst secondary pond

The purpose of the trials was to make modifications to the pond to allow evaluation of the improvements back against previous tracer studies performed on the existing pond by Shilton & Kerr (1999).

The first trial performed was using a vertically up-turned inlet. A fabricated bend was placed in the existing inlet, this altered the flow to enter the pond vertically heading toward the surface. The inlet diameter remained the same. Figure 3-14 depicts the inlet structure for the first field trial.

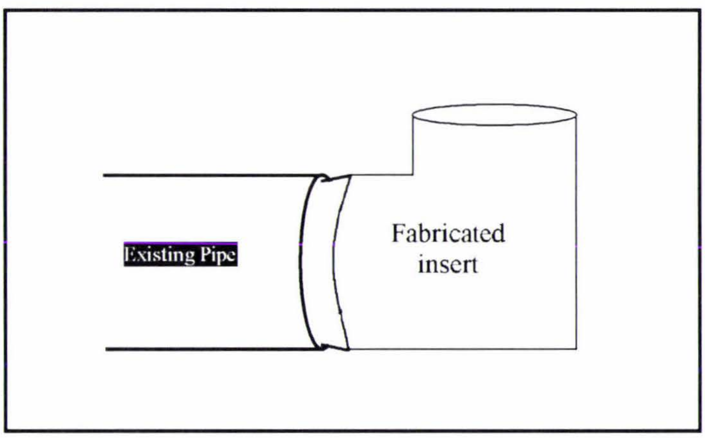


Figure 3-14 Fabricated insert for field trial - Ashhurst (diagram not to scale)

The second field trial involved the installation of a short stubby baffle, combined with a right angle-bend on the inlet to change its direction. This followed promising results from a process of CFD modelling on the Ashhurst pond. The following figure (Figure 3-15) shows the modified pond layout.

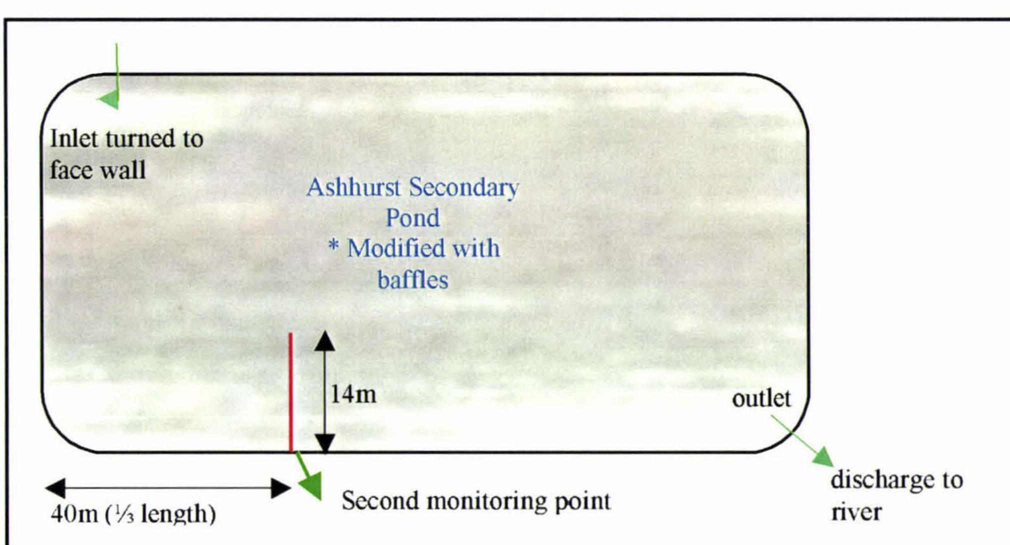


Figure 3-15 Schematic Layout - Ashhurst Field Trial 2 (diagram not to scale)

An inlet was fabricated as for the modified inlet trial, but with a bend facing horizontally into the side wall as shown in the diagram above. A photo showing the inlet is seen in Figure 3-16. The baffle was constructed out of 650gsm PVC, fabricated by Straitline Canvas, Palmerston North. A heavy chain was placed at the bottom of the baffle to hold it down, with 100mm ϕ PVC pipes used as floats at the top of the baffle. A simplified schematic of the baffle construction is shown in Figure 3-17. A wire rope was threaded through the top of the baffle and secured on either side of the pond, this was tensioned to stop the baffle moving laterally.

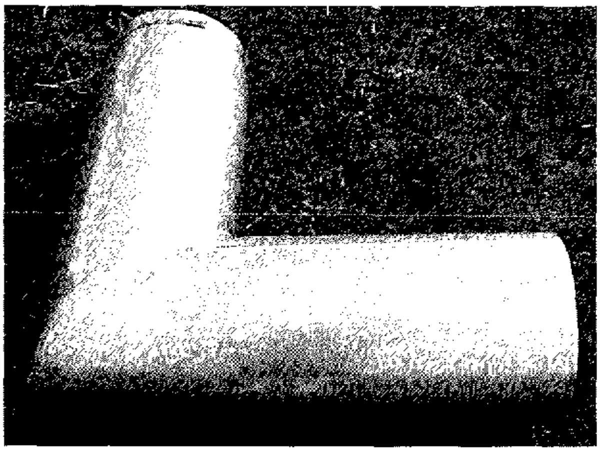


Figure 3-16 Fabricated insert for inlet, second Ashhurst field trial

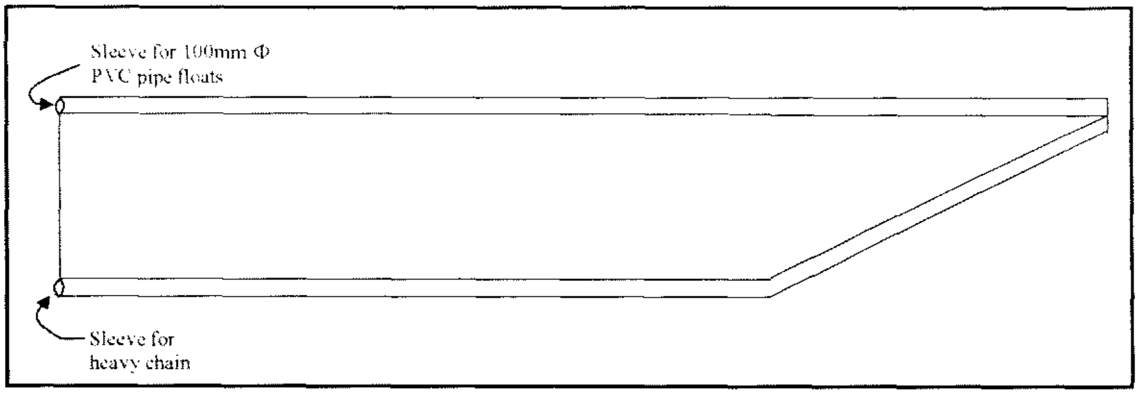


Figure 3-17 Schematic Diagram of Baffle

4. RESULTS OF CFD MODELLING

As discussed in the Chapter 1, a specific objective of this work was to investigate the use of baffles in waste stabilisation ponds, and the effect of inlet type and outlet position. In order to undertake a comprehensive investigation, CFD modelling was used in conjunction with laboratory and field work. As indicated in Section 2.7.2.3, CFD modelling has shown its potential for predicting step changes in performance, the laboratory and field experimentation undertaken gives further insight and confidence in the CFD results.

This chapter represents the use of a CFD model to test a wide range of designs on a typical pond. To date, no other research reviewed investigates pond design to this extent.

In this chapter, the results of the CFD modelling phase of this work are presented. A major focus of this work is on baffles, with various lengths, numbers and positions being considered. However, baffles cannot always be considered without discussion of the effect of, and interaction with, inlets and outlets. Therefore, some cases look at specific inlet types, and other at varied outlet positions.

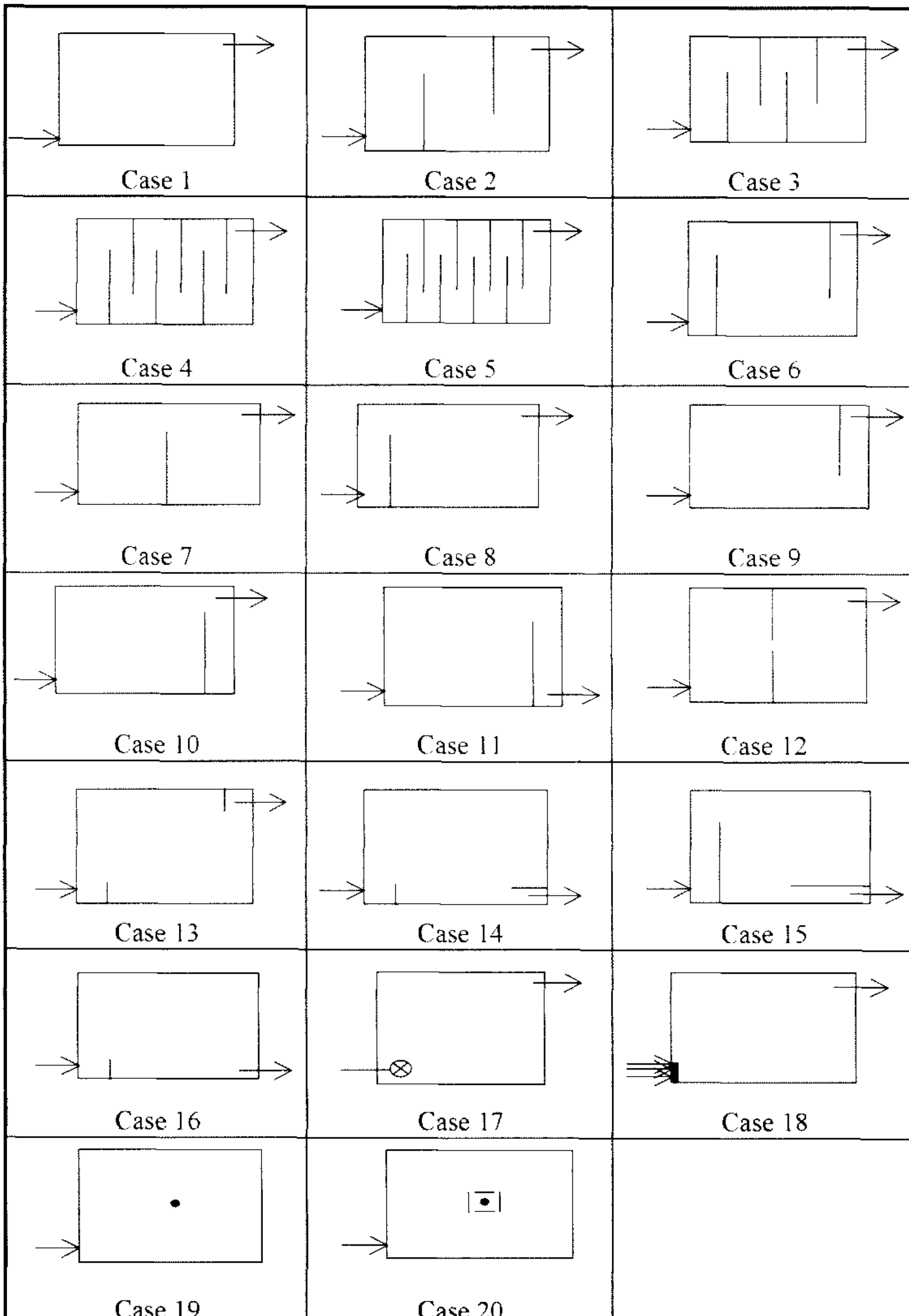
4.1 Overview of CFD Models Investigated

The pond modelled in the major phase of CFD modelling was a theoretical pond developed in accordance with current design manuals. It represents a typical system and was designed using the design criteria given by Mara & Pearson (1998).

The pond was sized on an average daily flow (ADF) of 10,000m^3/day. It is a primary facultative pond; the effluent has not undergone any form of treatment prior to entering the pond. The pond is 640 metres long, 320 metres wide, 1.5 metres deep with sloped sides. The inlet and outlet were initially located in diagonally opposite corners in accordance with the suggestion made by Mara & Pearson (1998). The inlet faecal coliform concentration was set at $1x10^8 cfu/100mL$.

A variety of designs of baffles, and inlets and outlets, were tested (Table 3). The cases chosen are a mixture of traditional baffle designs and innovative designs. The innovative designs were developed as a result of the performance of the traditional designs.

Table 3 - Cases modelled using CFD (diagrams not to scale)



The basic case (Case 1) was modelled to provide a basis for comparison. The inlet and outlet were located in opposite corners.

A series of cases evaluated traditional baffle designs, as tested in the laboratory by Watters *et al.*, 1973 (Cases 2, 3, 4, and 5 in Table 3). Traditional baffles are long and evenly spaced within the pond. Watters *et al.*, (1973) determined that the optimum baffle length was 70% of the width of the pond. The work for this thesis tested the same four cases tested by Waters *et al.*, (1973) utilising the 70% baffle length.

Alternative inlets were investigated in Case 17 (vertical inlet), and Case 18 (diffuse inlet). These inlets were tested with the aim of slowing the momentum of the fluid at the front end of the pond.

The bulk fluid flow in an average pond is a general circulation pattern around the pond – therefore leaving a temporary dead space in the middle of the pond. The central outlets (Cases 19 and 20) were tested with the aim of delaying time to short - circuiting by sitting in this central dead space.

The rest of the cases represent innovative designs to improve on existing baffle knowledge. The traditional long baffle entails high construction costs for new and existing ponds, and increases the difficulty of retrofitting baffles to existing ponds. While the primary aim of the innovative designs is to optimise hydraulic efficiency in the ponds, they are also aimed at cost reduction - especially in the case of short stub-like baffles.

4.1.1. Presentation of Results

Traditionally, studies into the hydraulics of ponds use tracer studies and produce results in the form of hydraulic residence time (HRT) curves giving for example, time to short-circuiting, deviation from plug flow and volume of dead space. In this chapter, the results of the CFD modelling are presented visually in the form of flow patterns, and in terms of coliform concentration.

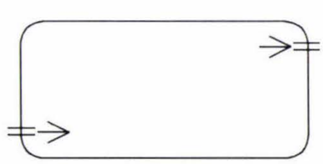
The visual assessment of the flow patterns and coliforms concentrations over the entire pond allows the identification of areas of low velocities and high coliforms concentrations. These shortcomings can then be improved with further design modifications.

The coliform concentration is given in two forms – a coliform concentration profile throughout a slice of the pond, and a discrete concentration value at the outlet. This approach is relatively new, but is unique in that it provides a direct measure of the treatment efficiency of each design by integrating bacterial decay kinetics into the CFD models. As discussed in Section 3.2.4, the CFD model uses exact boundary conditions present in each cell of the pond to integrate reaction kinetics. This differs from the traditional methods, which assume a flow regime and therefore boundary conditions over the whole pond.

In the flow patterns presented in this work, arrows represent the velocity at the point in the pond. The size of the arrow corresponds to the flow velocity. The units for velocity are metres per second. In the coliform concentration profiles, colour represents the concentration of coliforms. A red colour indicates the highest concentration, with blue representing the lowest concentration. The units for coliform concentration are the number of coliform forming units per 100mL

4.2 Basic Pond

4.2.1. Case 1



4.2.1.1. Design Rationale

The basic case of the pond without baffles was simulated first to provide a benchmark against which to evaluate the treatment of coliforms.

4.2.1.2. Results and Discussion

A broad circulation pattern was produced as seen in Figure 4-1. The basic pond was designed with the inlet and outlet in opposite corners (in accordance with Mara &

Pearson, 1998), this results in the bulk flow moving straight from the inlet around and past the outlet. This direct flow to the outlet allows a portion of the influent to leave the pond very quickly. This phenomenon is described as short-circuiting.

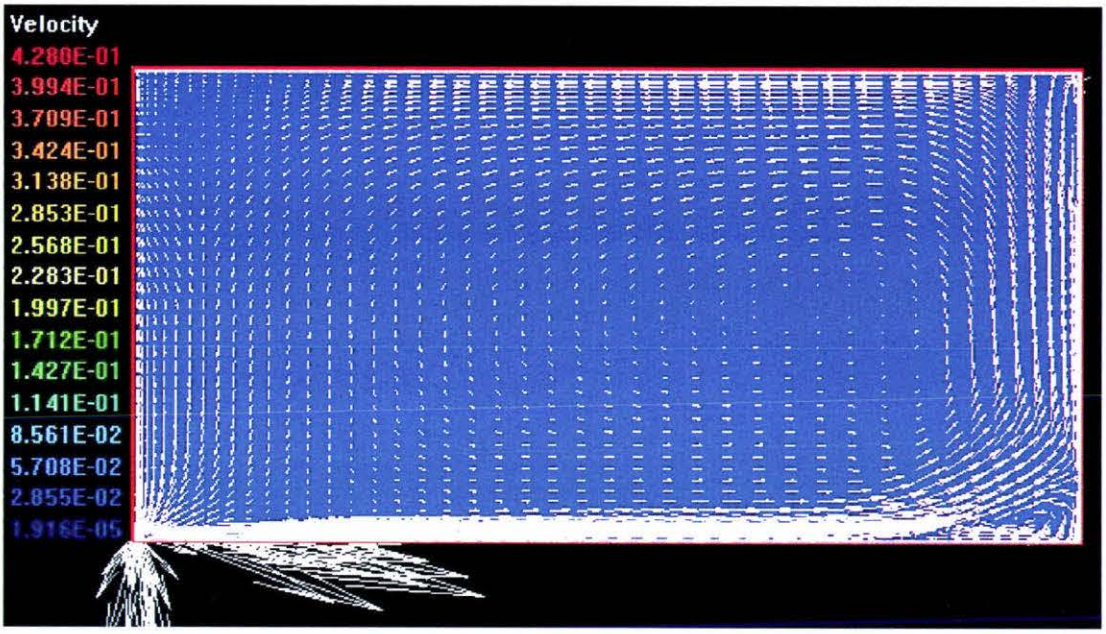


Figure 4-1 Flow Pattern Case 1 (basic pond)

The concentration profile of faecal coliforms is depicted in Figure 4-2. The inlet concentration was set at $1x10^8$ cfu/100mL. The colours depict the concentration, with red being the highest concentration of coliforms and blue depicting a lower concentration.

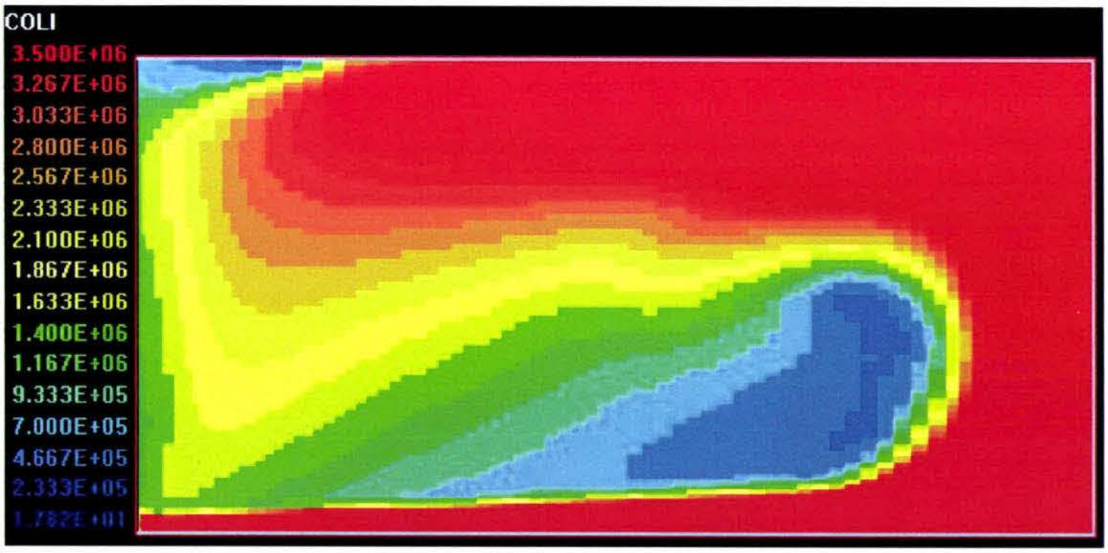


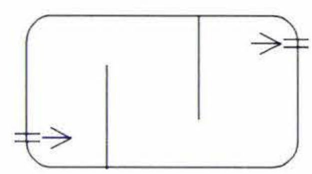
Figure 4-2 Coliform Concentration Case 1 (basic pond)

As can be seen, the highest concentration of coliforms is found along the main flow path. The resulting coliform concentration at the outlet was <u>*$6.15x10^6$ cfu/100mL*</u>.

The position of the outlet does not appear to significantly affect the main flow path. The direction of the arrows in the velocity profile, do not seem to show the main flow pattern being 'pulled' towards the outlet corner. The effect of outlet position was investigated by Shilton (2001). He concluded that the position of the outlet had only a very localised effect i.e. no effect on the bulk flow pattern, and that its position is a secondary function to the inlet and shape. This was also seen in Case 1.

4.3 Evenly Spaced Multiple Baffles, Standard Length

4.3.1. Case 2 – Traditional two baffle design



4.3.1.1. Design Rationale

Case 2 is similar to one of those tested by Watters *et al.*, (1973), and here was evaluated using CFD modelling to see if similar results would be seen. The baffles in the pond are evenly spaced and extend 70% across the width of the pond.

4.3.1.2. Results and Discussion

The flow pattern for Case 2 is shown in Figure 4-3. It can be seen that each third of the pond acts as a separate 'cell'. The flow patterns within each cell are similar to the bulk fluid flow in Case 1. In the first cell, the flow is in an anti-clockwise direction, clock-wise in the second cell, and anti-clockwise in the final cell.

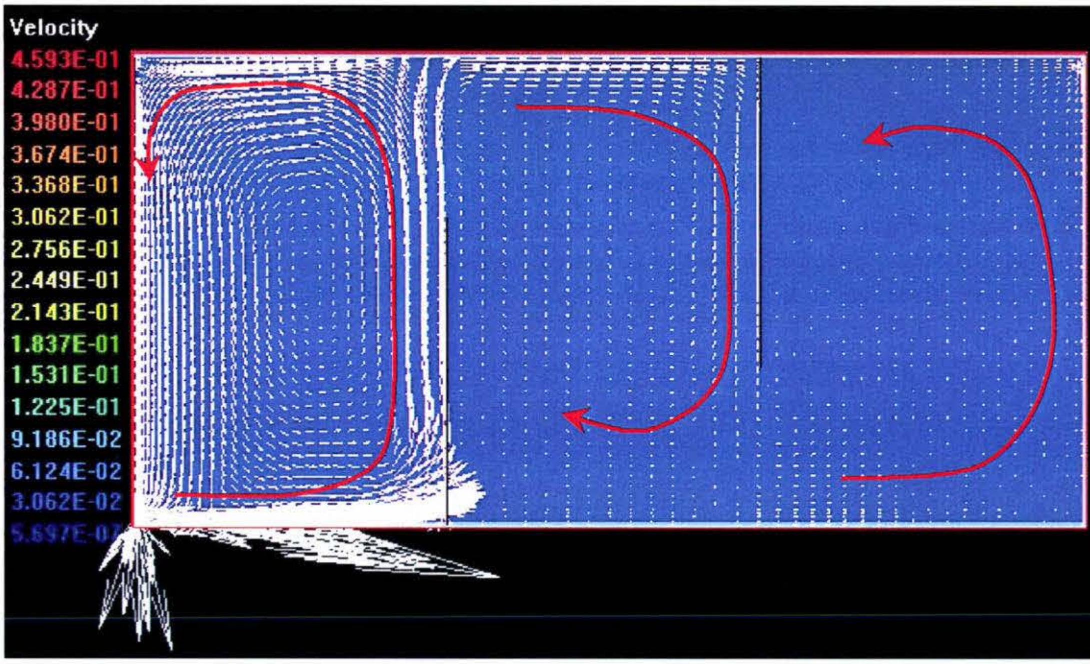


Figure 4-3 Flow Pattern Case 2 (traditional two baffle case)

The concentration of faecal coliforms throughout out the pond is depicted in Figure 4-4. The coliform level at the outlet was *$6.00x10^3$ cfu/100mL.*

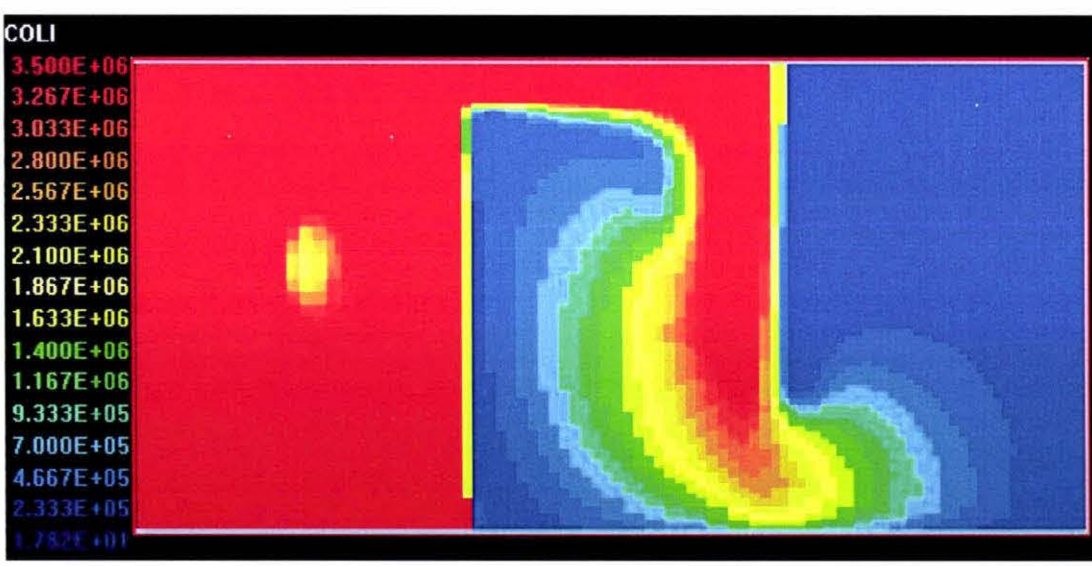


Figure 4-4 Coliform Concentration Case 2 (traditional two baffle case)

This two-baffle case showed a significant improvement on the basic case. The circulation effect produced in each 'cell' of the pond, prior to its entrance into the following cell gives a closer approximation to plug-flow.

This case resulted in a 5-log reduction in the level of coliforms, which is a significant improvement on the 2-log reduction of the basic case. This indicates that short-circuiting is reduced. The flow pattern also indicates that the premature exit of large portions of the wastewater is delayed in each cell.

The slower velocity of the fluid at the outlet can be seen by the smaller size of the arrows in the velocity profile compared to the arrows in Case 1 (basic case). A comparison between the two outlet corners of Case 1 and Case 2 is shown in Figure 4-5.

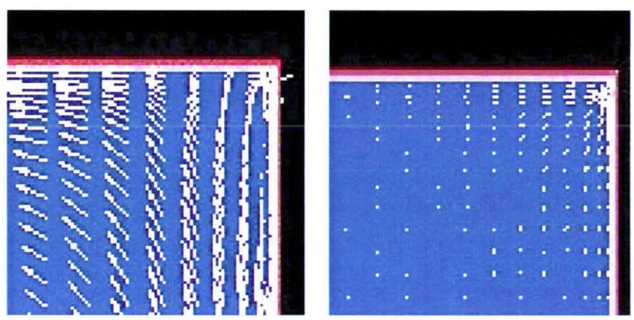
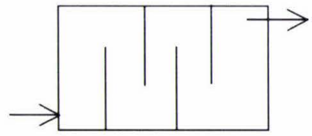


Figure 4-5 Comparison of Outlet Velocities Case 1 – Basic Case (left) and Case 2 (right)

As this case showed a significant improvement on the basic pond, and is a traditional design previously tested by Watters *et al.*, (1973), it was chosen to test in the laboratory situation, the results are given in Section 5.5.

4.3.2. Case 3 – Traditional four baffle case



4.3.2.1. Design Rationale

Case 3 is another tested by Watters *et al.*, (1973) using baffles that are 70% of the width of the pond.

4.3.2.2. Results and Discussion

The flow pattern, as seen in Figure 4-6, is similar to that exhibited in Case 2. It has the individual circulations within each 'cell' of the pond. The mixing seen in Case 2 is present in the first two cells. The pattern in the thir d cell is not easily defined. The pattern exhibited in the last two cells shows two distinct areas, one of higher velocity and one lower (as shown by the red dashed lines on Figure 4-6.

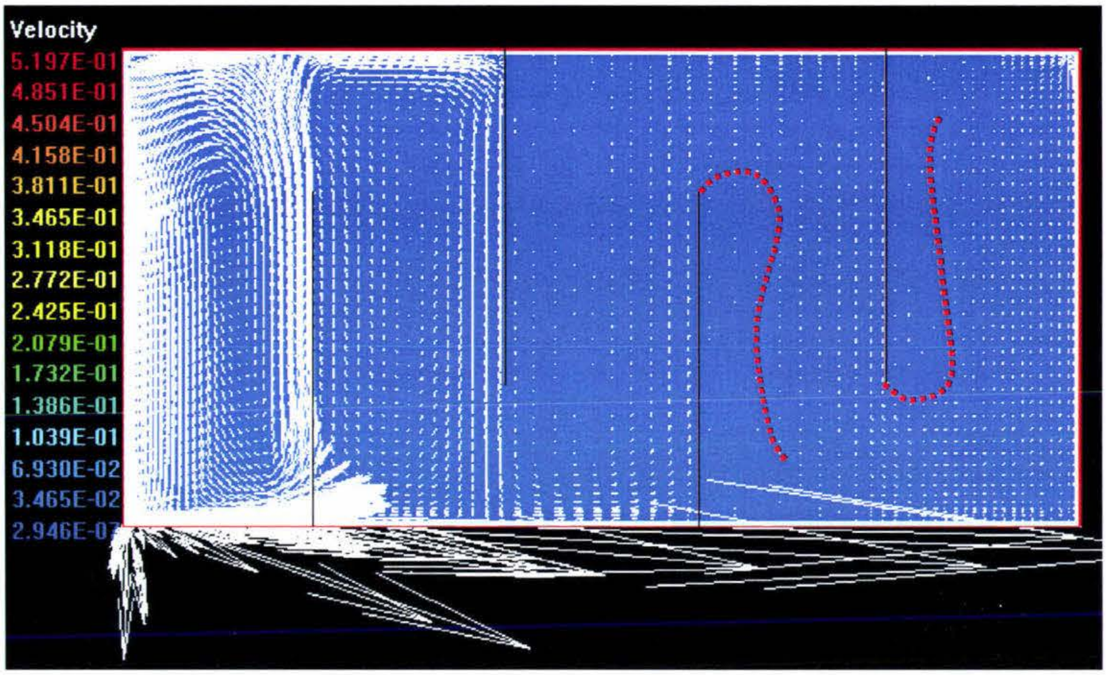


Figure 4-6 Flow Pattern Case 3 (traditional four baffle case)

There is a similarity between the flow patterns on the final two cells and an explanation proposed by Watters *et al.*, (1973) for the worse performance of the 90% width baffles. Their conclusion was that channelling causes the velocity of the fluid to increase around the ends of the longer baffles. Their diagram that depicted this phenomenon is shown in Figure 4-7.

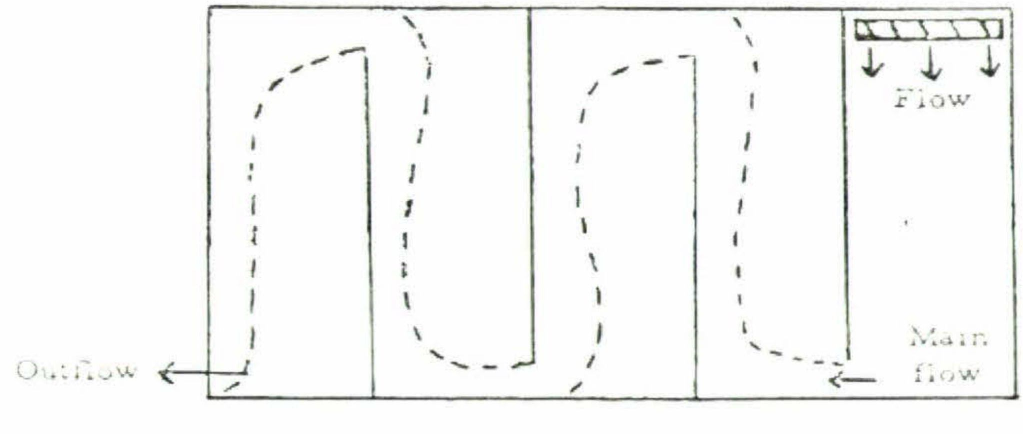


Figure 4-7 Channelling due to 90% width baffles (Watters *et al.*, 1973, pg 49)

This channelling phenomenon may also be occurring due to the close nature of the baffle to the end wall, suggesting that the channelling effect is in fact caused by length to width ratio. This effect will be further discussed and developed in Section 7.4.

The coliform concentration profile is shown in Figure 4-8, the concentration at the outlet is *3.86×10^2 cfu/100mL*. This is similar to the treatment in the six -baffle case (Case 4).

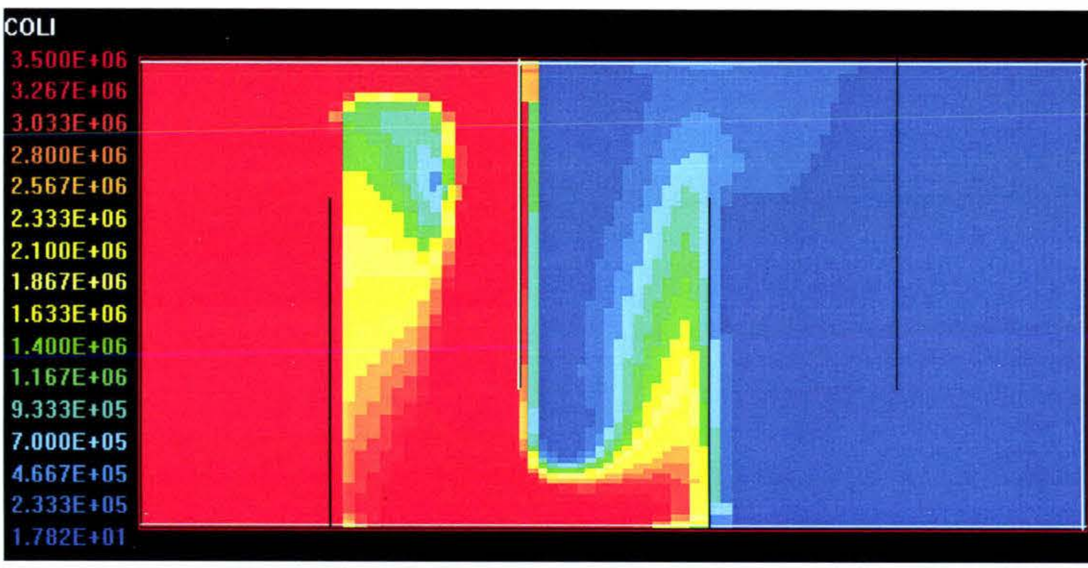
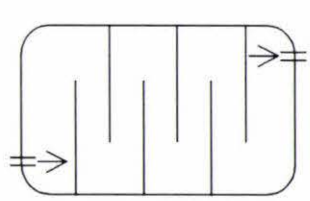


Figure 4-8 Coliform concentration profile - Case 3 (traditional four baffle case)

4.3.3. Case 4 – Traditional six baffle design



4.3.3.1. Design Rationale

Case 4 is again, a repeat of a baffle configuration tested by Watters *et al.*, 1973. This case has six baffles which are 70% of the width of the pond. This case was obviously expected to be an improvement on Case 2 (two baffles, 70% width) and on Case 3 (four baffles, 70% width), due to the addition of extra baffles. In particular it was important to determine just how much better the performance would be in order to justify the expense of extra baffles.

4.3.3.2. Results and Discussion

The flow pattern for Case 4 is seen in Figure 4-9.

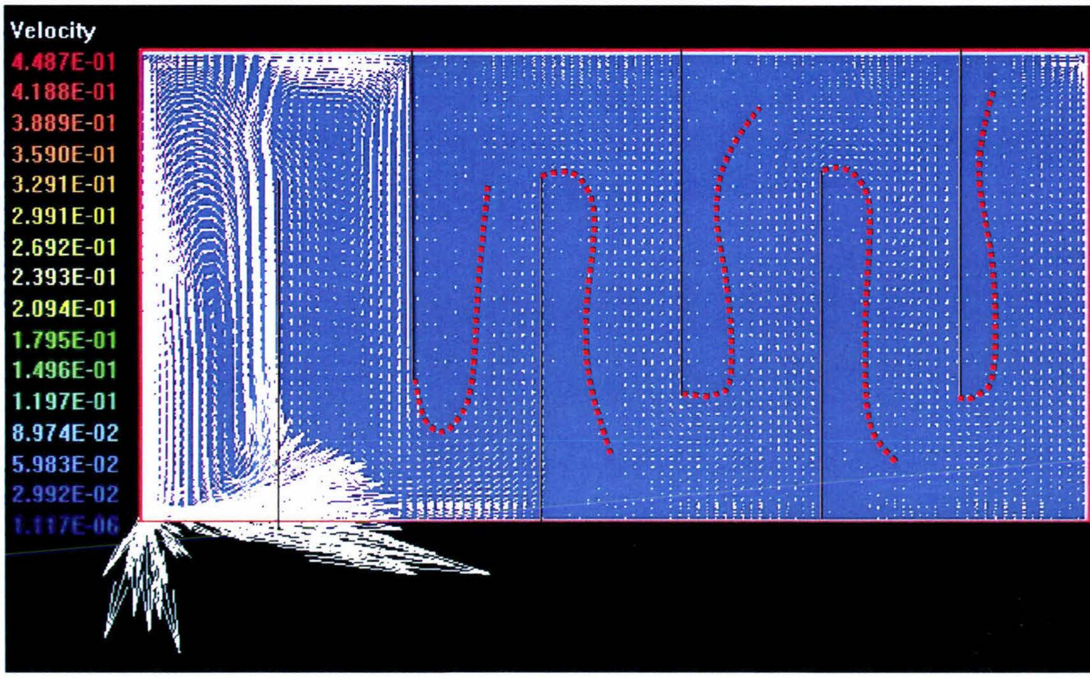


Figure 4-9 Flow Pattern Case 4 (traditional six baffle case)

The pond was now divided up into seven cells instead of the three in Case 2 – a mixing pattern similar to that seen in Case 2 is repeated here, but mainly in the first two cells. The red lines indicated on the flow diagram show a flow pattern in the third to seventh cells that was similar to that of the final two cells in Case 3.

The coliform concentration profile for Case 4 is seen in Figure 4-10.

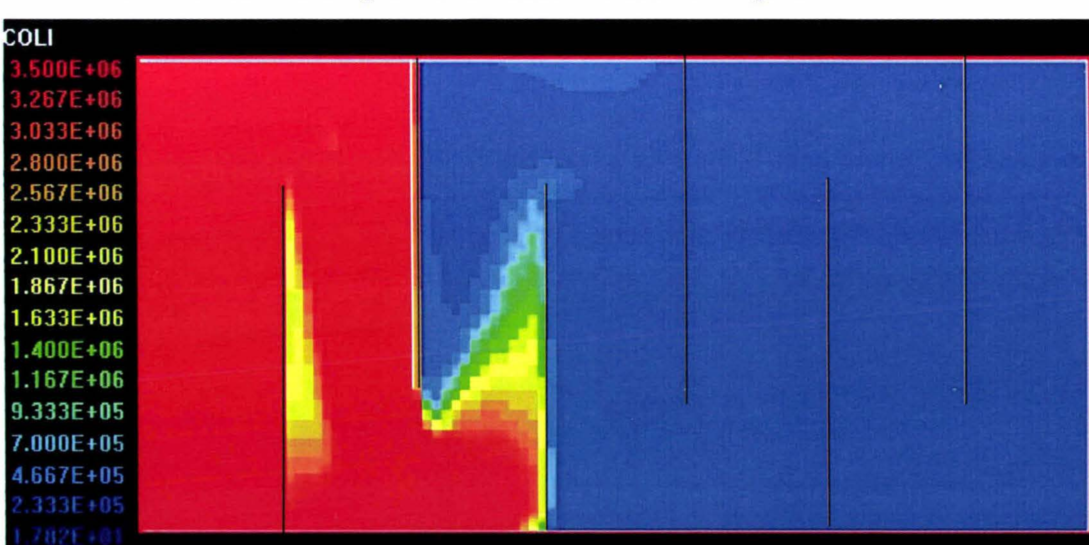


Figure 4-10 Coliform Concentration Case 4 (traditional six baffle case)

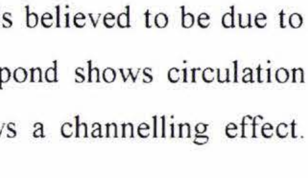
The coliform concentration at the outlet was *$5.65x10^2 cfu/100mL$*. This 6-log reduction represents a significant improvement on the basic case (2 log reduction). However, the addition of four extra baffles only results in a further 1 log reduction on the performance of the traditional two baffle case (Case 2, 5 log reduction in coliform concentration).

The treatment efficiency achieved for Case 3 (4 baffle case) and this case are very similar. This was not expected due to the addition of two further baffles in Case 4. The similarity in treatment is believed to be due to the changing nature of the flow path. The front end of the pond shows circulation and mixing patterns, while the back end of the pond shows a channelling effect. This phenomenon is discussed further in Section 7.4.

This case performed very well, however its treatment level needs to be considered in conjunction with the cost of installing four extra baffles. Case 2 had 448 metres of baffles, while Case 4 had 1344 metres of baffles.

This case was also tested in the laboratory, see Section 5.6 for results.

4.3.4. Case 5 – Traditional eight baffle case



4.3.4.1. Design Rationale

Case 5 is also one tested by Watters *et al*., (1973). It completes the suite of 4 (Cases 2, 3, 4, 5) that were tested by Watters *et* al., (1973).

4.3.4.2. Results and Discussion

The flow pattern, Figure 4-11, is similar to those seen in Cases 2, 3, and 4. Again, the change of flow patterns from the second to third cell is seen. In addition, the circulation pattern in the first two cells is not as well defined as in Cases 2, 3 and 4.

