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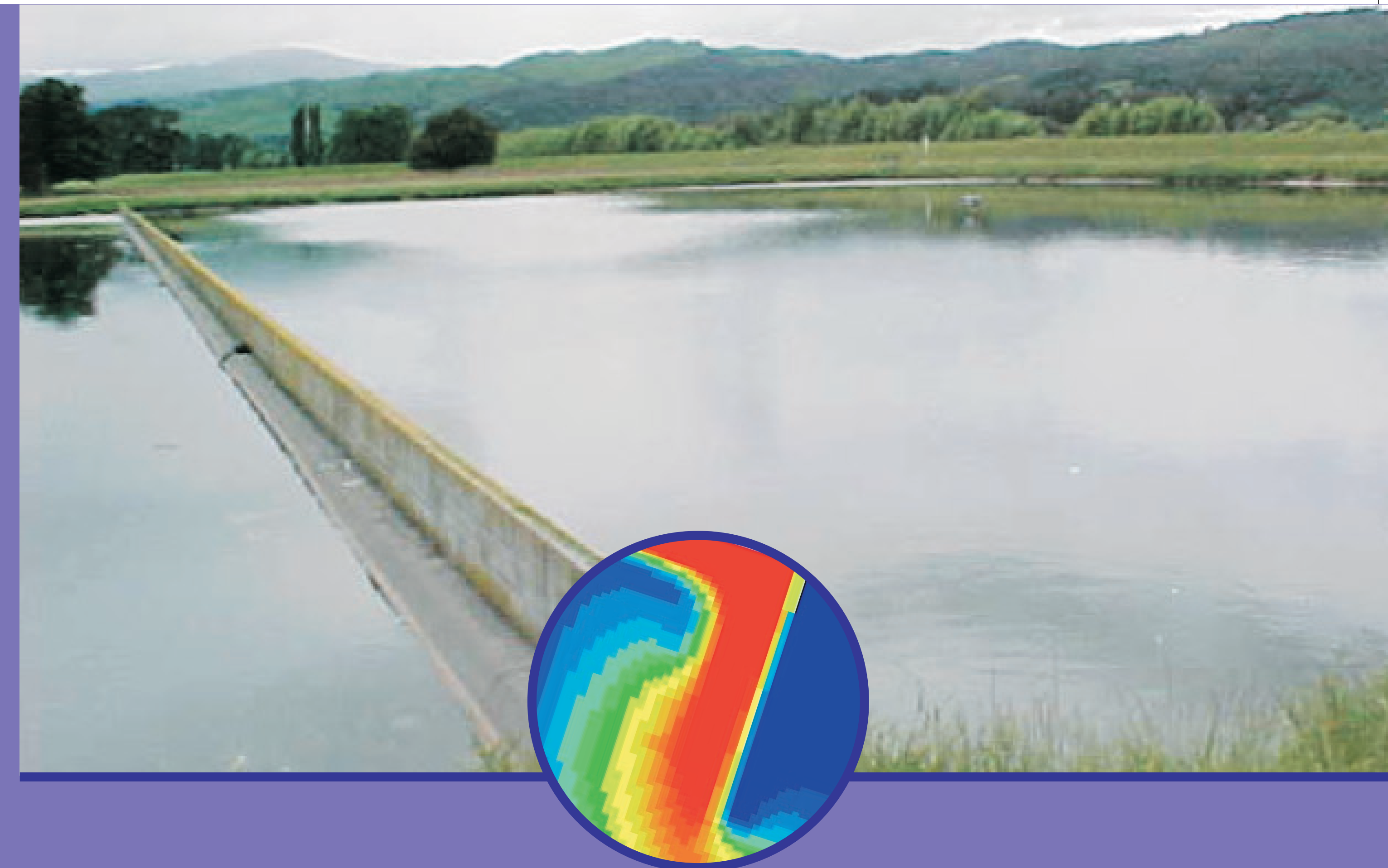

Guidelines for the Hydraulic Design of Waste Stabilisation Ponds

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Guidelines for the HYDRAULIC DESIGN of Waste Stabilisation Ponds

Andy Shilton & Jill Harrison

Institute of Technology and Engineering
Massey University
Private Bag 11-222
Palmerston North
NEW ZEALAND

ISBN 0-473-08735-9

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Preface

While not intended to be a conclusive design manual, these guidelines represent a significant advance from the rough ‘rules of thumb’ and guesswork that engineers have had to rely on in the past when trying to improve pond hydraulics. However, we must stress that the need for engineering judgment is still required as it is impractical to provide a single set of criteria that covers all site variations.

Through the peer review process we have been encouraged to make as many practical recommendations as possible. In the research supporting the development of these guidelines, we have tried to cover a broad range of areas but, of course, in any project resources are finite. There are certainly still many areas that deserve more work.

Given the above we do, however, believe that the review and research work undertaken for the development of this document and the ideas and guidance that has come from it, has certainly gone a long way to help fill the knowledge gap in the pond hydraulics area. We do trust that readers will find these guidelines to be user-friendly, informative and that they assist in the improved hydraulic design of waste stabilisation ponds.

Andy Shilton and Jill Harrison

Massey University, Palmerston North
New Zealand, 2003

A Guide to Using the Guidelines

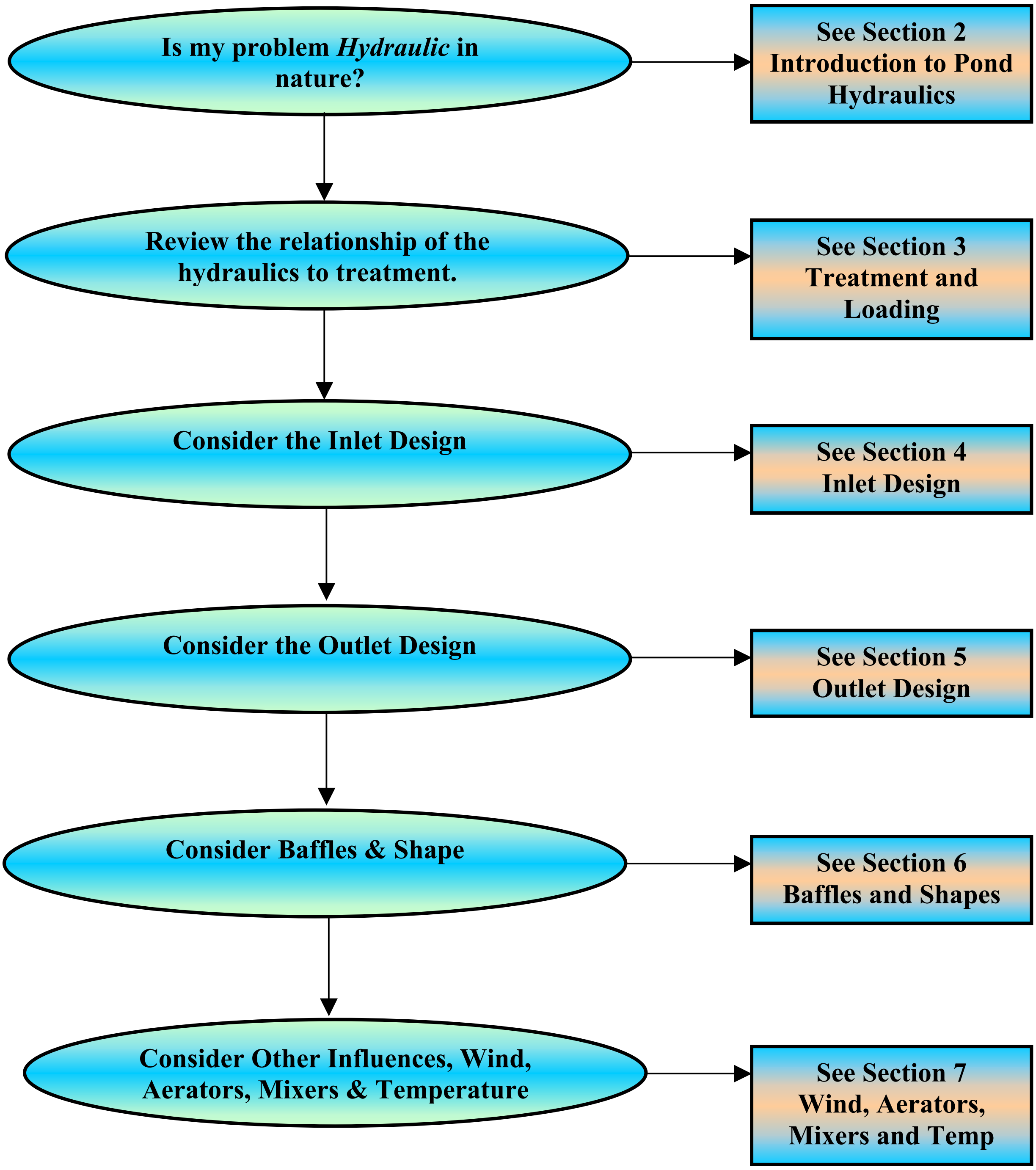

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Table of Contents

1 OVERVIEW

This section will briefly outline the need for these guidelines, their use, and how they were developed

1.1 The Need – Why are these Guidelines Needed?

Waste stabilisation ponds are extensively used both throughout New Zealand and internationally for the treatment of urban, agricultural and industrial wastewaters. This treatment technology is well known for its simplicity of construction and operation. The efficiency of pond systems is, however, often compromised by hydraulic problems.

Pond hydraulics are strongly influenced by shape (including the use of baffles) and by the inlet/outlet configuration. It has been noted, "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" (Wood, *et al*., 1995, p 112).

At the moment design engineers have no published guidelines in the area of pond hydraulics only rough 'rules of thumb'! While this document cannot provide a simple answer for all situations, it will certainly provide valuable insight and guidance compared to the knowledge gap that currently exists.

1.2 Use of this Manual

These guidelines relate to the hydraulic behaviour of pond systems. They are not intended as a means of sizing ponds. A brief guide to sizing ponds has been added as an appendix to this document (Appendix 3). Comprehensive design guidelines are also available at: http://www.leeds.ac.uk/civil/ceri/water/tphe/publicat/pdm/pdm.html

It must also be noted that the means to achieving an improvement in pond hydraulic performance will be site specific. Each pond has its own individual characteristics with regard to influent flows and loads; shape; and environmental conditions. Therefore, the addition of features such as modified inlets or baffles, will have differing effects on different ponds. Engineering judgement is still required!

1.3 The Development of this Manual

These guidelines build on previous research, but also incorporate findings from new research that has involved the use of computer simulation, laboratory research and field-testing.

Computer simulation using the PHOENICS Computational Fluid Dynamics (CFD) software has been used extensively to investigate potential hydraulic improvements due to different inlet, outlet and baffling configurations.

Laboratory and field-testing were used to produce data on the flow patterns (using drogue tracking techniques) and tracer responses. In both situations these was undertaken for a range of different pond modifications.

2 INTRODUCTION TO POND HYDRAULICS

This section answers common questions about pond hydraulics to give a basic understanding of the issues and the terminology.

2.1 What are the 'Inputs' and 'Influences' that affect Pond Hydraulics?

Understanding pond hydraulics requires consideration of the inputs and influences on the flow momentum within a pond. These broadly include:

- Flowrate – higher flowrates increase inlet momentum;
- Inlet size – smaller inlets increase the inlet velocity and so also the inlet momentum;
- Inlet position and orientation – defines the way the inlet momentum is introduced into the main body of the pond, and as a result influences the main flow pattern;
- Outlet position – sets the distance from the inlet and, therefore the time, for the main flow to reach the outlet;
- Pond geometry and baffles – strong influence on flow patterns and defines the degree of 'channelling';
- Temperature/density effects – may influence the channelling and circulation of the main flow;
- Wind shear – higher wind velocities and greater pond surface areas increase the momentum inputted, and as a result influences the main flow pattern;
- Mechanical aerators – if present constitute significant momentum input, and as a result can have a strong influence on the main flow pattern.

This document seeks to provide guidance on improving pond design by better consideration of these effects, however, it must be recognised that the current understanding of some of these 'inputs' and 'influences' is still very limited.

2.2 What is the 'Theoretical' Hydraulic Retention Time (HRT) of a Pond?

The Theoretical HRT is simply calculated by:

$$\theta_{Theo} = \frac{V}{Q}$$

Where: θ_{Theo} = Theoretical hydraulic retention time, (d)
V = Pond Volume, (m^3);
Q = Average (or design) Flowrate, (m^3/d).

2.3 What is the 'Mean' Hydraulic Retention Time (HRT) of a Pond?

In reality ponds don't operate at their theoretical HRT. This is because:

- Compared to the constant value used to calculate the theoretical HRT, in reality the flowrate is constantly changing;
- They are partly filled with sludge.

Even if a pond was operating at its theoretical HRT, its hydraulic efficiency is still likely to be sub-optimal due to:

- Hydraulic dead space;
- Hydraulic short-circuiting.

To investigate the hydraulic efficiency of a pond and to determine its mean HRT, a tracer test must be undertaken (see Section 2.11).

2.4 What is 'Dead Space'?

The volume occupied by settled sludge is 'physical' dead space. It reduces the 'effective' volume of the pond, thereby reducing hydraulic and treatment efficiency.

The term 'dead space' is also used to refer to areas that are out of the main flow path, corners for example. The term 'stagnant' is also sometimes used. However, this is a little misleading as, in practice, most of the fluid in a pond is moving to some extent. There are simply ranges of flow velocities from fast to very slow.

Zones, such as back-eddies in corners, are slow to mix and interchange fluid with the main flow of the pond and, therefore, their contents are retained for long periods. This effectively reduces the 'active volume' of the pond that is left to provide the treatment to the main flow.

To illustrate this concept further, let's consider an exaggerated example. Imagine we have an irregular shaped pond with one corner (say 10%) that is relatively inaccessible and is bypassed by the flow in the rest of the pond. What if the water entering this corner sat there for a year before finally mixing back into the main body of the pond? If we did a tracer study for long enough, and if there was no sludge and a constant flow, we could eventually show that all the tracer that goes in comes out, and we would then know that the mean HRT equalled the theoretical HRT. However, in practice most researchers wouldn't wait around for years until all the tracer came out and their results would indicate that the mean HRT was less than the theoretical HRT. This is what we might then call the 'hydraulic' dead space. It's not really filled up with anything but is it essentially ineffective space! There is so little flow in and out of this zone that in essence the 'effective' pond volume has been reduced by 10% and it is the other 90% of the pond that is providing the treatment to practically all the wastewater.

Dead space in a pond reduces its effective treatment volume and therefore its overall treatment efficiency.

2.5 What is 'Hydraulic Short-circuiting'?

When wastewater enters a pond it does not all move uniformly together from the inlet to the outlet. It mixes and disperses.

Some of the water might enter a hydraulic dead zone and remain there for some time. Most will mix into the main body of the pond and then slowly discharge with the effluent over a reasonable period.

However, some water will enter and leave the pond in a very short period of time - often just a matter of a few hours in ponds that have theoretical hydraulic retention times measured in weeks! This is called hydraulic 'short-circuiting' because it has short-circuited the full treatment process.

2.6 Why does Short-circuiting occur?

Researchers undertaking tracer studies have consistently reported the presence of short-circuiting. Various reasons have been given to explain why this may occur. Different authors have blamed this effect on a number of possible causes including thermal stratification, channelling directly from inlet to outlet, and wind effects.

However, it has also become recognised that the momentum from the inlet, especially if horizontally aligned, will cause the influent to swirl around the pond. Should this influent circulate around past the outlet then short-circuiting will occur resulting in the discharge of only partially treated wastewater.

Flow 'swirling' around the pond from an inlet past the outlet will cause short-circuiting.

2.7 Why is Short-circuiting a problem?

If some wastewater leaves a few days too early, isn't this balanced out by wastewater that stays in the pond a few days too long?

No! Researchers believe that the reduction of organic contaminants and pathogens follows a non-linear relationship with respect to time. A relationship called 'first order kinetics' is often assumed to describe this behaviour.

This means that if some wastewater short-circuits through the pond too quickly, it misses out on a very large amount of treatment, whereas if some wastewater stays in the pond a very long time, it receives only a relatively small amount of 'extra' treatment. Section 3 discusses this further.

Wastewater that short-circuits through a pond misses out on a significant amount of treatment.

2.8 What is 'First-order Kinetics'?

This refers to the rate at which the contaminants are removed. Put simply, it means that the rate of treatment of a contaminant at any time is proportional to the contaminant concentration remaining at that time. This is a non-linear relationship because the contaminant concentration is decreasing over time.

The significance of this in relation to pond hydraulics is explained further in Section 3.

2.9 What is 'Plug-flow' and 'Completely Mixed Flow'?

There are two theoretical extremes of flow behaviour - plug flow and completely mixed flow.

The concept of 'plug flow' assumes that there is no mixing or diffusion as the wastewater moves through the pond. Alternatively, 'completely mixed flow' assumes the wastewater is instantaneously fully mixed upon entering the pond. These theoretical flow extremes are known as 'ideal-flow'.

By assuming these types of flow behaviour when integrating the rate equation for first order kinetics, equations can be derived that allow calculation of the treatment efficiency achieved after a certain period of time. These are known as the ideal flow equations and are again explained further in Section 3.

Because plug flow conditions mean that the concentration is not diluted by mixing, then for first order kinetics, the higher concentration means that the rate of treatment is faster and, therefore, the overall efficiency is better.

For pond design, some researchers have proposed the use of the plug flow equation. Others have argued for the application of the completely mixed flow equation, partly because it is less efficient and therefore gives a more 'conservative' design. In the process design approach given in Appendix 3, an application of the design equation for completely mixed ponds in series is used.

2.10 What does 'Non-ideal Flow' and the 'Dispersion Number' refer to?

An alternative to using the ideal flow equations is to use the Wehner-Wilhelm equation. This equation is for what is called 'non-ideal flow' which is somewhere between the two extremes of plug flow and completely mixed flow. To do this it incorporates something called the dispersion number.

As the dispersion number tends to 0, more plug flow conditions exist – as it increases a higher degree of mixing is represented.

The dispersion number is derived by calculation from the results of a tracer study. This means that it is a function of all the physical influences that affected fluid flow within the pond during that study period.

However, to actually use this approach for pond design the dispersion number must be predicted in advance. A number of researchers have tried to present design equations to predict the dispersion number, but it is fair to say that none of these equations have become standard practice.

Currently researchers appear to focus less on this approach and more on the application of computer modelling to directly predict flow behaviour in ponds instead of trying to represent it by a single 'dispersion number'.

