final report

Project code: A.ENV.0107

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Date submitted: June 2012

PUBLISHED BY
Meat & Livestock Australia Limited
Locked Bag 991
NORTH SYDNEY NSW 2059

Using Covered Anaerobic Ponds to Treat Abattoir Wastewater, Reduce Greenhouse Gases and Generate Bioenergy

Churchill Abattoir

Meat & Livestock Australia acknowledges the matching funds provided by the Australian Government and contributions from the Australian Meat Processor Corporation to support the research and development detailed in this publication.

Abstract

Churchill Abattoir (Ipswich, QLD) has developed a novel anaerobic pond design for the treatment of abattoir waste water. Conceptually the design consists of 5 smaller ponds (~2.2ML) arranged in cells. The novel design of the ponds has been driven by a number of factors including, low cost construction, manageability (for desludging) and ease of removing and applying covers (with potential to reuse covers). The use of 5 smaller ponds instead of 1 larger pond has proven successful in terms of crust and sludge removal. Key findings in assessing the effectiveness of the system revealed that the covered ponds are capable of efficient waste water decomposition and biogas production. The primary issue with the covered ponds at Churchill was the build up of fat/crust that prevented the capture of biogas and effective use of the cover. A key recommendation which supports findings within the red meat processing industry is that fat removal systems such as dissolved air flotation (DAF) units is a prime requirement for effective anaerobic pond operation, both in covered and uncovered situations. Biogas modelling also indicated that the potential production of biogas can be significantly influenced by COD reduction efficiency (due to overloading by fats oils and greases) and the configuration and operation of the ponds. Combined, these factors can dramatically influence the feasibility of bioenergy produced from the site with the quantity of biogas potentially varying tenfold.

Executive Summary

The Australian red meat processing industry is beginning to install covered anaerobic pond technology in an effort to confront and solve its two most pressing problems with existing anaerobic pond technology, namely odour and methane emissions. The technology has had an indifferent introduction to the industry with problems including crust and solids build up under the covers and inappropriate cover materials leading to early failure of expensive covers. One advantage of covered ponds is the ability to capture energy-rich biogas and utilise it in technologies such as gas engines or dryers.

There is currently a lack of knowledge within the red meat processing industry regarding the design and operation of anaerobic ponds and upgrading these to covered anaerobic ponds to minimise greenhouse gas emissions from wastewater treatment operations. Also, the recoverable quantity and quality of such gas remains unclear. Consequently there is a need for research into these areas to mitigate the technical risks of the technology. This project takes advantage of the new covered anaerobic ponds being installed at Churchill Abattoir to gather information useful in understanding the above issues. Specific objectives of this present study include:

- Inform criteria for the novel design of covered anaerobic pond technology (and management) suitable for the treatment of high strength abattoir waste water.
- Monitor the start up behaviour of a covered pond to identify the time needed to bring the pond up to full performance
- Monitor across the duty cycle biogas (and GHGs) quantity and quality to refine design and management criteria for covered anaerobic ponds
- Determine the feasibility of bio energy production from covered anaerobic ponds.
- Provide sufficient technical and economic information on the performance of the technology for the meat and livestock industry.

Construction of a series of 5 smaller anaerobic ponds, with an effective volume of 2.2ML each, was built in place of the existing larger anaerobic pond to investigate the use of covered ponds. The concept of the smaller ponds was to allow rotation of the ponds and easier cleaning of the ponds and application/removal of covers. The covered ponds were commissioned before the project was initiated which meant that the start up behaviour of the ponds was unable to be assessed. It was observed, however, that gas was produced about 1 week after the cover was installed and wastewater introduced to the pond with water from the existing aerobic lagoon one month prior may have been instrumental in the rapid activation of the anaerobic treatment. Biogas production was consistent until an accumulation of crust prevented biogas permeation into the cover. The two primary ponds (A and B) were in operation for approximately 18 months and 22 months respectively before being desludged.

Inflow and outflow effluent of ponds A and B including the outflow of the last pond in the system (pond E) was monitored over the duration of the project. Monitoring of pond performance revealed that, while the two primary ponds (ponds A and B) were operated well above nominal organic loading rates, the five pond system was working efficiently in the elimination of organic (COD, BOD) load from the wastewater. Wastewater characterisation showed that the ponds generally maintained good performance for the entire duration of operation to support the complex microbiological processes that lie behind the efficient anaerobic digestion of abattoir wastewater. Parameters such as pH, acetic acid, alkalinity, ammonia, ORP, and temperature were all in the optimum range to promote the conversion of waste to biogas as evidence by the

composition of methane in the gas produced from pond B. This pond was producing up to 62%-72% methane just prior to being desludged in June 2012.

Due to the presence of the thick crust which developed during the initiation of the ponds in 2010, biogas quantity was unable to be accurately determined. The thick crust also interacted with the cover causing leakage of the biogas emissions. An alternate measure of gas production was provided using the modelling software BioWin to predict biogas production based on wastewater data. To simulate the anaerobic ponds at Churchill, BioWin was first calibrated against measured data from the field monitoring programme. The model was calibrated by assuming a reduction efficiency of the influent COD and adjusting this to best match the measured effluent COD of pond B. The model was calibrated with a COD reduction efficiency of 30%. The remaining 70% of the COD can be accounted for through the accumulation of fat/crust and undigested sludge at the bottom of the pond, which was consistent with observations at the site. BioWin was able to successfully simulate the behaviour of the wastewater treatment system and therefore biogas yield was determined with some confidence. BioWin simulated an average biogas yield of 328 m^3/day for the 5 pond system based on 30-40% operating efficiency. When modelled under ideal conditions (ie 85% COD removal) the 5 pond system is expected to produced a biogas total yield of 1183 m^3/day. Given the range in biogas determined for the site, direct measurement of the biogas would have provided limited value in terms of bioenergy feasibility. One the other hand, a direct measurement of biogas would have offered the ability to assess the current operating point of the ponds; however, this would not provide any insight into the potential range of biogas production which the modelling affords.

A simple economic analysis was undertaken to assess the feasibility of biogas energy recovery and use at Churchill. The economic assessment was based on a simple payback period (SPP) approach for a combined heat and power generation plant. The results from the SPP analysis indicated a payback on the investment (including an allowance for life time O&M costs) of 2.2 years with a SPP less than 3 years considered as an attractive proposition for the Meat Processing Industry. Biogas modelling results however suggested significant variation in the economic benefit of biogas energy, with the quantity of biogas potentially varying by tenfold depending on site factors such as pond efficiency, pond configuration and operational practices.

Based on the outcomes of this study and on current operating circumstances at Churchill Abattoir, some key recommendations can be made in relation to maximising pond efficiency and biogas production. These include:

1. Routine removal of crust and sludge throughout the life time of the ponds to optimise the effective volume of the pond and thus maximise biogas production.
2. Addition of a clarifier to the system to recycle the activated sludge leaving the system or the addition of baffles to increase the solids retention time.
3. Installation of fat removal systems such as a dissolved air flotation (DAF) unit to pre-treat the effluent and thus reduce the organic loading into the ponds.

Since the inception of covered anaerobic ponds at Churchill Abattoir, this site has undertaken a trial installation of a DAF unit to assess the efficiency of removal of FOGs from wastewater streams. Churchill Abattoir will be running the DAF continuously over the coming months which will provide a unique opportunity to assess pond behaviour and gas production before and after DAF operation. The results will be written up as an addendum to this final report and will provide preliminary assessment of the efficiency of the overall anaerobic system in breaking down organic matter and generating methane when FOGs are removed prior to effluent entering a covered anaerobic pond.

Contents

Acknowledgements

NCEA Project team

Bernadette McCabe
Craig Baillie
Peter Harris (Technical assistance)
Pam Pittaway (Sludge study)
Talal Yusaf and Ihsan Hamawand (BioWin modelling)

A number of NCEA and Churchill Abattoir personnel have participated in this project. The following are gratefully acknowledged for their contributions on various aspects of this study:

NCEA staff
Victor Skowronski
Steve Rees
Rick Cameron
Phil Szabo
Raed Ahmed Mahmood (Sludge study)

Faculty of Sciences staff
Oliver Kinder (Construction of sludge sampler)

Churchill Abattoir

The generous support provided by the following CA staff is also gratefully acknowledged:

Mike Spence (Company Engineer)
Ken Jackson
Steve Broderick
Troy Broomfield
Mick Collingwood

List of Abbreviations

AD	Anaerobic digestion
ARE	Absolute relative error
ATA	Anaerobic toxicity assay
BMP	Biochemical methane potential
BOD	Biochemical oxygen demand
CA	Churchill Abattoir
$CaCO_3$	Calcium carbonate
CH_4	Methane
CNG	Compressed natural gas
CO_2	Carbon dioxide
CO_2-e	Carbon dioxide emissions
COD	Chemical oxygen demand
DAF	Dissolved air flotation
EC	Electrical conductivity
FOGs	Fats, oils and greases
GHG	Greenhouse gas
GTE	Gas turbine engine
H_2S	Hydrogen sulphide
HDPE	High density polyethylene
HRT	Hydraulic retention time
ICE	Internal combustion engine
LPG	Liquid petroleum gas
N_2	Nitrogen gas
NH_3	Ammonia
NH_3-N	Ammonia-nitrogen
NH_4-N	Ammonium-nitrogen
NCEA	National Centre for Engineering in Agriculture
O_2	Oxygen
O&M	Operation and management
OL	Organic load
OLR	Organic loading rate
ORP	Oxidation reduction potential
ppm	Parts per million
PVC	Polyvinyl chloride
SPP	Simple payback period
SRT	Solids retention time
TA	Total alkalinity
tHSCW	Tonnes of hot standard carcass weight
TKN	Total Kjeldahl nitrogen
TN	Total nitrogen
TP	Total phosphorus
TSS	Total suspended solids
VFA	Volatile fatty acids
VS	Volatile solids
VSS	Volatile suspended solids

1. Background

1.1. Anaerobic wastewater treatment in the red meat processing industry

Anaerobic waste treatment ponds (also known as lagoons) are one of the oldest and simplest forms for domestic and industrial waste and are used extensively for agricultural industries such as piggeries, dairies, tanneries and abattoirs. They are the preferred method for treating agricultural wastewater in Australia due to their simplicity to build and operate (Laginestra and van-Oorschot, 2009). Anaerobic ponds are widely used in the meat industry as the first stage of secondary treatment of high strength abattoir wastewater and are an efficient means whereby the biochemical oxygen demand (BOD) and COD (chemical oxygen demand) are reduced by around 90%. However, they have a couple of issues including odour emissions and the generation of methane, a powerful greenhouse gas (GHG). Subsequently, the red meat industry is beginning to install covered anaerobic pond technology in an effort to confront and solve these two most pressing problems. Despite higher initial infrastructure costs when compared to uncovered anaerobic ponds, covered anaerobic ponds offer significant advantages such as odour control, intensification of the decomposition process and BOD removal, an increase in feed rate and the potential for capturing methane-rich gas as a fuel source for bio energy and the reduction in GHGs.

One of the major problems that the industry confronts, however, is that there are many ways of designing abattoir waste stabilisation ponds but there is no standard way. Designed works which have been carried out at some Australian abattoirs do not rely on real data for support. This section provides an overview of the current literature outlining the various design considerations and performance issues of anaerobic ponds. It also provides a background to the development of a novel anaerobic pond design and cover construction at Churchill Abattoir (CA) Pty Ltd.

1.1.1. Characteristics of organic waste in the red meat processing industry

Red meat processing produces wastewater with a high pollutant load consisting of paunch, manure, fats, oils and greases, and uncollected blood. These components contribute to a high-strength waste which must be treated to reduce the following parameters: biochemical oxygen demand (BOD), chemical oxygen demand (COD), fats oils and greases (FOGs) and total suspended solids (TSS). The Australian meat processing industry is very diverse in nature processing a wide range of animals. In addition, the type and degree of pre-treatment and product recovery also varies from plant to plant. A broad range of waste loads and waste components are generated as a result of these factors.

Table 1.1 compares typical abattoir wastewater pollutant loads (Johns 1993) with a red meat processing (sheep) plant (UNSW, 1998). As a comparison, piggery (Ra *et al.* 2000); and dairy wastes (Demirel *et al.* 2005) are included to illustrate some key differences.

Table 1.1:Typical meat processing plant wastewater characteristics in relation to piggery and dairy wastewater

Parameter (mg/L)	Typical abattoir raw wastewater (all meats)[1]	Southern meats (sheep)[2]	Piggery	Dairy[4]
BOD	1600-3000	~1/2 COD	887.77- 3904.23	NR
COD	4200-8500	3100-11500	4056.77-7073.23	1150-9200
FOG	100-200	290-2670	NR	NR
TSS	1300-3400	1150-5700	1-3.62	340-1730
VSS	n/a	1040-5300	0.89-3.09	255-830
TN	114-148	180-440	NR	14-272
NH_4-N	65-87	18-135	204.06-295.94	NR
TP	20-30	26.4-60	297.15-469.853	8-68
VFA	175-400	61-600	NR	NR
Alkalinity	350-800	340-700	NR	320-970

[1] (Johns 1993),
[2](UNSW 1998),
[3](Ra *et al.* 2000),
[4] (Demirel *et al.* 2005)
NR = not reported

Biochemical oxygen demand (BOD) and chemical oxygen demand (COD) are measures of organic pollution with respect to the amount of oxygen required to degrade the organic matter. While BOD refers particularly to the amount of oxygen required by detritivores and specifically bacteria to aerobically decompose the organic waste, COD does not differentiate between biologically available and inert organic matter and includes slowly biodegradable and recalcitrant organic matter (US EPA 2002). Agricultural industries such as abattoirs, piggeries and dairies produce high strength wastewater with COD values ranging from as low as 1000mg/L in dairy wastewater (Demirel *et al.* 2005) to as high as 11500mg/L in abattoirs processing sheep (UNSW 1998).

Fats, oils and greases (FOGs) are large contributors to BOD and COD and are extracted from wastewater as hexane-extractable materials (US EPA 2002). While FOGs have the potential to produce large quantities of methane, their recalcitrant nature generally results in a number of problems. Some of the problems attributed to the build-up of FOGs include: clogging of pipes; foul odour generation; adhesion to the bacterial cell surface and reducing their ability to treat wastewater; and flotation of sludge and loss of active sludge (Cammarota & Freire 2006). While dairies and piggeries tend to produce very little FOGs, abattoirs produce very high concentrations of FOGs, from typically as little as 100mg/L to several thousand mgFOG/L (Johns 1993; UNSW 1998).

Suspended solids (TSS) include proteins, carbohydrates, lipids and other materials such as hair. Table 1.1 shows that the values of TSS are generally lower in piggery and dairy wastewater than those reported as typical values for abattoirs at 1600-3000mg/L and 3100-11500mg/L for the Southern Meats sheep abattoir (UNSW 1998).

Typically, the wastewater treatment systems of abattoirs are capable of reducing the BOD, COD and TSS load of their wastewater by 97%, 96% and 95% respectively. Nitrogen removal varies depending on the treatment applied, with aerobic and anaerobic ponds removing less than 35% (Mittal 2006). Conversely, FOGs tend to accumulate on the surface of ponds to form a recalcitrant scum layer or ‘crust’ (UNSW 1998; Wan *et al.* 2011).

However, primary treatment systems such as dissolved air flotation units (DAF) are capable of reducing FOGs by up to 90-98% (Johns 1995).

1.1.2. Anaerobic digestion process

Anaerobic digestion is a naturally occurring biological process and follows four basic stages: hydrolysis, acidogenesis, acetogenesis and methanogenesis (Gujer & Zehnder 1983; figure 1.1). Hydrolysis involves the action of exo-enzymes excreted from fermentative bacteria. These enzymes hydrolyse large insoluble organic matter such as proteins, carbohydrates and lipids, converting them into soluble compounds such as amino acids, simple sugars, fatty acids and alcohols. Once hydrolysed, these soluble compounds are capable of passing through cells walls and membranes of fermentative bacteria for digestion. Hydrolysis is the slowest of the four stages and limits the rate at which methane production can occur.

Acidogenesis involves the degradation of the previously mentioned soluble compounds by fermentative bacteria to even simpler compounds, which are then excreted to the environment. These simple compounds include volatile fatty acids (VFAs), alcohols, lactic acid, carbon dioxide, hydrogen, ammonia and hydrogen sulphide.

Acetogenesis involves the digestion of fatty acids such as propionate and butyrate which are produced during hydrolysis. These intermediary acid products are converted to acetate, hydrogen and carbon dioxide.

The final stage in anaerobic digestion, methanogenesis involves the action of two groups of methanogenic bacteria. The first group (aceticlastic methanogens) splits acetate into methane and carbon dioxide, and the second group (hydrogenotrophic methanogens) combines hydrogen and carbon dioxide to produce methane.

Anaerobic digestion is said to be working optimally when the acid formation phase (hydrolysis and acidogenesis) and the methane production phase (acetogenesis and methanogenesis) occur simultaneously in dynamic equilibrium. Stability of the anaerobic process is difficult to maintain because a balance favourable to several microbial populations is necessary. The methane producers are the most sensitive to conditions and can be affected by a change in the pH of the digesting sludge or inhibited by the accumulation of toxic by-products such as VFAs and ammonia. Each species is limited to the use of a few compounds, mostly alcohols and organic acids. The comparatively stable nature of the acid formers and the fastidious nature of the methane formers creates a biosystem that is prone to upset as a result of shock loads or temperature fluctuations. Therefore, for the design of an anaerobic pond to perform optimally, it must be based on the limiting characteristics of these microorganisms.

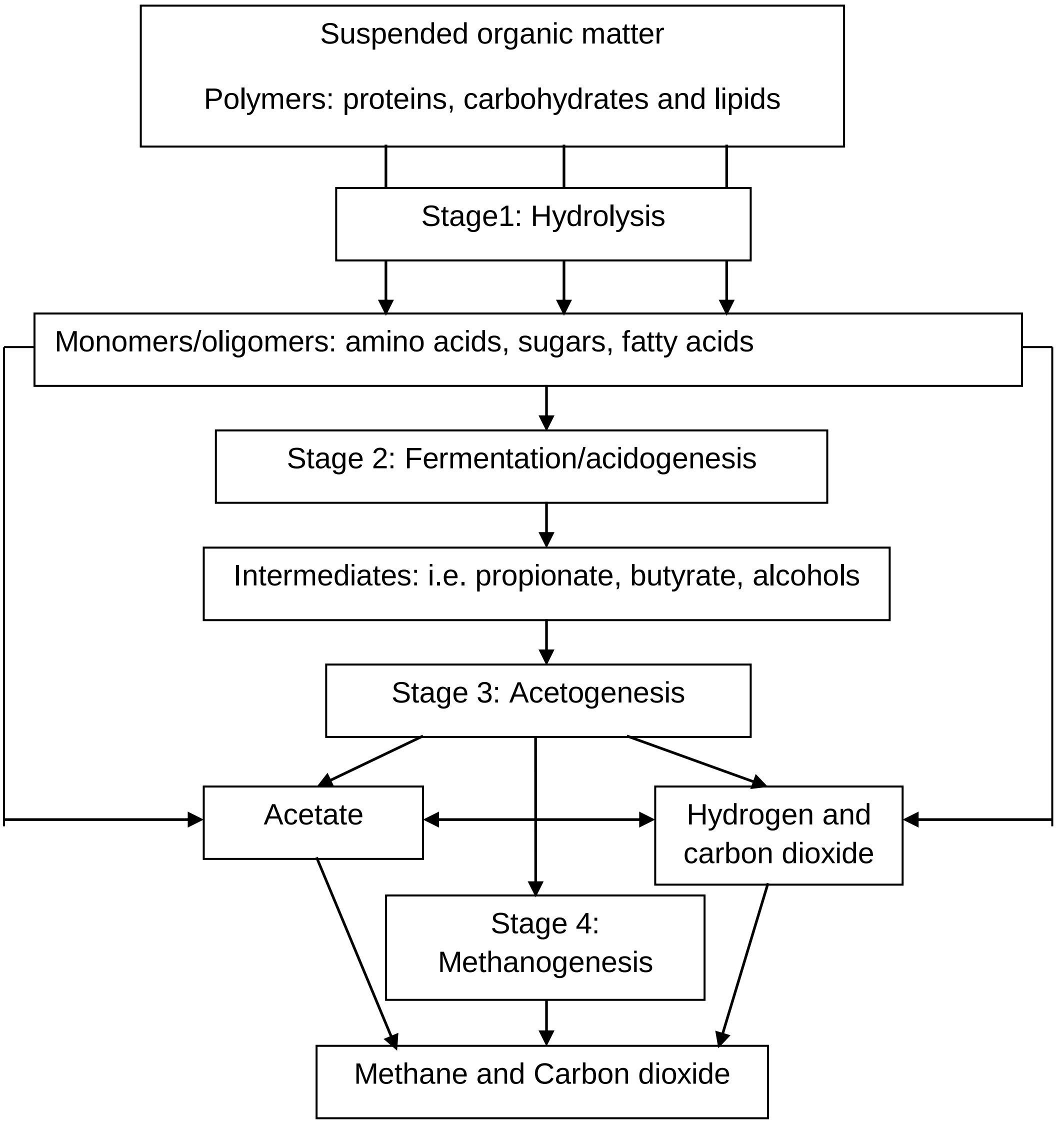


Figure 1.1: The anaerobic process (Adapted from Gujer & Zehnder 1983).

1.1.3. Design, operation and performance parameters of anaerobic ponds

Design criteria

Criteria for anaerobic pond design are poorly defined and no widely accepted overall design equation exists. Previously, pond construction criteria for the red meat processing industry has been borrowed from other industries, and this has resulted in pond designs which have not necessarily been suitable. Some design criteria that have been produced include: American Society for Agricultural Engineers (ASAE 2000) Engineering Practice 403: Design of Anaerobic Lagoons for Agricultural Waste Management; Mara D and Pearson H (1998) Design Manual for Waste Stabilisation Ponds in Mediterranean Countries. European Investment Bank, Lagoon Technology International Ltd.; and Tchobanoglous G, Theisen H, and Vigil S (1993) Integrated Solid Waste Management: Engineering Principles and Management Issues. McGraw-Hill Inc. A recommended, though not standard, set of design parameters for abattoir anaerobic ponds in Australia has been put forward (CSIRO 2010).

Design is typically based on organic loading rates and hydraulic retention times from pilot plants and observations of existing pond systems (US EPA 2002). Hydraulic retention time refers to the amount of time that a liquid with soluble compounds remains in a pond or digester, and is highly variable depending on temperature and wastewater composition (Monnet 2003). Generally, the desired goal is to achieve significant reductions in wastewater organic load with the least hydraulic rettion time (HRT) possible (UNSW 1998). Generally accepted parameters for determining pond volume include an organic loading rate of 500-800gCOD/m^3/d with a hydraulic retention time of 20-40 days (CSIRO 2010).

Anaerobic ponds are required to be deep in order to maintain anaerobic conditions at the active sludge layer. The depth of a pond will depend on what is practicable and at what level the water table resides (CSIRO 2010). While a pond depth of 2.4-6 meters with a minimum freeboard of 500mm can be used, the latter is preferable as deeper ponds reduce the surface area to volume ratio and acts to conserve heat within the pond (CSIRO 2010; US EPA 2002). It is recommended that a length to breadth ratio of 3:1 and an internal slope of 2-3:1 depending on soil type and that the pond must be lined with clay or a polymer material to prevent seepage of wastewater into the water table (CSIRO 2010).

Typically, wastewater enters near the bottom of an anaerobic pond and mixes with the active biomass in the sludge layer. The surface loading approach for waste stabilization ponds is the most widely accepted design specification, inlets and outlets to the pond should be near the bottom and around 300mm below the water surface respectively, and positioned as to avoid short circuiting (Shilton & Harrison 2003; Pearson *et al.* 1995). Mixing in the pond is generally seen as an added unnecessary cost, but is intended to mix fresh effluent with bacteria-containing digestate, and carries the added bonus of limiting temperature gradients within the pond and improving access of bacteria to wastewater (Verma 2002). Safley and Westerman (1988) observed the development of particular active and quiescent zones within ponds that were not mixed. For this reason it was recommended that the majority of the pond surface be covered. While the introduction of further wastewater to the system would cause some mixing, it is reasonable to suggest that gentle mixing of wastewater in anaerobic ponds could improve pond performance.

Another important factor to consider is temperature. Ponds should be designed best on the mean minimum temperature of the coldest month since temperature affects biological activity (Shilton 2005). While methanogenesis may occur at temperatures as low as 4°C, efficiency is greatly reduced below 21°C (Stevens & Schulte 1977; Mittal 2006).

Performance Parameters

While many designs and operation procedures have been trialled to improve anaerobic digestion techniques and utilise gas production, only more recently has work been conducted to investigate the effect of various wastewater characteristics on treatment efficiency and biogas production.

As previously mentioned, the comparatively stable nature of the acid formers and the fastidious nature of the methane formers creates a biosystem that is prone to upset as a result of shock loads or temperature fluctuations. Therefore, for the design of an anaerobic pond to perform optimally, it must be based on the limiting characteristics of these microorganisms. Pond oxidation-reduction potential (ORP), temperature, NH_3 concentration, pH, volatile fatty acid to total alkalinity (VFA/TA) ratios are all parameters which are indicative of pond performance and should be monitored. The optimum and extreme ranged for these parameters are summarised in table 1.2 below.

Table 1.2: Ideal operating ranges for methanogenesis.

Parameter	**Optimum range**	**Extreme range**
ORP (mv)[a]	~-200	-175
Temperature (°C)[b](mesophilic)	30-35	25-40
pH[b]	6.6-7.6	6.2-8.0
Alkalinity (mg$CaCO_3$/L)[b]	2000-3000	1000-5000
Volatile acids (mg/L as acetic acid)[b]	50-500	2000
VFA:TA ratio[c]	0.25-0.35:1	
TA:VFA molar ratio[a]	>1.4:1	

[a] Appels *et al.* (2008)
[b] US EPA (2002)
[c] Kuglarz *et al.* (1992)

The process of methanogenesis requires strict anaerobic conditions, indicated by an ORP around -200mV or less. This is important to monitor as ORP conditions above -175mV will inhibit the growth of the obligate anaerobic methanogens and anaerobic digestion will not occur (Appels *et al.* 2008).

Temperature affects biological activity and therefore directly impacts both the organic reduction and biogas production achieved by anaerobic ponds. Methanogenesis occurs at temperatures as low as 4°C (Johns 1995), however, increases in temperature from 4°C to 25°C dramatically increases rates of methanogenesis (Stevens & Schulte 1977). Furthermore, the minimum temperature at which methanogenesis occurs was found to decrease as the age of the anaerobic pond increased. Therefore it is recommended that OLRs are increased with mean ambient temperature (Safley & Westerman 1988). Thermophilic anaerobic digestion systems (50°C-60°C) offer many advantages to mesophilic (25°C-40°C) systems. While mesophilic systems are well understood, easier to operate and cheaper, thermophilic systems exhibit greater rates of methanogenesis, are more effective at sterilising wastewater, and operate much faster, requiring a HRT of only 12-14 days compared with 15-30 days (Monnet 2003). However, thermophilic methanogens are more sensitive to temperature fluctuations than their mesophilic counterparts and are more sensitive to shock loadings and long chain fatty acid toxicity (Appels *et al.* 2008).

Monitoring pH change in anaerobic ponds is one method used to identify pond failure. For this method, a healthy pond pH range is recognised to be 6.5-7.5, while the optimum range is 6.8-7.2 (Monou *et al.* 2008; Ward *et al.* 2008). It is understood that in cases of pond failure involving overloading, or toxicity towards methanogens, an overloading of acetic acid occurs due to inappropriate removal (Weiland 2010). If this occurs, a drop in pH can be detected, and a change in operation can occur to return the pond to suitable operating parameters before the pond fails completely. However, it is recognised that pH is a far less reliable method of indicating pond failure than focusing on buffering capacity (measured as alkalinity), as an accumulation of short chain fatty acids will reduce the buffering capacity significantly before decreasing the pH (Ward *et al.* 2008).

To determine pond stability from alkalinity and VFA accumulation, two common calculations can be applied. A weight ratio of VFA:TA of 0.25-0.35:1 is indicative of a healthy pond system (Kuglarz *et al.* 1992). Alternatively, a molar ratio of TA:VFA greater than or equal to 1.4:1 should be maintained for a stable and well buffered system. Furthermore, the stability of this ratio is more important than the magnitude (Appels *et al.* 2008).

The anaerobic process involves the degradation of nitrogen-containing compounds including amino acids and urea, resulting in ammonia formation. An essential nutrient for anaerobic bacteria, ammonia is believed to be beneficial to anaerobic digestion at concentrations below 200mg/L. Concentrations responsible for 50% inhibition of methane production range from 1.7-14g/L (Chen *et al.* 2008).

The high concentration of fats, oils and greases (FOGs) in the wastewater reduces solids removal efficiency rates due to the insoluble nature of the fats (Battimelli *et al.* 2009). Fats are less dense than water, limiting the physical mass transfer from the solid to the liquid phase, and/or the presence of some long chain fatty acids may inhibit some methanogenic organisms (Rinzema *et al.* 1994). It has been found, however, that only shock loads of FOGs are inhibitory, with the microbial community recovering to produce far greater methane yields through the digestion of lipids (Kabouris *et al.* 2009). Pre-treatment such as the removal of fat and grease using screens or dissolved air flotation (DAF) (Arvanitoyannis & Ladas 2008), or the saponification or exposure to low frequency ultrasound may assist in solubilising these recalcitrant organics (Erden *et al.* 2010).

Operation and Maintenance

Start up is generally considered the most critical stage of the operation of an anaerobic pond (Ike *et al.* 2010). Anaerobic ponds are generally the slowest anaerobic system to start up, often taking three to six months (UNSW 1998; Ike *et al.* 2010). This time is required for the initial inoculum of slow growing methanogenic bacteria to acclimatise and accumulate a sufficient level of active biomass for the satisfactory removal of organic wastes and methane production (UNSW 1998).

During start up, ponds are loaded at low organic loading rates (OLR) typically $0.3\pm0.1 kgCOD.m^{-3}.d^{-1}$. Care must be taken during the start up phase to provide adequate substrate for bacterial proliferation, while over-feeding may lead to pond failure. However, under-feeding of organic waste into the pond will not cause failure, but will prolong the start up period. It is essential to monitor volatile fatty acid content, alkalinity, COD and pH to determine whether OLR is satisfactory during start up (UNSW 1998). Stabilisation of an anaerobic digestion system is determined by the percentage of COD or VS removed from the wastewater. When a benchmark percentage (for example 75% VS removal) is reached OLR may be increased and again stabilised.

Following a successful start up, anaerobic ponds are expected to run with minimal attention so long as operational conditions remain relatively constant (Ike et al. 2010). Anaerobic ponds are subject to several parameters which affect the operation of the system. These include the OLR, the system temperature, HRT and the degree of mixing within the system. Historically, anaerobic digestion systems have proven easy to overload. The capacity of anaerobic digestion systems is determined by measuring the OLR. This parameter is expressed as either $kgCOD.m^{-3}$ or $kgVS.m^{-3}$. Compared with anaerobic digesters, anaerobic ponds are designed for relatively low OLRs. Overloading of ponds has the undesirable effect of accumulating inhibitory substances which inhibit biogas production and reduce biogas yield. As a general rule, an increase in organic loading must be balanced by an increase in HRT to achieve equivalent treatment efficiency of the wastewater.

Anaerobic ponds are designed based on an OLR to promote sedimentation of wastewater solids and efficient anaerobic digestion to biogas methane. However, higher OLRs generally result in lower bioconversion efficiency and will accumulate large amounts of sludge which requires periodic removal. Depending on the sludge thickness, this may be pumped out or may require machinery (Battimelli *et al.* 2009; Green *et al.* 1995).

1.1.4. Covered anaerobic pond technology

Covered anaerobic ponds are preferred for their high performance, low capital cost and limited maintenance requirement. Furthermore, the addition of a cover reduces heat loss from ponds, reduces odour emissions, and allows the capture of methane gas for flaring or energy generation (Johns 1993). With greater understanding of the harm done to the environment by releasing these gases, many smaller ponds resort to flaring biogas – burning the methane to produce the less potent greenhouse gas carbon dioxide. Others, however, have turned to using biogas to produce heat, generate electricity, and fuel engines (CSIRO 2010).

The concept of covering anaerobic ponds to improve wastewater treatment, reduce odours and capture biogas has been applied to a number of industries both in treatment of domestic and industrial waste. Some examples in Australia include:

- Werribee 115E wastewater treatment plant ,Vic (Melbourne Water Corp)
- Shepparton, Mooroopna and Tatura (Vic) wastewater management facilities, (WMF)
- Warrnambool, Vic (Dairy)
- McCain's, Ballarat, Vic (potato and food effluent)
- Ingham's, Brisbane (Chicken abattoir)
- Tarac, South Australia (Distillery)
- Throsby, Singleton, NSW (meat processor)
- Teys Bros, Beenleigh, QLD (meat processor)

There are various designs available for covering anaerobic ponds (Golders Assoc. 2009). Pond covers may be broadly categorised into either fixed or floating. Fixed covers are held in place around the pond and never contact the pond surface. Many of these cover designs involve entrenching and burying the edges of the cover in the banks, making it very difficult to remove covers and subsequently perform pond management such as de-sludging and crust removal. Floating covers rest on the pond surface, and may rise or fall with the level of wastewater. These covers may be placed under positive or negative pressure. Covers under positive pressure have air pumped into them to lift the cover material off the surface of the water. Those under negative pressure have had the air sucked out, and are in constant contact with the wastewater surface. In the case of negative pressure covers, the cover material may be subject to degradation through reaction with wastewater components such as fats, oils and greases (FOG). In both instances, it is difficult to remove these covers to perform pond management such as de-sludging without damaging the covers.

When covers applied to anaerobic ponds are subject to sunlight, high temperatures can be achieved which increases methanogenesis and thus the decomposition process. Furthermore, covers reduce heat loss and maintain higher degrees of pond efficiency and biogas production.