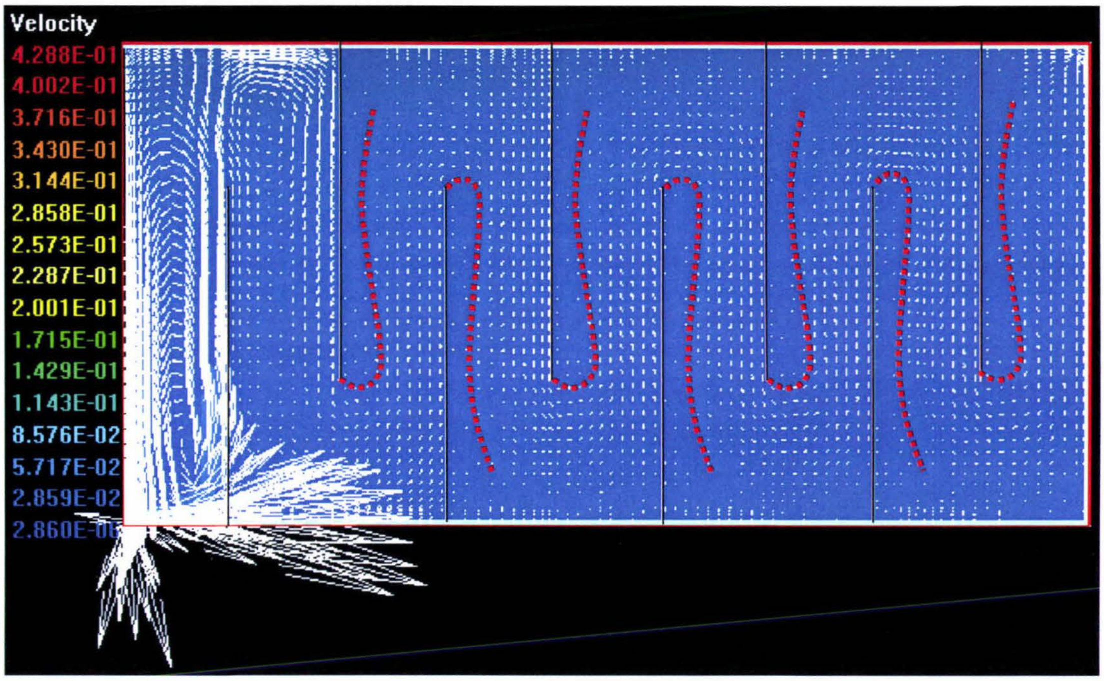


Figure 4-11 Flow Pattern Case 5 (traditional eight baffle case)

The coliform concentration profile is shown below in Figure 4-12, the concentration at the outlet is *9.60 cfu/100mL*. This is a significant improvement on the basic case, and is also better than the 4 and 6 baffle cases.

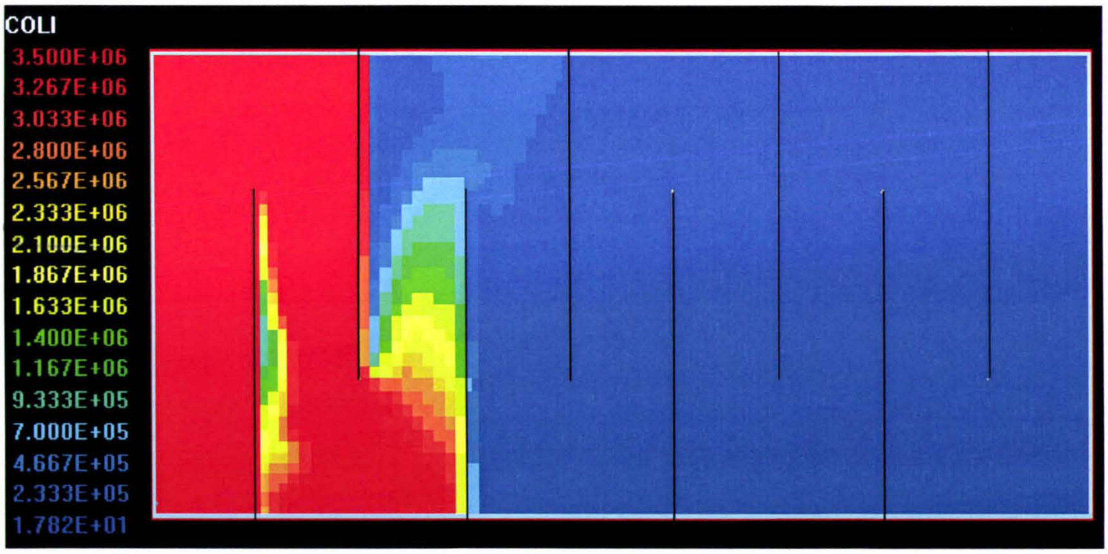


Figure 4-12 Coliform Concentration Profile Case 5 (traditional eight baffle case)

The treatment achieved in this case is very good. The channelled flow path is prevalent in this pond, more so than for the 4 baffle case and the 6 baffle case.

To summarise, in the 8 baffle case, only the channelling effect is seen, in the 2 baffle case only the circulation and mixing patterns were evident, in the 4 and 6 baffle cases a mixture of the two different flow patterns is seen. This suggests that a transition occurs between the two types of flows, and may explain why the treatment for the 4 and 6 baffle cases were similar. This phenomenon is discussed further in Section 7.4.

The addition of eight full-length baffles into a pond will come at considerable cost. This cost needs to be weighed up against the treatment efficiency gain.

4.3.5. Summary

The investigation into the use of the evenly spaced baffles of standard length has shown that as the number of baffles increase, the treatment efficiency generally improves. However, this efficiency improvement is not linear. There is a lack of efficiency improvement from the four- to six-baffle cases, before a jump in improvement in the eight-baffle case.

The observation of the types of flow patterns present in each pond may explain the non-linear improvement in treatment efficiency. Two distinct types of flow pattern were seen, a circulation pattern and a channelled pattern. In the two extremes, the two and eight baffle cases, either the circulation or channelled pattern were seen. In the four and six baffles cases, both flow types were seen. These observations are further developed in Section 7.4.

4.4 Unevenly Spaced Baffles, Standard Length

4.4.1. Case 6 – Two baffles, unevenly spaced

4.4.1.1. Design Rationale

Case 6 is a variation of Case 2. It uses the same baffles as for Case 2, which were evenly spaced, and instead pushes them closer to the ends of the pond. They are located 128m from the end walls (20% of the length).

In this design the inlet baffle is intended to act as a 'momentum disperser' and not simply a barrier for directing flow. The aim of the design was to see if this would act to dissipate the 'jetting' effect of the inlet pipe. The larger central cell of the pond would therefore act as a basic un-baffled pond with a slower momentum. The outlet baffle would then act to shield the outlet, further delaying the effluent being discharged.

4.4.1.2. Results and Discussion

The flow pattern diagram is shown in Figure 4-13.

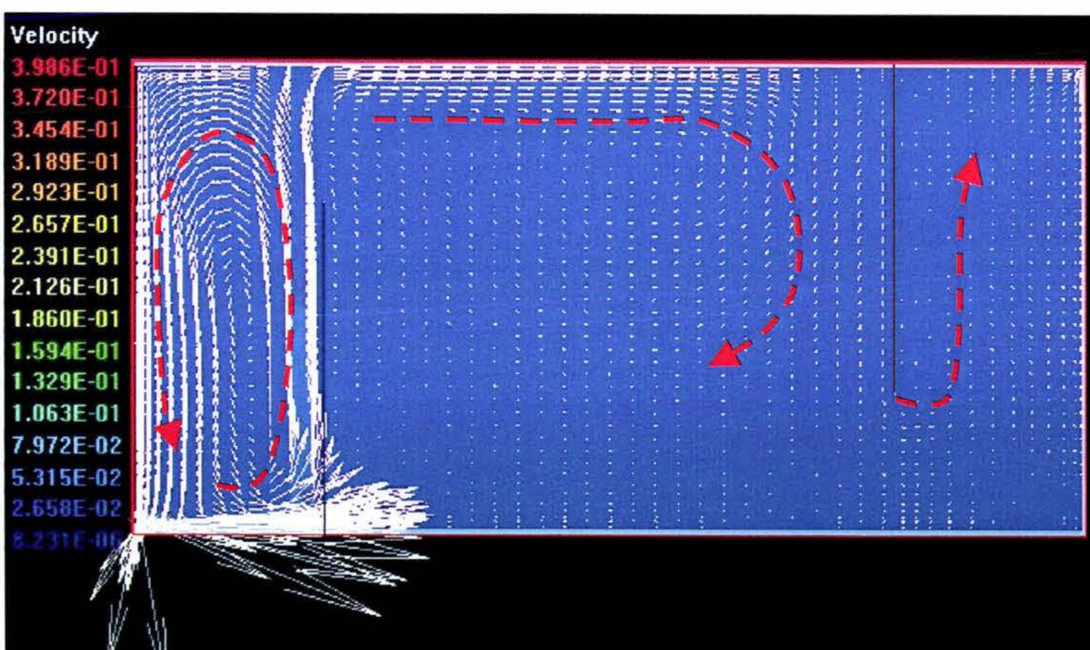


Figure 4-13 Flow Pattern Case 6 (two baffles evenly spaced)

Circulating flow is present in the first cell of the pond, as well as the large central cell. The third cell however, showed a channelled flow. As shown in the flow pattern diagram (Figure 4-13) the circulation is faster in the first cell and significantly slower in the second and third cells.

The coliform concentrations are shown in Figure 4-14. This case did not perform as well as Case 2 (two baffles, 70% width, evenly spaced). The coliform level at the outlet was *$2.39x10^4$ cfu/100ml*, the coliform concentration for Case 2 was *$6.00x10^3$ cfu/100mL.*

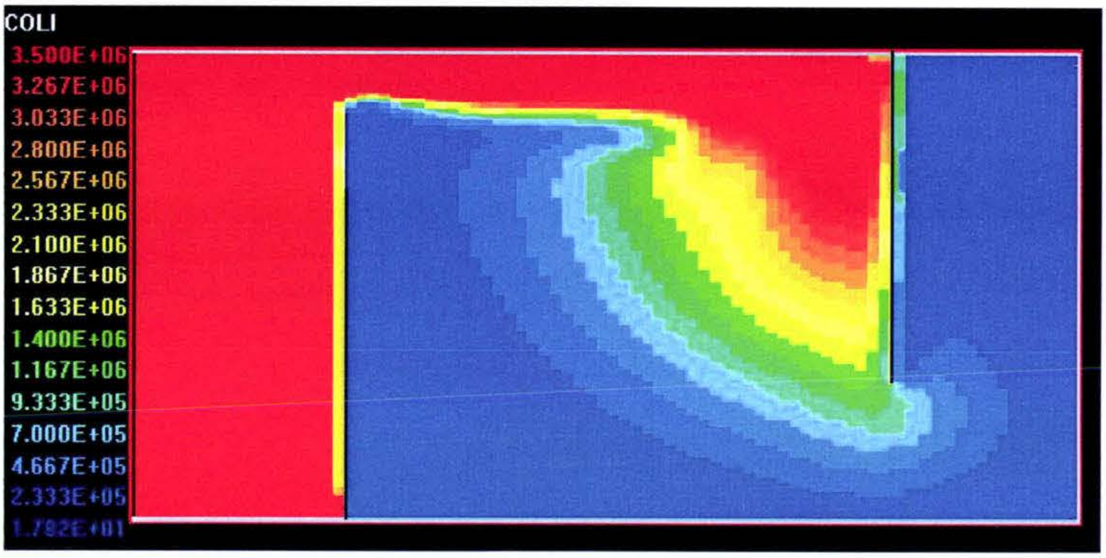


Figure 4-14 Coliform Concentration Case 6 (two baffles, evenly spaced)

The lack of improvement in this case over Case 2 was suspected to be momentum effects. The momentum is not dissipated and contained in the first cell as was expected. This appears to differ from Persson (2000), who found that the inclusion of an island or sub-surface berm (wall) close to the inlet had a beneficial impact on hydraulic efficiency.

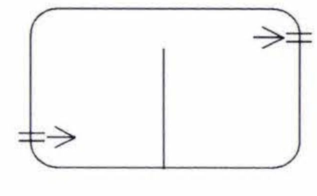
Some channelling, similar to that exhibited in the 3rd to 7th cells of Case 4, was also seen in the final cell, as shown by the red arrow on the right hand side of Figure 4-13.

4.4.2. Summary

The improvements expected by moving the position of the standard length baffles did not eventuate. A smaller front-end 'cell' did not dissipate momentum as expected. Despite the poorer performance than Case 2 (two baffle evenly spaced), the design still provided improved treatment efficiency over the basic case.

4.5 Single Baffles

4.5.1. Case 7 – Single central baffle



4.5.1.1. Design Rationale

Case 7 has a single baffle, 70% of the width of the pond, and located in the middle of the pond. The improvement was not expected to be as great as Case 2 (two baffles evenly spaced) however, it was hoped that some would be seen. Therefore, it could be shown that a single baffle would be better than no baffles.

4.5.1.2. Results and Discussion

The flow pattern and coliform concentrations for Case 7 are shown in Figure 4-15 and Figure 4-16.

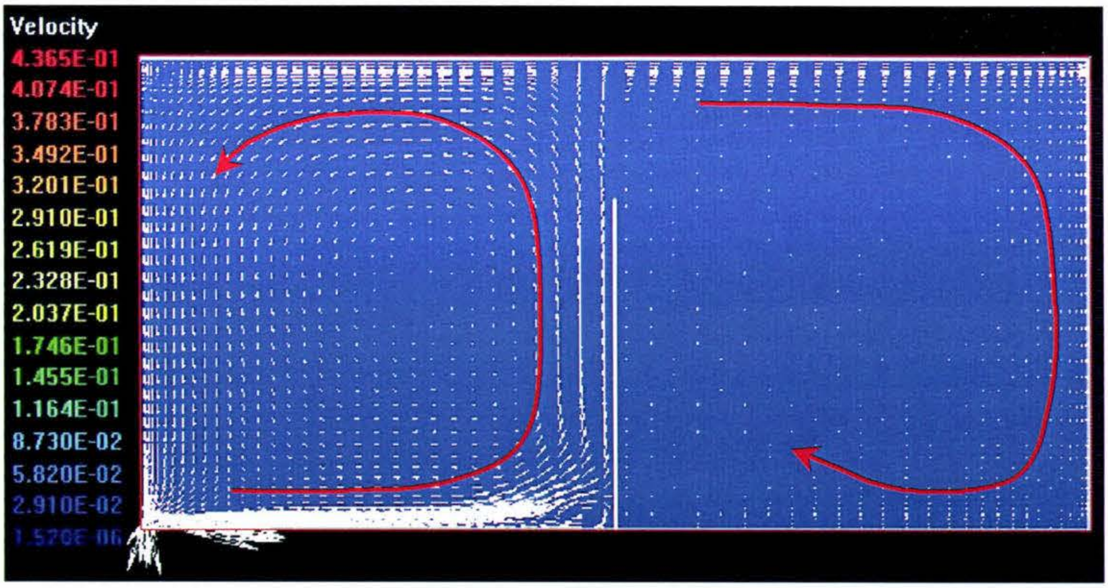


Figure 4-15 Flow Pattern Case 7 (single central baffle)

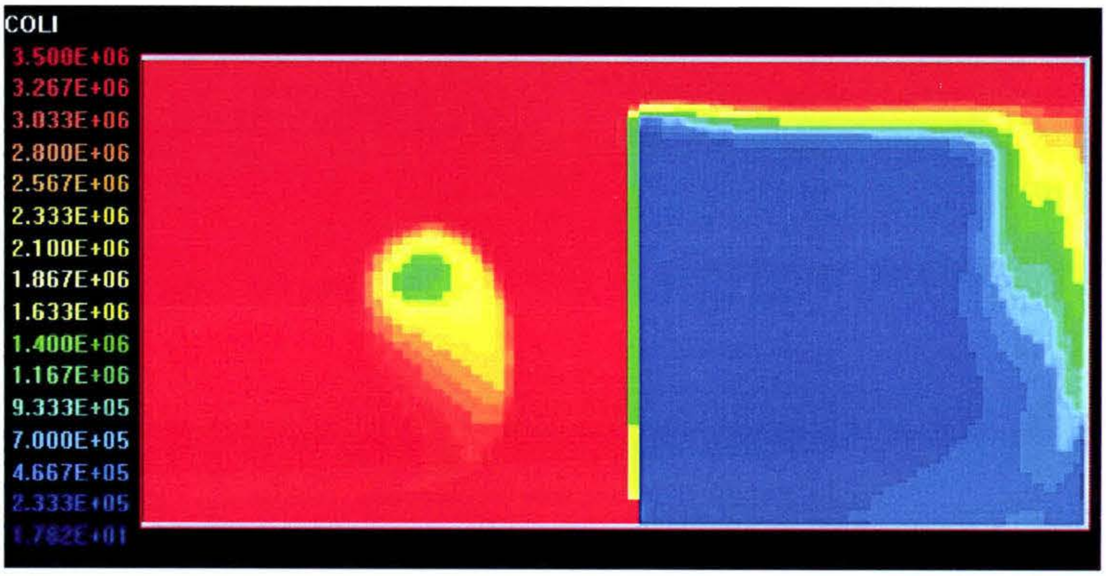


Figure 4-16 Coliform Concentration Case 7 (single central baffle)

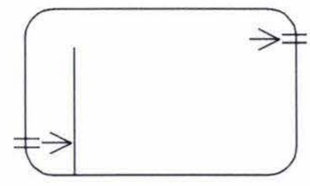
The coliform level at the outlet was *$4.10x10^6$ cfu/100mL*. This is the same order of magnitude as the basic pond case (Case 1) and therefore this design does not represent any significant improvement.

This finding indicates that the use of a single baffle will not improve the treatment efficiency of a pond. This is significant in that if a single baffle were effective, it would offer a quick and economic solution to improve pond efficiency.

The flow is well-mixed in the first half of the pond before entering the second half of the pond. However the treatment efficiency was shown to be only slightly better than the basic pond.

As can be seen in the above diagram (Figure 4-16) the highest concentration of coliforms in the second cell of the pond is in the corner containing the outlet. This clearly highlights that the inlet and outlet positioning must be carefully reviewed as part of any baffle installation.

4.5.2. Case 8 – Single baffle, inlet end



4.5.2.1. Design Rationale

Cases 8, 9, 10, and 11 sought to investigate alternative configurations of using a single baffle. Case 7 showed a single central baffle as ineffective at improving treatment efficiency; these next cases test whether innovative positioning of a single baffle can offer treatment benefits. This level of investigation into a single baffle does not appear to have been attempted before.

The idea of dissipating the inlet momentum was again used and is reflected in the close positioning of the inlet baffle in Case 8 (single baffle, close to inlet).

4.5.2.2. Results and Discussion

The flow pattern diagram (Figure 4-17) shows the tight circulation cell within the first 'cell' of the pond and the slowed momentum throughout the rest of the pond.

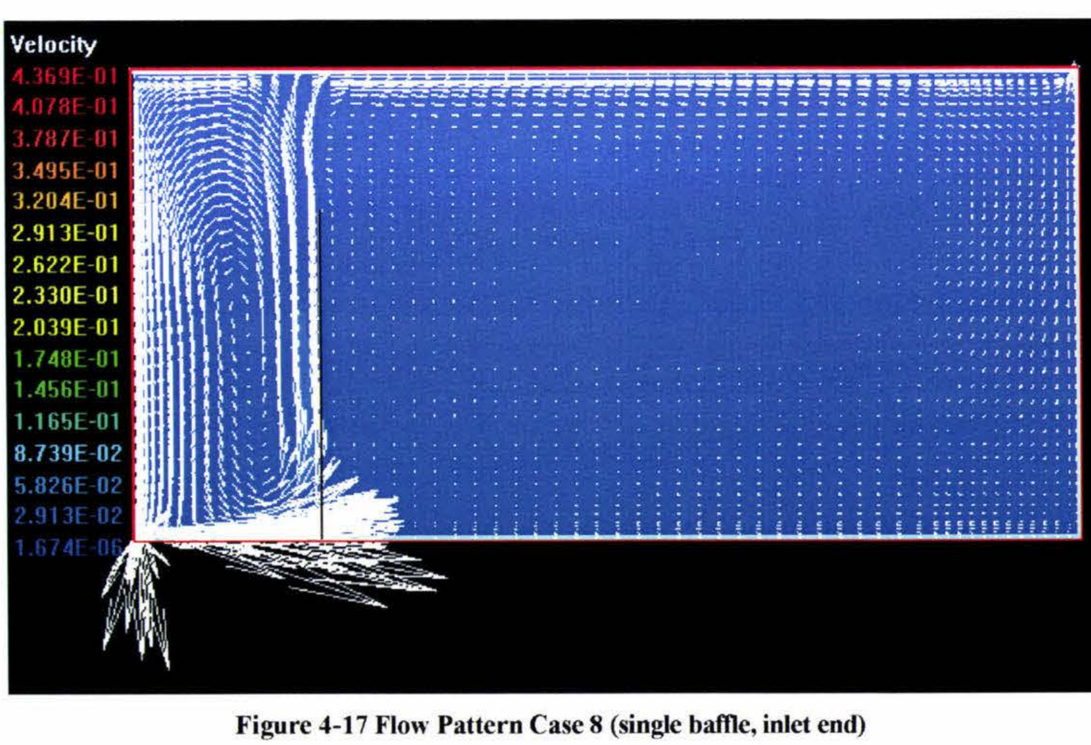


Figure 4-17 Flow Pattern Case 8 (single baffle, inlet end)

The coliform level at the outlet was $4.39x10^6 cfu/100mL$. This is in the same order of magnitude as the basic pond (Case 1), and as Case 7 (single central baffle). Therefore this design registers no significant improvement on a basic pond.

As can be seen in Figure 4-18, the coliform concentration at the outlet (top right hand corner) is in the 'red zone', that is, a high level of coliforms.

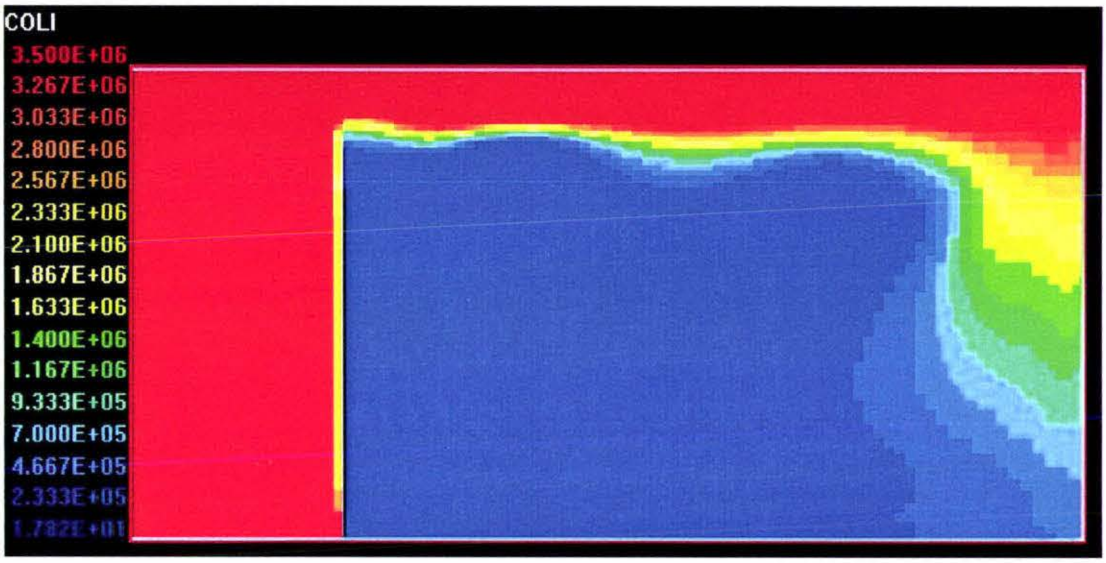
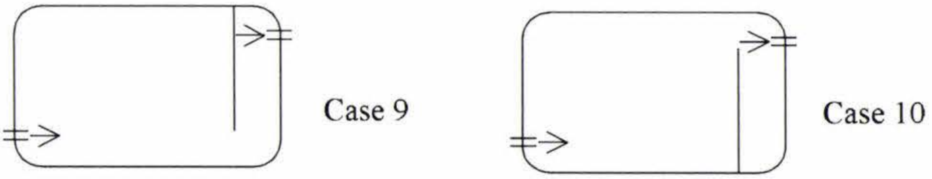


Figure 4-18 Coliform Concentration Case 8 (single baffle, inlet end)

From a visual assessment of the coliform diagram, it could be seen that the outlet may be better placed in the 'blue zone'. The bulk clockwise circulation pattern within the large 'cell' of the pond heads directly for the outlet.

4.5.3. Case 9 and Case 10 – Single baffles, outlet end



4.5.3.1. Design Rationale

Case 8 showed that the use of a single baffle as a momentum disperser did not improve treatment efficiency. Therefore Cases 9 (single baffle, outlet end) and 10 (single baffle, outlet end) involved outlet baffles that were intended to shield the outlet from the influent swirling around from the inlet.

4.5.3.2. Results and Discussion

As can be seen from the flow patterns (Figure 4-19 & Figure 4-20), the same main fluid flow circulations are seen in the large front cell in the pond and slower momentum in the small end cell.

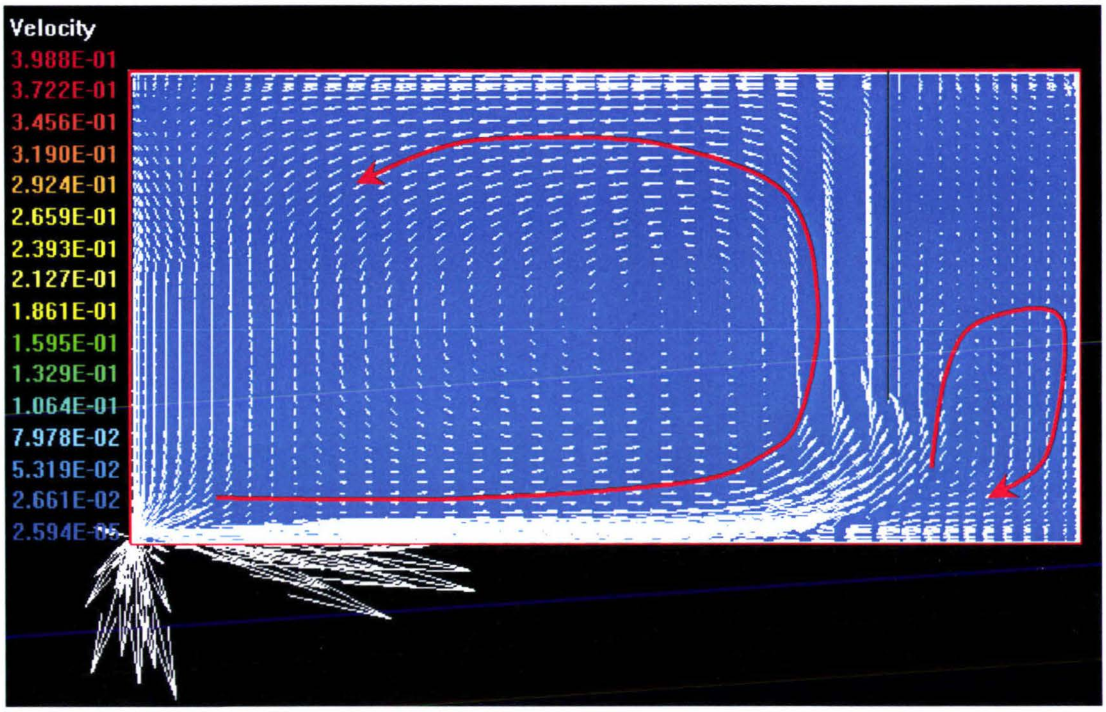


Figure 4-19 Flow Pattern Case 9 (single baffle, outlet end)

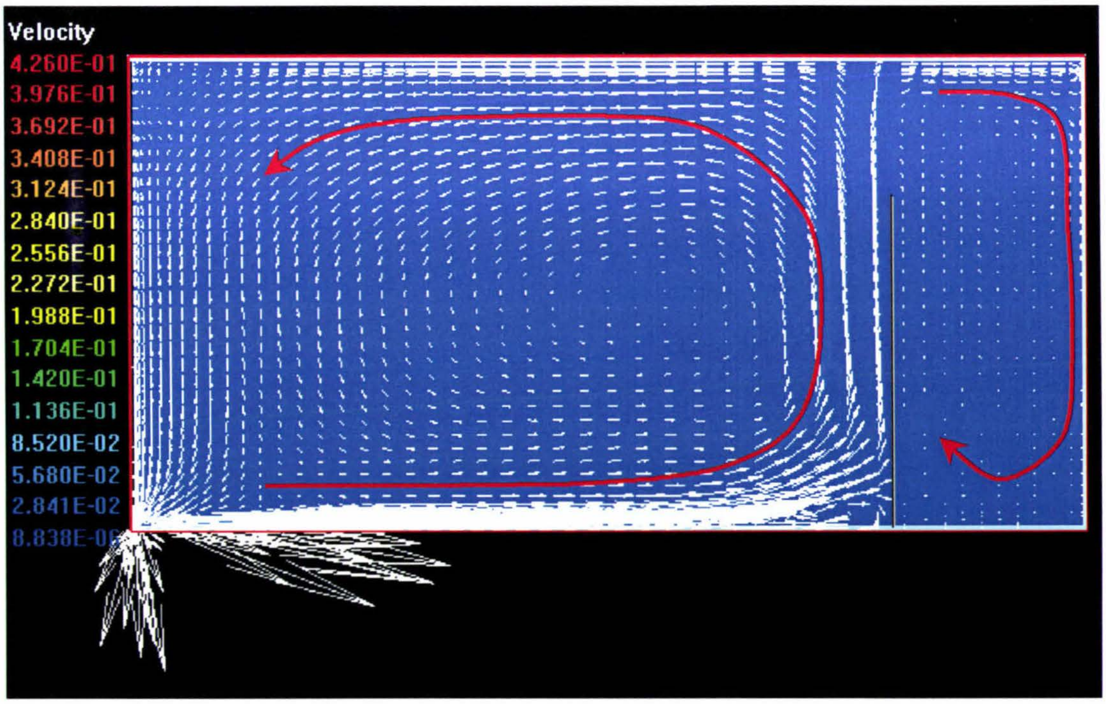


Figure 4-20 Flow Pattern Case 10 (single baffle, outlet end)

The coliform concentration is shown in Figure 4-21 and Figure 4-22.

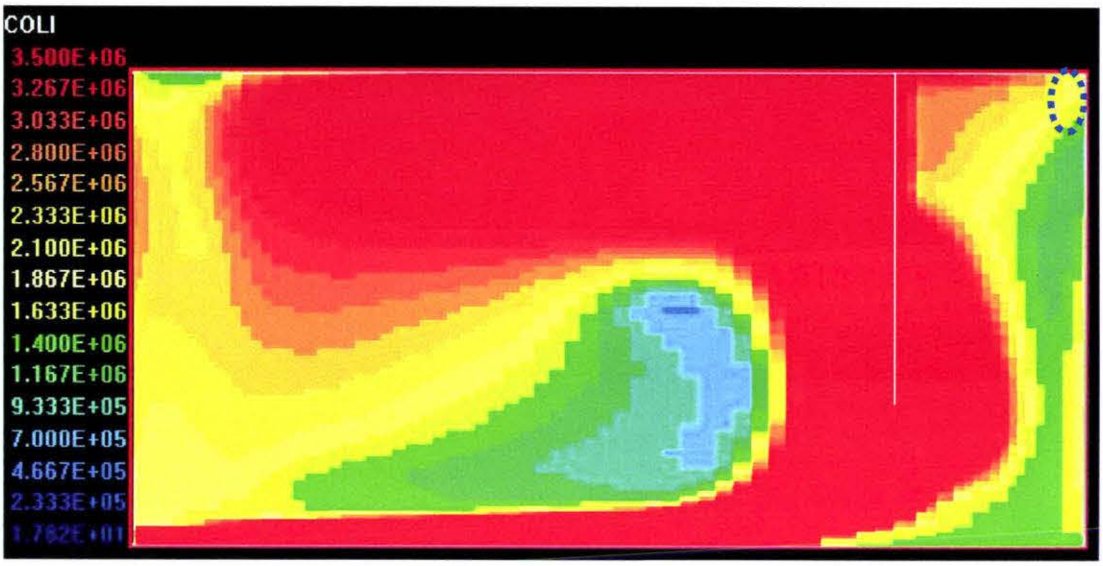


Figure 4-21 Coliform Concentration Case 9 (single baffle, outlet end)

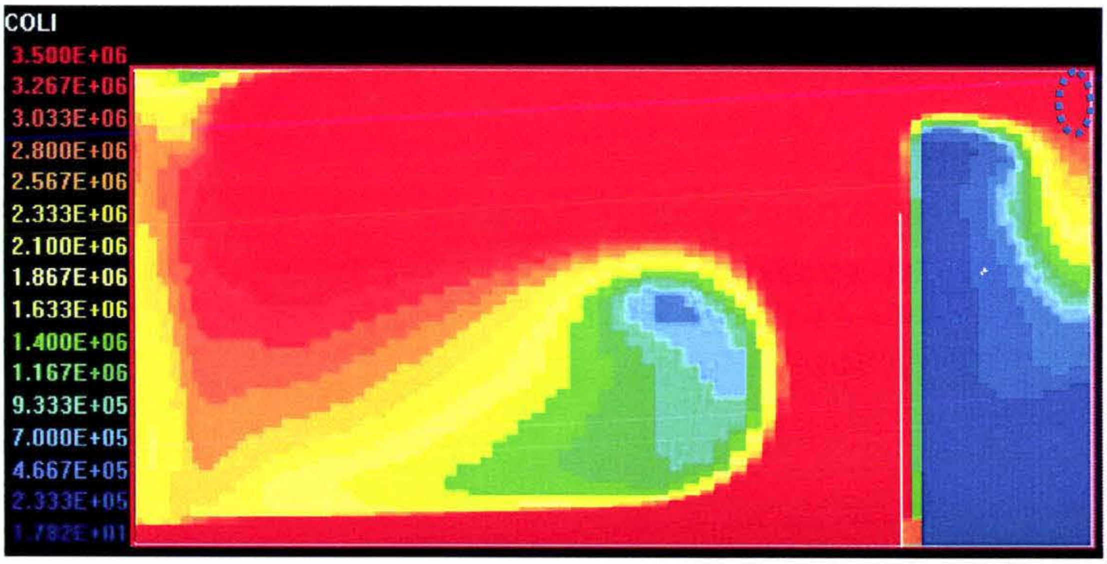


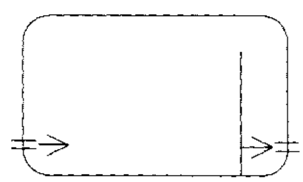
Figure 4-22 Coliform Concentration Case 10 (single baffle, outlet end)

The outlet concentrations were <u>*$1.35x10^6$cfu/100mL*</u> and <u>*$4.56x10^6$cfu/100mL*</u> for Case 9 and 10 respectively. These values are of the same order of magnitude as the basic Case 1 and for that of Case 7 (single central baffle) and Case 8 (single baffle, inlet end). However, the concentration at the outlet in Cases 9 and 10 (shown by blue dashed lines) are different. The outlet in Case 9 is situated in an area of lower concentration, hence the slightly lower outlet concentration of $1.35x10^6$cfu/100mL.

When the bulk flow reaches the end of the pond, the only exit for the momentum is the outlet, which is small in terms of the bulk flow, or it is forced to come back out into the large, more open, central 'cell' of the pond. Therefore the same bulk circulation is seen in the large cell as for previous cases, despite the appearance of a simple path from the inlet to the outlet.

The baffles have had little effect on the momentum of the bulk fluid flows, therefore little impact on treatment efficiency. It can also be seen from the position of the 'blue zones' (areas of low coliform concentration) that the position of the outlet was not appropriate for gaining a significant improvement in the performance of the single baffle designs. Therefore it was decided to re-run the model with the outlet on the same side of the pond as the inlet – as in Case 11 (single baffle, outlet end, outlet moved).

4.5.4. Case 11 – Single baffle, outlet end, outlet moved



4.5.4.1. Design Rationale

In all the previous cases, the inlet and outlet have been in fixed positions. The visual assessment of the patterns in Cases 8, 9 and 10, and in particular the outlet zone in Case 9 showed that moving the outlet may have treatment benefits.

4.5.4.2. Results and Discussion

The flow pattern and coliform concentrations for Case 11 are shown in Figure 4-23 and Figure 4-24.

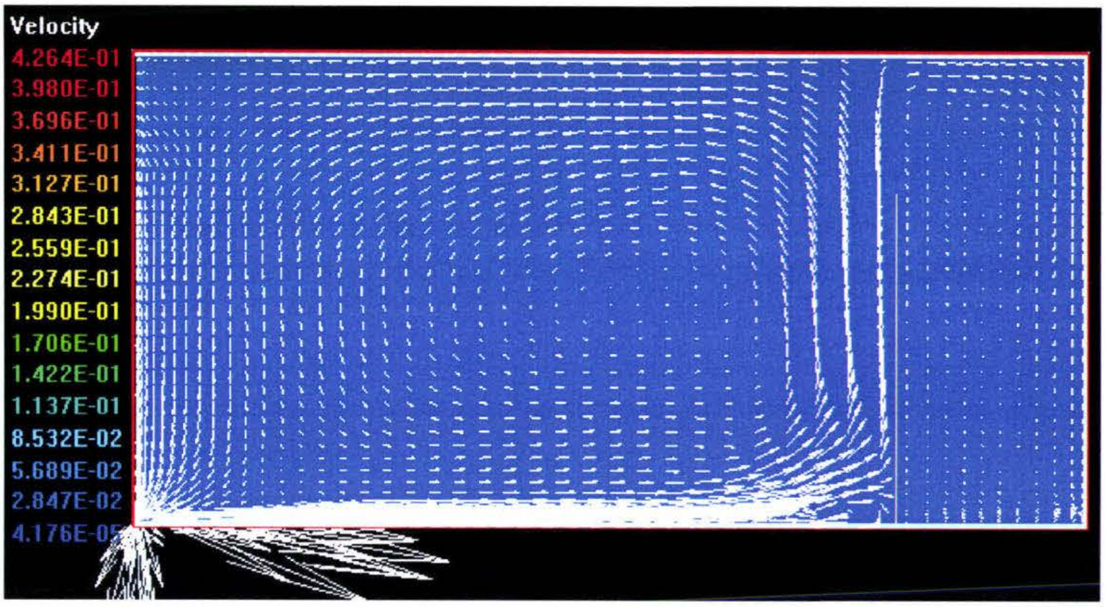


Figure 4-23 Flow Pattern Case 11 (single baffle, outlet end, outlet moved)

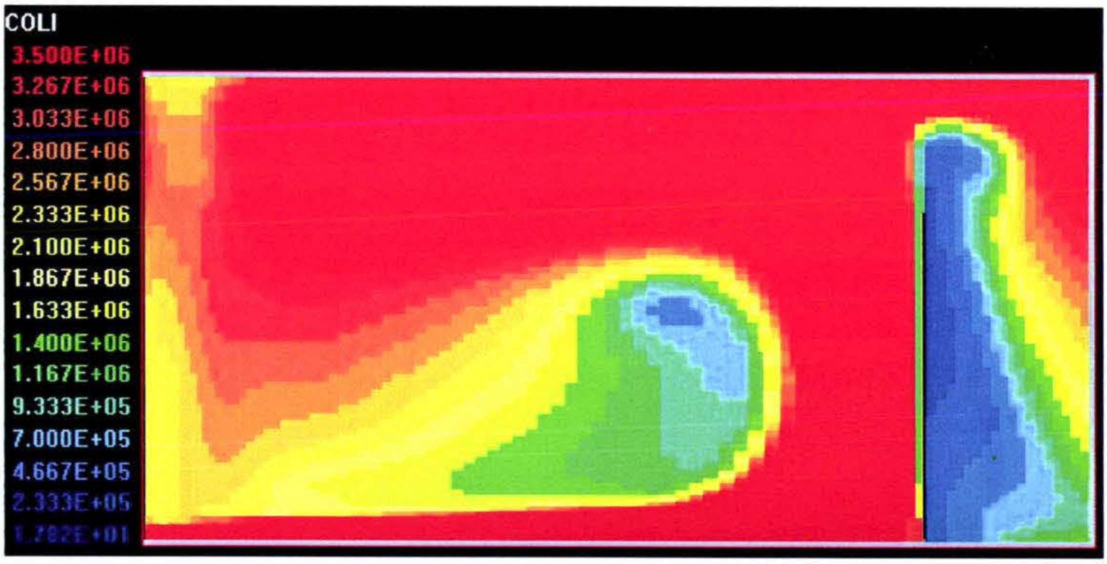
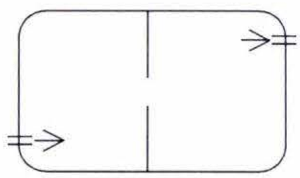


Figure 4-24 Coliform Concentration Case 11 (single baffle, outlet end, outlet moved)

In this case, the flow patterns and coliform concentrations were the same throughout the pond as Case 10. However, moving the outlet to the bottom right corner delayed the escape of the wastewater and improved the treatment. The outlet concentration was <u>*$8.00x10^5 cfu/100mL$*</u>, compared with a coliform concentration of <u>*$4.10x10^6 cfu/100mL$*</u> for Case 7. It also offers an improvement on the basic case.

While this case is still not as good a treatment as Case 2 (2 baffles, evenly spaced, 5 log reduction in coliforms), it further emphasises that the position of the outlet must be considered in conjunction with baffle design. For example, if the position of infrastructure dictates the inlet position, baffles can be designed to complement this inlet position. The position of the outlet can then be determined after the baffles design to optimise treatment efficiency.

4.5.5. Case 12 – Central wall with middle opening



4.5.5.1. Design Rationale

Case 12 involved the use of a single baffle across the width of the pond with a gap in the middle. The gap was 30% of the width of the pond.

In this case, it was thought that the bulk fluid flow at the 'gap' would be parallel with the baffle, and improve the containment of the circulation pattern to reduce short-circuiting.

4.5.5.2. Results and Discussion

The coliform level at the outlet was *$1.97x10^6$ cfu/100mL*, again representing no significant improvement in pond efficiency compared to the basic case and Case 7 (single central baffle). The flow pattern and coliform concentrations are shown in Figure 4-25 and Figure 4-26.