2.11 What is a Tracer Study and what does it tell you?

A tracer may be a chemical or microbe that travels with the flow essentially mimicking the movement of the contaminants. A tracer study involves adding a slug (or a pulse) of a tracer at the inlet and then measuring its concentration at the outlet over a period of time.

Using the data obtained from a tracer study allows various hydraulic parameters to be determined including the:

- Mean retention time;
- Dispersion number;
- Time to start of short-circuiting;
- Time for 10% and 90% (the t_{10} and t_{90} fractions) of tracer discharge, etc.

It is also possible to integrate these results with an expression for first order kinetics to directly determine the treatment efficiency achieved by the pond under these conditions.

Appendix 2 of this document includes a short guide to performing a tracer study, interpreting the results and highlights some of the limitations of this approach.

Figure 2-1 Tracer testing on a laboratory pond with 'stub' baffles

3 RELATING HYDRAULICS TO TREATMENT AND LOADING

What is the relationship between hydraulic efficiency and treatment efficiency?
What is the relationship between the hydraulics and the organic and/or solids loading?

3.1 Introduction

These guidelines focus on improving pond hydraulics, but what we really want to do is improve the treatment efficiency.

It is therefore important that before trying to improve pond hydraulics we understand the relationship to the 'kinetics' of treatment. It is also essential that we don't ignore the realities of solids and organic loading.

What would be the point of improving the mean hydraulic retention time without appreciating that it might be a prevailing short-circuiting problem that is actually compromising the treatment efficiency? Alternatively, what if we implemented an excellent 'plug flow' type of design only to find that we have created organic overloading and odour problems at the front end of the pond?

3.2 The Treatment Relationship

It is typical to assume that the decay of water quality indicators such as BOD and coliforms in a waste stabilisation pond can be predicted using first order reaction kinetics. This relationship is shown in the following equation:

Rate of treatment = (reaction rate constant) x (concentration of contaminant remaining)

Because the concentration of contaminant decreases with time, there is a 'non-linear' relationship between treatment and time. Simply put, this means that while the wastewater is still concentrated there is a lot of treatment occurring, but once the wastewater is stabilised to low contaminant concentrations then little further treatment is achieved.

3.3 Effect on Discharge Concentration

When we are trying to obtain high treatment efficiency we want the discharge concentration as low as possible. This is particularly the case when we are considering a water quality parameter such as coliforms in a strict regulatory environment. Because the concentrations of bacteria are so high we normally seek to reduce it by several orders of magnitude (i.e. more than 99%).

If only a small fraction of the total flow is short-circuiting without adequate treatment, then this still contributes a disproportionately large amount of the contaminant remaining in the effluent. To illustrate this concept consider the following simplified example.

A pond treats a wastewater containing $1x10^7$cfu/100mL. All but 1/100 of the flow is retained in the pond for enough time to achieve 99.99% treatment. The 1/100 of the flow that short-circuits receives only 60% treatment. So what is the current overall treatment efficiency provided by the pond?

Current efficiency = (99/100)x99.99% + (1/100)x60% = 99.59%

Consider if we did something to stop the small fraction of short-circuiting (eg change the inlet/outlet design or add baffles) so that all the flow received 99.99% treatment.It might seem that this is a total waste of time as there is hardly any difference between 99.59% and 99.99%! However, consider the effect on what is actually being discharged:

Original Discharge Concentration = $1x10^7$ x (1 – 0.9959) = ***41,000***

New Discharge Concentration = $1x10^7$ x (1 – 0.9999) = ***1,000***

Clearly reducing the discharge concentration from 41,000 cfu/100mL to 1,000 cfu/100mL is a very significant improvement!

A small amount of short-circuiting results in a large reduction in the discharge quality.

3.4 Integrating Hydraulic and Treatment Efficiency

Previous research into pond hydraulics has predominantly presented the findings in terms of hydraulic parameters such as 'mean retention time', 'dispersion number', 'dead space' and so on.

However as discussed previously, the rate of treatment in a pond is 'non-linear'. So what do the terms given above mean regarding actual pond treatment efficiency? The simple answer is that by using hydraulic parameters alone we can not be sure! For example, it is possible to have two ponds with the same mean hydraulic retention time, but with different treatment efficiencies if one has a greater degree of short-circuiting.

Hydraulic parameters, such as the mean HRT or dispersion number, don't give a direct measure of treatment efficiency.

There are a number of ways of sizing ponds. Loading rates give a ratio of, for example, BOD to pond area. Alternatively we can use the ideal flow equations, as mentioned previously, to calculate the retention time required. Regardless of which approach is used, they all have a common weakness – they take no account of the physical configuration. For example is the inlet pipe shooting its flow straight across a pond towards the outlet? Does adding a couple of baffles into a pond improve its treatment efficiency? If so, by how much?

Recently researchers have become interested in the application of computational fluid dynamics (CFD) computer modelling. In addition to predicting the hydraulics of ponds, it is relatively easy for these models to incorporate first order kinetics. Researchers might, however, tell us that the assumption of first order kinetics is 'simplifying' the complexity of the treatment mechanisms in the pond. This is true.

The reaction rate constant is essentially a single number that represents the net effect of a myriad of complex reactions/interactions. However, while the assumption of first order kinetics and the selection of a reaction rate constant from the literature (we used an equation given by Marais (1974) for $14^{o}C$ to calculate a constant of $0.916\ d^{-1}$) does not give the perfect mechanistic model, this ability to integrate the kinetics directly with the actual hydraulics still offers a powerful new tool for assessing pond design improvements. This sort of 'integrated' CFD modelling allows quantitative evaluation of the treatment efficiency given by any pond shape or configuration.

Integrated reaction and hydraulic CFD modelling allows direct evaluation of treatment efficiency for various physical pond improvements.

It seems likely that in the future, wastewater engineers will make more use of these sorts of modelling tools for design just as is done for structural analysis today. However for the present, the purpose of these guidelines is to complement existing design manuals for sizing ponds (a guide to this process is given in Appendix 3), by highlighting the mechanisms of flow and suggesting some techniques for improving the hydraulic efficiency.

3.5 Why not just Design for Plug Flow?

As discussed previously, the most effective hydraulic design will always be 'plug flow'. While in reality pure plug flow is a theoretical concept, there are certainly ways of making a pond more plug flow in its nature. These include:

- Designing a number of smaller ponds in series rather than just one large pond;
- Construction of long, narrow ponds or ponds fitted with many baffles (thus creating a large length-to-width ratio);
- Use of inlets that dissipate inflow momentum to reduce mixing.

Practical considerations may, however, not always make 'plug flow' type designs the best option. It has been suggested that long narrow ponds or multiple smaller ponds will be somewhat more expensive to construct. However, the most important consideration is with regard to loading. The first pond in the series will obviously be subjected to a much higher organic loading rate than the subsequent ones. This same concern also applies at the front end of a long, narrow or baffled pond. Variation in loading rates changes the nature of a pond and, at an extreme, may lead to organic overloading.

This restricts application of this approach to a series of maturation ponds where the organic loading has already been substantially reduced and indeed the use of a number of 'ponds in series' is a common practice for maturation pond design.

While 'plug-flow' type designs are often used for maturation ponds, they may not be appropriate for other pond types due to loading considerations.

Similar caution is needed for inlets that act to dissipate the inlet momentum (eg vertically orientated). For example, in a pond receiving a wastewater containing a significant organic and/or solids loading, the use of a vertical inlet will slow the velocity of the fluid in the inlet region. This could create problems of sludge build-up around the inlet and again create the potential for localised organic overloading (discussed further in Section 4). Secondly, as the vertical inlet acts to minimise horizontal momentum, the flow pattern may be dominated by wind effects alone, which in certain situations may also lead to poor hydraulic efficiency (discussed in Section 7).

Ideally, the best general behaviour for a pond, especially if receiving raw wastewater, is to get the influent rapidly mixed into the main body of the pond. This would distribute the solids and organics load more evenly. But at the same time the design must also avoid jetting the influent rapidly around past the outlet and therefore creating short-circuiting problems. Ways of achieving this by inlet/outlet design and use of baffles is discussed in latter sections.

Influent should be mixed into the main body of the pond to avoid localised overloading – but take care not to create short-circuiting problems.

3.6 Solids Deposition within the Pond

How do solids deposits on the base of the pond affect the hydraulics?

Pond influent should receive pre-treatment by screening and if warranted grit removal, but in practice this is often not provided. Inorganic solids such as grit and sand will settle rapidly upon entry to a pond and can result in build-ups (mounds) near the inlet. It is difficult to say exactly what result such a build-up will have. However, it might be assumed that in all but extreme cases where a mound physically deflects the flow, there wouldn't be a significant effect on the flow patterns in the main body of the pond.

Lighter organic material tends to settle more slowly and fine solids, in particular, are susceptible to being kept suspended by the water movement. As a result, the settled organic sludge is typically widely distributed across a pond with sludge build-up being in areas of low flow movement such as corners. This implies that the deposition of the solids within the pond is a *secondary function* to the hydraulics. That is to say that solids build-up occurs as a result of the flow rather than the flow being redirected as a result of the solids build-up.

Over an extended period of time the solids will obviously build up to a point where it is occupying a significant part of the pond volume and as a result will reduce treatment efficiency. At this point de-sludging will be required.

The solids build-up occurs as a result of the flow rather than the flow being redirected as a result of the solids.

4 INLET DESIGN

What about the inlet? What effect will its position and design have on the efficiency of the pond?

4.1 Introduction

Existing design manuals give little information on the importance of the position and design of an inlet in a waste stabilisation pond. In this chapter, previous work is briefly reviewed and new ideas presented on how inlet position and design affect pond hydraulics.

4.2 Previous Work

Recent research suggests that the inlet position and its relation to the outlet are more important than previously thought. Pearson *et al*., (1995) concluded "…the positioning and depths of the inlet and outlets may have a greater beneficial impact on treatment efficiency than pond shape." (pg 137).

Wood (1997); Persson (2000); and Shilton (2001) all noted that the position and design of the inlet does indeed have a significant impact on the hydraulic efficiency of a pond. However, little practical guidance exists on the design and positioning of inlets.

Inlet position and type has a significant impact on treatment efficiency in ponds.

4.3 New Thinking

4.3.1 Introduction

There has been uncertainty in the literature regarding the flow patterns that exist within waste stabilisation ponds. A number of researchers have assumed that fluid moves reasonably directly from the inlet towards the outlet. However, it has been found that horizontal inlets can drive the pond contents to circulate in large cells at velocities much faster than if the flow was simply moving from the inlet to the outlet in a 'plug flow' manner.

It is useful to think of the inlet as a small drive on a large flywheel where, in the case of the pond, the flywheel is the bulk volume. Although the jetting effect from an inlet pipe is quite localised, it provides a consistent source of momentum inputted in a fixed direction at a fixed point. This momentum is transferred into the bulk volume and thereby drives the main circulation.

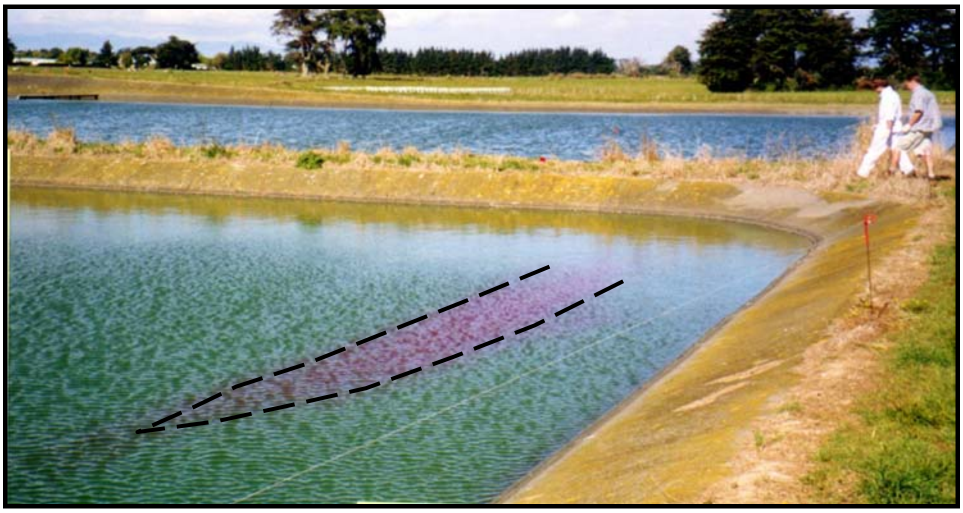


Figure 4-1 'Jetting' effect of the inlet as seen in a tracer study on a field pond

Laboratory experiments, computer modelling and fieldwork have all repeatedly highlighted the ‘jetting’ effect that a horizontal inlet creates in a pond. The picture in Figure 4-1 above of a tracer study performed on a field pond shows this jetting effect as wastewater flows from a primary pond into a secondary pond via a pipe in the embankment.

The inlet jet is relatively localised but provides a momentum source that drives circulation of the main flow pattern.

This effect is similar to a small drive on a large flywheel.

4.3.2 Use of Large Horizontal Inlets

In order to reduce the jetting effect associated with horizontal inlet pipes, laboratory experiments and computer modelling work were undertaken to assess the effect of increasing the cross-sectional area of the inlet, thereby slowing its velocity. Large pipe diameters and a large inlet channel were tested.

While the larger inlets did indeed decrease the velocity of the main flow circulation, the overall pattern of wastewater swirling around past the outlet at the opposite end of the pond was just the same. Short-circuiting was indeed delayed but the net effect, in terms of improving treatment efficiency, was not particularly significant.

While a larger inlet will slow the pond circulation and provide some delay in short-circuiting the improvement is not significant.

Rather than increasing inlet size it can also be important to use a smaller pipe to maintain inlet momentum, mixing and flow control. This is discussed further in section 4.3.8.

4.3.3 The Jet Attachment Technique

Rather than seeking to reduce the jetting effect created by a horizontal inlet pipe, this technique seeks to utilise it for flow control. The idea is simply an alternative to directing a horizontal pipe straight out into the main body of the pond. Instead, the inlet is kept close in against a sidewall. When this is done the inflow will tend to 'cling' to the side.

This is known as 'jet attachment'. The fluid from an inlet pipe creates localised inlet jetting. An inlet jet acts to suck in and entrain fluid from the surrounding water body. However, if a jet is positioned close to a sidewall it tends to suck into and attach on to this wall.

Previously it was noted that a common problem with pond hydraulics was that the influent swirled too quickly around from the inlet to an outlet located at the opposite end of the pond. So why would we want to use an inlet that encourages this effect?

If we wish to control the flow pattern in the pond in order to optimise the hydraulics, then this could be a useful tool. For example, in the following section we discuss locating an outlet in the centre of a pond. In this case we want to keep the influent around the edge and have it slowly spiral into the centre.

Another application is that used in the case study discussed in Appendix One at the rear of these guidelines. By adding a right angle bend and swirling the influent around the edge of the pond, the end wall then essentially acted as a baffle to contain and slow the inflow. The flow then circulated around, and into a short baffle located on the opposite side of the pond as shown in the following diagram.

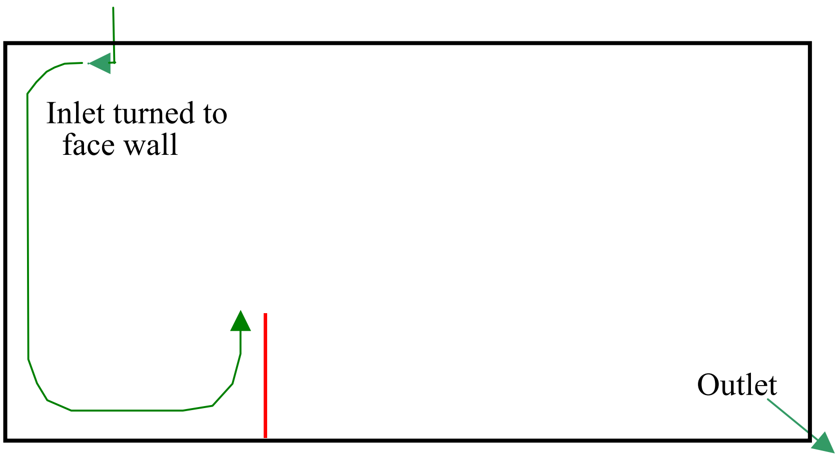


Figure 4-2 Pond with modified inlet and stub baffle

It is possible to control the inlet flow by 'attaching' the inlet jet along the edge of a pond.

While this alone won't necessarily reduce short-circuiting, it can be an effective tool when used in conjunction with other design improvements.

4.3.4 Vertical Inlet

If a horizontal inlet causes short-circuiting problems then a relatively cheap method of avoiding this would seem to be simply changing it to discharge vertically.

In initial laboratory testing it was found that the use of the vertical inlet provided a significant improvement. Further work on a different laboratory model again showed it to work very well. Given the ease and simplicity of installing a vertical bend to an existing horizontal pipe, this approach appeared very promising.

However, when a vertical inlet was computer modelled and tested on a full-scale pond (of somewhat different configuration to the laboratory experiments), it was not found to give any significant improvement over a horizontal inlet pipe. It had been assumed that the tracer would be discharged and then slowly spread out evenly across the pond. However, in this case the tracer appeared to move out in two plumes along either adjacent wall.

