Report

Review of Pathogen Reduction In Waste Stabilisation Ponds

Prepared for Masterton District Council

By CH2M Beca Ltd

18 March 2009

Revision History

Revision Nº	Prepared By	Description	Date
A	Graeme Jenner	Final	18 March 2009

Document Acceptance

Action	Name	Signed	Date
Prepared by	Graeme Jenner		
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1 Introduction

Effluent containing human sewage can contain potentially pathogenic microorganism that may pose a disease risk to humans, when discharged to receiving waters. The concentration of these micro-organisms can be reduced in the effluent by specific disinfection processes (e.g. Chlorination, UV lamps or maturation ponds). Further reduction in microbiological numbers will also occur after discharge to receiving waters, by processes of dilution and die-off when exposure to sunlight and other hostile environmental factors (e.g. predation and low temperatures) occurs.

The effectiveness of properly designed wastewater ponds in removing pathogens has been acknowledged by a number of key commentators. Mara and Pearson (1998) note that "*Well-designed maturation ponds are extremely efficient in the removal of excreted pathogens"*. Davis-Colley (2005) concluded that *"Waste stabilisation ponds (WSP) are remarkably efficient and effective at removing a great variety of pathogenic (disease-causing) organisms*". The Ministry of Health, 1994), in discussing the role of ponds in disinfection adds *"that the size and number of maturation ponds controls the quality of the final treated sewage. The design process specifically selects the optimum combination of maturation pond size and number required to achieve the final effluent quality desired".*

Note, that the IWA (International Water Association) has adopted "Waste Stabilisation Ponds" (WSP) as the overall term covering anaerobic, facultative, maturation and aeration ponds (with mechanical aerators). In this report, the terms "treatment ponds" or "ponds" will be used as an abbreviation. The commonly used term 'oxidation ponds,' refers to facultative and maturation ponds.

2 Main Pathogens in Wastewater and Indicator Organisms

The main categories of pathogenic microorganisms that may be present in human-derived wastewater and other organic wastes of faecal origin are summarised in Table 2.1.

Indicator organisms such as the coliform group (e.g. faecal coliforms, and E. coli) and the streptococci group (eg enterococci) have been traditionally used to indicate the presence of faecal contamination. Non-bacterial indicators such as bacteriophages (viruses that infect bacteria) have also been found to be useful in WSP studies and a convenient model of human enteric viruses in the environment. These “indicator organisms” are always present and usually at high concentrations in domestic sewage. This is not always the case within many pathogenic microorganisms that may only be present during epidemics in the connected population. The great variety of pathogens also makes monitoring for them in effluents and the receiving waters difficult. Many pathogens are difficult and expensive to measure and require sophisticated laboratories for detection and enumeration.

Table 2.1: Categories of Pathogenic Organisms That May Be Present In Human Sewage

Category	Example organisms	Illness caused
Bacteria	Salmonella spp, Shigella spp Escherichia coli (pathogenic strains), Campylobacter spp Yersinsia enterocolitica	Salmonellosis Bacterial dysentery Diarrhoea Campylobacteriosis Acute gastroenteritis
Viruses	Enteroviruses Hepatitis A Norwalk types Rotavirus Adenovirus Astrovirus	Meningitis Hepatitis Gastroenteritis Gastroenteritis and dysentery Gastroenteritis (particularly in children) Gastroenteritis (particularly in children)
Protozoan Parasites	*Giardia* spp *Cryptosporidium* spp	Giardiasis Cryptosporidiosis
Worm Parasites (helminths)	Tapeworms (eg *Taenia* spp) Roundworms (eg *Ascaris* spp)	Range of symptoms (but rare in New Zealand)

Source: After Bitton, (1999) in Davis-Colley (IWA, 2005)

3 Pathogen Removal Mechanisms

3.1 Overview

The removal mechanisms of pathogenic organisms in treatment ponds are described by Davis-Colley (2005). It is recognised that a large number of factors may influence disinfection on ponds and there is still some debate about underlying mechanisms. Table 3.1 summarises - the factors that have been proposed to cause or influence disinfection in WSPs.

Table 3.1: Factors Proposed to Cause or Influence Disinfection in WSPs

Factor	Likely Mechanism	Microorganism affected
Temperature	Affects rate of removal processes	Bacteria, viruses, protozoa, helminths
Hydraulic residence time	Affects extent of removal	Bacteria, viruses,protozoa, helminths
Algal toxins	Toxic to some bacteria	Mainly bacteria
Sedimentation	Settlement of infectious agent or settlement of aggregated solids including infectious agent.	Protozoa, helminths, (viruses and bacteria?)
Predation	Ingestion by higher organisms	Bacteria, viruses
Sunlight	DNA damage by solar UV-B radiation or photo-oxidation	Bacteria (protozoa?)

Source: Adapted from Davis-Colley (IWA, 2005)

3.2 Temperature

Maturation ponds are often designed for disinfection using the Marais (1974) formula for a prediction of faecal coliform reduction which is based on retention time, number of ponds in series and the pond temperature. However, several studies (eg Mills et al, 1992) suggest that temperature alone is not the primary cause of disinfection. As thermal shock is only lethal to most microorganisms above around 45^0C, temperature can only be regarded as a secondary factor influencing the rate of action of other factors. The use of temperature in the Marais formula should be regarded as a surrogate for sunlight as discussed later.

3.3 Hydraulic Residence Time

Hydraulic residence time (HRT) controls the time available for removal mechanisms within WSPs to operate and should be regarded as a secondary factor. The sometime variable removal of indicator bacteria in ponds is often partially due to short-circuiting, in which the influent wastewater is conveyed rapidly to the outlet. In this case, there is minimal time for the operation of primary removal mechanisms such as sunlight, sedimentation or predation.

3.4 Algal Toxins

Some researchers (eg Oufdou et al, 2001) have suggested that extra-cellular substances produced by some pond algae (eg cyanobacteria) can be toxic to faecal bacteria. However, others (eg Maynard et al, 1999) cited other studies that dismiss algal toxins as a major disinfection mechanism in WSPs. The relevance of this removal mechanism remains unclear.