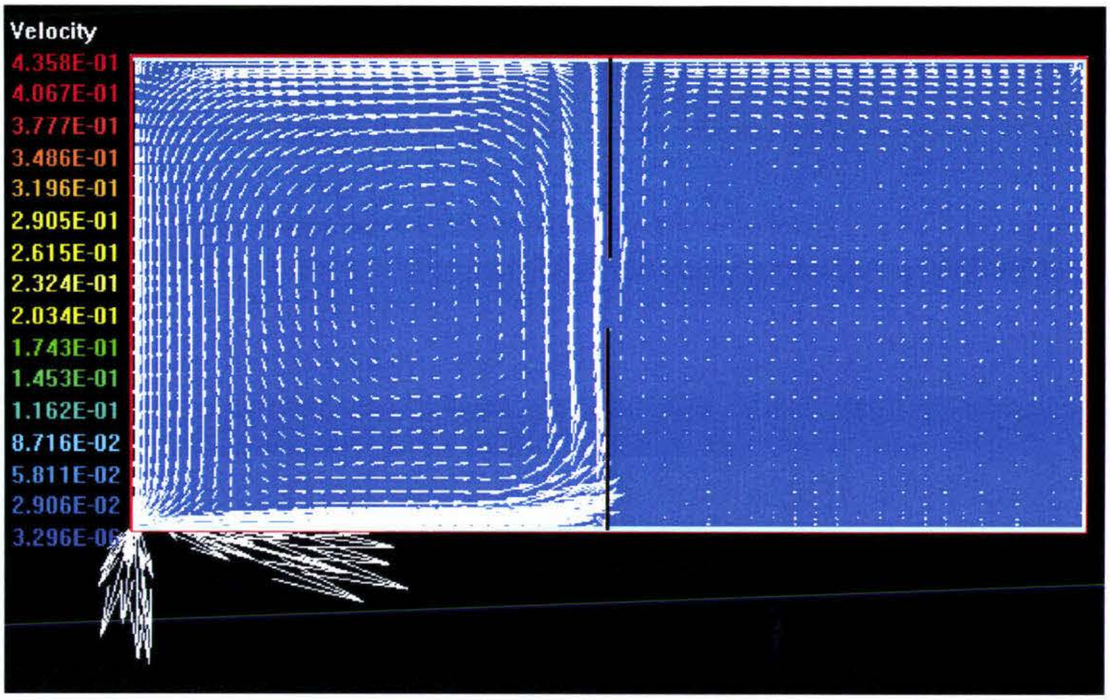


Figure 4-25 Flow Pattern Case 12 (central wall with middle opening)

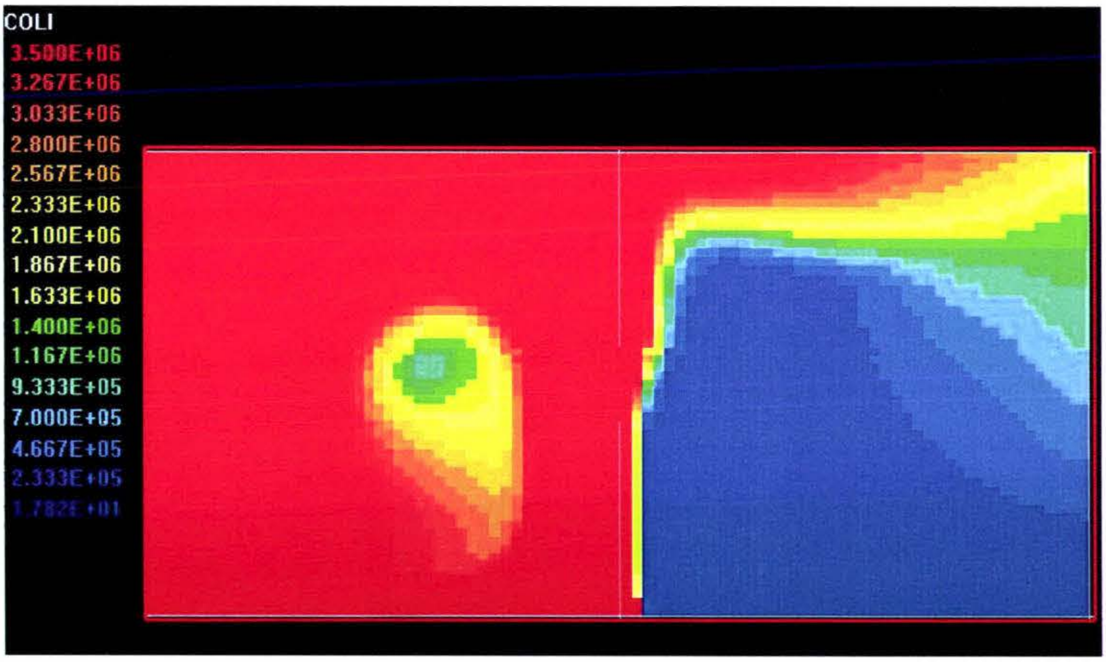


Figure 4-26 Coliform Concentration Case 12 (central wall with middle opening)

As can be seen from Figure 4-25, the velocity of the fluid entering the second cell is still significant, indicating that the attempted containment of the circulation pattern was not sufficient. The velocity of the flow is sufficiently large at the interface that even if the flow is parallel to the wall then there is a reasonable amount of mass transfer across to the second cell.

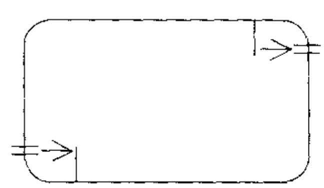
4.5.6. Summary

The use of a single baffle has shown to be not effective at improving pond treatment efficiency. The general pattern emerging from literature (Watters *et* al., 1973; Bors & Robinson, 1980; Pearson *et al.*, 19995; Lloyd *et al.*, 2002; and Pena *et al.*, 2002) is that the addition of baffles will improve pond performance. This work extends on this previous research to say that a single baffle will not generally produce significant performance improvements.

The movement of the outlet in Case 11 showed that the position of the outlet could have an effect on the treatment efficiency. Thus emphasising that the position of the outlet in a pond should be carefully considered to optimise th e treatment gains made by baffles.

4.6 Stub Baffles

4.6.1. Case 13 – Two stub baffles



4.6.1.1. Design Rationale

One of the difficulties with the installation of baffles, especially in the upgrade of existing ponds, is the extra construction cost. Obviously, the less baffling required the better.

In the Case 2 (two evenly spaced baffle, standard length), the flow alternated in the direction of the circulation in each cell. Further consideration of this led to the investigation of shorter baffle, is a full-length baffle required to achieve the turning of the flow?

This led to the investigation of 'stub' like baffles, with a length of only 15% of the width of the pond. Case 13 is a repeat of Case 6, which has the same baffle position.

4.6.1.2. Results and Discussion

The flow pattern for Case 13 is shown in Figure 4-27.

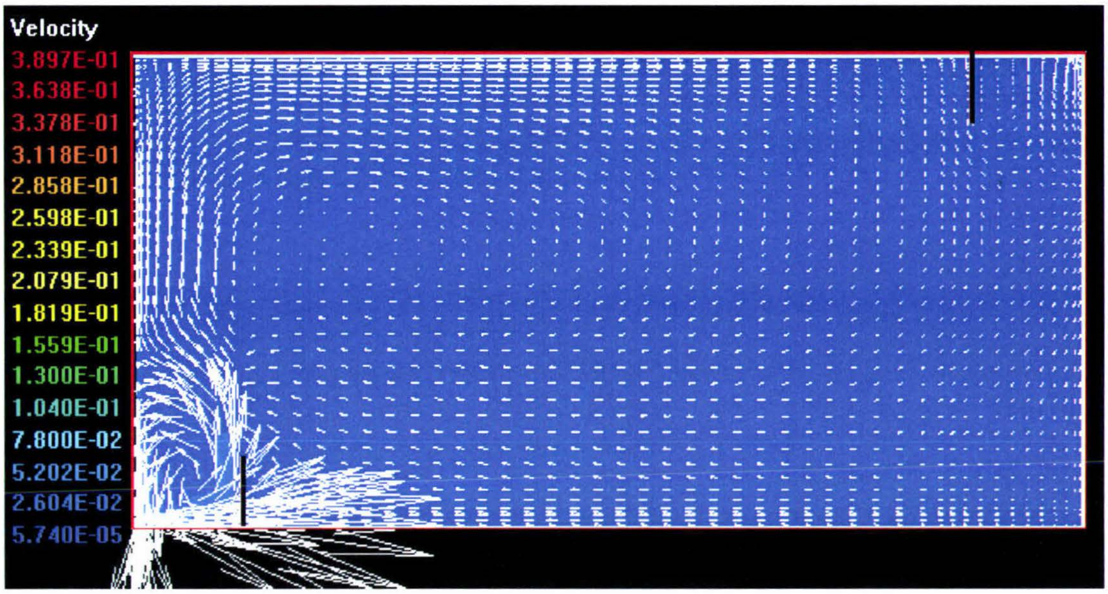


Figure 4-27 Flow Pattern Case 13 (two stub baffles)

The coliform concentrations throughout the pond are depicted in Figure 4-28.

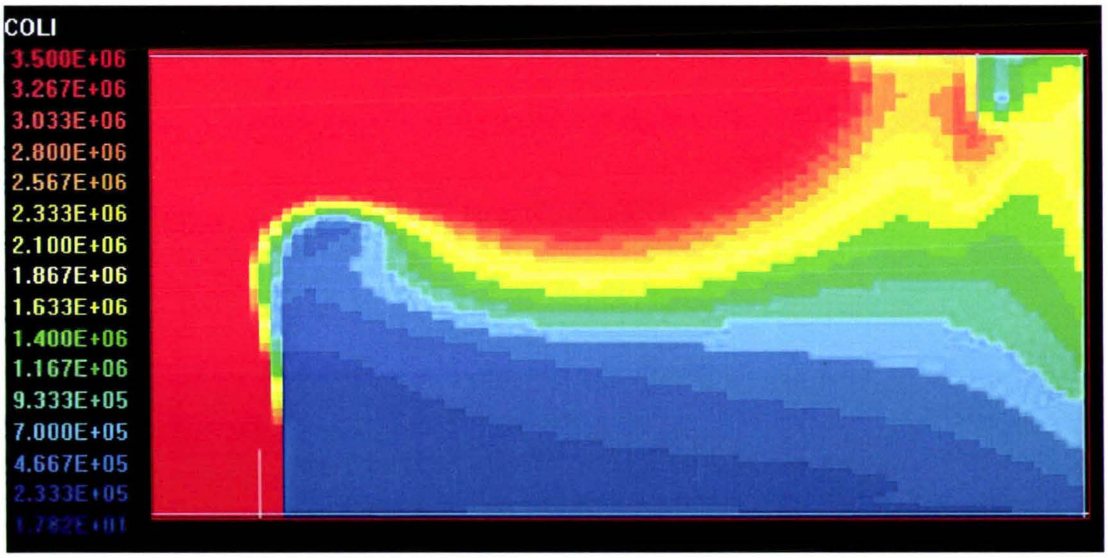


Figure 4-28 Coliform Concentration Case 13 (two stub baffles)

The outlet coliform concentration was *$1.37x10^6$cfu/100mL*. This is in the same order of magnitude as the basic case (Case 1). Therefore, this design offered no improvement over the basic case.

As can be seen in the enlargement of the inlet corner of the flow pattern for Case 13 (Figure 4-29), the stub baffle acts to turn the momentum. In a similar manner to Case

1, if the first baffle was not present, the bulk fluid flow in the pond would be in an anti-clockwise direction. In this case however, the bulk flow in the large cell of the pond is in a clockwise direction. The size of the velocity vectors (large vector = higher velocity) throughout the pond in Case 13 is also smaller than that exhibited in Case 1, indicating the dissipation and dispersion of momentum by the inlet baffle.

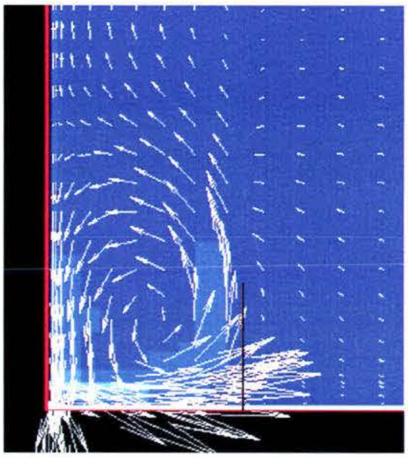


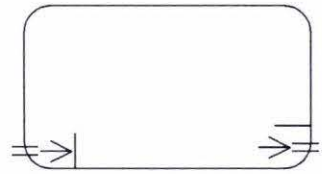
Figure 4-29 Enlargement of Inlet Corner of Case 13

Persson (2000) found that an island or sub-surface berm (wall) placed near the inlet significantly improved hydraulic performance. The dissipation of the momentum seen here in this work is likely to be the cause of the improvement seen by Persson (2000).

However, overall the stub inlet baffle has not been effective. The lack of improvement of treatment efficiency is due to the position of the outlet. The outlet is located in an area of high coliform concentration (see Figure 4-28).

Further stub baffle cases were investigated (see Cases 14 – two stub baffles, outlet moved; and 16 – one stub baffle, inlet end).

4.6.2. Case 14 – Two stub baffles, outlet moved



4.6.2.1. Design Rationale

In Case 11 (single baffle, outlet end, outlet moved), the importance of repositioning the outlet was highlighted. Case 14 now applied this thinking to the stub baffle case by repositioning the second baffle and the outlet.

The second baffle has been rotated to be parallel with the side-wall in order to shield the outlet from the clockwise direction of the fluid flow at that point. The distance between the side-wall and the outlet is 10m, and the distance between the side wall and the baffle is 20m. The baffles are still 15% of the width in length.

4.6.2.2. Results and Discussion

The flow pattern is shown in Figure 4-30.

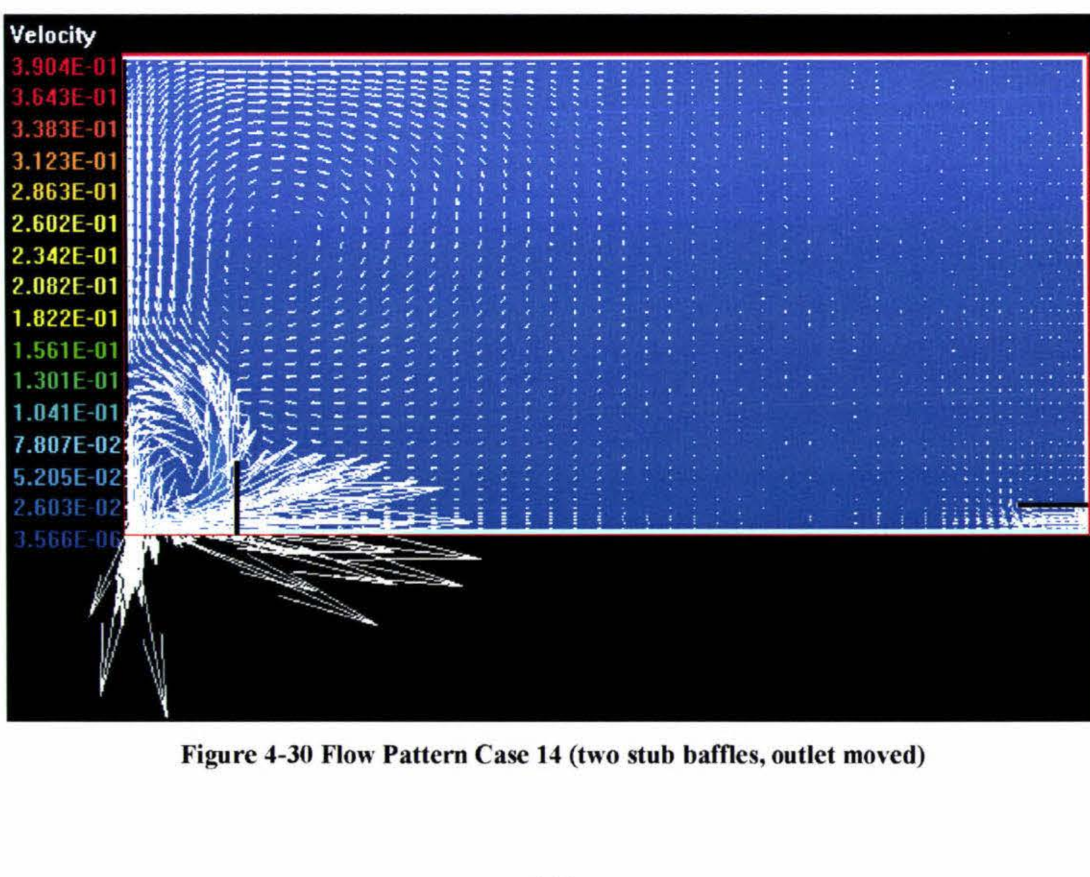


Figure 4-30 Flow Pattern Case 14 (two stub baffles, outlet moved)

The coliform concentration is shown in Figure 4-31.

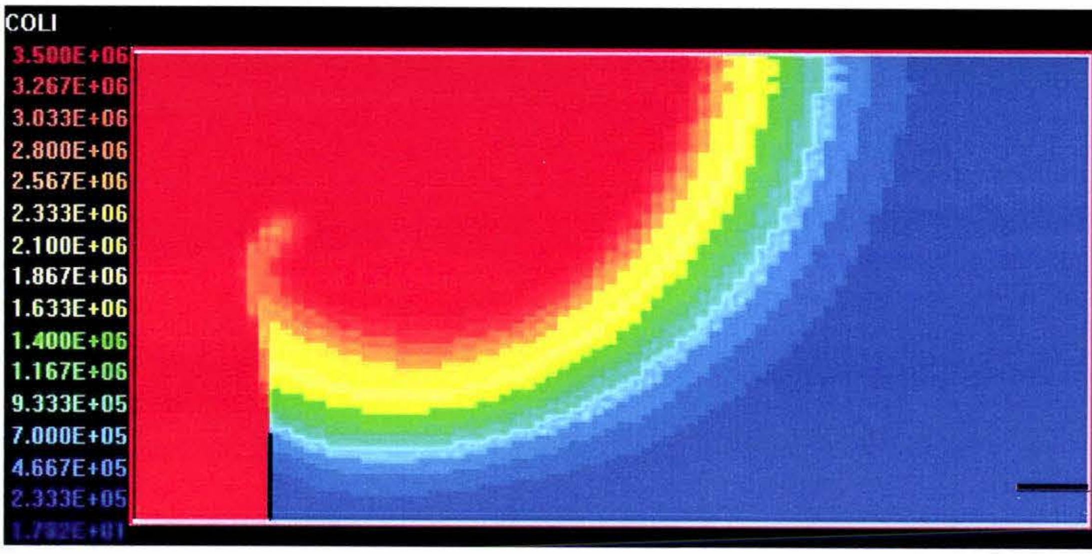


Figure 4-31 Coliform Concentration Case 14 (two stub baffles, outlet moved)

The outlet coliform concentration was *4.41x10^{3}cfu/100mL*. This is an extremely good result, it is in the same order of magnitude as Case 2, which uses two full length baffles, and yielded a concentration of *6.00x10^{3}cfu/100mL*.

As can be seen, after the flow has been turned by the inlet baffle, the concentration of coliforms evenly spreads out across the pond, as opposed to the other cases which show a more confined flow path.

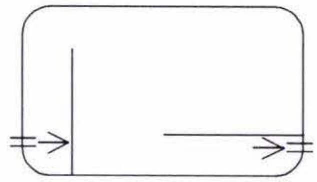
The use of short stub baffles in this configuration performed comparatively with the traditional two-baffle case (Case 2), this was surprising due to the small length of baffles.

The inlet momentum is partially dissipated by the inlet baffle, from there it spreads out over a larger area. This therefore allows the momentum to be slowed further, prolonging the time spent in the pond by the wastewater, maximizing treatment.

The striking aspect about this case is the comparatively small amount of baffling. Case 2, for the model pond, contained 448 metres of baffles (2 x 228m long), while this case contained 96 metres of baffles (2 x 48m long). This potentially represents very significant cost savings for similar efficiency improvements.

This design was also tested in the laboratory, these results are found in Section 5.8.

4.6.3. Case 15 – Case 14 design, standard length baffles



4.6.3.1. Design Rationale

Following the good result of Case 14, it was decided to investigate if the same arrangement with the standard length baffles would work even better if positioned in a similar manner. It also allowed further investigation of the perceived channelling effect discussed previously.

4.6.3.2. Results and Discussion

The flow pattern and coliform concentration profile can be seen in Figure 4-32 and Figure 4-33. It can be seen in Figure 4-32 that the velocity at the outlet baffle is greater heading toward the outlet than for the main area of the pond. This may be due to the channelling effect.

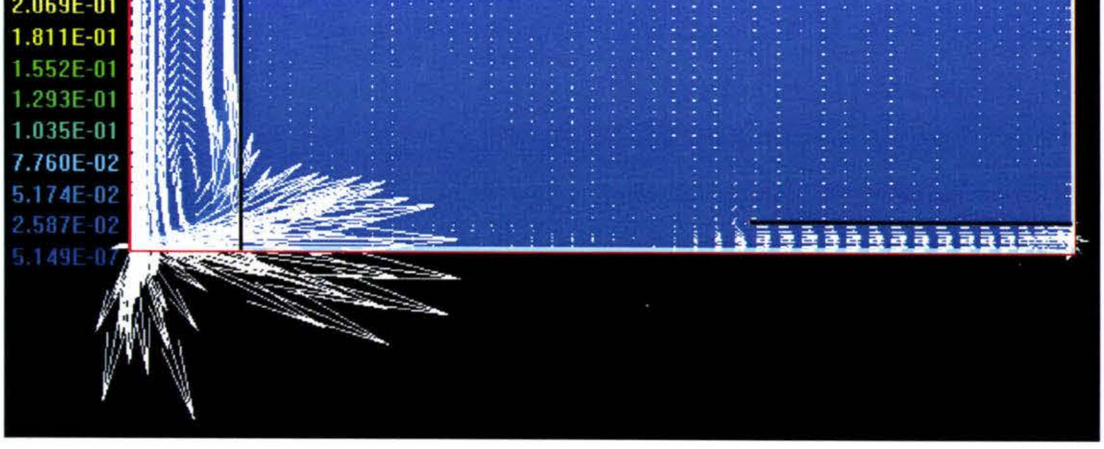


Figure 4-32 Flow Pattern Case 15 (two standard baffles, outlet moved)

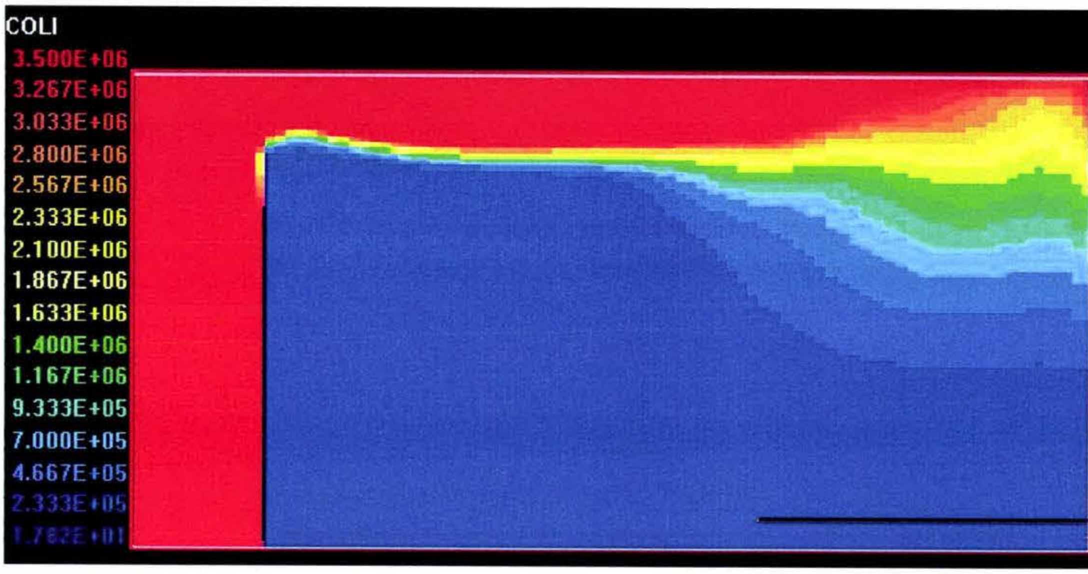


Figure 4-33 Coliform Concentration Case 15 (two standard baffles, outlet moved)

This case did not perform quite as well as Case 2 (two evenly spaced baffle, standard length). The coliform level at the outlet was *$1.08x10^4$ cfu/100mL*, with *$6.00x10^3$cfu/100mL* for Case 2.

As can be seen in Figure 4-34, the larger velocity vectors across the top of the pond in Case 15 are located in a more defined area than that of Case 14. This is indicative of channelling along the wall.

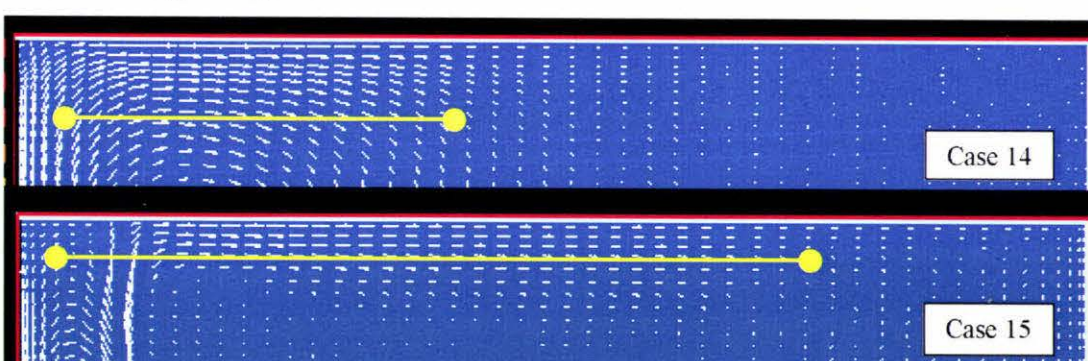
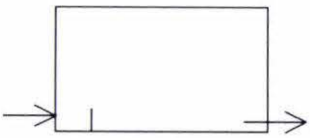


Figure 4-34 Comparison of velocity vectors: Case 14 and Case 15, yellow lines indicate extent of higher velocity area

The poor performance of Case 15 compared to Case 14 (two stub baffle, outlet moved) appears to be related to the mixing effect, as discussed for Case 13 (two stub baffles). As the flow is circulated in a tight space in the first cell, it doesn't lose momentum and may speed up around the end of the baffles.

Case 15 was also tested in the laboratory, later discussed in Section 5.9.

4.6.4. Case 16 – Single stub baffle



4.6.4.1. Design Rationale

Case 16 is a repeat of Case 14 without the outlet baffle. This is to see if the outlet baffle had a significant effect on the overall treatment efficiency within the pond. If the outlet baffle is not significant then further costs savings could be made.

4.6.4.2. Results and Discussion

The flow pattern, seen in Figure 4-35, is similar to that seen in Case 14, as is the coliform concentration profile seen in Figure 4-36.

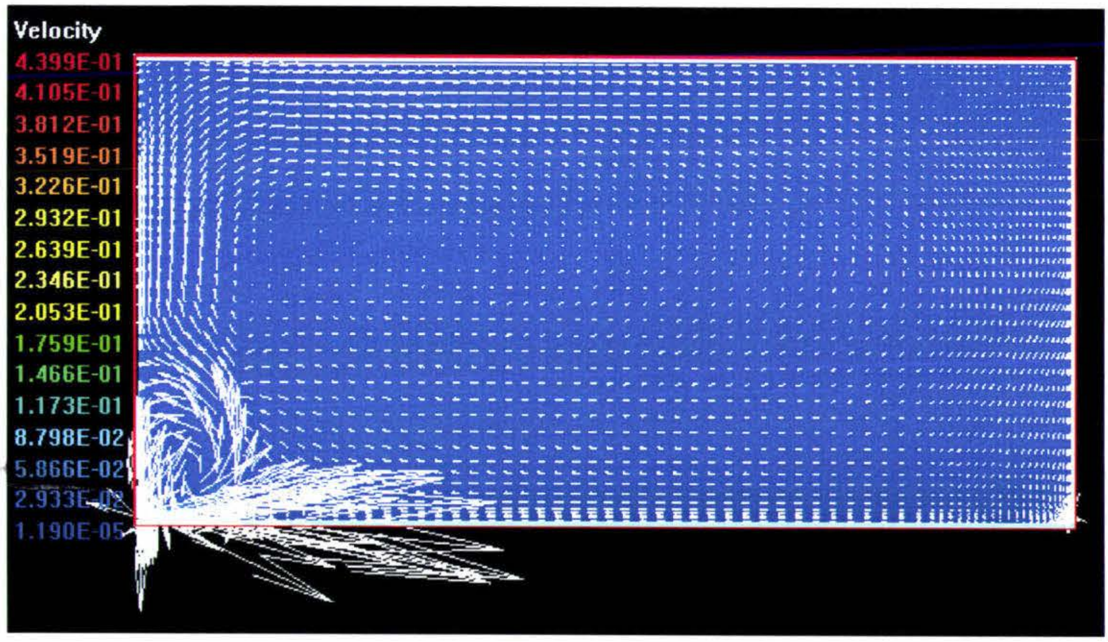


Figure 4-35 Flow Pattern Case 16 (one stub baffle)

The coliform concentration profile is shown in Figure 4-36, the concentration at the outlet was <u>*$4.28x10^5$ cfu/100mL*</u>. This only represents a 1-log improvement on the basic case, compared to <u>*$4.41x10^3$cfu/100mL*</u> for Case 14 (two stub baffle, outlet moved).

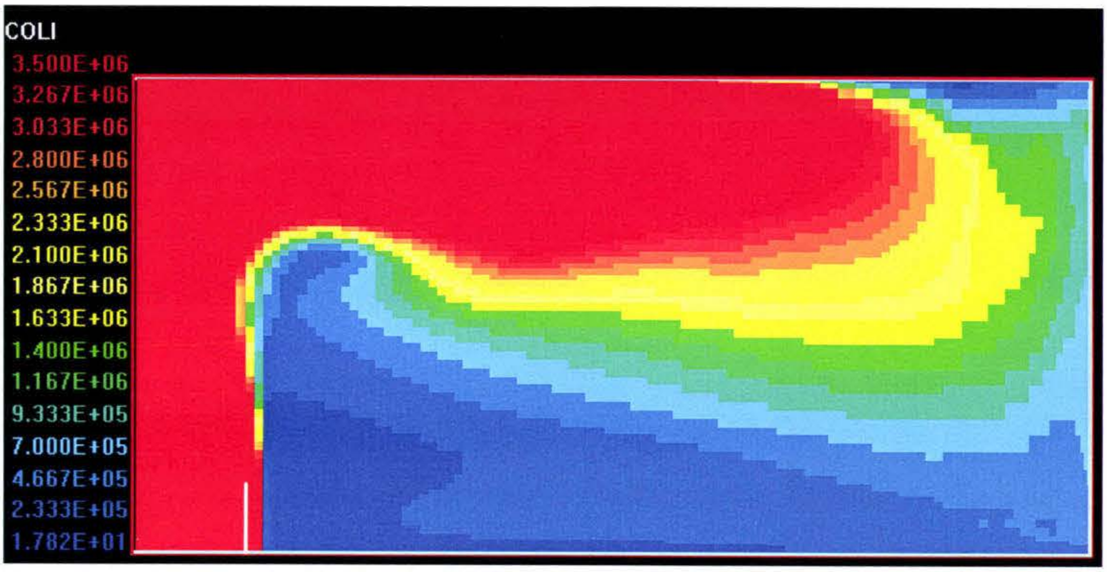


Figure 4-36 Coliform Concentration Profile Case 16 (one stub baffle)

Case 16 exhibited characteristics similar to that that of Case 14, however the effluent did not seem to spread as uniformly across the pond compared with Case 14. This may be due to the presence and orientation of the outlet baffle. The outlet end of Case 16 shows higher velocities than the outlet end of Case 14. The end baffle in Case 14 may have prevented the tracking of the flow around the walls. The stub baffle at the outlet in Case 14 also shields the outlet, delaying the exit of the wastewater.

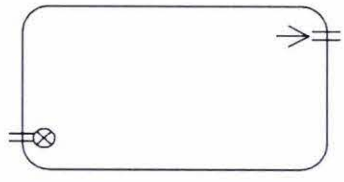
4.6.5. Summary

The investigation into the use of short stub-like baffles has shown that in the right configuration, stub baffles can perform as well as long baffles. In some cases, as in Case 15, the use of long baffles actually results in poorer performance than stub baffles (Case 14).

It has also been shown that the use of stub baffles can be very sensitive to small design changes. The design of Case 14 (two stub baffles, outlet moved) was very effective at improving the treatment efficiency of the pond, however Case 16 that simply removed the outlet stub baffle from the design of Case 14 produced a markedly poorer treatment performance. In fact, the treatment for Case16 was only 1 log better than the basic case.

4.7 Inlet Investigations

4.7.1. Case 17 – Vertical Inlet



4.7.1.1. Design Rationale

Case 17 is an alternative to a design tested by Shilton (2001). While he tested a vertical inlet, down-turned, this case has the inlet up-turned. Shilton (2001) found that the use of the down-turned inlet resulted in the reduction of the size of the peak and a significant increase in the time to the start of short-circuiting. Therefore, it was decided to investigate whether an up-turned inlet would produce similar results.

4.7.1.2. Results and Discussion

This case was difficult to model, and hence the modelling did not achieve mass balance and high errors were produced.

Assistance was sought from Flowsolve Ltd, a consulting firm specialising in computer modelling. The difficulty with the CFD model is mainly due to the complex nature of the flow around the inlet. As the pond is shallow relative to its total area, the grid is less dense in the vertical direction. Therefore the grid around the inlet affects the accuracy of the model.

The investigations undertaken by Flowsolve Ltd found that the patterns produced by the vertical inlet were similar to that found in a water reservoir, similar to that of Shilton *et al.*, 2000a in their work using CFD modelling on a water reservoir. Flowsolve Ltd provided useful advice in the upgrade of the model to improve its accuracy, however, in the timeframe required for this work it could not be achieved.

Despite the difficulty in the modelling it is interesting to note the circulation characteristics found. The predicted coliform concentration profile is shown in Figure 4-37.

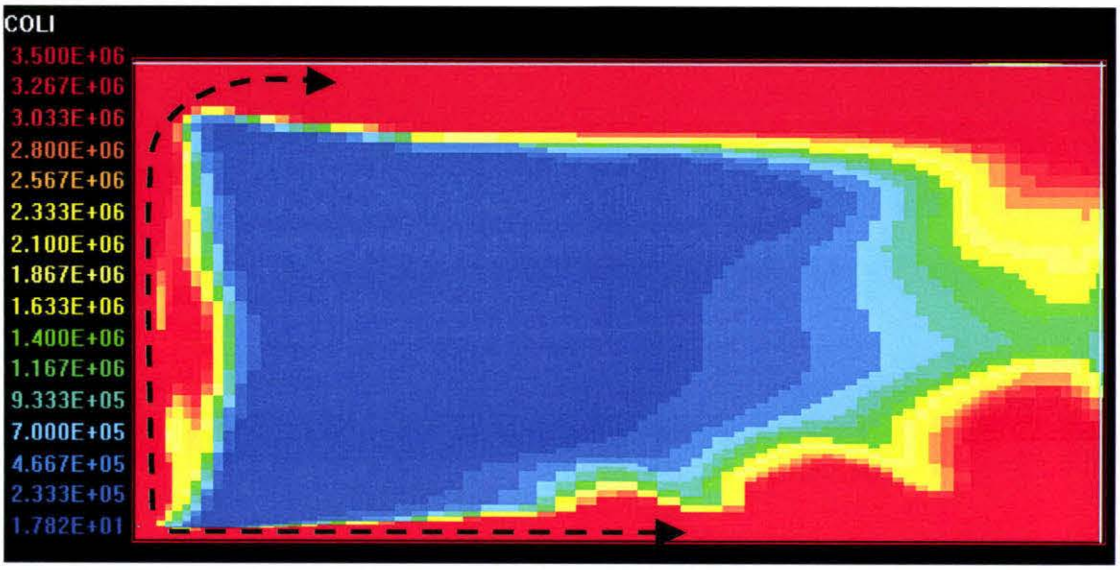


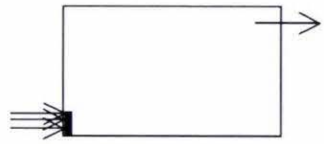
Figure 4-37 Case 17 (vertical inlet) - Coliform profile, arrows indicating circulation direction

As can be seen the flow extends away from the inlet in either direction (shown by arrows).

The up-turning of the inlet may also result in the slowing of the momentum at the front end of the pond, this has implications with respect to organic load. If the flow is slowed significantly around the inlet area, there is the potential for localised organic overloading. Therefore, this modification may not be appropriate for high-strength or high-solids wastewaters.

As this design produced good results in previous laboratory tests from Shilton (2001), this case was tested in the laboratory (refer Section 5.10). Due to the very economic nature of a turned inlet as an improvement measure, it was also decided to model this case in the field. The modification of an inlet can be as simple as adding a fabricated an insert to the existing inlet. The results of these further investigations are found in Section 6.2.

4.7.2. Case 18 – Diffuse Inlet



4.7.2.1. Design Rationale

This case was designed to simulate the effect of a diffuse inlet. For example, a channel 2m wide. The expectation was that the diffuse inlet would slow down the velocity in the bulk fluid flow and therefore improve the retention time and treatment efficiency.

4.7.2.2. Results and Discussion

As can be seen from the flow pattern (Figure 4-38), the same bulk circulation around to the outlet is seen as in the basic case. The velocities have been reduced from those seen in the basic case, but are still significant.

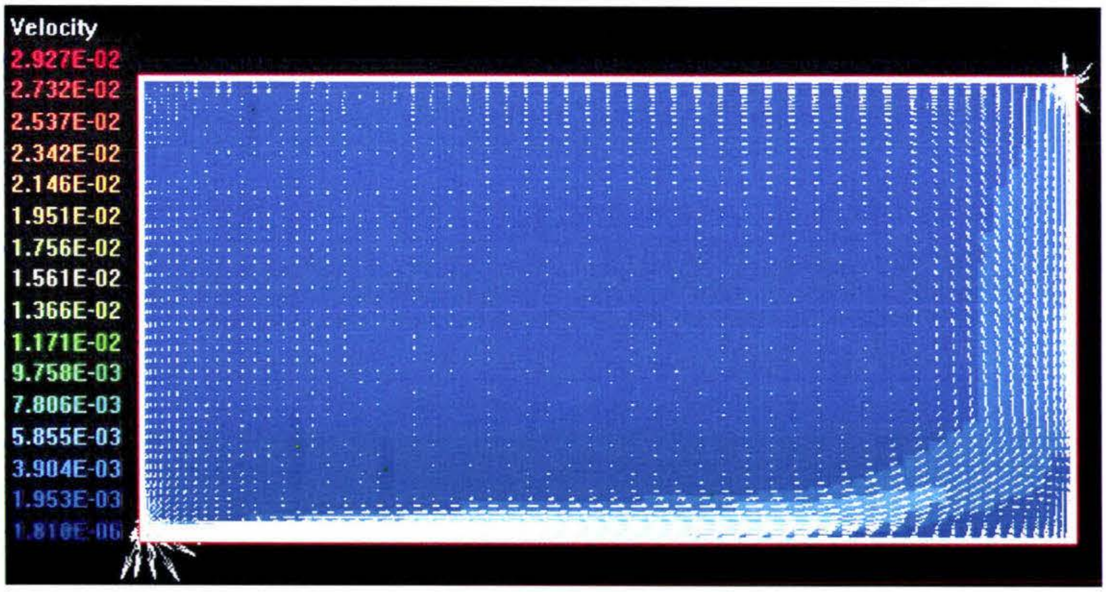


Figure 4-38 Flow Pattern Case 18 (diffuse inlet)

The coliform concentration throughout the pond is shown in Figure 4-39.

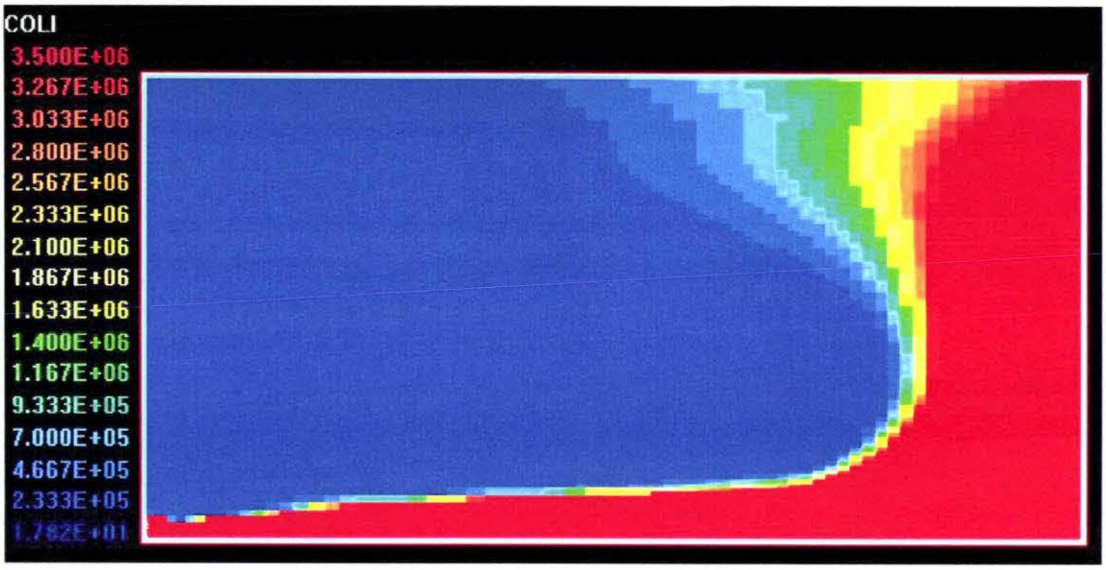


Figure 4-39 Coliform Concentration Case 18 (diffuse inlet)

The coliform level at the outlet was $4.10x10^6$ *cfu/100ml*. This represents no significant improvement on the basic pond (Case 1).

The results of this model indicate that despite the diffused inlet, the same general circulation as the base case is seen. However, it must be noted that despite this inlet being large relative to a standard pond inlet, it still represents only a short width compared to the pond width. Persson (2000) achieved good results from diffuse and multiple inlets, however the inlets extended the full width of the pond, thereby closely approximating plug-flow conditions which resulting in improved efficiency.

The practicalities of setting up a full-width inlet on a pond such as the one modelled here (320m wide) would be prohibitive.

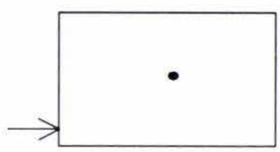
4.7.3. Summary

While the modelling was not completed for Case 17 (vertical inlet), the initial models showed a fluid flow pattern different to that of the basic pond (Case 1). This indicates that the type of inlet can have a significant effect on the flow pattern in a pond.

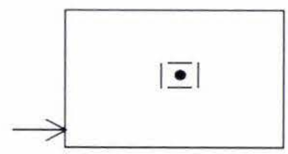
The diffuse inlet tested here did not result in any treatment improvements. While the inlet was diffuse when compared with a point inlet, it was still small in respect of the full width of the pond. Therefore, testing of full width diffuse inlets on suitably sized ponds may result in treatment improvements due to the closer approximation to plug - flow.

4.8 Outlet Investigations

4.8.1. Case 19 & 20 – Central outlet cases



Case 19



Case 20

4.8.1.1. Design Rationale

The central outlet cases were tested as a result of the flow pattern exhibited by the basic case (Case 1). In the basic case, the flow was seen to form a broad circulation pattern around the outside of the pond. This result was also observed by Shilton (2001). This circulation around the outside suggested a sl ower region in the centre of the pond, in effect, a dead space. It was thought that advantage could be taken of this dead space by placing the outlet here. A further addition to this idea was to add a 'shield' of baffles around this central outlet to further delay the flow reaching the outlet and increase the efficiency.

The model was very difficult to solve, and no mass balance could be achieved. This may be due reasons similar to that of a vertical inlet. The flow around the outlet as it will approach the outlet from all sides (a wall mounted outlet receives wastewater from one side) creating complex flow patterns. Later on in this work, the central outlet idea was attempted again, in the CFD modelling phase for the second field trial. These results are discussed in Section 6.3.

4.9 Limitations of CFD Modelling Undertaken

This work builds on that of previous researchers, in particular Shilton (2001). Shilton (2001) demonstrated that CFD modelling could be used to assess step changes in performance of various design options. For example, the addition of a baffle to a pond will result in a marked difference in the response of the model to that of the un-baffled pond.