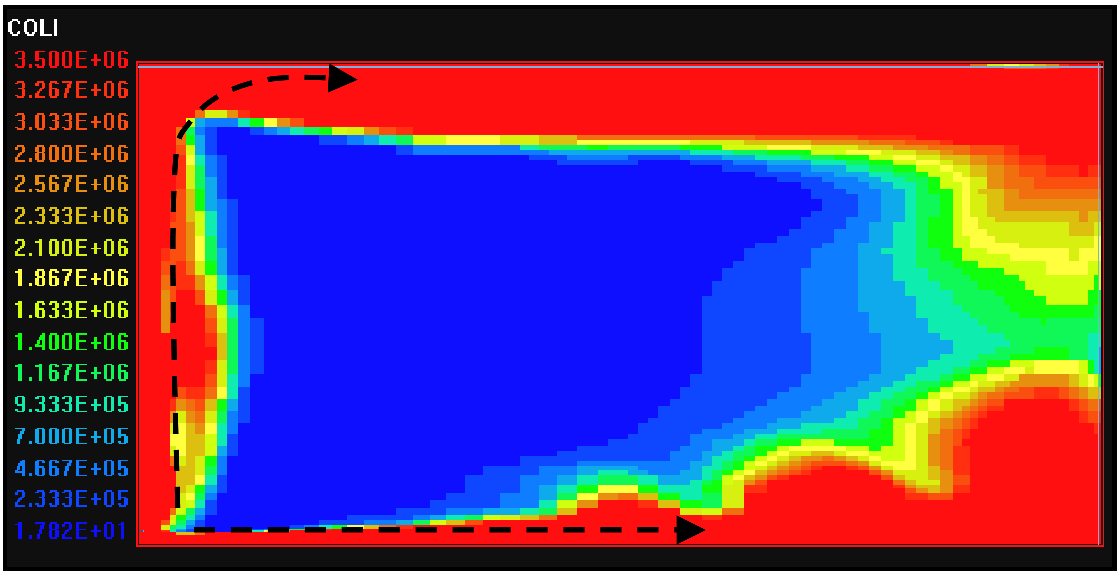


Figure 4-3 Flow pattern and direction from a vertical inlet

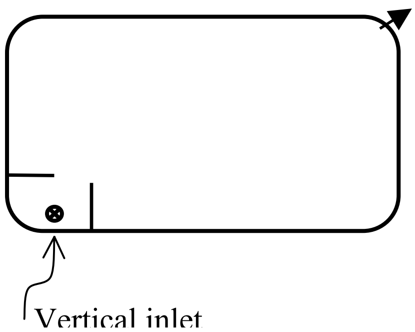
This finding is similar to a result found when modelling a water storage reservoir where again the inflow from a vertical inlet moved out around the walls of the tank.

It is not clear why this inlet design works well in some cases but not in others. While this type of inlet deserves further research, until we have a better understanding of this behaviour we need to be cautious before using this design approach.

Used alone, vertical inlets have variable performance and may not always offer an improvement over a horizontal inlet.

4.3.5 Vertical Inlet with Stub Baffles

This idea again involved using a vertical inlet but now with short baffles placed on either adjacent wall to block the circulation around the edges that had been seen previously.



This approach was tested in both the laboratory and in computer modelling of the full-scale pond. Both cases gave excellent results. The tracer was rapidly mixed within the baffled inlet area and then moved uniformly out into the main body of the pond through the gap between the two baffles. The following photo shows the tracer in a laboratory test moving out of the baffled corner.

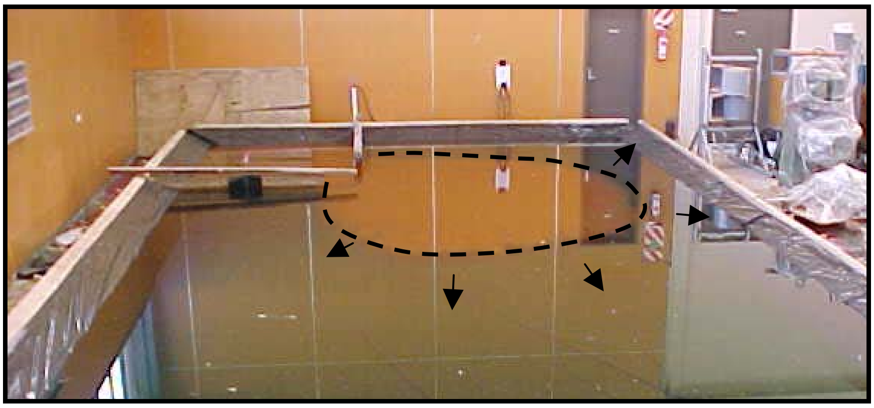


Figure 4-4 Dye movement in pond with vertical inlet and adjacent stub baffles

The addition of the stub baffles appears to have made the performance of the vertical inlet more effective and reliable than in the testing using vertical inlets alone.

Addition of stub baffles adjacent to a vertical inlet improved its reliability.

However, before considering this application consideration must be given to the effect of the loading in the inlet zone. This is discussed further in section 4.3.8.

4.3.6 Diffuse (Manifold) Inlet

Previous researchers have indicated that diffuse or manifold inlets offer potential as an inlet improvement option (Mangelson *et al.*, 1973; Fares *et al.,* 1996; Persson 2000).

A manifold inlet was tested in the laboratory. This consisted of an inlet pipe running the width of the pond, containing eight equally spaced small diffuser holes facing downward towards the base of the pond. As can be see in the photo below these had the effect of creating an even distribution of the tracer that then spread down the length of the pond. Surprisingly, however, the tracer still moved relatively steadily.

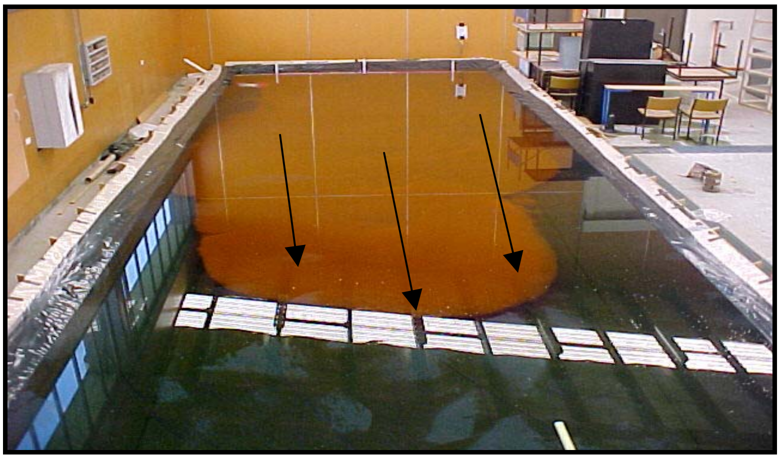


Figure 4-5 Dye movement down laboratory model due to diffuse (manifold) inlet

Although this gave an improvement over simply having a horizontal inlet pipe, this pond configuration was one of the cases mentioned previously where a simple vertical inlet gave far better results.

Based on this result, and the comments of previous researchers, the manifold inlet option clearly has some potential. However, installing and maintaining this sort of inlet on a large full-scale pond may not always be practical or cost effective compared to other options.

Diffuse (manifold) inlets can reduce short-circuiting, but may not always be practical or cost-effective.

4.3.7 Inflow Dropping from a Horizontal Pipe

Many ponds are currently fitted with a horizontal inlet pipe that discharges a short distance above the pond surface. So is this working like a horizontal inlet or a vertical inlet?

As the water plunges down into the pond it will certainly pick up a significant vertical velocity. However, even though the water drops rapidly down and appears vertical, the horizontal component of momentum still remains after discharge.

Figure 4-6 Field pond with inflow dropping from a horizontal pipe

Testing undertaken on a laboratory model confirmed the strong influence of the horizontal momentum. Even though the water seemed to be almost vertical when it impacted the pond surface it did in fact set up a rapidly circulating flow pattern, as was the case with a horizontal inlet. Tracer testing confirmed that for this type of inlet the influent swirled around to the outlet in a time very similar to that for the submerged horizontal inlet.

Dropping inlets from horizontal pipes above the water surface have similar behaviour as submerged horizontal inlets.

4.3.8 Inlet Type – Overall Recommendation

There is a range of alternative inlet designs, however, most of these are simply methods for avoiding/minimising the jetting effect that results from using a horizontal inlet pipe.

In the previous section we highlighted the need to consider organic and solids loading. While from a purely hydraulic viewpoint it may be useful to dissipate the inlet momentum, in so doing we lose the useful effect that this momentum has in rapidly distributing the organic and solids loading out into the main body of the pond. This is not, however, an issue for maturation ponds where organic and solids loads have already been significantly reduced by prior treatment.

A second practical consideration is wind. If the inlet design acts to dissipate the driving force of the inlet then it is more likely that, on a windy day, the wind will determine the flow pattern in a pond. In certain cases this may drive the influent rapidly towards the outlet again leading to short-circuiting problems and poor hydraulic efficiency.

Every case will have its own considerations for the design engineer to take into account, but as a general guide the following recommendations are proposed:

- For ponds receiving wastewater which has a significant organic and/or solids loading it is preferable to use a horizontal inlet pipe to ensure good distribution and mixing of the influent out into the pond. However, attention must be given to prevent the inflow swirling quickly around past the outlet. This could be achieved by careful consideration of the outlet position and the use of baffles (discussed further in Sections 5 & 6).

- For ponds receiving pre-treated wastewater with low organics and/or solids loadings consider alternatives such as a manifold or vertical inlets with adjacent stub baffles, but only after due consideration of the potential influence of wind.

For high load wastewaters: horizontal inlets may be needed to mix wastewater into the pond. Consider baffles and outlet positioning to avoid short- circuiting problems!

For low load wastewaters: consider a manifold or baffled vertical inlet but only after consideration of wind influences!

4.3.9 Inlet Position

Since the inlet is an important driving force on the main pond circulation, engineers need to assess the broad flow pattern that will result from inlet positioning as part of the design process. The ideal approach is to model this on a computer but, at the time of writing, this is still a relatively specialist application that many practitioners do not have access to and is not cheap to commission.

The alternative is simple. Use a plan diagram to sketch the circulation pattern that the inlet will set up. Consider a horizontal jet to be a source of momentum that will then drive the larger bulk circulation around the pond just like a small mixer would.

In our work we have observed that ponds that are roughly 1:1 to 1:2 in terms of their length to width ratio tend to circulate in a single large cell typically with small counter-current circulations tucked in the corners (back-eddies).

Also recall that the jet attachment technique, discussed in Section 4.3.3, can also be used to improve the predictability of the flow path. What gets harder to assess, is when multiple circulation cells will be established in longer/narrower ponds - this is discussed further in section 6.3.6.

In the past it has been very common for engineers to set the inlet and outlet positions with little or no consideration of their effect on the resulting flow pattern within the pond. While drawing a simple sketch prediction of the flow pattern is certainly not 'rocket science' the fact that the designer is giving due consideration to the inlet positioning is certainly a significant step forward. The next steps to be considered in this process are the application of baffles and finally the positioning of the outlet. These issues are considered in more detail in Sections 5 and 6.

Inlet positioning has a major influence on the flow pattern.

Designers need to consider the effect of inlet position in conjunction with outlet position and pond shape/baffles.

4.3.10 Effect of Varying Flowrate

In practice, the flow entering a pond system is constantly changing both through a daily cycle and more extremely during periods of wet weather. Will this cause problems when trying to design a pond for improved hydraulic performance?

Runs undertaken at different flowrates were compared and found to have similar flow patterns. This is a similar finding as discussed in Section 4.3.2 for larger inlets and is not surprising since in both cases we are simply discussing a change in momentum input.

This is good news for the designers as it would be difficult to optimise pond hydraulics if the flow pattern changed at different flowrates. The only time that this may not hold is when wind effects are able to dominate, which is more likely when inlet momentum is reduced. This aspect is discussed further in Section 7.

A pond should maintain a similar and reasonably well-defined flow pattern through a range of different flowrates.

Figure 4-7 An inlet manifold used on a surface flow wetland system

5 OUTLET DESIGN

What about the outlet? What effect will its position and design have on the efficiency of the pond?

5.1 Introduction

Significant research on the design and positioning of the outlet has been lacking, and there is little 'previous work' to report other than recommended depths.

More recently, research undertaken for these guidelines by Shilton (2001) has presented some insight into this area and this is reported below.

5.2 Previous Work

5.2.1 Outlet Depth

The design manual of Mara & Pearson (1998) recommends the following depths for outlets:

Anaerobic Ponds	300mm
Facultative Ponds	600mm

In anaerobic ponds the outlet should be deep enough to avoid any surface crust. In facultative ponds the depth is selected so as to discharge from below the maximum depth of the algal band. If an outlet weir is to be used, as opposed to a simple outlet pipe, then this should incorporate a scum guard that extends to the indicated depth (Mara & Pearson 1998).

In maturation ponds, where "algal bands are irrelevant" (Mara & Pearson, 1998, pg 62), the outlet should be located close to the surface.

5.3 New Thinking

5.3.1 Outlet Position – Influence on Efficiency

There is no doubt that the positioning of the outlet is critical in terms of hydraulic efficiency. As we now realise the wastewater tends to circulate around the pond rather than simply moving slowly from the inlet towards the outlet.

If wastewater swirls from the inlet around past the outlet, then short-circuiting will occur and treatment efficiency will be compromised. It is therefore important to ensure that the outlet is kept out of the main flowpath of the incoming wastewater.

Outlets should be placed out of the main flowpath of the incoming wastewater.

The engineer needs to consider what the likely flow pattern would be and then select an outlet position in a 'sheltered' spot. Some practical suggestions for doing this are given towards the end of this section, but firstly we need to consider what effect moving the outlet position might have on the overall flow pattern.

5.3.2 Outlet Position – Influence on Flow Pattern

Does the positioning of the outlet affect the main circulation pattern?

After discussions with engineers on this matter, the consensus was that if the position of the outlet is moved then it might alter the circulation pattern in the pond by 'dragging' the flow towards it. However, in practice this does not appear to be the case. Observations made during laboratory and modelling work indicated that the outlet had only a localised influence and moving it certainly did not alter the bulk flow pattern that existed in the pond. This is a useful observation as it means that the inlet and baffling can be sorted out first.

Clearly the outlet position must be carefully considered, but as a 'secondary function'. This is to say, that after the flow pattern has been optimised by design of the inlet and the shape/baffles, then the outlet can be placed for maximum efficiency without the likelihood that it will subsequently alter the flow pattern.

Final outlet positioning can be selected after the inlet position/type and pond shape/baffling have been designed.

5.3.3 Outlet Manifolds

Some engineers have raised the possibility of using outlet manifolds. These might consist of a weir running down the width of the pond at the opposite end from the inlet. However, as our understanding of flow behaviour has improved, we now realise that wastewater in a pond doesn't simply move slowly from one end to the other.

It therefore seems likely that despite the expense of installing such a structure, it would actually compromise pond performance because it exposes the outlet over a wide width therefore making it more difficult to shelter and protect.

Outlet manifolds are not recommended.

5.3.4 Outlet Position - Design Suggestions

It has generally been considered that the best position for an outlet is at the opposite end of the pond to the inlet. However, we now realise that wastewater can swirl rapidly around from the inlet past the outlet.

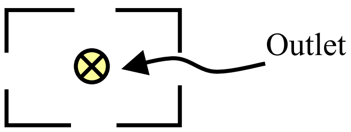
Picking the best spot for the outlet in any pond is still going to require some reasonable degree of judgment from the design engineer but the following ideas should help:

<u>Hydraulic Dead Spots</u>
'Tuck' the outlet close into a corner or, if you have an irregular shaped pond, into a zone that obviously is out of the main flow path.

<u>Use of Baffles as 'Shields'</u>
The application of baffles is, of course, far broader than for simply protecting the outlet. However, they can also be used to do exactly this with good results. In the following section on baffles, we will see the benefit of locating an outlet at the opposite end of the pond to the inlet and then placing a baffle to shield it from flow that swirls around towards it.

<u>Central Outlets</u>
This idea involves positioning the outlet in the middle of the pond and using the inlet to actually encourage a swirling action around the outer edge so that the flow slowly spirals into the centre. This idea was modelled for a pond on the computer and it worked extremely well. However, the probability that the wind could drive the flow over into the central zone needs to be carefully considered. Although this sort of a design offers great potential, at the moment it is untested in the field and a full-scale research study of its performance is perhaps needed before it can be generally recommended.

<u>Use of Flow Deflectors</u>
Further protection of a central outlet can be achieved by placing small walls or sheets of material around it to deflect flow away from this area (a simple diagram is shown below). The idea is to 'sort of' build a pond within a pond.



<u>Wind</u>
In a later section we discuss the relative significance of the inlet versus wind. However, for now it should be realised that on a windy day the wind will certainly have some effect and therefore a sensible separation distance is required between the inlet and outlet. This same point applies when using a central outlet. For example, on a rectangular pond if the outlet is to be placed in the centre zone it might be better kept towards the opposite end of this zone away from the inlet.

Tip: If using a baffle as a shield, be sure that it doesn't leak some of the flow through – baffle leakage is not uncommon!

6 BAFFLES & SHAPE

Baffles are known to improve pond performance. Here, the efficient use of baffling is discussed. How many? What length? What position?

6.1 Introduction

Baffles are commonly proposed for improving the hydraulic and treatment efficiency of ponds. There are numerous ways in which baffles can be built. Obviously it is easier to build baffles as part of the original design, in which case a concrete block or earthen wall is typically used. Retrofitting a baffle into an existing pond is, however, still relatively straightforward. An example of a baffle retrofit using a heavy anchor chain, surface floats and flexible sheeting is detailed in Appendix One. Regardless of the design, it is important to ensure that the baffle is well sealed and doesn't leak effluent from one side to the other to avoid any short-circuiting.

6.2 Previous Work

Watters *et al*., (1973) undertook an in-depth study on baffles and the following sections on horizontal, vertical and longitudinal baffling are derived from this work.

6.2.1 Horizontal Baffling (Transverse)

Three different lengths of baffles were tested: 50%, 70% and 90% of the width of the pond. Each length was tested using 2, 4, 6 and 8 evenly spaced baffles. The following figure illustrates the configurations tested for the 50% width baffles.

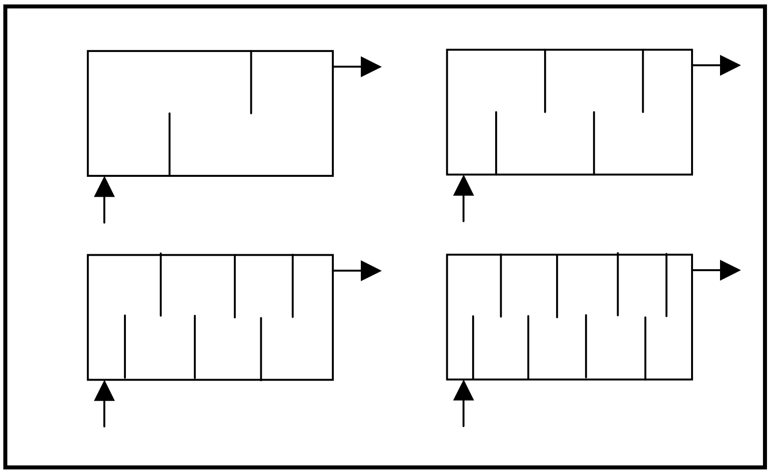


Figure 6-1 Experimental set-ups for 50% width baffles tested by Watters *et al*., (1973)

For the 50% width baffles, short-circuiting problems actually increased in the pond when more baffles were used. As can be seen in Figure 6-2, the flow tracked directly down the middle of the pond and, in effect, the baffle 'cells' create hydraulic dead space.

