OPERATION OF AN ACTIVATED SLUDGE PLANT FOR FELLMONGERY WASTEWATER TREATMENT

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ABSTRACT

Activated sludge is one of the most common wastewater-treatment processes used to reduce pollutant loads on the receiving environment. For efficient operation, there must be an effective process control and operation strategy in place to ensure that process problems are avoided. This research is a case study into the process control and operation of an activated sludge plant used for fellmongery wastewater treatment.

Analysis of the pretreated fellmongery wastewater showed that it is characterised by high total and volatile suspended solids concentrations, and high organic nitrogen concentrations. The plant was experiencing frequent problems that were attributed to the high influent suspended solids load coupled with ineffective solids management.

Operation of bench-scale simulations showed that solids retention time (SRT) control at 5 or 10 days will produce acceptable effluent suspended solids concentrations and soluble chemical oxygen demand (COD) removal. Soluble COD removal for both 5 and 10 days was high at 85 and 80 % respectively at a hydraulic retention time of 6.4 days. Effluent suspended solids concentrations were 100 and 157 g/m^3 respectively.

A steady state control model was developed based on, mass balances of biochemical oxygen demand (BOD) and volatile suspended solids (VSS), process performance equations, and the solids retention time (SRT). The model used three control points, the clarifier underflow pump, the clarifier influent pump and the waste sludge pump. The model was incorporated into an off-line Activated Sludge Operation Program (ASOP) to provide a user-friendly interface between the plant and operator. The main output from ASOP includes values for the three control points and suggestions to help avoid problems. A process control and operation strategy was developed using ASOP, the knowledge gained in this research, and an operation manual developed from accepted operation practises.

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Q	= Influent wastewater volume (m^3/d)
S_O	= Influent organic matter concentration (g CODor BOD/m^3)
S	= Effluent organic matter concentration (g CODor BOD/m^3)
X	= Activated sludge reactor biomass concentration (g VSS/m^3)
V	= Activated sludge reactor volume (m^3)
Q_W	= Waste activated sludge volume (m^3/d)
r_{su}	= Organic matter removal rate (g CODorBOD/m^3.d)
μ_m	= Maximum specific growth rate ($days^{-1}$)
K_S	= Half-velocity constant (g/m^3)
Y	= Biomass yield (g VSS/ g CODorBOD)
k_d	= Endogenous decay coefficient (day^{-1})
r_g	= Net biomass generation rate (g VSS/m^3.d)
F/M	= Food-to-microorganism ratio (g CODorBOD/g VSS.day)
HRT	= Hydraulic retention time (days)
X_V	= Mixed liquor volatile suspended solids concentration (g VSS/m^3)
E_S	= Organic matter removal efficiency (%)
R_S	= Organic matter removal rate (g CODorBOD/d)
WAS	= Waste activated sludge mass (kg TSS/d)
V	= Volume of the reactor (m^3)
$X_{CURRENT}$	= Current mixed liquor suspended solids concentration (g TSS/m^3)
X_{TARGET}	= Target mixed liquor suspended solids concentration (g TSS/m^3)
SMP_{nd}	= Non-degradable soluble microbial products
SRT	= Solids retention time (days)
Q	= Effluent flowrate (m^3/d)
G_{VSS}	= Net biomass generation rate (g VSS/d)
F	= Initial filter dry weight (g)
$(F+R_1)$	= Filter plus primary residue dry weight after evaporation at 105°C (g)
V_S	= Sample volume (ml)
$(F+R_2)$	= Dry weight of the filter and the residue left after ignition at 550°C (g)
SSV_{30}	= Settled sludge volume after 30 minutes (ml)
$MLSS_2$	= Mixed liquor suspended solids concentration in basin two (g TSS/m^3)
SVI	= Sludge volume index (ml/g TSS)
BOD_t	= Biochemical oxygen demand for time t (g BOD/m^3)
t	= Time (days)
COD	= Chemical oxygen demand (g COD/m^3)

1 INTRODUCTION

1.1 BACKGROUND

The main task of a fellmongery is to process raw animal skins from local slaughterhouses to produce preserved pelts, which are sold to local and offshore tanneries for making leather. The fellmongery process also produces significant quantities of high strength wastewater that is usually pretreated and then discharged to a local sewer. This study is concerned with optimising the operation of the Richmond fellmongery (Shannon) activated sludge plant.