It must be recognised that the models used in this work are not intended to provide perfect representations of each pond. They provide a research tool, whether it is for new ponds or for modifying existing ponds, and provide some confidence that a proposed design will be efficient.

While the use of CFD in this work has been shown to allow a quick assessment of the benefits and disadvantages of different design options, its limitations must also be recognised. These limitations come from the absence of a number of physical variables that exist in the field situation, and from limitations in the CFD models themselves.

4.9.1. Temperature

There are two temperature factors that may affect the performance of a field. These are the density effect and the rate of reaction.

Temperature affects the density of a fluid. While the density of the influent to the pond is fairly constant, the surrounding air temperature may cause the pond to cool, and result in stratification within the pond. That is, two distinct layers of differing temperatures. In severe cases this can cause the pond to 'turn over'. Also, if the pond is cooler and the influent warmer or vice versa, it will tend to skim through the pond which is detrimental to the efficiency of the pond hydraulics.

In this work, reaction kinetics are integrated into the CFD model. A value of 'k', the reaction rate constant, needs to be added into the model. This constant varies according to temperature. Therefore, the temperature needs to be selected carefully to obtain an appropriate value for 'k'.

4.9.2. Wind

Shilton (2001), in his discussion of the effect of wind, commented that wind may have been a previously overestimated influence on a pond system. Shilton (2001) added wind to the CFD model of a field pond and found that the simulations became very closely aligned with the experimental results. However, the difference between the model with wind, and model without wind was not as significant as expected. The addition of a baffle, for instance, results in a greater 'step change' in a model.

The incorporation of wind into a CFD model i s undertaken by applying an empirical shear stress equation at the surface boundary of the model. Also, a direction for the wind is incorporated into the model. As wind will be constantly changing in velocity and direction, the full effect of the wind is difficult to model.

4.9.3. Sludge Deposits

After a period of time, the sludge in the influent of the pond will deposit on the floor of the pond. Over a short amount of time, the effect on performance will be minor. However, over a long enough period of time, severe build-ups will affect the hydraulics. The design of the pond may also determine the extent of depositing. If an up-turned inlet is used in a pond with a large solids load, then the slowed momentum will allow the load to settle close to the inlet quicken the reduction of hydraulic performance.

4.9.4. Other Physical Influences

The CFD models are set with a constant inlet flow and fixed coliform inlet flux. In reality however, the flow and loading of a field pond will change with time. The computing power and time necessary to accommodate a changing inlet flow and load is restricting. This needs to be recognised as a possible limitation.

The CFD models are not set-up to exactly simulate field conditions due to their state of constant change. The models are set up by simplifying and holding certain parameters constant (temperature and flow) to allow the evaluation of different physical designs.

4.10 Chapter Discussion & Summary

This section has presented the results from a series of traditional and innovative ponds designs, modelled using CFD.

The use of evenly spaced baffles of standard length has been shown to provide an effective tool for improving the treatment efficiency of a pond. The investigations have also shown some possible reasons for channelling phenomenon seen by Watters *et al.*, (1973), originally attributed to baffle length. The presence of two quite distinct flow patterns within the same pond, circulating flow and channelling flow, also provided an explanation of the similar results achieved by the 4 and 6 baffle cases.

Further investigations showed that the evenly spaced arrangement of the standard length baffles performed better than the same baffles unevenly spaced.

Single baffles were shown to be generally ineffective. Through the course of the investigations it was shown that the movement of the outlet relative to the baffles could have an effect on the treatment efficiency.

It is considered significant, that results comparable to those achieved with long baffles can also be attained using short stub baffles. In some cases, it has been shown that longer baffles perform worse than stub baffles. However, the stub baffles are very sensitive to minor changes in design. In Case 16, the removal of the outlet baffle resulted in a significant drop in treatment efficiency.

The modelling indicates that the type of inlet can have a significant effect on the flow pattern in a pond. The use of a vertical inlet resulted in the bulk flow path being split into two major flows moving around the sides of the pond from the inlet. This was significantly different to the single circulation pattern noted using a standard horizontal inlet.

The use of a diffuse (wide channel) inlet did not affect the bulk circulation of the flow, but the velocities of flow were smaller. This indicates that the use of an even wider channel (e.g. multiple inlets along the width of the pond) would slow the flow further and approximate plug flow. However, setting up such an inlet on a full-scale pond such as the one modelled (320m wide) wo uld be considered impractical.

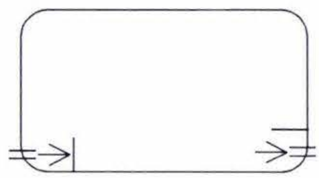
The performances of Cases 10 and 13 were improved by moving the position of the outlet (and the baffle in Case 13). These new cases, Cases 11 and 14, it was shown that the position of the outlet can have an impact on the treatment efficiency of the pond.

A summary of the performance of each case, expressed in terms of outlet coliform concentration is shown in Table 4 (- indicates unsuccessful modelling).

Table 4 - Performance Summary - CFD Modelling of a Theoretical Pond

Case Number	Case Description	Outlet Coliform Concentration (cfu/100mL)
Case 1	Basic case	*$6.15x10^6$*
Evenly Spaced Multiple, Standard Length		
Case 2	Two baffles, evenly spaced	*$6.00x10^3$*
Case 3	Four baffles, evenly spaced	*$3.86x10^2$*
Case 4	Six baffles, evenly spaced	*$5.65x10^2$*
Case 5	Eight baffles, evenly spaced	*9.60*
Unevenly Spaced		
Case 6	Two baffle, unevenly spaced	*$2.39x10^4$*
Single Baffles		
Case 7	Single central baffle	*$4.10x10^6$*
Case 8	Single baffle, outlet end	*$4.39x10^6$*
Case 9	Single baffle outlet end	*$1.35x10^6$*
Case 10	Single baffle outlet end	*$4.56x10^6$*
Case 11	Single baffle, outlet end, outlet moved	*$8.00x10^5$*
Case 12	Central wall with middle opening	*$1.97x10^6$*
Stub Baffles		
Case 13	Two stub baffles	*$1.37x10^6$*
Case 14	Two stub baffle, outlet moved	*$4.41x10^3$*
Case 15	Case 14 design, standard length baffles	*$1.08x10^4$*
Case 16	Single stub baffle	*$4.28x10^5$*
Inlet Investigations		
Case 17	Vertical inlet	-
Case 18	Diffuse inlet	*$4.10x10^6$*
Outlet Investigations		
Case 19	Central outlet	-
Case 20	Central outlet with baffles	-

As a result of the CFD modelling work, it is considered that Case 14 offers the optimum design for the theoretical pond. In a field situation, if the position of infrastructure dictates the inlet position, baffles can be designed to complement this inlet position. The position of the outlet can then be determined after the baffles design to optimise treatment efficiency.



Case 14

Case 14 incorporates two stub baffles. The second baffle has been rotated to be parallel with the side-wall. The distance between the side -wall and the outlet is 10m, and the distance between the side wall and the inlet baffle is 20m. The baffles are 15% of the width in length.

This design provides a 5-log reduction in the level of coliforms at the outlet (*4.41x10*^{3}*cfu/100mL*). It is considered optimum as it provides good treatment while keeping the costs of implementing the design to a minimum.

This initial CFD modelling phase of the work has produced an idea of what designs provided good treatment efficiency and provided insights into the reasons behind their performance. This insight into the reasons behind the performance of the baffles was then investigated in the laboratory. This will further add to the credibility of CFD modelling as a research tool, and as a tool to assist in the understanding of flow mechanisms and interaction.

The conclusions of this modelling process will be further developed with the addition of the laboratory and field work in later sections.

5. RESULTS OF LABORATORY STUDIES

5.1 Introduction

The objectives of this thesis were to investigate baffles (length, number and position), inlet type and outlet position. To this end, the CFD modelling undertaken in Chapter 4 has formed the basis of the majority of the work. However, CFD modelling is a relatively new approach to research for ponds, hence an evaluation of CFD as a research tool was also to be undertaken.

Recent work (Shilton, 2001) has provided confidence that CFD modelling can predict 'step changes' in the performance of various pond designs. CFD models are not intended to exactly fit every case modelled. If the CFD model of a basic pond shows poor performance, and the CFD model of that pond with four baffles shows improved performance, the comparison of the two sets of results will show that the model has successfully predicted the step change due to the baffle addition. As this approach is relatively new, the laboratory work is intended to give further insight and confidence in this regard.

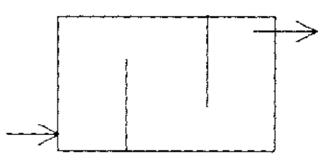
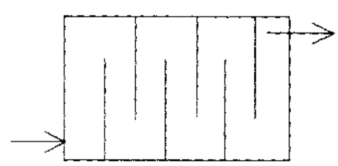
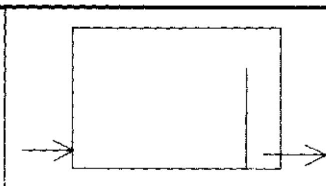
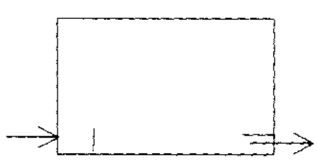
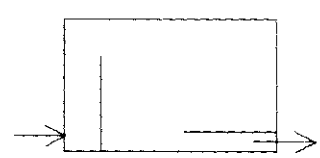
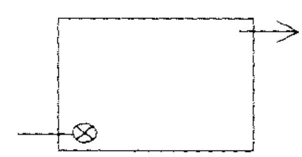
Laboratory scale models have been used to represent full-scale pond systems, although not often with the specific purpose of investigating pond hydraulics. Watters *et al.*, 1973 used a laboratory scale model as a major design tool for their investigation of pond hydraulics. The results of the laboratory work completed for this work is presented in this chapter.

It is important to note that the pond used in the laboratory testing is different to that used in the CFD modelling in the previous chapter. The laboratory pond represents a pond twelve times bigger than itself. However, by setting up the pond in a similar way to the theoretical pond modelled in Chapter 4 and testing it experimentally and with CFD, the ability of CFD modelling to predict step changes in performance can be demonstrated.

5.2 Review of Laboratory Experiments

The designs tested in the laboratory are shown in the following table (Table 5). The designs tested are similar to those tested on the theoretical pond in Chapter 4, therefore the same case number has been used with the addition of the prefix 'L' added to indicates that these cases were tested on the laboratory model.

Table 5 - Cases investigated in the Laboratory (diagrams not to scale)

 Case L2	 Case L4	 Case L11
 Case L14	 Case L15	 Case L17

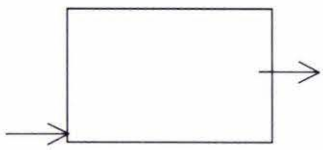
5.3 Presentation of Results

The techniques used in this section are similar to traditional investigations into pond hydraulics. That is, HRT (hydraulic retention time) curves for each tracer study performed in the laboratory will be presented.

Each case has a set of photos taken by a camera mounted above the pond. These photos were taken at even intervals over the first 45-60 minutes of the tracer run, so as to record the actual flow pattern in each pond. The photos all have the inlet located in the lower right corner, they photos appear slightly distorted due to the wide angle lens required to capture the whole pond. A lighting problem was encountered in the controlled temperature room where the pond is located, and therefore the photos for Cases L4, L11, L15 and L17 are not of as good a quality as those for Cases L2 and L14.

5.4 Base Case for Comparison

To assess the improvements achieved from the various modifications, a basic pond case was used. These results come from Shilton (2001) and his laboratory tracer studies on a basic pond. The basic pond has the same flowrate, inlet size, and retention time.



The full tracer study results are shown in Figure 5-1, with the first 120 minutes shown in Figure 5-2.

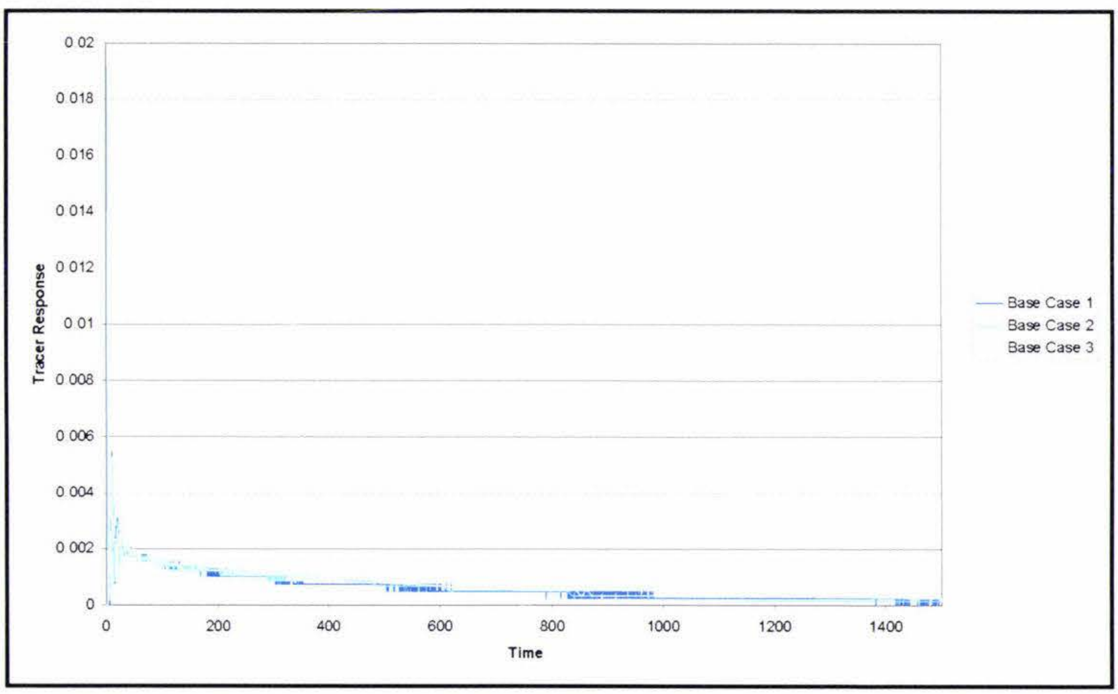


Figure 5-1 Full Tracer Study Results - Base Case (Shilton, 2001)

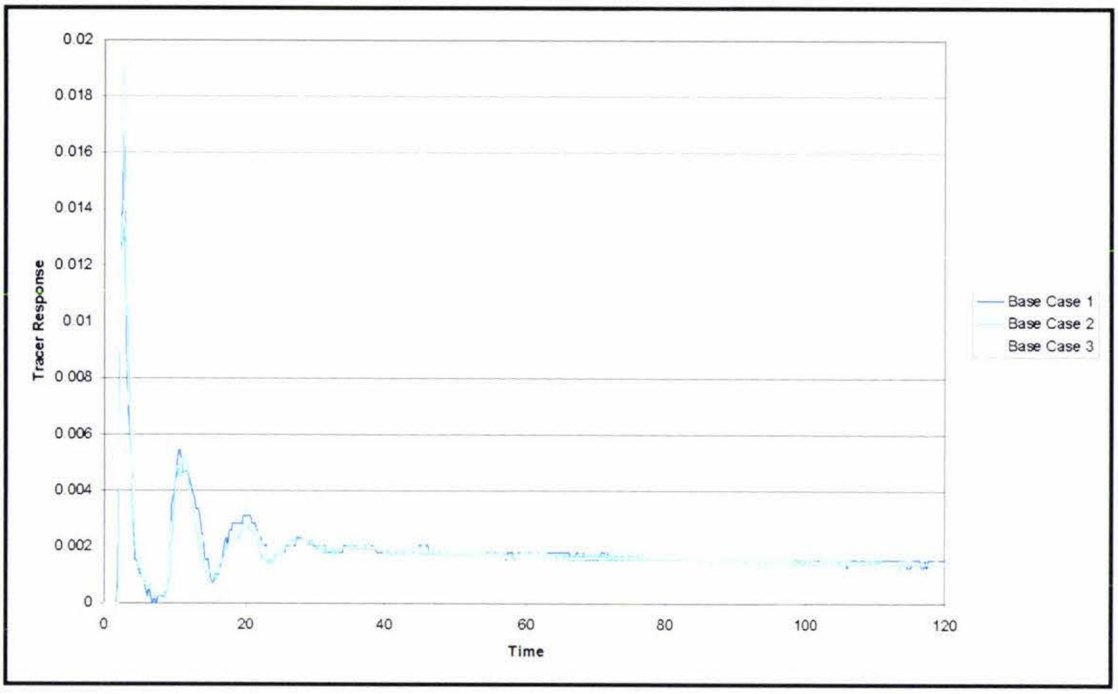


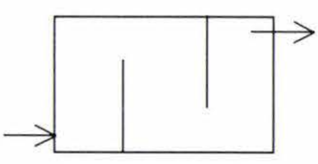
Figure 5-2 Tracer Study Results - Base Case, First 120 minutes (Shilton 2001)

As can be seen from Figure 5-2, dye is detected at the outlet after approximately 2 minutes, indicating severe short-circuiting with the basic design. The curve also shows a very high peak, indicating a concentrated slug of dye is circulating in the pond. The continued circulation of the dye in the pond causes a second and subsequent smaller peaks. This shows that the dye does not mix well into the pond, and there is a large degree of dead space.

Shilton (2001) also modelled this pond using CFD, a near perfect match was achieved.

5.5 Case L2 – Traditional two baffle case

Case L2 is a repeat of a design investigated by Watters *et al.*, 1973. It is a traditional design incorporating two baffles 70% of the width of the pond, and they are evenly spaced along the length of the pond.



5.5.1. Flow Pattern

The following suite of pictures depicts the flow path of the dye during the tracer study (Figure 5-3).

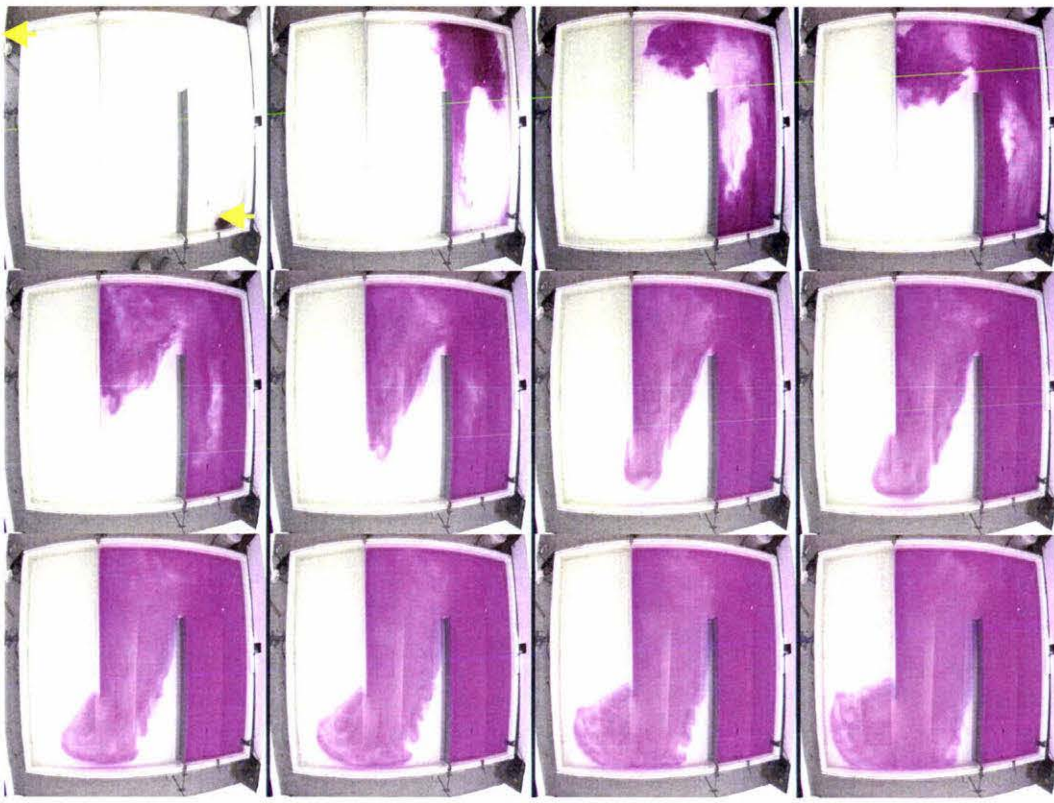


Figure 5-3 Dye flow path - Lab Tracer Study Case L2

As can be seen from the flow path of the dye in the first four pictures, the flow pattern is similar to that seen in the CFD simulation undertaken on the large-scale theoretical pond (see Figure 4-3).

As can also be seen, the circulation pattern that exists in the first cell of the pond forces the tracer to the outside edges. That is, the tracer is not very well mixed initially in the first cell of the pond before it goes to the next cell. It was observed that it may take the slug of tracer up to 4 circulations for the first cell of the pond to become completely mixed. If the first cell of the pond is likened to a large basic pond, this can mean that the centre of the pond does not receive wastewater for sometime – effectively acting as a dead-space.

5.5.2. Tracer Study Results

The tracer study results from the two laboratory runs are shown in Figure 5-4.

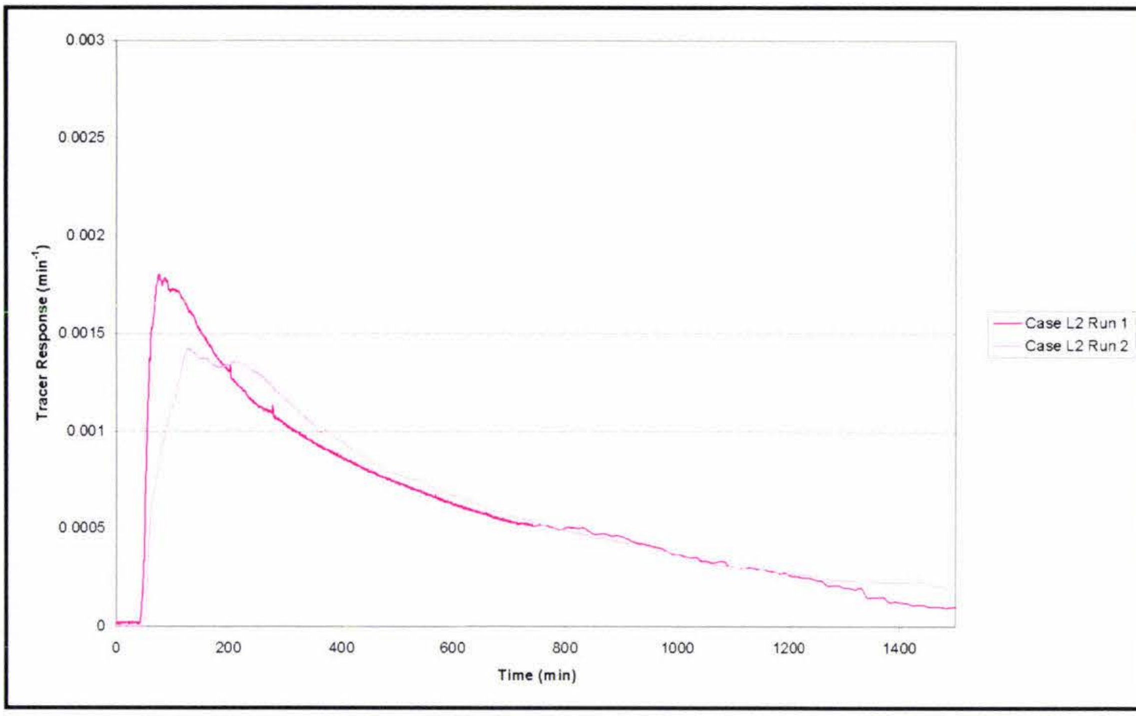


Figure 5-4 Tracer Study Results Case L2 (traditional two baffle case)

The above figure shows the two runs performed on this case as being similar. The rising to a single peak and then tailing off is seen in both curves, and the first tracer appears at the outlet at approximately similar times. The average time to short-circuiting for this case was 47.5 minutes as compared to the basic case where tracer was noted at the outlet after 2 minutes. This case is a significant improvement on the base case.

5.5.3. CFD Modelling Results

The laboratory pond was modelled as it was set-up for Case L2. The results of the CFD tracer study compared with the actual laboratory results in Figure 5-5.

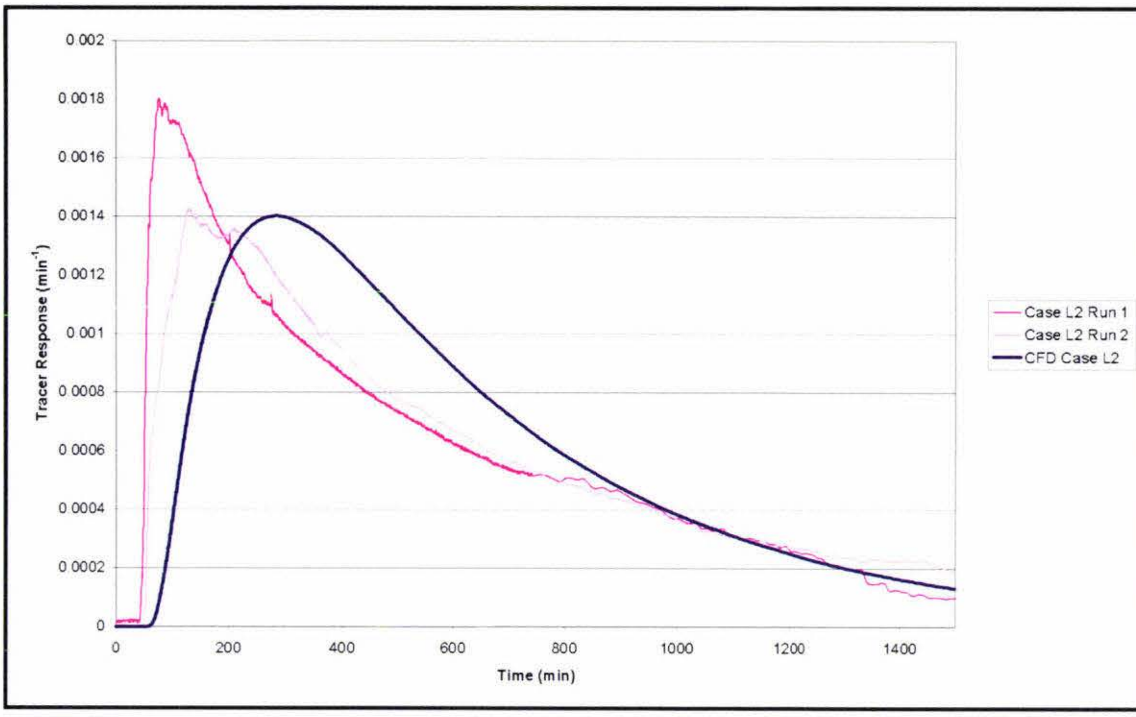


Figure 5-5 Comparison Plot - CFD & Laboratory Tracer Studies, Case L2

As can be seen, the CFD tracer study produces a similar curve to that of the laboratory run. The CFD model shows tracer reaching th e outlet after approximately 60 minutes, compared with an average of 47.5 minutes for the laboratory runs.

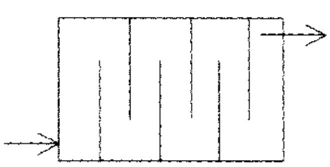
Shilton (2001) also noted discrepancies in the time to the start of short-circuiting between his laboratory runs and the CFD models. One of the explanations of this phenomenon related to the actions of the tracer. He noted that even with no inflow to the pond, the tracer settled and spread along the base of the pond. However, this was noted when the pond was set at a 10-day HRT, the models tested for this work were run at a 1.5-day HRT. Therefore it cannot be concluded that this tracer effect has caused the lag seen in Case L2 without further investigation. Shilton (2001) noted that general experience with rhodamine as a tracer found that at higher concentrations, its high density (476g/mole vs 18g/mole for pure water) caused the settling and spreading out on the base of the pond. He found it helpful to add larger amounts of less concentrated tracer.

Shilton (2001) also discussed the differencing scheme used by the CFD model as a cause of the time lag in the CFD tracer studies. The default differencing scheme for the PHOENICS programme is Upwind differencing. He noted that this scheme causes errors when the flow does not correspond to the grid direction (Versteeg and Malalasekera, 1995 in Shilton, 2001). The effect is known as 'numerical' or 'false' diffusion. It occurs in areas where the flow of the fluid does not follow the 'straight line's' of the grid, e.g. around the end of a baffles. If the flow in a cell is influenced from two different directions, an intermediate value of the influences is used in that cell, therefore the next cell is affected by this intermediate value.

After his investigations into higher order differencing schemes, Shilton (2001) adopted the Minmod scheme due to its more accurate results. The Minmod scheme has been used in this work also, however the time lag has still been noted. This may be due to the presence of two baffles (and more in later cases) and more opportunity for 'false diffusion'.

Despite the difference in the time to the start of short-circuiting, the CFD model of the two-baffle case predicts the laboratory results well.

5.6 Case L4 – Traditional six baffle case



Case L4 is the traditional six baffle case. It has 6 baffles, 70% of the width of the pond, evenly spaced along the length of the pond. This design was one of those tested by Watters *et al.*, (1973).

5.6.1. Flow Pattern

The flow path of the dye for this case is shown in Figure 5-6.

Figure 5-6 Dye Flow Path - Lab Tracer Study Case L4 (traditional six baffle case)

As can be seen from the above pictures (Figure 5-6), a significant slug of dye tracked around the pond. This is shown especially well in Figure 5-7, a lighter front of dye can be seen ahead of the slug (slug is marked by the circle) and again behind the slug.

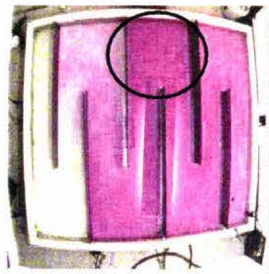


Figure 5-7 Slug of Dye, Case L4 (traditional six baffle case)

The slug of dye indicates an element of plug-flow, with mixing either side of the slug. This is in line with what would be expected with this multi-baffle arrangement – the more baffles, the closer the approximation to plug flow.

5.6.2. Tracer Study Results

The evidence of the slug and the preceding lighter front can be seen in the HRT curves. The full tracer study results are shown in Figure 5-8.

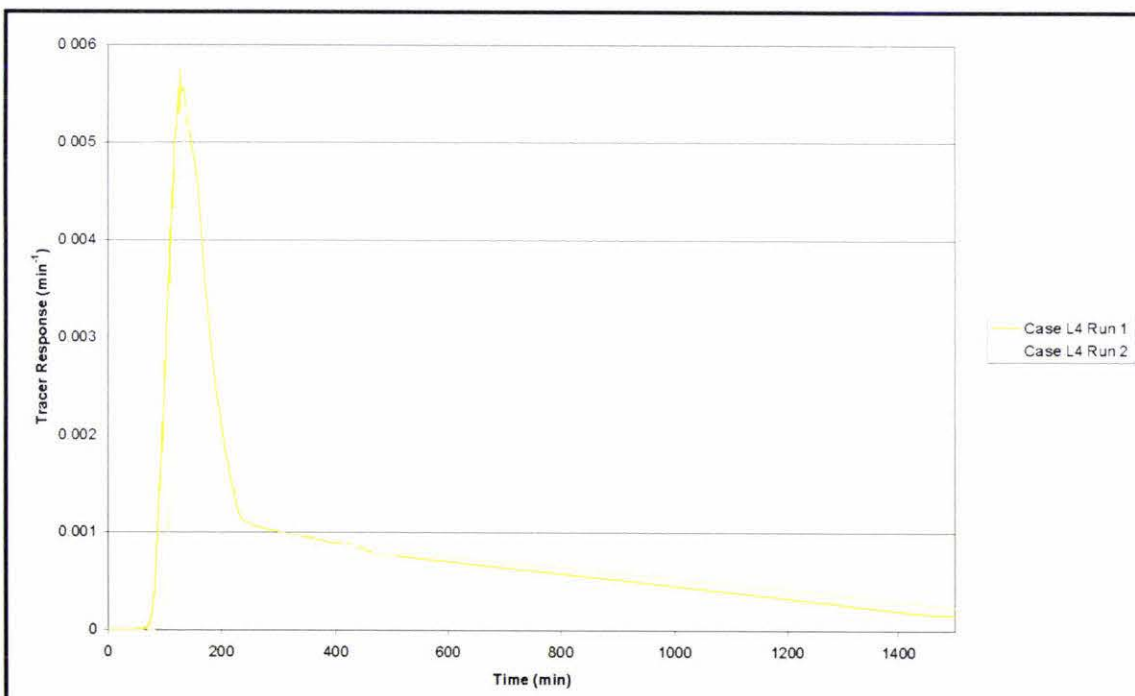


Figure 5-8 Full Tracer Study Results Case L4 (traditional six baffle case)

It can be seen that the curve leading up to the peak is not sharp. It rises up comparatively slowly compared to the basic case. What is immediately obvious, is the significantly better treatment afforded by this 6 baffle arrangement over the basic case – tracer is not seen at the outlet until 82.5 minutes (averaged over the two runs) compared to 2 minutes for the base case.

The following HRT curve (Figure 5-9) compares the 2 baffle case (Case L2) with the 6 baffle case (Case L4).

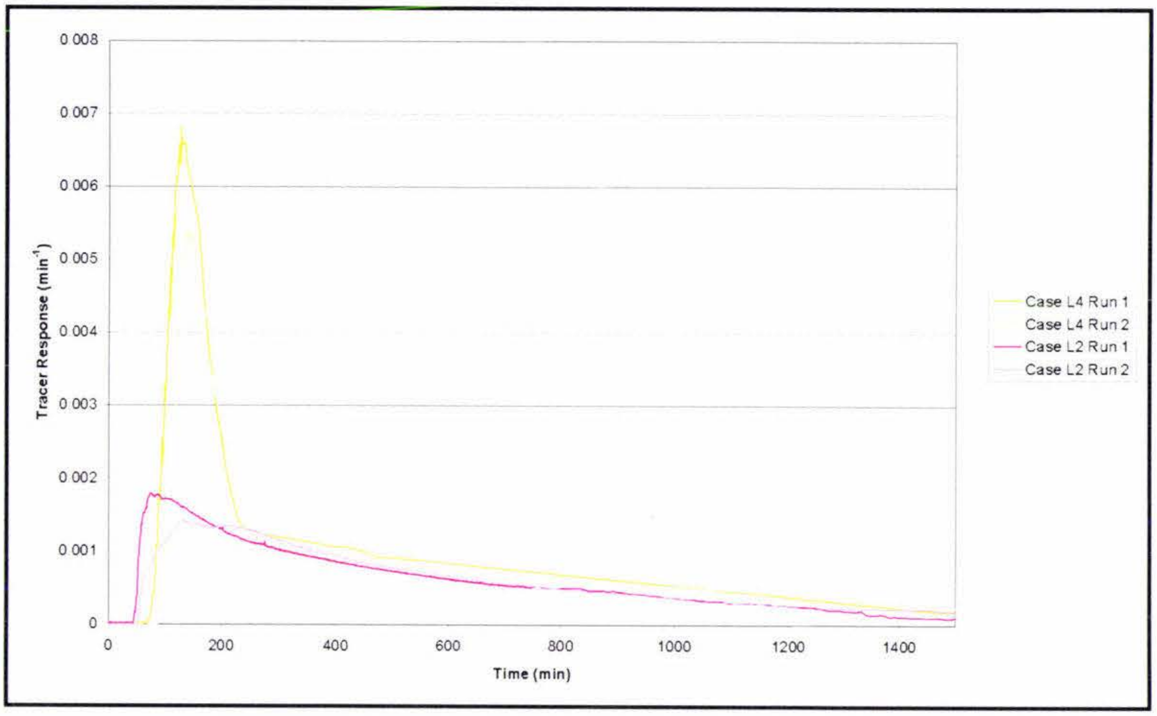


Figure 5-9 Comparison HRT - Case L2 (traditional two baffle) and Case L4 (traditional six baffle) Full Results

The time to short-circuiting in Case L2 is 30 minutes quicker than in Case L4. This corresponds with the initial CFD modelling results on a large-scale theoretical pond, where an increased level of treatment was seen in Case 4 (six baffles, standard length), the coliforms at the outlet were *6.00x10³ cfu/100mL & 5.65x10² cfu/100mL* for Case 2 (two baffles, standard length) and 4 respectively.

In Case L4, the curve shows a higher peak than Case L2, indicating that a portion of the dye moves around the pond in a defined 'slug'. The dye was better mixed in each 'cell' of the pond for Case L2 than Case L4. This seeming lack of mixing within each 'cell' of Case L4 was clearly shown by the colour patterns in the cells after the major slug of dye had come through. The first four cells of the pond are shown in Figure 5-10.

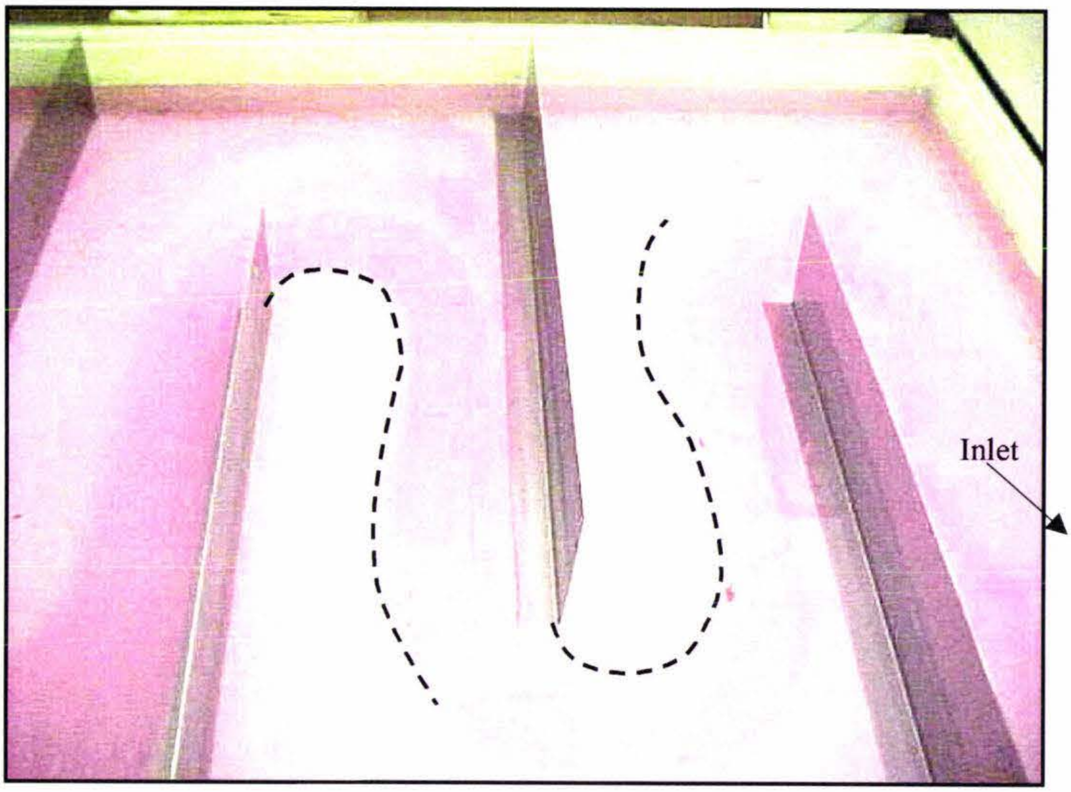


Figure 5-10 Cell flow pattern, showing channelling, Case L4

The dashed lines indicate a distinct change in the dye colour though the cells. This can be directly compared back to the work of Watters *et al.*, (1973), and against the following diagram (Figure 5-11) taken from their work.

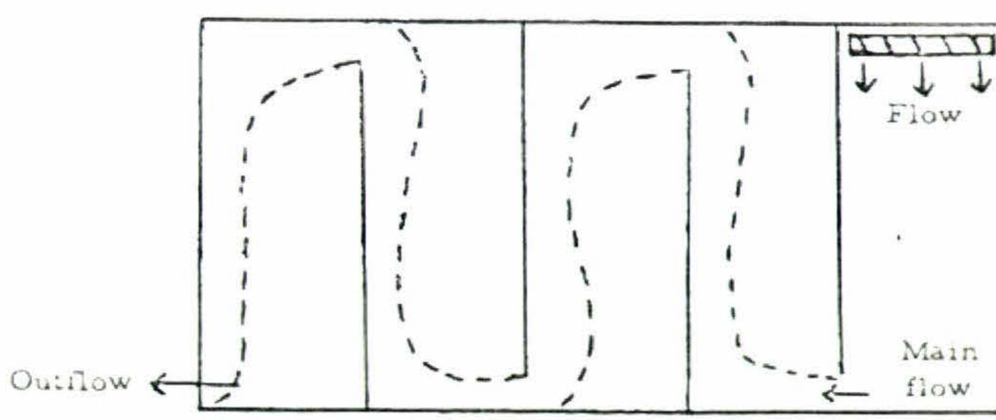


Figure 5-11 Currents caused by 90% width baffles (Watters *et al.*, 1973, pg 49)

Watters *et al.*, (1973) concluded that baffles that were 90% of the width of the pond were not efficient as they caused channelling as shown in the above diagram, and used this argument to explain why 70% baffles were more efficient. In Case L4, the baffles are 70% of the width of the pond and yet this channelled effect can be seen to still be present (Figure 5-10). It is now proposed that this phenomenon may not be caused by the length of the baffle, but by the relatively close spacing of the baffles. This is further confirmed by the absence of this effect in Case L2. As seen in Figure 5-12 below, the cells are well-mixed.

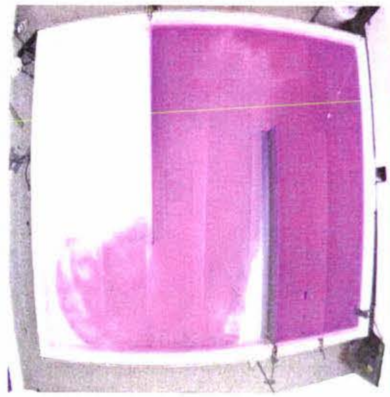


Figure 5-12 Cells of Case L2, showing they are well-mixed

This flow pattern was also seen during some of the modelling work for the field trials and is discussed further in Section 7.4.

5.6.3. CFD Modelling Results

The CFD tracer study results for Case L4 are shown compared with the laboratory runs in Figure 5-13.