Increasing to 90% width baffles was found to give a lower hydraulic efficiency than was seen for the 70% width baffles. Watters, *et al*., (1973) believed that this was due to the narrow channel created at the end of the baffles that increased the velocity of the fluid in this area. The effect of channelling within baffled systems is explored further in Section 6.3.2.

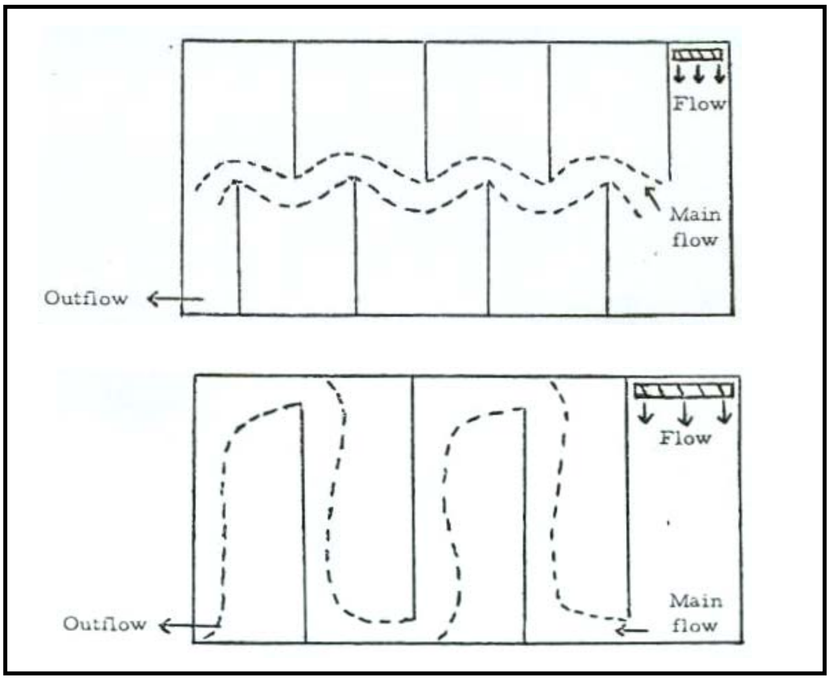


Figure 6-2 Flow patterns produced in the 50% & 90% width baffle runs (Watters *et al.*, 1973, pg. 49)

The conclusion was made that the 70% width baffles were the most hydraulically efficient option out of the three lengths tested.

Long, evenly spaced baffles improve pond efficiency.

Baffles of 70% width gave superior performance compared to 50% and 90% baffle widths.

6.2.2 Vertical Baffling

Vertical baffles were tested as shown in the following diagram.

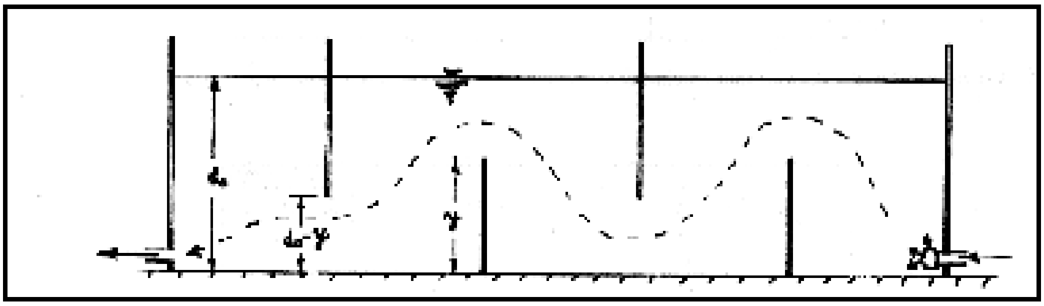


Figure 6-3 Experimental set-up for vertical baffle runs (Watters *et al.*, 1973, pg. 50)

Four experiments were performed: two with four baffles and two with six baffles. Surprisingly, the 4-baffle cases proved to be more efficient than the 6-baffle cases. Again this was attributed to channelling effects. However, when the results were compared against the horizontal baffle experiments, for a comparable amount of baffling it was found that the horizontal configuration was more efficient.

Horizontal baffles were found to be more efficient than vertical baffles.

6.2.3 Longitudinal versus Transverse Baffling

Longitudinal baffles are horizontal baffles that extend along the length of the pond, instead of across the width as shown in the following diagram from Watters *et al.*, (1973).

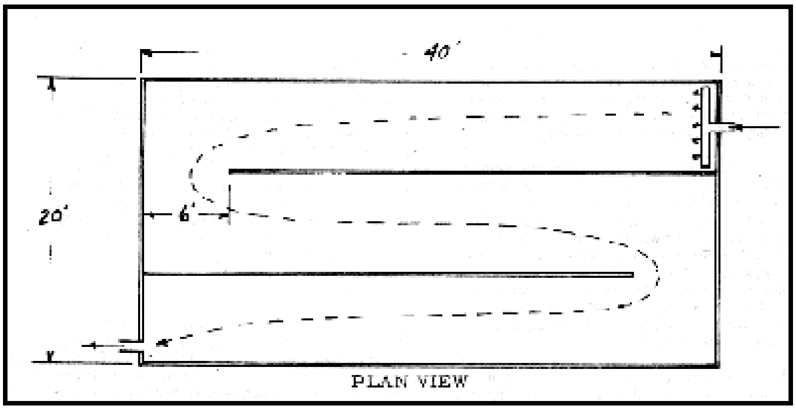


Figure 6-4 Experimental set-up for longitudinal baffle (Watters *et al.*, 1973, pg. 50)

It was found that for a comparable length of baffling, essentially the same result was achieved as for transverse baffling across the pond width.

Longitudinal baffling was found to be no more efficient than transverse baffling.

It is noted, however, that this experiment used a manifold inlet. If a simple horizontal inlet was used then it could be expected that transverse baffling might be more effective.

6.2.4 Interactions of Baffles and Inlets

Persson (2000) investigated the use of sub-surface berms or islands (in effect, baffles) located close to the inlet. He found that these resulted in a reduction in short-circuiting. This will have been due to the dissipation and redirection of the inlet jet. Similar work was done using baffles located close to the inlet in this study and this is reviewed later.

Shilton (2001) tested the effect of installing a single baffle (67% of the pond width) located halfway down the length of a laboratory model. The baffle was tested with three different inlets. In the first two tests horizontal inlets were used. It was found that after baffle addition the time taken for tracer to reach the outlet was lengthened considerably. However, in the final comparison using a vertical inlet, the baffle addition gave no further improvement over the un-baffled case.

While generally effective on ponds with horizontal inlets, traditional full-length baffles may not always further improve the efficiency in ponds with other inlet types.

6.3 New Thinking

The length, number and positioning of baffles has been extensively researched during the development of these guidelines. The majority of the research has been carried out using computer modelling, however, laboratory and field testing was also undertaken.

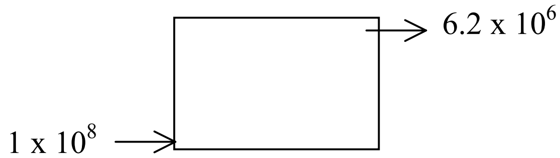
The computer modelling was undertaken in two broad stages. Initially a 'typical' primary facultative pond was sized according to a modern design manual (Mara & Pearson, 1998) and then simulated by computer modelling. The second stage of the computing modelling work was then based on the upgrade of an existing field pond. The details of this second stage work are presented in the appendices as a case study.

In both stages a range of baffle modifications were tested to assess their impact on hydraulic and treatment efficiency. The general flow pattern was studied and the treatment efficiency was quantified by integrating first order bacterial decay kinetics within the computer model.

The configurations shown in this current section come from the initial testing on the 'typical' primary facultative pond.

NOTE: For a benchmark, an inlet coliform concentration of $1x10^8$ cfu/100ml was used and the resultant efficiencies were calculated. This does not mean that any pond with a similar configuration will achieve the same concentration. In practice this will depend on the influent concentration, retention time, temperature and a host of other variables. The values presented here are only intended to be used to compare and contrast the <u>relative</u> improvements in efficiency between the different pond configurations.

The standard case of the pond without baffles was simulated first to provide a basis against which the baffled designs could be evaluated.

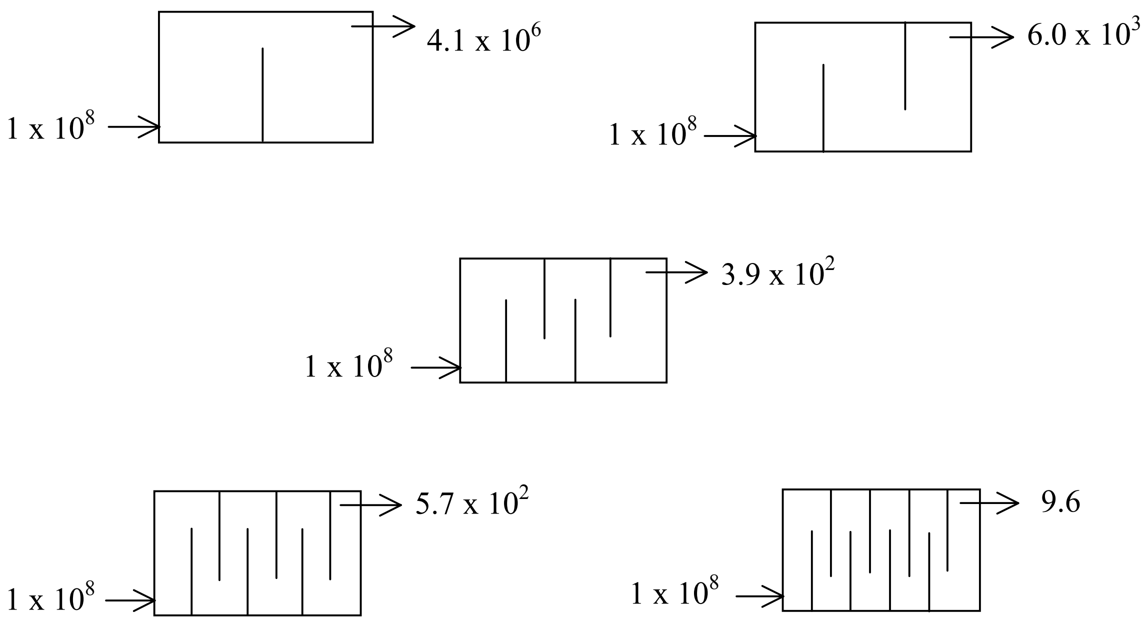


The flow pattern produced in the un-baffled pond was a large circular swirl. Despite the inlet and outlet being in opposite corners the bulk flow moved straight from the inlet around past the outlet, thereby allowing some influent to escape very quickly (short-circuiting) and impacting on the treatment efficiency.

6.3.1 Number of Baffles

Typically baffles tend to be ‘long’ extending across most of the width of the pond. A number of previous studies have, not unsurprisingly, concluded that using more baffles gives better hydraulic efficiency. But with cost in mind we need to better understand the effect of baffle number on treatment efficiency.

In this project a series of models were tested using evenly spaced, 70% width baffles. These configurations are illustrated below and their results are plotted in Figure 6-7.



A single baffle does give an improvement over an un-baffled case, but clearly stepping up to a two-baffle system was far superior. The study showed a further, but smaller, improvement was achieved by increasing to four baffles and where a high efficiency is trying to be achieved this may be warranted. However, the use of six baffles offered no further improvement and the extra gain provided by using eight baffles might not seem to warrant the extra cost in most applications.

A further argument against the use of too many baffles is discussed in Section 3. Unless the pond has a low organic and solids load (ie it is a maturation pond), then excessive baffles will create much higher localised loading near the inlet as compared to the outlet.

It is believed that lack of improvement between the 4 and 6 baffle cases is due to a change in the flow behaviour that exists between the baffle cells. This is discussed further in the following section.

A minimum of 2 baffles is recommended.

A further improvement was achieved using 4 baffles and this extra cost may be warranted in some cases.

Based on the results of this study, the use of more than 4 baffles would not be recommended.

6.3.2 Channelling versus Mixing within Baffle Cells

Previous work by Watters *et al*., (1973) mentioned a channelling effect on flow by baffles that were 90% of the pond width. A distinct pattern was observed and flow seemed to speed up around the end of the baffles.

The first two cells of the 6-baffle case tested in the laboratory work undertaken in support of these guidelines are shown in Figure 6-5.

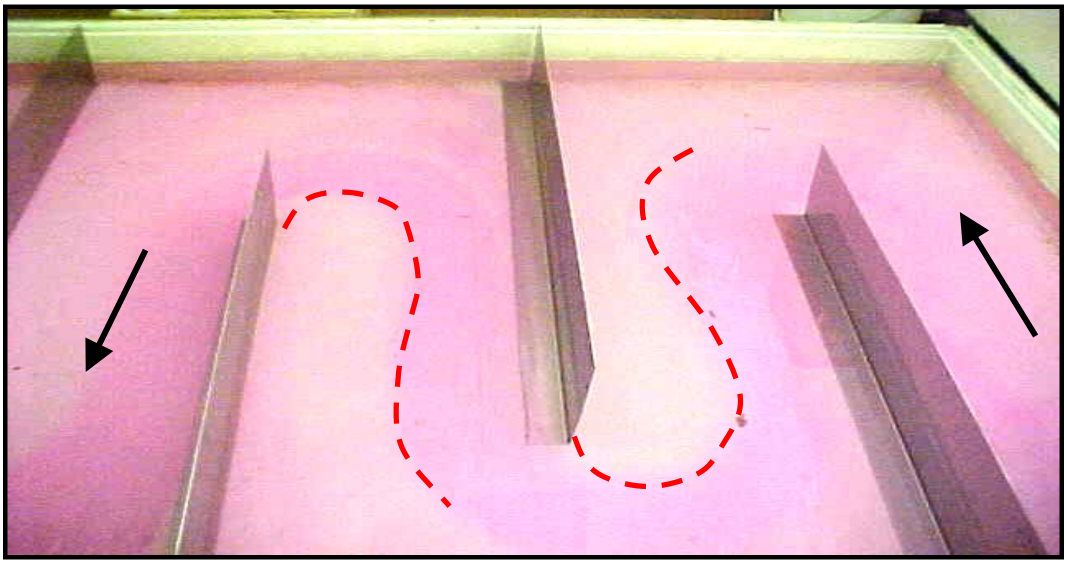


Figure 6-5 Channelling due to baffles

Figure 6-6, over the page, is a diagram produced by Watters *et al*., (1973) showing their observations.

Clearly these flow patterns are very similar but in Figure 6-5, this type of flow behaviour was seen when 70% width baffles were used.

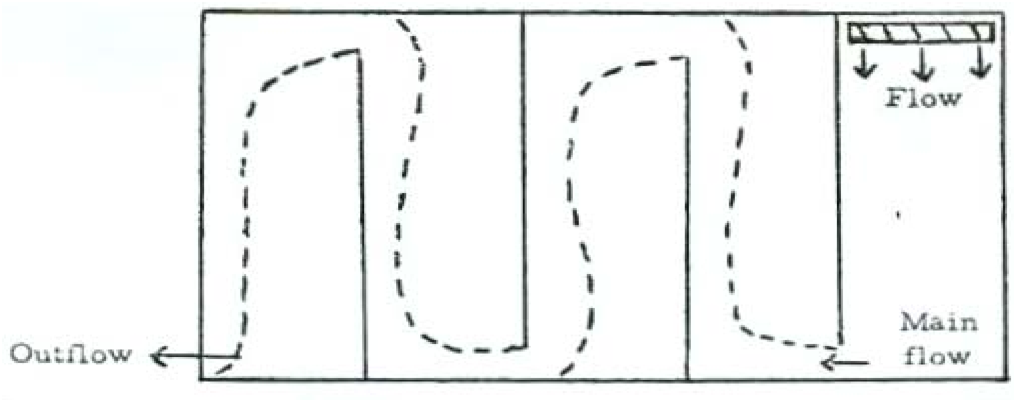


Figure 6-6 Channelling due to 90%width baffles (Watters *et al.*, 1973)

In the initial computer-modelling work, and in subsequent laboratory testing, the two-baffle case did not exhibit this characteristic. It showed a well-mixed circulation pattern in each cell. These observations have led to the conclusion that this channelling effect is not related to the baffle length, but instead is related to the spacing between the baffles/walls.

Occurrence of channelling between baffles is dependent on baffle spacing.

From the results obtained in the computer modelling work described in Section 6.3.1, a plot of treatment efficiency versus the number of baffles was made as shown in Figure 6-7.

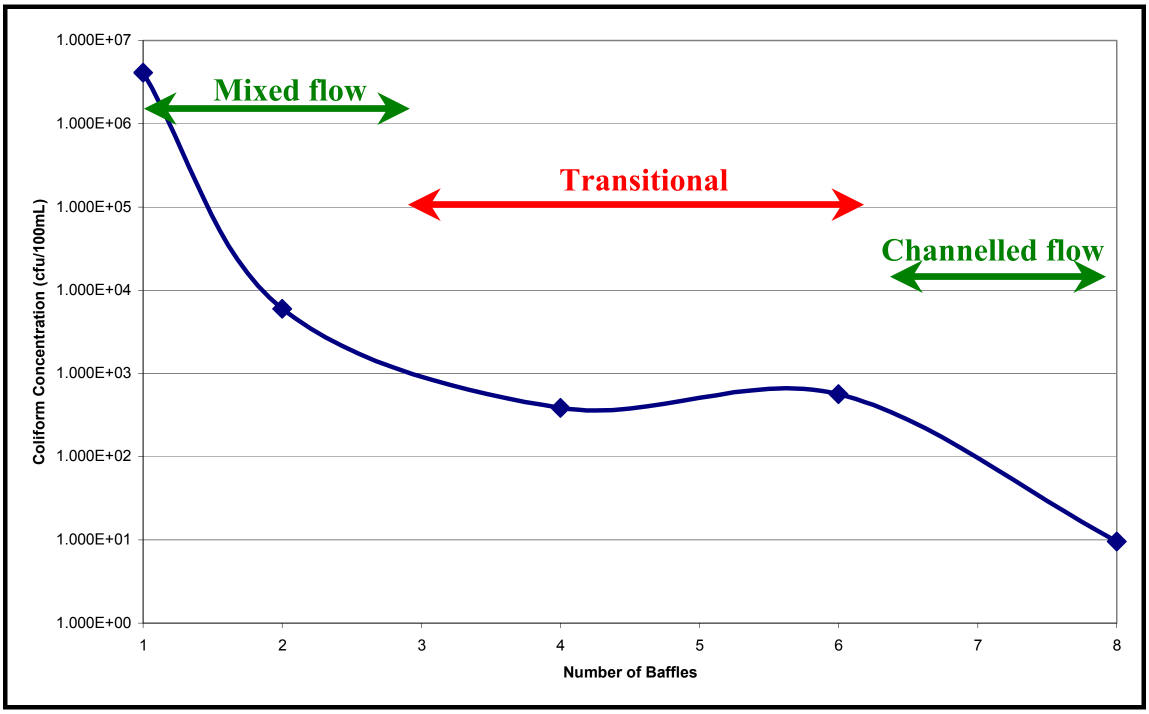


Figure 6-7 Plot of baffle number versus treatment

The treatment provided in the four and six baffle cases is very similar. During the research it was observed that in these cases, the cells near the inlet still had more of a mixed, circulating flow pattern with the channelled behaviour then dominating in the latter cells. This indicates a transition from mixed circulating flow through to channelled flow. This behaviour is discussed further in the following section.