The activated sludge process is a continuous system that involves a mixed population of microorganisms that remove pollutants from a wastewater solution for growth and other cellular processes. Activated sludge is difficult to control in reality because there are many parameters that influence process performance and effluent quality, which is a reflection of it being a biological process. Control and operation of activated sludge also depends on the type of wastewater and its relative biodegradability. Therefore, unless the operator understands how a particular activated sludge plant performs under different conditions, the process may periodically fail.

Figure 1.1 is a schematic representation of the Richmond activated sludge plant. The function of this plant is to reduce the organic and solid loadings of the pretreated fellmongery wastewater in order to meet the effluent-quality limits listed in Table 1.1. These levels were set by the fellmongery as performance targets to ensure that the effluent is well below the related resource-consent limits.

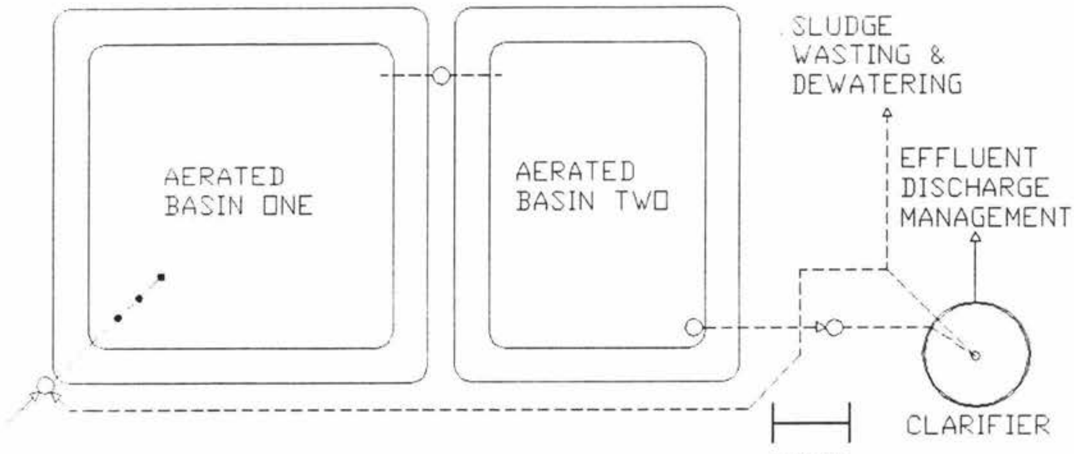


Figure 1.1: The fellmongery activated sludge plant (scale bar = 8.6 m).

Characteristic		Target (kg/d)
Biochemical oxygen demand	BOD	450
Total suspended solids	TSS	900
Ammonia	Ammonia	540

Table 1.1: Effluent quality targets for total suspended solids, biochemical oxygen demand and ammonia.

The effluent quality targets (except BOD) are frequently exceeded due to process problems that often lead to poor effluent quality. These process problems were attributed to an inadequate process control and operation strategy and large variations in the pretreated fellmongery wastewater-characteristics.

1.2 PRIMARY AIM

The primary aim of this project was to characterise the pretreated fellmongery wastewater and provide the fellmongery with a refined process control and operation strategy for their activated sludge plant.

1.3 THE PROJECT TASKS

1.3.1 Task 1: Characterise the fellmongery wastewater and diagnose observed process problems in the activated sludge plant

Task 1 was based on the first objective to obtain data on particular wastewater characteristics and diagnose process problems with possible solutions. The wastewater characteristics measured were those that were known to be important for successful activated-sludge operation.

1.3.2 Task 2: Evaluate solids retention time control (SRT) using bench-scale simulations

The objective of this task was to use bench-scale simulations of the fellmongery activated-sludge plant, to obtain data on Solids Retention Time (SRT) control. SRT was chosen as the central control parameter due to its current popularity and relationship to microbial growth rate.

1.3.3 Task 3: Develop a steady-state mathematical model of the activated-sludge plant

The objective of task 3 was to generate a simple mathematical model for describing the biochemical and physical operations occurring in the fellmongery activated-sludge plant. During development, the critical process-control points were identified and included in the model.

1.3.4 Task 4: Develop a new process-control and operation strategy

The objective of task 4 was to construct and refine the new process-control and operation strategy using results from tasks 1, 2 and 3. The strategy was to be embodied in a user-friendly computer program.