Table 1.3 below compares the biogas production from a variety of ponds of varying sizes, treating agricultural wastes including that from piggeries, dairies, swine abattoirs, poultry farms, and beef feedlots. A relationship appears to exist between loading rate and biogas quality. Those ponds receiving lower OLRs tend to produce more methane per kilogram of VS removed, while those ponds receiving higher OLRs tend to produce less methane per kilogram of VS removed. Furthermore, the ponds receiving lower OLRs are producing better quality biogas, with a methane content ranging from 65-90%, while the higher loaded ponds produce biogas with a methane content of 53.6-64.1%. This occurs despite the higher loaded ponds operating at higher temperatures. Not listed in table 1.3 is the data from the sheep abattoir Southern Meats (UNSW 1998). This abattoir utilises a 3ML covered anaerobic pond with baffles and sludge recycling to treat wastewater with an OLR of 0.5-0.6KgCOD/m3/d with a HRT of 10-12 days, achieving COD removal of greater than 80%. Measurements of biogas production or quality were not performed by the time the report was published (UNSW 1998).

Table 1.3: Comparison of biogas production from animal wastes; adapted from Safley and Westerman (1988) and Park and Craggs (2007).

Waste type	Temp °C	Loading rate (kg VS/m^3/d)	Biogas productivity (mean)		Biogas quality (%CH_4)	References
			m^3/kgVS removed	m^3/m^3/d		
Piggery	4-9	0.15	1.03	0.16	72	(Park & Craggs 2007)
Dairy	4-9	0.017		0.011	80.3	(Park & Craggs 2007)
Swine	-	0.36	1.45	0.11	70	(Pain *et al.* 1984)
Swine	-	0.11	1.2	0.13	69	(Allen & Lowery 1976)
Swine	24.4-30.0	0.05	0.8	0.22	75-85	(Safley & Westerman 1988)
Poultry	22.8-27.8	0.16	1.38	0.04	65-85	(Safley & Westerman 1988)
Poultry	24.4-27.8	0.02	1.5	0.03	85-90	(Safley & Westerman 1988)
Dairy	27.2-33.3	0.02	1.5	0.03	78-80	(Safley & Westerman 1988)
Beef feedlot	35	3.4	0.35	1.02	61	(Hills 1983)
Poultry caged layer	35	1.95	0.44	0.87	62.2	(Converse *et al.* 1983)
Poultry caged layer	35	1.63	0.38	0.80	58	(Safley *et al.* 1987)
Dairy	32	3.06	0.255	0.78	53.6	(Pain *et al.* 1984)
Swine	35	2.48	0.42	1.04	60.9	(Hashimoto 1983)
Swine	30	1.77	0.58	1.01	64.1	(Pos *et al.* 1985)

1.2. Covered anaerobic ponds at Churchill Abattoir

1.2.1. Plant operation and processing

Churchill Abattoir Pty Ltd is a medium-sized meat processing facility which provides meat to retail outlets in Queensland and northern New South Wales. The abattoir slaughters and processes around 3000 head of cattle per week resulting in around 660 tonnes of hot standard carcass weight (tHSCW) per week. The components of the abattoirs plant operation and water treatment system is illustrated in figure 1.2.

Cattle are held in a yard where they are washed by sprinklers to remove dirt and dust. After slaughter the carcass is transported to the kill floor for skinning and organ removal, and washed and prepared for boning. The organs and other by-products of slaughter such as blood and bone are processed for either disposal or generation of further products. Blood from bled animals is gravity fed to a cooking room where it is cooked and bagged for use in agricultural fertilisers. Skins are purchased by external bodies for production of leather and other good. Gut contents (paunch; consisting of recently ingested grain, grass and other matter) is washed and gravity fed to an open tank where it is then pumped to a separator which squeezes the paunch using a screw press to separate liquids from solids. The gut is then sent to the cooking room and cooked in a gas fired rotary drum cooker. Solids are separated from the liquids and sent to be bleached for use as food products. Bones are augured in the hogger to produce small chips. Following this, a screening process is used to remove solids including meat and bone from liquids. The wastewater and separated liquids from these and other processes mix at the save-all and are pumped to the anaerobic ponds for treatment.

1.2.2. Wastewater management at Churchill Abattoir

Churchill Abattoir has a water consumption of around 215ML of water annually and produces approximately 1ML of high strength wastewater per day. Wastewater is composed of a complex mixture of hand wash water, sterilizer water (containing dissolved fats, blood, particulates, hair and dirt), gut wash and paunch water (including grain, grass, dissolved fats, oils, greases and grit), stick water from the by-products room, fat rich water from cooking and tallow washing, general wash down water including chemicals for cleaning, ash water, and cattle yard wash down waster containing manure, mud and sand.

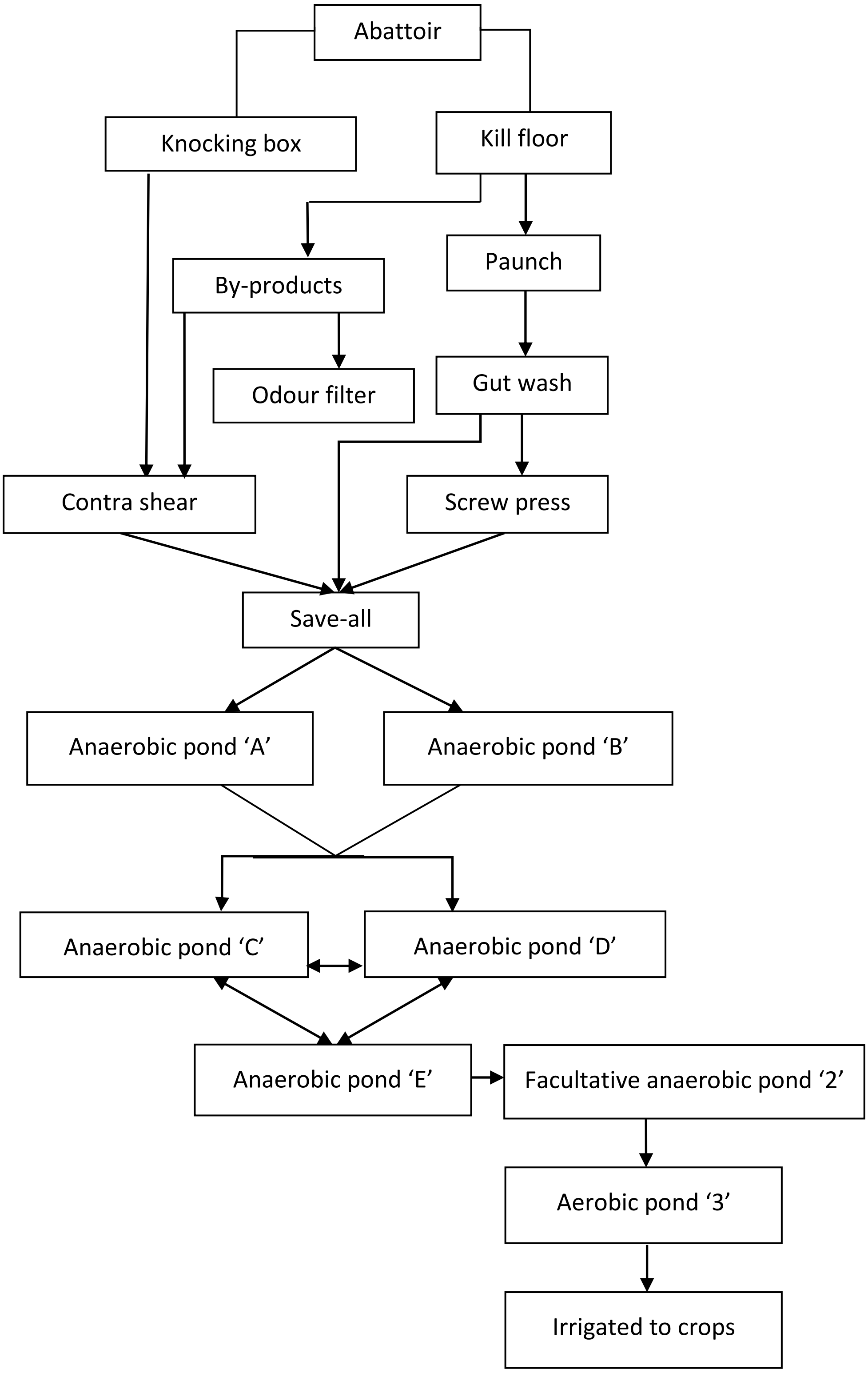


Figure 1.2: Flow of wastewater and plant processes at Churchill Abattoir. Instances of solid waste removal from the system are not indicated.

After mixing at the save-all, wastewater is pumped to the anaerobic ponds labelled ‘A’ and ‘B’ which run in parallel. The combined effluents from ponds ‘A’ and ‘B’ flow into ponds C and D, which are interconnected and flow into pond E. Each of these anaerobic ponds generally operated at a 2-3 day retention time for a system retention time of around 10-12 days. From pond E, effluent flows into the facultative pond ‘2’, and from here, flows into the aerobic pond ‘3’. After 10-12 days of retention in the aerobic pond, wastewater is irrigated to on-site cropland for use as an aqueous fertiliser.

1.2.3. Novel anaerobic pond design and cover construction

Prior to 2001 the then QLD Abattoir Corporation had no wastewater treatment system; this created a significant environmental problem including odour. In 2000, three ponds were constructed based on a BOD loading of 300g/m^3/day, with a 20 day HRT (M. Spence pers. comm. 2010). Figure 1.3 shows the pond layout at Churchill Abattoir. The previous anaerobic pond (pond 1) was 5m deep, with a capacity of 10ML. Effluent from the anaerobic pond flowed into a facultative pond (pond 2; 5m depth, 10ML capacity) and an aerobic pond (pond 3; 2m depth, 16ML capacity) in series.

The anticipated lifespan of the system was 10 to 15 years. However, within 5 years of construction, the ponds had failed. A comparison of the average BOD loading of raw influent and pond 1 effluent over 10 years of operation indicates a removal efficiency of 91%. Desludging was attempted in 2006, but the presence of a hardened crust (1m thick) and the viscous nature of the sludge below made the task difficult. Figure 1.4 illustrates how fat has built up over the years and shows the fat layer that was partially removed using an excavator. It was found that while the harder top layer could be removed mechanically, there remained a ‘sloppy under-layer’ which became impossible to shift mechanically. The volume of fat is estimated at possibly 4000m^3 not including the sloppier material accumulated over 10 years.

Although several unforseen problems were encountered due to limited industry knowledge, much information was gained over this five year period. This included design consideration of the ponds, long term water quality and the requirement for periodic maintenance of the ponds; as well as the generation of hydrogen sulphide producing odours and greenhouse gases in the form of carbon dioxide and methane liberated to the atmosphere during the anaerobic process.

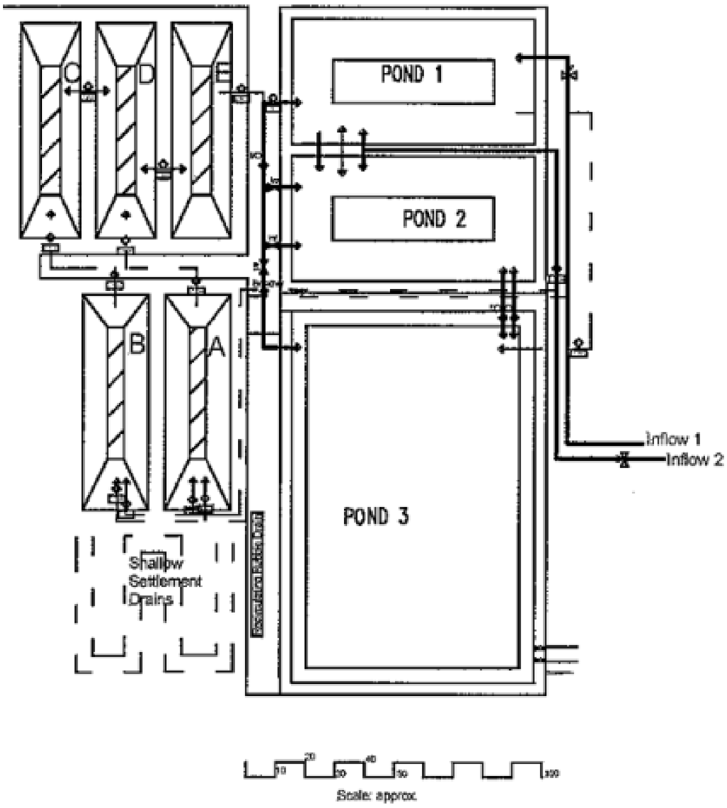


Figure 1.3: Final layout of the five pond system including pipework. 150 mm HDPE pressure pipe was used to deliver wastewater to the ponds

Figure 1.4: Desludging of Pond 1 and removal of crust in 2006

To address the issues identified previously Churchill Abattoir started to investigate the use of covered anaerobic ponds in 2009 to reduce offensive odours and greenhouse gas emissions with the subsequent capture of methane for bioenergy. This prompted a redesign of the wastewater treatment system. Initially, a 6-pond system based on the 20 day retention time was developed instead of the 5-pond system. The concept was to make the ponds smaller to allow rotation of the ponds and easier cleaning. Initially a depth of 6 metres was included in the design, however, this could not be achieved in the area selected as a ‘prior stream’ (possibly a cut-off from the Bremer River several million years ago) was found at about 5m below surface level (figure 1.5). After excavation, the ponds were levelled, rolled, and sealed with bentonite to prevent leakage.

Figure 1.5: Pond D showing gravel bed of prior stream during construction

The five smaller anaerobic ponds (A-E; figure 1.3) were constructed, each 50m in length, 20m in width and 5m in depth, with an effective volume of 2.2ML. Each pond operates with approximately 500mm free board. This design was selected for two main reasons, namely manageability for desludging ponds and ease of removing and applying covers. Furthermore, this pond size is the most economical to construct with an excavator, lending itself to the most economical configuration for cleaning and maintenance. Table 1.4 provides dimensions of the new anaerobic ponds and existing ponds at Churchill Abattoir. Figure 1.6 provides an aerial view of the ponds shortly after construction.

Table 1.4: Dimensions of the new anaerobic ponds and existing ponds at Churchill Abattoir.

Base length			**Area**	**Top length**		**Area**	**Height**	**Volume**
Pond	**B1 (m)**	**B2 (m)**	**A (base) (m^2)**	**T1 (m)**	**T2 (m)**	**A (top) (m^2)**	**H1 (m)**	**(m^3)**
A	4	40	160	63	17	1071	4.2	2302.939
B	4	39	156	58	18	1044	4.7	2512.250
C	4.5	43	193.5	68	17	1156	3.7	2247.694
D	4.5	40	180	67	15	1005	3.7	1986.066
E	6	50	300	62	16	992	3.4	2082.531
							Total	11131
Existing ponds								
1				40	80		5	9.83
2				40	80		5	9.83
3				80	120		1.5	13.51

NB: Allows for 500mm freeboard

Figure 1.6: Aerial view of the ponds shortly after construction (source: http://www.nearmap.com/?ll=27.646008,152.739127&z=18&t=h&nmd=20100605)

A new floating cover design was proposed (figure 1.7) whereby covers are attached to a floating raft or truss which holds the cover off the surface of the pond. The actual design (figure 1.8) is very similar to the proposed raft design.

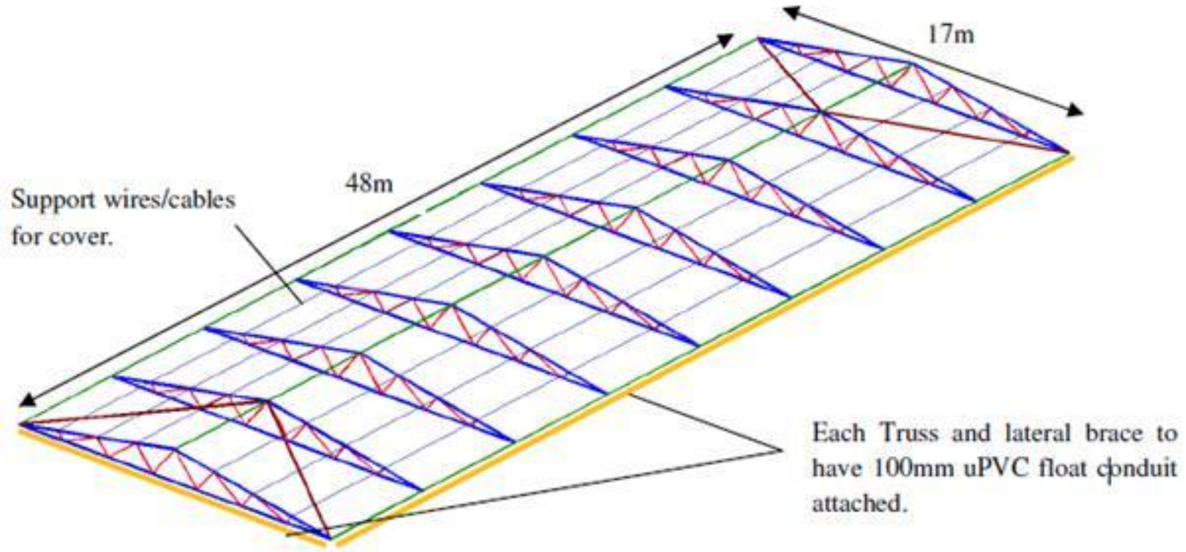


Figure 1.7: Idealised design for 17m x 48m truss concept

Figure 1.8: Actual design for 17m x 48m trust concept

A range of materials were available to develop these covers. The most cost effective of these, 100mm HDPE pipe, was used to form the skeleton of the raft. These pipes were filled with expansive foam in an attempt to stiffen the structure and aid in floatation. The cover to accompany the raft was initially produced from a spray on product Liquid Rubber^{TM} applied to a commercially available geo-textile membrane. An advantage to this approach was the concept of fixing small leaks by patching with further application of Liquid Rubber^{TM}. However, when applied to a small-scale test raft the rubber cover produced significant leakage, failed to capture gas, and this material was subsequently abandoned. HDPE mats had been used previously for pond covers. Although known to react with FOG, the Churchill Abattoir raft design keeps the HDPE mat relatively out of contact with the FOG. Furthermore, the HDPE is strong, flexible, captures gas, and is relatively inexpensive when compared with other approaches. However, an initial difficulty of the design was the 10% differential expansion and contraction of the HDPE.

1.2.4. Cover installation and pond start-up

The first full-scale raft cover to be produced was put into operation over the first of the smaller anaerobic pond (pond A) on 19 Aug 2010. Figure 1.9 illustrates the cover being positioned into place.

Figure 1.9: Positioning of the floating cover to pond A

The pond had previously been filled for approximately 1 month with water from the existing aerobic pond (pond 3). Biogas was collected about 1 week after the raft was launched and wastewater from the plant introduced to the pond. Figure 1.10 illustrates the successful installation of the cover on pond A inflated with biogas and figure 1.11 shows the interim arrangement for gas collection using a 75mm flexible hose. This image was taken on 22 Oct 2010 (about 8 weeks after installation). The flexible hose was connected to a HDPE welded flange with a stainless flange and a butterfly valve (not shown). The hose was run into the adjacent pond to filter the gas.

Gas was produced about 1 week after the raft was launched and wastewater introduced to the pond with water from the existing aerobic pond one month prior may have been instrumental in the rapid activation of the anaerobic treatment. A previous study using covered anaerobic ponds indicated that to create optimal anaerobic conditions a 3 month start-up period was needed plus the addition of sludge from an active anaerobic lagoon (UNSW 1998). In the case of pond A start-up the onset of gas was rapid and given the order of events described above, within one month.

Figure 1.10: Installed cover on first pond, inflated with captured biogas.

Figure 1.11: Interim arrangement for gas collection using 75mm flexible hose

Biogas production was consistent until an accumulation of crust prevented biogas permeation into the cover. The pond A raft was removed on 23 November 2010. Pond B cover was completed late November 2010. Rain and other issues interfered with placement of the cover over pond B which was installed on 15 June 2011.

2. Project objectives

2.1. Scope of work

Anaerobic ponds are major greenhouse gas (GHG) emitters and while the basic science involved in minimizing these emissions via covering the ponds is relatively well known, there are currently major technical knowledge gaps in relation to the design, operation and maintenance of covered anaerobic ponds in the red meat processing industry. At present there is additionally only very limited information available with respect to how to build a pond and cover it to achieve benefits in odour reduction and methane capture in red meat abattoirs.

The lack of historical data means this technology is effectively unproven in large scale operations. The development of a novel pond design at Churchill Abattoir has provided the opportunity for the assessment of anaerobic pond behaviour which could potentially help the Australian red meat industry gain a better understanding of how pond design and covers can work and as a result develop new methods and technologies.

This project focussed on the monitoring of the two primary ponds of the 5-pond system at Churchill over a 12 month period in order to evaluate pond performance and design.

2.2. Objectives

Currently, industry design and management standards are based on generalized metrics for anaerobic ponds rather than specific data for the Australian red meat processing industry. One of the main tasks is to determine design criteria/procedures that are economical and reliable to provide a performance that consistently produces effluent of a quality that falls within environmental and design expectations of the system.

The aims of this research project were to improve the design and management of covered anaerobic ponds in the meat processing industry. The initial specific objectives of this work included:

- Inform criteria for the novel design of covered anaerobic pond technology (and management) suitable for the treatment of high strength abattoir wastewater.
- Monitor the start up behaviour of a covered pond to identify the time needed to bring the pond up to full performance.
- Monitor across the duty cycle biogas (and GHGs) quantity and quality to refine design and management criteria for covered anaerobic ponds
- Determine the feasibility of bio energy production from covered anaerobic ponds.
- Provide sufficient technical and economic information on the performance of the technology for the meat and livestock industry

3. Methodology

3.1. Monitoring schedule

The methodology for monitoring the performance of the novel anaerobic pond system was based on 2 stages around the dates provided in table 3.1. A total of 19 weeks sampling was performed in stage 1 while a total of 43 weeks was performed during stage 2.

Table 3.1: Monitoring schedule for ponds A and B

Stage	Description	Monitoring Period	Pond
	Start-up	Observation only: August-Oct 2010	Covered pond A
1	Initiate monitoring	July 2011– Nov 2011	Uncovered pond A Covered pond B Pond E outflow
2	Extended monitoring	July 2011 – May 2012	Covered pond B Pond E outflow

These sampling periods were dictated largely by delays due to weather (rain) and the installation of covers on ponds.

The purpose of the monitoring was to characterise the effluent of both inflow and outflow water samples in a covered anaerobic pond to gauge:

a) Performance of the ponds in terms of the decomposition process.
b) Performance of the ponds in terms of biogas quality.

A flow meter (CVT100-AOD150) was planned to be installed to determine approximate volumetric flow rate to enable the determination of gas quantity. However, due to the presence of the thick crust which developed during the initiation of the ponds in 2010 and interfered with the cover ability to capture biogas, gas quantity was unable to be accurately determined for the duration of the project. An alternate measure of gas production was provided using BioWin modelling software to predict biogas production based on wastewater characteristics (see section 3.5).

Sampling ports were installed as shown in figure 3.1 and included the inlets to ponds A and B, and the outlets of ponds A, B and E.

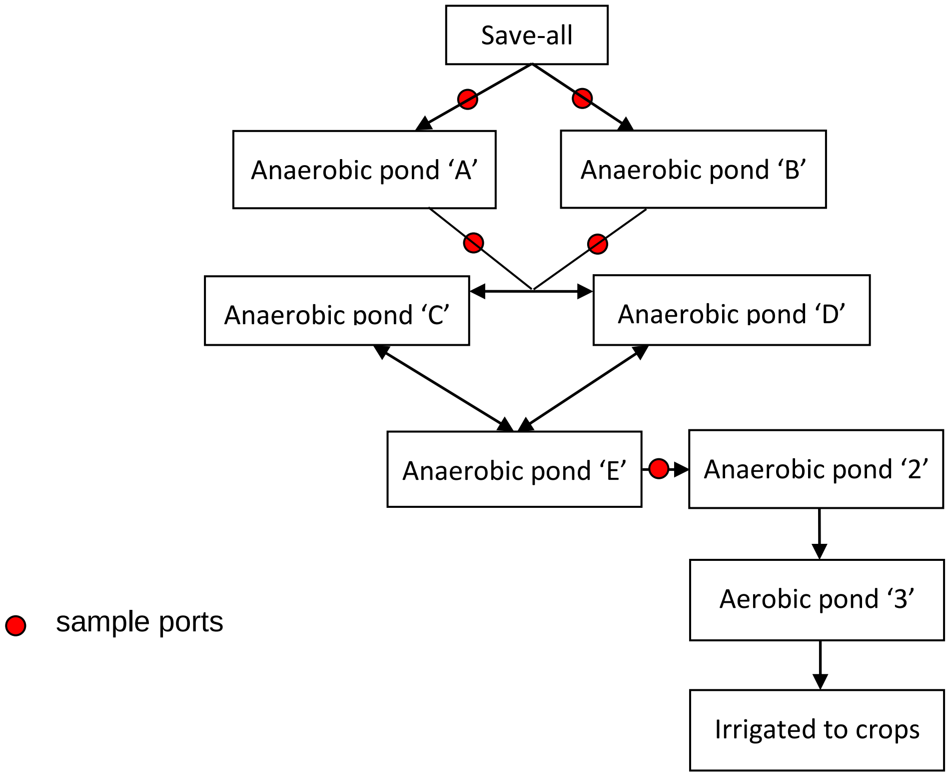


Figure 3.1 Schematic of pond layout indicating sampling points

3.2. Site instrumentation

Fixed ultrasonic flow meters (Dalian Zerogo RV-100F) were attached to the external surface of the inflow pipes to ponds A and B in a V configuration and measured minutely over the duration of the wastewater monitoring (figure 3.2). Flow meter data was logged at a frequency of one minute and stored on a CR1000 data logger.

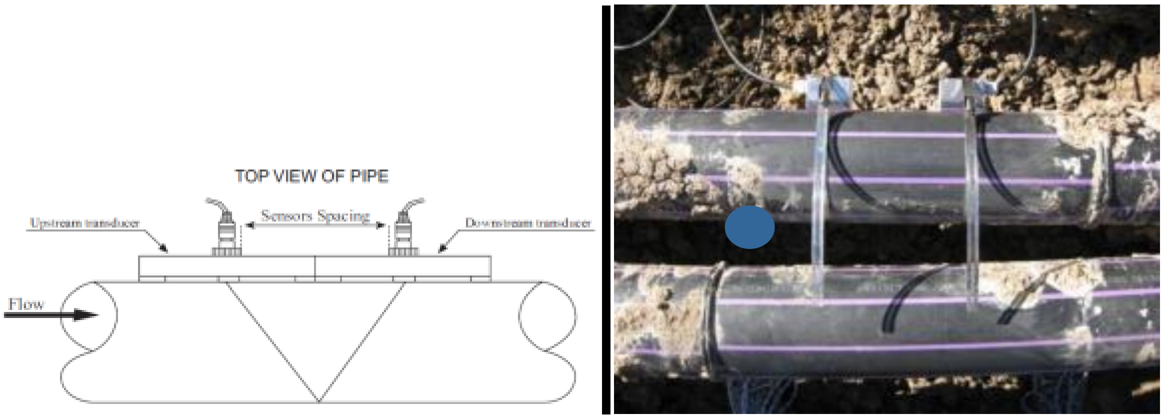


Figure 3.2: V configuration of ultrasonic flow meters

Gas quality was analysed by a Geotech GA3000 and GA2000 landfill gas analyser which is capable of measuring methane, carbon dioxide, hydrogen sulphide and oxygen to within 98%.

Figure 3.3: Instrument enclosure mounted at the head of Pond A

Figure 3.4: GA3000 gas analyser installation at northern end of pond B.

3.3. Sampling regime and analysis

The operating monitoring schedule provided in table 3.2 lists the basic sampling requirements that were implemented as part of the monitoring protocol for the covered anaerobic ponds. This monitoring schedule provided regular data on the status and performance of the pond.

Sampling episode reports

Grab sampling was carried out by NCEA personnel using the sample tapping points as illustrated in figure 3.1. The following information was obtained during each sampling episode:

- Dates and time of sample collection
- Flow data corresponding to each sample
- Production data corresponding to each sample
- Design and operating parameters and treatment technologies characterised during sampling
- Information about site information that has changed since the site visit or that were not included in the site visit report
- Temperature, pH, EC and ORP of the sampled wastewater.

Reporting of results included:

- All monitoring data plotted against time
- Calculation of % removal of COD and BOD with time
- Calculation of weekly BOD loadings (kgBOD/m^2/day and kgBOD/m^3/day) using the inflow BOD concentration and the average daily flow for the week.
- Calculation of weekly COD loadings (kgCOD/m^2/day and kgCOD/m^3/day) using the inflow COD concentration and the average daily flow for the week.
- Calculation of HRT
- Calculation of VFA:TA ratios

Both on-site and laboratory analysis was conducted on these samples. On-site wastewater analysis involved the measurement of wastewater temperature, pH, EC and ORP from all samples using a YSI professional plus field logger. Biogas was analysed for methane, carbon dioxide, oxygen, carbon monoxide, and hydrogen sulphide content, as well as the remaining balance using a Geotechnical instruments GA2000 portable gas analyser.

Wastewater samples for laboratory analysis were collected in specially prepared bottles supplied by ALS group in Brisbane, Queensland, Australia. Laboratory analysis of these samples was also conducted by ALS group. Measured parameters included COD, BOD, TSS, FOG, NH_3-N, TKN, VSS, alkalinity, and volatile acids. Biogas samples for laboratory analysis were conducted using a modified evacuated contained method. For this process, a 3L Tedlar bag was placed inside a 5L sealable container. Two tubes were inserted through the lid of the container and sealed using glands. One tube connected the gas bag to the gas source, while the other tube connected the container to a 12V battery powered pump (figure 3.5). Once activated, the pump produced a vacuum inside the container which caused the system to draw gas into the bag to equalise pressure. This method prevented harmful biogas compounds from damaging the pump. Biogas samples were analysed by SGS environmental services in Sydney, New South Wales, Australia. Samples were analysed for methane, carbon dioxide, hydrogen sulphide, ammonia, nitrous oxide, carbon monoxide and volatile fatty acids.

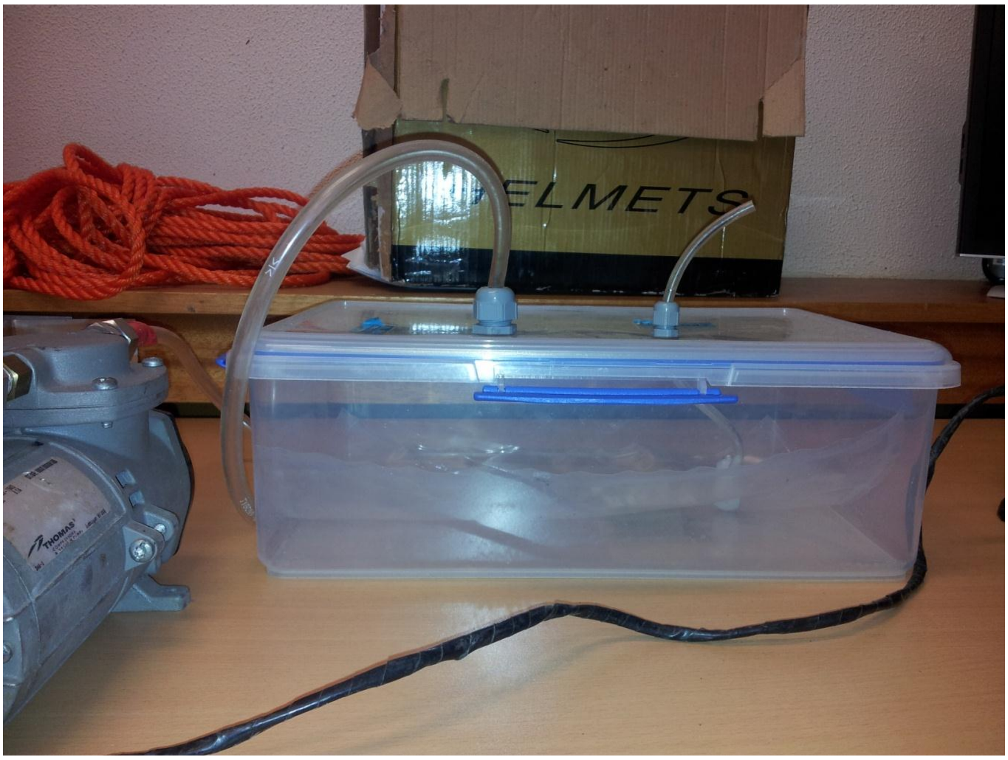


Figure 3.5: Evacuated container method for collecting biogas. The tube on the left is connected to the pump which draws a vacuum on the container. A tube connected to the cover would be connected to the tube on the right, which is attached to a Tedlar bag inside the container. The vacuum drawn by the pump forces the Tedlar bag to draw gas into the bag for collection.

Table 3.2: Operating Monitoring Schedule

Parameter	**Frequency**	**Sampling method**
Influent flow rate	Daily	Electronic meterering of flow automatically logged so that daily flows can be accurately recorded, including weekends.
Temperature (environment and water)	Continuous	Temperature probe port.
pH	Daily	pH probe port
Effluent characteristics: Inflow and outflow samples • COD • BOD_5 • TSS • TKN • NH_3-N • Oil and Grease • EC • ORP (redox)	2 x/week over the first 4 - 6 weeks initially to ensure the data quality is suitable given the likely variability in the inflow to the pond. Once this is established sampling occurred 1 x/week.	Sampling ports/taps will be installed at the exit of the covered anaerobic ponds so that samples of the outflow can be obtained before it mixes into subsequent ponds. In addition, there will be a sampling point for anaerobic pond inflows
Effluent characteristics: Outflow samples • VFA (as mg/L acetic acid • Total alkalinity (as mg$CaCO_3$/L)	1 x/week	
Biogas quality • CH_4 • CO_2 • H_2S • Sulfur dioxide • NH_3-N • VFA	Periodically	GeoTechnical GA2000 landfill gas analyser GeoTechnical GA3000 landfill gas analyser SGS Sydney laboratory analysis

3.4. Sludge sampling

In addition to determining the effluent characteristics of the pond contained in the operating monitoring schedule (table 3.2) sludge was sampled from two of the five ponds (ponds B and C) twice during the monitoring period.