3.5 Sedimentation

Sedimentation in the WSPs is believed to be the dominant mechanism for the removal of helminth ova (Maynard et al, 1999). Protozoan parasites are also fairly efficiently removed by sedimentation (Grimason et al, 1993). Since the settling velocities of isolated oocysts are low (2.2-2.8cm/hr for Cryptosporidium oocysts), their aggregation with settleable solids seems likely. Viruses and possibly bacteria can also be removed by sedimentation, if sorbed on to settleable solids within ponds (Ohgaki et al, 1986).

3.6 Predation

WSPs contain a diverse range of micro-fauna. Ingestion of smaller organisms such as viruses, bacteria and perhaps oocysts, by larger species may cause inactivation by exposure to digestion fluids. Even if not inactivated, containment of viruses etc, within faecal pellets seems likely to reduce infectivity and promote removal by sedimentation. Manage et al. (2002) reported the removal of virus-like particles by flagellate ingestion in a hypereutrophic urban pond and it seems highly likely that similar processes occur in WSPs. Indeed, predation may be the major process of virus and bacteria removal in ponds where sunlight exposure is limited.

3.7 Sunlight

An increasing body of evidence indicates that sunlight is the single most important disinfection factor in WSPs (eg Maynard et al., 1999; Leduc and Gehr, 1990). Shorter wavelength visible and ultra-violet radiation has long been known to be bactericidal. Gates (1929) showed that 265nm light was the most lethal and that energy dose required for a given “kill” was strongly related to wavelength. It appears that the disinfection mechanism involves the absorption of UV light, by the DNA within the organism that then becomes damaged preventing successful growth and reproduction. There is strong experimental evidence that sunlight inactivation is rapid at the surface of ponds, but is diminished by light attenuation in the water column (eg Davis-Colley, 1995).

There appear to be three main mechanisms operating simultaneously in ponds. Mechanism 1 involves the absorption by solar UV-B by DNA causing direct damage by pyrimidine dimer formation (Jagger, 1985). The process is independent of oxygen and other pond conditions. Mechanism 2 involves the absorption of UV-B and some shorter wavelength UV-A by cell constituents including DNA (called endogenous photosensitisers). The activated constituents react with oxygen to form highly reactive photo-oxidising species that damage genetic material within the cell or viral particle. Mechanism 3 involves absorption of a wide range of UV and visible wave lengths in sunlight by extra-cellular constituents of the pond medium (exogenous photosensitisers-notably humic material). The activated photosensitisers react with oxygen to form highly reactive photo-oxidising species. These damage the membrane of bacterial cells on potentially host-binding particles on viral particles.

3.8 Effects of Oxygen, pH and Humic Substances

Mechanisms 2 and 3 both rely on the presence of dissolved oxygen in the medium. Mechanism 1 may be mainly responsible for the reduction of some microorganism (notably DNA-viruses), that lack the ability to repair DNA damage. But reduction of higher organisms (eg bacteria) which are capable of DNA repair, is most likely reliant on Mechanisms 2 and 3. Curtis et al (1992) has shown that supersaturated oxygen conditions alone are not toxic to pathogenic microorganisms. It is the interaction of oxygen and sunlight that is the effective disinfection process. A dissolved oxygen concentration greater than 4 mg/l enhances photo-oxidative disinfection and this concentration occurs most of the time in a maturation pond.

A variety of studies (eg Parhad et al, 1974) have suggested that pH is a primary disinfection mechanism in WSPs. However simple experiments, exposing faecal indicator bacteria in the dark to elevated pH, has shown that pH alone is not toxic, except at extreme values not normally encountered in ponds. Instead, pH interacts with sunlight, such that at the same sunlight exposure, disinfection increases with increasing pH.

Although much of the total light absorption in WSPs is by algal cells, these components are likely to be inefficient photosensitisers (Mechanism 3) because the reactive oxygen species that they produce tend to be utilised before contacting pathogenic microorganisms. Humic-type substances dominate light absorption (Davies-Colley et al, 1995) and may be the most important photosensitiser for disinfection (Curtis et al, 1992b).

4 Evidence of Reduction of Bacteria and Viruses in Treatment Ponds

4.1 Christchurch WWTP

Christchurch City Council (CCC) engaged ESR in 2002 to determine the reduction profile through the Christchurch Wastewater Treatment Plant (CWTP) of the more common pathogens. The winter results are significant because little data is available worldwide for temperate climates. In particular, it was thought that removal of pathogens might not be significant under winter conditions, due to reduced sunlight. The results in Figure 4.1 and Table 4.1 show that significant reductions were being achieved by the former pond layout of three ponds-in-series, particularly for virus, salmonella and campylobacter, as well as the indicators. It should be noted that the CWTP pond system had two parallel trains of three ponds in series in 2002. Hence Ponds 5 and 6 were third in the series. Refer to (Archer, O'Brien, Bourke, 2006) Appendix A.

In 2004 and 2005, CCC undertook further pathogen testing of the effluent from the ponds after the configuration of the ponds was changed to seven ponds in series. The results in Table 4.2 show similar, to slightly improved, pathogen concentrations compared to the 2002 results, indicating that the system has possibly reached the maximum capacity for removal of pathogens. It should be noted that the Christchurch pond system has an overall retention time of approximately 20 days which is much less than typical pond systems in the 30 to 50 days range. The settlement of solids in the "in-tank" processes upstream of the Christchurch ponds, would equate to settlement of solids in primary ponds in a multiple pond-in-series system.