1.4 THE FELLMONGERY PROCESS

1.4.1 Introduction

The Richmond fellmongery (Shannon) processes sheep and lamb-skins, to produce preserved pelts and wool for local and offshore tanneries and garment manufacturers. A basic block diagram of the fellmongery process is shown in Figure 1.2. In New Zealand, the fellmongery process usually stands alone from the tannery, which is a carryover from the days when New Zealand was a major player in exporting associated meat products (Ryder, 1976). In 1976, New Zealand was ranked as the third largest producer of fellmongered pelts in the world (Aloy *et al,* 1976). More recently, New Zealand ranks second and produces 30 % of the world's garment leather material.

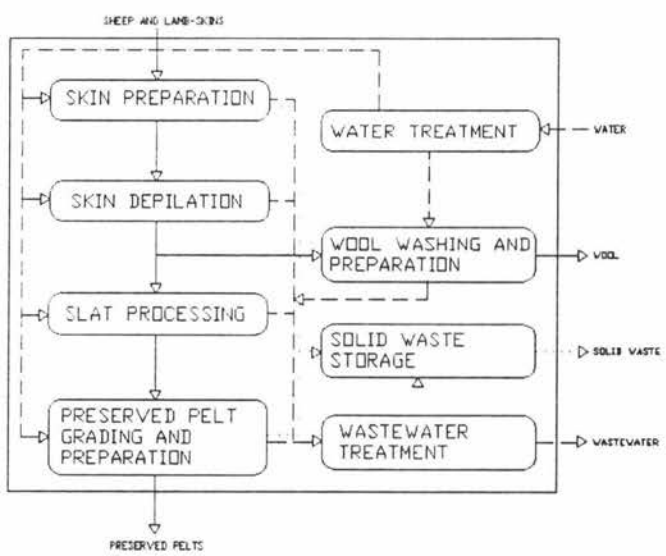


Figure 1.2: A block diagram of the fellmongery process showing flows of water, wastewater and solid waste.

1.4.2 The Animal Skin

In general, an animal skin can be divided into three main parts: the epidermis, the dermis, and the flesh layer as shown schematically in Figure 1.3.

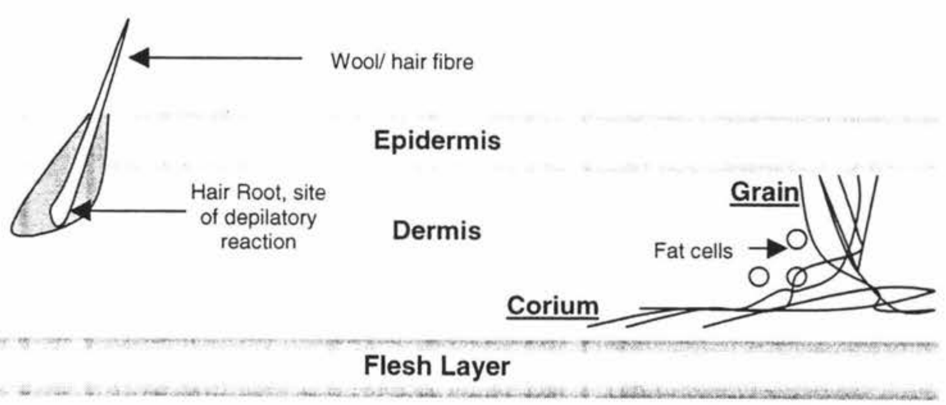


Figure 1.3: A simple diagram illustrating the general parts of a typical animal skin.

1.4.3 Skin Preparation

The aim of Skin Preparation is remove the flesh layer and excess fluid from the skin so as to expose the corium side of the dermis. Flesh and related solids are discarded to solid waste. Wastewater consisting of blood, fat and salt is generated.

1.4.4 Skin Depilation

Skin Depilation involves application of the depilatory paint to the exposed corium. This removes wool and hair at the root and exposes the epidermis. The depilatory paint is made from sodium sulphide (Na_2S, depilatory agent), caustic soda (NaOH, for alkalinity) and hydrated lime ($Ca(OH)_2$, a thickener). Wasted paint is drained away and directed to wastewater treatment along with the wastewater from Skin Preparation.

1.4.5 Wool Washing and Preparation

Wool recovered from Skin Depilation is sorted and taken by trolley to the wool washer. The wastewater generated is pretreated to remove excess wool and gross solids and then mixed with the wastewater from the previous unit processes. Washed wool is fed to the Wool Drier, which uses dry air to remove excess moisture from the wool. The dried wool is stored in lots and graded before it is packed for export.