6.3.3 Length to Width Ratio and the Invisible Baffle Effect

There is a general belief that increasing the length to width ratio of a pond helps force its hydraulic behaviour towards plug flow. As seen in the previous section where six to eight baffles were installed (giving length to width ratios approaching 20) this might be true but at lower ratios the picture is less clear-cut.

From our experiences with both laboratory and field ponds we have observed that at low ratios of 1:1 to 1:2, the flow tends to circulate right around the circumference of the pond if a horizontal inlet is positioned in a corner so as to discharge down the longer length.

However in laboratory testing on a pond with a ratio of 1:3 it was found that when the inlet was aligned to discharge along the shorter width, the behaviour changed dramatically. The flow moved across the width and around the corner, but then instead of travelling to the far end, it travelled about one third of the pond length and then turned quite sharply back into the middle of the pond. It appeared as if an ‘invisible’ baffle was in place!

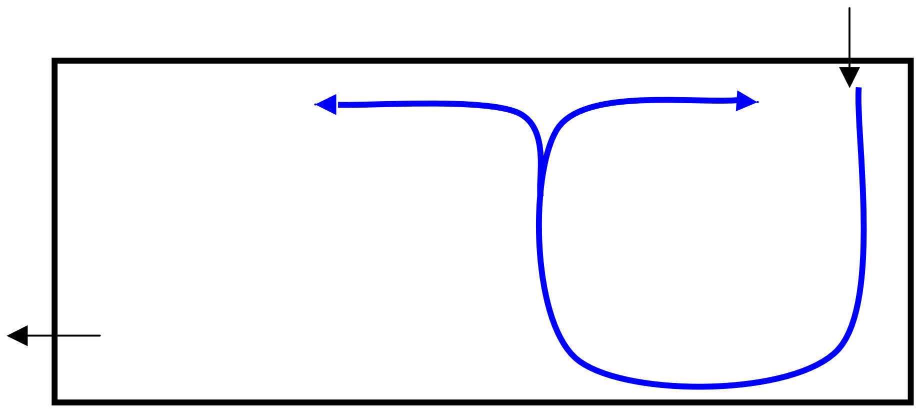


Figure 6-8 Illustration of the 'invisible baffle' effect

The reason for this phenomenon was actually quite obvious in retrospect. As the pond becomes narrower then it is possible to set up a series of counter-current, circulation cells that are roughly the diameter of the pond width. This is what may be happening in the transition zone discussed in the previous section. Circulating cells are established near the inlet end, but as the momentum decreases along the length these die out and channel flow starts to dominate.

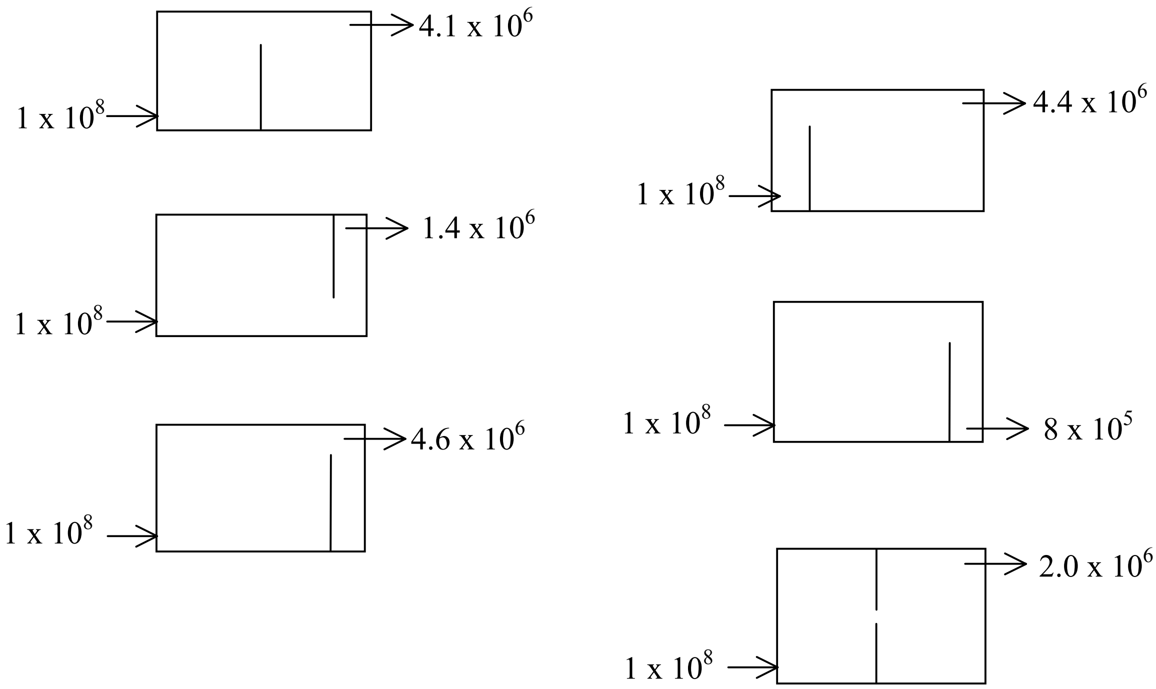
A series of these circulation cells could actually work very effectively, but further research is needed to better define this effect before it can be recommended for general application. What is very clear, however, is that the traditional thinking that in a long narrow pond, the influent simply flows slowly, in a plug flow manner, from one end to the other is not necessarily correct except at very high length to width ratios.

Traditional thinking that in a long narrow pond the influent simply flows slowly from one end to the other is not necessarily correct except at very high length to width ratios.

6.3.4 Alternative Single Baffle Positioning

As discussed previously, while a single baffle can produce an improvement in efficiency, two or more baffles are really far more effective. However, with the important consideration of cost in mind, it still seemed that single baffles warranted further investigation, particularly, if alternative placement options were considered.

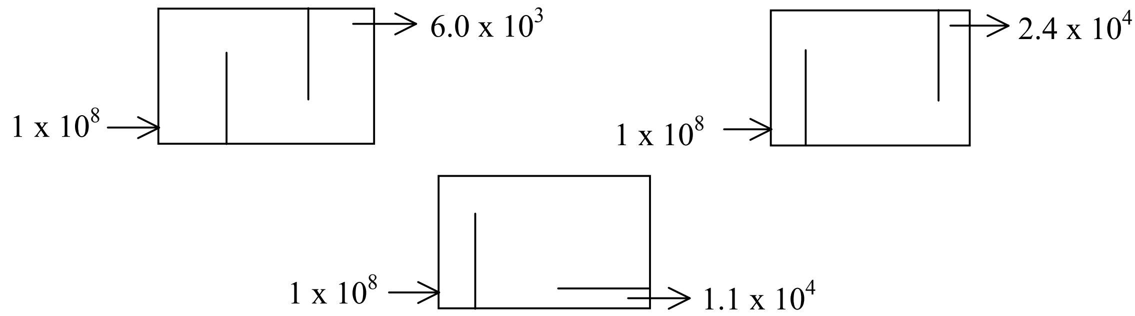
The following configurations were tested by mathematical modelling, however as can be seen, none of these designs came close to the results achieved by the use of two baffles.



Even with consideration of alternative designs, the use of two baffles gives far better performance than a single baffled pond.

6.3.5 Alternative Twin Baffle Positioning

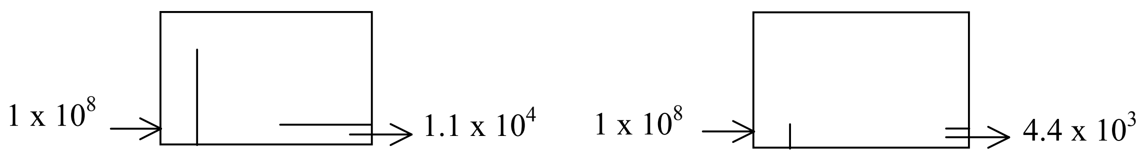
Usually long baffles are evenly spaced along the length of the pond. However, possibilities for alternative, baffle layouts have not been previously investigated. The second two of the three cases shown below modelled alternative baffling placement, but as can be seen these gave no improvement over the standard even spacing of the first case.



Normal, even baffle spacing across the pond is most effective.

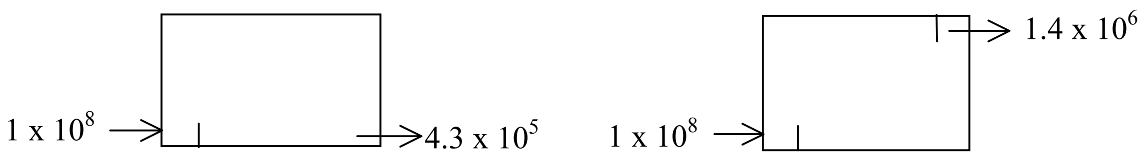
6.3.6 The Stub Baffle

It was felt that after a baffle has worked to 'turn the flow' it might not need to extend right across the pond. The cases below compare two standard 'long baffles' (70% width) against two much shorter 'stub' baffles (15% width).



Upon testing these designs by computer modelling and in the laboratory, it was found that the stub baffling performed extremely well. The stub baffle set up a tight circulation localised in the inlet corner. This appeared to mix and help disperse the flow evenly out into the larger main pond area. While the longer baffles obviously had benefits at blocking the flow, the tight circulation pattern was not set up and instead the flow was forced up along the channel.

Both configurations had similar treatment efficiency (as determined by computer modelling) and similar times to short-circuiting (as confirmed in the laboratory). Clearly for this particular configuration, the shorter and cheaper stub baffle could be just as effectively used. However, testing undertaken on the application of the stub baffles in the different configurations as seen below, didn't produce the same level of treatment efficiency as their long baffle counterparts did (see Sections 6.3.4 and 0).



Clearly while the stub baffle can work extremely well in some cases, its performance is sensitive to changes in pond configuration. This finding was also reinforced in the later work on the case study as discussed in Appendix One.

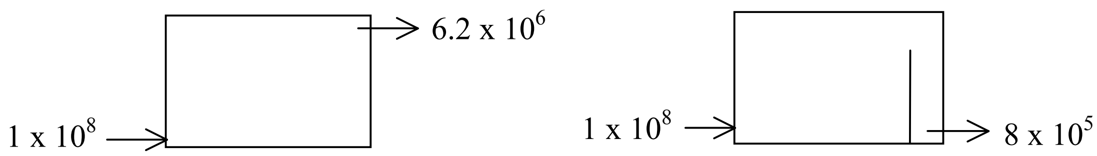
We have discussed previously how stub baffles have been successfully used to improve a vertical inlet and in the following section we note their effectiveness for shielding an outlet. However for traditional baffling applications we recommend that while stub baffles have a lot of potential they can not yet be considered a substitute to long baffles in general application. Clearly this is an area deserving of more research.

Stub baffles have the potential to provide similar treatment improvements as longer baffles but this performance is inconsistent on different pond configurations.

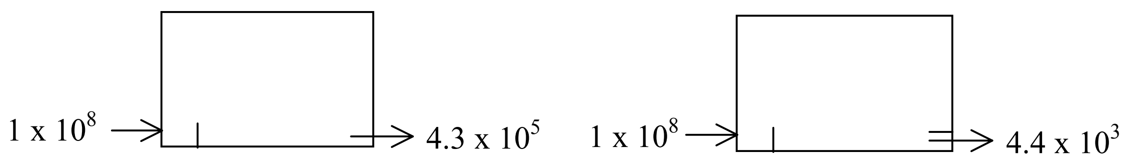
6.3.7 Baffles as an Outlet Shield

As shown previously in Section 6.3.4, the addition of a single baffle placed in front of the outlet, improved treatment efficiency from 6.2×10^6 to 1.4×10^6 cfu/100mL. However, this arrangement wasn't ideal as the entrance to the outlet channel was in a direct line with the inlet jet.

One possibility would be to move or redirect the inlet. The other, as shown below, is to position the baffle to block the 'swirl' from the inlet and then relocate the outlet so that it is shielded behind the baffle. As seen below, this achieved a result of 8×10^5 cfu/100mL, which represents almost another order of magnitude in improvement.



Another example of using a baffle to shield the outlet can be seen in comparison of two of the stub baffle cases from the previous section. As seen below, for this particular pond design, even a small stub baffle worked effectively to shield the outlet.



Baffles that 'shield' the outlet are beneficial.

7 WIND, AERATORS, MIXERS AND TEMPERATURE

What effect does wind, aerators/mixers and temperature have on the flow pattern in a pond?

7.1 Introduction to Wind Effects

It is generally believed that wind provides a positive influence on ponds. This is because of the perceived improvement in aeration and mixing.

There are two main mechanisms of oxygenation in pond systems: mass diffusion from the atmosphere and oxygen production by algae within the pond. It is, however, the oxygen provided by the algal population that is the most significant. The aeration provided by wind mixing is actually not as important as is commonly believed.

With regards to mixing, a number of researchers are noting that wind may create flow patterns in ponds that encourage short-circuiting problems. Because of this there is a growing belief that wind may have more of a negative influence on pond performance than a positive one!

Contrary to general belief, exposure to wind can have a negative influence on pond performance.

7.2 Previous Work

It is often stated in the literature, that wind has a major effect on the mixing and flow patterns in waste stabilisation ponds. However, there has actually been very limited experimental work reported to quantify this assertion.

Because of the limited research in this area we can only provide this section of the guidelines based on limited understanding and new, and relatively untested, ideas!!!

Research on wind effects on pond hydraulics is very limited, current understanding is largely based on assumptions.

7.2.1 Wind Induced Circulation

Several researchers have proposed that wind action across the surface of ponds induces a three-dimensional, circulation pattern consisting of surface flow, as a result of the wind shear, and a reverse bottom current. This work was based on computer modelling alone and not tested against direct experimental measurement. However, when a breeze is blowing across a pond it is actually possible to visually observe opposing currents in a pond. A very shallow wind driven surface flow can sometimes be seen to be moving in the opposite direction to the main flow circulation.

In contrast, experimental drogue tracking work presented by Shilton (2001), and confirmed again in research undertaken in this project, indicated the flow pattern was predominantly two-dimensional, circulating in the horizontal rather than the vertical plane. Shilton (2001) also conducted mathematical modelling of the wind effect on the pond studied. He found the model did show evidence of a reverse bottom current but it was only present near the very bottom of the pond. At the depths of 0.5 metres and 1.0 metre, which corresponded to the depths of the experimental drogues, the model confirmed the flow to be circulating two-dimensionally in the horizontal plane.

It may be that as wind dominance increases the circulation in the vertical plane also increases, but when a horizontal inlet dominates then the flow predominantly swirls around in the horizontal plane. Understanding the circulation patterns in a pond subjected to wind shear is clearly a complex problem, but it seems important that the engineer at least has an appreciation of these behaviours. A potential design approach for controlling flow behaviour is discussed in later sections.

7.3 New Thinking

7.3.1 Just how important is Wind?

As mentioned, the literature generally suggests that wind has a major influence on the mixing and flow patterns within waste stabilisation ponds, however, on close review there is actually very limited experimental work to support this assumption. Recent research by Shilton (2001) used three arguments to question the significance of wind effects on waste stabilisation ponds:

1. Wind shear was incorporated into a computer simulation of a tracer study on a field pond. While adding the wind was found to improve its agreement against experimental data, it was noted that the overall effect was not substantially different to the simulation results obtained when wind was neglected.
2. A broad theoretical analysis of two ponds, sized using a modern design manual, showed the power input via the inlet to be more dominant than the power input due to the wind, except at high wind speed or if a large inlet was used.
3. Whilst wind is highly variable in speed and direction, the flow from the inlet is relatively consistent over time and is always inputted as a concentrated point source in a fixed position and direction.

There are, however, several reasons why the inlet power may not always be so dominant in all pond systems:

1. Overly large inlets are often used, which means that the inlet velocity (and its power input) is significantly reduced.
2. A significant number of ponds in current use are oversized with larger surface areas than modern designs. This increases the relative influence of the wind.
3. For periods of time the wind speed will be significantly higher than the average value used in the calculations.

However, given the above, it is still very clear that in many cases we have tended to underestimate the influence that the inlet has (or could have) on the pond hydraulics.

The influence of the inlet is often underestimated.

7.3.2 Controlling the Effect of Wind on Pond Hydraulics

Whilst the occurrence of wind across a pond cannot be easily controlled, the inlet pipe is a physical structure that can be easily manipulated. By designing an inlet that dominates the power input into a pond, this could be used to force the flow into a predetermined pattern rather than allowing it to wander with fluctuation in wind direction.

This technique potentially offers engineers a practical method of controlling the flow pattern so as to optimise the hydraulic efficiency of a pond. This is, of course, just a very broad and theoretical evaluation and does not account for mechanisms such as the internal transfer and dissipation of energy. However, when this evaluation was applied to a field pond it was found to predict somewhat higher dominance for wind than was actually observed in experimental and computer modelling. Given that this approach appears to overestimate the wind effect rather than underestimate it, then it could be considered to provide a conservative estimate of wind influence.

7.3.3 A Method for Approximating Wind and Inlet Power Inputs

As a design tool this approach is novel and untested, but in the absence of any other approach we believe that it could, at least, give the design engineer a 'rough tool' for evaluating the relative influences of the wind and inlet.

The power input (P_I) from an inlet can be estimated by:

$$P_I = 0.5\ \rho_w . v^3 . A$$

where: ρ_w = density of water (kg/m^3);
v = velocity of water (m/s);
A = cross-sectional area of inlet (m^2).