A stainless steel depth pole was designed to measure the depth of water to settled solids, using a smaller diameter horizontal base-plate than the system used by Anderson *et al.* (2000). The equipment was fabricated in stainless steel in detachable units of not more than 1.6mm in length for transport and storage. The stainless steel tubular sleeve was designed to fit over the depth pole, enabling monitoring probes attached to the end of the tube to be lowered into the water to specific depths (figure 3.6). A conductivity and temperature probe, a pH probe and a 60 mL catheter syringe were fixed to the end of the monitoring sleeve to enable accurate water quality monitoring to be undertaken at the same time and at the same depth sludge or water column samples were taken. The probes were attached to a TPS 90 FL water quality meter by 6mm long cables (figure 3.7). The sampling system was designed and fabricated by staff at the University of Southern Queensland.

A pontoon supported by two aluminium dinghies was prepared by staff from Churchill Abattoir, to provide a platform for pond depth monitoring and sludge sampling (shown in figure 3.8). A metal frame bolted to the pontoon provided support for anchoring equipment and for lowering the depth pole and sampling sleeve.

Preliminary depth monitoring in Pond A highlighted that the extensive crust of fat and grease readily fouled the instruments. A solution for physically excluding the crust and maintaining a clear patch of water for the sampling device to be lowered through was developed. The device was a long bucket with the base removed, and the larger diameter lid was fixed at one point to the base. A cord held the lid in place while the bucket was partially submerged through the crust. The cord was released when the sampling probe was lowered through the bucket, pushing the base lid down into the water.

Figure 3.6: Prototype sludge depth pole (right hand side) and the monitoring and sludge sampling sleeve (left hand side).

Figure 3.7**:** Monitoring water conductivity, pH and sampling the sludge from the base of pond A. The depth of the pond was 4.3 m. The white bucket later modified to clear fat and grease from the surface water, is tied to the frame.

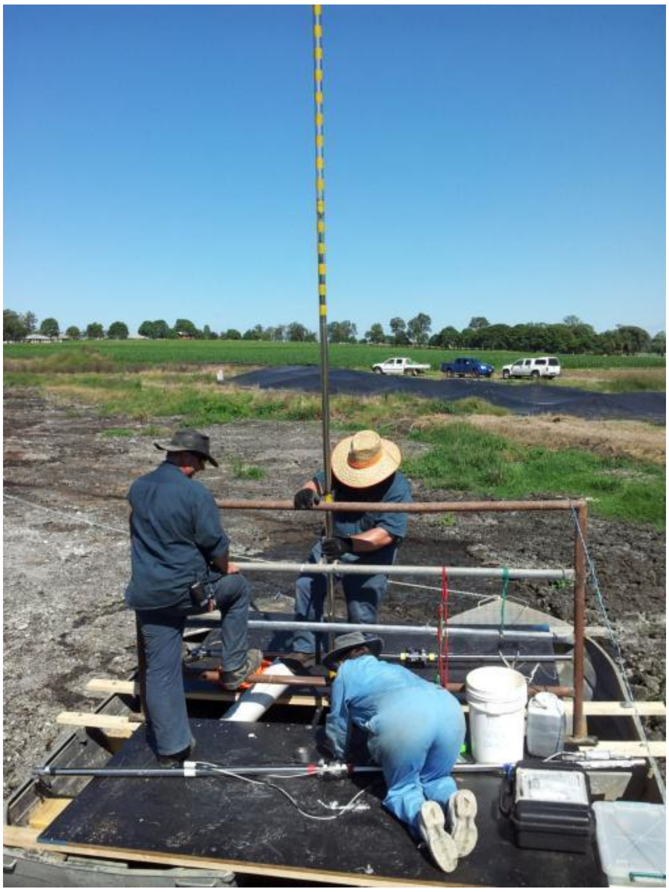


Figure 3.8**:** Removing the depth pole from the pond. The dismantled units of the sampling sleeve are lying across the surface of the pontoon deck, with one unit either side of the support frame.

Sludge samples were taken by pulling a cord attached to the top of the 60 mL hypodermic catheter syringe. The sampling sleeve was removed from the pond and the syringe was removed, sealed with plastic film and the cap, and placed in an insulated container prior to storage in a 4°C cold room. Sludge samples were prepared for COD measurements by diluting sample volumes in distilled water and filtering through glass fibre filter paper.

3.5. Biogas modelling

Prediction of potential biogas production

Due to the difficulties encountered in measuring biogas production at the site, dynamic wastewater treatment modelling using the software BioWin was undertaken to estimate biogas production. BioWin is a windows based computer simulation model developed by EnviroSim Associated LTD (Canada). BioWin is able to simulate the behaviour of a covered anaerobic pond by integrating biological and chemical processes to effectively determine biogas yield. BioWin contains two operational modules which include a steady state module and an interactive dynamic simulator. The steady state module is used for simulating systems based on constant conditions while the dynamic simulator allows the user to change time varying inputs or changes in operational strategy which reflect real life conditions.

BioWin uses a large number of expressions, default factors and kinetic rate for describing an ideal biological process which can be customized to fit various circumstances. It has the ability to simulate large and complicated wastewater treatment plants because it includes most of the elements in wastewater treatment plants with the ability to simulate more complicated processes by simply combining elements (multiple processes) together.

Comparison of wastewater models

BioWin, GPS-X and West are well known simulation software packages; each simulator has specific strengths and weaknesses depending on their application. The features of these models which vary include speed, customization, data processing, data display, control options, and built-in features, making each one a powerful tool for different applications (Rasi *et al.* 2011). In comparison to other models, BioWin is relatively more flexible for simulating complex wastewater treatment systems and is user friendly making it a much more powerful simulation tool than GPS-X and WEST (Stafford *et al.* 1981). There are many other software in the market such as SIMBA, Aquifas , SimuWorks, WRc, and STOAT. Although these are not as extensively used as the other models described above.

How BioWin works

BioWin simulates wastewater treatment processes, predicting variables such as VSS, TSS, undegradable and degradable fractions of COD. BioWin is divided into two modules, which include steady state and dynamic modules. The steady state module is a useful tool when there is constant flow and water composition to the system. On the other hand, the dynamic simulator is used to simulate systems with unsteady state inflow and water composition. BioWin uses a general model called ASDM (Activated Sludge/Anaerobic Digestion) which is standardized by the International Water Association (IWA). This model uses fifty state variables and sixty process expressions to describe the biological processes occurring in the system. In addition, the model includes some chemical precipitation reactions, and the gas-liquid mass transfer behaviour for six gases, among them methane, carbon dioxide and oxygen. BioWin also models the pH in the process and its effect on the biological and physical process. Additionally, BioWin can carry out a complete mass balance on each element and recycled side streams. The simulation can be carried out for any given time period. The output results can be directly viewed from the interactive graphs and tables or via a word-base report.

4. Results and Discussion

4.1. Pond study

4.1.1. Sampling history

Table 4.1 below provides details of the sampling history and the parameters analysed over the sampling period.

Table 4.1. Sampling history for ponds A, B and E

Pond	Effluent	Sampling periods Start	 End	Number of samples	Parameters
A	Inflow & outflow	17/06/2011	26/10/2011	16	TSS, alkalinity, NH_3-N, TKN, FOG, COD, BOD, VFA. pH, EC, ORP, temperature
B	Inflow & Outflow	17/06/2011 10/02/2012	26/10/2011 15/05/2012	40	
E	Outflow	10/08/2011 10/02/2012	26/10/2011 15/05/2012	17	

Stage 1

A total of 19 weeks of sampling was performed at various times on ponds A, B and E during stage 1 (refer to table 3.1, section 3). During 2011 the first nine weeks of sampling focused on monitoring the inflows and outflows of ponds A and B and included twice-weekly sampling. In the remaining ten weeks of this first sampling campaign, sampling was conducted once per week and included the monitoring of pond E effluent. The initial monitoring protocol focused only on the effluent from ponds A and B. These two ponds run in parallel and feed into a further series of three anaerobic ponds, C, D and E (refer figure 3.1, section 3). Ponds C, D and E function as a single unit with bidirectional flow between ponds, with flow direction dependent on pond level, although flow should be generally unidirectional C→D→E→pond 2.

The treatment efficiency of ponds C-E was investigated in order to further understand the operation of the novel anaerobic pond system as a whole. Wastewater currently mixes at the save-all to some degree before being pumped to the ponds, therefore ponds A and B receive similar wastes. It was determined using T-tests on outflow data from ponds A and B that there is no significant difference between the two effluent sources. Subsequently, inflow effluent samples to C and D were taken from the outlet of pond A and B. Also, as there is no flow meter on the outlet of pond E, it was assumed that as ponds are maintained at relatively constant volumes, the outflow from pond E is approximately equal to the inflow to A and B.

Stage 2

Sampling was resumed in 2012 to determine the long term performance of covered pond B and also included some further sampling of pond E to determine the efficiency of the 5 pond system. A total of 24 weeks sampling was performed over this second sampling campaign.

4.1.2. Wastewater characterisation

The table below shows a range of wastewater characteristics measured at Churchill Abattoir. For comparison, typical characteristics of Australian abattoir wastewater from Johns (1993) and another red meat processing abattoir (UNSW 1998) are also presented in table 4.2. Tables A7.1 to A7.3 in section 7 lists monthly wastewater raw data.

Generally, the characteristics of Churchill's wastewater were similar to typical industry and Southern Meats wastewater. Some key differences include level of FOGs and total nitrogen. Both Churchill Abattoir and Southern Meats show significantly higher levels of FOGs (approximately 10 times the industry norm). Admittedly, Churchill has only screens to remove FOGs whereas the wastewater at Southern Meats was pre-treated with both screens and DAF. The level of TN for both Churchill and Southern Meats are comparable and are higher than industry norm.

Of particular note are Churchill's effluent alkalinity levels. This was quite high in comparison to industry norms and indicates that the ponds have quite good buffering capacity. Effluent VFA is within the range of typical abattoir wastewater.

Table 4.2 CAs wastewater characteristics and comparison with other plants

Parameter (mg/L)	Typical abattoir wastewater (all meats)	Southern meats (sheep)	Churchill Abattoir (beef)						
			Stage 1				Stage 2		2000-2010
			Pond A	Average pond A	Pond B	Average pond B	Pond B	Average pond B	Average
BOD (mg/L)	1600-3000	~1/2 COD	1410-5150	3402.67	163-7020	3273.04	1060-24500	5088	2799
COD (mg/L)	4200-8500	3100-11500	2630-12100	7442	1040-12100	7051.48	4330-24200	9216	NR
FOG (mg/L)	100-200	290-2670	73-962	491.87	5-2110	618.74	173-4570	1388	1242
TSS (mg/L)	1300-3400	1150-5700	1370-6830	3235	457-6870	2991	1760-6130	3875	2473
TN (mg/L)	114-148	180-440	343-615	450	296-785	460	18-500	368	499
NH_4-N (mg/L)	65-87	18-135	36-202*	142*	23.8-349*	164*	4-192*	111*	NR
TP (mg/L)	20-30	26.4-60	NR	NR	NR	NR	NR	NR	79
Alkalinity	350-800	340-700	1020-1980	1378	1180-1730	1360	1050-1510	1245	
VFA (mg/L)	175-400	61-600	70-906	515	162-618	376	91-616	292	NR

*Value is for NH_3-N
NR indicates not recorded

4.1.3. Organic loading rates and hydraulic retention time

The OLR is calculated as kilograms of COD applied per cubic metre of pond volume per day (kgCOD.m^{-3}.d^{-1}). The average flow data into ponds A and B over the sampling periods is shown in figures 4.1 and 4.2 and the corresponding OLRs achieved for these 2 ponds during this time are summarised in table 4.3 below and figures 4.3 and 4.4.

While every reasonable effort was made to reduce variables, major variation in pond operation arose from general plant operation and events including pump malfunctions and replacements, pipe blockages and pond cleaning. It is important to note that as a result of this variation, both the hydraulic retention time and organic loading rate of the ponds were highly variable.

Table 4.3 Organic loading rates of ponds A and B

	Pond A			**Pond B**		
Month	***n***	**COD loading (KgCOD/m^3/d)**	**BOD loading (KgBOD/m^3/d)**	***n***	**COD loading (KgCOD/m^3/d)**	**BOD loading (KgBOD/m^3/d)**
June-11				8	2.35	0.96
July-11	6	1.99	0.92	9	2.97	1.40
August-11	2	1.98	0.83	4	3.60	1.53
September-11	3	2.64	1.30	3	2.67	1.34
October-11	3	2.49	1.08	3	3.51	1.55
February-12				2	3.92	2.04
March-12				4	4.66	2.08
April-12				4	3.17	4.98
May-12				3	11.17	2.65

The OLR of both pond A and B during stage 1 of the monitoring program are particularly high. Both BOD and COD loading rates are outside the required operating parameters (over double). Given the short HRT this would be expected, however, this ultimately impacts the bioconversion efficiency of ponds A and B.

Due to excessive crust and sludge build up pond A was taken offline in January 2012 and was desludged during the early part of 2012. All production wastewater was diverted into pond B from this time to June 2012. Accordingly, OLRs of pond B have increased during 2012 as shown in table 4.3. A spike in wastewater flow occurred in May 2012 (figure 4.2) and corresponds with an increase in OLR at this time.

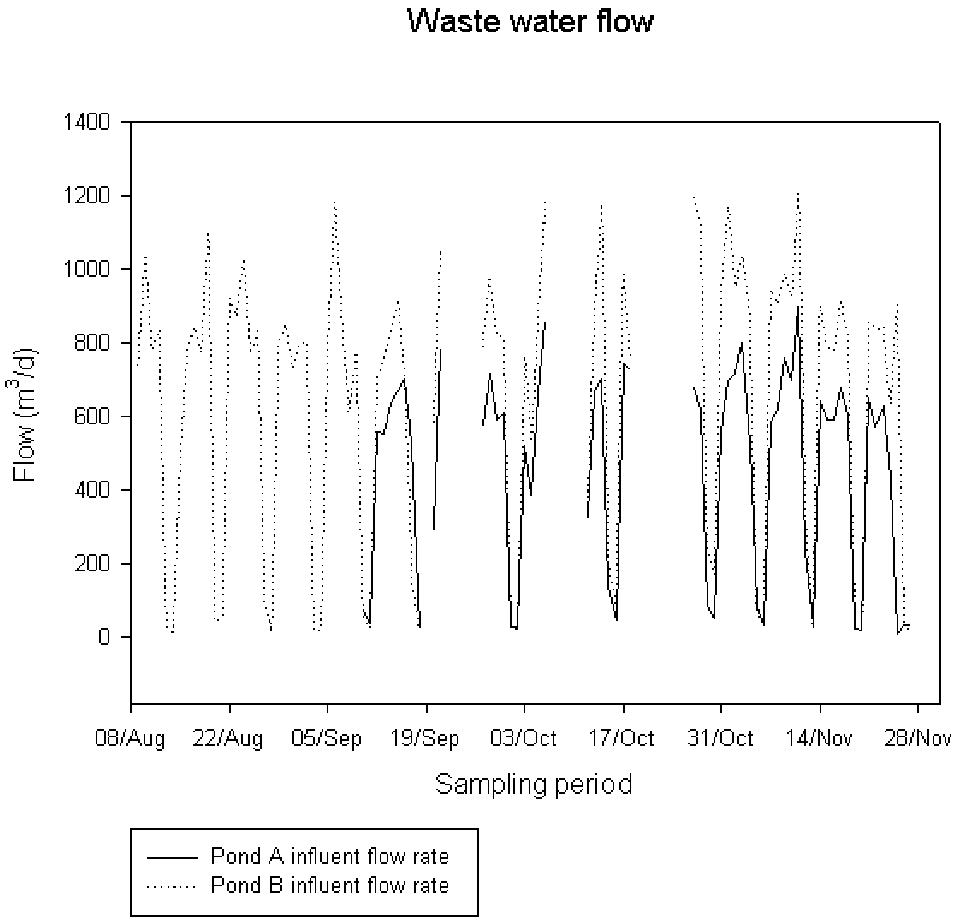


Figure 4.1: Wastewater flow of ponds A and B during stage 1 sampling 2011

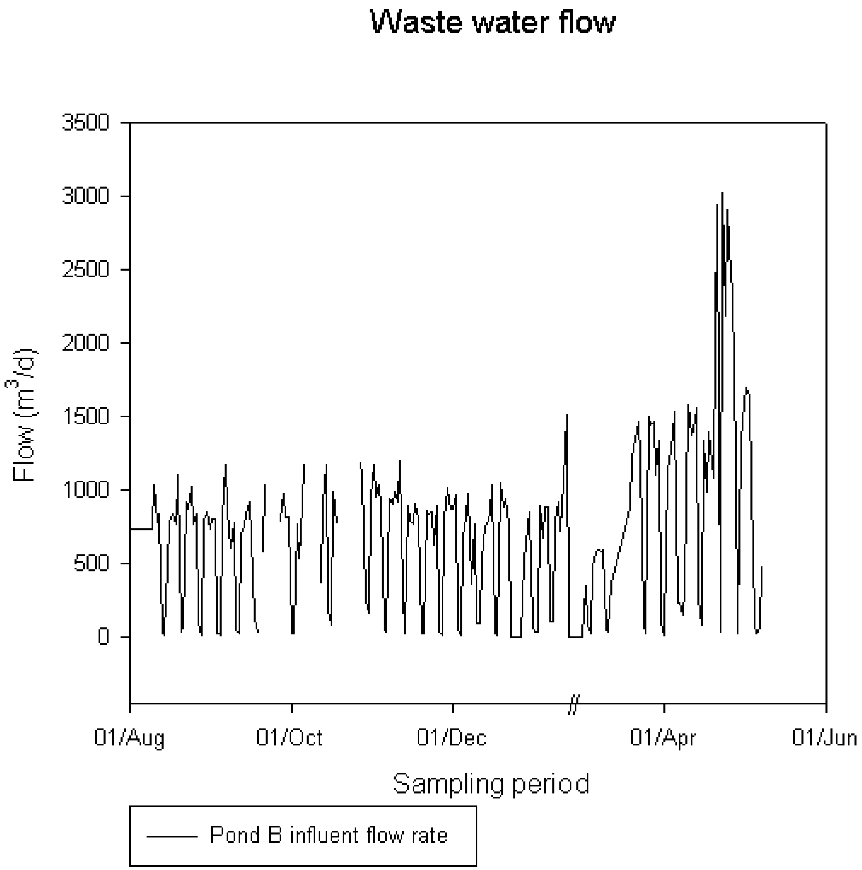


Figure 4.2: Wastewater flow of pond B during stage 1 and stage 2 sampling (2011 and 2012)

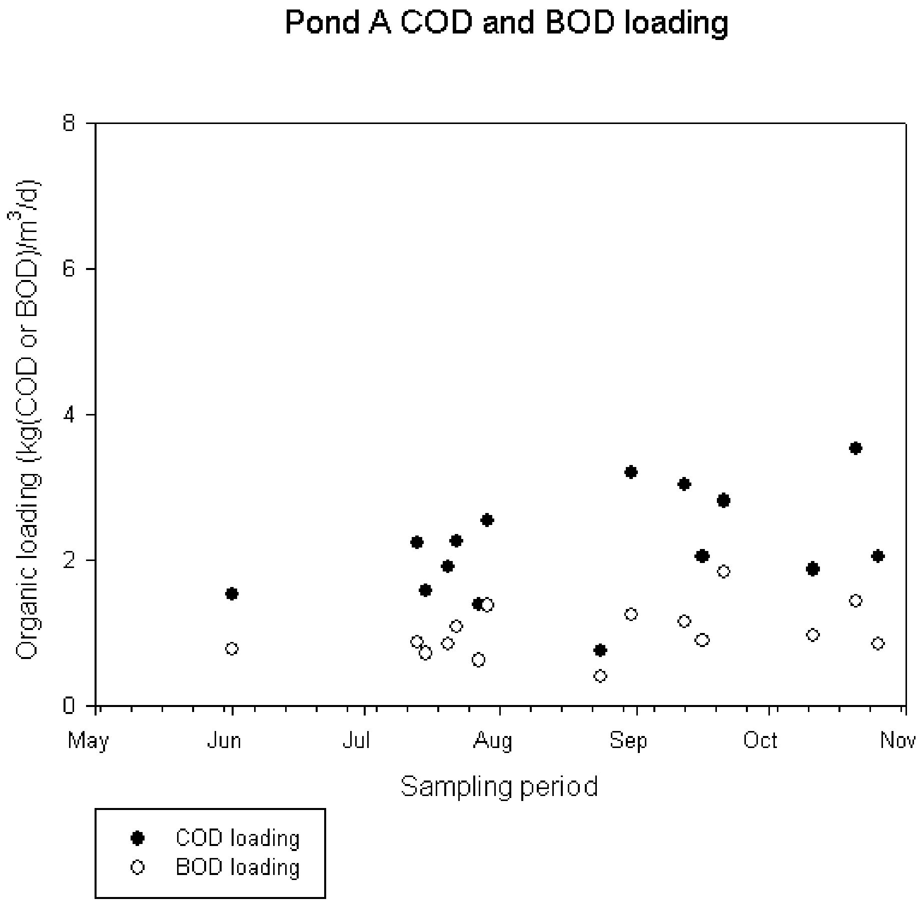


Figure 4.3: COD and BOD loadings of pond A during stage 1 sampling 2011

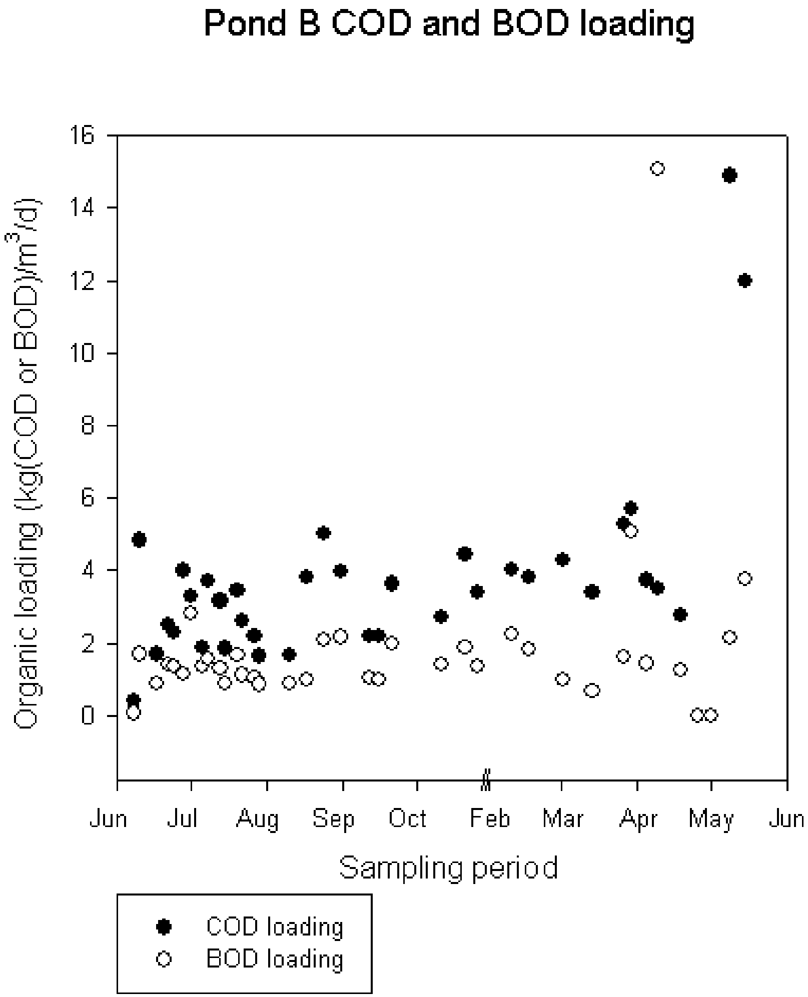


Figure 4.4: COD and BOD loadings of pond B during stage 1 and 2 sampling (2011 and 2012)

4.1.4. Decomposition efficiency

Tables 4.4 and 4.5 summarise the solids removal of ponds A, B and E at various sampling times.

COD and BOD removal

During the stage 1 sampling period (table 4.4) pond A achieved 73% COD removal while pond B achieved a lesser removal of 53%. The total % COD removal of the 5 pond system was 84% based on the outflow of pond E. The lower COD removal of pond B reflects the OLR of this pond which was calculated higher than pond A during the same time period (table 4.3). The COD removal efficiency of pond B was not detrimentally affected when pond A was taken off line in January 2012 for desludging. The higher OLR of pond B appears during the 2012 sampling period did not result in a corresponding decrease in solids removal efficiency with the % COD removal maintained at 59% (table 4.5). A similar trend exists for BOD removal for the 3 ponds over the two sampling periods. Figures 4.5, 4.6 and 4.7, 4.8 illustrate the COD and BOD of influent and effluent samples of pond A and B.

It is observed that both COD and BOD removal efficiencies (particularly the latter) has decreased over the 12 month sampling period for the 5-pond system owing to the accumulation of crust and sludge over this time. The COD and BOD of outflow samples of pond E at the end of the 2012 sampling period are 73% and 78% respectively. This compares to the earlier efficiencies of COD and BOD removal of 84% and 94% at the end of the 2011 sampling period.

Suspended solids removal

The TSS in the influent and effluent were measured to assess the pond's performance with regard to suspended solids removal. In addition two measurements of VSS were made on pond B influent and effluent during stage 2.

The suspended solids removal was more efficient for pond A then pond B with 76% and 40% recorded respectively over the first stage of monitoring. This probably contributed to the increase in sludge build up that occurred in pond A leading to its subsequent desluding at the end of its first 18 months of operation. The overall TSS removal of pond B was low over both stage 1 and stage 2 monitoring periods as shown in figure 4.10. This indicates that the short HRT of these ponds are not permitting adequate sedimentation of wastewater solids.

The two VSS measurements taken during May 2012 for pond B of 5760mg/L and 5010mg/L are quite high in comparison to average data (table 4.2) but is within the range (high end) when compared to the Southern Meats study. The removal of VSS from these measurements was 87% and 70%. Thus, it appears that pond B is fairly efficient in removing the organic component of the suspended solids, although evidence is limited to just two readings.

Fats, oils and greases (FOGs) removal

The removal of FOGS by the five ponds is 95% during stage 1 (pond E data, table 4.4) and is generally maintained throughout stage 2 at 92% (pond E, Table 4.5. The increase in OLR for pond B during 2012 marginally decreased the FOG removal efficiency from 89% to 83% and this would have contributed to the slight decrease in FOGs removal efficiency of the whole system at this time.

Figures 4.5a and 4.5b shows the fat accumulated on uncovered pond A and covered pond B respectively. Both ponds A and B have accumulated about 1m of crust since operation began in

August 2010 since these two ponds receive the majority of organic load. This crust accumulation means a reduction in the effective volume of the pond will occur over time which will impact on the bioconversion efficiency of the two ponds. After fat load is reduced by approximately 85% in ponds A and B the wastewater that enters ponds C, D and E is relatively less fat-laden and therefore appear to have minimal surface crust as seen in figure 4.6 below.

Figure 4.5a: Appearance of crust accumulation on pond A at the end of 2011 prior to desludging

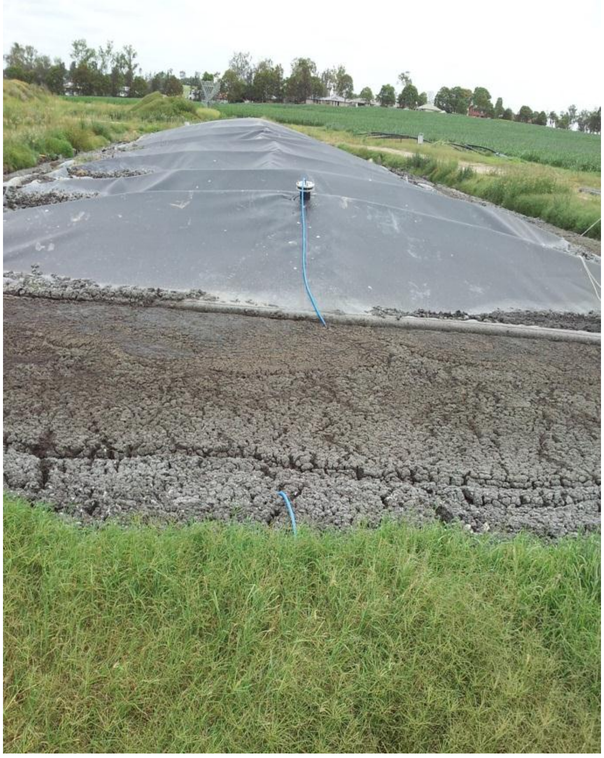


Figure 4.5b: HDPE cover on pond B showing the tube supplying the gas analyser with biogas from the pond. Note the presence of the thick crust

Figure 4.6: Relatively crust-free pond E. Straw was placed periodically on the pond to promote anaerobic conditions and reduce odour.

Table 4.4 Removal efficiencies of the five pond system during stage 1 sampling

Parameter	***n***	**Average**	**σ**	**Range**	**Av % reduction**
Pond A					
Flow rate (m^3/d)[a]	79200	503.29	11.65	10.04-899.38	
Influent COD (mg/L)	15	7442.00	2678.12	2630-12100	
Effluent COD (mg/L)	23	2885.30	2220.68	798-9150	73.22
Influent BOD (mg/L)	15	3402.67	1109.87	1410-5150	
Effluent BOD (mg/L)	24	1318.39	1203.00	188-4610	74.95
Influent TSS (mg/L)	15	3235.00	1353.16	1370-6830	
Effluent TSS (mg/L)	23	1496.09	1568.08	292-5640	76.25
Influent FOG (mg/L)	15	491.87	259.52	73-962	
Effluent FOG (mg/L)	24	111.30	816.54	<5-4080	85.26
Pond B					
Flow rate (m^3/d)[a]	142560	658.44	15.78	15.16-1207.68	
Influent COD (mg/L)	27	7051	2895.10	1040-12100	
Effluent COD (mg/L)	27	2696.30	870.97	1680-4710	53.47
Influent BOD (mg/L)	27	3273.04	1461.68	163-7020	
Effluent BOD (mg/L)	27	852.26	184.13	575-1500	62.19
Influent TSS (mg/L)	27	2990.63	1573.18	457-6870	
Effluent TSS (mg/L)	27	1196.15	755.13	567-4020	39.79
Influent FOG (mg/L)	27	618.74	509.83	5-2110	
Effluent FOG (mg/L)	27	95.85	89.34	21-520	89.25
Pond E					[b]
Effluent COD (mg/L)	10	1155.20	265.98	672-1660	83.62
Effluent BOD (mg/L)	10	188.80	67.49	78-302	94.23
Effluent TSS (mg/L)	10	704.10	421.36	138-1700	76.46
Effluent FOG (mg/L)	10	29.40	26.3	8-98	95.25

[a] Flow data contains values obtained from weekends which lowers the production volume average

[b] % total reduction for five-pond system

Table 4.5 Removal efficiencies of the five pond system during stage 2 sampling

Parameter	n	Average	σ	Range	Av % reduction
Pond B					
Flow rate (m^3/d)[a]	89280	1019.30	820.04	21.57-3028.04	
Influent COD (mg/L)	13	9216.15	5978.34	4330-24200	
Effluent COD (mg/L)	13	2898.92	1024.00	836-5020	58.89
Influent BOD (mg/L)	13	5087.69	6131.70	1060-24500	
Effluent BOD (mg/L)	13	714.62	436.91	246-1920	73.49
Influent TSS (mg/L)	13	3874.62	1533.58	1760-6130	
Effluent TSS (mg/L)	13	1988.77	1292.53	824-5360	35.11
Influent FOG (mg/L)	13	1388.23	1310.21	136-4570	
Effluent FOG (mg/L)	13	91.54	38.95	23-167	83.39
Pond E					[b]
Effluent COD (mg/L)	7	900.07	618.74	126-2150	72.94
Effluent BOD (mg/L)	7	88.79	33.33	5-130	77.67
Effluent TSS (mg/L)	7	413.64	220.47	210-867	77.89
Effluent FOG (mg/L)	7	27.71	45.75	49-143	91.98

[a] Flow data contains values obtained from weekends which lowers the production volume average