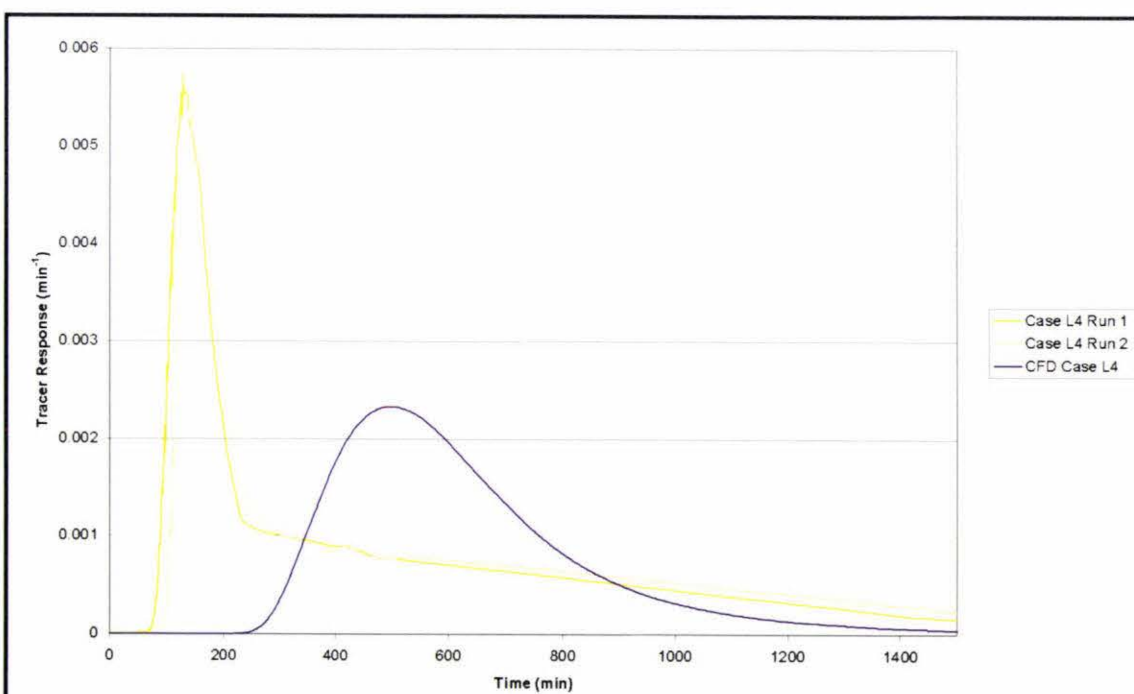
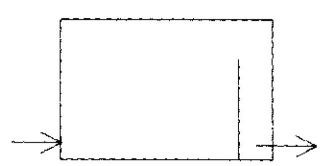


Figure 5-13 Comparison Plot - CFD and Laboratory Tracer Studies, Case L4

Clearly, the CFD model is significantly lagging the laboratory results. The laboratory runs show tracer reaching the outlet after an average of 82.5 minutes, whereas the tracer reaches the outlet after approximately 250 minutes (4.2 hours) in the CFD model. The size of the peak in the CFD model is also significantly smaller.

As previously discussed in Section 5.5.3, 'numerical diffusion' is a smearing effect that can occur in areas where the flow does not align with the grid direction. The tight flow path experienced by flow around the end of six baffles may therefore compound the smearing effect and further reduce the accuracy of the model. In his work, Shilton (2001) found that the Minmod differencing scheme overcame the effect of 'numerical diffusion'. However, the work did not cover multiple baffle cases such as Case L4, in which there are large areas of flow that may not align with the model grid.

5.7 Case L11 – Single baffle, outlet end, outlet moved



Case L11 was a design incorporating a single baffle, 70% of the width of the pond located at the outlet end. The outlet has been moved from the traditional position to the same side as the inlet.

5.7.1. Flow Pattern

The following pictures show the flow path of the tracer through the pond (Figure 5-14).

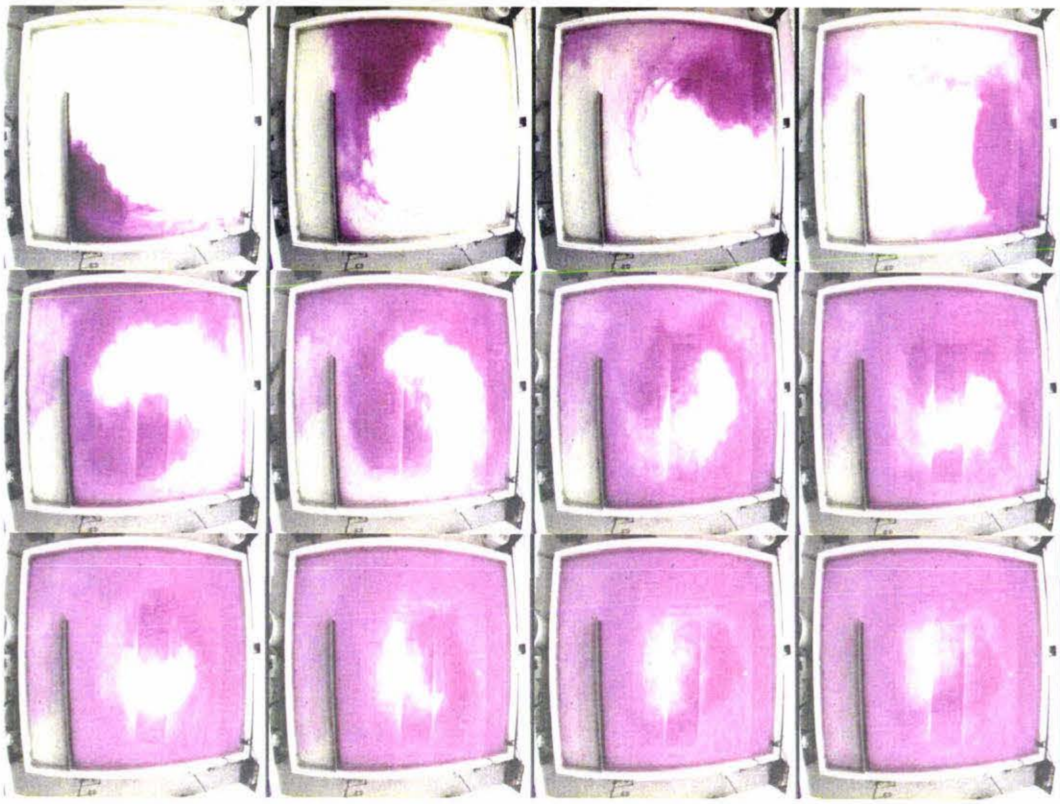


Figure 5-14 Dye Flow Pattern – Lab Tracer Study Case L11

This flow pattern is not encouraging from a hydraulic point of view. It shows that it takes some time for the bulk 'cell' of the pond to become well mixed. In fact, there is dye at the outlet before the bulk cell of the pond is well mixed. The baffle, while shielding the outlet somewhat from the main dye flow, does not protect it for very long.

5.7.2. Tracer Study Results

The tracer response for Case L11 (single baffle, outlet end, outlet moved) is shown Figure 5-15.

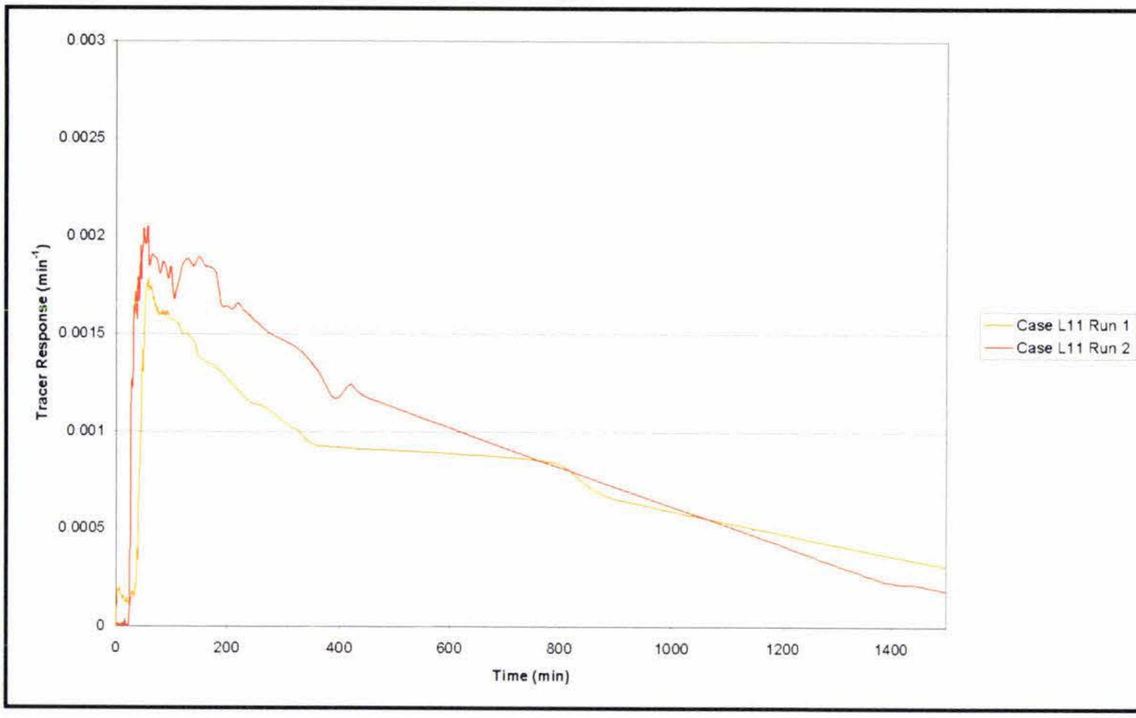


Figure 5-15 Full Tracer Study Results Case L11

This plot shows response curves that are similar to that of Case L2 (two baffles, standard length), i.e. the curve lags the base case, and the peak is much lower. The average time to short-circuiting for this single baffle case was 29.5 minutes (Base Case = 2 minutes, Case L2 = 47.5 minutes).

This is a significant improvement on the base case; however, it does not produce as good a result as that of Case L2. This is to be expected, as 'the more baffles the better'. This was also shown in the modelling on a large-scale theoretical pond in Chapter 4. Case 2 showed an outlet coliform concentration of <u>*$6.00x10^3 cfu/100mL$*</u>, with a concentration of <u>*$8.00x10^5 cfu/100mL$*</u> for Case 11 (one standard baffle, outlet moved). A comparison of the tracer response for Case L2 and Case L11 is shown in Figure 5-16.

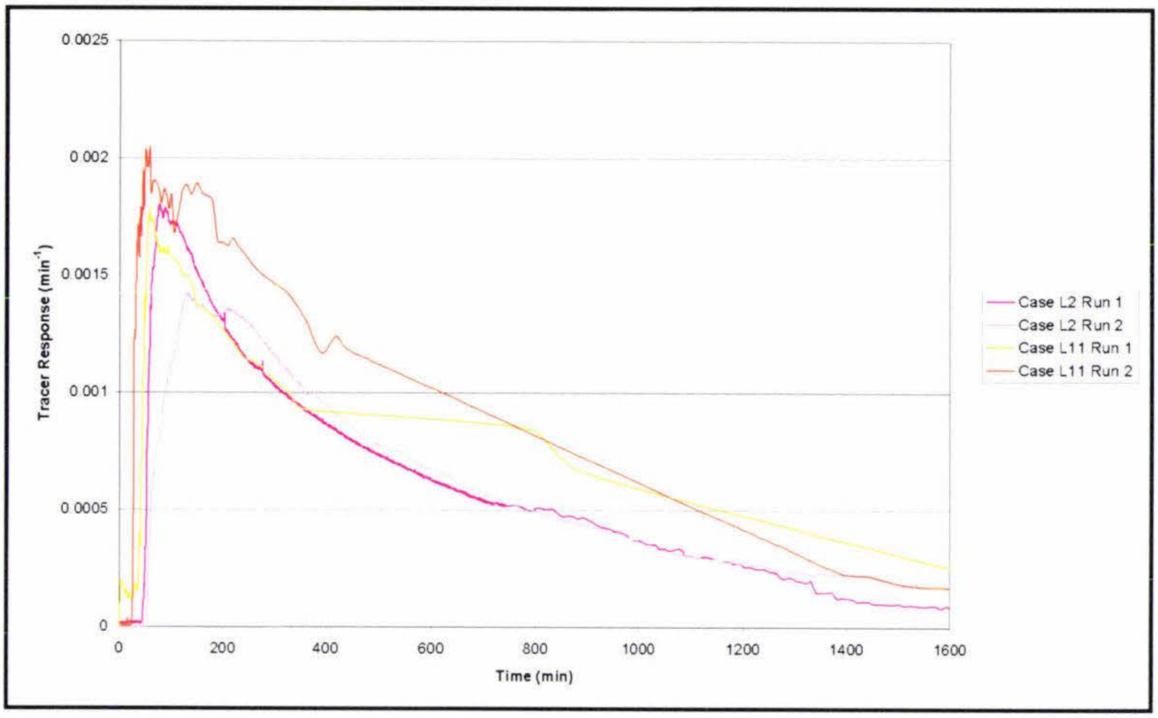


Figure 5-16 Comparison HRT - Case L2 (traditional two baffle) and Case L11 (single baffle, outlet end, outlet moved), first 120 minutes

5.7.3. CFD Modelling Results

This case was modelled in the CFD environment with a tracer study performed on the model. The results of this tracer study are shown Figure 5-17.

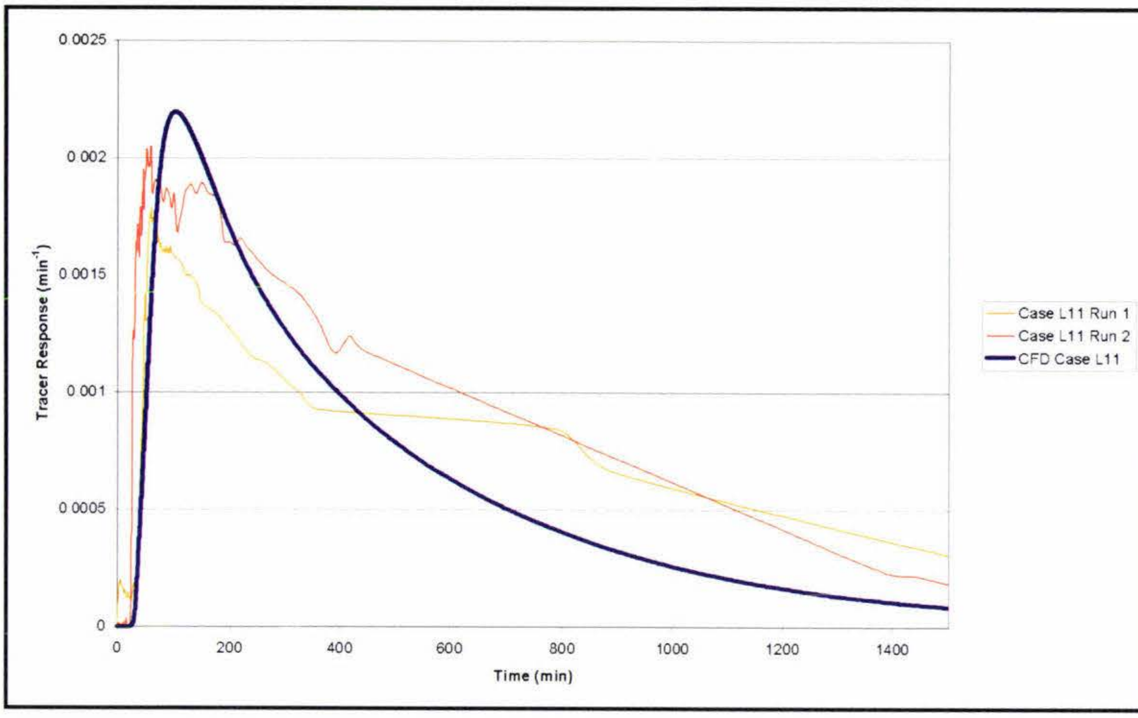
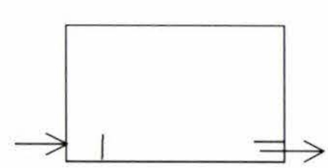


Figure 5-17 Comparison plot - CFD and Laboratory results, Case L11

As can be seen from the above plots, the CFD model of the laboratory pond predicts the actual performance extremely well. The CFD peak is of a similar size to that of the laboratory results. Also, the time to the start of short-circuiting is very similar. The average time to the start of short-circuiting for the laboratory run was 29.5 minutes, the CFD model predicts tracer at the outlet after approximately 30 minutes.

5.8 Case L14 – two stub baffles, outlet moved



Case L14 has two stub baffles (15% of the width of the pond) located near the inlet and outlet. The outlet has been moved to the same side of the pond as the inlet.

5.8.1. Flow Pattern

The following series of pictures, Figure 5-18, shows the flow pattern for Case L14.

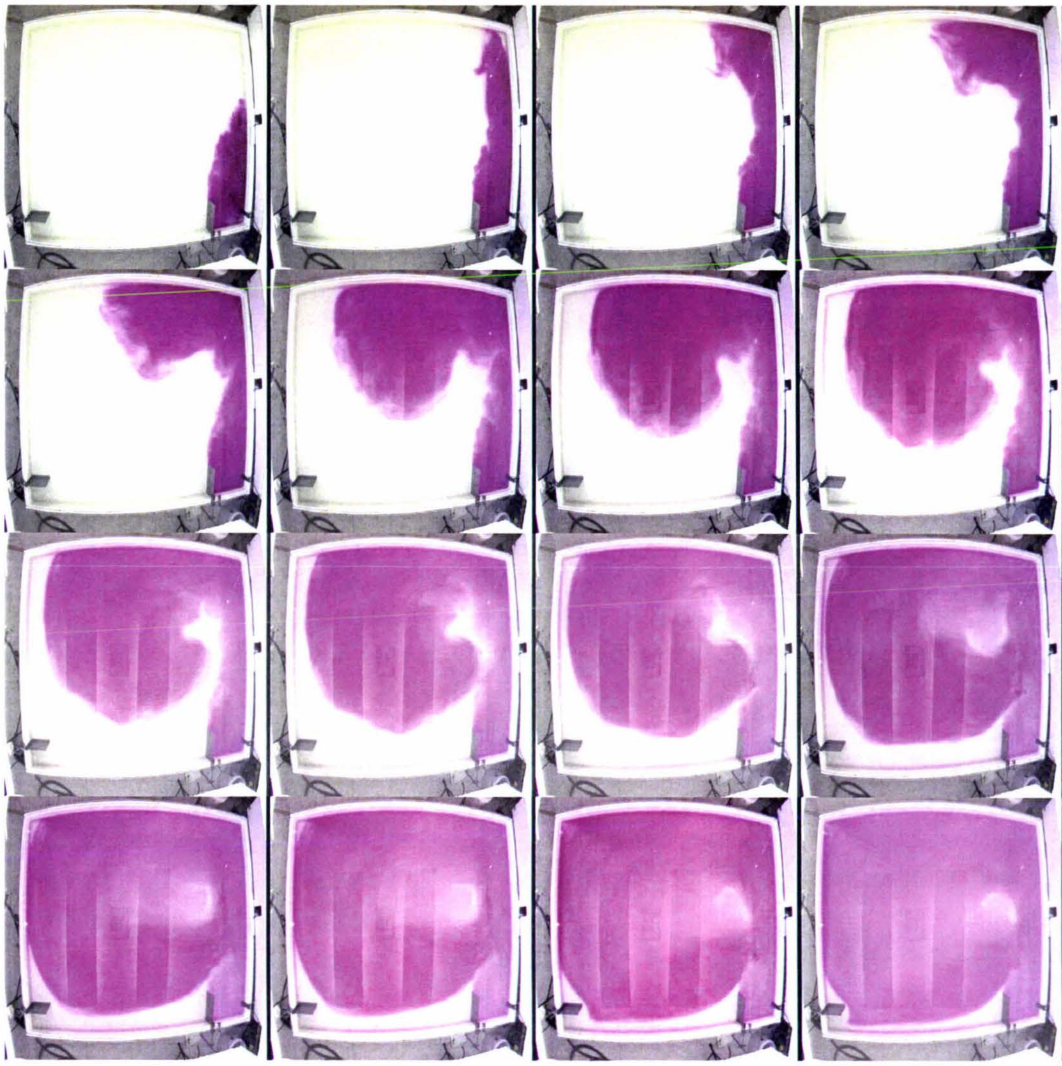


Figure 5-18 Dye Flow Pattern - Case L14 Laboratory tracer study

The flow pattern resulting from the baffles in Case L14 differ markedly from those of Case L2. Instead of the slug of tracer following the outside edges of the pond (the bulk of the pond after the initial baffle), it starts to mix well very early on. The flow is delayed from reaching the outlet, thereby increasing the time to the start of short-circuiting and increasing treatment efficiency. This is a significant improvement on the basic case.

5.8.2. Tracer Study Results

The results of the tracer studies are shown in Figure 5-19.

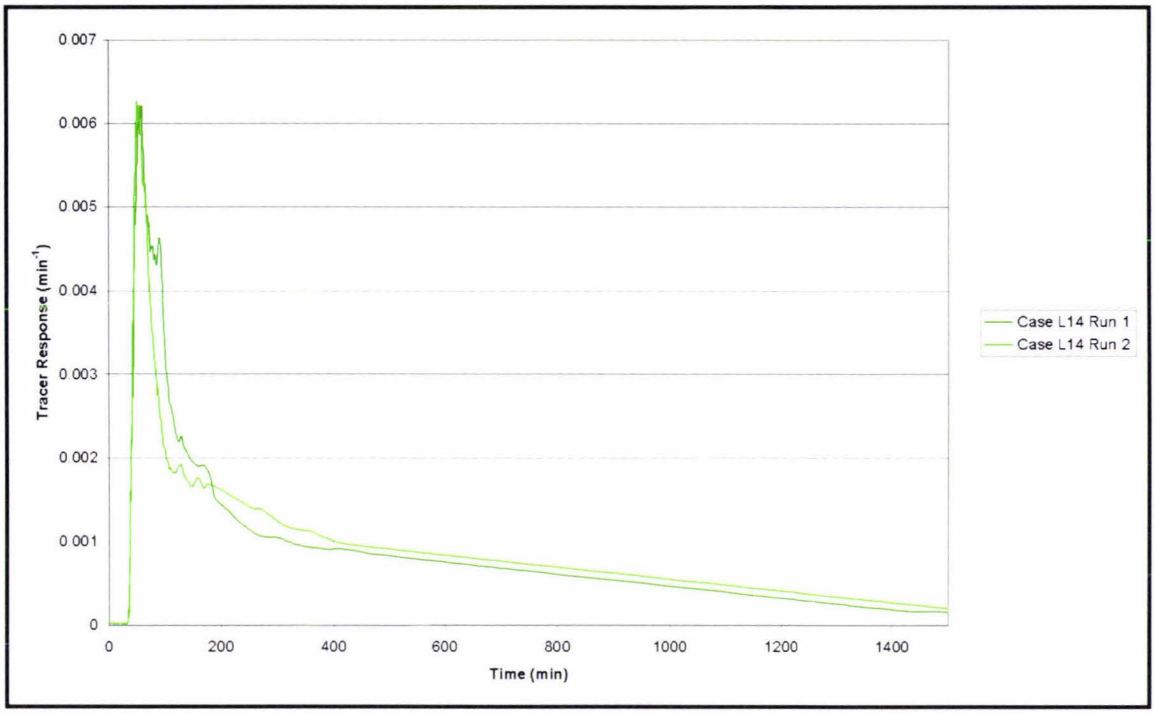


Figure 5-19 Tracer study results Case L14 (two stub baffles, outlet moved)

The peak is quite high, with Run 1 showing evidence of a second peak. The time to short-circuiting, averaged over the two runs, was 37 minutes (base case = 2 minutes). This is not as good as the 47.5 minutes for the traditional two baffle case (Case L2), but it is getting close with a significantly less length of baffle, and therefore less construction cost. A comparison of the tracer response for Case L2 and Case L14 are shown in Figure 5-20.

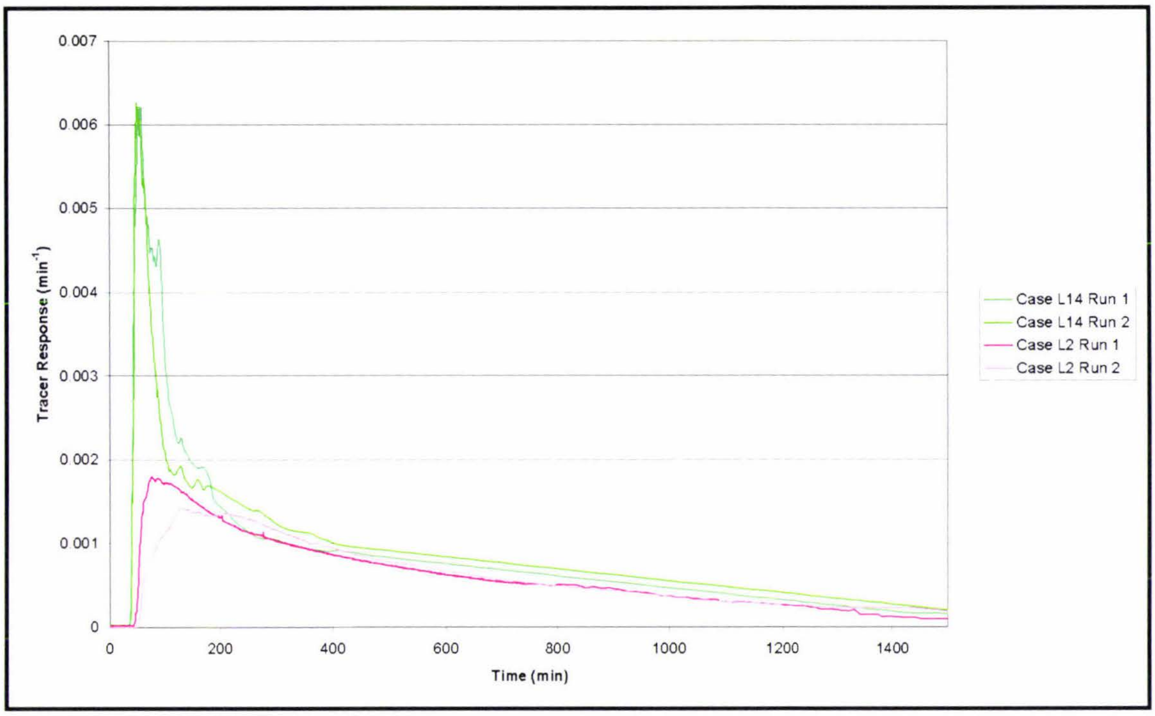


Figure 5-20 Comparison HRT of Case L2 (traditional two baffle) and Case L14 (two stub baffles, outlet moved)

The times to short-circuiting are all above the 35 minute mark, they also show that the peak for Case L14 (two stub baffles, outlet moved) is much sharper than the for Case L2 (traditional two baffle case). While this indicates that a high peak and high concentration of dye exiting the pond over the initial peak stage for Case L14, it is still a later peak which is desirable – and has been achieved with a minimum amount of baffling.

5.8.3. CFD Modelling Results

The results of the CFD model tracer study of Case L14, compared with the laboratory run, are shown in Figure 5-21.

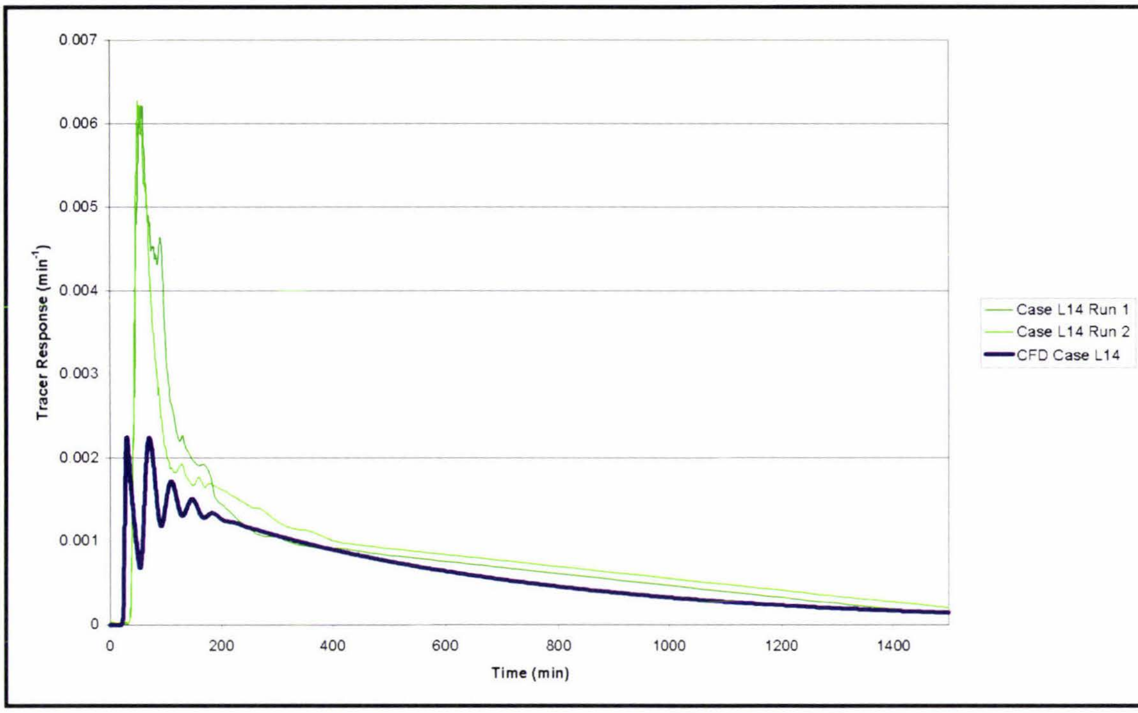
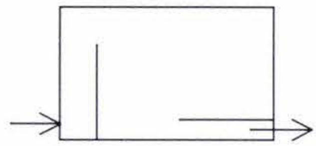


Figure 5-21 Comparison Plot - CFD and Laboratory Tracer Studies, Case L14

The CFD model predicts a series of low peaks, indicating a distinct circulation pattern of the tracer. The laboratory tracer run indicates one large peak, with Run 1 showing what may be a second small peak about the 90-minute mark. The series of photos in Figure 5-18 show the dye 'curling' which indicates circulation. Therefore, the model may be detecting this circulation as significant, therefore creating a series of peaks in the tracer response.

The photos of the laboratory run show the flow direction is turned by the inlet baffle, and then while still following a general circ ulation pattern, the flow gradually moves across the pond to the outlet. In the CFD model, the turning effect of the inlet baffle is picked up, however, the gradual movement of the bulk circulation of the pond may not be picked up. This could explain the d ifference in the CFD and laboratory tracer responses. This effect may be due to 'numerical diffusion' effect discussed in Section 5.5.3 and 5.6.3. The model may simplify the effect of the flow at the end of the inlet baffle causing the prediction of a simple bulk circulation rather than an increasing circulation as seen in the laboratory photos (Figure 5-18).

5.9 Case L15 – Two long baffles, outlet moved



Case L15 is of the same design as Case L14 (two stub baffles, outlet moved), except that it uses baffles that are 70% of the width of the pond. Case L14 uses baffles that are 15% of the width of the pond. The positioning of the baffles in these two cases is exactly the same.

5.9.1. Flow Pattern

Due to difficulties experienced with the photographic equipment, the overhead photos tracking the flow pattern for Case L15 are not available. Ho wever, photos of parts of the pond were taken by a digital camera.

The outlet end of the pond is shown in Figure 5-22.

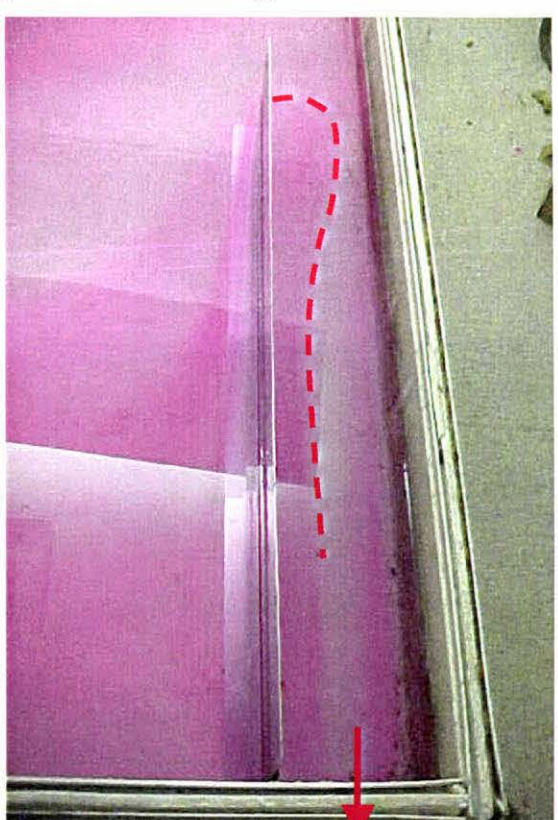


Figure 5-22 Outlet end of Case L15 (two long baffles, outlet moved) showing channelling pattern

This photo shows the same channelling pattern seen in Case L4 (traditional six baffle case). The effect has also been discussed in Chapter 4 where it was witnessed in the CFD modelling on a large-scale theoretical pond.

5.9.2. Tracer Study Results

The results of the tracer studies are shown in Figure 5-23.

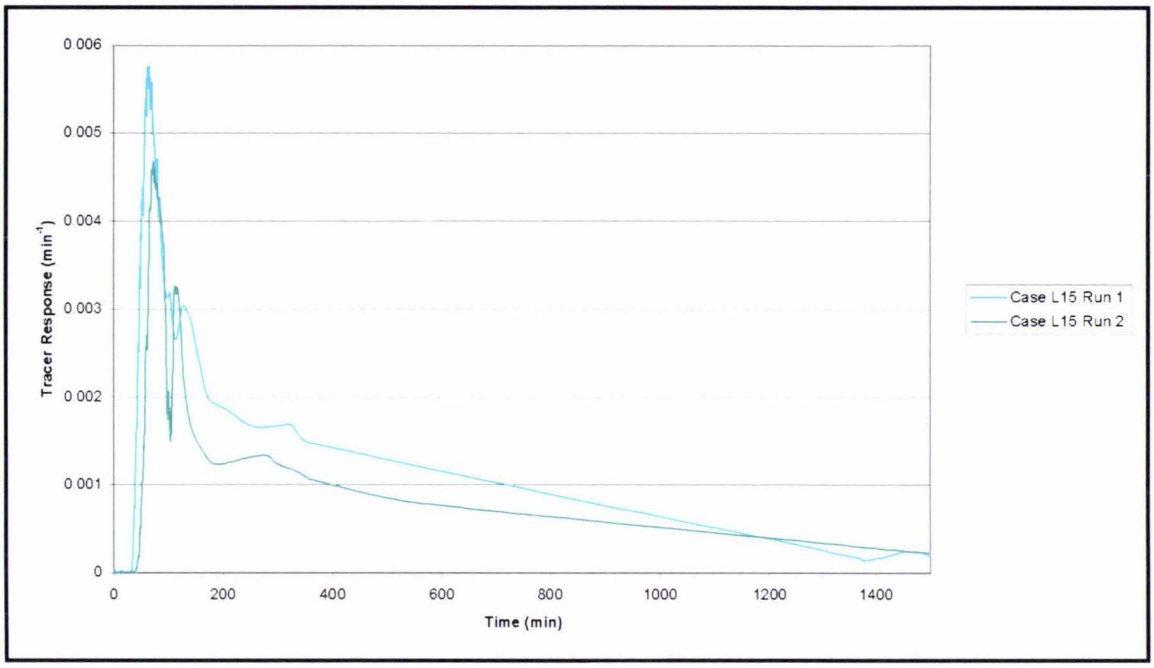


Figure 5-23 Tracer study results Case L15 (two long baffles, outlet moved)

Both sets of curves show evidence of a second and third smaller peaks. The CFD model of Case L14 predicted a series of peaks such as this, Case L14 has the same baffle arrangement as Case L15, but of a much shorter length.

The time to short-circuiting, averaged over the two runs, was 37.5 minutes (base case = 2 minutes). This is a significant result when compared to Case L14 which has the same design but shorter baffles. Case L14 had an average time to short circuiting of 37 minutes. A comparison of the two runs is shown in Figure 5-24.

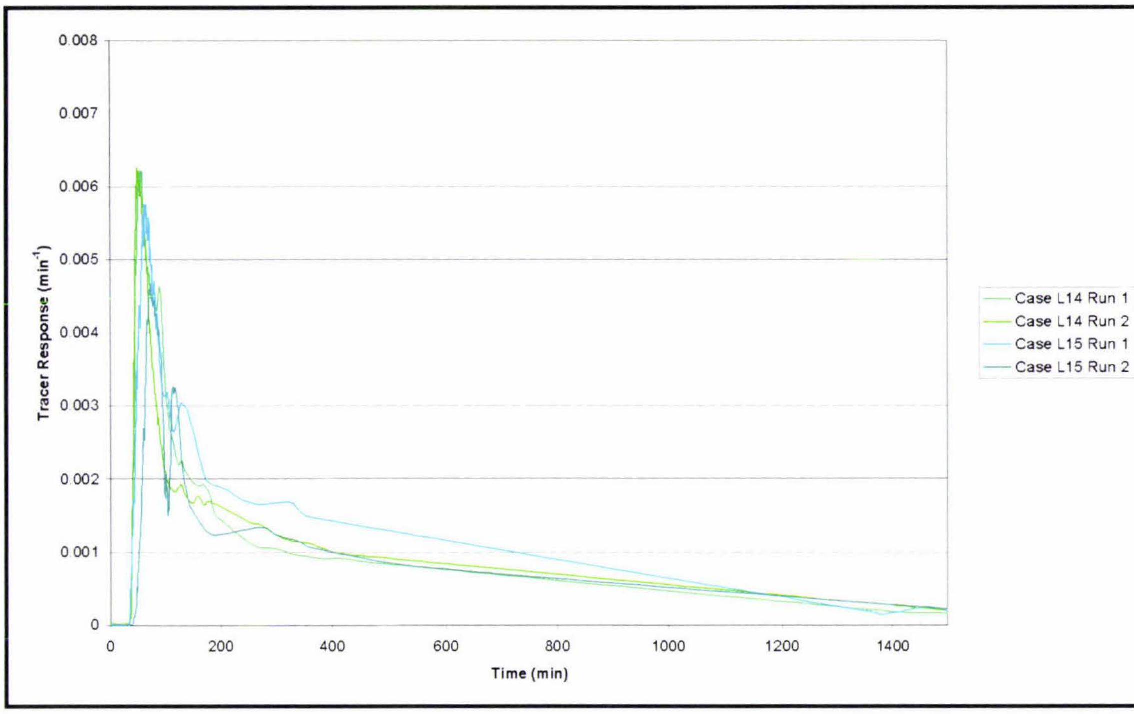


Figure 5-24 Comparison HRT of Case L14 (two stub baffles, outlet moved) and Case L15 (two long baffles, outlet moved)

The HRT curves for the two cases are very similar, with similar times to the start of short-circuiting. This indicates that the longer baffles in Case L15 do not improve the efficiency of the pond from the stub baffle of Case L14. This is a positive result as it shows that the basic pond can be improved upon significantly with minimum baffling.

This result differs from that achieved in the CFD modelling of a large scale theoretical pond in Chapter 4. In that work, it was shown that Case 15 (two long baffles, outlet moved, as in Case L15) did not perform as well as Case 14 (two stub baffles, outlet moved, as in Case L14). The coliform concentrations at the outlet were $1.08x10^4$*cfu/100mL* and $4.41x10^3$*cfu/100mL* for Cases 15 and 14 respectively, which showed that the extra length of baffles in Case 15 worsened the treatment efficiency.

It was concluded in Chapter 4 that the stub baffles were very sensitive to changes in design; the laboratory results of Cases L14 and CaseL15 indicate that they are also sensitive to the conditions present in a particular pond.

5.9.3. CFD Modelling Results

This case was modelled in the CFD environment and a tracer study performed on the model. The results of this tracer run compared to the laboratory tracer run are shown in Figure 5-25.

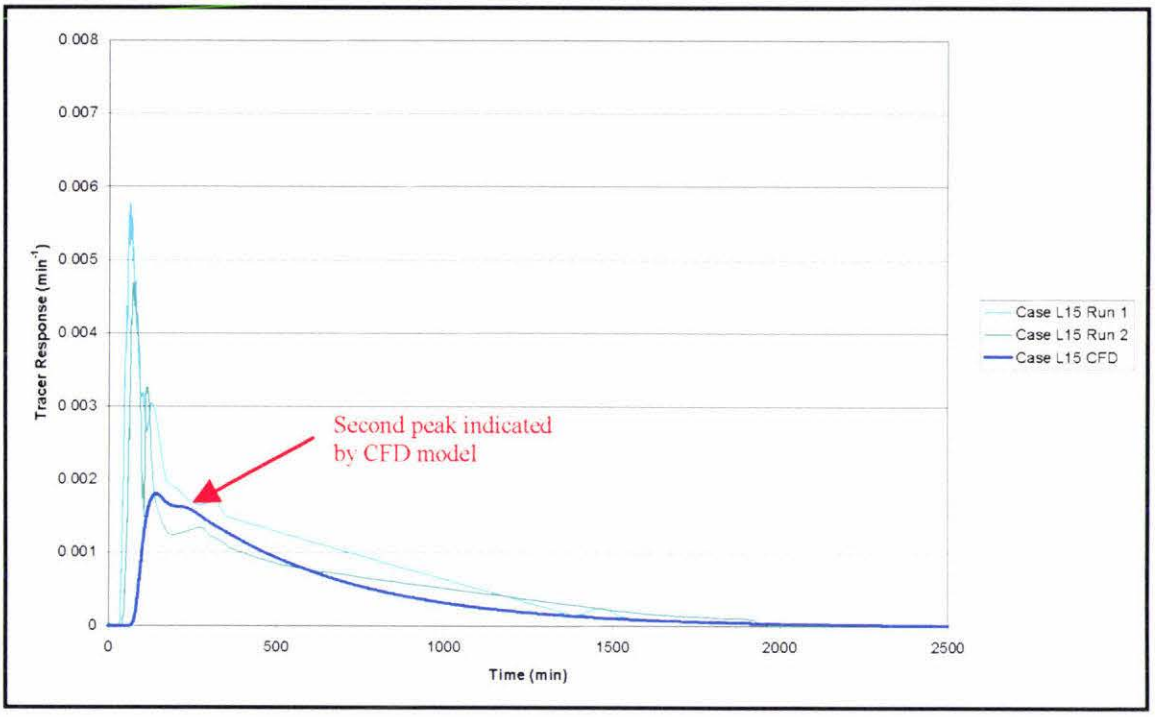


Figure 5-25 Lab and CFD Tracer study results – Case L15 (two long baffles, outlet moved)

The CFD tracer run lags the lab run somewhat and peak is also shorter. The CFD model also indicates a small second peak at approximately 250 minutes.

The time lag of the CFD model can most likely be contributed to 'numerical diffusion' (smearing) as discussed previously. In this case, the inlet and outlet baffles create narrow channels for the flow, in addition to this Figure 5-22 shows the complex channelling flow present at the outlet end of the pond. Therefore it is likely, that the smearing effect is present at both the inlet and outlet ends of the pond, and creates the time lag seen in the CFD results.

5.10 Case L17 – Vertical inlet

5.10.1. Flow Pattern

The flow pattern of the dye through the pond is shown in Figure 5-26. It can be seen that the dye flows away from the inlet in either direction, effectively following around the walls of the pond. This flow pattern is similar to that seen in the CFD modelling of a theoretical pond of similar shape in inlet/outlet design, in the previous chapter (see Section 4.7.1).