If this inflow enters via a circular pipe with a given flowrate Q (m^3/s) then, assuming a value of 1000kg/m^3 for water density, the relationship between the power input and the pipe diameter ϕ (m) is given by:

$$\boxed{P_I = \frac{811\, Q^3}{\phi^4}}$$

The input of wind power (P_w) can be determined by:

$$P_w = u_s . \tau_w . A_{pond}$$

where: u_s = surface water velocity, (m/s);
τ_w = shear stress of the wind on the water surface, (kg/m.s^2);
A_{pond} = surface area over which wind shear is exerted, (m^2).

The wind shear stress can be estimated from:

$$\tau = k . \rho_a . v_w^2$$

where: k = empirical constant;
ρ_a = density of air (kg/m^3);
v_w = velocity of wind (m/s).

Larsen (1999) stated that the surface velocity (u_s) on a water body is approximately equal to 3% of the wind velocity (v_W). This same value was used by Wood (1997) after a thorough review of the literature. By substituting in this relationship and the general empirical equation for wind induced shear stress, τ_W, the equation for wind power becomes:

$$P_w = (0.03\ v_W).(k.\rho_a.v_W{}^2).A_{pond}$$

$$\boxed{P_W = (0.03.k.\rho_a).v_W{}^3.A_{pond}}$$

For a pond of given area this equation allows calculation of the power input for a range of wind velocities.

Selection of the empirical constant, k, is important and depends on the height at which the wind velocity is measured. In his work on a model yacht pond 60m wide, 240m long and 2m deep, Van Dorn (1953) cites three values for the empirical constant depending on which height the wind speed is measured at. These range from 0.0037 for a measurement height of 0.25 metres to 0.0011 for a measurement height of 10 metres. For our work below we have interpolated to use a value of 0.0017.

7.3.4 Example of Application of Wind and Inlet Power Analysis

The equations given above can be used to determine the power supplied by the inlet (P_I) and the power supplied by wind (P_W). The table below shows P_I and P_W for a range of wind velocities and inlet diameters for a pond 640m x 320m (Area = 204800m^2) and a flowrate of 10,000 m^3/day (0.116m^3/s).

Average wind speed = 2.8 m/s

⇓

275W of power supplied

Wind Speed (m/s)	P_W (W)
0	0
0.5	2
1.0	13
2.0	100
	1567
6.0	2707

Inlet Diameter (m)	P_I (W)
0.100	12659
0.125	5185
0.150	2501
0.175	1350
0.200	791
0.225	494
0.250	324
0.275	221
0.300	156

Figure 7-1 Example of wind and power analysis

By using several years of meteorological records to determine an average wind speed of 2.8 m/s for the region used in this example, it can be seen that at this velocity the wind will supply 275W of power input. From the table for P_I, it can be seen that 275W of power will be supplied by the inlet at a diameter of between 0.25 and 0.275m.

Alternatively, the equation for P_I can be used to back calculate the inlet diameter at which equal power is inputted:

Example Calculation:

$$P_W = (0.03.k.\rho_a).v_W{}^3.A$$

$$P_W = (0.03 \times 0.0017 \times 1.3) \times 2.8^3 \times 204{,}800$$

$$P_W = 298W$$

If P_W = 298W, then for inlet equivalence $P_I = P_W$

$$P_I = \frac{811\ Q^3}{\phi^4}$$

$$298 = \frac{811 \times 0.116^3}{\phi^4}$$

$$\phi^4 = \frac{811 \times 0.116^3}{298}$$

$$\phi = 0.26\text{m}$$

Therefore, if the diameter of the inlet is less than 0.26m, then the inlet power will theoretically dominate over wind power (at average wind velocity). We need only reduce the inlet diameter slightly more and the inlet power markedly rises. For example, reducing to a 200mm diameter pipe would give a power input well over double that provided at the average wind speed. As mentioned the inlet adds this power input as a point source in a fixed direction and is relatively consistent as compared to wind shear, which is distributed over the whole pond surface and is highly variable in both velocity and direction. As a result the inlet might actually be expected to dominate the flow pattern even at equivalent power.

For a large pond such as in the above example, a designer might have normally chosen an inlet much bigger than this, say a 300mm to 400mm pipe or channel. However, after undertaking this ‘approximate’ calculation the inlet size might be reduced in an attempt to keep the flow pattern in the pond more controlled.

But where does this extra power actually come from? In the case of a pumped discharge or gravity sewer discharge into a pond reducing the inlet size will obviously increase the ‘head loss’ in the pipeline system and therefore reduce the maximum hydraulic capacity of the pipeline. As long as the inlet size reduction is not exaggerated then, in practice, this reduction of the maximum hydraulic capacity is probably not going to present a significant problem, although this should be checked before implementation.

Alternatively, if the inlet pipe comes in from another pond and, if there is not already an adequate drop in height between the two ponds, it means that the water level in the first pond will increase or ‘bank up’ so as to provide the extra energy required to drive the water through the smaller inlet. This increase in height (H) can be estimated from:

$$H = P_I/(9810.Q)$$

The recommended approach is, however, simply to install a ‘high flow’ bypass pipe adjacent to the reduced diameter inlet pipe to ensure the pond doesn’t bank up too high.

Cautionary Notes:

1. ***This approach is novel and untested!***
2. ***It is based on a broad theoretical evaluation and does not account for mechanisms such as the internal transfer and dissipation of energy.***
3. ***This analysis assumes a submerged horizontal inlet where the inlet momentum drives the circulation in the pond. It is not applicable to vertical inlets or where the inlet momentum is dissipated.***
4. ***Even if the inlet dominates the flow pattern at average wind speeds, high wind speeds may still dominate at certain periods of the year and inlet/outlet placement shouldn't be such that treatment is compromised at these times.***
5. ***In areas with very high average wind speeds this technique may be impractical to implement.***
6. ***If reducing the inlet diameter requires the water level to 'bank up' in the sewer, the deposition of solids in the sewer needs consideration.***
7. ***If reducing the inlet diameter requires the water level to 'bank up' behind a wall between two ponds, the pressure build up on the wall needs consideration.***

7.4 Aerators and Mixers

It can be seen from the analysis presented above that the actual power inputted from the wind and the inlet is not actually very high – being in the order of watts rather than kilowatts. If we add an aerator (or some other type of momentum source such as a mixer) into the pond how does this compare?

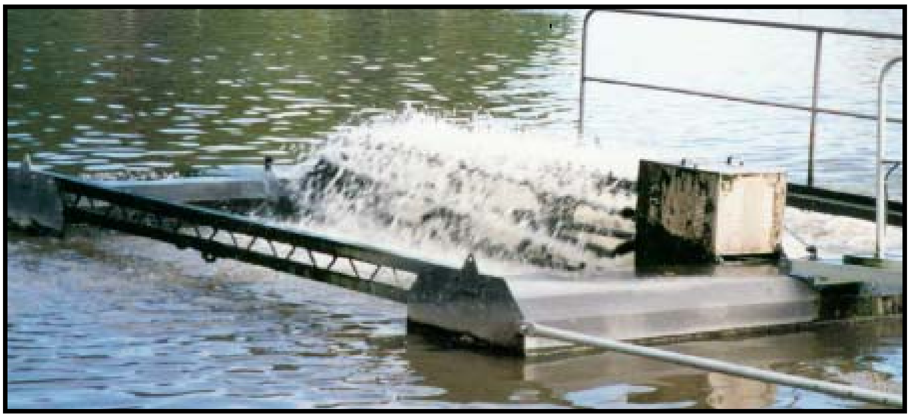


Figure 7-2 Example of an aerator

Taking cage aerators as an example, typical units range from 1.1kW to 4kW in rated power. However, it should be remembered that they don't actually operate at their rated capacity. Discussions with a manufacturer indicated that their unit, which was rated at 4kW, typically consumed only 1.2 kW. Further still, a reasonable percentage of this power is lost in the transmission efficiency with perhaps only around 75% of the power being actually transferred into the water. Therefore the actual power inputted from an aerator rated at 4kW may well be only 1kW (1000 watts) or less.

As before the same questions arise as to how this energy is then transferred and dissipated within the pond fluid. This is certainly not an exact analysis, but again as a rough guide we can see that compared to the example above, a single aerator rated at 4kW would still be inputting around 3 times as much power than the 0.26m diameter inlet pipe or the average wind shear.

This sort of rough analysis essentially tells us that aerators and other types of mixers are likely to be dominant when it comes to defining the flow pattern in the pond. Indeed the engineer may even choose to add a mixer to control the flow pattern in preference to reducing the inlet size.

Aerators and other types of mixers are likely to dominate the flow pattern in a pond.

This evaluation also illustrates that haphazard placement of aerators could have quite negative effects if they act to swirl the wastewater rapidly past the outlet. For design purposes, the previous comments given in regard to placement of horizontal inlets and shielding the outlet would also apply here.

7.4.1 High Rate Algal Ponds

Paddle wheel mixers, as seen in the photo below, are an integral part of the design of High Rate Algal Ponds. The gentle circulation (typically 0.15 m/s) of wastewater around the baffled pond maintains algae in suspension (Craggs, 2002, pers. comm.).

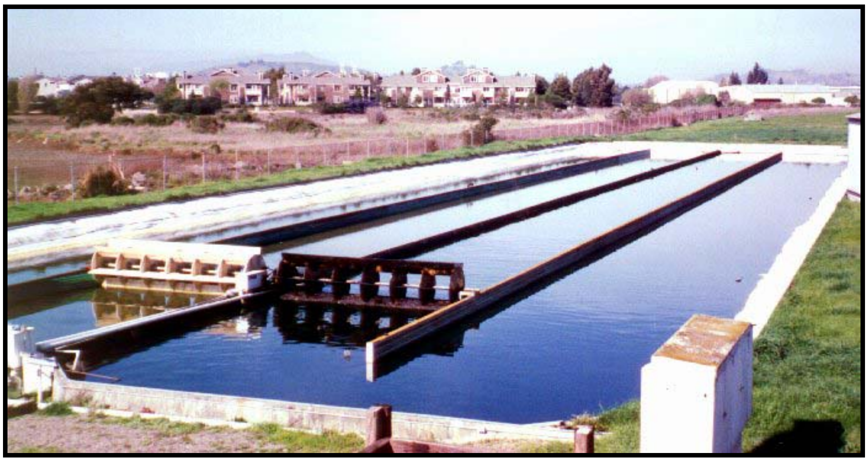


Figure 7-3 High Rate Algal Pond showing paddle wheel mixers

The influent is normally added 'downstream' of the paddlewheel near the base of the pond, while the outlet is located at the surface on the other side, thereby ensuring that the influent wastewater must make at least one circulation around the pond before any discharge (Craggs, 2002, pers. comm.). However the disadvantage of this circulating flow is that it does quickly move influent around the pond and back past the vicinity of the outlet, which essentially creates a short-circuiting problem.

Very little research has ever been published on the hydraulics of these systems, but it would seem likely that these systems could benefit from the use of flow shields/deflectors, as discussed previously, to shelter the outlet and prevent wastewater short-circuiting the treatment process after only the first few circulations.

High rate ponds may benefit from the use of flow shields/deflectors to shelter the outlet.

7.5 Temperature Effects

Stratification is a density-induced separation of the pond into layers. These layers may be characterised by different temperature, oxygen and redox measurements.

Stratification may be detrimental to the hydraulic behaviour of a pond system. It is possible that an inflow could ‘short cut’ across the top of a stratified pond instead of mixing into its full volume. This effect could be magnified, or occur in its own right, if the influent flow has a significantly different temperature to that of the main body of the pond and is not well mixed upon entry.

Inflow can ‘short cut’ across the top of a stratified pond instead of mixing into its full volume.

Wastewater that is confined to one layer will cause a significant reduction in retention time and, therefore, treatment efficiency. Macdonald and Ernst (1986) concluded that in addition to design aspects, thermal stratification was responsible for short-circuiting in the ponds they studied by tracer experiments. It is important to note, however, that this was an assumption drawn from the tracer data recorded at the outlet. There were no specific measurements made of the tracer moving through the pond itself.

Potential solutions to these problems might involve:

1. The use of vertical baffling to ensure the vertical mixing of the flow.
2. Ensuring adequate mixing of the influent into the main body of the pond.
3. Provision of mixing in the vertical profile.

Stratification is frequently assumed to imply some degree of convective mixing. However, it is important to note that the two are not necessarily linked. Convective mixing will only occur in a pond if it becomes thermally unstable. This results from a rapid cooling, such that the lower layers cannot become thermally equalised quickly enough by conduction. In this case the warmer lower layer convects up in exchange with the cooler and denser upper layer. Because convection currents act immediately to equalise any thermal imbalance this effect is very difficult to study experimentally. Extremely accurate temperature measurements taken simultaneously throughout the pond’s depth are required and to date this sort of work has not been undertaken.

What is well documented, however, is the incidence of pond turnover. Overturn has a serious impact on pond operation. An overturned pond at the Dan Region treatment system in Israel was observed to turn the pond from its normal green to a milky grey colour, release odours and reduce its treatment efficiency (Icekson, 1996).

Ponds in New Zealand have also been observed to follow similar rapid turnovers. Traditionally, this has been blamed on convective mixing of the stratified pond liquid layers. It is however possible, that the mechanism is somewhat different. Two separate studies (currently unpublished) in New Zealand have found that the sludge layer frequently has higher temperatures than the water column above it. Therefore it may be the case that rather than pond overturn being due to convection of the lower liquid layer, it is due to the rising of the sludge layer.

8 REFERENCES

Note: In developing the style of these guidelines, it was decided that they must be kept concise and practical rather than becoming a detailed academic report. As a result we have minimised the number of citations, preferring to generalise rather than getting into specifics. For a recent, detailed literature review in the pond hydraulics area, readers are directed to the PhD thesis by Shilton (2001).

Craggs (2002). National Institute of Water and Atmospheric Research, Hamilton, New Zealand. Personal Communication.

Fares, Y., Frederick, G., Vorkas, C. and Lloyd, B. (1996). Hydrodynamic effects on performance of waste stabilisation lagoons. Unpublished copy from author.

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MacDonald, R. and Ernst, A. (1986). Disinfection efficiency and problems associated with maturation ponds. *Water Science and Technology*, 18(10): 19-29.

Mangelson, K. (1971). *Hydraulics of Waste Stabilization Ponds and its Influence on Treatment Efficiency*. Doctorate Thesis; Department of Civil Engineering, Utah State University; Utah, USA.

Mara, D. and Pearson, H. (1998). *Design Manual for Waste Stabilization Ponds in Mediterranean Countries*. Lagoon Technology International; Leeds, England.

Marais, G. (1974). Faecal bacterial kinetics in stabilization ponds. *Journal of the Environmental Engineering Division, ASCE*, EE1: 120-139.

Pearson, H., Mara, D. and Arridge, H. (1995). The influence of pond geometry and configuration on facultative and maturation waste stabilisation pond performance and efficiency. *Water Science and Technology*, 31(12): 129-139.

Persson, J. (2000) *The hydraulic performance of ponds of various layouts*. Urban Water, 2, 243-250.

Shilton, A. (2001). *Studies into the Hydraulics of Waste Stabilisation Ponds*. Doctorate Thesis. Institute of Technology and Engineering, Massey University; Palmerston North, New Zealand.

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Watters, G., Mangelson, K., and George, R. (1973). *The Hydraulics of Waste Stabilization Ponds*. Research Report; Utah Water Research Laboratory, College of Engineering, Utah State University; Utah, USA.

Wood, M. (1997). *Development of Computational Fluid Dynamic Models for the Design of Waste Stabilisation Ponds*. Doctorate Thesis. Department of Chemical Engineering, University of Queensland; Brisbane, Australia.

Wood, M., Greenfield, P., Howes, T., Johns, M. and Keller, J. (1995). Computational fluid dynamic modelling of wastewater ponds to improve design. *Water Science and Technology*, (12): 111- 118.

9 APPENDIX ONE: UPGRADE STRATEGY – A CASE STUDY

How can the issues presented be integrated to upgrade an existing pond system?

9.1 Introduction

This section presents a case study. Its purpose is to show the reader how some of the ideas developed in this document were refined and applied to an existing pond.

The development work for this case study was commenced part way through the broader research programme. Through this process we were able to take some developing ideas and apply them to a real situation. In its own right this exercise then led to the refinement of many of the final ideas presented in previous sections.

9.2 The Pond Studied

The Ashhurst waste stabilisation pond system is approximately 20km east of Palmerston North, New Zealand. There are two ponds in the system, a primary pond and a smaller (≈ 120m x 60m) secondary pond divided by a block wall. They are connected by a 300mm diameter concrete pipe located approximately 18 metres from one end of the pond. These investigations focussed on improvements to the secondary pond shown below.

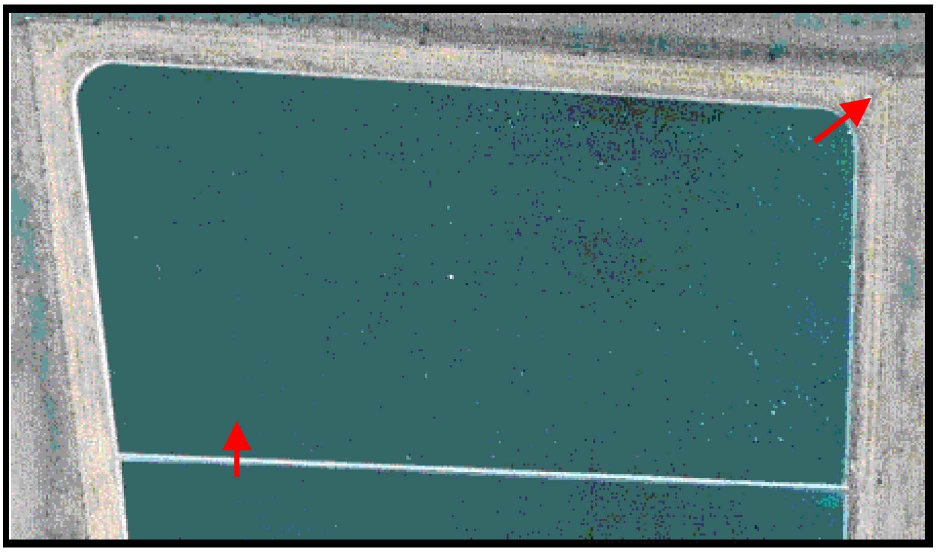


Figure 9-1 Ashhurst secondary pond – unmodified

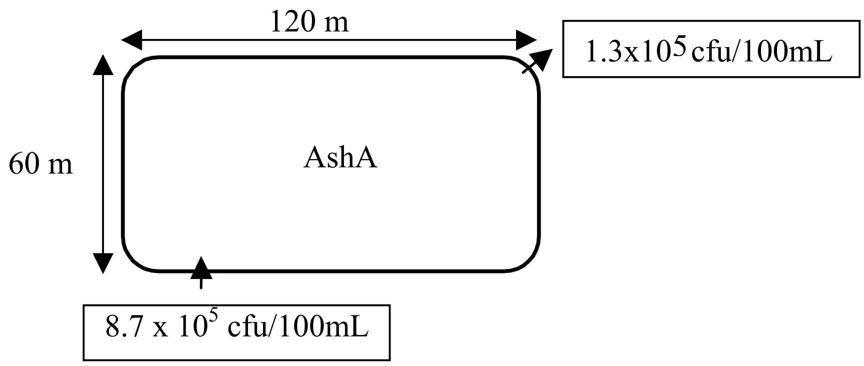
9.3 The Design Process

In total, twenty-five design modifications were evaluated by computer modelling for this part of the project. A number of these were simply minor variations to 'tweak' the design improvements. In this section some of the more effective design modifications are reviewed, while in Appendix 4 some of the other configurations that were tested, and the results obtained, are illustrated.