[b] % reduction for five-pond system

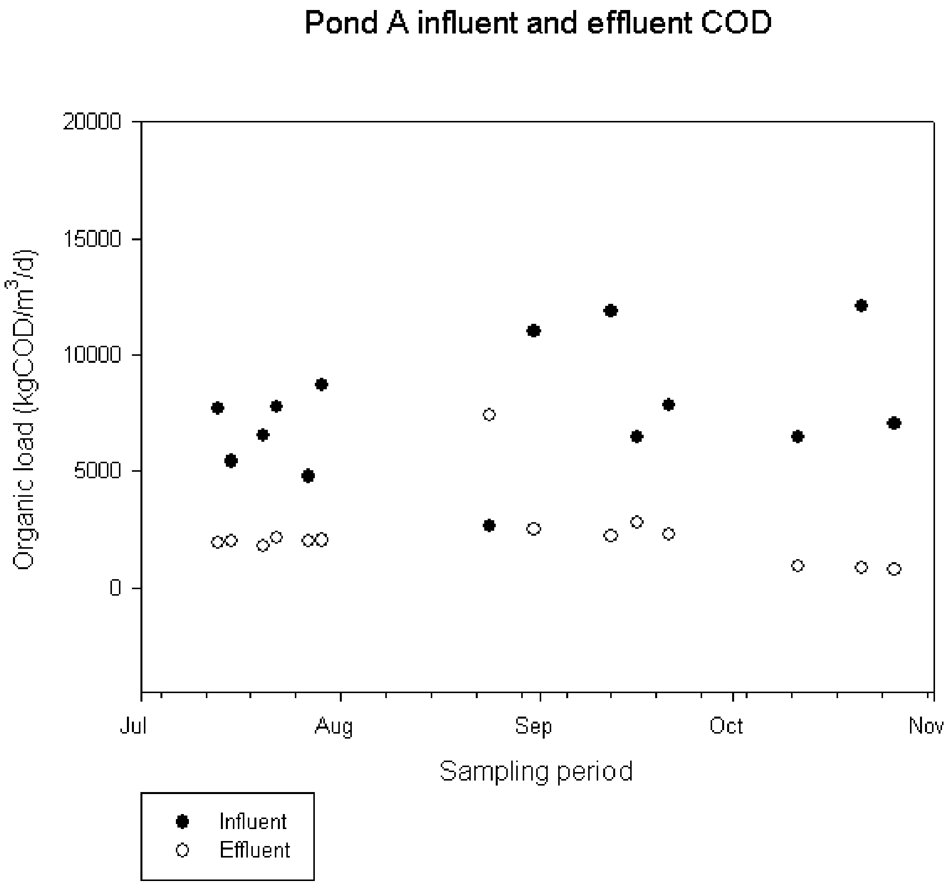


Figure 4.7: COD removal from pond A during stage 1 sampling 2011

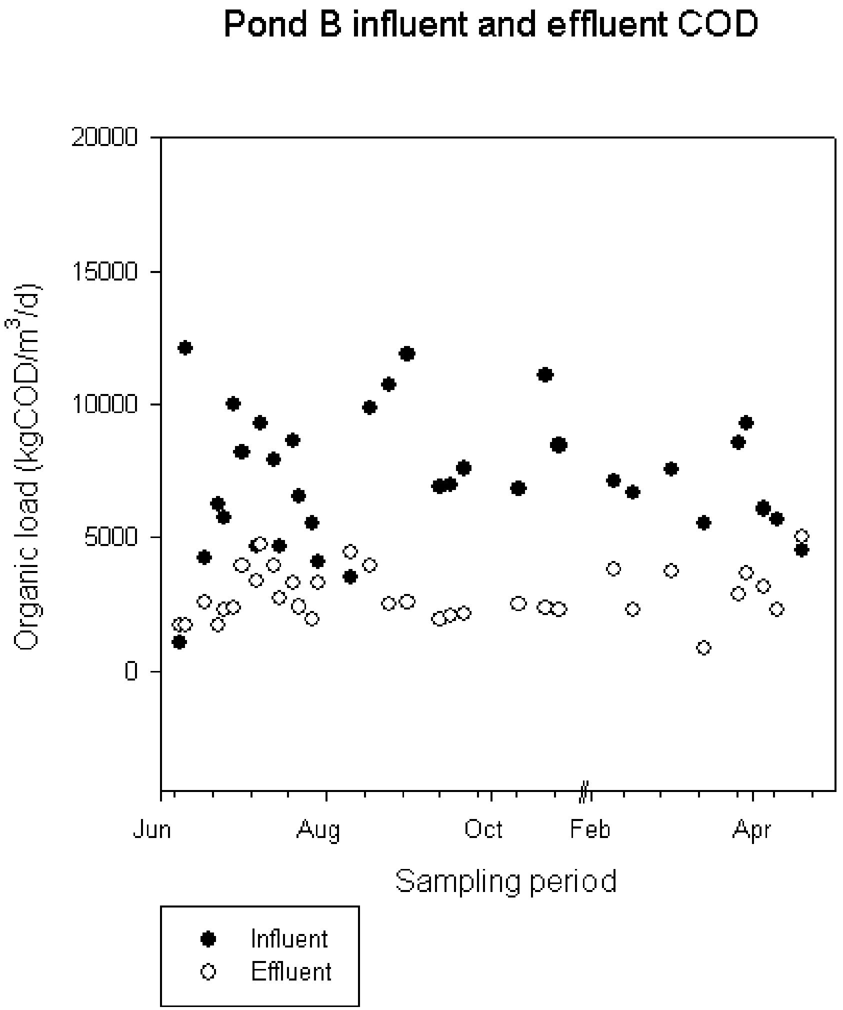


Figure 4.8: COD removal from pond B during stage 1 and stage 2 sampling (2011 and 2012)

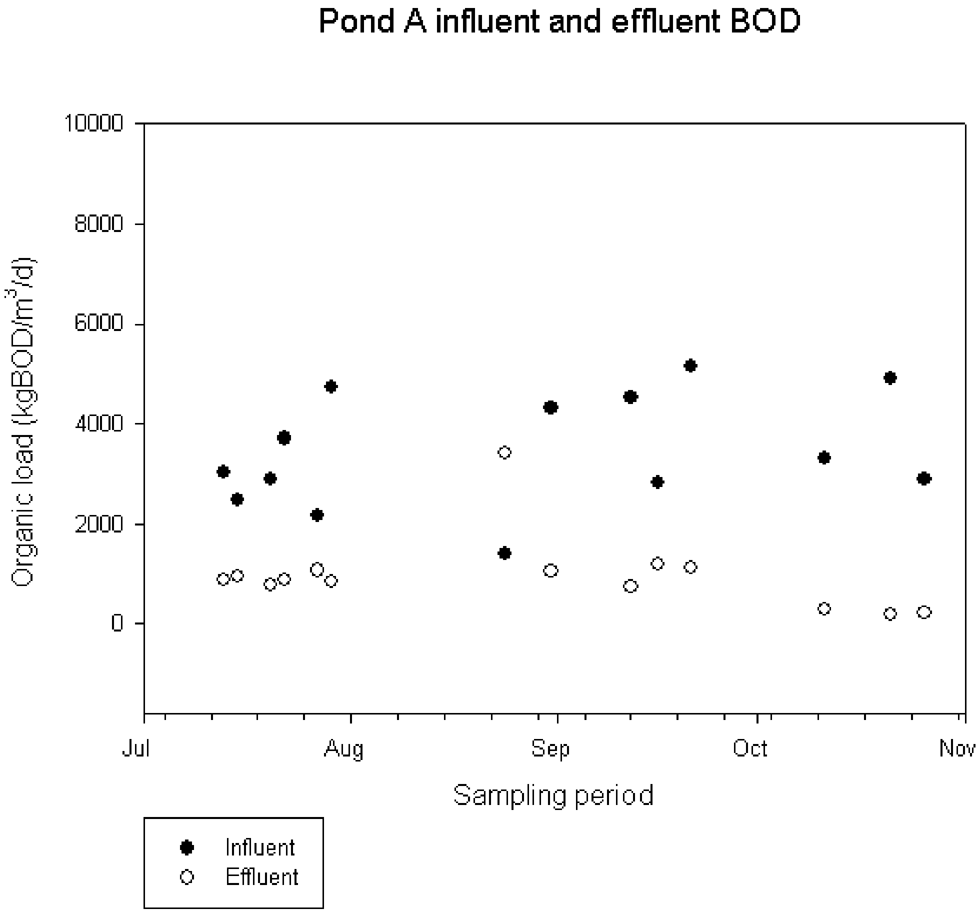


Figure 4.9: BOD removal from pond A during stage 1 sampling 2011

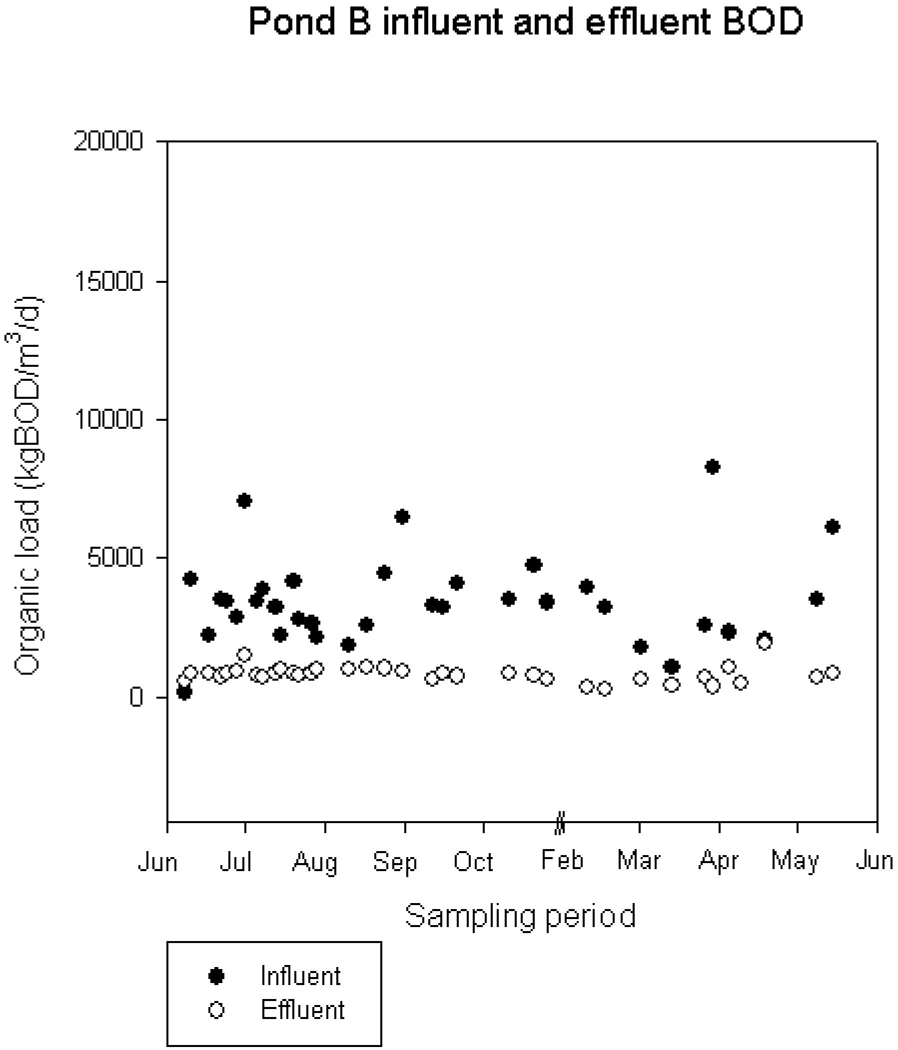


Figure 4.10: BOD removal from pond B during stage 1 and 2 sampling (2011 and 2012)

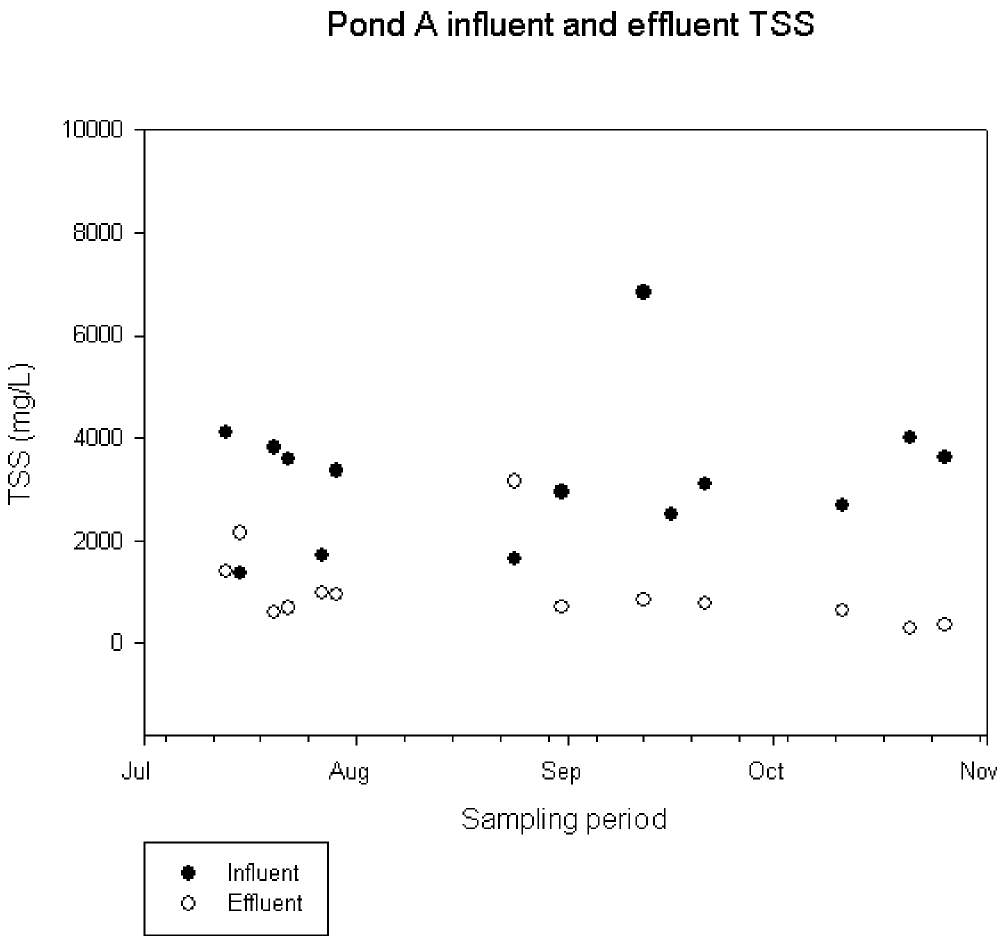


Figure 4.11: TSS removal from pond A during stage 1 sampling 2011

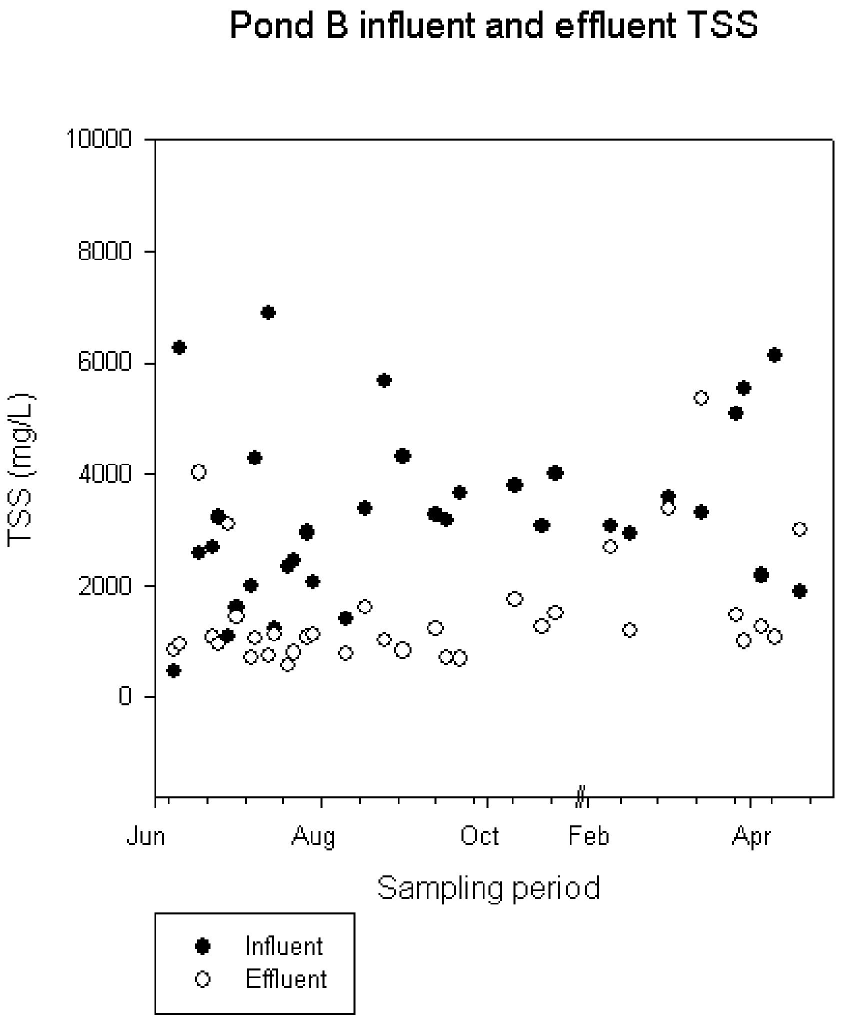


Figure 4.12: TSS removal from pond B during stage 1 and 2 sampling (2011 and 2012)

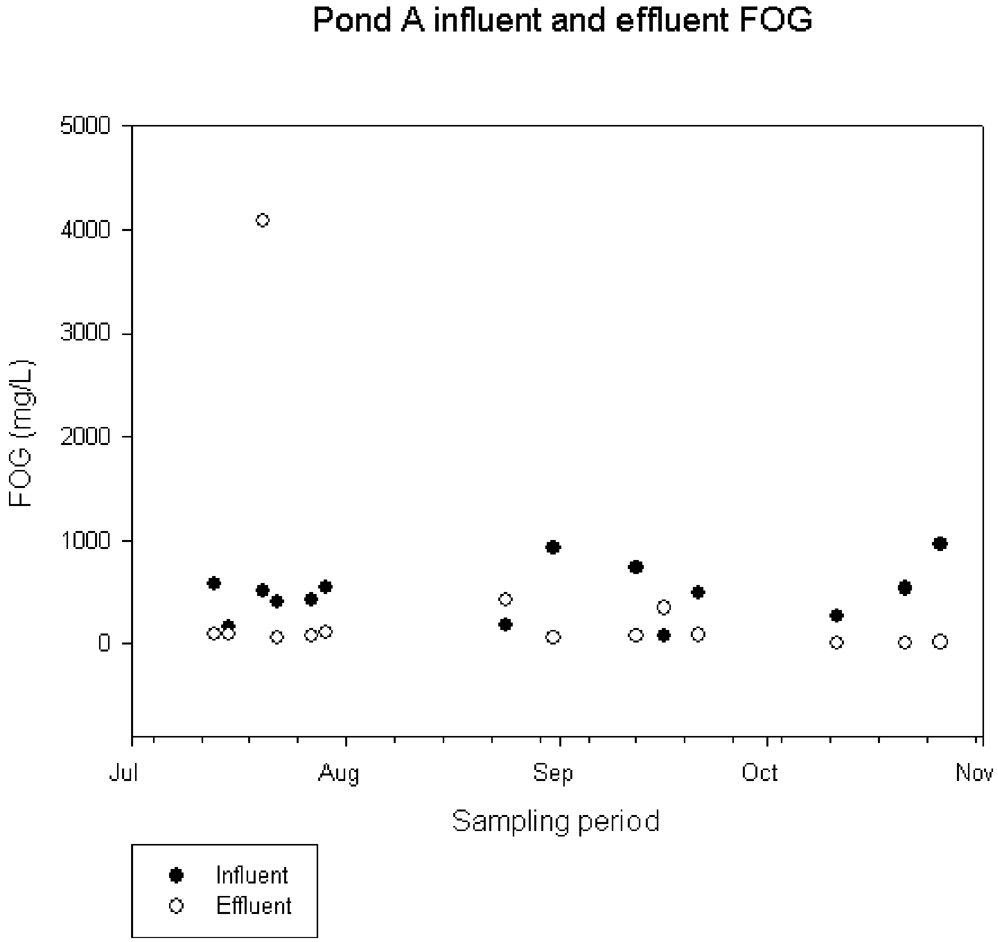


Figure 4.13: FOG removal from pond A during stage 1 sampling 2011

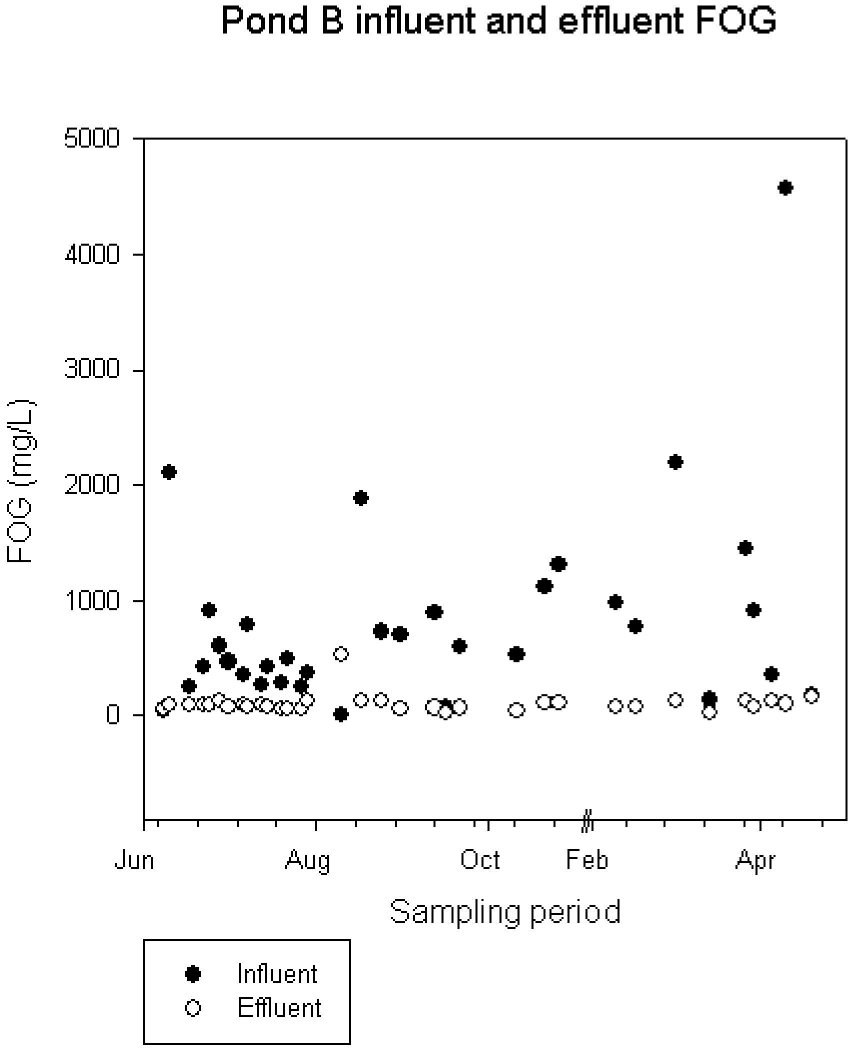


Figure 4.14: FOG removal from pond B during stage 1 and 2 sampling (2011 and 2012)

Desludging of pond A

In January 2012 pond A was taken off line for desludging and crust removal. A SludgeRat® was employed to remove the bulk of the sludge and crust was removed using an excavator. Rain and electrical problems with the SludgeRat® delayed the process and the procedure was completed in June 2012 (figure 4.17).

Figure 4.15 below illustrates the thick crust that accumulated at the inlet of pond A which settled after the sludge was pumped out. During the desludging process it was observed that more crust accumulated at the inlet pipe (seen in figure 4.15 below) whereas there was an increasing gradient of sludge toward the outlet pipe.

Figure 4.15: Section of crust removed by the excavator after sludge was pumped from pond A indicating crust thickness.

Figure 4.16: Pond A during sludge removal using a SludgeRat® sludge removal system. Removal of fat build up at the pond inlet (bottom of image).

Figure 4.17. Desludging of pond A recently complete showing clean water awaiting re-commissioning of cover.

4.1.5. Assessment of pond health

Table 4.6 and 4.7 summarises the key parameters for ponds A, B and E, namely temperature, pH, ORP, alkalinity, NH_3-N TKN and VFA.

Table 4.6: Stage 1 data for ponds A, B and E

Parameter	*n*	Average	σ	Range	Average	σ	Range
Pond A		Inflow			outflow		
Temperature	12	31.82	3.48	24.7-36.6	28.10	2.78	22.9-30.9
pH	13	7.44	0.20	7.27-7.79	7.21	0.07	6.83-7.04
ORP	10	2.38	53.65	-89.7-90.9	-198.81	23.39	-243.8--166
Alkalinity	23	-	-	-	1379.09	243.25	1020-1980
NH_3-N	15	142.21	72.06	35.8-292	275.61	83.78	58.2-432
TKN	15	450.21	80.95	314-615	387.83	43.71	256-434
VFA	23	-	-	-	515.14	198.66	70-906
Pond B							
Temperature	17	27.51	3.97	24.2-34.9	25.85	2.62	22.7-30.1
pH	22	7.37	0.35	6.75-7.9	7.24	0.32	6.89-7.9
ORP	12	19.71	84.17	-112--258.9	-217.80	21.02	-175--258.9
Alkalinity	27	-	-	-	1360	116.22	1180-1730
NH_3-N	27	164.16	83.67	23.8-349	274.24	65.78	63.6-380
TKN	27	459.52	121.17	296-785	375.96	60.12	276-500
VFA	27	-	-	-	376	117.33	162-618
Pond E							
Temperature	17	-	-	-	24.78	2.55	21.50-28.50
pH	17	-	-	-	6.94	0.07	6.83-7.02
ORP	17	-	-	-	-206.78	14.95	-188.60--232.00
Alkalinity	17	-	-	-	1435.90	320.64	609-1820
NH_3-N	17	-	-	-	320.20	64.73	156-366
TKN	17	-	-	-	364.10	39.96	307-425
VFA	17	-	-	-	128.10	88.52	49-350

Table 4.7: Stage 2 data for ponds A, B and E

Parameter	*n*	Average	σ	Range	Average	σ	Range
Pond B		inflow			outflow		
Temperature	13	31.89	3.17	25.9-38.2	30.08	2.76	25.2-34.3
pH	13	7.07	0.27	6.6-7.44	6.46	0.05	6.37-6.52
ORP	13	-16.36	72.38	-92-119	-209	16.64	-179—234
Alkalinity	13	-	-	-	1244.62	158.83	1050-1510
NH_3-N	13	110.68	60.86	4.35-192	193.46	102.22	21-300
TKN	13	367.51	115.32	17.6-500	319.62	91.76	49-420
VFA	13	-	-	-	291.92	130.6	91-616
Pond E							
Temperature	7	-	-	-	28.8	3.06	24.5-32
pH	7	-	-	-	6.57	0.02	6.54-6.60
ORP	7	-	-	-	-214.09	14.82	-192—238
Alkalinity	7	-	-	-	1283	542.46	228-1640
NH_3-N	7	-	-	-			
TKN	7	-	-	-			
VFA	7	-	-	-	79	28.64	47-125

Temperature, pH and ORP

Figures 4.18 and 4.19 show the trend in influent and effluent temperature and pH of ponds A and B respectively. Temperature of the wastewater is within the optimum operating conditions for mesophilic bacteria. It is noted that only the temperature of the wastewater was monitored at sample points rather than monitoring actual pond temperature. Pond temperatures were to be recorded using thermocouples at 16 locations at each pond A and B. However, the presence of a thick crust early in the monitoring program hindered any attempts to install the thermocouples. These thermocouples were to be centrally located, with 5 metres between each series of four thermocouples. Each series were to be arranged to detect temperature of the wastewater at four different depths; 0.1m, 1.4m, 2.8m and 4.2m.

The minimum and maximum air temperatures at Ipswich over the monitoring period are given in appendix 7.2 (figure A7.1).

The average outflow pH for ponds A, B and E during 2011 monitoring are all within the optimum range for methanogenesis with a minimum range not below 6.83 (table 4.6). An obvious downward trend does occur in pond B during the 2012 monitoring (figure 4.19) and coincides with an increase in organic loading. During this time the average outflow pH minimum range drops to 6.37 with an average of 6.47. This is just within the lower limits for methanogens.

The oxidation-reduction potential levels of wastewater effluent sampled from the outlet of the pond provide an indication that ponds A, B and E are all sufficiently anaerobic to support the growth of the obligate anaerobic methanogens (figures 4.25 and 4.21 and tables 4.6 and 4.7). It is important to note that the ORP of influent samples were taken at the sample point just before the wastewater entered the pond rather than near the inlet in the pond itself.

Ammonia and Total Kjeldahl Nitrogen

Figures 4.22 to 4.25 illustrate NH_3-N and TKN for ponds A and B throughout the 2011 and 2012 sampling periods. Both nutrients are within acceptable levels and ammonia concentrations are not at levels which would be deemed inhibitory to methanogens. Ammonia is believed to be beneficial to anaerobic digestion at concentrations below 200mg/L. Concentrations responsible for 50% inhibition of methane production range from 1.7-14g/L (Chen *et al.* 2008).

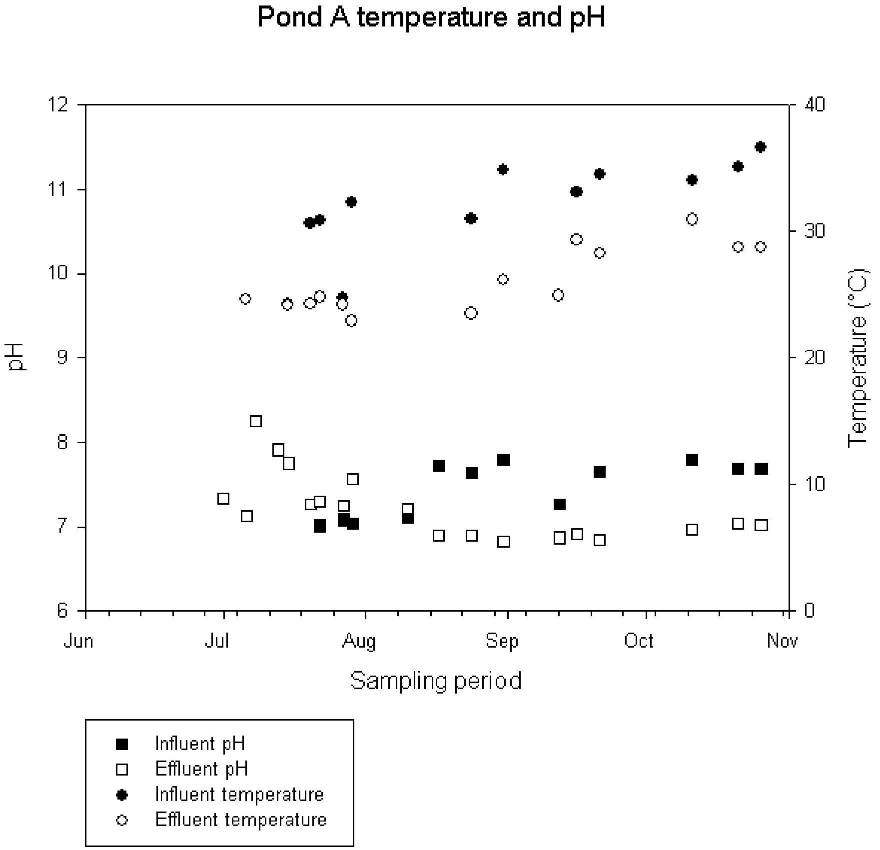


Figure 4.18: Pond A influent and effluent temperature and pH during stage 1 sampling 2011

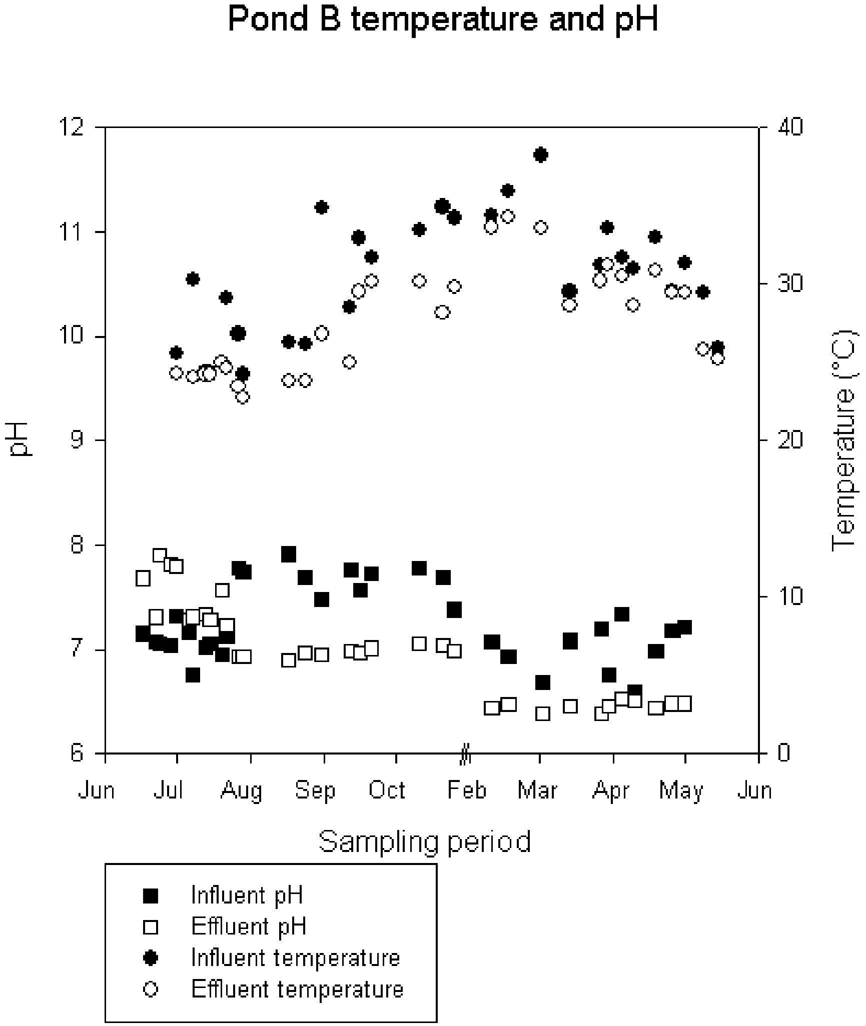


Figure 4.19: Pond B influent and effluent temperature and pH during stage 1 and stage 2 sampling (2011 and 2012)