1.4.6 Slat Processing

The skins now referred to as slats (skins minus wool) enter the Slat Processing stage. The "slat processors", usually referred to on the fellmongery-floor as the "challenge cooks" are huge rotating drums that process up to 7.5 tonnes of slats in one setting (cf. concrete mixer). The slats are processed in these rotating drums for eight hours to remove the epidermis and extraneous matter to expose the grain side of the dermis. The grain is the most important part of the skin because it will provide the sheen to a high-grade leather product. The slat processors are operated in three main steps.

1.4.6.1 Step 1: Liming

The first step is referred to as liming, because the original agent used was lime ($Ca(OH)_2$). The liming step involves dosing a load of slats with a sodium sulphide/water float for up to three hours to remove persistent wool fibres and pulp hair from the grain. The sodium sulphide/water float recipe for liming will depend on the slat type (sheep or lamb), and may change in response to poor depilation. After liming is complete, the processor is pumped down and washed out several times with water to remove the used liming liquors.

Collagen is a fibrous protein that occurs in long threads, it is water insoluble and it is the main constituent of the fibres that make up the dermis layer. During slat processing the skin "opens up" because the collagen fibres absorb water to "plump" or "swell" in the alkaline medium (Carrie *et al*, 1960). Mucins are non-fibrous proteins and form the interfibrillary tissue filling the spaces in the network of collagen fibres (Carrie *et al*, 1960). Mucins are insoluble in water and will swell; liming will dissolve them however so they can be removed in the wastewater (Carrie *et al*, 1960).

1.4.6.2 Step 2: Delime

Once the lime washouts are completed, deliming commences to remove persistent sulphide and residue from the processor and reduce the alkalinity. Delime uses carbon dioxide as a neutralising agent. CO_2 dissolves in water to form a carbonic acid (HCO_3^-) buffer solution that stabilises the pH at around 8-9 units. During deliming significant amounts of hydrogen sulphide evolves as the pH is reduced. Hydrogen peroxide (H_2O_2) is added intermittently as a counter agent to oxidise the H_2S and reduce risk.

1.4.6.3 Step 3: Bating

The third step called bating uses pancreatic enzymes to open the fibre structure of the pelt so that the grain is fully cleansed of detritus (Massey University Dept. of Biotechnology, 1976). Bating will only succeed if the delime step manages to stabilise the pH to between 8 and 9 (Carrie *et al*, 1960).

1.4.6.4 Step 4: Pickling

The pelts are finally subjected to the pickle step, which involves addition of sulphuric acid and salt. The acidic/ saline medium does not support microorganisms so the pickling step produces a pelt resistant to biological degradation and ready for the tannery. However, the mould *Alternaria tenuis* can find a pickled pelt nourishing, and is recognised as a dark-green almost black mould (Massey University Dept. of Biotechnology, 1976). Busan is added during this step as a fungicide to protect the pickled pelt from fungal degradation (Massey University Dept. of Biotechnology, 1976). The pickled pelts are unloaded from the processors into the pickle troughs. Once in the troughs, the pickled pelts are allowed to soak in the pickle until the pelt-graders are ready.

1.4.7 Preserved Pelt Grading and Preparation

The pickled (preserved pelts) are removed from the trough by hand, and the pickle is drained to wastewater treatment. Pickled pelts are graded according to the quality of the grain and the amount of residual wool. The graded pelts are pressed to squeeze out excess fluid and reduce volume for export. This is another source of wastewater especially when the grading floor is washed down with fresh water. Finally, the preserved pelts are heat packed ready for export.