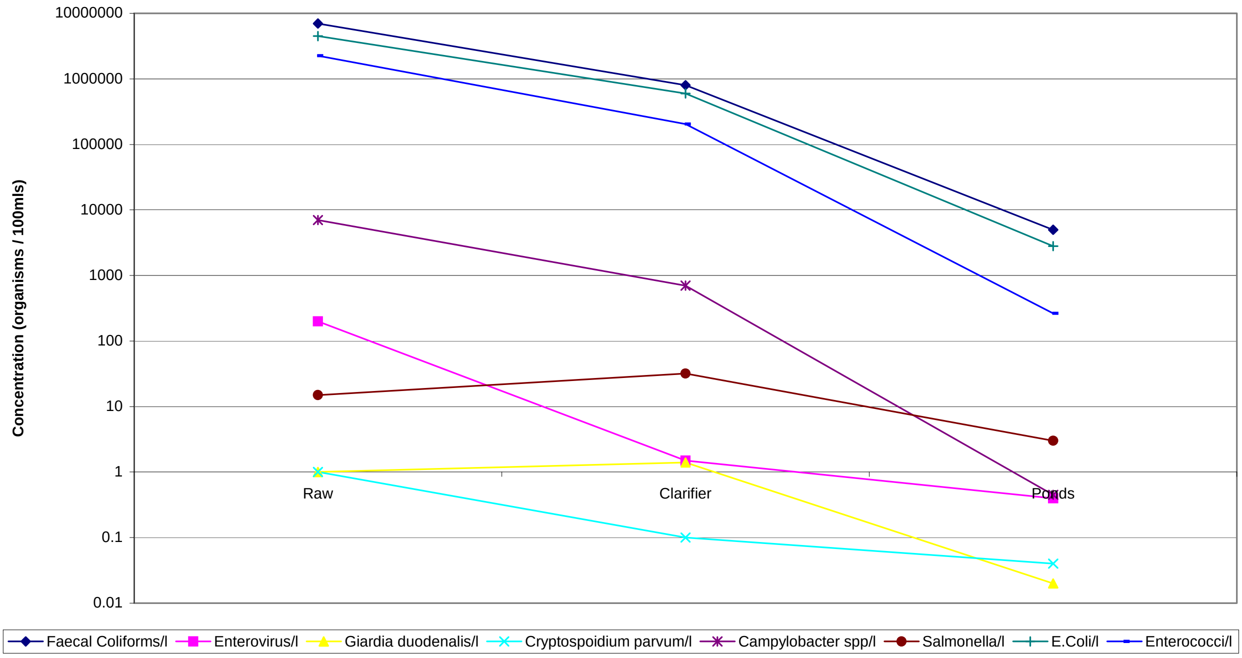

Figure 4.1: Pathogen Reduction Profile Through Christchurch WWTP - 2002

(Note: all concentrations in the graph are expressed per 100ml, but sample size results in Table 4.1 do vary).

Table 4.1 - Microbial Pathogen Concentrations at Christchurch WWTP in Winter 2002 (Prior to Upgrading)

Micro organism	Source	Pathogen Concentration on Sample Date in 2002					
		30 July	31 July	6 August	7 August	13 August	14 August
Entero-viruses pfu/L	Raw Sewage			1800	2000	N/A	1300
	Secondary	2.2	2.4	16.2	15.2	5	56.2
	Pond Effluent	4.8	1.6	1.3	2.8	2.6	31.8
F-RNA phage pfu/L	Raw Sewage	7100	2270	2950	2700	5300	7400
	Secondary	3950	2620	2210	1680	1780	1760
	Pond Effluent	1150	234	420	295	920	690
Giardia (confirmed viable) oocysts/L	Raw Sewage	5		38		10	
	Secondary	14		8		31	
	Pond Effluent	<0.01		0.16		0.8	
Cryptosporidium (confirmed viable) oocysts/L	Raw Sewage	<5		10		20	
	Secondary	0.02		1.96		2	
	Pond Effluent	<0.01		0.12		0.3	
Salmonella MPN/ 100 ml	Raw Sewage	2400	93	35	16	11	14
	Secondary	93	21	93	43	150	11
	Pond Effluent	<3	<3	<3	<3	<3	<3
Campylobacter jejuni MPN/ 100 ml	Raw Sewage	>6982	6982	>6982	>6982	>69800	12600
	Secondary	>698	>698	>698	>698	2342	1261
	Pond Effluent	1.8	<0.45	<0.4	0.45	<0.45	0.45
Campylobacter coli MPN/ 100 ml	Raw Sewage	<45	180	180	<45	<450	450
	Secondary	<4.5	18	18	4.5	<45	45
	Pond Effluent	<0.45	<0.45	<0.45	<0.45	1.8	<0.45
Clostridium perfringens MPN/ 100 ml	Raw Sewage	28000		165000		130000	
	Secondary	19500		35500		60000	
	Pond Effluent	2800		13500		12500	

Micro organism	Source	Pathogen Concentration on Sample Date in 2002					
		30 July	31 July	6 August	7 August	13 August	14 August
Faecal coliforms cfu/ 100 mL	Raw Sewage	8 x 10^6	3 x 10^6	8 x 10^6	4 x 10^6	6 x 10^6	8 x 10^6
	Secondary	1 x 10^6	0.6 x 10^6	0.8 x 10^6	0.6 x 10^6	0.8 x 10^6	1.3 x 10^6
	Pond Effluent	1,300	1,000	1,000	4,000	5,000	5,000
E. coli cfu/ 100 mL	Raw Sewage	5 x 10^6	3 x 10^6	8 x 10^6	3 x 10^6	4 x 10^6	5.7 x 10^6
	Secondary	0.6 x 10^6	0.6 x 10^6	0.7 x 10^6	0.5 x 10^6	0.3 x 10^6	0.95 x 10^6
	Pond Effluent	76,000	1,000	1,000	1,000	3,000	2,500
Enterococci cfu/ 100 mL	Raw Sewage	2.3 x 10^6	1.5 x 10^6	2.7 x 10^6	0.63 x 10^6	8.4 x 10^6	2.2 x 10^6
	Secondary	0.29 x 10^6	0.24 x 10^6	0.26 x 10^6	63,000	0.17 x 10^6	24,000
	Pond Effluent	2,900	<100	<100	<100	100	430

Table 4.2 - Microbial Pathogen Concentrations at Christchurch WWTP 2004/2006

(After Upgrading to Seven Ponds Operating in Series)