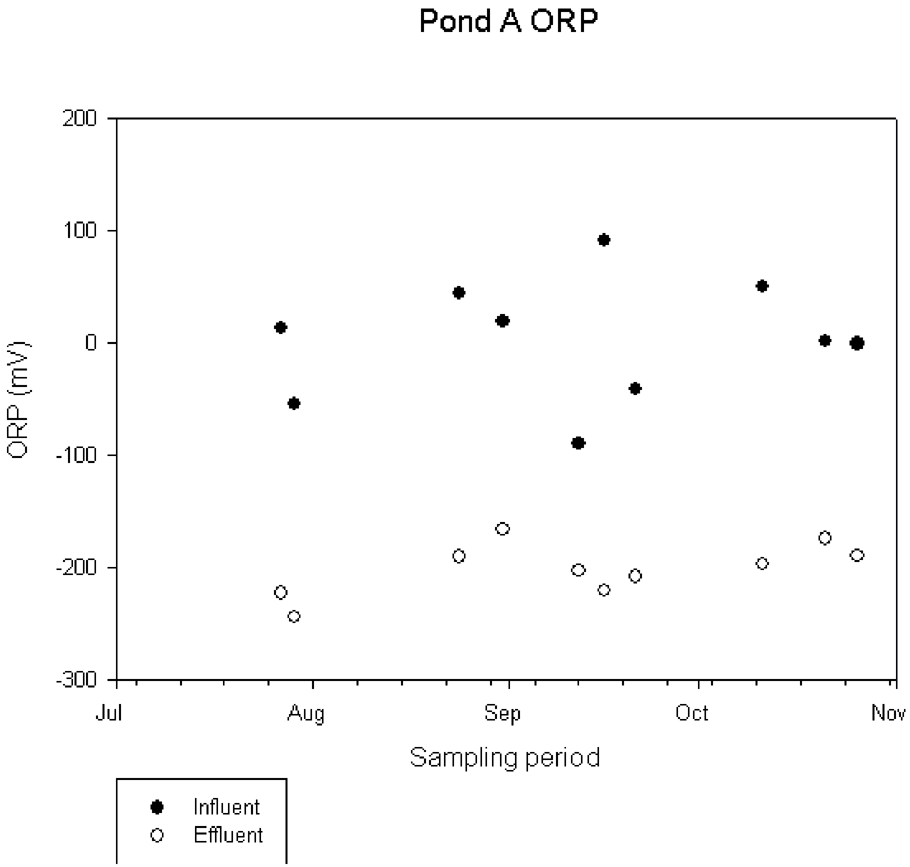


Figure 4.20: Pond A influent and effluent ORP during stage 1 sampling 2011

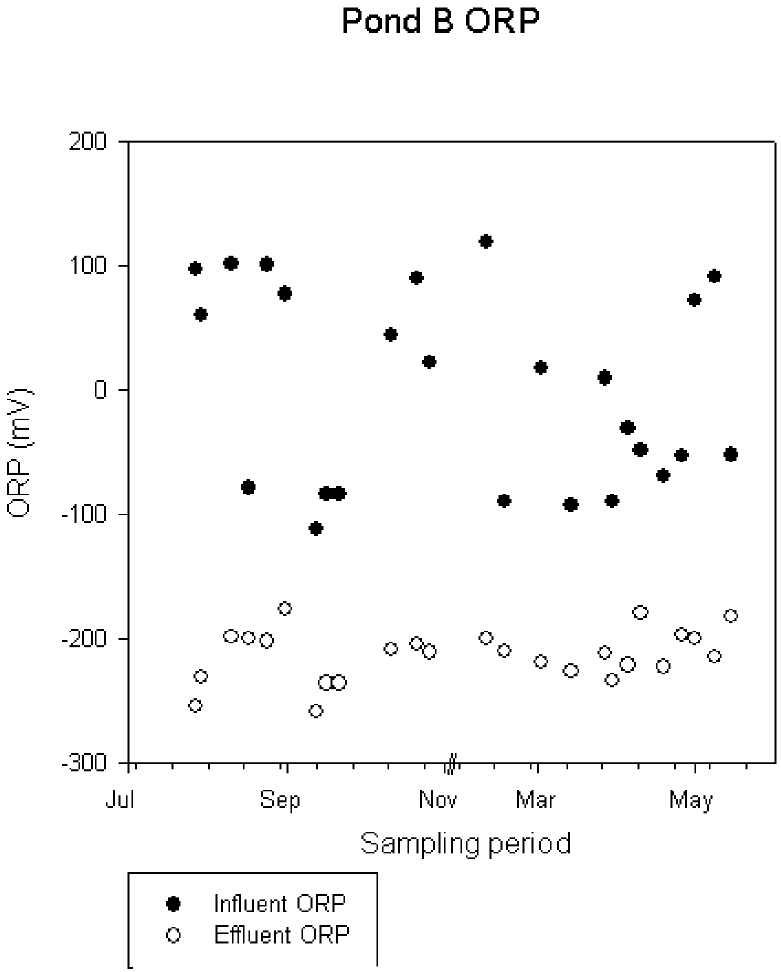


Figure 4.21: Pond B influent and effluent ORP during stage 1 and stage 2 sampling (2011 and 2012)

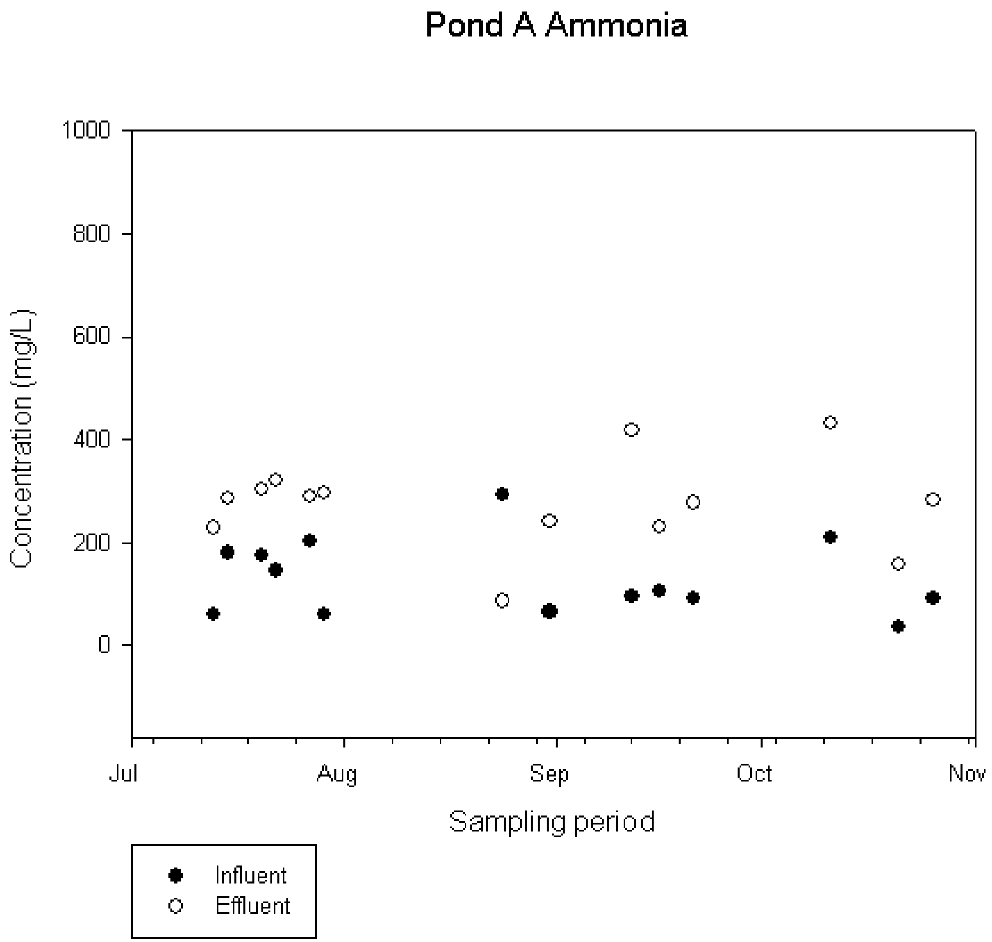


Figure 4.22: Pond A ammonia concentrations during stage 1 sampling 2011

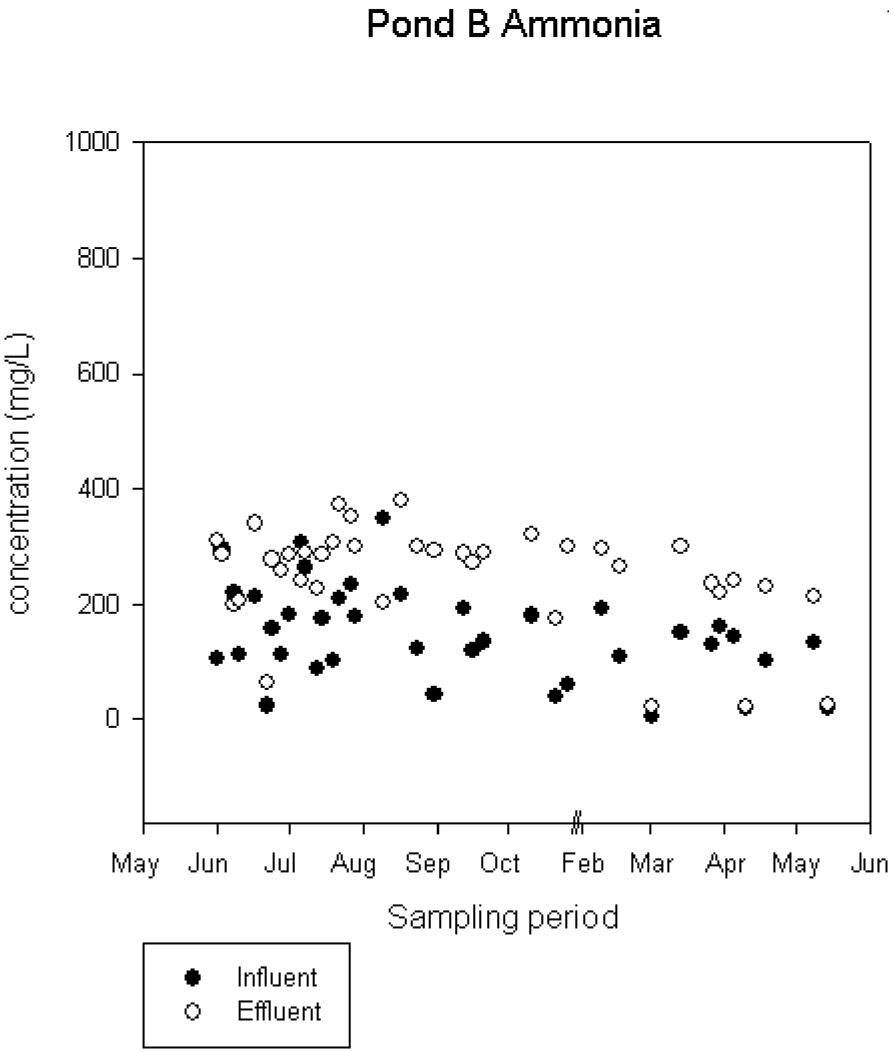


Figure 4.23 Pond B ammonia concentrations during stage 1 and stage 2 sampling (2011 and 2012)

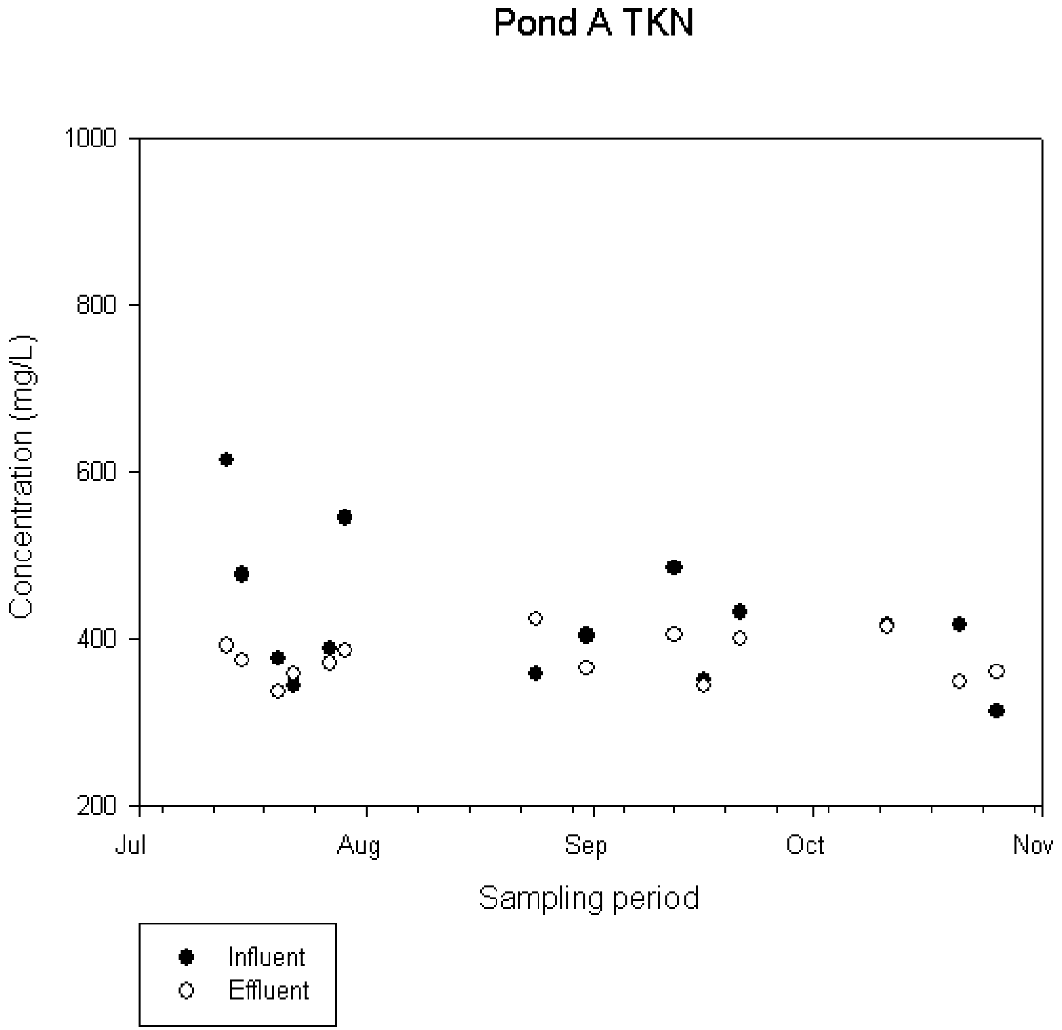


Figure 4.24: Pond A TKN concentrations during stage 1 sampling 2011

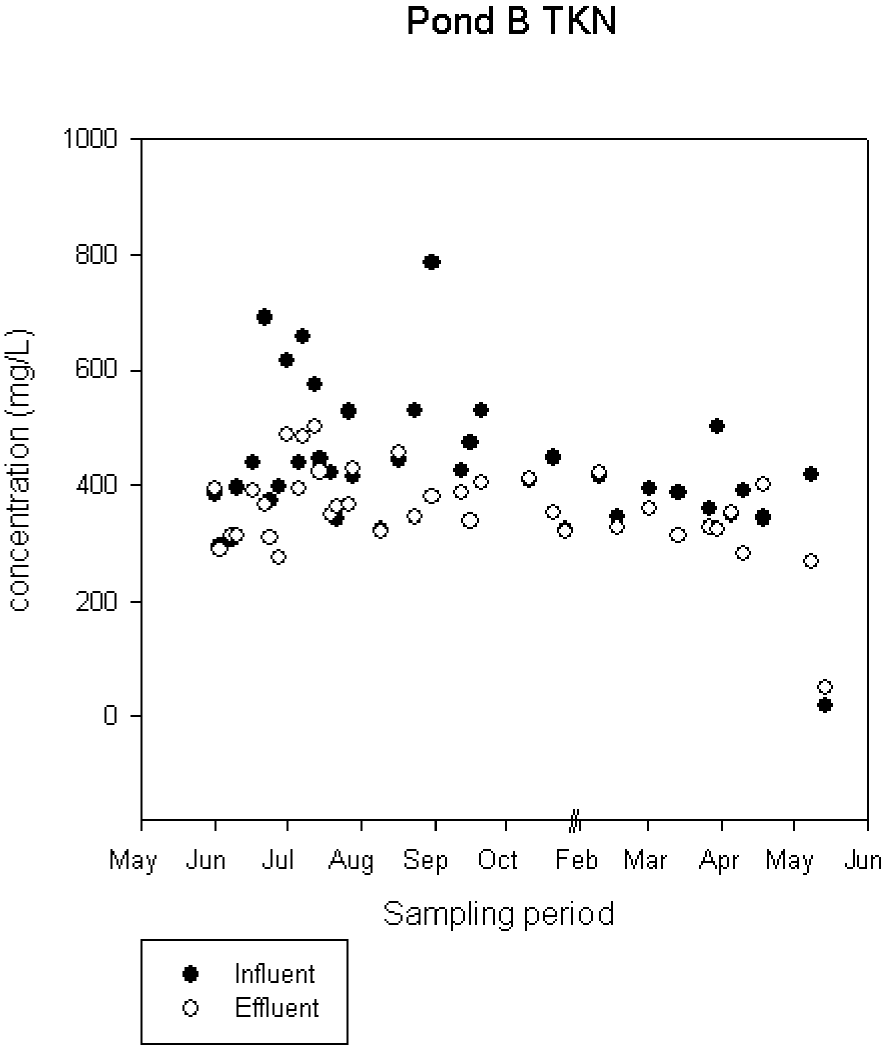


Figure 4.25: Pond B TKN concentrations during stage 1 and stage 2 (2011 and 2012)

Volatile fatty acid concentration and alkalinity

The average outflow VFA (measured as mg/L acetic acid) for ponds A, B and E during 2011 monitoring are within the optimum range for methanogenesis with an average no higher than 500mg/L (table 4.6). A few readings above 500mg/L were obtained for pond A and B during this time (figures 4.26 and 4.27 respectively). VFA concentrations of pond B have been generally maintained over the 2012 monitoring and have not entered into potentially toxic levels despite the high organic loading rate that this pond has been subjected to during this period.

Alkalinity is a measure of buffering capacity and is an important gauge of pond performance as an accumulation of potentially inhibitory short chain fatty acids will reduce the buffering capacity significantly before decreasing the pH (Ward *et al.* 2008). Alkalinity levels of both ponds A and B have been maintained at near optimal levels and have been found to be higher than levels recorded previously for typical abattoirs (see table 4.2), although the optimal range has been noted as between 2000 and 3000 mg/L $CaCO_3$ (see table 1.2). One anomaly has been recorded for pond B during May 2012, a time which coincides with a spike on OLR (see table 4.3).

To determine pond stability from alkalinity and VFA accumulation a weight ratio of VFA:TA is applied. A weight ratio of 0.25-0.35:1 is indicative of a healthy pond system. (Kuglarz *et al.* 1992). The ratio of VFA to TA for ponds A and B is shown in table 4.8. It appears that pond B demonstrates more favourable VFA:TA ratios than pond A and is quite stable over a 12 month monitoring period.

Table 4.8: Pond A VFA/TA ratios

Month	*n*	VFA (as mg/L acetic acid)	Alkalinity (as mg/L $CaCO_3$)	VFA/TA ratio
June-11	8	583.00	1226.25	0.482
July-11	8	506.50	1270.00	0.399
August-11	4	642.00	1080.00	0.603
September-11	3	543.00	1265.00	0.429
October-11	3	82.33	1893.33	0.044

Table 4.9: Pond B VFA/TA ratios

Month	*n*	VFA (as mg/L acetic acid)	Alkalinity (as mg/L $CaCO_3$)	VFA/TA ratio
June-11	8	359.71	1314.29	0.275
July-11	9	407.11	1316.67	0.309
August-11	4	371.50	1786.67	0.287
September-11	3	380.33	1426.67	0.267
October-11	3	274.33	1570.00	0.178
February-12	2	122.00	1455.00	0.083
March-12	4	252.5	1300	0.201
April-12	4	304.25	1167.5	0.260
May-12	3	331	850	0.297

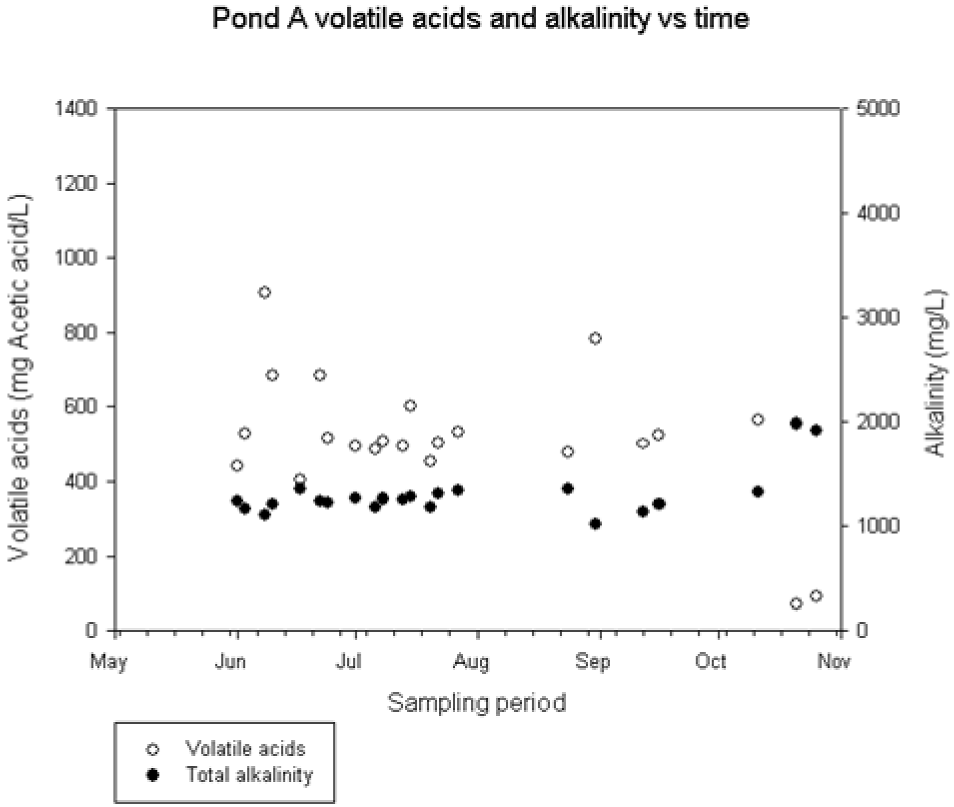


Figure 4.26: Pond A volatile acids and alkalinity concentrations during stage 1 sampling 2011

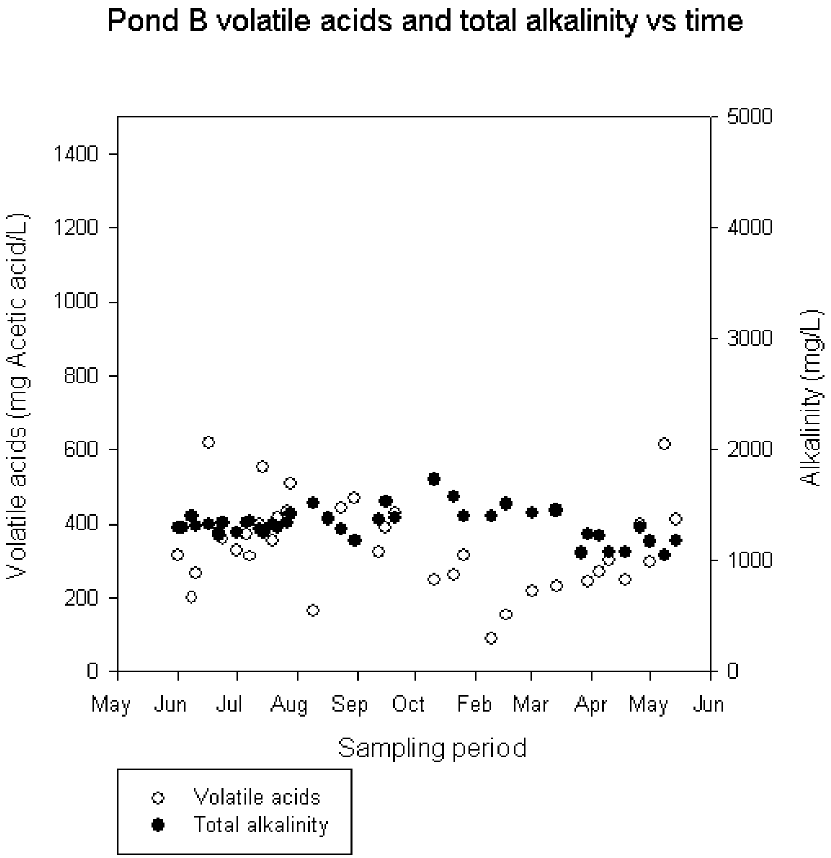


Figure 4.27: Pond B volatile acids and alkalinity concentrations during stage 1 and stage 2 (2011 and 2012)

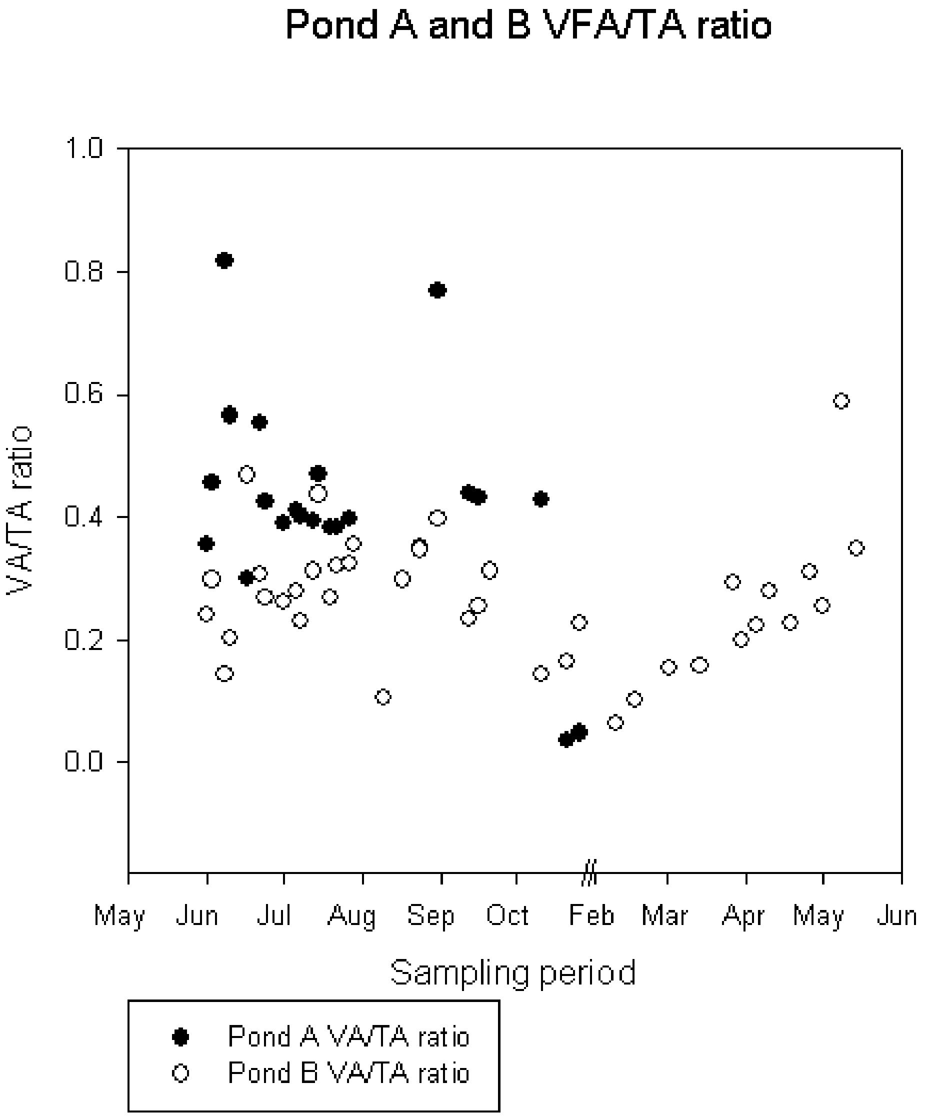


Figure 4.28: Pond A and pond B VFA/TA ratios during stage 1 and stage 2 sampling (2011 and 2012)

4.1.6. Sludge study

A key limitation of most anaerobic pond studies is lack of information on rates of sludge accumulation and lack of information on the biological methane potential and/or toxicity of the sludge to methanogens (UNSW 1998). This is understandable, as the presence of covers on anaerobic ponds limits the opportunity for sludge sampling, and previously published sludge depth monitoring equipment have too large a footprint for the scale of accuracy required for sludge and biogas production studies (e.g. Anderson *et al.* 2000).

In this anaerobic pond sludge scoping study, a novel depth monitoring probe capable of both measuring sludge depth, and monitoring and sampling water column profiles was designed and fabricated.

Preliminary sludge depth monitoring was undertaken in pond A prior to desludging. The crust was very thick, accumulating as the pontoon was pulled into the centre of the pond (rear of figure 3.8). Depth only measurements were made at several locations from the opposite end of the influent pipes. Sludge sampling occurred from one location only, as floating fat and grease posed too great a risk of fouling and damage to the monitoring probes at the other locations.

In contrast to other published reports (Papadopoulos *et al.* 2003; Paing *et al.* 2000), there was no evidence of distinct zones in the water column (table 4.10). The pH profile was within the recommended range of 6.6 to 7.6 (table 1.2). Water quality was very uniform throughout, with no evidence of the expected change in pH with peak methanogenic activity (Paing *et al.* 2000). Depth ranged from 1.3m within 2.5m of the shore, to 4.4m in the middle lower section of the pond, indicating no loss of pond depth due to settled sludge (original pond height 4.4 m; table 1.4). Suspended sludge was evident throughout the water column, as thick, suspended, black solids. There was no evidence of settleable solids. Unfiltered sludge samples had a COD ranging from 4.6g/L to 10.4g/L.

Table 4.10: Change with depth of pH, temperature and electrical conductivity in pond A.

Total depth (m)	Location	Depth (m)	Temperature (°C)	EC (mS)	pH
4.3	25Lx8W	1.25	29	4.1	6.76
	(28x8x4.3)	1.51	29	4.18	6.77
		2.08	29	4.17	6.78
		2.18	29	4.17	6.79
		2.75	29	4.17	6.78
		3.01	29	4.17	6.78
		3.59	29	4.18	6.78
		3.68	28	4.18	6.77
4.4		0.68	28.6	4.7	6.72
		1.25	29	4.53	6.77
		1.51	29	4.48	6.78
		2.08	29	4.4	6.74
		2.18	29	-	-
		2.75	29	4.45	6.78
		3.01	29	4.44	6.78
		3.59	29	4.45	6.78
		3.68	29	4.44	6.78
		4.26	29	4.44	6.81

Observations from pond C less than one month later were substantially different from pond A. The water column was clear for the 2.22m depth, with settleable, fine black solids evident only at the deepest point. As with pond A, there was no evidence of distinct zones in the water column, however. the pH was outside the recommended range of 6.6 to 7.6 (table 4.11).

Table 4.11: Change in pH, temperature and electrical conductivity relative to depth in the middle of pond C.

Total depth (m)	Location	Depth (m)	Temperature (°C)	EC (mS)	pH
4.3	middle	1.25	24.7	3.88	6.18
		1.51	24.7	3.89	6.22
		2.08	24.7	3.89	6.22
		2.18	24.8	3.69	6.26
		2.75	24.8	3.66	6.27
		3.01	24.9	3.64	6.22

The COD in the settleable black sludge of pond C was comparable to pond A. Results from this study indicate sludge deposition over the life of the smaller anaerobic ponds differs for the first overloaded receiving ponds (ponds A and B), and the three ponds in series (ponds C, D and E). Total pond volume in ponds A and B has been reduced by the excessive accumulation of fat and grease within 10 m of the influent pipes. The hydrophobicity of the fat and grease appears to have excluded any sludge in solution within this zone. Lack of settleable solids in pond A suggests the short HRT has not promoted sedimentation of wastewater solids and therefore limited the efficient anaerobic digestion to biogas methane.

Further studies including biochemical methane potential (BMP) and toxicity assays will elucidate the possible effects that pond overloading has had on the bioconversion efficiency of the ponds.

4.1.7. Biogas monitoring

Biogas quantity was unable to be accurately determined during the project due to the presence of the thick crust which developed during the initiation of the ponds in 2010. However, dynamic wastewater treatment modelling using the software BioWin was undertaken to estimate the biogas production of the 5 pond system using wastewater quality data obtain throughout the duration of the project (see section 4.2.3).

The quality of biogas produced from covered pond B (CH_4, CO_2, O_2 and H_2S) are shown in figures 4.29 and 4.30. Table A7.4 in appendix 7.3 provides the raw biogas quality data. Average methane content was 52%, while carbon dioxide and oxygen were 22% and 3% respectively. The levels of oxygen should be negligible; however, the cover did become compromised at various stages of the monitoring and did not achieve an air tight seal. Average hydrogen sulphide levels over the same period were 686ppm. It is noted that the later analysis using the GA2000 maybe more reliable as earlier monitoring using the GA3000 had issues with calibration. Table A7.4 stipulates the equipment used at each sampling time. To compare field results 3 samples were sent to SGS labs in April and May 2012. These results show that the methane values ranged from 59% to 62% with carbon dioxide and oxygen levels averaging 37% and 0.9% respectively. Hydrogen sulphide levels ranged between 47 and 196ppm.