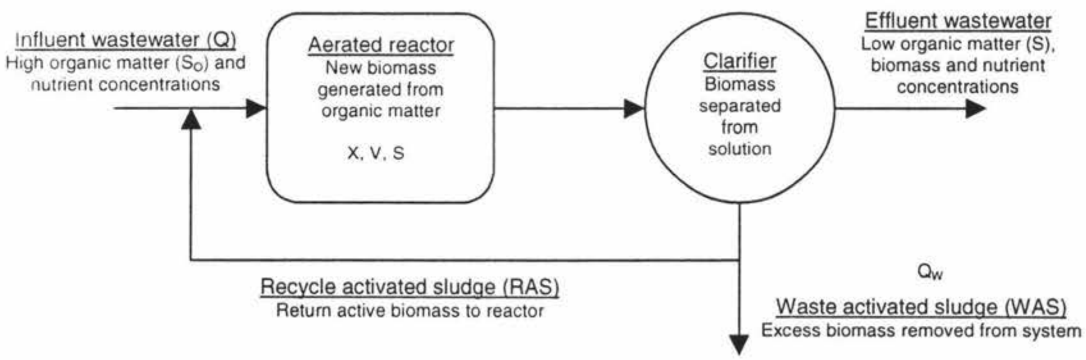
2 LITERATURE REVIEW

2.1 THE ACTIVATED SLUDGE PROCESS

2.1.1 Introduction

Activated sludge is the most common biological treatment method used to meet the stringent effluent quality standards imposed in industrial and municipal situations (Orhon *et al*, 1999). It was developed in England in 1914 by Arden and Lockett, and was termed "activated" because it involved the production of an active mass of microorganisms in an aerobic solution (Metcalf *et al*, 1993).

The basic activated sludge process involves an aerated reactor followed by a clarifier, as shown schematically in Figure 2.1.



Q = Influent volume (m^3/d)
S_O = Influent organic matter concentration (g CODorBOD/m^3)
S = Effluent organic matter concentration (g CODorBOD/m^3)
X = Reactor biomass concentration (g VSS/m^3)
V = Reactor volume (m^3)
Q_W = Waste biomass volume (g VSS/m^3)

Figure 2.1: A block diagram of the basic activated sludge system describing the basic function of each component.

2.1.2 The Activated Sludge Reactor

Removal of nutrients and organic matter from the influent wastewater solution occurs in the reactor (Metcalf *et al*, 1993). A mixed-culture of bacteria is continuously re-circulated through the reactor to remove soluble nutrients and organic pollutants from the wastewater solution. The reactor may be maintained in alternate aerobic, anoxic or anaerobic conditions. The original system was solely aerobic for the removal of organic pollutants. Modern systems may employ anoxic and/ or anaerobic reactors in what are generally referred to as biological nutrient removal (BNR) systems (Cloete *et al*, 1999). Different reactor types may be used such as plug-flow and completely-mixed depending on the situation and the reaction kinetics (Metcalf *et al*, 1993).

2.1.3 The Activated Sludge Microbial Floc

When the activated sludge reactor is aerated, bacterial flocs will form (Cloete *et al*, 1981). The activated sludge flocs are the central part of all the processes in activated sludge that successfully remove nutrients from the wastewater (Cloete *et al*, 1981). The aerobic floc consists of a biological fraction and a non-biological fraction (Jenkins *et al*, 1993).

The biological fraction contains a mixed population of heterotrophic[1] bacteria, fungi, protozoa and metazoa and a small amount of autotrophic[2] bacteria, which metabolise nutrients from the wastewater solution (Jenkins *et al*, 1993 and Henze *et al*, 1986). The non-biological fraction contains particulate inorganic and organic chemicals accumulated from the wastewater or by-products from microbial metabolism (Jenkins *et al*, 1993).

2.1.4 Microbial Metabolism

The underlying process in activated sludge flocs (and bacteria not attached to flocs) that removes chemicals and nutrients from the wastewater is microbial metabolism. Microbial metabolism liberates chemical energy bound up in chemical compounds and directs this energy to intra-cellular processes such as biosynthesis, maintenance and motility (Cloete *et al*, 1999). Two main processes make up microbial metabolism, catabolism and anabolism (Brock *et al*, 1984). These processes are coupled together by a flow of energy in an electron transport system as shown in Figure 2.2.

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[1] Heterotroph: a microorganism that requires organic compounds as a source of carbon.
[2] Autotroph: a microorganism that uses carbon dioxide as its sole source of carbon.