The success of each configuration was primarily evaluated in terms of the resultant effluent coliform concentration. In a field pond, conditions are constantly changing but for the purposes of this evaluation we needed to select a suitable inlet coliform concentration. Based on an average of samples collected at the inlet pipe into the secondary pond an inlet concentration of $\underline{8.7x10^5\ cfu/100mL}$ was used.

9.3.1 Existing Pond

Illustrated in the simplified diagram below is the existing base case with no modifications.



As seen the existing arrangement (basic case - AshA) did not significantly reduce the level of coliforms from the inlet.

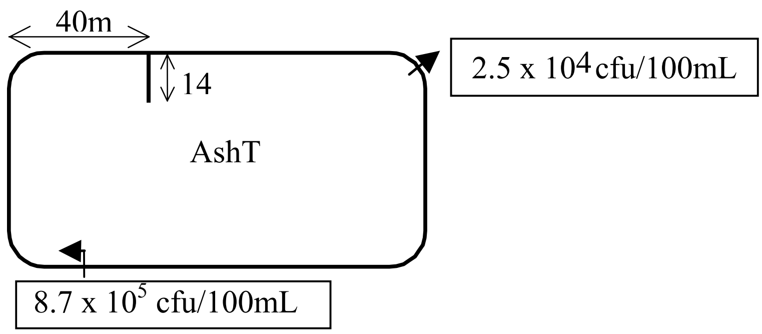
9.3.2 Stub Baffles and Inlet Modification

Because of a limited budget the option of using cheaper, short stub baffles were the main focus of the first of the series of configurations investigated. A number of arrangements were tested including varying baffle position, orientation, and slightly different lengths.

All of these cases gave improvement on the existing situation with the concentration of coliforms at the outlet being reduced by at least an order of magnitude compared to the base case.

Concurrent to this work, the idea of using inlet jet attachment, as discussed in Section 4.3.3, was developed.

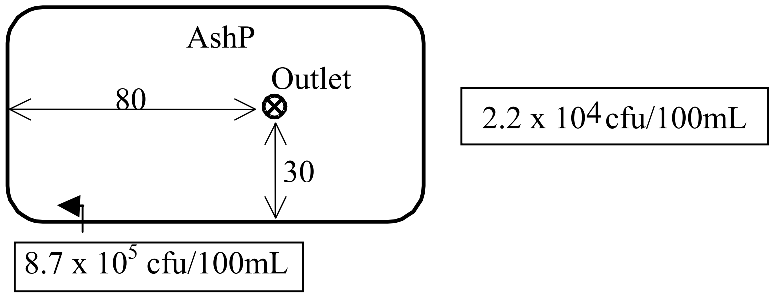
Ultimately it was found that in order to achieve the most effective results these concepts needed to be integrated and this was done in the AshT case shown following.



The coliform concentration for this case was the lowest achieved using a stub baffle and, therefore, held promise as an economic and effective upgrade option.

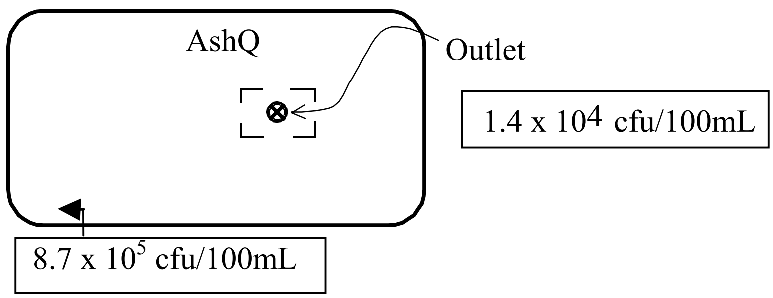
9.3.3 Central Outlet

As part of the development process in this case study research work, the idea of using a central outlet was developed. The tightly controlled flow pattern achieved by turning the inlet into the wall while using jet attachment could again be taken advantage of by placing the outlet in the central 'dead zone'. This was modelled in AshP.



The central outlet yielded a coliform concentration similar to that of the stub baffle case AshT. AshP has the advantage of avoiding the costs of the baffle, although in practice this modification would still have some reasonable cost to implement. Wind may also become an issue in such a design. When the wind speed increases then the tightly controlled outer flow pattern could be pushed across towards the central outlet.

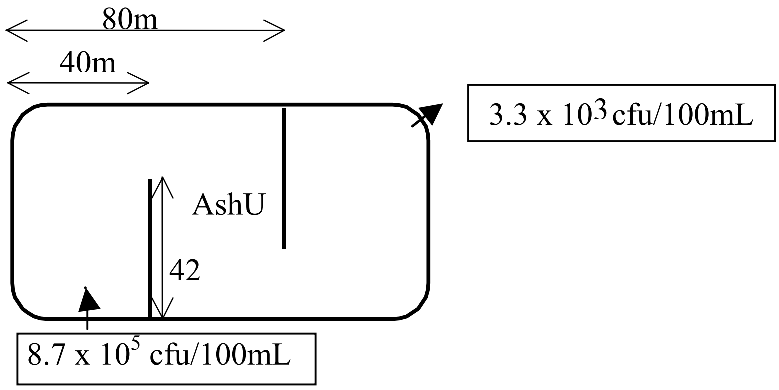
To refine this option further, outlet protection was provided by baffle/deflectors around the central outlet to divert the flow away from the immediate vicinity of the outlet as seen below AshQ.



This flow protection further provided a small further improvement to the treatment efficiency of the pond.

9.3.4 Long Baffles

'Long' evenly spaced baffles were also evaluated for this case study. The use of two long baffles in the traditional evenly spaced arrangement were tested (AshU).



This design produced the best treatment efficiency out of the cases tested.

9.3.5 Final Design

The final selection of an upgrade option for the field pond needed to take into account the following four questions:

1. Will the upgrade result in a reasonable improvement in treatment performance?
2. Is the upgrade practical – i.e. can the changes be implemented without difficulty?
3. What is the cost?
4. How innovative is this demonstration?

Based on the above criteria, it was decided to implement AshT (inlet turned for jet attachment and one stub baffle). This represents a relatively cheap but effective solution, and for the purposes of this project allowed a practical demonstration of two innovation ideas – the edge swirl and a stub baffle.

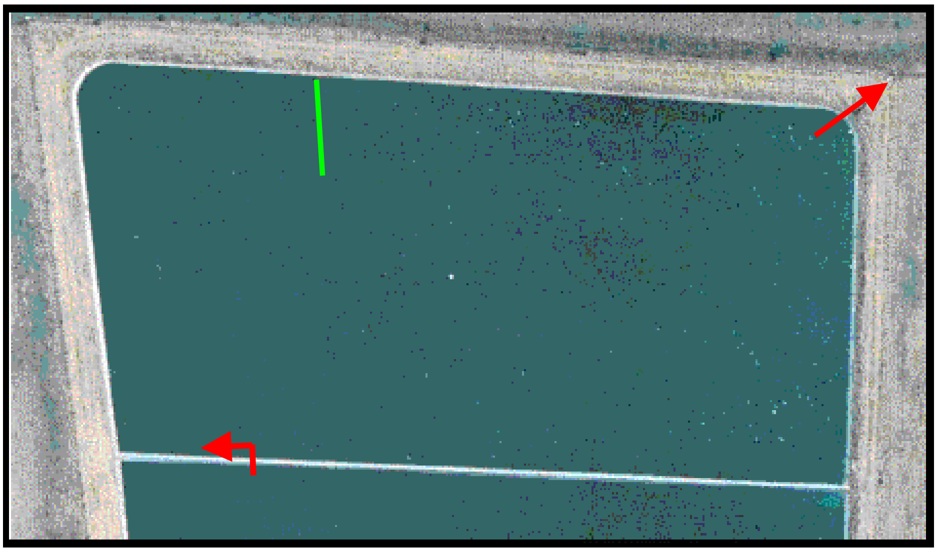


Figure 9-2 Final modification to Ashhurst secondary pond

The inlet was modified using a stainless steel right-angle bend as shown in the following picture. This was tapered at one end to allow it to be inserted and forced into place inside the existing concrete inlet pipe.

Figure 9-3 Inlet insert used in field trial

The baffle was fabricated out of heavy duty (650gsm) PVC, with a sleeve in the top and the bottom for floats and a heavy chain respectively. The floats were made of 3m lengths of 100mm diameter PVC sewer pipe sealed at the ends. The chain had a weight of 100kg per 12m.

The baffle was put together on dry land, bunched together and tied. It was then floated into place with the aid of extra 150mm diameter PVC sewer pipe floats and dropped into place. A wire rope threaded through the top sleeve was then secured on either side of the pond to ensure it maintained position. The following photos show the baffle installation.

Figure 9-4 Baffle being installed at Ashhurst secondary pond

9.4 Field Testing

A tracer study was performed and, as predicted by the computer modelling, the tracer plume from the inlet clung closely to the edge of the pond as it moved around to the stub baffle on the opposite side. At that point the baffle turned and directed the flow back towards the inlet side of the pond.

A comparison of tracer studies undertaken before and after this upgrade showed that this modification was successful in significantly reducing the short-circuiting problem within the pond. The time taken until the tracer concentration measured at the outlet reached its peak was improved by a factor of seven.

The table below shows the improvement expressed in terms of outlet coliform concentrations. The middle column shows the concentration predicted in the CFD computer modelling as presented previously. The column on the right shows the concentration calculated by integrating first order decay kinetics with the experimental tracer data. This calculation allows us to evaluate the hydraulic improvement in terms of treatment efficiency.

Table 9-1 Performance of Ashhurst Upgrade

	Outlet Conc. (cfu/100mL) ***Predicted via CFD Modelling***	Outlet Conc. (cfu/100mL) ***Calculated using Experimental Tracer Data***
Unmodified	1.30×10^5	1.29×10^5
Modified	2.5×10^4	1.1×10^4

The results confirm that the modifications provided an order of magnitude improvement. It also shows that the CFD prediction is very reliable when compared against the result derived from the experimental tracer data. This provides a good degree of confidence that the ideas that have been developed in this document using the computer modelling can indeed be practically applied with success to the field situation.

10 APPENDIX TWO – TRACER STUDIES

Tracer studies have been the most common method for undertaking research into pond hydraulics reported in the literature. The purpose of this appendix is to give a general overview of what they involve and a guide to undertaking them.

10.1 What is a Tracer Study and what does it tell you?

A tracer study involves adding a slug (or a pulse) of a tracer and then measuring its concentration at the outlet over a period of time. A commonly used tracer is rhodamine WT which is a red fluorescent dye that can be accurately measured in extremely low concentrations.

Plotting the concentration of tracer leaving the pond system against the time elapse from when it was added creates a hydraulic retention time distribution curve. An example of the result from a tracer study undertaken on a laboratory pond is shown in the figure below.

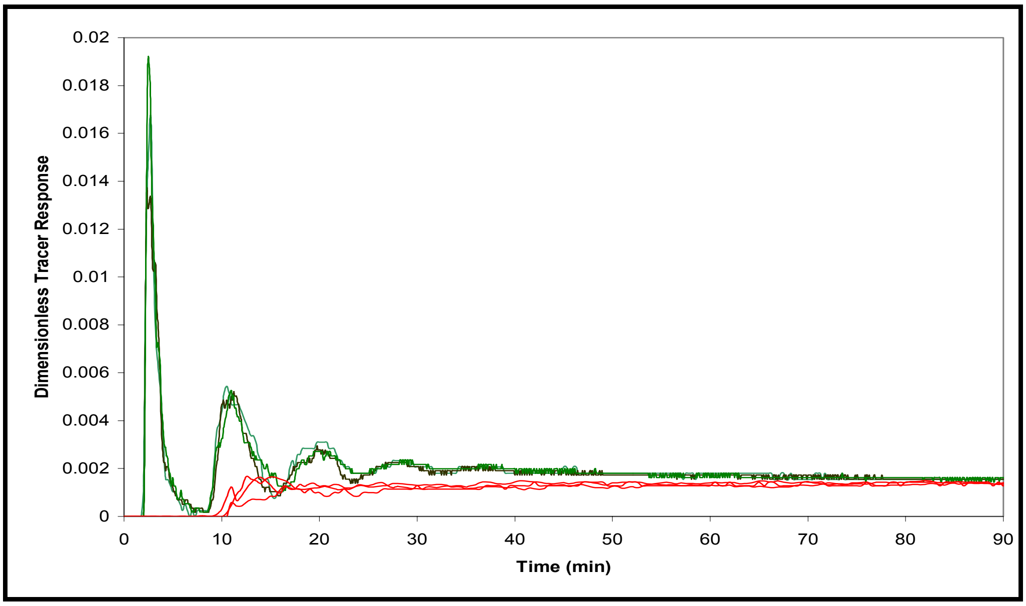


Figure 10-1 Example HRT curves from laboratory testing

The shape of the curves gives some insight of the performance of the pond. In the above example from a laboratory experiment, the green curves show a peak of the tracer reaching the outlet very quickly. The size and position of this peak indicates that a large portion of the incoming tracer reached the outlet in a short space of time. This is a case of severe short-circuiting. The red curves, which are from an experiment with a vertical inlet configuration, do not exhibit the same pattern. In particular, the large early peak does not appear. This is clearly an improvement and implies a better performing pond.

Using the data obtained from a tracer study various hydraulic parameters can be determined including the:

- Mean retention time;
- Dispersion number;
- Time to the start of short-circuiting;
- Time for 10% and 90% (the t_{10} and t_{90} fractions) of tracer discharge, etc.

It is also possible to integrate these results with an expression for first order reaction kinetics to directly determine the treatment efficiency of the pond, as was done in Appendix One.

10.2 Conducting a Tracer Study using Rhodamine WT

There are many different types of tracer that can be used. Rhodamine WT is one of the more frequently used tracers and was indeed used in research undertaken in support of these guidelines. Its concentration is measured by an instrument called a 'fluorometer'.

This section doesn't intend to provide an exact method, but rather a general guide to undertaking a tracer study with rhodamine WT.

Step 1. Calculate the quantity of tracer required
The cost of rhodamine WT isn't cheap, around $NZ180 per litre at the time of publication, so you will wish to minimise the amount used. However, if too little is used then the response measured at the outlet will be too low to give an accurate result.

The best starting point in this process is to gain experience in the measurement of the tracer. This will then give an idea of the lowest concentrations that can accurately be measured. By assuming that the tracer added to the pond becomes fully mixed, you can then back calculate the amount of tracer that needs to be added to the total pond volume to ensure that the effluent tracer concentration will be well within the range that can be accurately measured.

As an example, three litres of rhodamine WT (at 'stock solution' supplied by Trichromatic – West Inc.) were used for each tracer study conducted on the Ashhurst field pond (approx pond volume of 10 million litres).

Step 2. Add tracer and collect samples
Rather than simply adding the stock solution directly it is better to mix it into a container of 10-20 litres of pond water. This minimises any small temperature and density differences between the tracer and the pond. The tracer molecule is larger than a water molecule and while it will remain well suspended in a reasonable flow it can tend to slowly sink if added in high concentration into a slow flow.

The tracer must be added in a manner that is representative of the actual pond inflow. Simply pouring it in near the inlet is not really accurate. For submerged horizontal pipes between ponds we added the tracer via a smaller flexible tube inserted up inside the larger inlet pipe.

Sample collection can either make use of a field fluorometer with automatic sampling and data logging (however, these instruments are relatively expensive at around $US25,000) or more simply by use of an auto-sampler to collect samples which are then taken back to the laboratory for analysis. A number of researchers have opted to simply collect samples manually but the disadvantage of this is that, typically, not enough samples are collected.

Some of the more important information obtained from undertaking a tracer study includes the time to the first appearance of any tracer at the outlet (the start of short-circuiting) and the time to the subsequent tracer peak/s. To record these, regular sampling is important in the initial period. After this initial period the sampling interval can then be increasingly lengthened until eventually you are only recording the long tracer tail.

Our approach was to use an auto sampler. We would collect samples every hour for the first few days, then reduce this back to two hour sampling and eventually after around ten days we would reduce back to collecting a sample every 7 hours.

It normally takes at least three 'theoretical retention times' for the bulk of the tracer to wash out.

Note: It is important to ensure that all your equipment is reliable. Once tracer is added you need to wait a very long time until it is all washed out and a new run can be started!

<u>Step 3. Sample Analysis</u>
An instrument called a fluorometer is used to analyse rhodamine WT. The fluorometer needs to be set for an excitation wavelength of 540nm and an emission wavelength of 585nm.

Doing a standard curve (using a series of known dilutions) is recommended for testing your technique and the instrument, but translation of the instruments output back into an actual concentration isn't actually needed. This is because it is the relative response that is important not a plot of the actual concentrations.

The reading obtained from a fluorometer is sensitive to temperature. Field fluorometers can be purchased with automatic temperature measurement and adjustment. In the laboratory a simple solution is to do all the analysis in a controlled temperature room, but ensure that the samples are given time to equalise to this temperature first.

The tracer is also reported to have some sensitivity to light decay and as a sensible precaution it is recommended that the samples are stored in covered containers and, in particular, kept out of the direct sunlight.