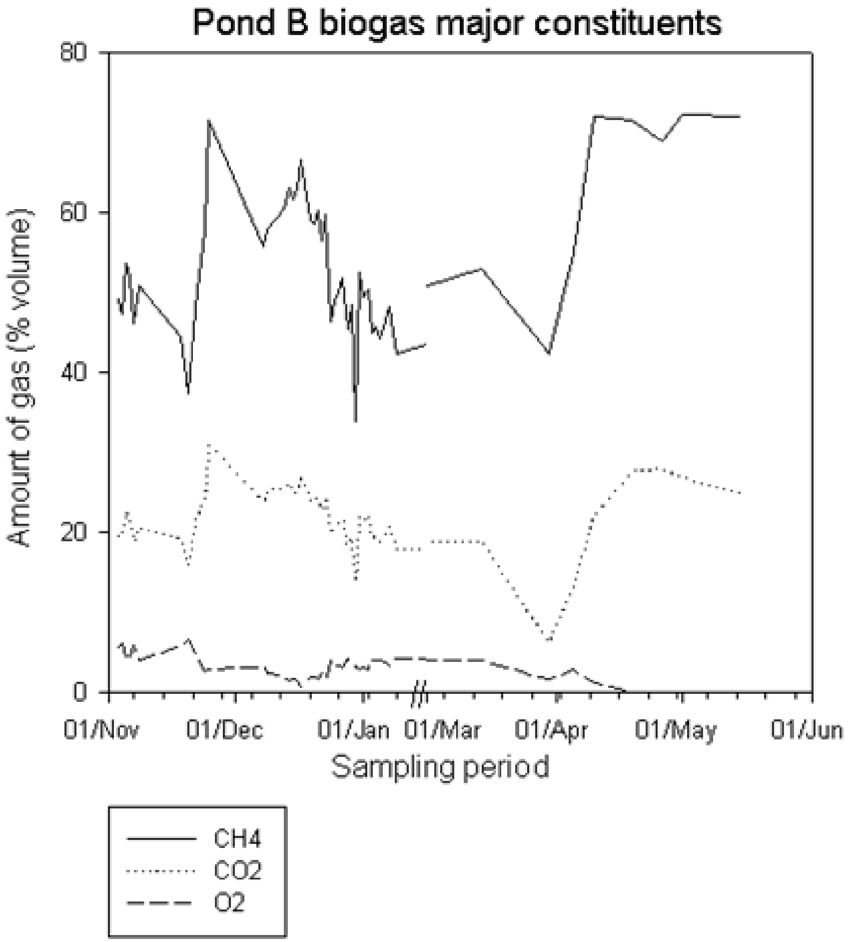


Figure 4.29: Pond B biogas major constituents during 2011 and 2012 sampling period

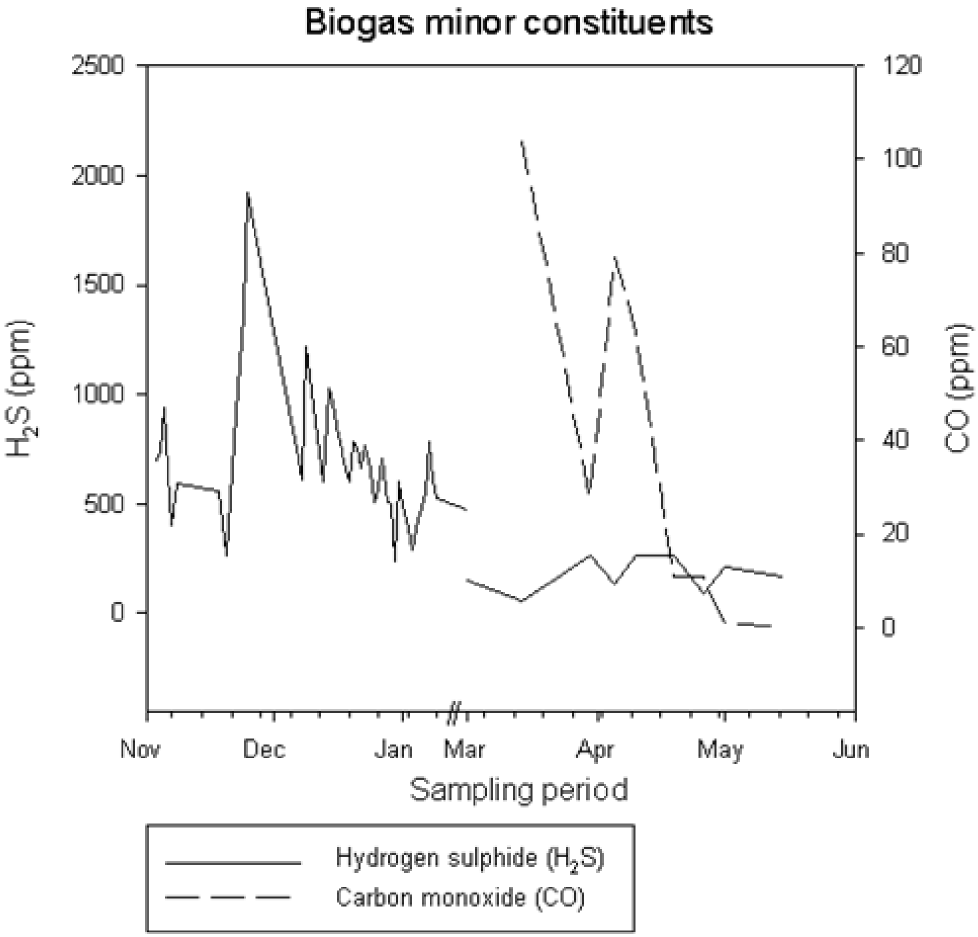


Figure 4.30: Pond B biogas minor constituents during 2011 and 2012 sampling period

4.1 Bioenergy feasibility study

Covered anaerobic ponds offer significant advantages to the red meat processing industry by capturing methane rich gas as a fuel source for bio energy while reducing GHG emissions. As the price of conventional fuels rise, biogas production becomes more of an attractive proposition particularly given the added GHG implications. Bioenergy from biogas generally requires less capital investment compared to other renewable sources of energy such as hydro, solar, and wind (Venkateswara Rao *et al.* 2010). Energy recovery from biogas has become one of the most prominent sources of waste-based bio-energy.

Table 4.12 shows the potential energy production per ton of waste from different waste materials. The energy content of these different materials is calculated based on the amount of biogas that can be produced. Notably the waste material from slaughterhouses is one of the best substrates for biogas production. The efficiency of biogas in producing energy is higher than biomass. For example, burning of dried dung has a heat efficiency of about 10% when burned. But if biogas is first produced from the dung then used, the heating efficiency is raised to 60% (Rabah *et al.* 2010)

Table 4.12: Energy content in term of biogas production from different waste (Briseid 2008)

Substrate	KWh/ton
Manure from Cow	140
Manure from Pigs	180
Manure from Poultry	450
Grass	810
Waste from fruits and vegetables	950
Household food waste	1300
Food waste from restaurants	1300
Waste from slaughter houses	2000
Pure carbohydrate / sugar	3900
Proteins	4900
Fat	8500

Biogas production and utilization technologies have improved dramatically over the last ten years. The feasibility of using biogas as an energy source is dependent on i) the amount produced, ii) the cost and iii) energy demands of a particular site. The traditional use of biogas is as a fuel for boilers and for producing heat. Increasingly biogas is being used as a fuel for engine generators or combustion turbines to generate electricity either for the waste treatment plant itself or for sale to the local power utility (Khanal 2008).

4.2.1 Energy use at Churchill Abattoir

Churchill Abattoir consumes energy from a number of different sources including, electricity, LPG, and coal. Electricity (figure 4.31) at Churchill is used mainly for cooling but also includes electrical motors and conveyers.

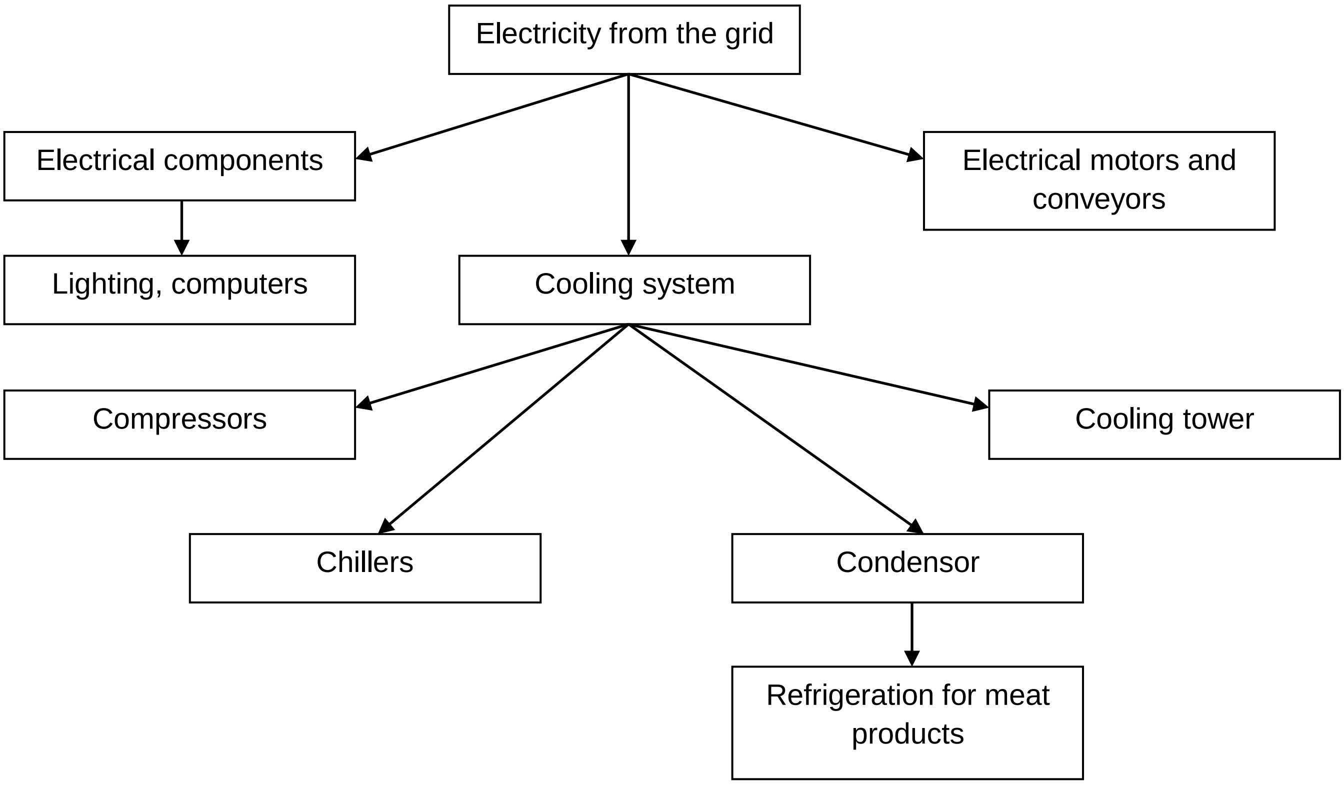


Figure 4.31: Electricity usage at Churchill plant

Coal (figure 4.32) has been used for generating steam which is then use for different activities at the plant.

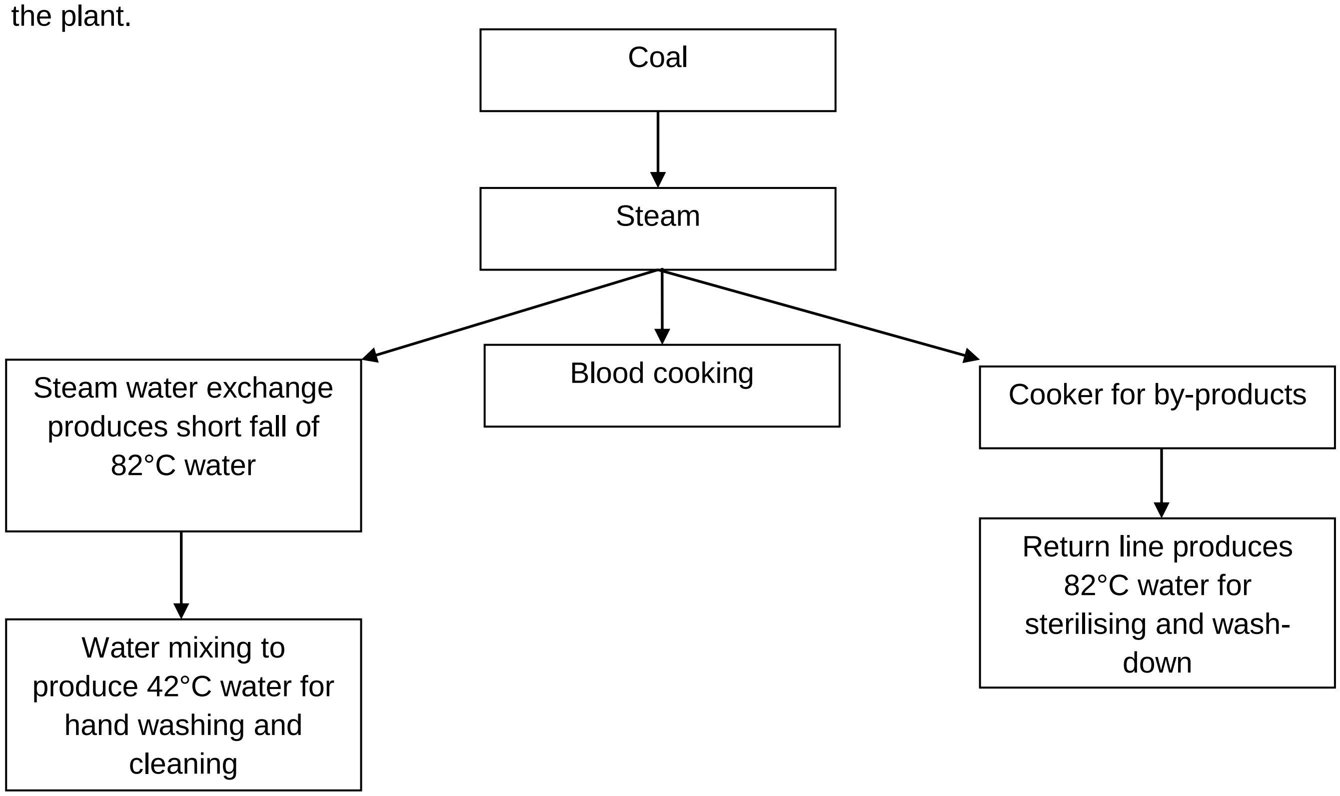


Figure 4.32: Coal usage at Churchill plant

LPG (figure 4.33) is used as a fuel for some equipment at the plant such as forklifts and for cooking and drying the blood.

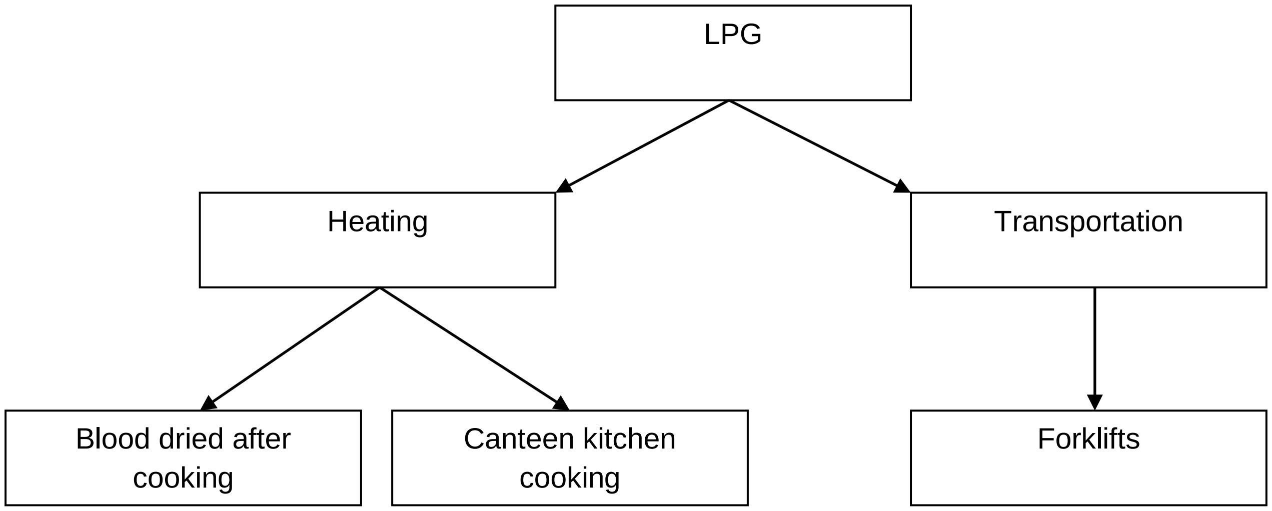


Figure 4.33: LPG usage at Churchill plant

A level 1 energy assessment was conducted at Churchill Abattoir to assess the total energy use of the site. The assessment considered major energy sources relating to the operation of the abattoir and included electricity, coal and LPG. Minor energy inputs such as diesel and petrol where excluded in the analysis given the energy assessment was conducted to inform the potential use of bioenergy generated at the site from biogas against core energy needs.

A level 1 assessment is a relatively simple and low cost energy assessment and is often referred to as a preliminary assessment or overview of the whole site. This involves collating all energy use data from the site for different energy sources based on site receipts and invoices (figure 4.34).

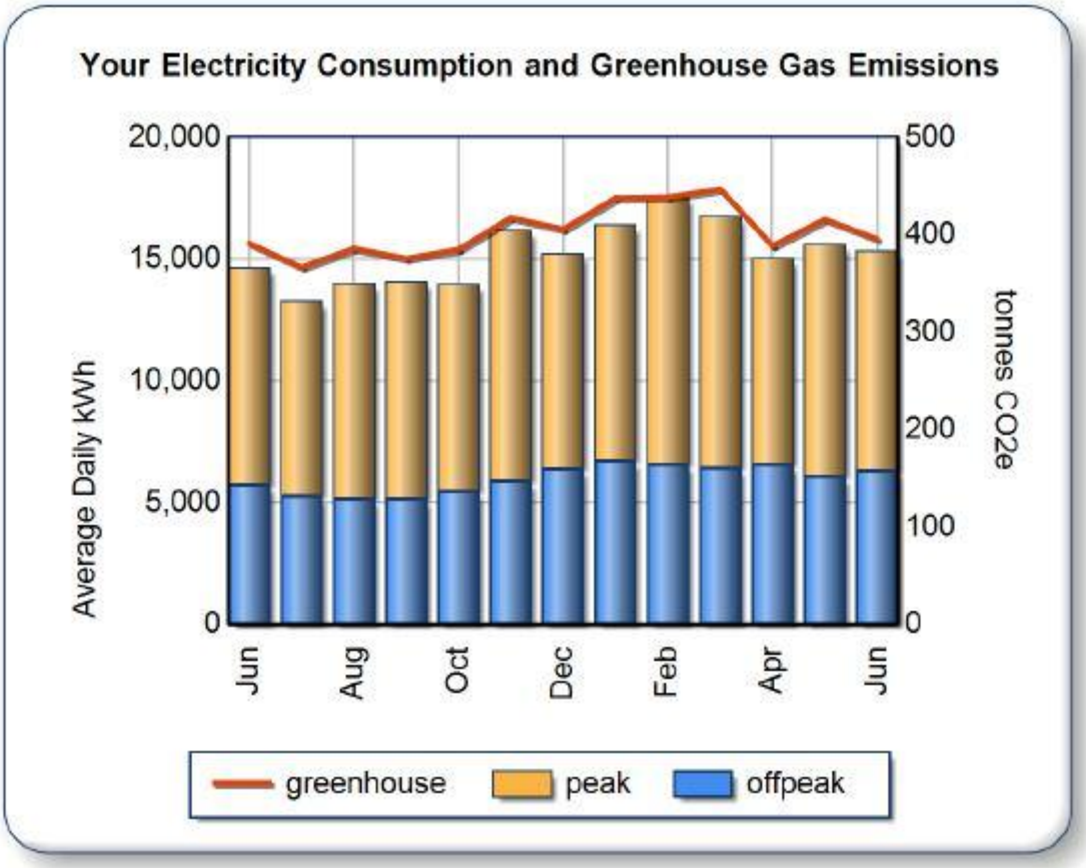


Figure 4.34: Annual electricity use at Churchill (from energy company site invoice)

Once energy use data is assembled, the total energy use is then divided by the total production (e.g. head of cattle or kg of beef) to determine indices of performance. This is useful for comparison between enterprises and benchmarking purposes. In this instance a level 1 assessment of Churchill provided some insight into comparative use of energy on the site. The energy assessment process described is consistent with national standards for conducting energy assessment which is used in the building industry (Australian/New Zealand Standard 2000) and has been applied in agriculture (Baillie & Chen 2011).

Based on the level 1 assessment a summary of the energy use, GHG emissions (relating to direct energy use) and the costs for major sources on energy at Churchill are presented in table 4.13. The abattoir is regarded as a small to medium size abattoir processing 545 cattle and producing 135 tHSCW per day. The total energy requirement of the site is 99,948 Gigajoules (GJ) at a cost of $1,026,939. The distribution of energy used in production includes electricity

(20%), coal (77%) and LPG (3%). The proportion of energy costs however is somewhat different with electricity being the major cost (73%) at the site and is $ $751,170, which includes network and additional charges.

Table 4.13: Annual Electricity, LPG and Coal consumed by Churchill Abattoir

Energy source	**Energy Inputs**	**Standard energy**		**GHG emissions**		**Cost**	
		GJ	**%**	**kg CO_2-e**	**%**	**$**	**%**
Elect. (kWh)	5,594,727	20,141.02	20%	4,923,360	41%	751,170	73%
Coal (tonne)	2,837	76,613.63	77%	6,781,725	57%	196,517	19%
LPG (L)	124,261	3,193.52	3%	191,363	2%	79,252	8%
Total		99,948.17	100%	11,896,448	100%	1,026,939	100%

In comparison to other meat (cattle) processing facilities the electricity consumption at Churchill of 150 kWh/tHSCW is relatively low. Electricity usage at sites processing between 500 to 1600 head of cattle per day and reported by Franklin *et al.* (2010) ranged from 655 – 1070 kWh/tHSCW. Notably these other sites had onsite freezing facilities which can account for over 50% of the total electricity use. Electricity usage at Churchill Abattoir doesn't include freezing and extensive deboning operations which accounts for this discrepancy. Both the electricity use and costs associated with freezing and deboning are incurred by Woolworths and Marcelford Meats who also operate from the site.

Key environmental performance indicators for energy and greenhouse gas emissions (direct energy) were also determined for Churchill from the level 1 energy assessment. These are presented in table 4.14 and are compared with 2008-2009 industry averages reported by (GHD, 2010). The data indicates energy and GHG emissions are lower per tHSCW and per head of cattle processed. Overall the data suggests a relatively high efficiency of energy at the site compared to industry averages and specifically relating to tHSCW.

Table 4.14: Environmental performance indicators for energy and GHG emissions at Churchill

Intensity Parameter	**Energy Consumption (GJ per …)**	**GHG Emissions (kg CO_2-e per …)**	**Energy Cost ($ per …)**
per head	0.663 (0.666)	78.96 (104)	6.82
per tHSCW	2.672 (4.108)	318 (554)	27.45

4.2.2 Biogas Use Considerations

The composition of biogas produced from anaerobic ponds is primarily methane and carbon dioxide. The concentration of methane in the biogas can vary depending on the type of the waste stream and the performance of the pond but is generally 60-70%. Biogas has significant energy potential and due to the methane content is a contributor to GHG emissions. Therefore the use of biogas not only harnesses potential energy for the site but significantly reduces the GHG emissions. Options for biogas utilisation applicable to the meat processing industry are presented in table 4.15.

Table 4.15: Biogas utilisation applicable to the meat processing industry

Option	**Description**
Flaring	Although a low cost option, flaring systems are primarily used to control odour and reduce GHG emissions. Unless odour or GHG emissions are a primary consideration it is unlikely this option will be adopted.
Burning in a gas-fire boiler	Utilising biogas in a gas fired boiler system also provides another opportunity for reducing energy consumption at the site. Commercial systems are available and existing natural gas fired boilers can be modified for biogas.
Absorption refrigerator plant	Absorption refrigerators are heat driven refrigerators that rely on heat and opposed to electricity. The technology is typically used to supply large cooling requirements
Power generation	Using biogas to fuel a gas engine or turbine for cogeneration i.e. power plant to produce electrical energy as well as excess heat energy for boilers

Other options include the compression and bottling of gas for use in vehicles converted to compressed natural gas (CNG).

In most cases combined heat and power generation is one of the most practical and cost effective methods for utilising the biogas produced at a site and indeed one of the most economical renewable energy options for a site (Franklin *et al.* 2010). Combined heat and power generation facilities generally consist of an internal combustion engine (ICE) and generator. A variation of this includes the use of gas turbine engines (GTE) instead of the internal combustion engine. The use of a GTE generally has a higher capital cost and requires specialised maintenance.

Combined heat and power generation facilities reuse waste heat via heat recovery systems for other processes such as heating water. Commercially available heat exchanges recover heat from the water cooling system and exhaust of an engine. This can increase the combined energy efficiency of a power plant from approximately 45% to 65% (85% on larger installations).

Utilising biogas to generate heat or for use in a boiler system also provides another opportunity for reducing energy consumption. Often a better outcome however, can be achieved by generating electricity (by ICE) and utilising the heat energy as a preheat treatment for water used in the boiler system.

Flaring offers the least potential for biogas. Flaring systems provide a legitimate option for gas disposal where the primary objective is to reduce odour and / or greenhouse gas emissions. Flaring however doesn't exploit the energy potential of the biogas.

Bottling gas is a relatively high capital cost solution and requires significant energy inputs to compress the gas which makes this option in most cases unfeasible, particularly compared to direct use of biogas on site.

Issues with Biogas Use

Biogas produced from anaerobic ponds is a mixture of methane and carbon dioxide. The percentage of each of these two gases is related to the type of the influent waste (COD concentration), the HRT and the performance of the pond. The presence of carbon dioxide and traces of other gases such as hydrogen sulphide in the biogas have a harmful effect on the efficiency and the process as a whole. Therefore biogas in a raw state cannot be effectively used and first needs to go through a purification process which reduces the corrosive ability of the hydrogen sulphide and reduce the carbon dioxide content. These trace elements must be removed to reduce corrosion possibilities (within any machinery used) and increase the heating value. Water vapour can also interfere with the equipment and reduce the energy value of the biogas. Biogas is produced at 100% relative humidity and condensate traps are required to remove moisture from pipelines. Table 4.16 identifies the effect of these gases;

Table 4.16: Effect of gases associated with biogas (Deublein & Steinhauser 2008)

Component	**Content**	**Effect**
Carbon dioxide (CO_2)	25-50 % by vol.	Low calorific value Increase the methane number and anti-knock properties of engine Cause corrosion (low concentrated carbon acid). In case the gas is wet Damage alkali fuel cells
Hydrogen sulphide (H_2S)	0-0.5 % by vol.	Corrosive effect in equipment and piping systems (stress corrosion): many manufacturers of engines therefore set an upper limit of 0.05 by vol.% SO_2 emissions after burners or H_2S emissions with imperfect combustion, upper limit 0.1 by vol.% Spoils catalyst
Ammonia (NH_3)	0-0.5 % by vol.	NOx emissions after burners damage fuel cells Increase the anti-knock properties of engines
Water Vapour	1-5 % by vol.	Causes corrosion of equipment and piping systems Condensates damage instruments and plants Risk of freezing of piping systems and nozzles
Dust	>5 µm	Blocks nozzles and fuel cells
Nitrogen (N_2)	0-5 % by vol.	Lowers the calorific value Increase the anti-knock properties of engines
Siloxanes	0-50 mg/m^3	Act like an abrasive and damages engines

Biogas Hazards and Risks

The main components of biogas are highly flammable and potentially hazardous to human health. As interest grows within the meat processing industry on biogas recovery and bioenergy generation, greater consideration is required of the potential risks and hazards associated with wastewater management and biogas recovery systems. It is envisaged that a detailed hazards and risk analysis is required once specific designs and plans are developed to implement a biogas recovery system for producing bioenergy at the site. A detailed biogas hazards and risk analysis would consider the following aspects.

Biogas production:

Biogas is a combination of methane CH_4, carbon dioxide CO_2 and hydrogen sulphide H_2S plus minor trace elements of nitrogen and oxygen. Anaerobic pond B at Churchill Abattoir is capable of producing biogas quantities in the range of 500 – 750m^3 per day (see next section) with a quality ranging from 50-80% methane, 38-48% carbon dioxide, and 700ppm hydrogen sulphide, with nitrogen and oxygen less than 1%.

Methane is an odourless and colourless gas with a density of 0.656kg/m3 at standard atmosphere. Methane is an extremely flammable gas which can provide rapid flame propagation and flash back with a flammable limit of 5-15% in a gas-air mixture. Inhalation is also a major hazard.

Carbon dioxide is an odourless and colourless gas with a density of 1.98kg/m3 at standard atmosphere. Adequate ventilation is required due to carbon dioxide being heavier than air and able to accumulate in low level confined spaces. Carbon dioxide is a non-flammable gas.

Hydrogen Sulphide is a colourless gas which emits an offensive rotten egg odour, at standard atmosphere hydrogen sulphide has a density of 1.45kg/m3. Hydrogen sulphide is an extremely flammable gas and may form an explosive mixture in air; hydrogen sulphide has a flammable limit of 4-44% in a gas air mixture. Hydrogen sulphide is highly toxic at low concentrations. Hydrogen sulphide can exhibit corrosive properties when in the presence of moisture.

4.1.8.

Wastewater system:
At Churchill there are five ponds each five meters deep with vegetation growing on the pond edges. The pond covers do not completely enclose the surface of the pond, therefore creating potential risk to personnel who may accidently fall into the ponds by working within the vicinity. This risk is also extended to the general public. To reduce the unauthorised entry to the ponds a perimeter fence may need to be installed, which also incorporates strict access procedures.

Consideration also needs to be given to how any maintenance is going to be conducted on the pond covers while *in situ.* A safe working practice needs to be established to repair any leaks or tears to the cover. The employment of a crane to carry personnel over the top of a cover to conduct repair work is one consideration; work platforms established over the ponds are another option. A safety harness is an appropriate device to minimise the chances of any personnel falling into the ponds.

Biogas distribution system:
From the location of the ponds to the final use of the biogas, the abattoir requires a network of pumps purification and piping which can extend a distance of 2km’s. The design and construction for gas pipelines needs to compile with Australian Standards 2885.1 (Australian Standards 2007). According to AS 2885.1 (2007), threat identification should include external interference, corrosion, natural events, electrical effects, operations and maintenance activities, construction defects, design defects material defects, intentional damage, and other threats such as seismic and blasting. These threats must be considered for any damage to the pipeline which may cause a loss of gases to the environment or any harm caused to the operators, or the public.

When determining the location of the pipeline, the environment around the pipe line and the use of the land must be taken into consideration. Factors such as whether the pipeline will be above or below ground can have an impact. The production rate of the ponds would not require a large pipe to transfer the gas but stock on the land may cause damage to any small piping structures above the ground.

There are residents within close proximity to Churchill, therefore a safety and operating plan must be devised to deal with any accidents or incidents on site such as a leaking or a ruptured pipe line. This must be isolated to protect the surrounding residents, property and equipment. A corrosion prevention plan would also need to be considered to prevent deterioration of the capital investment.

Flaring requirements:

Biogas flaring is a tool that can be used to burn excess natural gas, when the production rate of the ponds exceeds gas storage capacity, or the consumption rate for the energy recovery system. Other considerations include shut downs for routine maintenance or any unforseen repairs. The implementation of a biogas flare is a safe and adequate method to remove excess biogas from the vicinity.

Biogas Use at Churchill Abattoir

Previous Australian meat processing industry studies have identified that one of the most economical options for renewable energy is the capture and use of biogas from effluent ponds (Franklin *et al.* 2010). In addition the most effective use of this energy source is in a cogeneration plant (combined heat and power generator). This work was based on a number of case studies identifying renewable energy and energy efficiency options for meat processing facilities in Australia with a profile similar to Churchill Abattoir.

Preferred options for biogas use were discussed further with Quantum Power, a commercial supplier of biogas recovery and utilisation technology. Quantum Power confirmed that a combined heat and power generator was the most likely option for biogas use and therefore was considered as a robust basis for assessing the feasibility of bioenergy produced from biogas at the Churchill site.

The key components of a combined heat and power generation plant include:

1. Condensate trap for moisture
2. Scrubber to remove H_2S
3. Gas blower for gas transfer (from pond)
4. Internal combustion engine (or gas turbine)
5. Heat recovery system
6. Power generator
7. Control System

Most of these components, with exception to the condensate trap, are located as a single station near the point of use. This is generally because it is more practical to have close to the main infrastructure of the plant; better able to integrate with existing infrastructure and generally cheaper to pipe gas from the pond than to convey electricity generated from the process over an equivalent distance. The other advantage is the ability to use waste energy if close to the main infrastructure on site.

In addition to the power generation plant, the pond cover also provides an important function by acting as a balancing storage (i.e. in head space of cover) as well as a mechanism for capturing gas in the first place.

As a general guide (pers. comm. Quantum Power) the cost and sizing of gas handling and generation equipment is $1000 / kW (for generator equipment) where 40m^3/hr of biogas production requires a 100kW generator.

These rules of thumb exclude additional site costs that would include: design, planning, approval and project management. These all amount to an additional 20 – 30% of the capital costs for the power generation plant.

4.2.3 Biogas Production at Churchill Abattoir

Due to the difficulties encountered in measuring biogas production at the site, dynamic wastewater treatment modelling using the software BioWin was undertaken to estimate biogas production. BioWin is a windows based computer simulation model developed by EnviroSim Associated Ltd. BioWin is able to simulate the behaviour of a covered anaerobic pond by integrating biological and chemical processes to effectively determine biogas yield. The software contains two operational modules which include a steady state module and an interactive dynamic simulator. The steady state module is used for simulating systems based on constant conditions while the dynamic simulator allows the user to change time varying inputs or changes in operational strategy which reflect real life conditions.

To simulate the anaerobic ponds at Churchill, BioWin was first calibrated against measured data from the field monitoring programme. Data sets used in the calibration process included effluent COD concentration and TSS concentration. The calibration process was conducted using a relatively complete and parallel data set for ponds B and E over 150 days. Data for Pond B was used to test the skill of BioWin simulating a unit process while data for pond E (which was the output from the whole system of ponds) was used to test the skill in modelling the whole wastewater system.

Calibration of Unit Processes

The model was calibrated by assuming a reduction efficiency of the influent COD and adjusting this to best match the measured effluent COD of pond B. The model was calibrated with a COD reduction efficiency of 30%. In practice this means only 30% of the influent COD is participating in the digestion process and biogas production. The remaining 70% of the COD can be accounted for through the accumulation of fat at the top of the pond (creating a hard crust) and undigested sludge at the bottom of the pond, which was consistent with observations at the site.

The BioWin prediction of COD effluent from pond B is shown in figure 4.35. BioWin was able to accurately simulate the measure COD. Predicted and measured COD results were graphed against each other where the absolute relative error was found to be 14%. This was considered to be very good, particularly when considering the high fluctuation and instability of the flow rate and composition of influent to the pond. BioWin simulations were also able to demonstrate similar skill with data collected at different dates and pond temperatures as shown in figure 4.36. In addition to COD BioWin was able to show skill in simulating the effluent TSS. Figure 4.37 and 4.38 demonstrates a good match between measured TSS and BioWin prediction at two different dates with an absolute relative error of 18%.