Micro organism	26/4/04	4/8/04	9/8/04	11/8/04	17/8/04	18/8/04	23/8/04	25/8/04	30/8/04	8/2/05	15/2/05	22/2/05	1/3/05	14/9/05	23/2/06	Min	Med	Max
Enterovirus (pfu/l)	<0.05	111	0.2	0.2	0.65	18	0.3	5.8	114	2	4	1	0.5	7.5	-	0.2	2	114
Giardia (viable cysts/l)	<0.15	0.14	1.41	0.625	2	0.147	0.75	0.36	0.42	0.69	0.85	0.65	0.0465	<0.092	0.267	0.0465	0.625	2
Cryptosoridium (oocysts/l)	<0.15	0.14	0.176	0.125	2	0.147	0.38	0.36	0.21	0.046	0.85	3.9	0.0465	<0.092	<0.133	0.046	0.193	3.9
Salmonella (MPN/100ml)	<3	1.5	1.5	-	1.5	1.5	1.5	1.5	4.0	1.5	1.5	1.5	1.5	<3	<3	1.5	1.5	4
Thermotolerant Campylobacter (MPN/100ml)	<3	4	4	4	4	23	1.5	4	1.5	15	15	15	15	23	93	1.5	9.5	93
F-RNA Phage (pfu/ml)	1	411	363	99	44.5	1156	220	225	126.5	1.4	0.6	0.1	0.3	100	0.25	0.1	71.75	1156
Faecal coliforms cfu/100ml	-	65	1555	600	270	275	35	60	255	90	520	475	340	30	310	30	273	1555

Note: From 15/2/05 – 23/2/06, the dates of results of indicator bacteria monitoring (ie faecal coliforms) does not strictly align with dates of results of pathogen monitoring. However, it is noted that effluent quality in pond treatment systems does not vary significantly on a day to day basis, because of the buffering effect of long residence time.

4.2 Overseas Experience

Overseas studies also indicate that there is substantial die-off of bacteria and viruses when maturation cells-in-series are used for disinfection. Table 4.3 shows the results of viral die-off using E. Coli and coliphages (viruses that infect bacteria) as indicators, at Melbourne's Western WWTP. From Table 4.3, it can be seen that coliphages were not detected after Cell 5. The authors (Hodgson et al, 1996) concluded that *"even though E Coli were still present, it would be reasonable to assume that viruses such as Hepatitis A, for which no host is available, would be effectively removed"*.

A study of a five ponds-in-series system in Brazil (Curtis et al, 1987) confirmed the effectiveness of maturation ponds-in-series as an effective method of disinfection. The 25^{0}C pond temperature in this study is reached in summer in many NZ treatment ponds.

The USEPA (1985) provided a summary of enteric virus removal from three pond systems in the USA. Results showed that viral concentrations in the final effluent were consistently low, with only a slight decrease in removal efficiency in winter (see Table 4.5).

It should be noted that sample sizes vary between studies, partly due to the need to have larger quantities to enable detection of the organisms, which are rare in some cases.

Table 4.3 - Die off of E. Coli and Coliphages at Melbourne's Western WWTP

	E. Coli/100 mL	Coliphage/100 mL
Raw Sewage	1.2×10^7	380
Pond 1	8×10^6	250
Pond 3	2.5×10^6	54
Pond 5	800	18
Pond 7	80	<1

Source: Hodgson et al (1996)

Table 4.4 - Die off of Micro-Organisms in Ponds/Maturation Cells in Brazil

Organism	Raw	Pond 1	Pond 2	Pond 3	Pond 4	Pond 5	% Removal
Faecal coliforms	2×10^7	4×10^6	8×10^5	2×10^5	3×10^4	7×10^3	99.97
Faecal streptococci	3×10^6	9×10^5	1×10^5	1×10^4	2×10^3	300	99.99
Clostridium	5×10^4	2×10^4	6×10^3	2×10^3	1×10^3	300	99.40
Campylobacter	70	20	0.2	0	0	0	100.00
Salmonella	20	8	0.1	0.02	0.01	0	100.00
Enteroviruses	1×10^4	6×10^3	1×10^3	400	50	9	99.91
Rotaviruses	800	200	70	30	10	3	99.63

Source: Curtis et al (1987) – pond temperature 25 ^{o}C.

Notes: 1. Bacterial numbers per 100 ml; 2. Viral numbers per 10 L

Table 4.5 - Enteric Virus Removal from Three US Pond Systems

	Enteric Virus (PFU/L)		
	Influent	**Effluent**	**% Removal**
Location			
Shelby, MS, 72d, 3 cells:			
Summer	791	0.8	99.9
Winter	52	0.7	98.7
Spring	53	0.2	99.6
El Paso, TX, 35d, 3 cells:			
Summer	348	0.6	99.8
Winter	87	1.0	98.8
Spring	74	1.1	98.5
Beresford, SD, 62d, 2 cells:			
Summer	94	0.5	99.5
Winter	44	2.2	85.1
Spring	50	0.4	99.2

Source: USEPA (1985)

5 Reduction of Protozoa in Treatment Ponds

Protozoa of concern in New Zealand include Giardia and Cryptosporidium. Cysts, which are the potentially infective stage of a protozoan lifecycle, are very hardy and can withstand extreme environments. Helminths, including tape and round worms and liver flukes, can also be pathogenic (especially at the ova and egg stage). However, these organisms are rare in New Zealand.

The monitoring data from the CWTP shown in Table 4.1 shows that treatment in multiple ponds is effective in reducing giardia and cryptosporidium concentrations to low concentrations.

Protozoan cysts and helminth eggs have a higher specific gravity than water and appear to be quite easily removed by sedimentation within multiple cells in series-type systems. Equations, which can be used to design ponds to maximise human intestinal nematode removal, have been developed by Ayres, R M et al, 1992. These researchers suggested that although results appear to indicate that high egg removals are obtained in ponds with long retention times, it is recommended that a number of smaller ponds in series are used to increase removal efficiency and minimise hydraulic short-circuiting. Table 5.1 shows predicted percentage removal of eggs for a range of pond retention times, and it can be seen that predicted egg removal exceeds 99% after 3 days retention time.