<u>Step 4. Data Analysis</u>
As mentioned previously, there are various parameters that can be derived from the results of a tracer study. A very common parameter is the mean retention time, t_{mean}, which is determined as shown overleaf, where t is time from the start of the tracer addition; C is the tracer measurement at time t (units are not important) and dt is the time interval between samples.

$$t_{mean} = \frac{\int_0^\infty tCdt}{\int_0^\infty Cdt}$$

The output from the fluorometer is typically scaled so that the area under the hydraulic retention time distribution curve is equal to one, thereby eliminating the need for calculation of concentrations, adjustment for amount of tracer added and so on. When comparing tracer results obtained from the field, the standard practice is to calculate t_{mean} and then divide all the measurements of time by this value. This makes time dimensionless, which is useful when comparing studies undertaken at different flowrates (and therefore retention periods).

10.3 The Trouble with Tracer Studies is….

While tracer studies are an important research tool, it is important that the limitations and drawbacks of this technique are clear. These include:

Resources
To do a tracer study properly requires significant time, expense and, depending on the type of tracer used, specialist analytical equipment.

Weather – Repeatability
Field ponds have transient inflow rates. Additionally, they have large surface areas that are exposed to constantly changing wind and temperature conditions. Field studies are therefore only indicative of the hydraulic behaviour resulting from the conditions that existed during the study period. It is quite likely that repetitive tracer testing on a single pond will have some variation in the results.

Need for Benchmarking
Once a tracer study is conducted and you have your results what does it really tell you? There are a number of results of tracer studies presented in the literature but are you really prepared to research all of these so as to see if your particular situation is comparable and if so to try and determine if it is working better or worse?

In our studies, the reason a tracer study was undertaken was to correlate against a mathematical model or to provide a 'before' and 'after' comparison of improvement following some physical alteration to a pond.

Black Box Results
Tracer results can be plotted and characterised in several different ways. However, their limitation is that they provide only 'black-box' results. This technique doesn't actually show you what the flow pattern and mixing that is occurring within the pond looks like.

The Other Alternatives

As mentioned, tracer studies on field ponds are the most commonly used technique for evaluating pond hydraulics. It is, however, important to be aware that other techniques are also available to investigate pond hydraulic behaviour. The use of computer and laboratory modelling, for example, has been mentioned several times throughout these guidelines.

Another approach to collecting experiment data is drogue tracking. Typically, a drogue consists of an underwater 'sail' attached to a small indicator float at the water surface. As the drogue is swept around the pond with the flow, the flow pattern can be recorded by using a team of two surveyors to triangulate the changing position of the indicator float. These results can then be plotted to give a picture of the flow pattern and if the drogue is tracked at regular time intervals, allows calculation of the in-pond flow velocities.

Figure 10-2 An alternative to tracer studies is 'drogue tracking'. The arrow shows the surface indicator of an underwater drogue.

11 APPENDIX THREE – PROCESS DESIGN

This appendix contains an article on how to size/design ponds. This article first appeared in the 'Water and Wastes in NZ' journal (issue 82) in September 1994. It is reproduced here with the kind permission of the Author and the New Zealand Water and Wastes Association.

WASTE STABILISATION POND ADVANCES – PART II

John de B. Ashworth, Senior Environmental Engineer, Beca Steven

Part I of the paper on waste stabilisation pond design which appeared in the July Journal, laid the foundations of effluent standards, based on helminths, and the superior pathogen removal which can be obtained by ponds, as against conventional sewage treatment. Part II presents the design parameters developed by Duncan Mara and Howard Pearson in their Waste Stabilisation Ponds, A Design Manual for Eastern Africa. The anaerobic and facultative pond designs are temperature dependent, which makes the parameters suitable for the New Zealand climate.

The temperature used in pond design is very important. It refers to the mean monthly air temperature during the coldest month. This provides a 2 – 3°C safety margin over the actual sewage temperature over the winter period.

Facultative and maturation ponds traditionally have been used in New Zealand, but to save space it is preferable to use an anaerobic pond first.

Anaerobic Ponds are typically 4 metres deep and the pH of the pond is maintained at close to 7.5 to maximise the bisulphide ions and minimise the smelly hydrogen sulphide. To achieve the lower pH, volumetric loadings, based on the mean minimum monthly temperature, are calculated from one of the equations below.

Temperature Degrees Celsius	Volumetric Loading $g.BOD_5/m^3.day$	BOD Removal Percentage
< 10	100	40
10 – 20	20T to 100	2T + 20
> 20	300	60
T = Temperature in Degrees Celsius		

The anaerobic pond retention time is usually between 0.85 to 1.5 days. If the pond is to be used for settling grit and screenings, just as with the septic tank, greater than 1 day's retention would be recommended. De-sludging or de-gritting would then only be required about every two years.

Facultative Ponds can either be for secondary treatment, after a land saving anaerobic pond, or to receive untreated sewage directly. Ponds are typically 1.5 metres deep. Again, the use of a temperature related equation is used, but on this occasion, based on surface BOD_5 loadings:

Surface Loading = $350.(1.107 – 0.002T)^{T-25}$ kg BOD_5/hectare day T = Temperature in degrees Celsius

If the facultative pond is not preceded by an anaerobic pond, the first quarter length of the pond can be deepened to create a sump for grit and organic material to drop into. Again, this will need de-sludging every two to three years.

BOD_5 removal in facultative ponds is in the region of 85% (assuming algae have been filtered out). With algae still present there is a 70% BOD_5 reduction. If an anaerobic pond precedes the facultative pond the combined BOD removal will be about 90%.

Maturation Ponds are not designed on a temperature basis, but on a depth of 1.25 metres, surface loading and minimum retention times to prevent wash out of the algae:

Surface Loading < 120kg BOD_5/hectare day Minimum Retention of 3 days

One to three maturation ponds can be used in series depending upon the effluent quality required.

BOD_5 removal for each of the maturation ponds in series can be taken as no more than 25%

Pathogen Removal is based on first order kinetics: four ponds in series, of say 100 square metres, will remove more pathogens than one pond of 400 square metres. The effluent faecal coliform analysis goes as follows:

$k_T = 2.6.(1.19)^{T-20}$ $Ne = Ni / \{(1 + k_T.Da) (1 + k_T.Df) (1 + k_T.Dm)^n\}$ *Escherichia coli*/100 mL k_T = First Order Kinetic Constant T = Temperature in degrees Celsius Ne = Effluent faecal coliform, *Escherichia coli*/100 mL Ni – Influent faecal coliform, *Escherichia coli*/100 mL Da = Retention time in anaerobic pond, days Df = Retention time in facultative pond, days Dm = Retention time in maturation pond, days N = Number of maturation ponds

Helminth level in the effluent is a better indicator of the health dangers than faecal coliform. Generally, achieving less than one nematode egg per litre will ensure a safe effluent for all but irrigation of uncooked crops, where WHO recommend a faecal coliform level of 1,000 *Escherichia coli*/100mL should be achieved as well. The calculation for each pond in series is as follows:

$R = 100 \{1 – 0.41 \exp (-0.49 D + 0.0085^2)\}$ R = Percentage egg removal D = Pond retention time in days

Phosphorus removal can only be calculated crudely for waste stabilisation ponds on the basis of 45% removal.

Nitrogen removal can be assessed in two parts. First ammoniacal nitrogen reduction is given by the Pano and Middlebrooks equation:

Temperature below 20°C
$Ce = Ci / \{1 + [A/Q (0.0038 + 0.000134T) \exp ((1.041 + 0.044T) (pH – 6.6))]\}$

Temperature above 20°
$Ce = Ci / \{1 + [5.035 . 10^{-3} A/Q] \exp [1.540 (pH – 6.6)]\}$

Ce = Effluent ammoniacal concentration in gN/m^3
Ci = Influent ammoniacal concentration in gN/m^3
T = Temperature in degrees Celsius
A = Pond Area in m^2
Q = Influent Flow in m^3/day
PH = 7.3. exp (0.0005. Alkalinity in $gCaCO_3/m^3$)

Total Nitrogen removal is assessed by Reed's equation for use in individual facultative and maturation ponds:

$Ce = Ci . \exp\{-[0.0064 (1.039)^{T-20}] [D + 60.6 (pH – 6.6)]\}$

Ce = Effluent total nitrogen concentration in gN/m^3
Ci = Influent total nitrogen concentration in gN/m^3
T = Temperature in degrees Celsius
D = Retention time in days

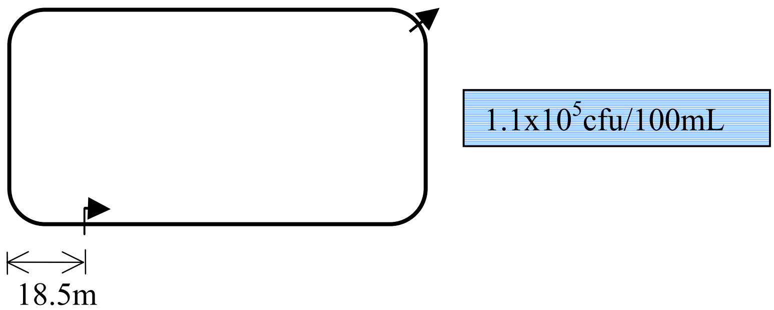
A very important part of pond design is the inlet and outlet arrangement. It is probably the most frequent error designers make. The arrangements shown in Figure 2 (refer Part 1) have been developed to ensure algae are not inadvertently removed from the pond effluent or washed forward at the inlet end of the pond.

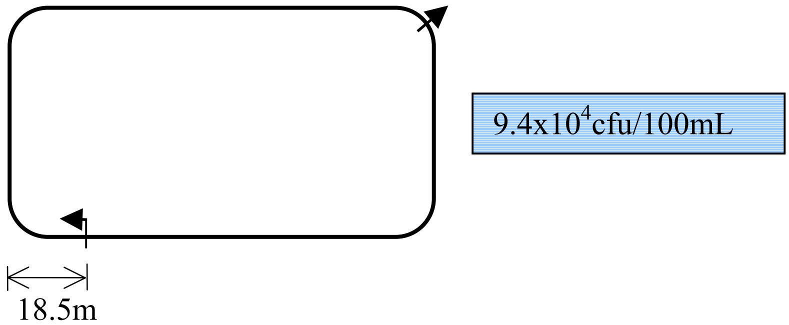
References
Marecos do Monte HH, Waste Stabilization Ponds in Europe (1992, March). Journal of the Institution of Water & Environmental Management.
2. Design of Municipal Wastewater Treatement Plants (1992). Manual of Practice No 8. WEF. USA.
3. Health guidelines for the Use of Wastewater in Agriculture and Aquaculture (1989) Technical Report Series 778. World Health Organization.
4. Public Health Guidelines for the Safe Use of Sewage Effluent and Sewage Sludge on Land (1992). NZ Department of Health, Public Health Services.
5. * Mara DD, Pearson HW et al (1992). Waste Stabilization Ponds, A Design Manual for Eastern Africa. Overseas Development Administration, UK.
6. Arthur JP (1983). Notes on the Design and Operation of Waste Stabilization Ponds in Warm Climates of Developing Countries. Technical Paper No 7. Washington DC. The World Bank.
7. Mara DD, Sewage Treatment in Hot Climates, John Wiley & Sons Ltd, 1976.
* Recommended by author

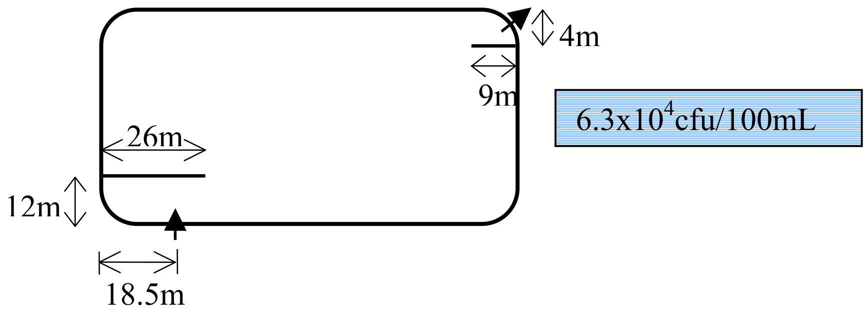
12 APPENDIX FOUR: CASE STUDY CONFIGURATIONS

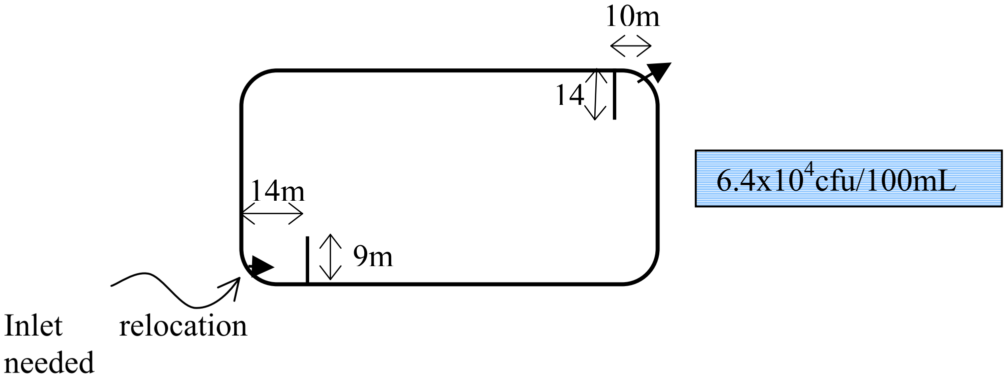
The appendix details some of the models tested as part of the investigation undertaken as discussed in Appendix A.

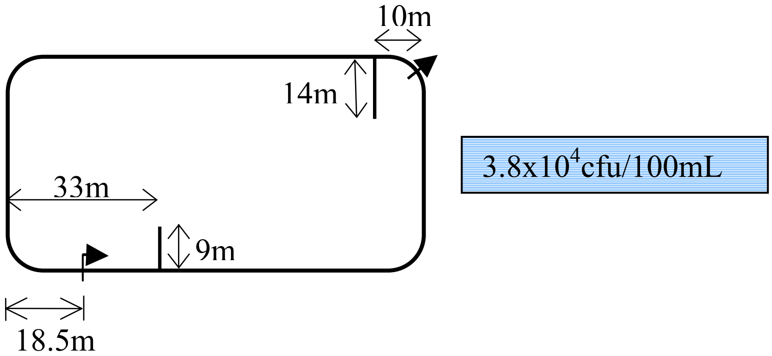
The initial value for coliforms was set at *$8.7x10^5$cfu/100mL*, this value was taken from coliform monitoring of the pond.

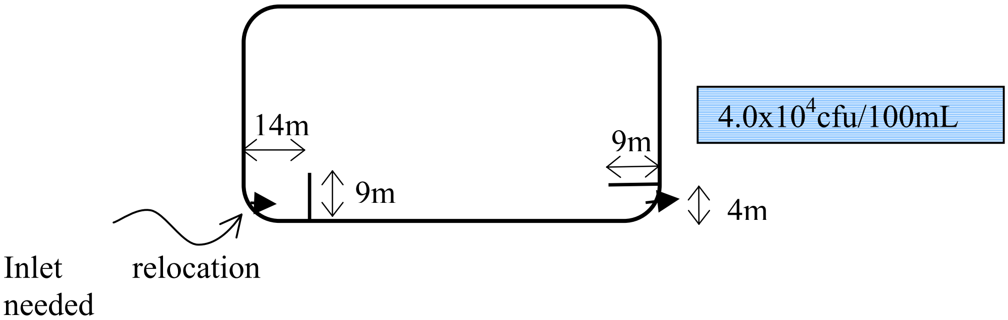


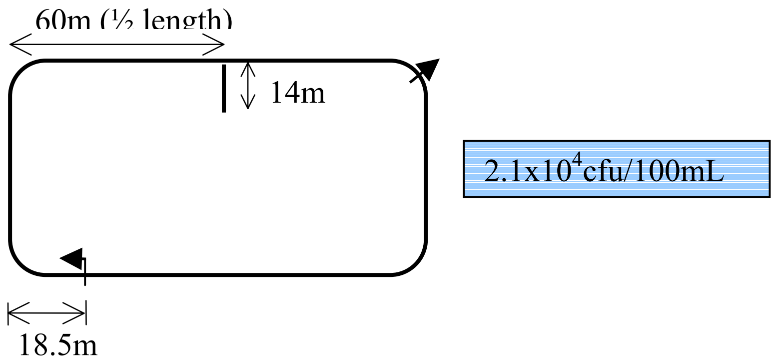


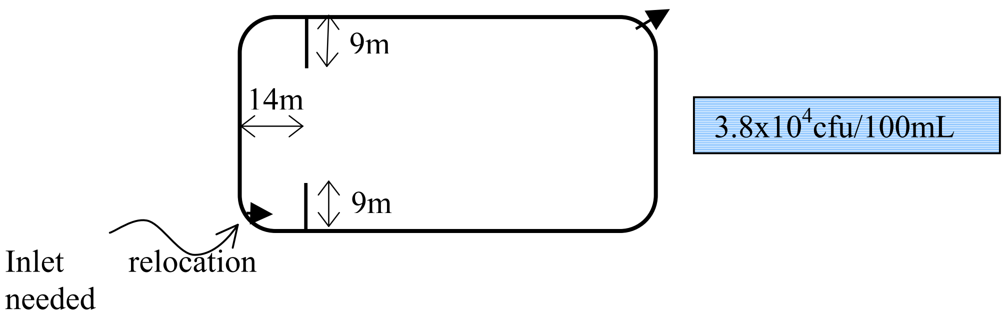


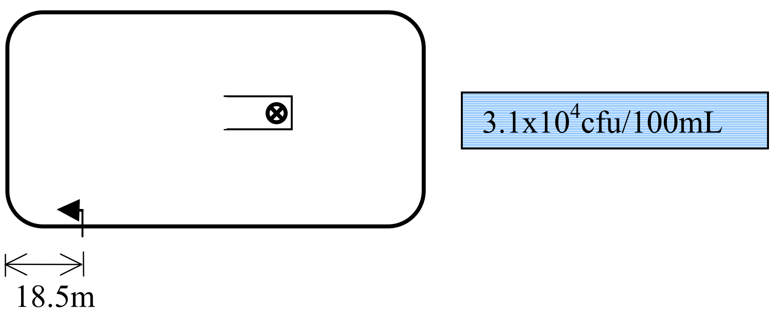



10m
14m
33m
9m
18.5m
3.8x10^4cfu/100mL


14m
9m
9m
4m
Inlet relocation needed
4.0x10^4cfu/100mL


60m (½ length)
14m
18.5m
2.1x10^4cfu/100mL


9m
14m
9m
Inlet relocation needed
3.8x10^4cfu/100mL


18.5m
3.1x10^4cfu/100mL