This first part of the calibration process demonstrated that BioWin was able to accurately simulate a single anaerobic digester despite the severe fluctuation in both the inflow rate and inlet water composition.

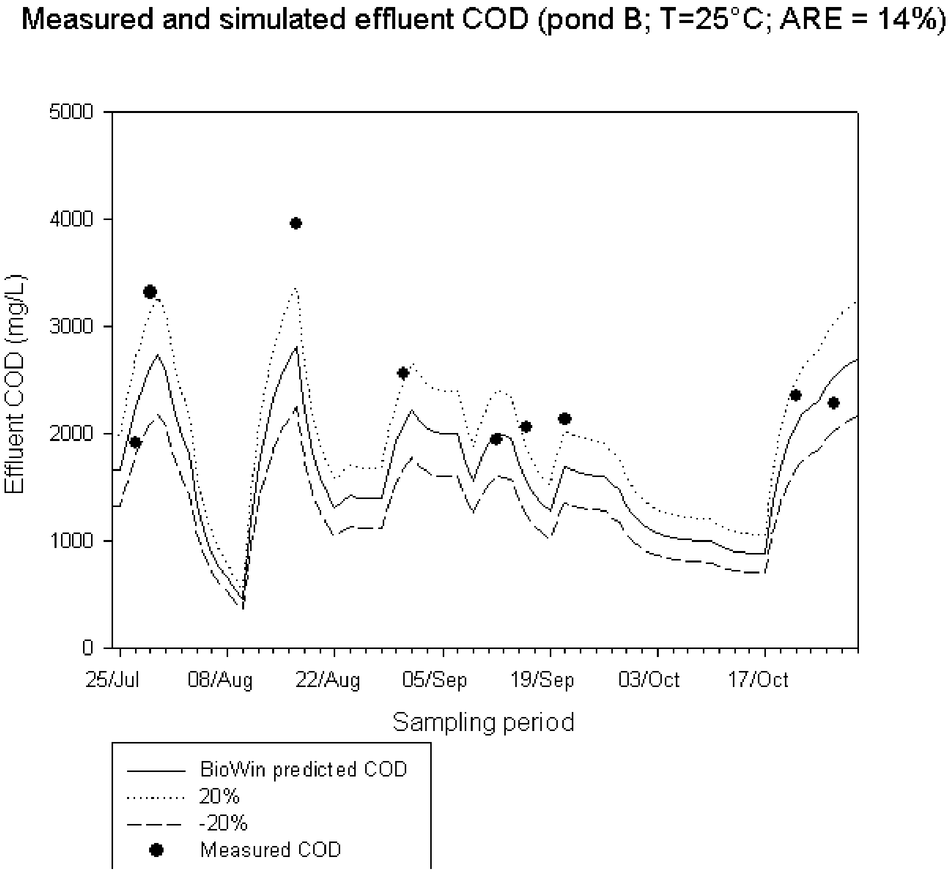


Figure 4.35: Measured and simulated effluent COD from Pond B at CA for 2011

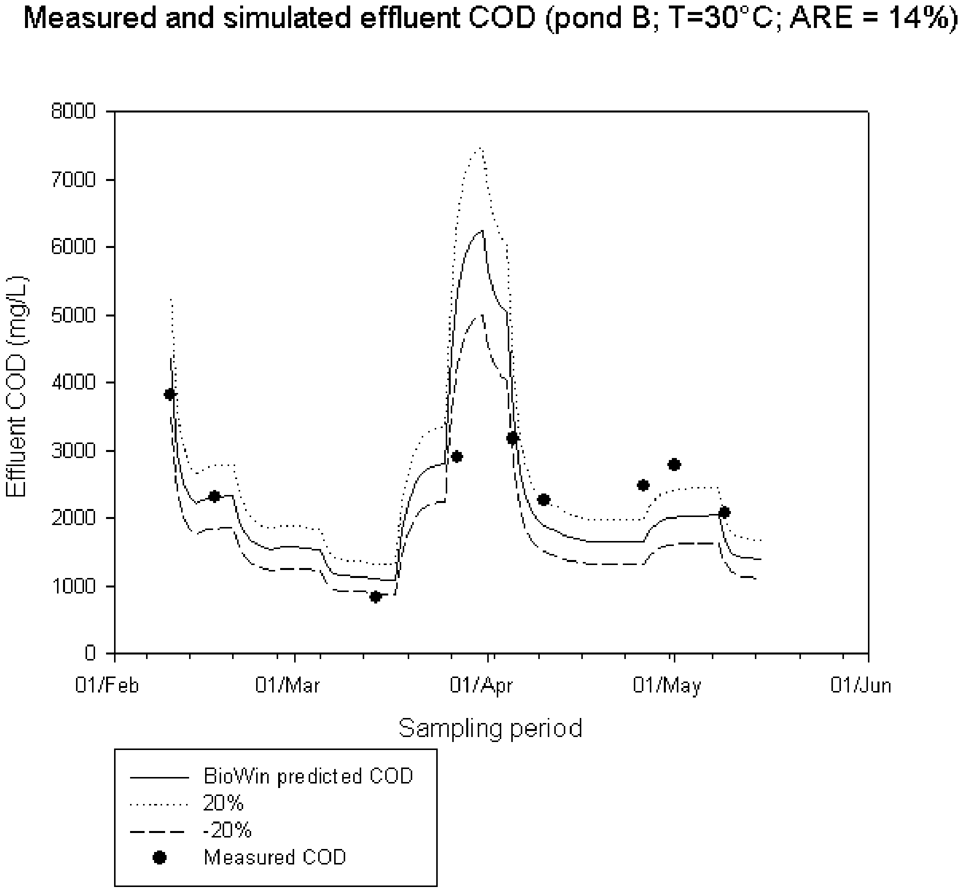
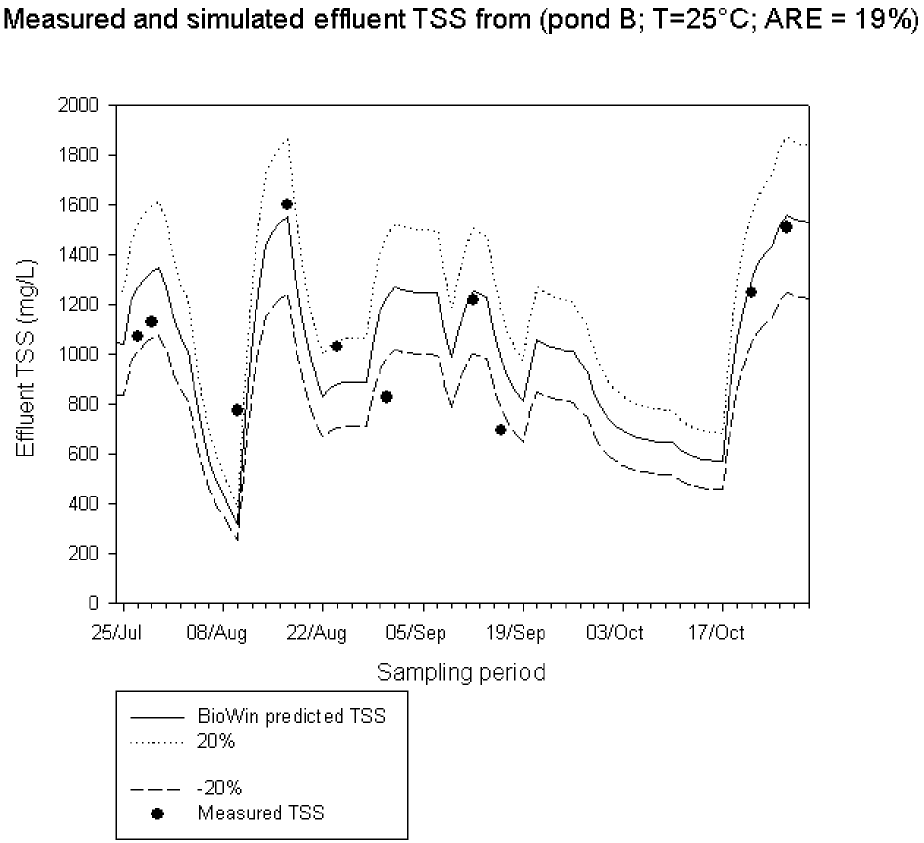
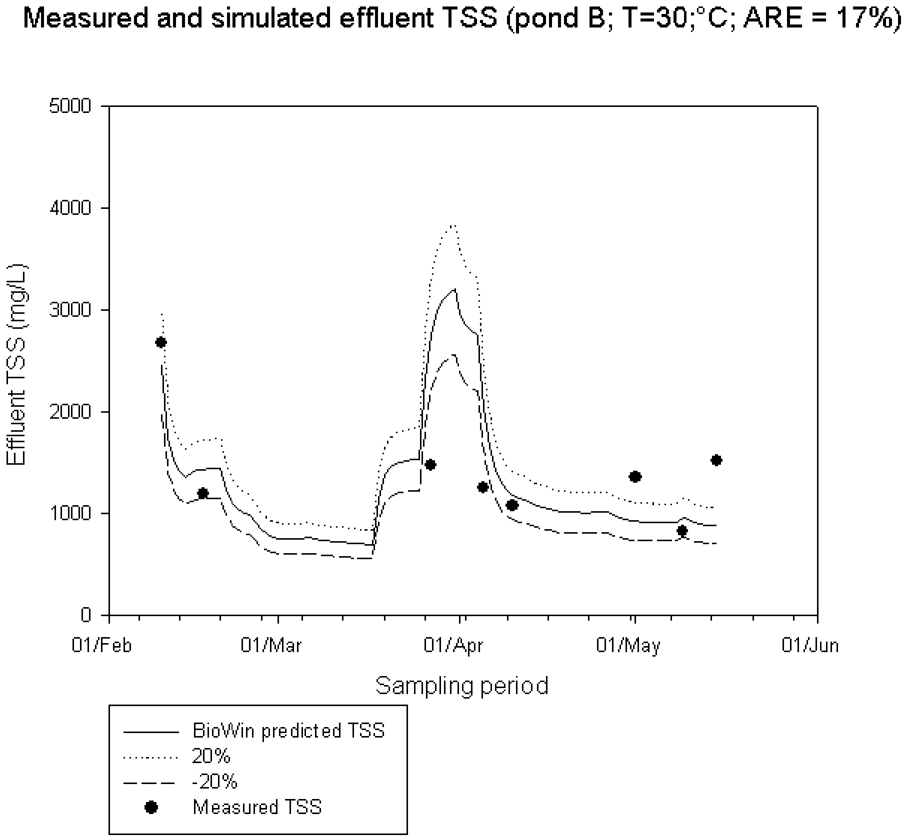


Figure 4.36: Measured and simulated effluent COD from Pond B at Churchill for 2012



Measured and simulated effluent TSS from (pond B; T=25°C; ARE = 19%)

Figure 4.37: Measured and simulated effluent TSS from Pond B at Churchill for 2011



Measured and simulated effluent TSS (pond B; T=30;°C; ARE = 17%)

Figure 4.38: Measured and simulated effluent TSS from Pond B at Churchill for 2012

Calibration of Whole System

The next stage of the calibration process focused on the ability of BioWin to simulate the five pond system. The five pond system was configured in BioWin and measured effluent COD from Pond E which represents the final outflow was plotted against BioWin predictions of COD. As shown in figure 4.39 the measured COD of the outlet wastewater from Pond E again correlates very well with the BioWin predictions with an absolute relative error value of 16%. In addition to the simulations of COD, TSS measured at the outlet of pond E was also compared against the data predicted by BioWin and is shown in figures 4.40. Simulation of TSS gave an absolute relative error value of 21%.

This analysis and interpretation demonstrates clearly the ability of BioWin to simulate both a single element and the whole system of wastewater treatment at Churchill. Once calibrated BioWin was able to accurately predict important parameters such as COD and TSS.

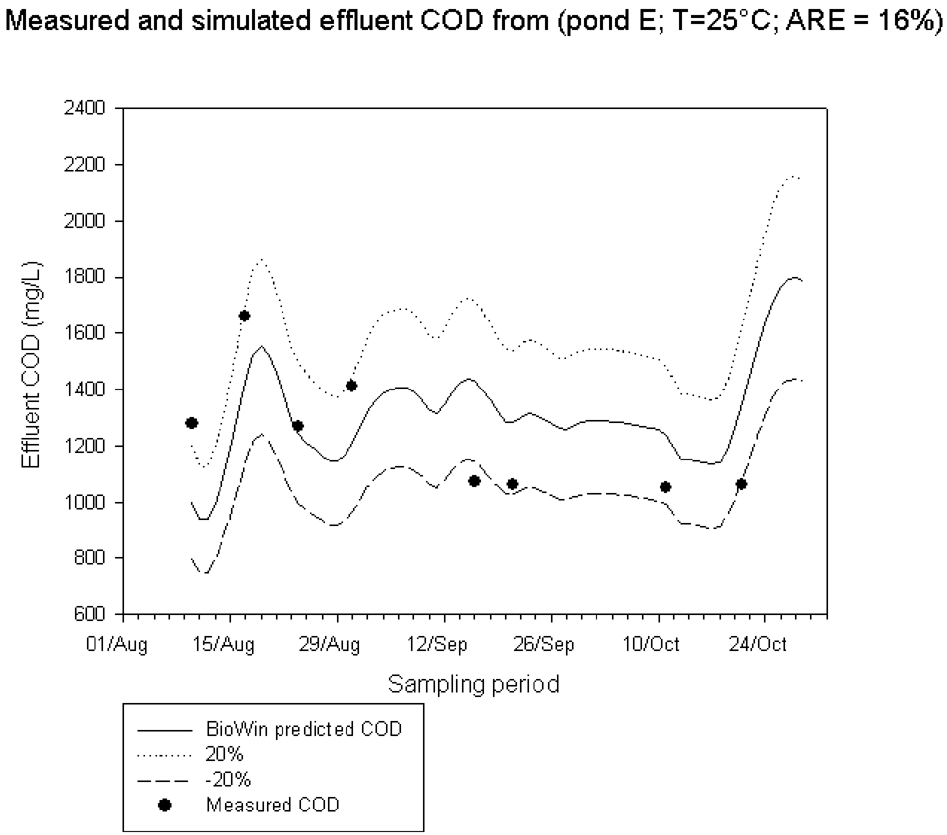


Figure 4.39: Measured and simulated effluent COD from Pond E at Churchill during 2011

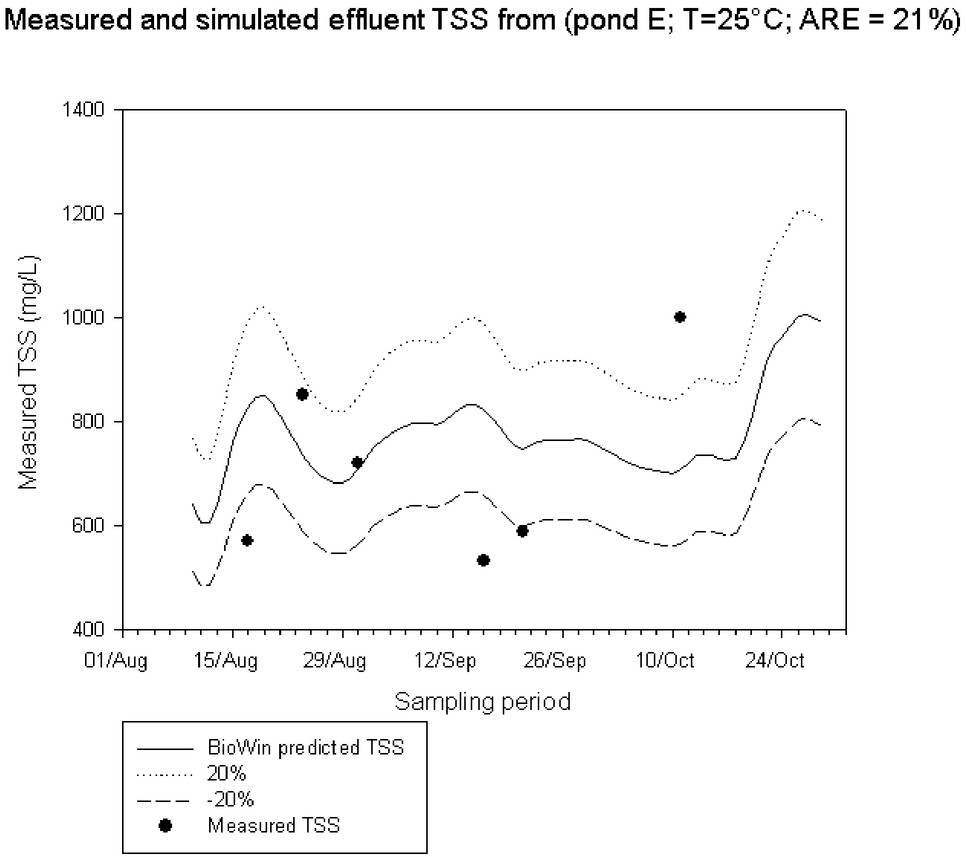


Figure 4.40: Measured and simulated effluent TSS from Pond E at Churchill during 2011

Once BioWin was calibrated, potential biogas production was determined by simulating the anaerobic processes within the ponds over 364 days to represent annual biogas production. Measured data from the monitoring program at Churchill including flow rates and COD were used as inputs into the BioWin simulations. To assess biogas production for the current system and management practices, two scenarios were modelled including, Scenario 1: ideal results (uncalibrated model; default settings) and Scenario 2: likely results (calibrated model; adjusted settings). Scenario 1 represents a COD reduction efficiency of 85% while Scenario 2 represents a COD reduction efficiency of 30%.

The data contained in table 4.17 is a summary of the modelled results for potential annual production of biogas under the current configuration and management of ponds at Churchill under an ideal circumstance (ie scenario 1) where the efficiency of the pond is high and governed by 85% COD reduction (default within BioWin). This is conceptualised in figure 4.41, which displays a screen capture of the BioWin user interface. The data contained in table 4.17 includes min, max, and average biogas production during this period. Total annual biogas production of 431,404m^3 was found by summing the simulated daily gas production.

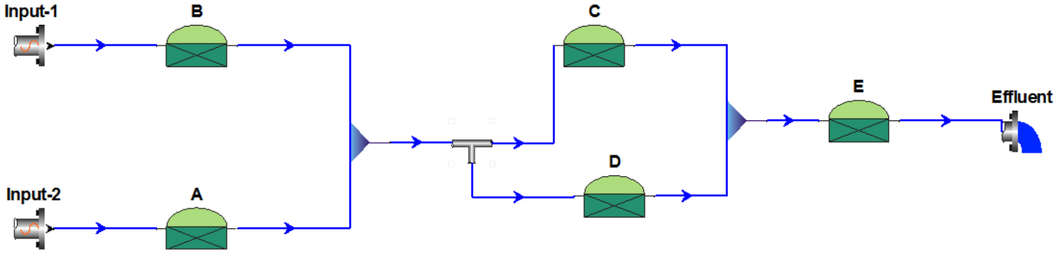


Figure 4.41: Anaerobic pond configuration at CA

Table 4.17: Scenario 1 - Total and individual Biogas production from the ponds at Churchill plant (Ideal: 85% efficiency).

Pond	Biogas Production m^3/year	Production m^3/day	Production m^3/day	Production m^3/day
		Min	Max	Average
Pond A	130639	119	556	362
Pond B	136821	37	742	380
Pond C	58264	61	228	161
Pond D	52604	50	212	146
Pond E	48344	49	184	134
Total Biogas production m^{3}per year	431,404			1183

The calibration of the model however indicated that the ponds only process 30% of the inlet COD. This means only 30% of the input COD is participating in the generation of biogas and the other 70 precent is accumulating as crust (fat) at the top of the ponds or undigested sludge at the bottom. This was consistent with observations at the site. The annual gas production at Churchill is therefore most likely to be similar to the data presented in table 4.18 (i.e. scenario 2) which is based on a 30% reduction in COD resulting in a significantly lower annual biogas yield of 120,000m^3.

Table 4.18. Scenario 2 - Total and individual Biogas production from the ponds at the Churchill plant (30% efficiency).

Pond	Biogas Production m^3/year	Production m^3/day	Production m^3/day	Production m^3/day
		Min	Max	Average
Pond A	48881	59	103	94
Pond B	54822	24	142	111
Pond C	21200	58	79	49
Pond D	19552	18	71	45
Pond E	14671	4	90	29
Total Biogas production m^3per year	120,000			328

Modelling suggested other factors, despite ideal digestion (80-90% COD reduction) are likely to significantly affect the process. These include the HRT, solid retention time (SRT), temperature and flow rate. The current design of the ponds through the modelling process was assessed to be operating at 30–40% efficiency when combining these factors. It is important to note that this represents the final production yield of the ponds. It is reasonable to expect that over the lifetime of the ponds the biogas production yield will initially be much higher due to a greater useable volume of the pond (ie before crust and sludge accumulation). The final production yield of the pond could in fact be enhanced through the routine removal of crust and sludge throughout the lifetime of the ponds.

Although increasing the fraction of COD participation in the digestion process may not be possible because it consists mostly of fats, changing the configuration of the ponds, adding pre-treatment elements, modifying operational procedures and altering the chemical properties of the wastewater provides some opportunity to enhance biogas quantity and quality.

Alternative Configurations and Operational Options

Previous lab based studies by Borja *et al.* (1998) suggest that increased biogas production can be achieved when the variables affecting the performance of the anaerobic process (i.e. ponds) are better controlled. To examine these possibilities and by exploiting the functionality of BioWin, alternative configurations and operational options were simulated to identify the impact on biogas yield.

As an example, a new configuration is shown in figure 4.42 which includes the addition of a clarifier to recycle the activated sludge leaving the system. According to many wastewater design criteria this enhances the performance of the digestion process. Simulation modelling of this system by BioWin did show a significant improvement in the performance of the ponds by increasing biogas yield.

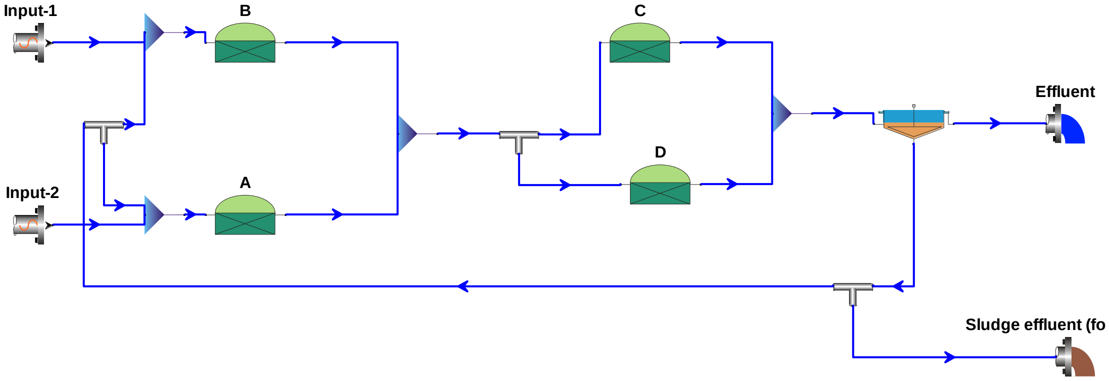


Figure 4.42: Alternative Ponds' Configuration at Churchill Abattoir

Tables 4.19 presents the biogas production from an alternative pond configuration (scenario 3) where most of the inlet COD is considered as degradable materials (ideal scenario presented earlier). The potential biogas production is around 3284m3/day. Even by reducing the amount of degradable COD to 30% (likely scenario at Churchill presented earlier) the results shown in table 4.20 (scenario 4) demonstrates significant improvement in biogas production (i.e. 572m^3/day from 328m^3/day). These figures indicate the potential to significantly increase biogas production by a relatively minor change in the configuration of the treatment system. In this instance the last pond at Churchill (pond E) could be used as a clarifier pond to recycle the activated sludge back into the top of the system.

Table 4.19: Scenario 3: Total and individual Biogas production from the ponds at the Churchill plant, ideal

Pond	Biogas Production m^3/year	Production m^3/day	Production m^3/day	Production m^3/day
		Min	Max	Average
Pond A	311510	198	1516	855
Pond B	375046	544	1630	1030
Pond C	267285	435	1091	734
Pond D	242162	383	1007	665
Pond E				
Total Biogas production m^3per year	1,209,139			3284

Table 4.20: Scenario 4 - Total and individual Biogas production from the ponds at the Churchill plant, 30% efficiency

Pond	Biogas Production m^3/year	Production m^3/day	Production m^3/day	Production m^3/day
		Min	Max	Average
Pond A	66952	216	270	184
Pond B	64169	128	302	176
Pond C	40849	49	278	112
Pond D	36115	42	246	100
Pond E				
Total Biogas production m^3per year	209,000			572

BioWin was able to successfully simulate the behaviour of the wastewater treatment system and therefore biogas yield was determined with some confidence. BioWin is a powerful simulation tool that can be used in design and developing wastewater treatment elements and systems. In this instance BioWin was able to simulate the behaviour of the anaerobic ponds and simulated an average biogas yield of 328 m^3/day. Modelling also suggests this can be significantly increased with relatively minor changes to the system configuration and operation.

4.2.4 Biogas cost/benefit analysis

One of the most likely options for biogas capture and use at Churchill Abattoirs is via a combined heat and power generation plant to offset electricity and heating demands at the site. Based on the BioWin modelling results the amount of biogas produced from the site is 120,000 m3/year (328 m3/day). Each cubic meter of biogas contains the equivalent of 6 kWh or 21.6 MJ of energy. However, when biogas is converted to electricity, via a biogas powered electric generator, approximately 35% of the total energy is converted to electricity due to the efficiency of the generator. The remainder of the energy is converted into heat, some of which can be recovered for heating applications. It is assumed that 35% of the total energy can also be recovered for low grade heating purposes.

Energy Offsets

Based on the assumptions described above the amount of useable energy for the site, produced from biogas, is presented in table 4.21. Scenario 2 (shaded cells) highlights the likely biogas production from the current operation of the ponds (described earlier) and the opportunity to exploit biogas based energy on the site. Energy savings based on other BioWin modelling scenarios are also presented in 4.21.

Table 4.21: Energy saving at Churchill Abattoir plant

Scenario	Biogas (m^3/year)	Useable Energy from Biogas	Energy Amt. (GJ/year)	Energy Amt. (kWh)	Energy Savings ($)	Energy Offset
1	431,404	Electricity	3261	905,948	$90,595	Electricity
		Heat	3261	905,948	$10,630	Coal
2	120,000	Electricity	907	252,000	$25,200	Electricity
		Heat	907	252,000	$2,957	Coal
3	1,209,139	Electricity	9141	2,539,192	$253,919	Electricity
		Heat	9141	2,539,192	$29,793	Coal
4	209,000	Electricity	1580	438,900	$43,890	Electricity
		Heat	1580	438,900	$5,150	Coal

Assuming a conservative electricity price of $0.1 / kWh, electricity costs on site can be offset by $25,200 per annum. Given a coal price of $88/tonne, the total cost of coal is offset by $2,957 per annum due to the recoverable heat energy from the biogas power generation process. Combined the total energy costs at Churchill can be offset by 28,157 (scenario 2) under current operating conditions. It is important to note however that the potential is much greater depending on the operational configuration and performance of the ponds. Based on other BioWin modelling results, energy costs could be offset by $49,040 by changing the operating configuration of the ponds at the current efficiency (scenario 4). By changing both the operational configuration, while at maximum efficiency, energy costs could be offset by as much as $283,712 (scenario 3).

Economic Assessment of Biogas Recovery and Use

A rudimentary economic analysis was undertaken to assess the feasibility of biogas energy recovery and use at Churchill and for the scenarios described above. The economic assessment was based on a simple payback period (SPP) approach for a combined heat and power generation plant. The assessment was based on the following assumptions:

- The capital cost of the generation equipment plus additional costs including design, planning and project management is $1,200 / kW.
- The generator required is based on 100 kW per 40m^3/hr of biogas
- Other lifetime costs for Operation and Maintenance (O&M) is half of the initial capital cost

The results from the SPP analysis are presented in table 4.22 and indicate a payback on the investment including an allowance for life time O&M costs of 2.2 years. As a general guide and for this exercise an investment with a payback of less than 3 years is considered to be an attractive proposition for the Meat Processing (pers. comm. Mike Spence June 2012). Given the analysis is based on proportional costs and returns relative to the quantity of biogas produced the SPP for each scenario is the same. The financial proposition however will be significantly different over the lifetime of the investment for each scenario and requires a more detailed analysis. The impact of the carbon tax is not considered here with electricity prices expected to increase by 20% (pers. comm. Mike Spence June 2012).

Table 4.22: Simple payback period (SPP) based on the investment in construction of a combined heat and power generation plant

Scenario	Biogas (m^3/hr)	Power Generator Size (kW)	Capital Cost ($)	O&M ($)	Total Costs ($)	Offset ($)	SPP (years)
1	49	123	$147,875	$73,938	$221,813	$101,225	2.2
2	14	34	$41,000	$20,500	$61,500	$28,157	2.2
3	137	342	$410,500	$205,250	$615,750	$283,712	2.2
4	24	60	$71,500	$35,750	$107,250	$49,040	2.2

4.3 Evaluation of pond design and operation

The following information applies to the two primary ponds (A and B) that were monitored over the course of the project and provides an assessment of their design and operation. The ponds at Churchill should have the ability to accommodate a flow rate around 1500m^3/day and an average COD loading of 7000 to 8000 mg/L (3.5 KgBOD/m^3). The volume of each pond and the current HRT is around 2200m^3 and three days respectively. The SRT is same as the HRT. As observed and predicted using BioWin simulation the current design is achieving only 30% efficiency. In the evaluation to follow, the design parameters of the ponds at Churchill were compared to recommended pond design parameters.

Design based on organic loading rate

The organic loading rate can be defined by the following equation:

$$OLR = \frac{S_o \times Q}{V}$$

OLR: organic loading rate (kg BOD (or COD)/m3-day)
S_o: Wastewater biodegradable BOD (or COD) (mg/L)
Q: Wastewater flow rate (m3/day)
V: Pond volume (m^3)

Given the following values for CA:

S_o = 7100 COD (mg/L), or 3500 BOD (mg/L)
Q = 1500 (m^3/day)
V = 2200 (m^3)

Based on flow rate of 1500 (m^3/day) input to two ponds, then the flow rate input to each one will be;

$$Q = \frac{1500\, m^3/day}{2} = 750\, m^3/day$$

The BOD loading is;

$$3500\, \frac{mg}{L} \times \frac{1000\, L}{1\, m^3} \times \frac{1\, Kg}{1000000\, mg} = 3.5\, \frac{Kg\, BOD}{m^3}$$

Calculation of OLR for one pond;

$$VOLR = \frac{3.5 \frac{Kg}{m^3} \times 750\, m^3/day}{2200\, m^3} = 1.2\, \frac{KgBOD}{m^3.day}$$

The hydraulic retention time of this pond is;

$$SRT\ (HRT) = \frac{V}{Q} = \frac{2200\, m^3}{750\, m^3/day} = 3\ days$$

Based on an optimum OLR of 0.05-0.08 kgBOD/m^3/day and a HRT of between 20 to 40 days (CSIRO 2010), the BOD loading to the Churchill primary ponds (A and B) are ten times more than what is recommended. Also, the HRT is roughly less by ten times. Increasing the HRT will:

- Eliminate short circuiting
- Provide and allowance for reduction of pond volume due to sludge build up
- Enable more tolerance to shock load

Below are some considerations that may be applied to CAs pond designs that promote higher SRT since anaerobic treatment of wastewaters requires long SRT to achieve better treatment efficiency

There are different ways to achieve a higher SRT regardless HRT:

1. Either adding a clarifier, to allow for higher SRT irrespective to the HRT or
2. Decrease the inflow to each pond and adding baffles

In the first instance, adding a clarifier (settling tank) will allow the settled biomass to be recycled back to the pond. This alternate operational option has been discussed in section 4.2.3 (see figure 4.39).

The second option may be more applicable. Storing the influent from the abattoir in a reservoir during the day (working hours 10 to 15 hours) and then pumping it to the digester ponds for 24 hours will help to reduce the flow rate and at the same time provide the ponds with continuous inflow. Also by adding baffles and changing the inlet-outlet structure of the ponds a higher SRT can be achieved.

Inlets and outlets of the wastewater must be located to avoid short-circuiting and maximise HRT. This will be very difficult in practice without tracer studies (Shilton & Harrison 2003). In general, for square ponds, inlet location and baffles may be necessary to prevent significant short-circuiting. Outlet location is also important, sheltered positions are preferred and it is usually found in the corners of square ponds. In the case of the Churchill ponds, the best option is to direct a horizontal inlet with installing baffles which may create a series of counter-circulating currents that die out as momentum decreases with distance from the inlet (figure 4.43).

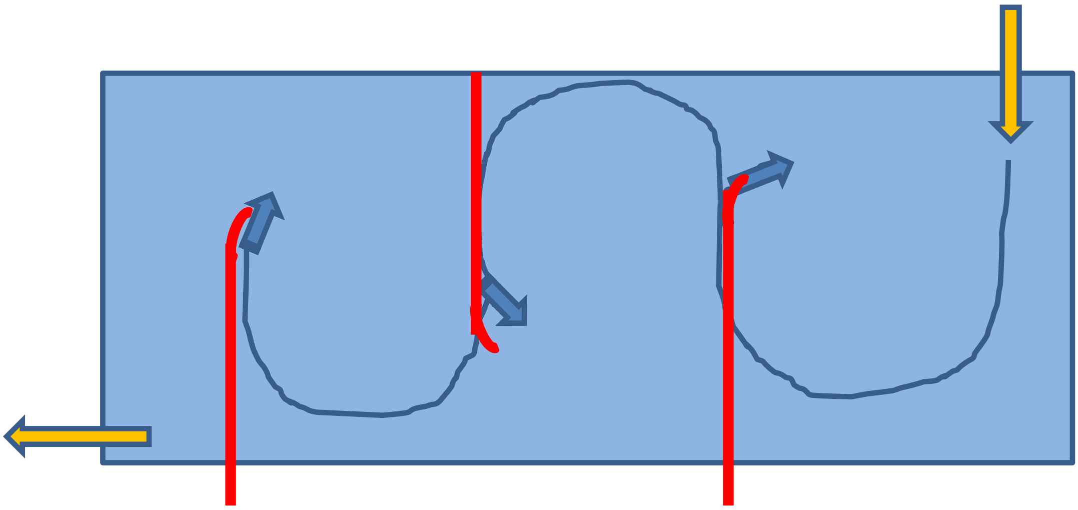


Figure 4.43. Circulatory currents in ponds with a length-to-width ratio of 3 or more (adapted from Shilton and Harrison (2003)).