Table 5.1 - Predicted Percentage Removal of Nematode Eggs for a Range of Pond Hydraulic Retention Times

Retention time (d)	% Removal	Retention time (d)	% Removal
1.0	74.7	5.5	96.4
1.2	76.9	6.0	97.1
1.4	79.0	6.5	97.6
1.6	80.9	7.0	98.0
1.8	82.6	7.5	98.3
2.0	84.1	8.0	98.6
2.5	87.3	8.5	98.8
3.0	89.8	9.0	99.1
3.5	91.8	10.0	99.3
4.0	93.4	15.0	98.8
4.5	93.4	18.0	99.9
5.0	95.6	20.0	99.9

Source: Ayers, RM et al (1992)

6 Summary

Well-designed WSPs are a cost-effective means of disinfecting faecally-contaminated wastewaters. Significant reductions can occur in all four main categories of pathogens (bacteria, viruses, protozoan and helminth parasites). A combination of complex, but not fully understood disinfection processes operate in WSPs. These include:

- Sedimentation - (especially for helminth ova and possibly protozoan cysts)
- Predation - (notably protozoans and flagellates that can ingest bacteria and viruses)
- Sunlight - exposure to short wavelengths acting in combination with dissolved oxygen and pH

Sunlight exposure is the most universally important disinfection mechanism in WSPs for bacteria and viruses (and possibly for protozoan parasites). However, the primary processes of disinfection in WSPs can be affected by other factors such as temperature, and actual hydraulic residence time (degree of short circuiting).

Monitoring data from the Christchurch WWTP, as well as from overseas, supports the observation that substantial die-off of bacteria and viruses occurs when multiple ponds-in-series are used for disinfection. Significant reduction in larger organisms, such as protozoan parasites, is also shown in the Christchurch WWTP data.

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Appendix A

Christchurch Wastewater Treatment Plant Pond Upgrading, Paper Presented to NZWWA Conference 2006

CHRISTCHURCH WASTEWATER TREATMENT PLANT POND UPGRADING

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ABSTRACT

The Christchurch Wastewater Treatment Plant (CWTP) consists of screening, primary sedimentation, trickling filter/solids contact process and secondary clarification, followed by 220 ha of maturation ponds. Historically, these ponds operated as two parallel trains of three ponds in series.

In early 2004, the maturation ponds were reconfigured to operate as a single train of seven ponds in series. The primary aim of the upgrade was to reduce the public health risk from the existing discharge into the Estuary of the Avon and Heathcote Rivers and the proposed ocean outfall discharge into Pegasus Bay. The new serpentine flow path greatly reduces the risk of short circuiting and increases the minimum retention time, even though the nominal overall retention time is relatively short at 20 days.

An experimental aeration cascade was also constructed between Ponds 4 and 5, with the aim of reducing ammonia concentrations by stripping ammonia gas to atmosphere. However, it was found that it had no effect on ammonia concentrations, but dissolved oxygen increased by 3 g/m^3.

The conclusions from this major modification to New Zealand's largest area of maturation ponds, are that significant performance improvements can be realised by creating a serpentine flow path through multiple maturation ponds in series, particularly in terms of reduced faecal coliforms, BOD and suspended solids concentrations.

KEYWORDS

Wastewater stabilisation ponds, maturation ponds, disinfection, pathogen reduction, pond effluent quality

1 INTRODUCTION

1.1 RATIONALE FOR UPGRADING MATURATION PONDS TO SERIES OPERATION

Wastewater containing human sewage can contain pathogenic bacteria, viruses and larger organisms (e.g. protozoa such as giardia and cryptosporidium) that may pose a disease risk to swimmers, surfers and people eating shellfish. The concentration of these micro-organisms can be reduced in the effluent by specific disinfection processes (e.g. UV lamp disinfection, chlorination or maturation ponds). The efficacy of disinfection is measured by the number of "indicator" bacteria (e.g. faecal coliforms, *E.coli* or *enterococci*) present in the effluent and the receiving environment.

The *Public Health Guidelines for the Safe Use of Sewage Effluent and Sewage Sludge on Land* (Department of Health, 1992) acknowledges the effectiveness of properly designed treatment ponds in removing pathogens. These guidelines note that *"the size and number of maturation ponds controls the quality of the final treated sewage. The design process specifically selects the optimum combination of maturation pond size and number required to achieve the final effluent quality desired".*

The Design Manual for Waste Stabilization Ponds In Mediterranean Countries (Mara and Pearson, 1998) makes the following statement: *"Well designed maturation ponds are extremely efficient in the removal of excreted pathogens. Nitrogen and phosphorus removal can also be significant, and there can also be small reductions in BOD."*

The Christchurch City Council had been granted a short term consent to continue to discharge to the Estuary until an ocean outfall could be consented and constructed. There was a strong likelihood that UV disinfection would be required not only to meet the conditions of the short term consent but also for the longer term ocean outfall. Conditions of this short term consent were appealed, in particular the requirement for UV disinfection and the term to a realistic timeframe in which an ocean outfall could be constructed. In the decision on the ocean outfall, the Council resolved to build an ocean outfall of at least 2 km length and to make provision for UV disinfection, if it was shown to be required. There was therefore a strong driver to improve the performance of the ponds in the expectation that a full UV disinfection plant would not be required. Many opponents of the ocean outfall were calling for a "bathing standard in the pipe" prior to discharge.

1.2 CWTP MATURATION PONDS UPGRADE DESCRIPTION

The Christchurch Wastewater Treatment Plant (CWTP) serves a population equivalent of about 520,000 and has an average flow of 160,000 m³/d. It consists of primary sedimentation, trickling filter/solids contact process and secondary clarification, followed by six maturation ponds with a combined area of 220 ha and an average hydraulic retention time of 20 days. From 1962 to 2004, these ponds operated as two parallel trains of three ponds in series (see Figure 1). The final discharge is into the Estuary of the Avon and Heathcote Rivers, which is used for various recreational activities, including fishing, sailing and windsurfing.