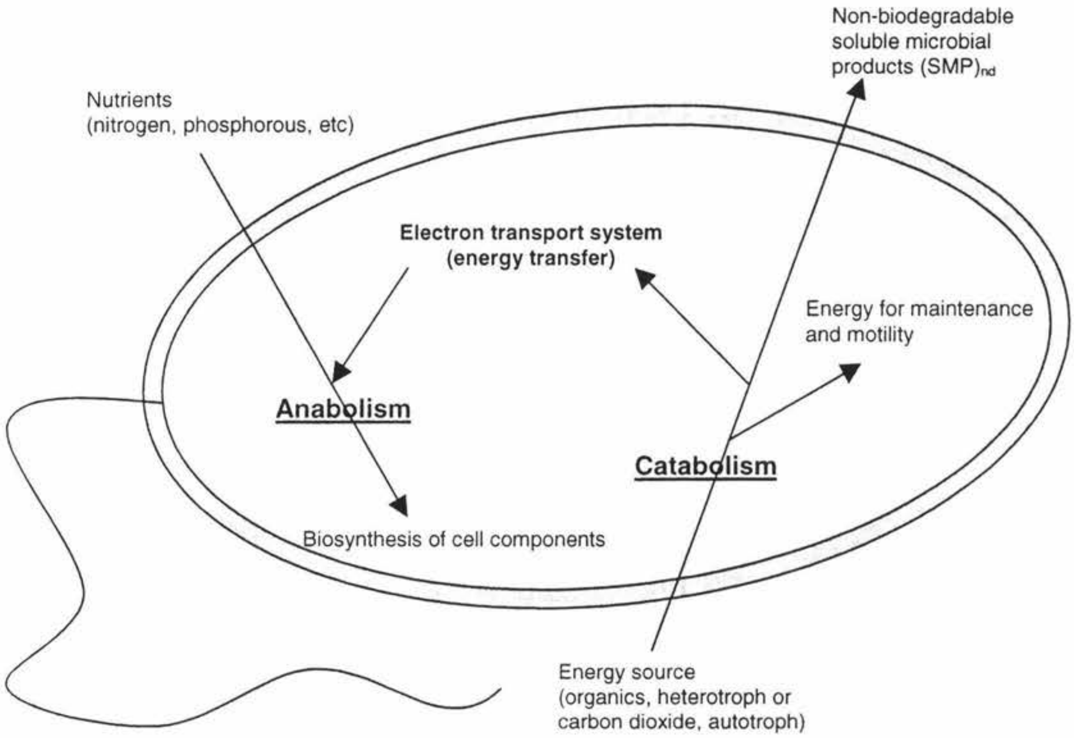

Figure 2.2: A simplified view of microbial metabolism in a bacterial cell (re-drawn from Brock *et al*, 1984).

During catabolism, soluble readily biodegradable pollutants found in the wastewater are broken down inside the cell to release the chemically bound energy (Brock *et al*, 1984). The biodegradable pollutant becomes a primary electron donor in the electron transport system. Energy release and transfer begins as the electron donor goes through a series of enzymatic oxidation-reduction (O-R) reactions (Pelczar *et al*, 1993). Each O-R reaction releases energy, which is used to generate high-energy storage compounds such as adenosine triphosphate (ATP) (Pelczar *et al*, 1993).

The terminal electron acceptor terminates the O-R reactions of the electron transport system and produces water (H_20). If the terminal electron acceptor is molecular oxygen (O_2), the overall process is termed aerobic respiration (Pelczar *et al*, 1993). During anoxic respiration, NO_3^- and SO_4^{2-} replace O_2 as the terminal electron acceptors. Anaerobic microorganisms use internally balanced O-R reactions in a process called fermentation, which does not require an external electron acceptor. The fermentation process is maintained in an anaerobic reactor of a BNR system.

Aerobic respiration is capable of releasing more energy (in the form of ATP) than anoxic respiration or fermentation because the O-R reactions of the electron transport system chemically reduce the electron donor far more effectively. Thus biosynthesis under aerobic respiration is comparatively rapid and proportionally more significant in order to consume the available energy (ATP). Equation 2.1 and Equation 2.2 show the overall aerobic respiration reactions (heterotrophic) with reference to the microbial cell (Figure 2.2).

$$\text{organics} + O_2 + N + P + \text{biomass} \rightarrow \text{new biomass} + H_2O + SMP_{nd}$$

SMP_{nd} = Non-degradable soluble microbial products

Equation 2.1: Removal of nutrients and organics from the wastewater solution to generate new biomass in an aerobic reactor (Eckenfelder *et al*, 1995).

$$\text{biomass} + O_2 \rightarrow CO_2 + H_2O + N + P + \text{nondegradable cellular residue} + SMP_{nd}$$

Equation 2.2: Oxidation of biomass in an aerobic reactor (Eckenfelder *et al*, 1995).

This is a simple overview of microbial metabolism, the O-R reactions themselves are very complex. The success of microbial metabolism and indeed the metabolism pathways used in the activated sludge floc depends on the wastewater characteristics, the floc size and morphology and environmental conditions such as dissolved oxygen concentration and pH.