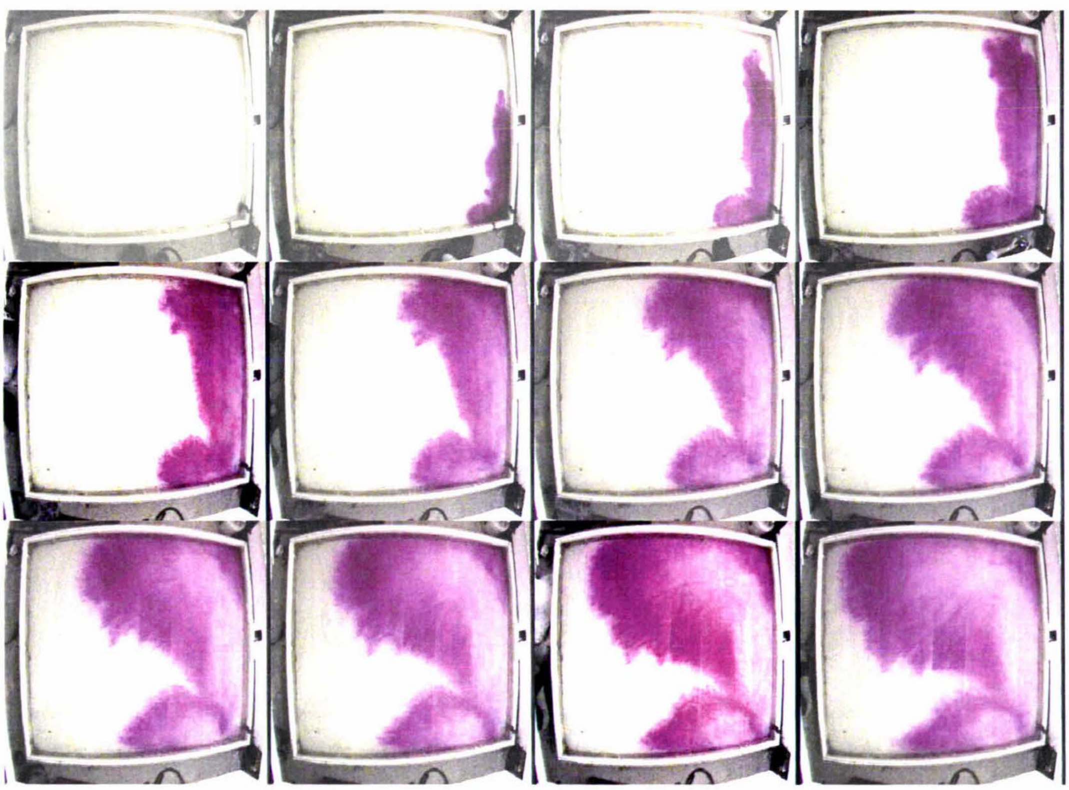


Figure 5-26 Dye flow pattern - Case L17 (vertical inlet)

5.10.2. Tracer Study Results

The tracer study results for this case are shown in Figure 5-27.

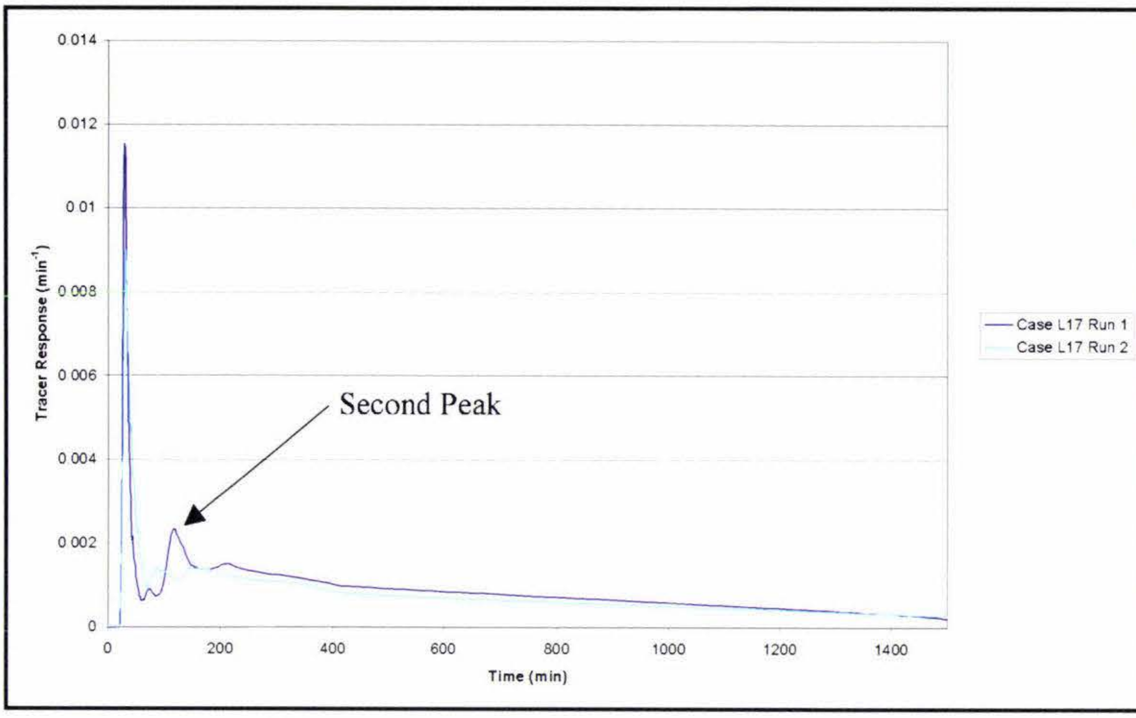


Figure 5-27 Full Tracer Study Results Case L17 (vertical inlet)

It can be seen that the peak for the vertical inlet case appears later than for the base case. The average time to the start of short-circuiting was 24 minutes compared to 2 minutes for base case. This shows that the vertical inlet offers a significant improvement on the base case. The peak is still quite high, which shows the dye is not well mixed in the pond environment.

A second peak can be seen (shown by arrow on Figure 5-27). As the flow branches away from the inlet in two directions, this second peak is most likely due to the slower branch of the flow reaching the outlet.

Shilton (2001) also found that the use of a vertical inlet reduces the peaks and significantly increases the time to the start of short-circuiting. In his, work Shilton (2001) used an inlet turning vertically downwards. The down-turned inlet, combined with an outlet located in the centre of the end wall, increased the time to the start of short-circuiting from 2 minutes (base case) to an average value of 95 minutes.

The comparison of Case L17 with the work of Shilton (2001) indicates that the vertically up-turned inlet performs worse than the vertically down-turned. It is unclear as to why this is the case. The flow exiting t he down-turned inlet will hit the base of the pond, dissipating momentum, therefore slowing the flow and delaying the time to the start of short-circuiting. In the case of the up-turned inlet, the flow does not hit a barrier, other than atmosphere, in which to dissipate momentum. Therefore the delay in the time to the start of short -circuiting in the up-turned case will only be due to the changed nature of the flow pattern compared with the basic case.

5.10.3. CFD Modelling Results

The modelling of this case was c onsiderably more difficult than the other five cases. Difficulties were also experienced modelling this type of inlet on the large-scale theoretical pond in Chapter 4, with attempts being unsuccessful. Again, attempts to model a vertical inlet on the laboratory pond model were unsuccessful. This inability to get a working model is considered to be due to the complex nature of the flow around the inlet, especially in the vertical direction. With further attempts and assistance it is believed both the large -scale theoretical pond and the laboratory pond could be successfully modelled. Time constraints restricted these attempts in this instance.

5.11 Chapter Summary & Discussion

A summary table of the times to short-circuiting for the laboratory tracer studies is shown in Table 6.

Table 6 - Summary table - Time to short-circuiting for laboratory tracer studies

Case	Time to Start of Short -circuiting	
	Laboratory	*CFD*
Base (Shilton, 2001)	2	-
L2 (traditional two baffle)	47.5	65
L4 (traditional six baffle)	82.5	250
L11 (single baffle, outlet end)	29.5	30
L14 (two stub baffles)	37	25
L15 (two long baffles, as Case10)	37.5	70
L17 (vertical inlet)	24.0	-

The table shows that all of the modified pond designs tested in the laboratory achieved improvement over the basic case. In practical terms, these designs may not be appropriate for all pond systems. Their use will be dependent on the site and cost requirements.

The key objective of this chapter was to demonstrate the ability of CFD modelling to predict the step changes in performance from implementing different pond designs. Out of the five cases successfully modelled, four (Cases L2, L11, L14, and L15) produced results similar to that of the laboratory tracer studies. While the laboratory and CFD tracer studies do not match perfectly, they still show the step-change due to the design modifications.

These step changes are highlighted in the following figures (Figure 5-28 and Figure 5-29). Figure 5-28 shows a comparison plot of the laboratory results for the basic case (Shilton, 2001) and Case L11 (one standard baffle, outlet moved. Figure 5-29 shows the same comparison, but of the CFD results.

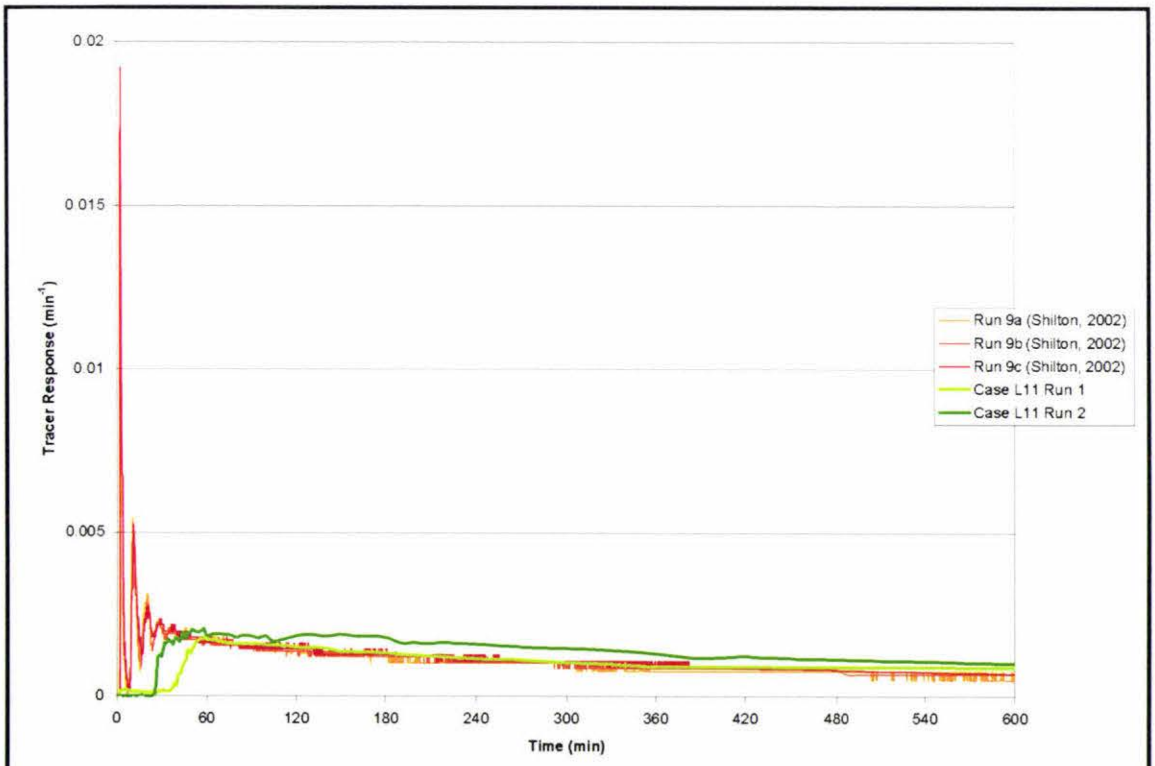


Figure 5-28Comparison Plot of Laboratory Results - Basic Case (Run 9, Shilton, 2001) and Case L11

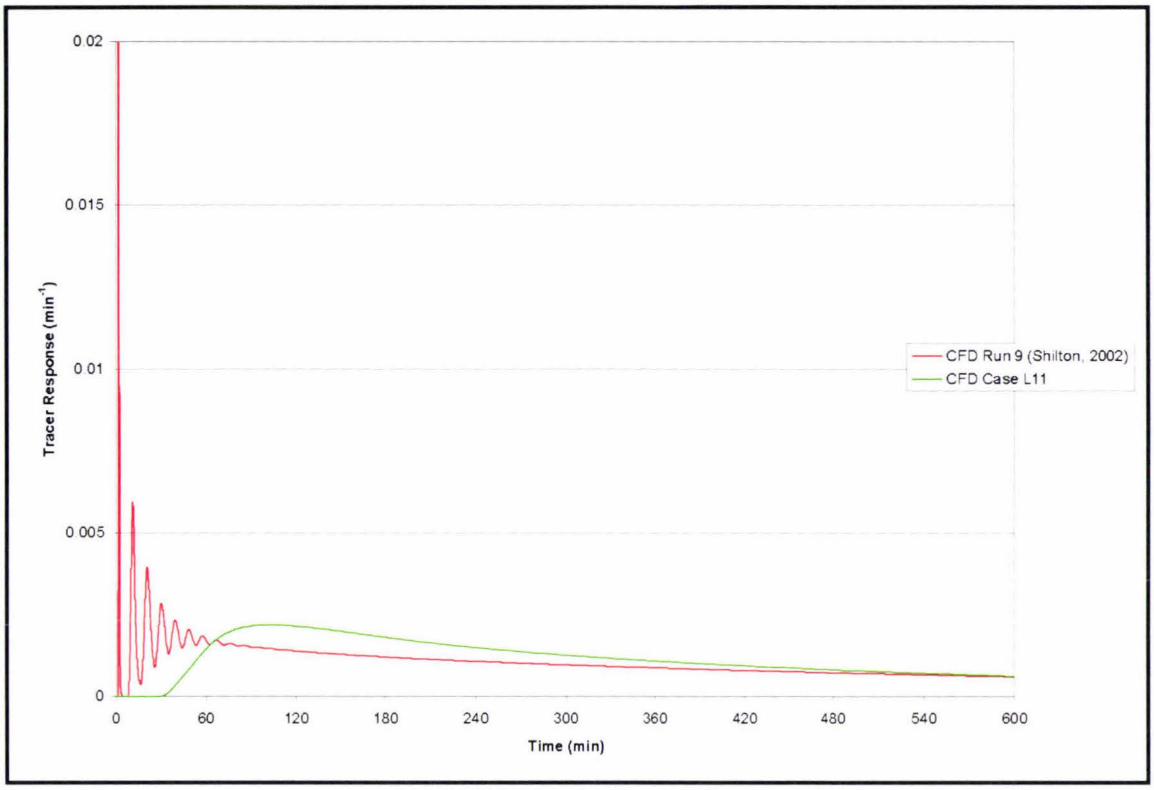


Figure 5-29 Comparison Plot of CFD Results - Basic Case (Run 9, Shilton, 2001) and Case L11

The plots show the step change in performance achieved by the addition of one baffle, and the repositioning of the outlet. This change is clearly seen in the laboratory results **and** the CFD results. The benefit of CFD as a tool for predicting step changes in performance has been highlighted.

6. ASHHURST POND STUDIES

6.1 Introduction

The primary aim of this thesis is to investigate baffle designs for optimum efficiency in waste stabilisation ponds. CFD was the major tool in achieving this aim and while recent work (Shilton, 2001) has provided confidence in the use of CFD, more laboratory and field work is still required to give further insight and confidence in its use. This chapter presents the results of two field trials.

Field studies are timely and costly to perform. A tracer study typically take several months to complete. The natural variances in present in a field situation also introduce complications. These complications include varying influent flowrate and weather conditions (wind and temperature).

Field studies were performed on the secondary pond at Ashhurst. Ashhurst is a small community about 20km east of Palmerston North, New Zealand. Section 3.5 details the Ashhurst pond system.

Due to their long duration, a simple inlet modification was tested in order to get a field trial started. This modification involved the use of a vertical inlet. The vertical inlet had shown its potential to provide treatment improvements in the laboratory studies and in previous research by Shilton 2001. In addition, the use of a vertical inlet is relatively cheap and easy to achieve. Therefore, it was decided that to test the vertical inlet in the field despite the unsuccessful attempts to model the vertical inlet in during the initial CFD modelling. At the time of the first field trial, the CFD modelling of the Ashhurst pond had not yet started.

While the first field trial was underway, modelling work carried on to determine an appropriate modification to implement for a second field trial. This allowed the application of the knowledge gained from the modelling of the theoretical pond in Chapter 4, and the laboratory testing in Chapter 5 to a model of a field pond. A range of designs were tested on the Ashhurst model to find a suitable design modification that was within the projects budget to implement.

6.2 Field Study 1 – Vertical Inlet

6.2.1. Introduction

In the first field trial, a vertical inlet was fabricated to fit over the existing inlet to the secondary pond at Ashhurst. This insert was horizontal and fitted with a bend to discharge vertically upwards. The inlet was the same size as the original inletFigure 6-1 shows the secondary pond at Ashhurst, and the approximate position of the inlet and outlet.

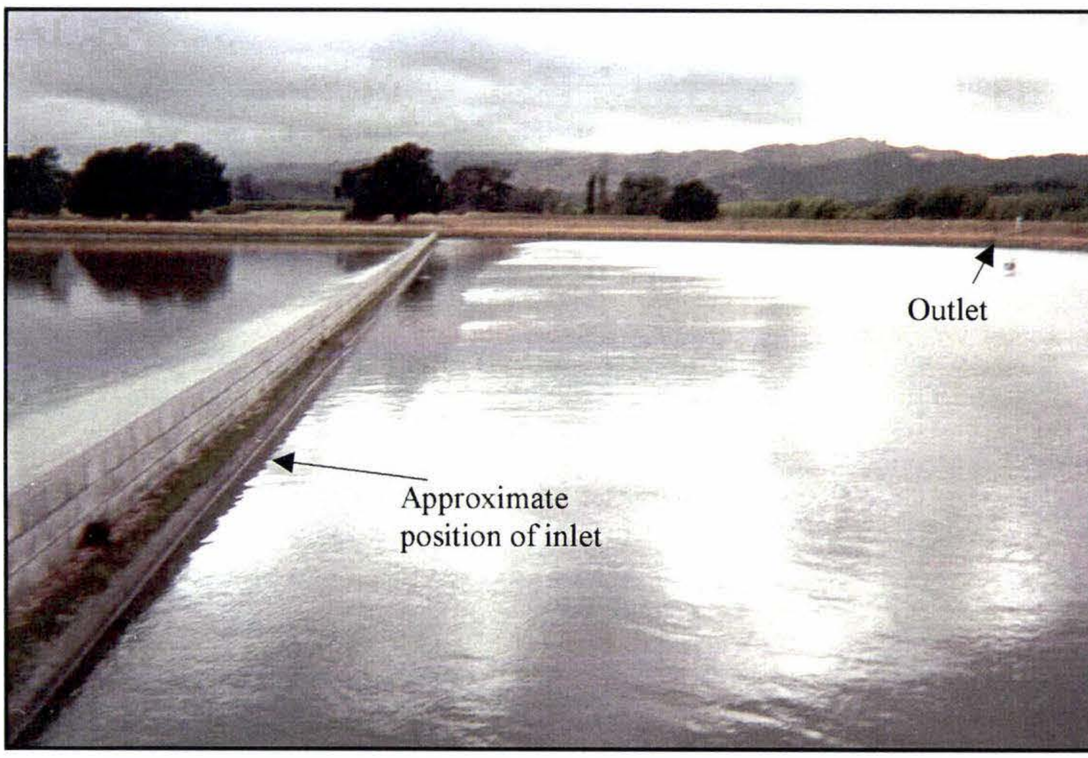


Figure 6-1 Ashhurst secondary pond

Figure 6-2 shows the auto-sampler equipment at the outlet end of the pond., the calm weather conditions can also be seen. The still conditions experienced on the first day of the field trial can also be seen.

Figure 6-2 Auto-sampler set-up at outlet - Ashhurst pond

6.2.2. Study Conditions

The tracer study was started on a clear and relatively still day. The weather throughout the initial few days of the trial were very good, fine to slightly overcast with winds ranging from a light breeze to slightly windy. This fine weather was after a short period of unsettled weather, and the pond was observed to have a lot of solids floating on the surface.

After the initial few days, the weather worsened considerably. Windy conditions were experienced, a lot of rainfall occurred and subsequently the level in the pond rose considerably. The flow at the outlet therefore greatly increased, and the level in the pond was approximately a foot higher than normal due to the combined effect of a partially blocked outlet and the rainfall.

6.2.3. Study Results & Discussion

Figure 6-3 shows the tracer welling up from the vertical inlet and entering the pond.

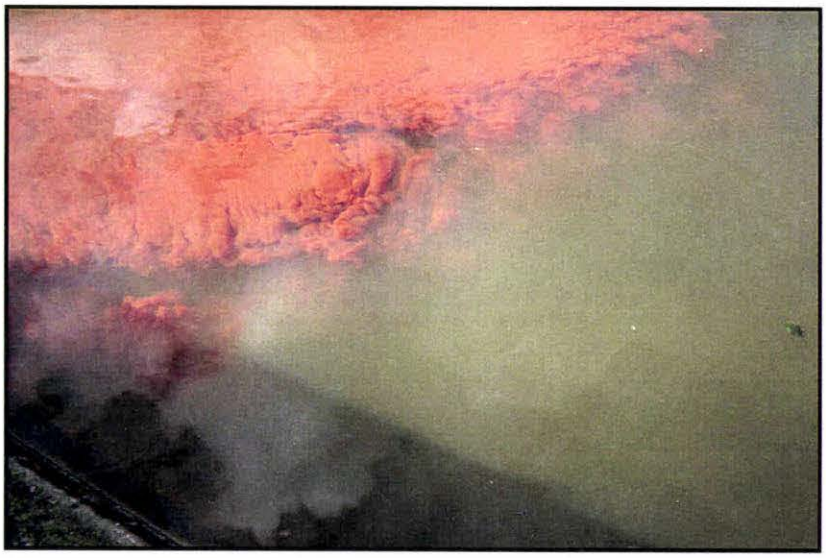


Figure 6-3 Tracer welling up from vertical inlet - Ashhurst Field Trial 1

A plume of dye can be seen moving across the pond away from the inlet in Figure 6-4. Observations of the dye plume over approximately the first hour, also showed a plume of dye extending down the long side of the pond by the dividing wall. This plume appeared to be moving quite quickly compared to a second plume extending across the pond from the inlet. A diagram showing the two plumes of dye is shown in Figure 6-5.

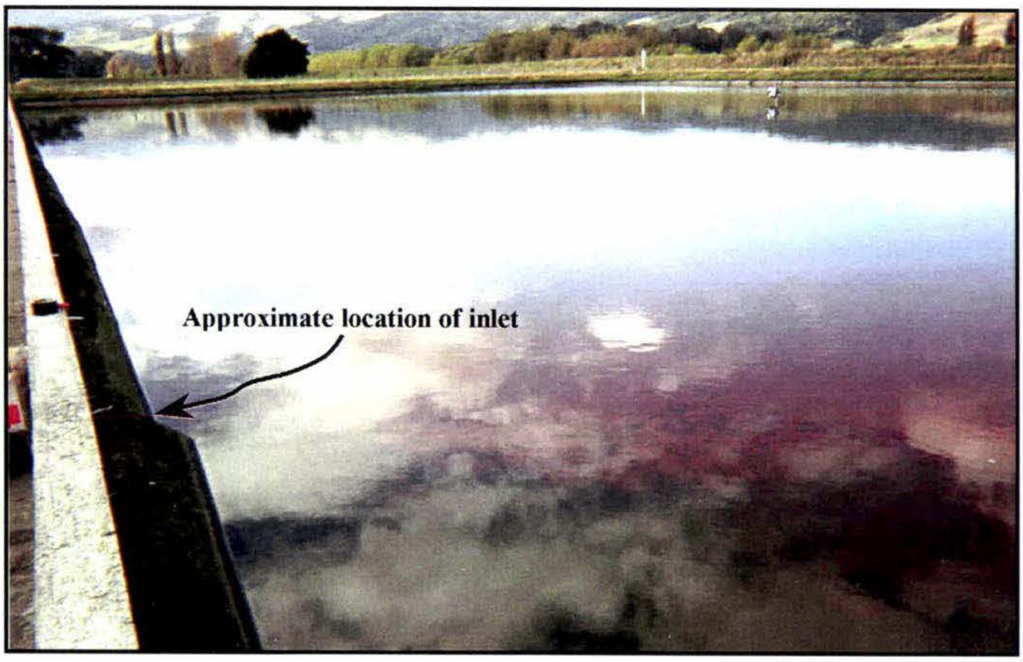


Figure 6-4 Dye movement - Ashhurst Field Trial 1

Figure 6-5 Diagram depicting dye movement - Ashhurst Field Trial 1

Figure 6-6 shows the full tracer study results for the vertical inlet trial at Ashhurst.

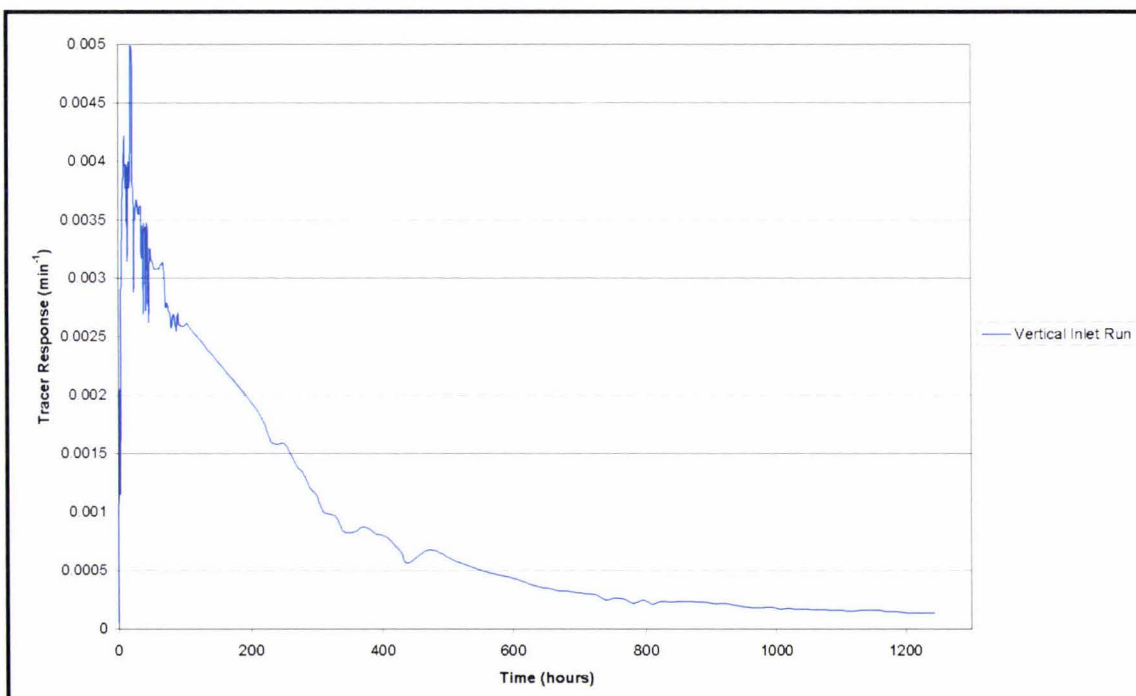


Figure 6-6 Full Tracer Response - Vertical inlet trial, Ashhurst

Shilton (2001) performed tracer studies on the basic (no modifications) Ashhurst pond. In the next two figures (Figure 6-7 & Figure 6-8), the results of this field trial and those of Shilton 2001 are compared. Field conditions result in varying flow rates, therefore direct comparison of raw data cannot be made. To allow the comparison of tracer studies undertaken at different flowrates, the mean retention time was used to make the time axis of each run dimensionless.

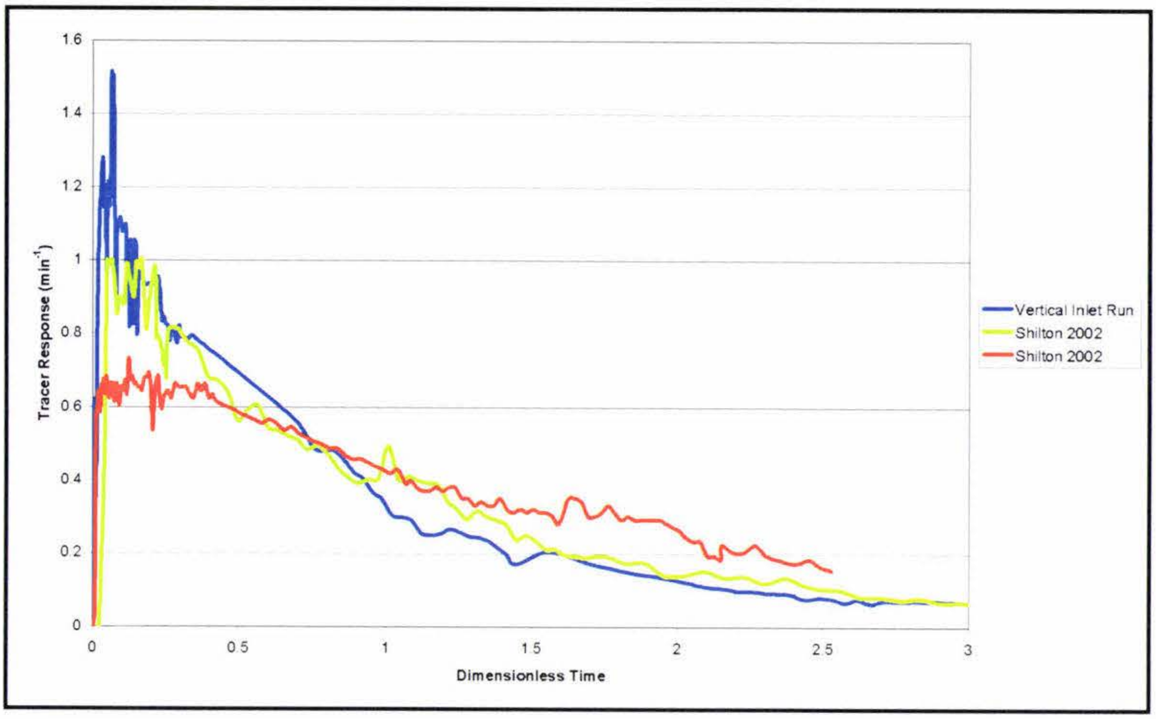


Figure 6-7 Comparison HRT plot - normal & vertical inlet, Ashhurst

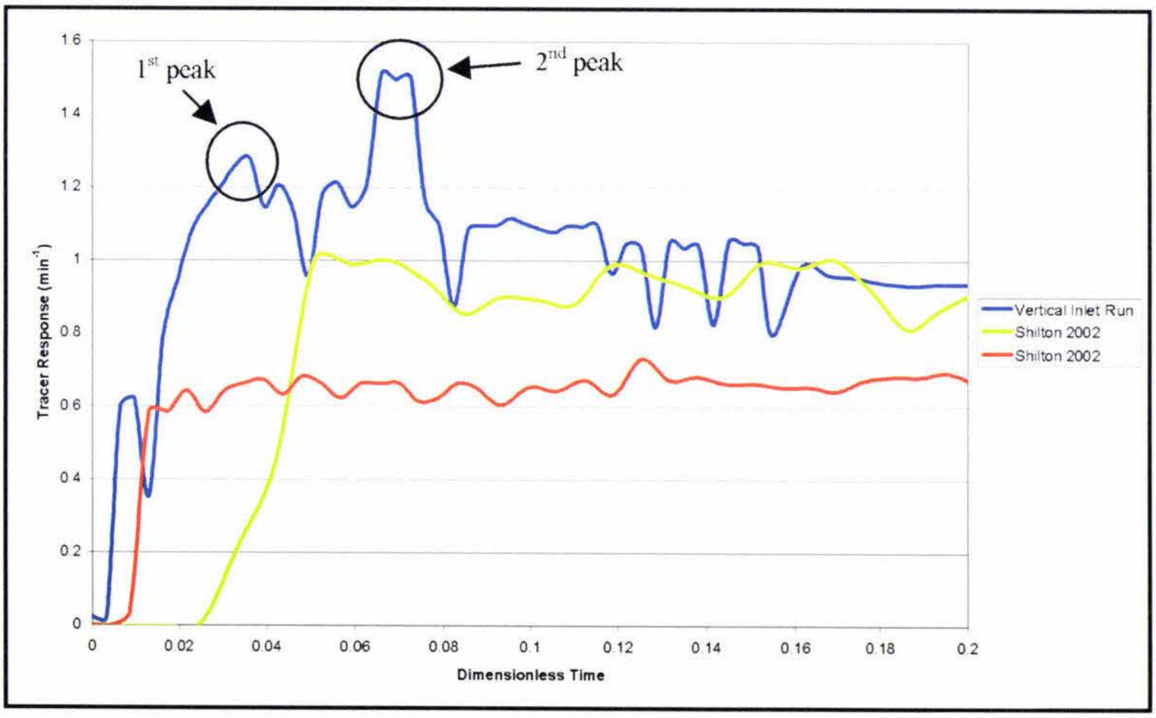


Figure 6-8 Comparison HRT Curve - normal & vertical inlet, Ashhurst - first portion of tracer run

As can be seen from the above figures (Figure 6-7 & Figure 6-8), the use of the vertical inlet has not improved the performance of the Ashhurst pond. Shilton (2001) recorded an average wind speed of 2.05m/s at a height of 5.5m on the first day of the tracer study in 2000.

The HRT curve (Figure 6-8) for the vertical inlet indicates no improvement on the normal inlet case. This differs from the testing on the laboratory model (Section 5.10) that showed the use of a vertical inlet decreased the time to the start of short-circuiting. This was also found in laboratory testing by Shilton (2001). This highlights that different ponds, while shaped and configured in a similar manner, may perform with varying degrees of success due to the unique circumstance present in each situation.

As noted in 6.2.2, the weather conditions that occurred during the trial, and there were considerable changes in the level of the pond. These influences will most likely have had a large effect on the results of this. It would be useful to repeat this field trial to provide further confidence in the field results. This not undertaken as part of this work due to time constraints.

Shilton (2001) noted the large circulation pattern, from the inlet around the pond in an anti-clockwise direction to the outlet, in his studies on the Ashhurst pond. In the vertical inlet field trial undertaken for this work, a circulation pattern could also be described. However, as shown in Figure 6-5 the circulation for the vertical inlet occurred in two directions – across the pond from the inlet, and down the wall dividing the primary pond from the secondary pond. The two plumes of dye evident during the field observations can also be seen in the HRT curve (indicated by arrows in Figure 6-8).

This 'two plume' circulation was also exhibited when CFD modelling of the large-scale theoretical pond was undertaken (Section 4.7.1.2), and a tracer study performed on a smaller-scale laboratory model (Section 5.10.1). Therefore, the modelling of three entirely different ponds, similar in shape and configuration, has produced similar flow patterns. This provides considerable confidence in the results of the three different investigative methods.

In their modelling of a water reservoir, Shilton *et al.*, (2000a) also noted a 'two-plume' flow pattern. In that instance the inlet was located above the level of the reservoir and dropped vertically downwards. The tracer was seen to drop down to the floor of the reservoir, radiate in two plumes on the floor before rising to the surface opposite the inlet, and tracking back to the inlet side of the reservoir. The flow on the floor of the reservoir is shown in Figure 6-9.

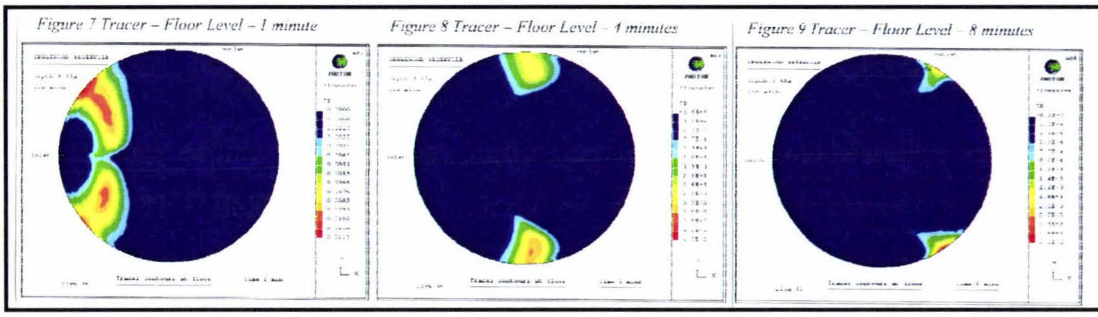


Figure 6-9 Flow pattern at Floor Level in Water Reservoir (Shilton *et al.*, 2000a, pg 7)

The purpose of the vertical inlet study was to assess a modification in a field situation. The field trial was undertaken successfully, however the weather conditions have had a negative effect on the results. However, this is a driving force behind the undertaking of field trials, what has tested well in the early CFD modelling and the laboratory work may not necessarily translate into a successful field application. This study has shown that the use of a vertical inlet may not be appropriate in extreme weather areas.

Attempts were made to modelling this pond configuration during the modelling undertaken for Field Study 2 (Section 6.3). These attempts were unsuccessful, a discussion of the reasons for this can be found in Section 6.3.2.7.

6.3 Field Study 2 – Combination of Inlet modification and Baffle

6.3.1. Introduction

To determine the best modification to install on the Ashhurst for the second field trial, an extensive CFD modelling process was undertaken. Knowledge gained from modelling the theoretical pond (Chapter 4) and the laboratory studies (Chapter 5) ahs been applied to the CFD model of the Ashhurst pond. The modifications included extensive use of baffles, combined with variations to the inlet and outlet of the pond. The modelling process will be broadly summarised to show the successful models as well as the unsuccessful models.

The study involves two stages, a tracer study carried out on the modified pond, followed by a CFD tracer study carried out on a model of the pond.

6.3.2. Design Process

Firstly, the existing pond situation was modelled to form a basis of comparison for all subsequent design modifications. This case was labelled Case AshA, all further cases were labelled AshB, AshC etc. The parameter used for comparison of the different models was the outlet coliform concentration. The inlet value for coliforms was set at *$8.66x10^5$cfu/100mL*, this value was a mean taken from coliform monitoring of the pond (Shilton & Harrison, 2002b). The flow patterns produced by each case were examined in order to provide explanations as to why a case was successful or not.

6.3.2.1. Basic Case – Unmodified Pond

The modelling of the basic case (AshA), produced an outlet concentration of *$1.3x10^5$ cfu/100mL*.

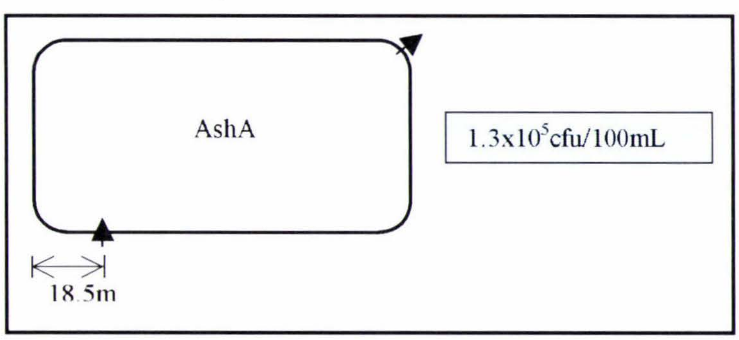


Figure 6-10 Case AshA - Unmodified Ashhurst Pond

6.3.2.2. Stub Baffles

Short stub baffles had already shown their potential in the CFD modelling of the theoretical pond in Chapter 4, and the laboratory modelling in Chapter 5. In addition to this, the cost of installing a long baffle in a full-scale pond was prohibitive. The use of two short baffles at the inlet and outlet ends of the pond had proved successful in Case 14 (Section 4.6.2) and Case L14 (Section 5.8), therefore two stub baffles were used in Cases AshB and AshC.

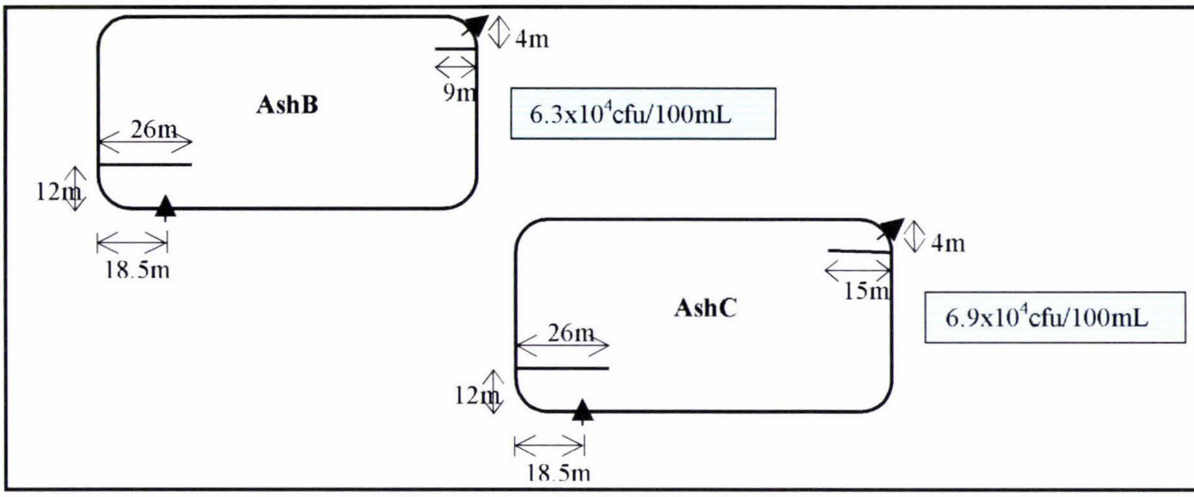


Figure 6-11 Cases AshB and AshC - two stub baffles

As can be seen, the outlet concentration of Case AshB only represented a reduction to the high '$x10^4$' range. Therefore, the outlet baffle was lengthened in Case AshC to further 'shield' the outlet and delay the exit of the wastewater. However, the lengthening of the outlet baffle did not improve the treatment.

The poor performance of these two cases was thought to be due to the location of the inlet with respect to the baffle. In Cases 14 and L14, the inlet was located such that the flow hit the base of the baffle, i.e. where the baffle attached to the side wall. This led to the development of Cases AshD through to AshG.

Due to the difference between the Ashhurst pond and the theoretical (Chapter 4) pond, the results were not expected to be the same. In particular with respect to the differences in the hydraulic residence time, and due to Ashhurst being a secondary treatment pond rather than a primary treatment pond. However, the flow patterns and behaviours in relation to the elements within the pond (inlets, outlets, and baffles) observed in Chapter 4 were applied to the Ashhurst model.

6.3.2.3. Stub Baffles, Turned Inlet

Cases AshD to AshG involved turning the inlet into the first baffle to imitate the situation in the theoretical pond (Chapter 4). In the theoretical pond, the inlet momentum hit the inlet baffle near the base of the baffle, i.e. where the baffle meets the side wall. Cases AshD to AshG are shown in Figure 6-12.