5. Conclusions and recommendations

5.1. Conclusions

The purpose of the project was to gauge covered anaerobic performance in terms of both waste treatment efficiency and subsequent biogas production. Observations from this work indicate that the successful design and operation of the covered anaerobic ponds is highly sensitive to the inclusion of FOGs in the effluent stream entering the ponds. This problem is not unique to Churchill Abattoir and is a systemic problem in the red meat processing industry which hinders the successful uptake of technologies such as covered anaerobic ponds.

Despite the operational difficulties in relation to fat/crust accumulation, results indicate that satisfactory, stable operation has been achieved for the smaller 5 pond system, notwithstanding the higher than desired organic loading rate of the 2 primary ponds (A and B). One major alteration that occurred after the project was commenced was an increase in the volume of water used to wash cattle (using recycled water) as the result of a customer requirement. This meant that the volume of water being treated increased by 100%. It was designed to use 1 primary pond then 2 of the back 3 ponds (figure 1.3). However, to cope with the increase in production volume all 5 ponds were used. Pond volumes balance well but with 5 ponds in operation meant that the ability to take one pond out of service is difficult. Even though the volume of wastewater increased, the use of 5 ponds instead of 1 pond has proven very successful in terms of easier sludge removal. Pond A has been desludged with pond B commencing shortly.

Operating parameters such as pH, acetic acid, alkalinity, ammonia, ORP, and temperature were all in the optimum range to promote the conversion of waste to biogas as evidence by the composition of methane in the gas produced from pond B. This pond was producing up to 62%-72% methane just prior to being desludged in June 2012 after 22 months of continuous operation.

The use of BioWin has proven to be a complementary means of determining biogas yield due to the difficulty of measuring biogas quantity (due to the presence of the thick crust that formed under the covers) and the potential for significant biogas production depending on site factors limiting the value of a single direct measurement. BioWin has also been an effective tool in approximating the efficiency of the ponds. There is significant potential for BioWin to be used as a tool in the red meat processing industry to simulate the behaviour of anaerobic ponds and explore options for improvement. Once calibrated, BioWin was found to closely predict measured data at Churchill, despite the severe fluctuation in both inlet flow rate and water quality parameters. BioWin was able to successfully simulate the behaviour of the wastewater treatment system and therefore biogas yield was determined with some confidence. Modelling also suggests this can be significantly increased (by a factor of ten at Churchill) with relatively minor changes to the system configuration and operation.

5.2. Recommendations

The 5 pond system has been operating to various capacities for the past two years (Aug 2010 – June 2012). During this time operational experience has been gained and the following recommendations are made in relation to pond maintenance and design:

- Installation of fat removal systems such as a dissolved air flotation (DAF) unit to pre-treat the effluent and thus reduce the organic loading into the ponds.
- Routine removal of crust and sludge throughout the life time of the ponds to increase the effective volume of the pond and therefore the anaerobic treatment capacity of the system (COD, BOD, TSS and FOG).
- Investigate alternative pond configurations and operational practices such as the addition of a clarifier to the system to recycle the activated sludge leaving the system or the addition of baffles to increase the solids retention time.
- Further consideration of the bioenergy aspects once anaerobic digestion processes are optimised.

Since the inception of covered anaerobic ponds at Churchill Abattoir, this site has undertaken a trial installation of a DAF unit to assess the efficiency of removal of FOGs from wastewater streams. Churchill Abattoir will be running the DAF continuously over the coming months which will provide a unique opportunity to assess pond behaviour and gas production before and after DAF operation.

Future work emanating from this present study therefore includes:

- Additional work with BioWin to more extensively evaluate the tool for CA and other plant locations leading to the use of the tool for optimising anaerobic pond design and operation.
- Lab scale investigations assessing biochemical methane potential (BMP) and anaerobic toxicity assays (ATA) in order to elucidate the biogas potential of waste streams of varying organic composition. The collective results of this study with the results contained in this final report could provide an understanding of the role that FOGs play in methane generation and subsequent covered anaerobic pond performance. This work could also play a role in informing definitive design criteria for covered anaerobic ponds and the need for ancillary equipment such as DAF units.

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7. Appendices

7.1. Wastewater data

Table A7.1: Pond A, B and E: flow, HRT, OLR (COD & BOD), Temp, pH and ORP

Pond A										
Date	**Flow (KL/d)**	**HRT**	**COD loading (KgCOD/m3/d)**	**BOD loading (KgBOD/m3/d)**	**Temp in (°C)**	**Temp out (°C)**	**pH in**	**pH out**	**ORP in (mv)**	**ORP out (mv)**
1/06/2011	640.65	3.47	1.53	0.78	-	-	-	-	-	-
3/06/2011	640.65	3.47	-	-	-	-	-	-	-	-
8/06/2011	640.65	3.47	-	-	-	-	-	-	-	-
10/06/2011	640.65	3.47	-	-	-	-	-	-	-	-
17/06/2011	640.65	3.47	-	-	-	-	-	7.33	-	-
22/06/2011	640.65	3.47	-	-	-	-	-	7.12	-	-
24/06/2011	640.65	3.47	-	-	-	-	-	8.26	-	-
28/06/2011	640.65	3.47	-	-	-	-	-	7.91	-	-
1/07/2011	640.65	3.47	-	-	-	-	-	7.75	-	-
6/07/2011	640.65	3.47	-	-	-	24.60	-	7.27	-	-
8/07/2011	640.65	3.47	2.23	0.88	-	-	7.01	7.3	-	-
13/07/2011	640.65	3.47	1.58	0.72	24.30	24.10	7.08	7.24	-	-
15/07/2011	640.65	3.47	1.91	0.84	30.60	24.30	7.04	7.57	-	-
20/07/2011	640.65	3.47	2.27	1.08	30.80	24.80	7.11	7.22	-	-
22/07/2011	640.65	3.47	1.39	0.63	24.70	24.20	7.73	6.90	13.2	-222.6
27/07/2011	640.65	3.47	2.54	1.38	32.30	22.90	7.63	6.90	-54	-243.8
24/08/2011	640.65	3.47								
31/08/2011	640.65	3.47								
12/09/2011	640.65	3.47								
16/09/2011	640.65	3.47	0.77	0.41	31	23.5	7.79	6.83	44.00	-190.30

21/09/2011	640.65	3.47	3.20	1.26	34.80	26.10	7.27	6.87	19.90	-166.00
11/10/2011	560.88	3.92	3.03	1.15		24.90		6.91	-89.7	-202.30
21/10/2011	703.44	3.13	2.06	0.90	33.10	29.30	7.65	6.85	90.90	-219.90
26/10/2011	789.12	2.79	2.82	1.85	34.50	28.30	7.79	6.97	-41.40	-207.80
17/02/2012	-	-	-	-	-	34.20	-	6.59	-	-200.00
2/03/2012	-	-	-	-	-	39.30	-	6.63	-	-193.80
14/03/2012	-	-	-	-	-	26.40	-	6.59	-	-208.00

Pond B

Date	Flow (KL/d)	HRT	COD loading (KgCOD/m3/d)	BOD loading (KgBOD/m3/d)	Temp in (°C)	Temp out (°C)	pH in	pH out	ORP in (mv)	ORP out (mv)
1/06/2011	877.66	2.86	2.41	0.86	-	-	-	-	-	-
3/06/2011	877.66	2.86	0.71	0.26	-	-	-	-	-	-
8/06/2011	877.66	2.86	0.41	0.07	-	-	-	-	-	-
10/06/2011	877.66	2.86	4.83	1.70	-	-	-	-	-	-
17/06/2011	877.66	2.86	1.69	0.89	-	-	7.15	7.68	-	-
22/06/2011	877.66	2.86	2.48	1.40	-	-	7.07	7.31	-	-
24/06/2011	877.66	2.86	2.30	1.37	-	-	7.06	7.9	-	-
28/06/2011	877.66	2.86	3.99	1.14	-	-	7.03	7.81	-	-
1/07/2011	877.66	2.86	3.27	2.80	-	-	7.32	7.8	-	-
6/07/2011	877.66	2.86	1.86	1.36	25.60	24.30	7.17	7.28	-	-
8/07/2011	877.66	2.86	3.69	1.56	30.30	24.00	6.75	7.31	-	-
13/07/2011	877.66	2.86	3.16	1.28	24.40	24.20	7.02	7.33	-	-
15/07/2011	877.66	2.86	1.85	0.88	24.40	24.20	7.06	7.29	-	-
20/07/2011	877.66	2.86	3.45	1.67	-	25.00	6.94	7.56	-	-
22/07/2011	877.66	2.86	2.61	1.12	29.10	24.60	7.12	7.23	-	-
27/07/2011	877.66	2.86	2.20	1.05	26.80	23.40	7.77	6.93	96.7	-254
29/07/2011	877.66	2.86	1.63	0.85	24.20	22.70	7.74	6.93	60.1	-231
10/08/2011	1043.04	2.11	1.65	0.89	-	-	-	-	101.9	-198.1
17/08/2011	845.04	2.60	3.79	0.98	26.30	23.80	7.91	6.89	-78.30	-199.40
24/08/2011	1030.8	2.13	5.01	2.09	26.10	23.80	7.69	6.97	101.00	-202.00
31/08/2011	733.63	3.00	3.97	2.16	34.80	26.80	7.47	6.94	77.60	-175.80
12/09/2011	700.80	3.14	2.20	1.06	28.50	25.00	7.76	6.99	-112.00	-258.90

16/09/2011	687.84	3.20	2.17	1.00	32.90	29.50	7.57	6.96	-83.20	-235.70
21/09/2011	1052.16	2.09	3.63	1.97	31.70	30.10	7.73	7.01	-83.20	-235.70
11/10/2011	877.66	2.86	2.72	1.40	33.40	30.10	7.78	7.06	44.00	-208.00
21/10/2011	877.66	2.86	4.43	1.89	34.90	28.10	7.69	7.03	89.90	-204.30
26/10/2011	877.66	2.86	3.37	1.36	34.20	29.80	7.38	6.98	22.00	-210.70
10/02/2012	1249.62	1.76	4.04	2.24	34.40	33.60	7.07	6.44	119.00	-200.00
17/02/2012	1249.62	1.76	3.81	1.83	35.90	34.30	6.93	6.47	-90.00	-210.00
2/03/2012	1249.62	1.76	4.28	1.01	38.20	33.50	6.68	6.39	18.30	-219.40
14/03/2012	1352.88	1.63	3.39	0.65	29.50	28.60	7.08	6.46	-92.00	-226.00
27/03/2012	1352.88	1.63	5.28	1.59	31.20	30.20	7.19	6.39	10.00	-212.00
30/03/2012	1352.88	1.63	5.71	5.07	33.50	31.20	6.76	6.46	-90.00	-234.00
5/04/2012	1352.88	1.63	3.73	1.43	31.70	30.50	7.33	6.52	-30.90	-221.00
10/04/2012	1352.88	1.63	3.49	15.07	31.00	28.60	6.60	6.51	-48.00	-179.00
19/04/2012	1352.88	1.63	2.77	1.26	33.00	30.80	6.99	6.44	-69.00	-222.60
26/04/2012	1352.88	1.63	2.66	2.15	29.60	29.40	7.18	6.48	-52.10	-197.00
1/05/2012	1352.88	1.63	6.64	2.04	31.30	29.40	7.22	6.48	72.00	-200.00
9/05/2012	1352.88	1.63	14.88	2.15	29.40	25.80	7.44	6.37	92.00	-214.00
15/05/2012	1352.88	1.63	11.99	3.76	25.90	25.20	7.40	6.52	-52.00	-182.00

Pond E

Date	**Flow (KL/d)**	**HRT**	**COD loading (KgCOD/m3/d)**	**BOD loading (KgBOD/m3/d)**	**Temp in (°C)**	**Temp out (°C)**	**pH in**	**pH out**	**ORP in (mv)**	**ORP out (mv)**
10/08/2011	1521.69	1.45	2.30	0.69	-	21.50	-	6.83	-	-223.00
17/08/2011	1521.69	1.45	3.08	0.69	-	22.10	-	6.84	-	-200.10
24/08/2011	1521.69	1.45	2.74	0.73	-	22.10	-	6.90	-	-224.50
31/08/2011	1521.69	1.45	1.74	0.71	-	24.30	-	6.92	-	-201.00
12/09/2011	1521.69	1.45	1.77	0.64	-	22.60	-	6.95	-	-206.00
16/09/2011	1521.69	1.45	1.34	0.43	-	27.00	-	6.95	-	-232.00
21/09/2011	1521.69	1.45	1.42	0.58	-	26.20	-	7.01	-	-199.40
11/10/2011	1521.69	1.45	1.47	0.51	-	26.60	-	7.02	-	-188.60
21/10/2011	1521.69	1.45	1.72	0.60	-	26.90	-	7.02	-	-204.60
26/10/2011	1521.69	1.45	1.63	0.52	-	28.50	-	6.94	-	-188.60
10/02/2012	1249.62	1.76	2.17	0.18	-	32	-	6.58	-	-210

17/02/2012	1249.62	1.76	1.31	0.14	-	31	-	6.57	-	-223.1
2/03/2012	1249.62	1.76	1.74	0.16	-	31.50	-	6.58	-	-216.55
14/03/2012	1352.88	1.63	1.52	0.15	-	28.7	-	6.54	-	-238
27/03/2012	1352.88	1.63	1.63	0.15	-	29	-	6.59	-	-217
9/05/2012	1352.88	1.63	1.58	0.15	-	24.5	-	6.60	-	-202
15/05/2012	1352.88	1.63	1.60	0.15	-	24.90	-	6.55	-	-192.00

Table A7.2: Pond A, B and E: NH_3-N, TKN, VFA & alkalinity

Pond A

Date	NH_3-N in	NH_3-N out	TKN in	TKN out	Volatile acids	Alkalinity
1/06/2011	179	336	383	341	442	1240
3/06/2011	-	301	-	299	529	1160
8/06/2011	-	191	-	434	906	1110
10/06/2011	-	245	-	401	684	1210
17/06/2011	-	274	-	388	406	1360
22/06/2011	-	58.2	-	426	686	1240
24/06/2011	-	278	-	305	517	1220
28/06/2011	-	250	-	256	494	1270
1/07/2011	-	290	-	415	485	1180
6/07/2011	-	275	-	375	507	1260
8/07/2011	60.8	228	615	392	493	1250
13/07/2011	180	285	477	374	603	1280
15/07/2011	176	302	376	336	452	1180
20/07/2011	145	320	343	358	502	1310
22/07/2011	203	289	389	371	530	1340
27/07/2011	60	296	545	386	480	1360
24/08/2011	292.00	85.90	358.00	424.00	783.00	1020.00
31/08/2011	65.20	241.00	404.00	366.00	501.00	1140.00
12/09/2011	95.00	418.00	485.00	406.00	522.00	1210.00
16/09/2011	105.00	229.00	350.00	344.00	-	-
21/09/2011	91.30	277.00	432.00	400.00	564.00	1320.00
11/10/2011	210.00	432.00	416.00	414.00	70.00	1980.00
21/10/2011	35.80	156.00	416.00	349.00	92.00	1920.00
26/10/2011	91.60	282.00	314.00	360.00	85.00	1780.00
17/02/2012	-	448	-	421.00	65.00	2280.00
2/03/2012	-	37.4	-	419.00	697.00	2380
14/03/2012	-	468	-	408.00	41.00	2400

Pond B

Date	NH_3-N in	NH_3-N out	TKN in	TKN out	Volatile acids	Alkalinity
1/06/2011	104	310	385	392	313	1300
3/06/2011	294	286	296	290	387	1300
8/06/2011	220	199	307	312	201	1400
10/06/2011	112	205	395	313	264	1310
17/06/2011	213	339	440	389	618	1320
22/06/2011	23.8	63.6	690	367	377	1230
24/06/2011	158	277	372	310	358	1340
28/06/2011	113	257	397	276	3240	1340
1/07/2011	183	285	615	487	326	1250
6/07/2011	306	240	440	392	372	1340
8/07/2011	263	288	657	485	312	1350
13/07/2011	86.6	226	575	500	399	1280
15/07/2011	175	285	446	423	550	1260
20/07/2011	101	306	420	348	352	1320
22/07/2011	210	372	340	362	414	1290
27/07/2011	234	352	527	365	433	1340

29/07/2011	179	300	414	429	506	1420
10/08/2011	349	202	322	320	162	1520
17/08/2011	216.00	380.00	444.00	455.00	411.00	1380.00
24/08/2011	122.00	300.00	530.00	344.00	443.00	1280.00
31/08/2011	43.10	291.00	785.00	380.00	470.00	1180.00
12/09/2011	193.00	287.00	426.00	387.00	321.00	1370.00
16/09/2011	118.00	271.00	474.00	337.00	390.00	1530.00
21/09/2011	135.00	290.00	530.00	403.00	430.00	1380.00
11/10/2011	180.00	321.00	409.00	412.00	248.00	1730.00
21/10/2011	40.70	174.00	447.00	352.00	260.00	1580.00
26/10/2011	60.20	298.00	324.00	321.00	315.00	1400.00
10/02/2012	192.00	296.00	416.00	420.00	91.00	1400.00
17/02/2012	108.00	265.00	345.00	328.00	153.00	1510.00
2/03/2012	4.35	22.00	392.00	359.00	219.00	1430.00
14/03/2012	151.00	300.00	387.00	314.00	229.00	1450.00
27/03/2012	130.00	235.00	358.00	328.00	317.00	1080.00
30/03/2012	160.00	219.00	500.00	325.00	245.00	1240.00
5/04/2012	144.00	239.00	350.00	351.00	271.00	1220.00
10/04/2012	18.10	21.00	389.00	281.00	302.00	1080.00
19/04/2012	102.00	230.00	343.00	401.00	246.00	1080.00
26/04/2012	167.00	262.00	388.00	365.00	398.00	1290.00
1/05/2012	113.00	188.00	474.00	366.00	298.00	1170.00
9/05/2012	132.00	213.00	418.00	268.00	616.00	1050.00
15/05/2012	17.40	25.00	17.60	49.00	410.00	1180.00

Pond E

Date	NH$_3$-N in	NH$_3$-N out	TKN in	TKN out	Volatile acids	Alkalinity
10/08/2011	-	333.00	-	309.00	350.00	1390.00
17/08/2011	-	332.00	-	394.00	137.00	1510.00
24/08/2011	-	342.00	-	382.00	163.00	1440.00
31/08/2011	-	360.00	-	425.00	163.00	1390.00
12/09/2011	-	366.00	-	374.00	82.00	1440.00
16/09/2011	-	262.00	-	332.00	78.00	609.00
21/09/2011	-	353.00	-	402.00	128.00	1540.00
11/10/2011	-	358.00	-	374.00	61.00	1820.00
21/10/2011	-	156.00	-	342.00	49.00	1690.00
26/10/2011	-	340.00	-	307.00	70.00	1530.00
10/02/2012	-	301	-	312	47.00	1640
17/02/2012	-	23.2	-	295	75.00	1580
2/03/2012	-	162.10	-	303.50	61.00	1610.00
14/03/2012	-	270	-	319	59.00	1630
27/03/2012	-	271	-	332	75.00	853
9/05/2012	-	303	-	321	125.00	228
15/05/2012	-	29.20	-	48.40	111.00	1440.00

Table A7.3: Pond A, B, and E: EC, TSS, FOG, COD & BOD

Pond A										
Date	**EC in**	**EC out**	**TSS in**	**TSS out**	**FOG in**	**FOG out**	**COD in**	**COD out**	**BOD in**	**BOD out**
1/06/2011			1990	560	612	98	5270	2460	2680	1100
3/06/2011				346		90		2620		623
8/06/2011				5300		489		9150		4610
10/06/2011				5640		294		8440		4610
17/06/2011		4090		4090		80		2290		798
22/06/2011		4290		773		132		1730		890
24/06/2011		3740		900		79		2130		817
28/06/2011	3270.6667	3930		780		491		1790		686
1/07/2011		4130		540		71		2180		1810
6/07/2011		4140		460		80		1980		788
8/07/2011	4370	4770	4120	1400	584	86	7670	1900	3030	872
13/07/2011	4270	3860	1370	2140	161	87	5410	2010	2480	949
15/07/2011	3130	3860	3810	587	505	4080	6560	1790	2900	781
20/07/2011	3530	3940	3580	690	401	56	7790	2160	3710	871
22/07/2011	2852	1935	1720	990	414	76	4770	2010	2160	1070
27/07/2011	1472	3593	3360	950	540	106	8730	2040	4740	845
16/09/2011	2732	3784	1630	3150	182	424	2630	7380	1410	3410
21/09/2011	2160.00	3721	2940	710	922	61	11000	2500	4320	1060
11/10/2011		3864	6830	854	739	70	11900	2190	4530	734
21/10/2011	3082.00	4208	2520		73	344	6440	2810	2810	1200
26/10/2011	2928.00	4383	3100	780	488	84	7850	2260	5150	1120
17/02/2012		6293		78		5		796		42
2/03/2012		7154		135		5		433		39
14/03/2012		5577		139		5		385		50
Pond B										
Date	**EC in**	**EC out**	**TSS in**	**TSS out**	**FOG in**	**FOG out**	**COD in**	**COD out**	**BOD in**	**BOD out**
1/06/2011			2090	687	709	52	6030	2080	2160	622
3/06/2011			890	735	153	52	1790	1960	659	905
8/06/2011		4067.5	457	840	40	52	1040	1680	163	575
10/06/2011			6260	950	2110	92	12100	1720	4250	862
17/06/2011	3960	4020	2580	4020	252	86	4230	2600	2220	814
22/06/2011	4330	4310	2670	1070	415	85	6220	1710	3500	731
24/06/2011	3860	3940	3220	950	915	87	5770	2290	3430	841
28/06/2011	2560	4000	1090	3090	605	134	10000	2340	2860	932
1/07/2011	3790	4120	1610	1440	464	71	8200	3970	7020	1500
6/07/2011	4080	4190	2000	713	357	86	4670	3390	3420	758
8/07/2011	4060	4060	4270	1050	793	73	9260	4710	3900	690
13/07/2011	4310	4440	6870	730	269	87	7910	3950	3210	813
15/07/2011	4190	3890	1240	1130	414	81	4640	2710	2200	973
20/07/2011	2440	3650	2320	567	276	58	8650	3310	4180	869
22/07/2011	3660	3930	2450	789	493	59	6530	2390	2800	803
27/07/2011	3050	1941	2940	1070	252	58	5510	1920	2620	851
29/07/2011	2960	3654	2060	1130	371	129	4090	3320	2140	1000
10/08/2011			1400	775	5	520	3480	4450	1880	1000
17/08/2011	3149	3843	3380	1600	1880	129	9860	3960	2540	1060
24/08/2011	2905	3552	5660	1030	724	125	10700	2520	4460	1030
31/08/2011	2757	3777	4330	827	706	64	11900	2560	6480	932

12/09/2011	4029	4043	3270	1220	886	66	6910	1940	3320	626
16/09/2011	3302	4378	3160	693	73	21	6950	2060	3200	839
21/09/2011	3343	4666	3670	690	588	66	7590	2130	4110	740
11/10/2011	3238	4402	3800	1740	526	44	6810	2490	3500	870
21/10/2011	3076	4122	3070	1250	1120	108	11100	2360	4750	755
26/10/2011	3349	4410	3990	1510	1310	103	8450	2280	3400	620
10/02/2012	3612	4469	3060	2680	973	76	7110	3820	3940	316
17/02/2012	3375	4575	2910	1190	773	78	6700	2300	3230	246
2/03/2012	2594	4247	3600	3370	2190	125	7530	3710	1770	639
14/03/2012	3489	4066	3320	5360	136	23	5520	836	1060	406
27/03/2012	3012	3993	5080	1470	1440	129	8580	2890	2590	693
30/03/2012	3694	4386	5530	1000	904	76	9280	3660	8250	372
5/04/2012	3283	4123	2180	1250	354	121	6070	3170	2320	1070
10/04/2012	2764	3236	6130	1070	4570	100	5680	2270	24500	459
19/04/2012	2990	4081	1880	2990	173	167	4510	5020	2050	1920
26/04/2012	3024	3908	1760	1770	607	53	4330	2480	3500	716
1/05/2012	3013	3373	3950	1360	797	89	10800	2790	3320	897
9/05/2012	3036	3362	5960	824	1790	47	24200	2080	3500	717
15/05/2012	2887	3597	5010	1520	3340	106	19500	2660	6110	839

Pond E Date	**EC in**	**EC out**	**TSS in**	**TSS out**	**FOG in**	**FOG out**	**COD in**	**COD out**	**BOD in**	**BOD out**
10/08/2011	-	3880	-	1700	-	98	-	1280.00	-	199
17/08/2011	-	4088	-	572	-	19	-	1660	-	193
24/08/2011	-	3948	-	852	-	45	-	1270	-	278
31/08/2011	-	3913	-	720	-	24	-	1410	-	190
12/09/2011	-	4047	-	418	-	26	-	672	-	78
16/09/2011	-	4366	-	533	-	8	-	1070	-	126
21/09/2011	-	4440	-	588	-	13	-	1060	-	132
11/10/2011	-	4464	-	1000	-	13	-	1050	-	212
21/10/2011	-	4245	-	520	-	17	-	1060	-	302
26/10/2011	-	4532	-	138	-	31	-	1020	-	178
10/02/2012	-	4705	-	210	-	5	-	677	-	49
17/02/2012	-	4518	-	375	-	7	-	764	-	66
2/03/2012	-	4611.50	-	292.5	-	6	-	720.50	-	57.50
14/03/2012	-	4371	-	458	-	130	-	2150	-	106
27/03/2012	-	4386	-	440	-	26	-	803	-	107
9/05/2012	-	3809	-	253	-	5	-	126	-	93
15/05/2012	-	3981	-	867	-	15	-	1060	-	143

7.2. Maximum and minimum temperatures (Ipswich)

Figure A7.1 illustrates provides maximum and minimum temperatures experienced during the sampling period (Sourced from Amberley weather station).

(http://www.bom.gov.au/climate/dwo/201106/html/IDCJDW4002.201106.shtml).

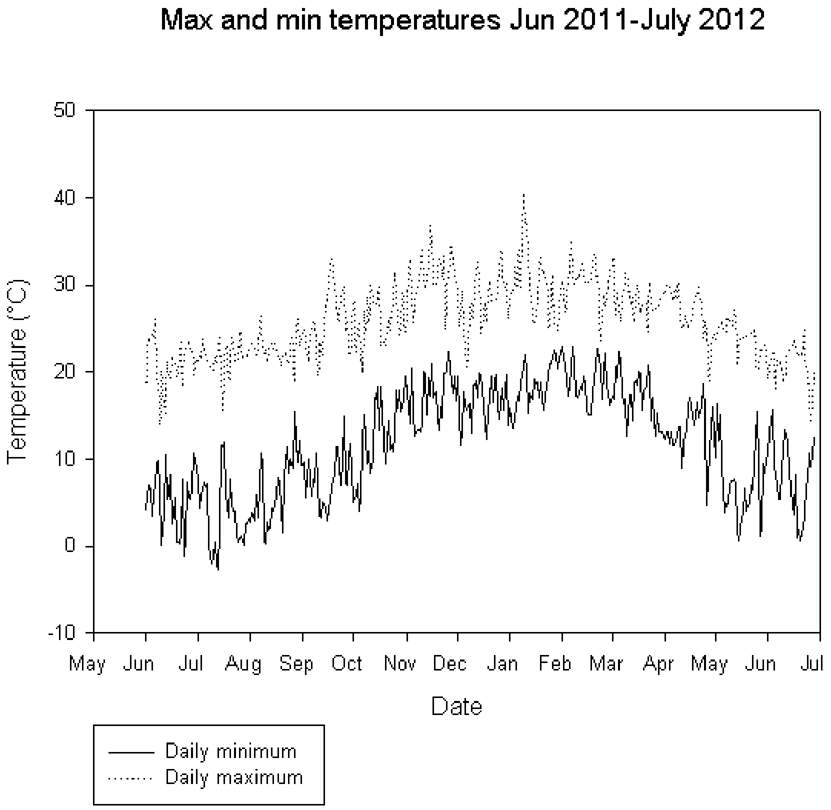

Figure A7.1: Maximum and minimum temperatures for the period June 1st 2011 to July 28th 2012

7.3. Biogas data

Table A7.4: Biogas data collected from the GA3000 and GA2000 landfill gas analysers

Date	**CH_4 (%)**	**CO_2 (%)**	**O_2 (%)**	**H_2S (ppm)**	**H_2S (%)**
3/11/2011	49.13%	19.67%	5.75%	699	0.07%
4/11/2011	47.42%	19.59%	6.07%	735	0.07%
5/11/2011	53.66%	22.62%	4.23%	941	0.09%
6/11/2011	52.11%	21.68%	4.55%	643	0.06%
7/11/2011	46.23%	18.91%	5.89%	403	0.04%
8/11/2011	50.93%	20.64%	4.11%	596	0.06%
18/11/2011	44.52%	19.23%	5.89%	561	0.06%
20/11/2011	37.39%	15.92%	7.53%	267	0.03%
22/11/2011	50.35%	22.05%	4.38%	911	0.09%
24/11/2011	57.67%	24.54%	2.68%	1365	0.14%
25/11/2011	71.66%	30.95%	2.92%	1921	0.19%
8/12/2011	55.72%	23.90%	3.16%	606	0.06%
9/12/2011	58.05%	25.32%	2.41%	1220	0.12%
13/12/2011	60.57%	25.44%	1.99%	603	0.06%
14/12/2011	63.02%	26.22%	1.46%	1024	0.10%
15/12/2011	61.59%	25.07%	1.73%	970	0.10%
16/12/2011	63.01%	25.06%	1.46%	852	0.09%
17/12/2011	66.62%	26.81%	0.79%	781	0.08%
18/12/2011	63.64%	26.00%	1.29%	690	0.07%
19/12/2011	59.09%	24.08%	1.94%	598	0.06%
20/12/2011	58.73%	24.04%	1.86%	781	0.08%
21/12/2011	60.35%	24.21%	1.64%	760	0.08%
22/12/2011	56.45%	22.82%	2.32%	665	0.07%
23/12/2011	59.82%	24.44%	1.65%	769	0.08%
24/12/2011	46.29%	19.84%	4.02%	654	0.07%
25/12/2011	49.08%	20.81%	3.44%	510	0.05%
26/12/2011	49.92%	21.30%	3.28%	569	0.06%
27/12/2011	51.78%	21.79%	3.01%	707	0.07%
28/12/2011	45.54%	18.46%	4.18%	503	0.05%
29/12/2011	48.44%	19.45%	3.72%	496	0.05%
30/12/2011	33.82%	13.85%	3.14%	238	0.02%
31/12/2011	52.48%	22.14%	2.85%	600	0.06%
1/01/2012	49.55%	21.61%	3.10%	491	0.05%
2/01/2012	50.49%	22.27%	2.88%	394	0.04%
3/01/2012	45.09%	19.34%	4.12%	291	0.03%
4/01/2012	45.72%	19.57%	3.96%	386	0.04%
5/01/2012	44.30%	18.88%	4.17%	449	0.04%
6/01/2012	46.29%	19.69%	3.76%	547	0.05%
7/01/2012	48.21%	20.76%	3.35%	779	0.08%
8/01/2012	45.03%	19.51%	3.86%	612	0.06%
9/01/2012	42.43%	17.93%	4.37%	524	0.05%
14/03/2012	53.00%*	18.90%*	4.00%*	55*	0.01%*
30/03/2012	42.30%*	6.20%*	1.60%*	260*	0.03%*
5/04/2012	55.00%*	13.50%*	2.80%*	131*	0.01%*

10/04/2012	72.10%*	22.20%*	1.30%*	260*	0.03%*
19/04/2012	71.60%*	27.70%*	0.00%*	260*	0.03%*
26/04/2012	69.00%*	28.00%*	0.00%*	90*	0.01%*
1/05/2012	72.30%*	26.90%*	0.00%*	212*	0.02%*
15/05/2012	72.10%*	24.90%*	0.00%*	169*	0.02%*

* indicates samples measured using the GA2000 landfill gas analyser

Table A7.5: SGS biogas analysis results

Component	**26/04/2012**	**1/05/2012**	**15/05/2012**
Methane (%)	59	62.1	60.5
Carbon dioxide (%)	39	36	34.7
Oxygen (%)	0.6	0.9	1.2
Ammonia (ppm)	0.6	0.1	0.5
Nitric oxide & nitrogen dioxide (ppm)	<0.5	<0.5	<0.5
Nitrous oxide (ppm)	<5	<5	<5
Volatile petroleum hydrocarbons (ppm)	2.9	5	4
BTEX (ppm)	80	105	45.9
Carbon monoxide (ppm)	<2	<2	<2
Hydrogen sulphide (ppm)	47	187	196
Sulphur dioxide (ppm)	<1	<1	<1
Acetic acid (ppm)	0.008	0.074	0.015
Propanoic acid (ppm)	<0.002	0.005	<0.002
i-butanoic acid (ppm)	<0.002	<0.002	<0.002
Butanoic acid (ppm)	<0.002	<0.002	<0.002
i-valeric acid (ppm)	<0.002	<0.002	<0.002
Valeric acid (ppm)	<0.002	<0.002	<0.002
i-capric acid (ppm)	<0.002	<0.002	<0.002
Capric acid (ppm)	<0.002	<0.002	<0.002
Total VFA (ppm)	0.01	0.01	0.01
Balance (nitrogen and argon (%)	1.4	1.4	3.6