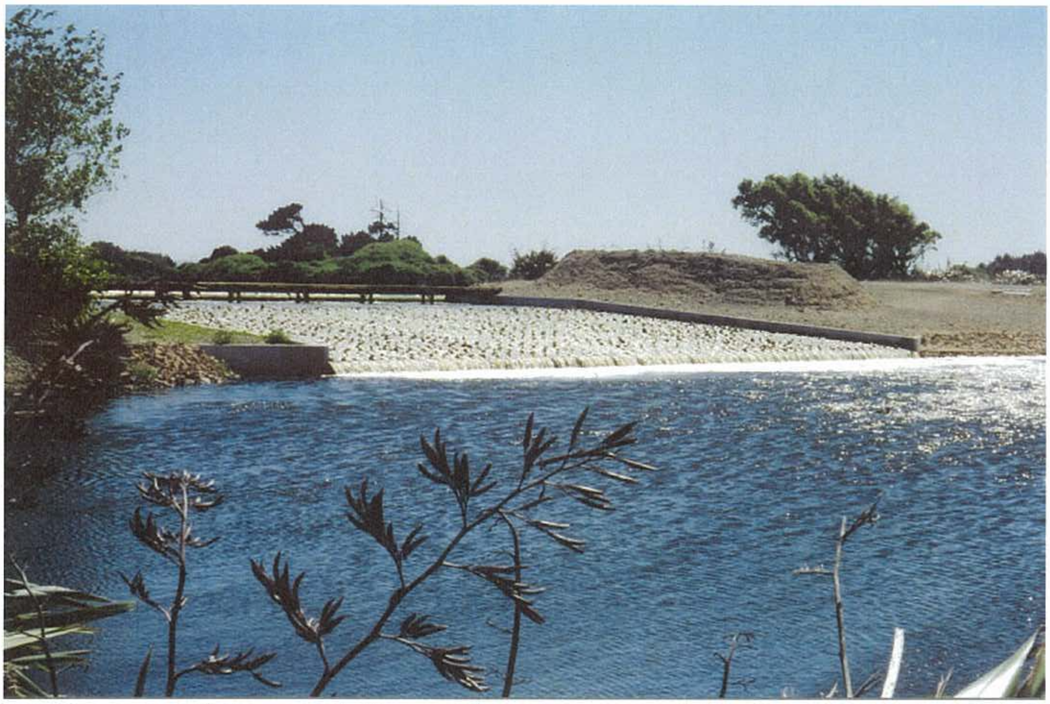
Figure 1: Pond Layout and Flow Paths Before Upgrade

As a result of detailed model and tracer studies on Ponds 1 and 2, the maturation ponds were reconfigured in early 2004 to a single train of seven ponds in series with a serpentine flow path. These studies considered pond bottom shape (varying depth) and the use of stub baffles out from the pond banks to reduce short circuiting and increase minimum retention times. All cases modeled included a long baffle in Pond 2 that effectively divided Pond 2 into two cells. The modeling predicted a four fold improvement in faecal coliform reduction in just Ponds 1 and 2 for the case of no stub baffles and a flat bottom with Pond 2 divided into two cells. No modeling was done on the remaining four ponds, however with the conversion from two parallel trains of three ponds in series to the seven cells in series, at least one log reduction in faecal coliform was predicted using the Marais formula.

An aeration cascade was constructed between Ponds 4 and 5, making use of the 1.7 m head difference between these ponds (see Figure 3). This took the form of a concrete spillway embedded with round rocks. The intention of the aeration cascade was to increase the dissolved oxygen concentration in the wastewater and so improve faecal coliform removal due to photo oxidative damage, as well as reduce the ammonia concentration by stripping of ammonia gas to atmosphere.