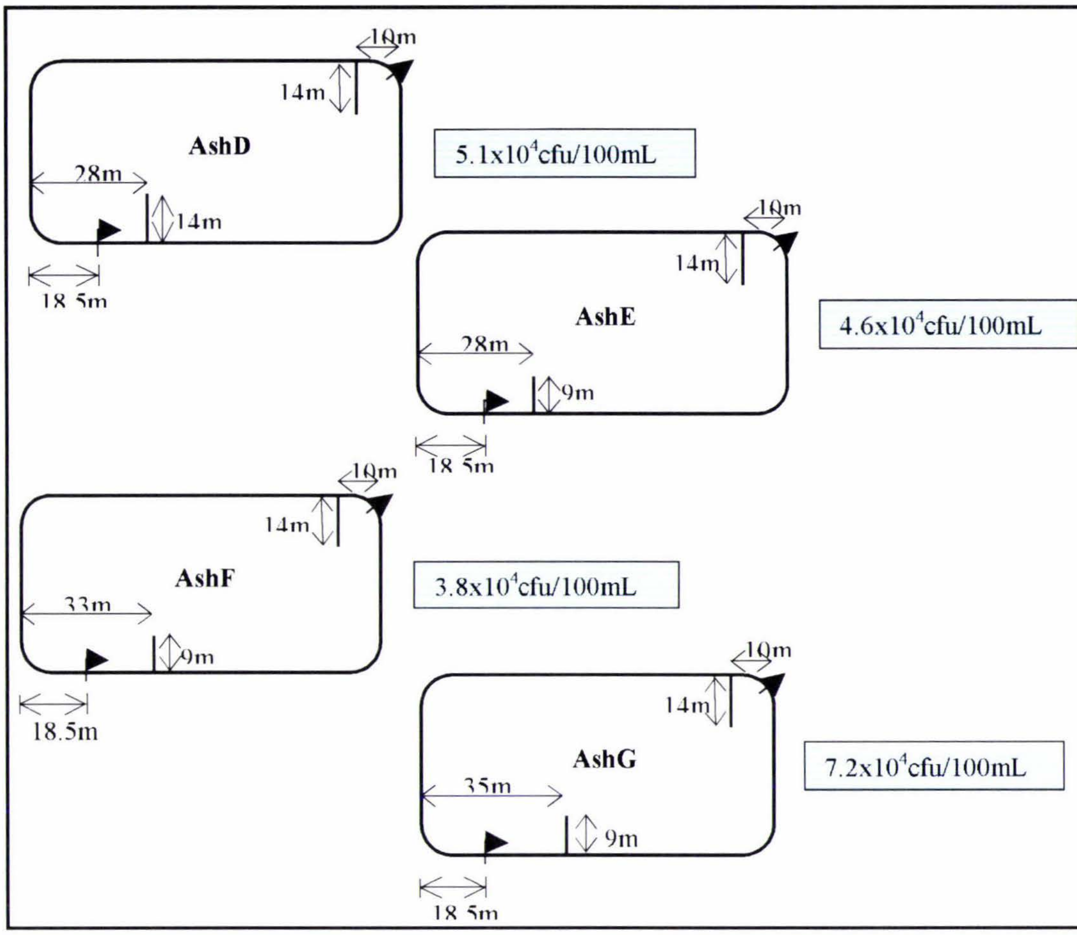


Figure 6-12 Cases AshD to AshG - Two stub baffle, inlet turned.

Cases AshD to AshG represented no significant improvement on the basic case, with only a one log reduction the coliform level. The flow patterns of each of these cases was compared against the flow pattern seen in Case 14 (two stub baffle, outlet moved). Cases AshD to Ashg, and the previous cases (AshB and AshC), did not replicate the flow patterns observed in Case 14. The way the flow moved after the end of the inlet baffle was quite different.

At this stage of the work, it was decided to start again look at each element of the pond in turn. Therefore Cases AshH, AshI, and AshJ were designed to investigate the manipulation of the inlet.

6.3.2.4. Inlet Manipulation

Cases AshH and AshI tested the effect of turning the inlet in two directions – towards the side wall closest to the inlet, and to the side wall furthest from the inlet.

Case AshJ tested the effect of creating a jetting effect by halving the diameter of the inlet.

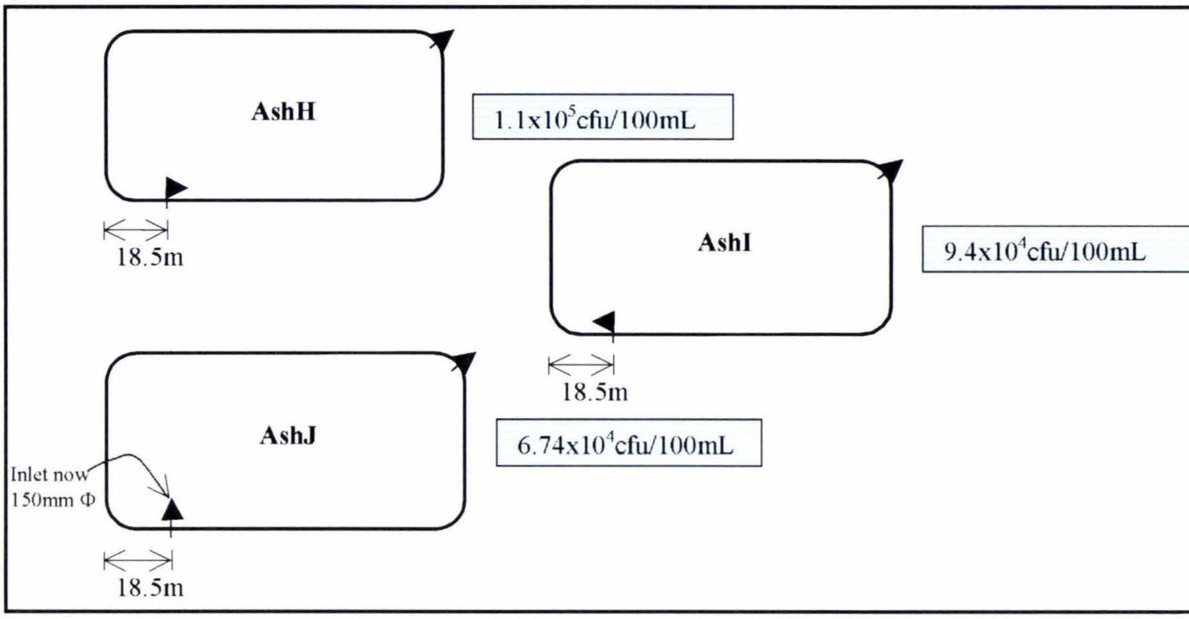


Figure 6-13 Cases Ash to AshJ - Inlet Manipulation

The manipulation of the inlet in these cases did not produce results significantly better than the base case. However, an interesting flow pattern (shown in Figure 6-14) was noted in Case AshI, which had an inlet turned into the side. The flow seemed to 'hug' closely to the walls around the pond.

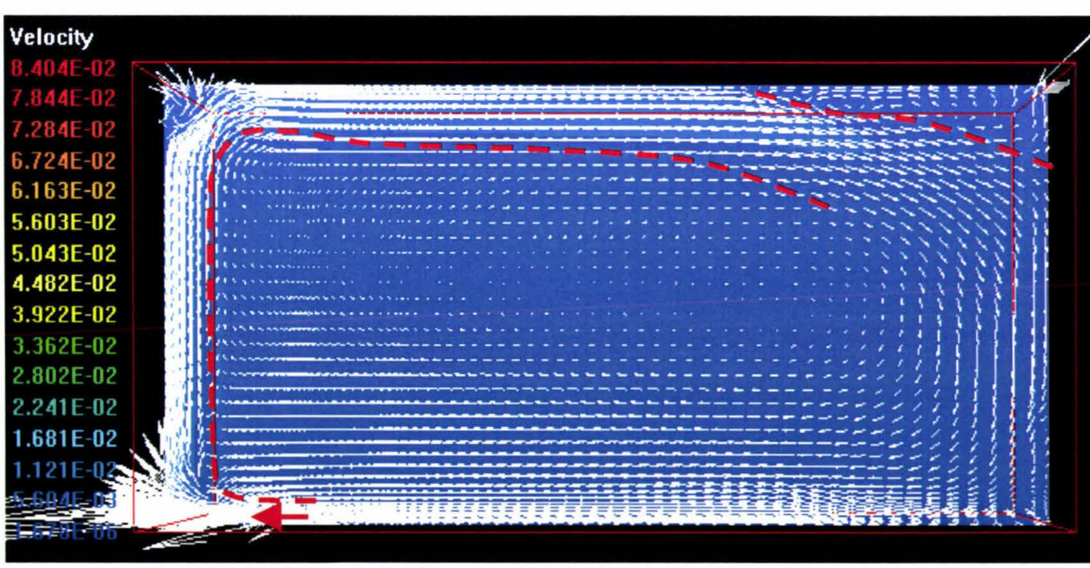


Figure 6-14 Flow Pattern - Case AshI

Upon discussion (Shilton pers. comm.), it has been determined this unique flow effect may be due to a venturi effect. The inlet jet is turbulent in nature, as the flow swirls and moves around it 'sucks in' the flow adjacent to it. In this instance, as the flow nears the wall, it then 'sucks in' to the wall, resulting in a "side attachment of a turbulent jet". Due to the turbulent nature of the flow throughout the pond, this effect is seen until two-thirds down the opposite of the pond from the inlet.

The performance of Case AshI wasn't an improvement on the basic case with respect to treatment, however the resulting flow pattern offered the opportunity to place a baffle or baffles to compliment the unique flow pattern. This was tested in Case AshK.

6.3.2.5. Combination of Turned Inlet and Stub Baffle

Due to the unique nature of the flow in Case AshI, the turned inlet was combined with a short baffle located within the 'tight' path of the flow and tested in Case AshK.

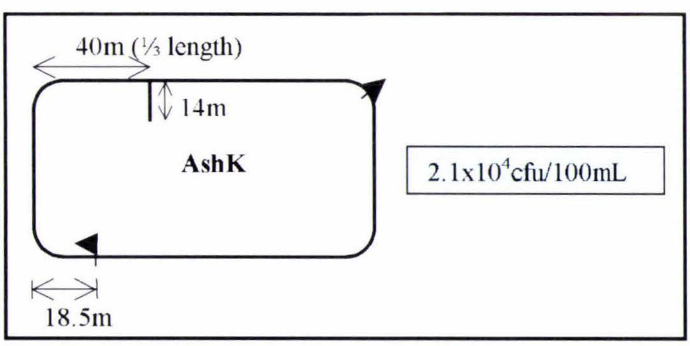


Figure 6-15 Case AshK - Combination of turned inlet and stub baffle

Case AshK was the first case that tested in the lower end of the '$x10^4$' range for coliform concentration. Cases AshL (Figure 6-16) involved the addition of an outlet baffle to 'shield' the outlet, and AshM (Figure 6-16) a repositioning of the stub, in order to optimise the treatment by the repositioning the stub baffle.

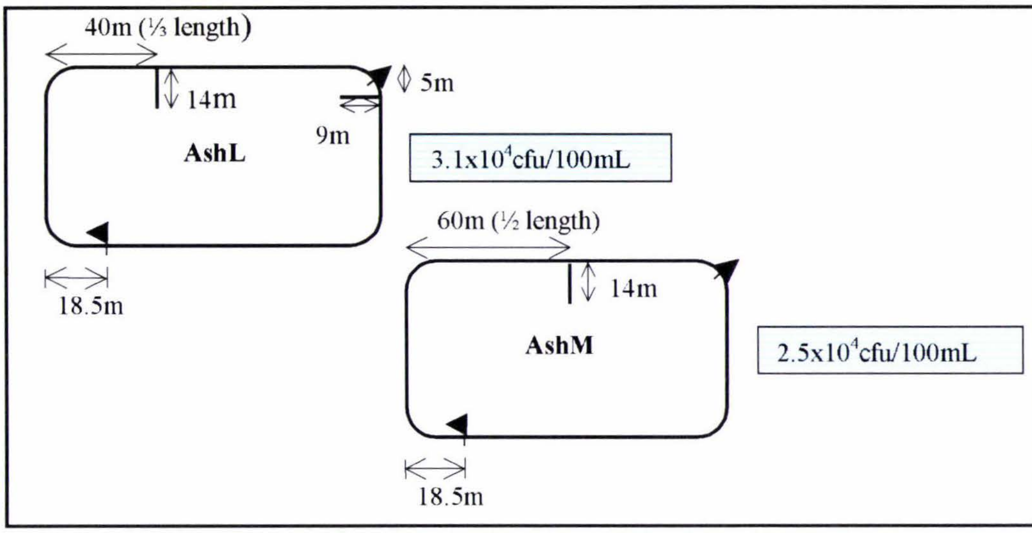


Figure 6-16 Cases AshL and AshM - Manipulations of Case AshK

As can be seen Case AshK still offered the optimum combination of turned inlet and stub baffle position. This design was considered a practical solution to implement on the Ashhurst pond, both in terms of cost and simplicity of installation. However, in order to ensure a robust research process into the optimum design solution, a series of cases testing central outlets were tested, along with a vertical inlet case, and a traditional standard length case.

6.3.2.6. Outlet Investigations

A series of cases were tested using a central outlet, Cases AshN through to AshR , and are shown in Figure 6-17.

The turned inlet (into the closest side wall) was retained from Case AshK. As can be seen in Figure 6-14, the central area of the pond has very low velocities compared to the rest of the pond. Therefore, a carefully placed central outlet may shield itself from the early exit of wastewater as it is an area of low velocity.

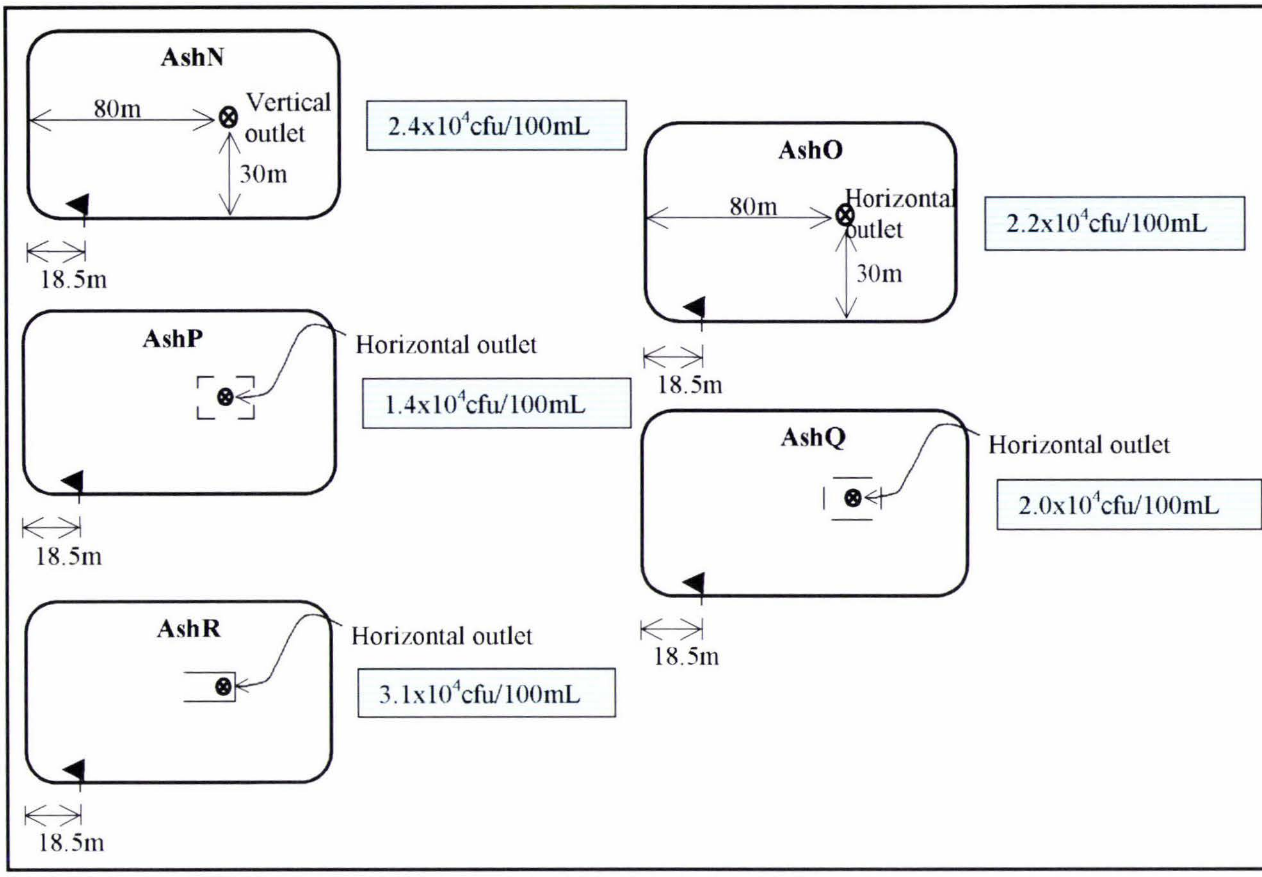


Figure 6-17 Cases AshN to AshR - Central Outlet Investigations

These modified outlet cases tested very well, particularly in Case AshP which was the lowest of those tested to that point. Cases AshO and AshQ tested with similar outlet coliform concentrations, despite the addition of baffles in Case Ash O.

The subtle change in baffle design in Case AshP was enough to improve treatment. The flow circling the outlet appears to have been affected by the 'closing' of the corners by the baffles.

Despite the good treatment offered by the central outlet cases, it was considered impractical to implement them in the field situation. Sampling equipment would most likely need to be set up in the middle of the pond to simulate an outlet, this creates difficulty with on going monitoring and changing of sampler bottl es.

6.3.2.7. Vertical Inlet plus Baffles

Attempts were made to model the vertical inlet case (as in the first field trial), however they were unsuccessful. The flow pattern (two plumes of dye moving away from the inlet) presented an opportunity to add stub baffle in the path of each dye plume – as in Case AshS.

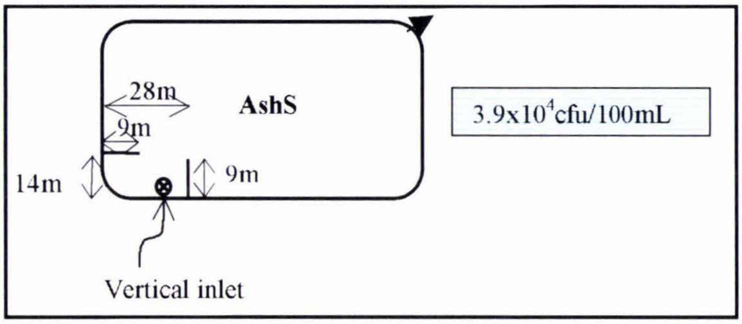


Figure 6-18 Case AshS – Vertical Inlet plus Baffles

An attempt was also made to model Case AshS and was successful. This was surprising due to the inability to model the case without the baffles. However, it is possible that the two baffles on either side of the vertical create 'churned up' flow within them, and the opening to the rest of the pond is then a wide channel that acts like a second inlet.

The case did not test as well as Case AshK (inlet turned, one stub baffle) of Case AshP (central outlet with baffles), but still offered an improvement on the basic case. The possible drawback of such a design, may be in situations of high organic load. The vertical inlet cmbined with the baffles may slow the flow to such a point that localised organic overloading may occur. In addition to this, slow flow will be more susceptible to wind effects.

6.3.2.8. Standard Length, Evenly Spaced Baffles

Finally, a case using traditional longer baffles was tested. Case 2 (Section 4.3.1) and Case L2 (Section 5.5) had produced good results in the previous work, so the same two-baffle design was applied to the Ashhurst model (AshT).

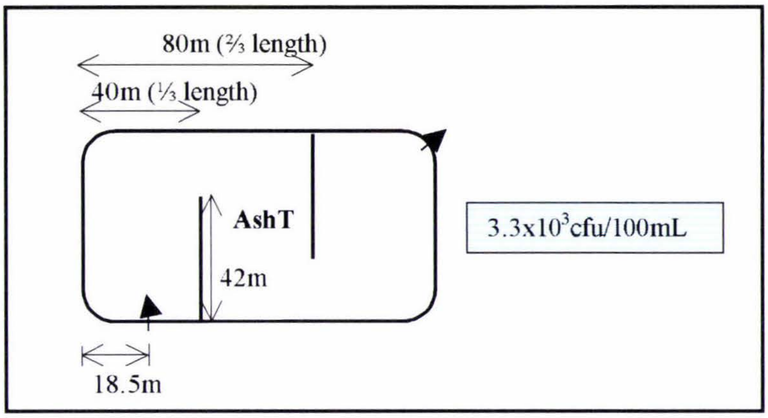


Figure 6-19 Case AshT - Standard length, evenly spaced baffles

As expected, Case AshX produced very good results, a further log reduction on all other cases tested. Similar flow patterns to the previous work (Case 2 and Case L2) were also seen. However, the cost implications of installing two 42m long baffles was prohibitive for this research study.

In summary, the design chosen for the second field trial was Case AshK. It provides the optimum balance of improvement possibility with cost and simplicity of implementation. Figure 6-20 shows the full design.

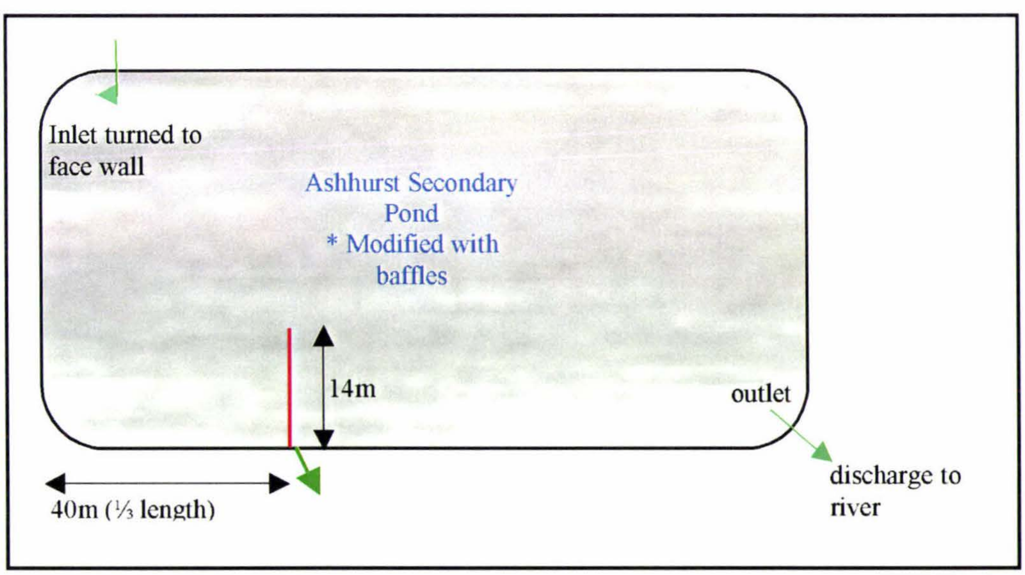


Figure 6-20 Second Field Trial Design - Ashhurst Pond

A second monitoring point was set up behind the baffle to simulate another outlet. The idea was to determine if hiding the outlet behind the baffle would be beneficial to the performance.

6.3.3. Study Conditions

As discussed in the methodology (Section 3.5), the baffle was fabricated off -site and brought to site where it was assembled and floated into position. Two auto-samplers were set-up, one at the pond outlet and a second at a point behind the baffle, as shown in Figure 6-21.

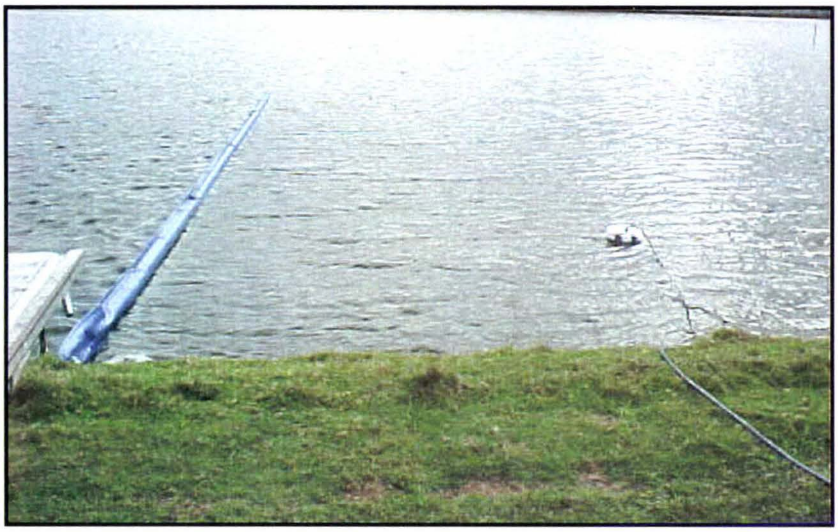


Figure 6-21 Second monitoring point - second field trial

The tracer study was started on a clear and still day. The trial was started in the winter months, so periods of unsettled weather were experienced throughout the course of the trial. For example, in the second week of the trial a period of approximately two days in which very strong winds occurred.

The tracer was observed to track along the wall from the outlet to the corner of the pond, from there, a defined line zone of dye extended down the side of the pond and around to the baffle. The following diagram, Figure 6-22, shows the pattern of dye observed over approximately the first hour.

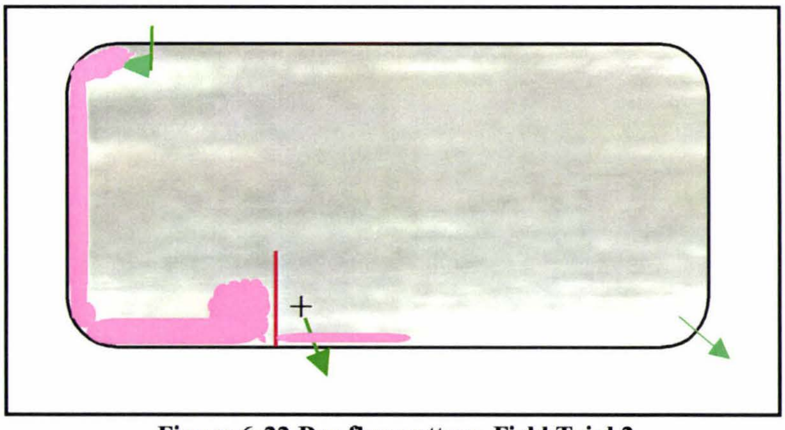


Figure 6-22 Dye flow pattern, Field Trial 2

As shown, a small amount of tracer leaked through baffle where it meets the pond wall. The design of the baffle will need to be modified before use in another field pond. This leakage of dye reached the second monitoring point behind the baffle very quickly, it also tracked down the edge of the pond to reach the main outlet. The results of the study therefore needed to be interpreted with this leakage in mind.

The defined pattern along the side-wall of the pond was similar to the defined region shown by the CFD modelling in Figure 6-14 (the flow pattern of the case with a similar inlet). The venturi effect discussed in Section 6.3.2.3, involving the rolling and swirling of the turbulent inlet flow was seen during the initial stages of the field trial. In addition, the presence of the defined flow along the side-wall corresponded to the 'side attachment of a turbulent jet' (Shilton, pers.comm.).

The outlets were monitored for tracer for a period of 63 days at both the main outlet and the monitoring point behind the baffle.

6.3.4. Study Results & Discussion

The full tracer study results for both the main outlet and the outlet behind the baffle are shown in Figure 6-23 and Figure 6-24.

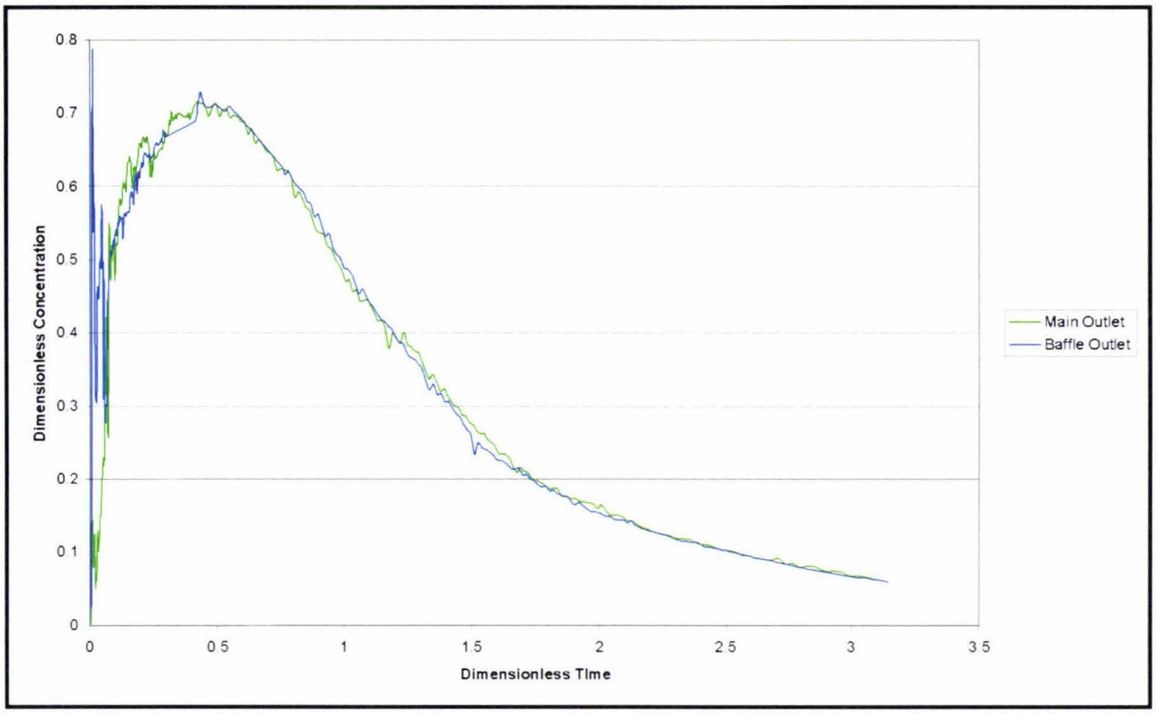


Figure 6-23 Dimensionless tracer study results - Field Trial 2, main outlet and baffle outlet, full data

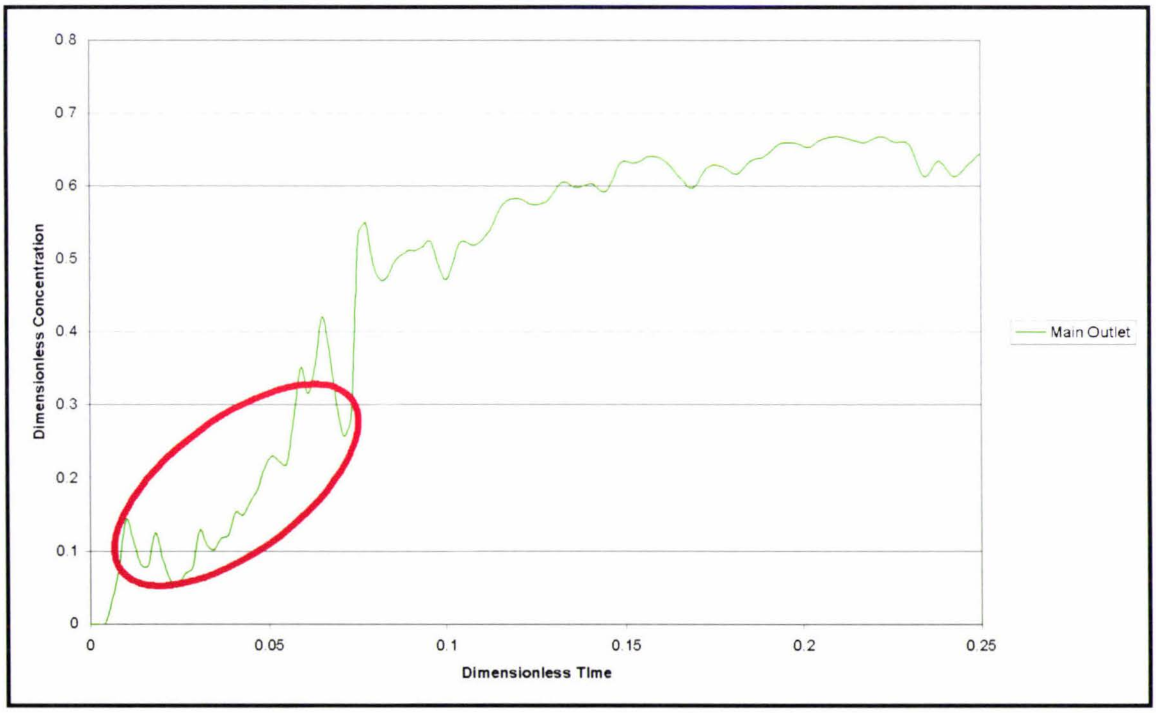


Figure 6-24 Dimensionless tracer study results - Field Trial 2, main outlet, initial data

As can be seen from Figure 6-24, tracer appears early at the outlet, this is due to the tracer that leaked behind the baffle. The red circle indicates the peaks caused by the leakage reaching the outlet. This leakage effectively ruined any chance of assessing the idea of repositioning the outlet behind the baffle with any accuracy.

To assess if the modification has improved the performance of the pond, the tracer results need to be compared with the tracer results of the un-modified pond. As mentioned previously, Shilton (2001) carried out a tracer study on the un-modified Ashhurst secondary pond in 2000. The following two figures, Figure 6-25 and Figure 6-26, show the two sets of results.

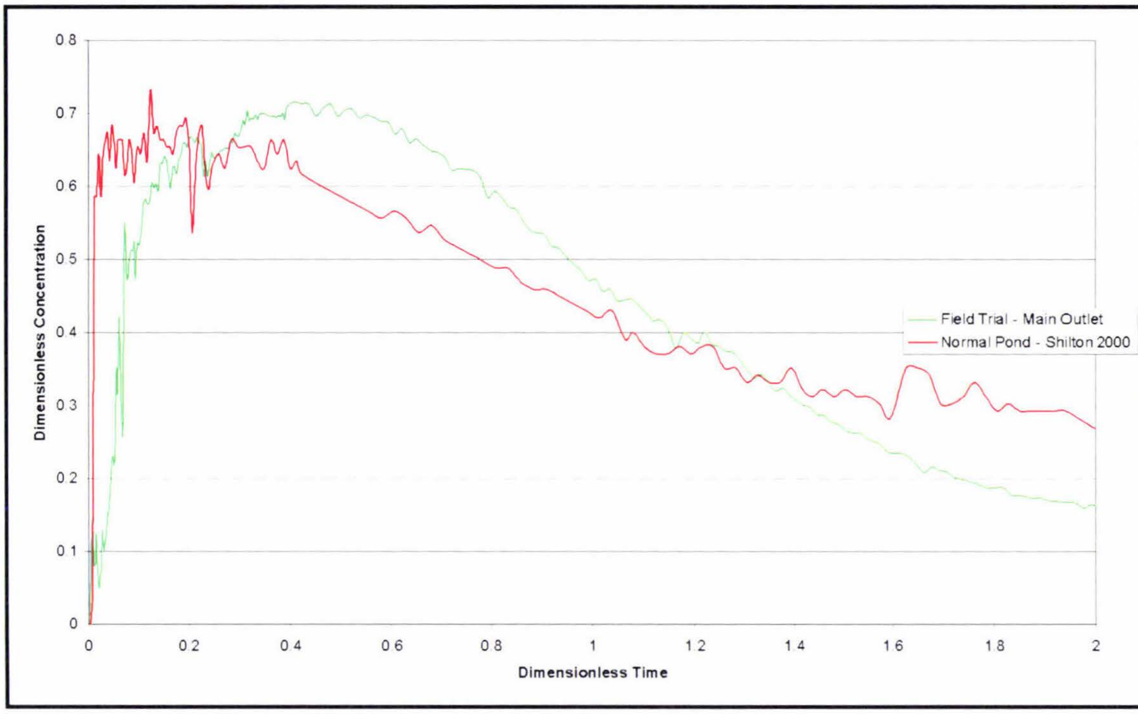


Figure 6-25 Comparison Plot - Field Trial 2 and Un-modified Pond

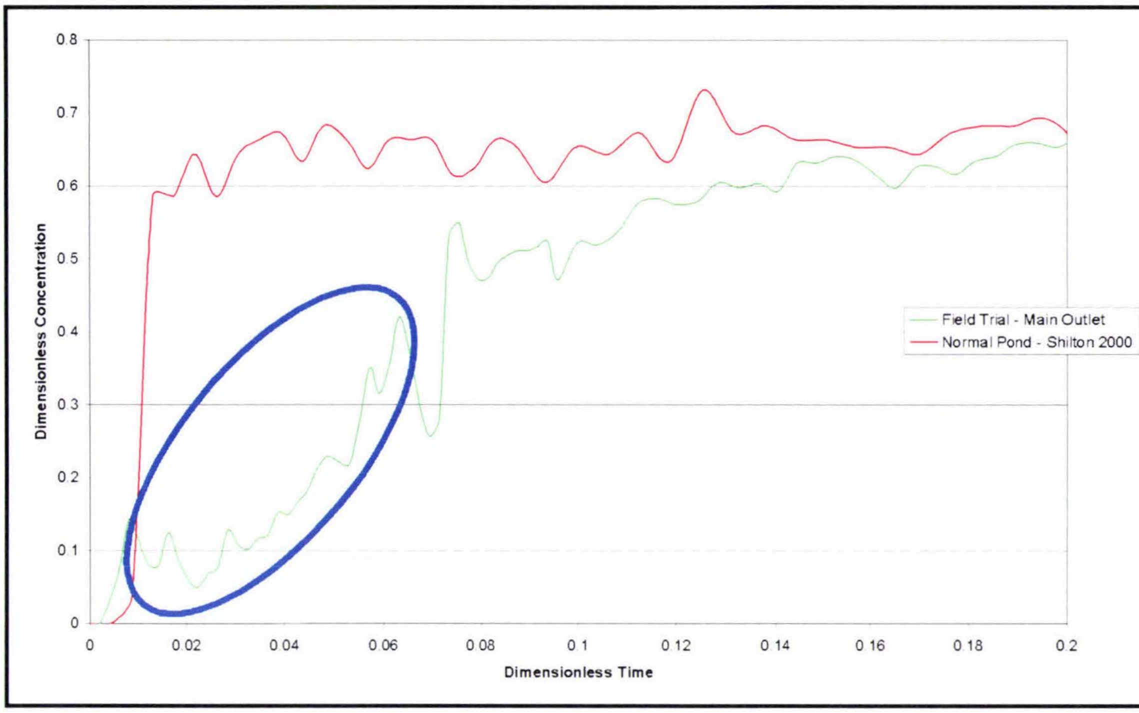


Figure 6-26 Comparison Plot - Field Trial 2 and Un-modified Pond, initial data

The results indicate that the performance of the modified pond was a significant improvement when compared with the un-modified pond. The time to the start of short-circuiting in the modified pond is increased, ignoring the effect of the leakage past the baffle, over that of the un-modified pond. Tracer is recorded at the outlet after 0.01HRT, compared with approximately 0.07HRT (again, taking into account the leakage past the baffle). The peaks are similar in size, with the tail of the modified pond drops down quicker than that of the un-modified pond.

To ensure confidence in the results, it is recommended that the trial be repeated with the baffle modified to avoid leakage. This could not be done for this work due to time constraints.

6.3.5. CFD modelling of Field Trial 2

In Chapter 5, CFD tracer studies were compared to laboratory tracer studies on the laboratory pond, in order to give further confidence to t he use of CFD to predict the step changes resulting from design modifications. As the use of CFD modelling determined the optimal design to implement for the second field trial, it is only fitting to conduct CFD tracer studies and compare the results to the actual data.

The following figure, Figure 6-27, shows the comparison of the CFD simulation against the actual results for the main outlet of the second field trial.

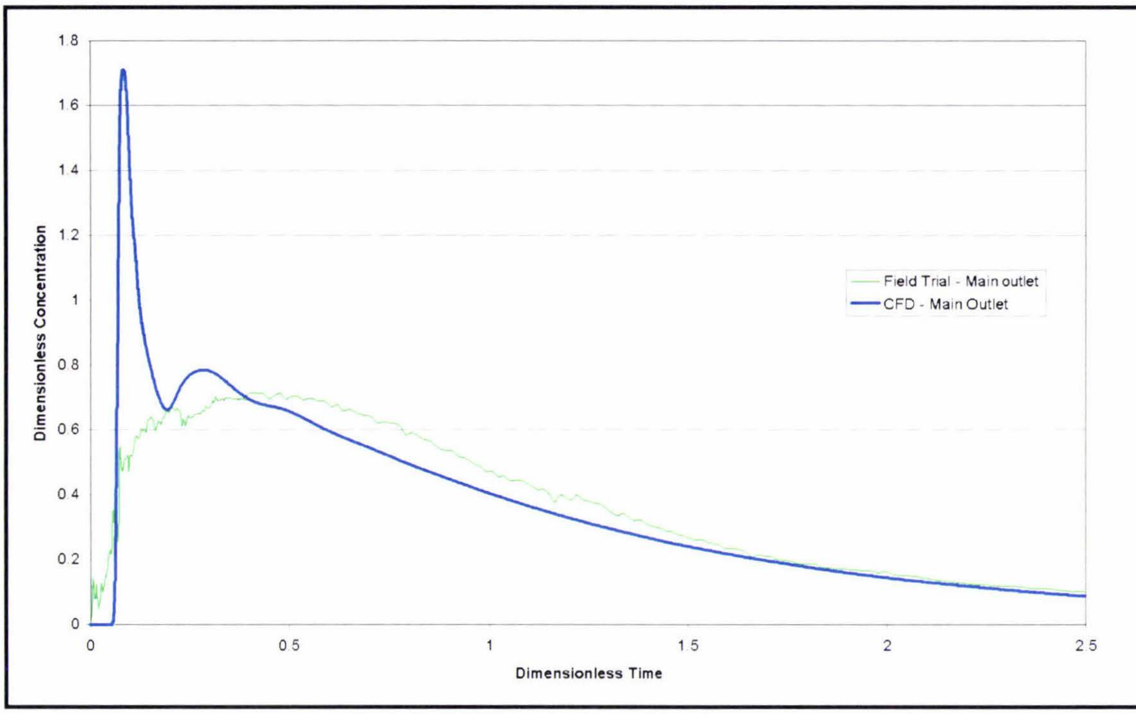


Figure 6-27 Comparison plot - CFD and actual results, main outlet, Field Trial 2

If the leakage behind the baffle is taken into account, then CFD model predicts the time to the start of short-circuiting very well.

The peak of the CFD curve is somewhat higher than that of the actual results. This indicates that the initial pulse of tracer is not very well mixed in the CFD model. Conditions such as wind and influent flowrate, may allow the initial pulse of tracer to be dispersed in the field pond, hence the lower peak. The CFD model assumes a constant flowrate and no wind, and may therefore predict a very defined flow path throughout the bulk of the pond.

The repositioning of the outlet behind the baffle was modelled using CFD; the results are compared to those of the main outlet in Figure 6-28.

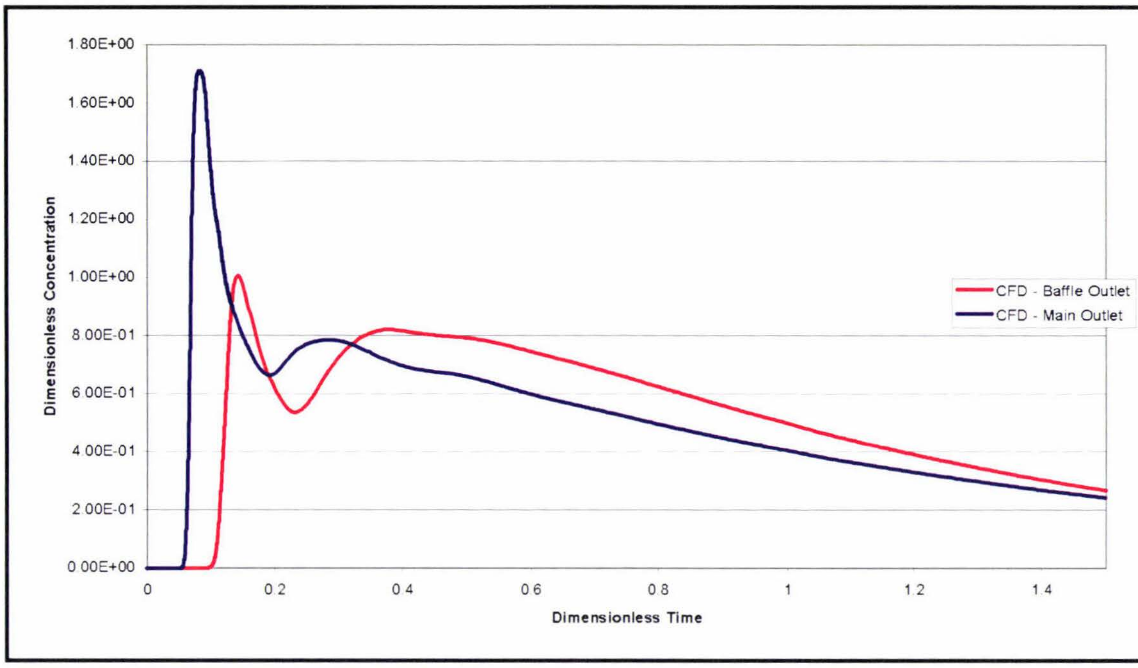


Figure 6-28 Comparison plot - CFD results, main and baffle outlets, Field Trial 2

The shape of the curve of the baffle outlet curve is similar to that of the main outlet. The initial peak is lower; this may be due to the extra distance the tracer travels to reach the baffle outlet, which allows the initial pulse of dye to disperse. Both models predict the similar flow patterns; therefore the position of the outlet does not alter the flow pattern, but simply delays the exit of the tracer.

6.3.6. Treatment Efficiency

The method described by Levenspiel (1972), using the standard 'k' value, has been used to determine the treatment efficiency of the modified pond, and the un-modified pond using the data of Shilton (2001). In addition to this, the un-modified pond was modelled as part of this work with the addition of coliforms. The data is presented in the following table, Table 7.

Table 7- Treatment Efficiency Data, Ashhurst Pond

Pond	Inlet Coliform Concentration (cfu/100mL)	Predicted Concentration at Outlet (CFD)	Calculated Concentration at Outlet
Un-modified Pond (Shilton 2001)	$8.66x10^5$	$1.30x10^4$	$1.29x10^4$
Field Trial 2, Main Outlet	$8.66x10^5$	$2.10x10^4$	$1.10x10^4$

As can be seen the CFD modelling has predicted the coliform concentration at the outlet very well, when compared with the value calculated using the experimental data. This provides confidence in the use of coliform concentration as an appropriate method of assessing the CFD models.

6.4 Chapter Summary & Discussion

The undertaken of field studies is time consuming and due to variable environmental conditions prone to problems. In this work, two field studies have been undertaken, with results that have shown the benefits or lack of, implementing design modifications.

The implementation of a vertically upturned inlet on the Ashhurst did not show an improvement in efficiency. However, it is likely that weather conditions had an affect on the final result. Despite this, the flow pattern observed is similar to that seen in the CFD modelling of a large-scale theoretical pond in Chapter 4, the laboratory and CFD modelling of the laboratory pond in Chapter 5, and in research carried out on a water reservoir with a vertically down-turned inlet (Shilton *et al.*, 2000a). This provides confidence in the results of the methods used to test the vertical inlet.

CFD modelling was used as a research tool to test a wide range of designs on the Ashhurst pond prior to implementing a design in the second field trial. The results of the second field trial have shown that the modification implemented has resulted in an improvement of the performance of the pond. In addition to this the results of the CFD tracer study compares well with the actual results. The use of coliform concentration to assess the effectiveness of each design has also been tested with good results. The values for outlet coliform concentration calculated using the experimental data match extremely well with the CFD predicitons.

CFD modelling has proven to be effective as a tool for determining a practical design modification. It allows the researcher to assess the performance of different pond modifications in a timely manner, prior to committing to an expensive and timely field trial.

7. DISCUSSION

In this section, the work is discussed in terms of the objectives set out in Section 1.2. It also links the finding of this work with previous research as reviewed in Section 2.

The objectives of this work are repeated below:

- To investigate the use of baffles in waste stabilisation ponds in terms of:
    - Length of baffles
    - Number of baffles
    - Position of baffles
- To investigate the effect of inlet type, and outlet position
- To evaluate the use of CFD as a design tool to investigate various baffle configurations
- To apply the findings of the work into the field environment

This chapter follows through the discussion of these objectives. In addition other findings of this work are discussed.

7.1 Baffles in Waste Stabilisation Ponds

The application of baffles in waste stabilisation ponds was a key focus of this work. While a lot of this work was carried out in the CFD environment, it has also been tested in the laboratory and field settings. This work produced some interesting insights into the interaction of flow with baffles in the pond. This is discussed in Section 7.4. In this section, the effect of baffles on the efficiency of the ponds will be discussed in terms of the three important factors - length, number and position.

7.1.1. Length of Baffles

One of the only major pieces of research to look at the effect of baffle length on efficiency was Watters *et al.*, (1973). Their work used three different baffle lengths, 50%, 70% and 90% of the width of the pond. Each baffle length was tested using two, four, six and eight baffles, evenly spaced along the length of the pond.

Watters *et al.*, (1973) found that the 70% baffles were the most efficient; they concluded that there is a channelling effect produced by the 90% width baffles. The length of the baffles causes the flow to speed up around the end of the baffle, as the flow is restricted. Watters *et al.*, (1973) depicted this effect in Figure 4-7.

The laboratory work undertaken for this thesis produced a similar looking flow pattern in a pond utilising 6 baffles that were 70% of the width of the pond. This led to the conclusion that the channelling effect seen in 90% width baffles may not be entirely due to the baffle length.

In the CFD modelling undertaken on a theoretical pond (Chapter 4), four of Watters *et al.*, (1973) configurations were tested. These were 2, 4, 6, and 8 baffles, 70% of the width of the pond. The measure of efficiency for the CFD work came in the form of the concentration of coliforms at the outlet. Another case involved 1 baffle, again, 70% of the width of the pond. A plot of number of baffles versus the coliform concentration at the outlet is shown in Figure 7-1.

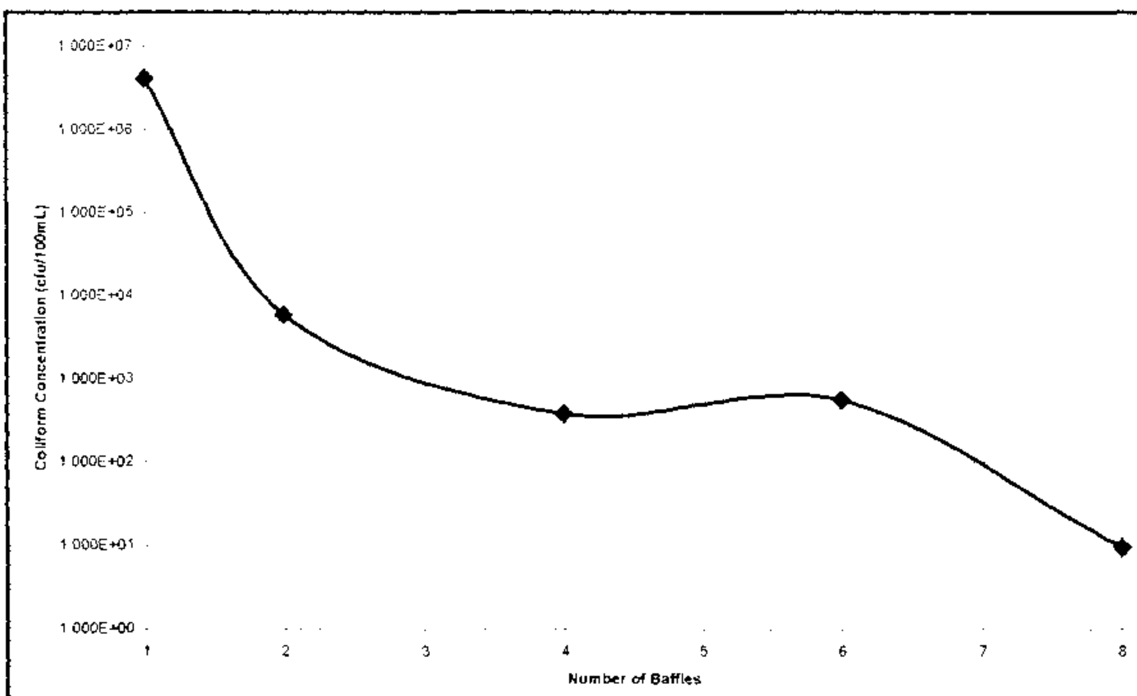


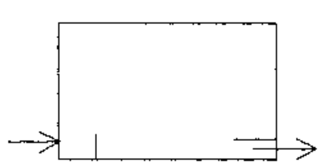
Figure 7-1 Number of Baffles versus Coliform Concentration at outlet

The y-axis has a logarithmic scale. As can be seen, one baffle does not afford very good treatment, two baffles is significantly hetter. However, t he treatment efficiency achieved for the four and six baffle cases are very similar. It then takes a doubling of the number of baffles, from four to eight, to achieve treatment improvements.

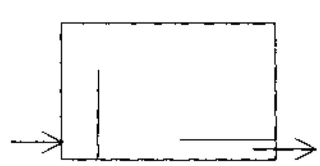
The predicted flow pattern in the CFD models of the theoretical pond, and the laboratory run on the six baffle case indicate that two different flow patterns, circulating flow and channelling flow, are present. In the four and six baffle cases a mixture of these two types of flow is seen. In the two and eight baffles cases, either the circulating or the channelling flow is present.

It was decided to test whether the baffles needed to be long. Watters *et al.*, (1973) found that significant short-circuiting occurred (as depicted in Figure 2-9) that reduced efficiency. However, they did not test significantly shorter baffles. Therefore shorter baffles of 15% of the width were tested in this work.

The traditional design of baffles, evenly spaced along the length of the pond, was considered inappropriate with considerably shorter (stub) baffles. Therefore the position of shorter baffles was carefully considered. Cases 14 and 15, tested o the large-scale theoretical pond in Chapter 4, illustrate the effect of short baffles compared with long baffles.



Case 14



Case 15

The modelling showed that Case 14 performed better than Case 15. In fact, Case 14 was better by 1 log reduction of coliforms. The reason the stub baffle performs well is that it acts to disperse momentum. A tight circulation is set up in the inlet corner, and once past the inlet baffle, the flow has the bulk of the pond in which to further disperse the momentum. The tight circulation in the inlet corner also allows the corner act like a wide channel inlet.

However, the stub baffle is very sensitive to minor design changes. Case 16 involved the same inlet baffle and outlet positioning of Case 14, except the outlet baffle was moved. The removal of the outlet baffle resulted in a worsening of the coliform concentration by 2 logs. In addition to this when Case L14 and L15 were tested on the laboratory pond, the times to the start of short-circuiting were very similar. Indicating that the standard length baffles worked as well as the stub baffles.

The potential of stub baffles has been highlighted, however it has also been shown that they may not work in all cases.

7.1.2. Number of Baffles

Many researchers (Watters *et* al., 1973; Lloyd *et* al., 2002; Persson, 2000; Pena *et al.*, 2002 are of the same conclusion that 'the more baffles the better'. Watters *et al.*, (1973) showed that with 70% width baffles, an increasing number of baffles resulted in an improvement in efficiency. The CFD modelling for this work has also indicated this. In Figure 7-1, it was shown that an increasing number baffles resulted in increasing treatment efficiency.

In the CFD modelling of a theoretical pond in Chapter 4, (Cases 7 to 12) a single baffle was not generally effective. In most cases, the inclusion of the single baffle did not result in any improvement on treatment efficiency. In only one case (Case 11), which involved the moving the outlet in conjunction with the positioning of the baffle, were any minor improvements in treatment efficiency noticed. In general, a minimum of two baffles will be required to achieve measurable gains in treatment efficiency.

While single baffles were not generally effective in the modelling of a theoretical pond, the Ashhurst field studies showed a single baffle in conjunction with other design changes could be effective. The combination of a single short baffle with a modified inlet resulted in an improvement over the un-modified pond. However, the CFD modelling undertaken on the field pond indicated that the use of two standard baffles would have resulted in a much greater improvement in efficiency.

It has been shown that in general, a minimum of two baffles will be required to achieve measurable improvements in pond performance.

7.1.3. Position of Baffles

The addition of baffles will generally offer an improvement over an un-baffled pond. The extent of this improvement is a factor of the length and position of that baffle. In conjunction with length, the positioning of any baffles is vital to maximise the hydraulic and treatment efficiency.

As discussed in Section 7.1.1, the CFD modelling of a theoretical pond showed that an inlet stub baffle acts to disperse inlet momentum and can be used to redirect flow into a desirable direction.

The stub baffle can also be used as in the second field trial. In that instance, a turned inlet produced a flow pattern that 'hugged' the walls around the outside of the pond, a stub baffle was placed in the path of this flow on the opposite of the pond to the inlet. This resulted, in an improvement in the pond performance. Near outlets, a stub baffle may effectively 'hide' the outlet and delay the effluent exiting before a reasonable level of treatment has been achieved.

7.1.4. Traditional versus Innovative Baffle Design

The use of the traditional baffle designs, that is, longer baffles evenly spaced, is effective. However the required length of baffling may be cost prohibitive. Also, while the traditional two-baffle case offered significant improvement, the traditional four- and six-baffle cases only offered a 1-log improvement on the two-baffle case. To achieve significant improvements in efficiency over the two baffles case, the jumps needed to be made to the eight-baffle case, which was 3-log better than the two baffle case.

As has been shown with Case 14 (two stub baffles, outlet moved), the innovative placement of two stub baffles resulted in a similar treatment efficiency gain to the traditional two-baffle case. Also, the use of a stub baffle in a 'non-traditional' position resulted in efficiency gains. However, it has also been shown that stub baffles can be very sensitive to design changes.

7.1.5. Final Evaluation

The length, number and position of baffles in a pond will be dependent on two factors – the individual characteristics of the pond, and cost.

The use of long baffles in traditional, evenly spaced baffle layouts, provide a consistent improvement in the treatment efficiency of a pond.

Stub baffles have been shown to achieve treatment efficiency gains in certain situations, however they are very sensitive to design changes.

The number of baffles within a pond will mainly be dependent on the cost. In general, single baffles are not effective. In general, a minimum of two baffles will be required to achieve measurable improvements in pond performance.

Positioning of baffles in waste stabilisation ponds is dependent on the length and number of baffles used, and the individual characteristics of the pond and its inflow.

The optimal position for baffles, as well as length and number, will be dependent on the individual site characteristics. What is also important is the interaction of flow with the baffles, and other elements in the pond.

7.2 Effect of Inlet

It is generally accepted in previous research (Watters *et al.*, 1973; Moreno, 1990; Shilton 2001) that the inlet plays a major role in determining the movement of the bulk fluid of the pond.

7.2.1. Diffuse Inlet

The diffuse inlet tested in Chapter 4 (Case 18) did not offer any improvement on the basic case (Case 1). However, it must be noted that in relation to the full width of the pond, the diffuse inlet – while larger than a standard pond inlet – was still a relatively narrow inlet compared with the width of the pond (2m wide inlet, 320m wide pond). Work that has been conducted, on multiple or diffuse inlets, that extend the full width of the pond, has been successful. For example, Persson (2000) found that multiple inlets along the front wall of the pond proved extremely effective in reducing short-circuiting and dead volume. The use of multiple inlets in the field may present some practical problems: if flow is slowed too much localised organic overloading may occur; the use of multiple inlets may increase the maintenance and operation required in what is normally a low-maintenance, low operation system. Because of the practical drawbacks of this form of inlet design, it is not recommended for primary and secondary ponds. However, it may be beneficial when used in maturation ponds.

7.2.2. Vertical Inlet

The vertical inlet was investigated in the initial CFD modelling (Chapter 4), again in the laboratory (Chapter 5), and finally in the first field trial (Chapter 6). The initial CFD modelling was not successful. However it is a simple and economic upgrade and was considered appropriate to continue with in the investigations.

The laboratory run (Case L17, Section 5.10) showed that both the time to short-circuiting and the size of the slug of tracer first exiting could be reduced. Two plumes of dye could be seen radiating away from the inlet and around the edge of the pond.

This flow pattern was also exhibited in the attempted CFD modelling of this case. The dye travelled away from the inlet in either direction, following the edges of the pond. The CFD model still had a large degree of residual error, despite this; the results could still provide some clues as to the flow path.

The flow pattern was again seen in the field trial involving the vertical inlet. There was an extension of two plumes in either direction from the inlet. The results from the trial did not indicate any improved hydraulic efficiency in the Ashhurst pond. As a possible explanation for this, periods of high wind and rainfall were experienced throughout the course of the field trial.

In the modelling for the second field trial, the addition of baffles on either side of the vertical inlet was tested successfully with good results. The level of coliforms at the outlet was predicted to be *$3.92x10^3$ cfu/100mL* (inlet value = $8.66x10^5$cfu/100mL), which was one of the best results found in the modelling exercise. The baffled inlet area acted like a wide channel inlet. However, the practical aspects of the design needed to be considered.

For a sheltered pond site, with an influent without a low organic load (for example, a maturation pond), this inlet may offer an appropriate solution for modification. If the organic load is too high, the inlet region may cause localised organic overloading.

The vertical inlet, while not proven effective in the field trial performed for this work, is still considered a cost-effective modification for the appropriate site. In the laboratory, the use of the vertical inlet increased the time to short-circuiting from 2 minutes to around 24 minutes. This is a considerable 'step-change' on the basic case.

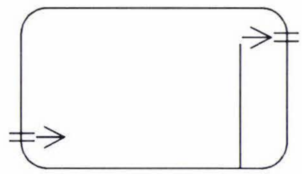
7.2.3. Final Evaluation

In conclusion, the consideration of the inlet in a pond is extremely important. Whatever inlet structure is chosen, horizontal, vertical, or diffuse, will have a significant impact on the bulk fluid flow within the system.

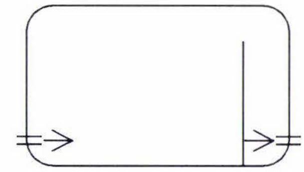
7.3 Effect of Outlet

Previous work has investigated or discussed different inlet and outlet configurations (Watters *et al.*, 1973; Moreno, 1990; Fares *et al.*, 1996; Persson, 2000), but not focussed on the outlet in detail. Shilton (2001) investigated the effect of different outlet positions on the bulk fluid flow and found there to be negligible effect on the bulk fluid flow pattern. The conclusion made was that the outlet is a secondary function to that of the inlet, baffles, and shape. That is, after the inlet has been positioned and baffles positioned accordingly, the outlet can then be placed to achieve the greatest benefit without altering the bulk flow pattern.

In practise baffles are often positioned with little consideration of the inlet/outlet placement. In this work, the position of the outlet was moved in relation to the flow patterns exhibited. This importance of the outlet position was shown when Cases 10 and 11 were modelled.



ase 10



Case 11

These two cases involve the same inlet, and baffle type, and position. The only distinguishing feature is the position of the outlet. Case 6b resulted in an outlet coliform concentration of *$4.56x10^6$cfu/100mL* (inlet = $1x10^8$cfu/100mL). Case 6c resulted in an outlet concentration of *$8.00x10^5$cfu/100mL* a further log reduction on Case 6b.

This is further emphasised by the fact that one of the most efficient and cost-effective designs was Case 14 (two stub baffles, outlet on the same side of the pond as the inlet). This used two short baffles coupled with the moving of the outlet to the same side of the pond as the inlet.

To further test the effect of outlet position, the second field trial involved monitoring of the pond outlet, and the setting up of a second sampling point for tracer. While this act as a second outlet to the pond – it serves as an indication of the advantages or disadvantages of placing the outlet at that point. The CFD modelling of the Ashhurst pond that showed the second monitoring point as having a greater time to the start of short-circuiting than that the actual outlet. The field results however, show similar times to the start of short-circuiting because some tracer was able to leak through the baffle.

7.3.1. Final Evaluation

The position of the outlet can have a significant effect on the effluent quality. This supports the work undertaken by Shilton (2001).

7.4 Flow Mechanisms and Interaction

It is important to investigate the impact of inlets, outlets and baffles on the efficiency of waste stabilisation ponds. However, definitive statements cannot be made as to what is the 'perfect' combination of these that will apply to any pond system.

7.4.1. Does the same design work for all ponds?

In the initial CFD work, Case 14 (Section 4.6.2), which consists of two stub baffles, one located near the inlet and one near the outlet, proved to be an effective and cost-effective design. In addition to this, the Case 14 design was tested using full length baffles in Case 15, which did not perform as well. The Case 14 design was then pursued in the laboratory testing (Chapter 5).

In the laboratory testing, it was found that Case L14 produced similar result to that of Case L15. Therefore, the pond in Case L14 (laboratory model) did not act in the same way as for Case 14 (large-scale theoretical model). This is due to the different conditions, such as HRT, inlet momentum, that exists in each pond.

Therefore, it cannot be assumed that what works for one pond will work for another.

7.4.2. Channelling - Baffles

The laboratory work undertaken, tested two cases previously tested by Watters *et al.*, (1973): two, and six, 70% width baffles. As was expected, the six baffle case produced a much longer time to short-circuiting, and as it was a closer approximation to plug-flow, a higher peak resulted. What was interesting to note was the flow patterns within each 'cell' (i.e. slice of the pond between baffles). The first two cells of the six-baffle case (Case 4) are shown in Figure 7-2. A distinctive pattern can be seen, and has been described as a 'channelling flow'.

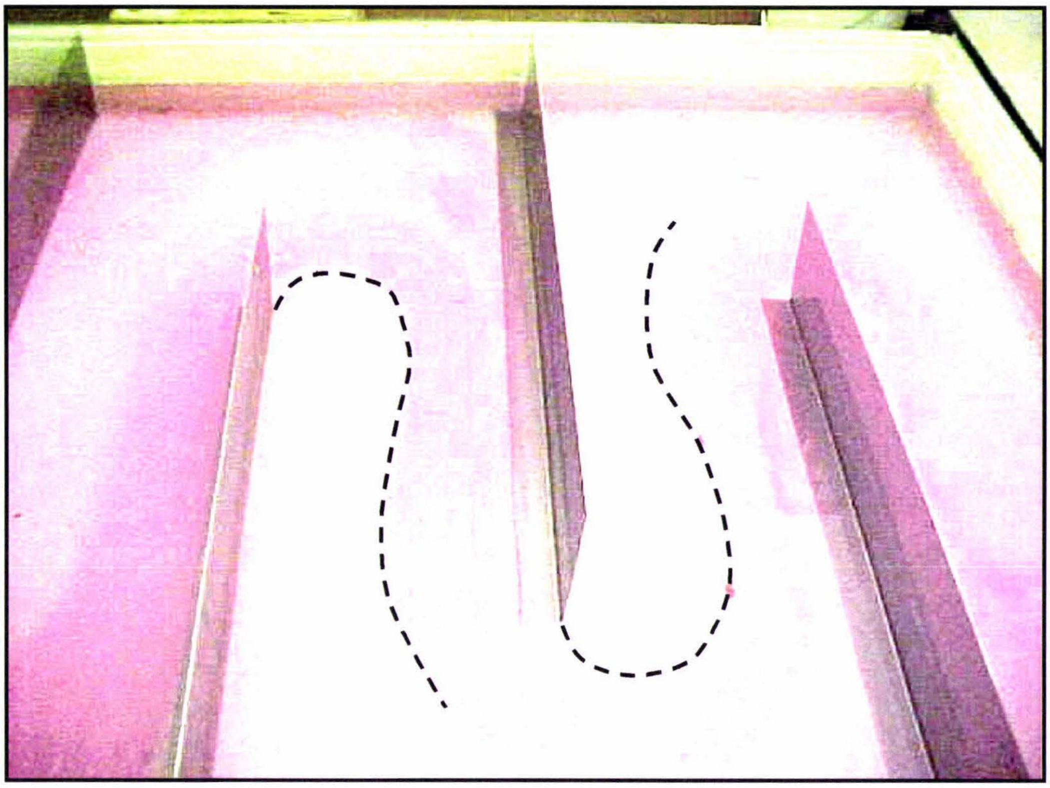


Figure 7-2 Flow pattern within each cell, 6 baffle case (Case 4)

The following figure depicts the phenomenon described by Watters *et al.*, (1973) which was used to explain why 90% width baffles did not perform as well as 70% width baffles.

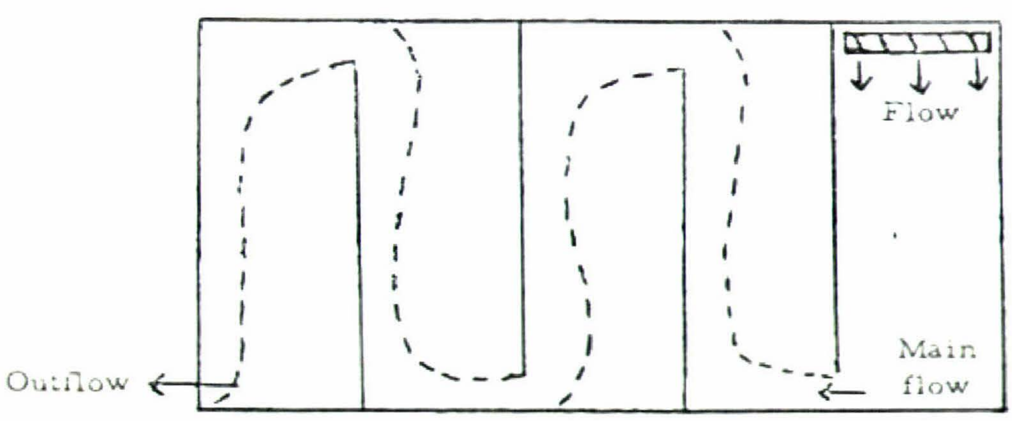


Figure 7-3 Channelling caused by 90% width baffles (Watters *et al.*, 1973)

This channelling effect was attributed to the 'speeding up' of the flow around the end of the 90% baffles. The speeding up was due to the narrow gap between the end of the baffle and the wall.

In the case of the six baffle laboratory run, this phenomenon was seen when **70% width** baffles were used. This has lead to the idea that it is the distance between the baffles was the determining factor for the flow pattern. This conclusion was further emphasised upon seeing the dye pattern (Figure 7-4) at the outlet ends of Case 15 (two long baffles, outlet moved).

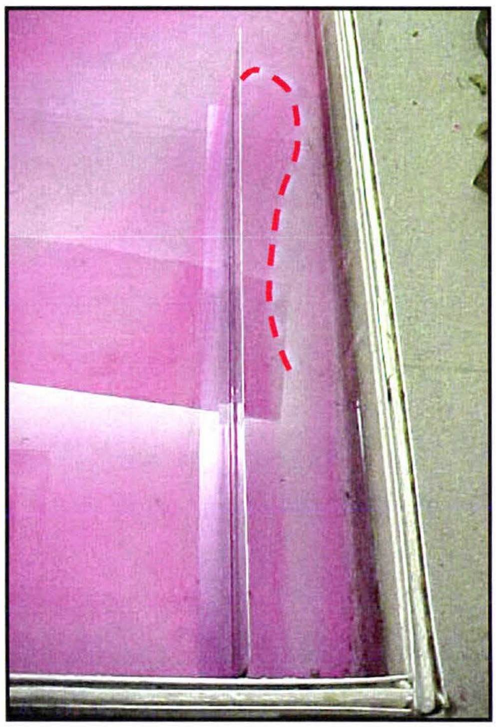


Figure 7-4 Outlet end of Case 15 (two long baffles, outlet moved) showing channelling pattern

The photos show the channelling effect clearly, and in this case it cannot be attributed to the narrow gap present at the end of the baffle. The outlet baffle is parallel to the length of the pond and there is a large gap between the end of the outlet baffle and the inlet baffle. Therefore, the channelling effect most likely the proximity of the baffles to the wall, and in Case 4 (traditional six baffle case) – to each other.

In the CFD modelling undertaken on the large-scale theoretical pond in Chapter 2, this channelling flow was not exhibited in Case 2 (two evenly spaced baffles, standard length). Instead, each cell was well mixed before dye was seen mixing into the next cell, a circulating flow.

In the CFD modelling for cases 3, 4 and 5, (four, six and eight 70% width baffles) the channelling flow is seen in the last cells. What is interesting is that in Cases 3 and 4 (four and six baffles), this pattern is not dominant until the third cell.

The two-baffle and eight-baffle cases contain either the circulating or channelling flow respectively, while the four- and six baffle cases contain both types of flow. Therefore, there is a transition period in which neither type of flow is dominant. This explains why the four and six baffle cases produced approximately the same treatment efficiency. Figure 7-5 shows the plot of baffle number versus coliform concentration at the outlet. It shows a flat point in the curve at the four and six baffle points.

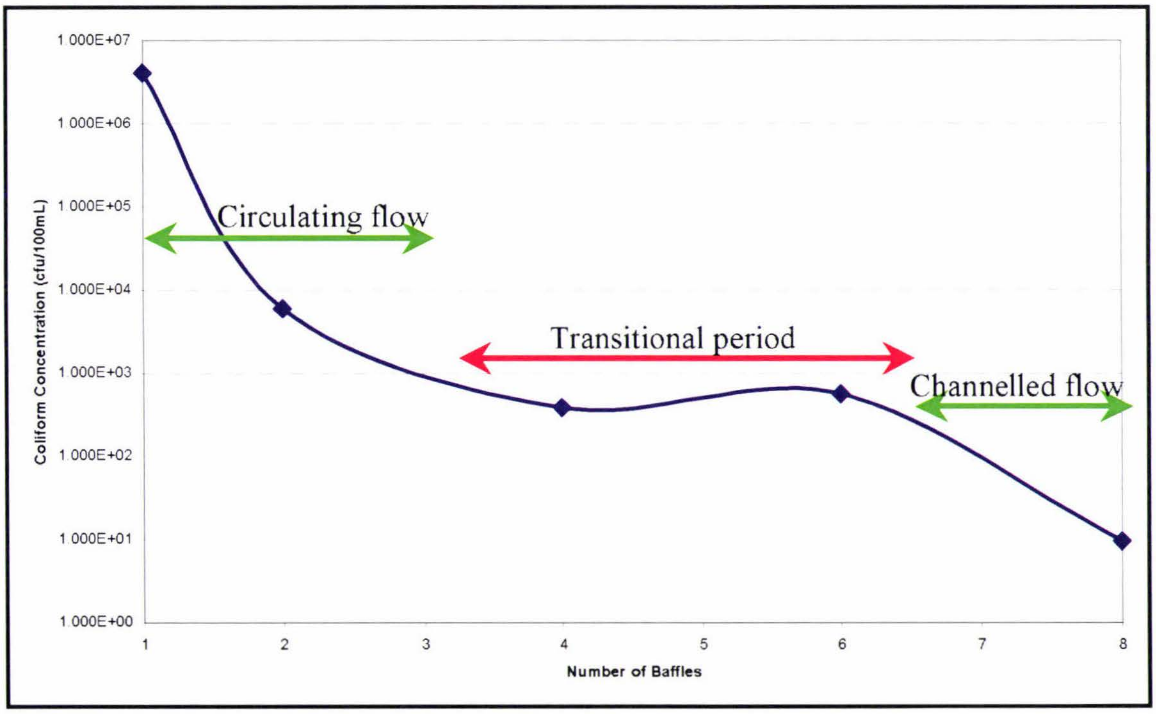


Figure 7-5 Number of baffles versus outlet coliform concentration, CFD modelling, Chapter 4

It is believed that this plot illustrates the transition from circulating flow through to channelled flow, with a transitional period (i.e. where neither mixed or channelled flow is dominating). Therefore to gain a significant measure of treatment improvement, then the design must 'jump' from two baffles, to eight baffles. This therefore significantly increases the cost.

7.4.3. Channelling – Interaction of Inlet and Walls

As a result of the CFD modelling for the Ashhurst second field trial, some new insights have arisen into the interaction of flow with walls and baffles. In the initial stages of the modelling for the field trial, the inlet was turned into a baffle. This was an attempt to recreate the 'front-end' of the pond, and so the pattern seen in Case 14 (two stub baffles, inlet and outlet on same side of pond).

The modelling of the modified inlet showed an interesting, almost channelled flow around the end of the pond and continuing along the opposite wall from the inlet. This is shown in Figure 7-6.

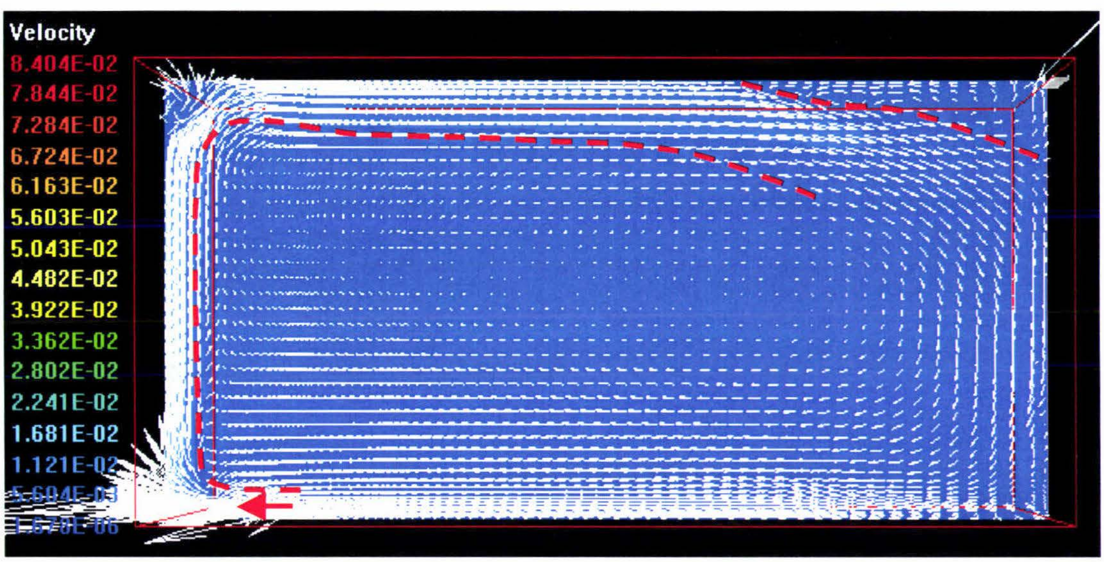


Figure 7-6 Ashhurst model, inlet turned into side wall

As can be seen the flow is held very tightly against the wall until midway down the opposite wall. While the treatment was still not of a high enough standard to justify this inlet modification only, it potentially useful in terms of controlling flow. It suggests that channelling of flow can be achieved without the addition of baffles.

The addition of a baffle one third of the way down the opposite wall, however, did improve the treatment seen in the model. The following figures (Figure 7-7 and Figure 7-8) show the flow pattern and the resulting coliform concentrations. The coliform concentration was approximately $2x10^4$cfu/100mL (inlet = $8.66x10^5$ cfu/100mL). This concentration, while not the desirable extra log reduction on the basic case (Case 1), was in the low end of the 10^4 range. This was one of the lowest concentrations achieved while still being economic to consider as an upgrade option.

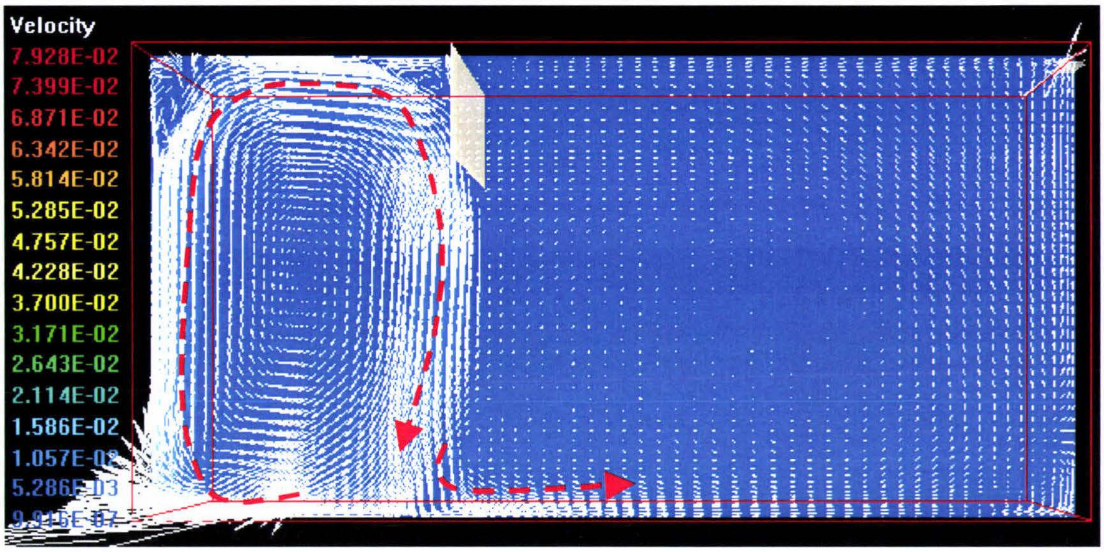


Figure 7-7 Ashhurst, inlet turned back to wall, 14m baffle located 1/3 length from end wall

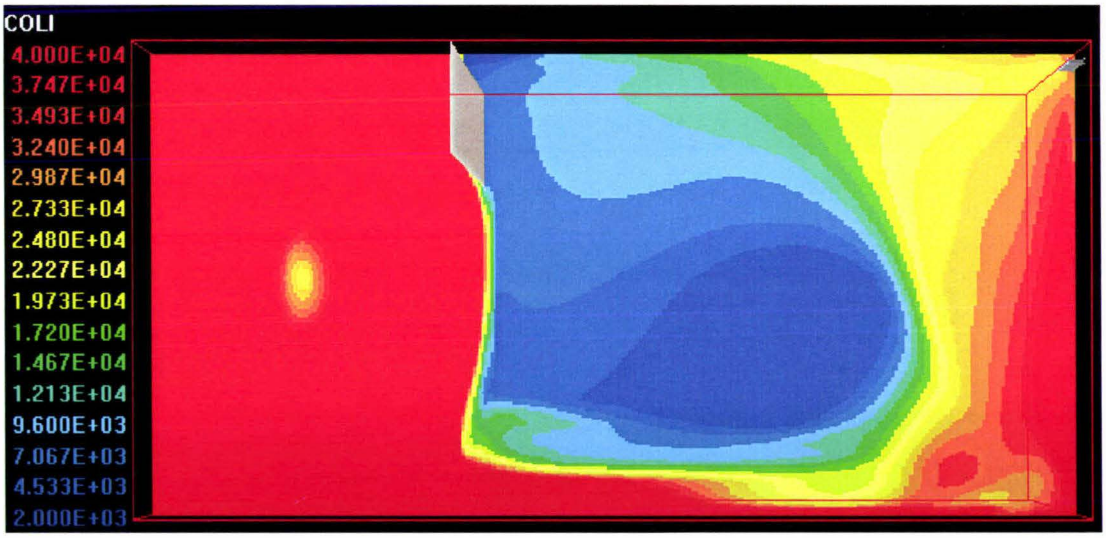


Figure 7-8 Ashhurst, coliform concentration profile, inlet turned into side wall and 14m baffle, star indicates second monitoring point

Discussion of this result (Shilton pers. comm.) has lead to the conclusion that this effect of 'channelling' around the walls is due to a venturi effect. The turbulent jet of the inlet rolls and swirls around, 'sucking' in flow from nearby. As the flow nears the wall, the 'sucking' in continues and the jet 'attaches' to the side -wall. This effect was noticed during the initial stages of the second field trial and continued around to the stub baffle on the opposite side of the pond. As can be seen in Figure 7-7, this effect still occurs as the flow rolls off the end of the baffle and back to the inlet side of the pond.

The careful consideration of the benefits of using the pond walls, effectively as baffles, to channel flow may result in treatment benefits.

7.4.4. Final Evaluation

This investigation into improving the hydraulics of waste stabilisation ponds has resulted in the improved understanding of the fundamental flow mechanisms and interactions involved with the elements in ponds. This is probably the most significant contribution of this work, as it allows the consideration of individual elements in a pond - inlets, outlets and baffles - in relation to each other, and to a specific pond system.

The channelling effect noted in previous research (Watters *et al.*, 1973) as being due to the length of the baffles, is in fact due to the width of the flow path, or length to width ratio. An interaction of flow, in which the flow is held tightly together, is seen between the inlet direction and the walls of a pond.

8. CONCLUSIONS

The literature review undertaken highlighted the need for further and extensive research to evaluate the use of baffles for improving the hydraulics of waste stabilisation ponds. A greater understanding of the flow mechanisms and interaction by the use of baffles, and the other elements in ponds (inlets, outlets and walls) was also required to assist with the design process.

The first objective of this work was to investigate the use of baffles in waste stabilisation ponds in terms of length, number and position. The following conclusions have been made:

- The use of multiple, evenly spaced baffles of standard length, was shown to provide consistent improvement in the treatment efficiency of a pond.

- Short (stub) baffles can be used to produce similar, and in some cases better, improvements in treatment efficiency as the traditional standard length (long) baffles. However they don't always work, they have shown to be sensitive to minor design changes. Caution must be taken when implementing them, and further research is necessary.

- Single baffle arrangements are not generally effective; in general, a minimum of two baffles will be required to achieve significant treatment improvements.

- Two baffles will provide treatment improvements; the use of four and six baffles makes only a small improvement on two baffles. To ensure maximum treatment efficiency eight baffles are required, however there are subsequent cost implications.

- The channelling effect attributed to baffle length by Watters *et al.*,(1973), can now be attributed to the proximity of two objects, whether it is two baffles, or a baffle and a wall.

- By turning an inlet back onto a side-wall, the flow can be channelled in a tight pathway, due to a venturi effect. Baffles can then be placed to take advantage of this.

The inlet of a pond will have a large impact on its performance. In conclusion, the consideration of the inlet in a pond is extremely important. Whatever inlet structure is chosen, horizontal, vertical, or diffuse, will have a significant impact on the bulk fluid flow within the system. As inlet momentum is dispersed using a vertical inlet, their use may only be appropriate in maturation ponds, where low organic loads re present.

The position of the outlet can have an impact on treatment efficiency; this supported the findings of Shilton (2001).

The final objective of the work was to apply the findings of the work into the field environment. This work has shown that with use of CFD modelling, a design solution that will provide improvements in pond performance can be obtained. In this instance, a combination of a modification to the inlet, and a single stub baffle produced a significant improvement in the performance of the Ashhurst secondary pond.

This work has tested many more configurations than ever previously researched before. In addition, the understanding gained from the testing process has been brought forward to improve the insight of why certain designs worked well. Previous research has looked at the pond using a 'black-box' approach, this work seeks to open and explain the flow patterns within that 'black-box'.

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