Figure 2: Pond Layout and Flow Paths After Upgrade

Figure 3: Aeration Cascade

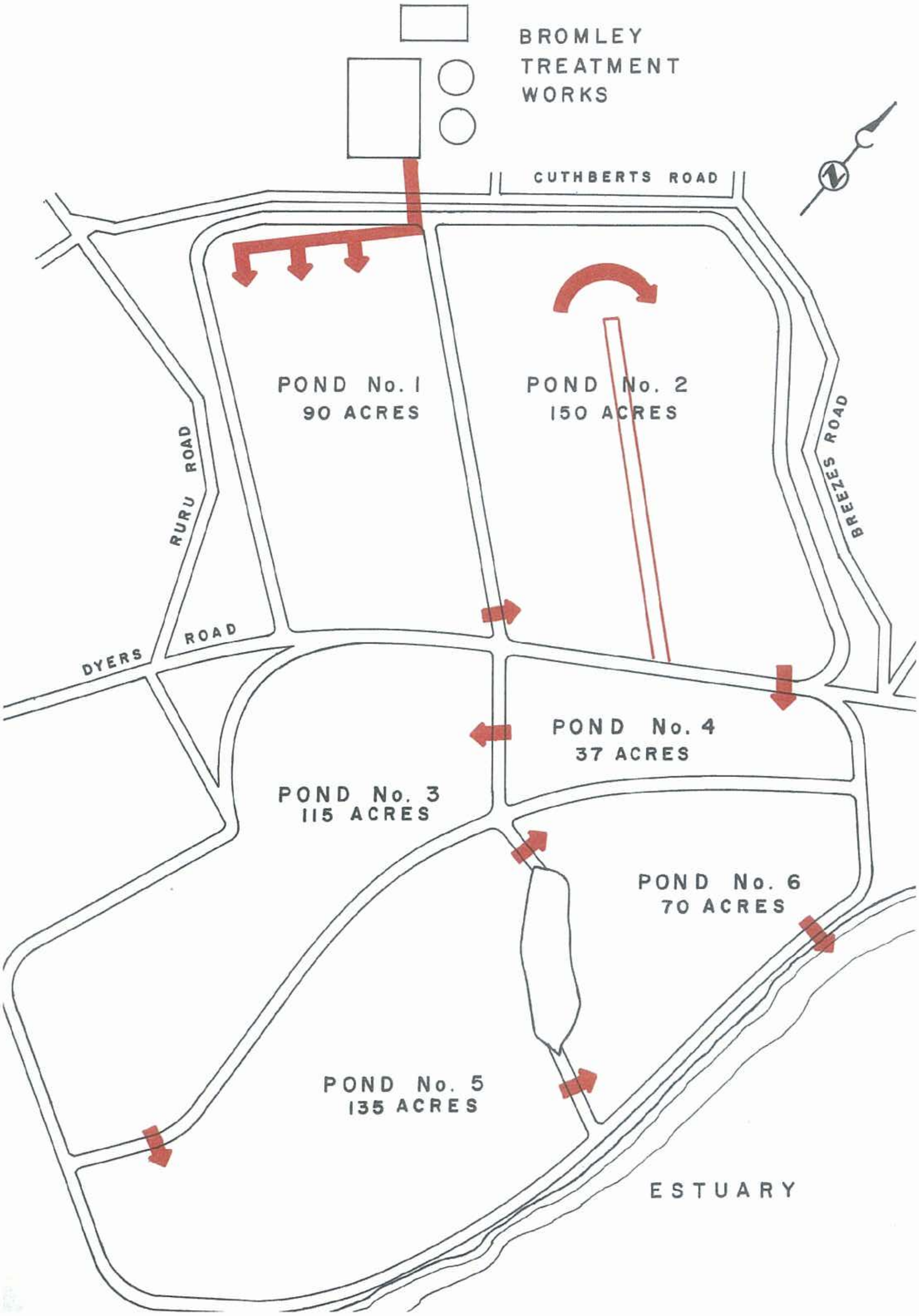


It is interesting to note that a very similar pond layout was proposed by Brown and Caldwell in 1973 (USA Consulting Engineers who designed the original CWTP, see Figure 4), who made the following observations:

"Pond Alternative C depicts a series operation wherein pond 1 is a primary pond and the remainder of the ponds are in series sequence as shown on the figure. A dike or barrier structure is envisioned in pond 2 to avoid short-circuiting and to better utilize the entire pond area in a series sequence of seven ponds in total. ...This sequence optimises the bactericidal properties of the ponds as recommended by many authors."

This illustrates well, that it is important to record long-term visions and for engineers to review historical reports. In this case, the vision took 30 years to "mature" and be implemented – good things take time!

Figure 4: Schematic Pond Layout Proposed in 1973 (after Brown & Caldwell, 1973)



2 RESULTS

Tables 1 to 4 summarise the final pond effluent quality results for various parameters, before and after the upgrade. There is little data in the literature on statistical variations for pond effluent parameters and these tables should be helpful in other situations where ponds follow a full secondary treatment process. A pond system receiving raw wastewater, would not perform to the same standards as for the Christchurch case.

At times, both before the upgrade of the ponds and after, there have been periods of some months at a time where major process units have been out of service (e.g. trickling filters, secondary sedimentation tanks, pairs of aeration tanks, half the final clarifiers). These results have been included in the statistical analysis given in these tables, as the periods when the plant was operating normally were rare. Thus, the results would be conservative for existing flows and with all units in service in future, results at increased flows are expected to be similar. Figure 4 shows the seasonal variation in faecal coliform concentration before and after the upgrade.

Table 1: Summary of Pond Effluent Faecal Coliform Concentration Results Before and After Upgrade

Statistic	**Faecal Coliform Concentration (cfu/100 ml)**	
	Before Upgrade	**After Upgrade**
10th Percentile	450	80
Median	4,500	210
Average	22,400	340
90th Percentile	36,500	660
95th Percentile	69,500	930

Table 2: Summary of Pond Effluent Suspended Solids Concentration Results Before and After Upgrade

Statistic	**Suspended Solids Concentration (g/m^3)**	
	Before Upgrade	**After Upgrade**
10th Percentile	15	5
Median	35	15
Average	40	20
90th Percentile	73	41
95th Percentile	82	48

Table 3: Summary of Pond Effluent BOD Concentration Results Before and After Upgrade

Statistic	**BOD Concentration (g/m³)**	
	Before Upgrade	**After Upgrade**
10th Percentile	14	7
Median	21	13
Average	25	14
90th Percentile	41	22
95th Percentile	47	24

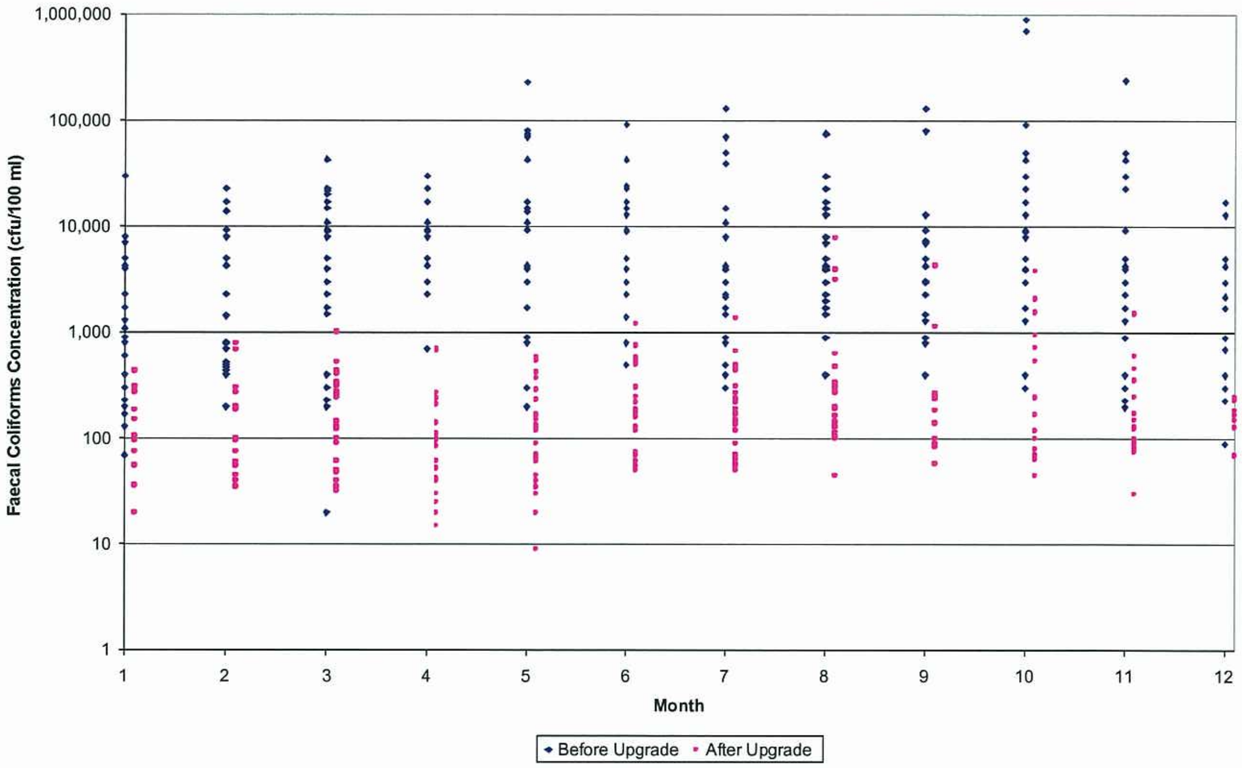
Table 4: Summary of Other Pond Effluent Concentrations Before and After Upgrade

Parameter	**Median**		**90th Percentile**	
	Before Upgrade	**After Upgrade**	**Before Upgrade**	**After Upgrade**
Dissolved oxygen (g/m³)	8	9	14	16
Dissolved BOD (g/m³)	13	4	34	7
Ammonia (g/m³)	28	32	33	36
TKN (g/m³)	35	36	40	40
Nitrate (g/m³)	0.11	0.12	0.28	0.26
Nitrite (g/m³)	0.04	0.01	0.18	0.11

Table 5: Comparison of Faecal Coliform from Christchurch Ponds (without UV) to Hamilton WWTP (Activated Sludge with UV)

Statistic	**Christchurch Ponds After Upgrade (no UV)**	**Hamilton WWTP (Activated Sludge with UV)**
10th Percentile	80	30
Median	210	185
90th Percentile	660	3,000
95th Percentile	930	9,000

Figure 4: Seasonal Variation in Faecal Coliform Concentration Before and After Upgrade



3 DISCUSSION

Clearly there has been a marked improvement in the reduction in indicator bacteria. The median has improved by more than one order of magnitude and the 90th percentile improved by nearly two orders of magnitude. Using the Marais (1974) formula, as shown in Mara and Pearson (1998), and a k_T value of 2 d^{-1}, it was predicted that the median faecal coliform concentration would be 8 cfu/100 ml. However, it was thought that the contribution from birds on the ponds would be significant and that the actual median faecal coliform concentration would more likely be in the range of 200 to 600 cfu/100 ml (CH2M Beca, 2002). The actual median of 213 cfu/100 ml since the upgrade, is close to this prediction. Perhaps different k_T values need to be used in the Marais formula for later ponds where there are many ponds in series.

Since the upgrade, the seasonal variation in faecal coliform concentration has also reduced. Before the upgrade, there was an order of magnitude difference between summer and winter faecal coliform concentrations, but there is little seasonal difference after upgrade.

From Table 5, it can be seen that the Christchurch Ponds are producing a similar effluent indicator quality as the Hamilton WWTP (with UV disinfection) at the median, and significantly better, at the 90th and 95th percentiles.

The total BOD and suspended solids have both shown a marked improvement, with concentrations being halved. Improvements in these two parameters will in part be due to improved quality of effluent entering the ponds but also in part due to lower levels of algae production in the ponds with the lower loads entering the ponds.

The ammonia concentration in the final discharge has increased while the total nitrogen has remained essentially the same. One explanation of this is that the greater concentrations of algae previously in the ponds (that is before the upgrade), sequestered more of the ammonia as organic nitrogen in the algae, while after the upgrade with lower algae numbers, there are higher ammonia concentrations with lower organic nitrogen concentrations.

Despite the reduction in algae concentrations in the ponds, the dissolved oxygen increased slightly. This is probably due to the aeration cascade which increases DO by 3 g/m^3 when upstream DO is less than about 5 g/m^3.. The Pano and Middlebrooks (1982) formula for ammonia removal predicted that the ammonia concentration would be 16 g/m^3 in winter and 8 g/m^3 in summer following the upgrade. These predictions have not been realised, indicating that stripping of ammonia gas to atmosphere is not occurring despite the aeration cascade, supporting our earlier argument that volatilisation is not a significant method of ammonia removal in ponds at pH 7.5 to pH 8.5 (Archer & O'Brien, 2005).

Before the pond upgrade, Environment Canterbury gave a recreational water quality grading of "poor" for nearby beaches at Sumner and Scarborough. This was largely due to high indicator bacteria concentrations in the pond effluent. Based on the significant improvements seen in the final effluent concentration in the winter after the upgrade, the effluent discharge was no longer considered to be the highest risk factor at Sumner and Scarborough beaches and the recreational water quality grading was revised to "good" for Sumner and "fair" for Scarborough.

Based on the marked improvement in indicator numbers, Christchurch City Council applied for a discharge consent from a proposed 3 km long ocean outfall and without UV lamp disinfection. Consents were granted on this basis, as described in the paper also presented at this conference "Christchurch Ocean Outfall Design", by C. Tipler et al.

4 CONCLUSIONS

This upgrade of the ponds to more cells-in-series has produced indicator bacterial reductions much better than expected. The discharge from the ponds now often meets the former contact recreation standard of a median of 200 faecal coliforms per 100 ml. From the Council's perspective this is an excellent result as it clearly negates the need for an artificial UV plant, saving not only the capital cost of UV, but also the substantial ongoing operating costs for electricity and lamp replacement.

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