2.1.5 Biomass Generation and Substrate Removal

Many different mathematical relationships have been presented to describe the overall process of substrate removal and consequent biomass generation which occur as a result of microbial metabolism. Henze *et al* (1986) presented the Activated Sludge Model No.1, which incorporates complex rate equations and dynamic mass balances to describe the biochemical reactions in activated-sludge. However, a simple expression for the overall rate of substrate removal can be used, and is based on the Monod formula for biochemical removal of a single substrate, shown as Equation 2.3.

$$r_{SU} = -\frac{\mu_m XS}{Y(K_S + S)}$$

r_{su} = the substrate removal rate ($g/m^3/d$)
μ_m = maximum specific growth rate ($days^{-1}$)
K_S = half-velocity constant (g/m^3)
Y = maximum biomass yield (g VSS/g CODorBOD)
X = the reactor biomasss concentration (g/m^3)
S = the effluent substrate concentration (g/m^3)

Equation 2.3: The substrate removal rate for the basic activated sludge system.

The rate of substrate removal is related to the net biomass generation rate by Equation 2.4 (Metcalf *et al*, 1993).

$$r_g = -Yr_{su} - k_d X$$

k_d = endogenous decay coefficient (day^{-1})
r_g = the net biomass generation rate ($g/m^3/d$)

Equation 2.4: The relationship between biomass generation and substrate removal for the basic activated sludge system.

Equation 2.4 also shows that a portion of the substrate energy is used for microbial processes (generally referred to as maintenance) other than anabolism (biomass generation). Thus, the observed biomass yield is given by Equation 2.5.

$$Y_O = -\frac{r_{su}}{r_g}$$

Equation 2.5: The observed biomass yield.

2.1.6 The Clarifier

The primary function of the clarifier is to separate the Mixed Liquor Suspended Solids, MLSS (the activated sludge flocs plus any other suspended solids from the reactor), from the wastewater suspension (Metcalf *et al*, 1993). Efficient separation of the MLSS from the supernatant is crucial in an activated sludge system, because the performance of the system depends on the return of active bacterial flocs to the reactor (Hasselblad *et al*, 1998). The effluent quality is also dependent on efficient clarification of the supernatant.

2.2 CHARACTERISTICS OF FELLMONGERY WASTEWATER

The majority of the wastewater volume from a fellmongery process is produced during the liming-step of the slat-processing stage (M^{c}Farlane, 1979 and O'Donnell, 1995). Wastewater from this stage is strongly alkaline and contains sulphide, bisulphide, dissolved albumin, mucoids, mucopolysaccharides, keratin, dissolved and emulsified fats and insoluble organic and inorganic compounds (M^{c}Farlane, 1979). The older style process contained significant amounts of calcium carbonate (lime), hence the term liming (Massey University Dept. of Biotechnology, 1976).

Deliming and bating produce a relatively moderate volume of slightly alkaline medium strength wastewater (Ryder, 1973). This effluent contains sodium sulphite (Na_2SO_3) and organic acids, the older style process would have contained significant amounts of ammonia because the delime-agent was often ammonium chloride (Ryder, 1973).

Table 2.1 summarises the important data extracted from fellmongery and tannery-wastewater characterisation studies for comparison. The variability of wastewater characteristics between the different sources shows that fellmongery and related wastewaters are unique to the specific situation. These differences are due to process improvements and new chemical agents that have changed the fellmongery process in recent times.

Wastewater Characteristic	Units	O'Donnell (1995) Fellmongery	Cooper (1987) Fellmongery	Orhon (1999) Tannery	Rawlings (1976) Fellmongery
CBOD	g/m³	2052	-	-	-
CBOD (soluble)	g/m³	1300	-	-	-
COD	g/m³	8900	2255	6622	13560
COD (soluble)	g/m³	2502	1298	5622	11610
TKN	g/m³	887	214	1000	-
TKN (soluble)	g/m³	-	180	902	-
NH_3-N	g/m³	27	164	366	-
Total Phosphorous	g/m³	-	-	-	-
Grease	g/m³	679	-	252	-
Sulphide	g/m³	30	37	244	700
TSS	g/m³	3686	768	2059	3210
VSS	g/m³	-	467	-	1760

Table 2.1: Fellmongery and tannery wastewater characteristics from several sources.

2.2.1 Organic Matter

The chemical oxygen demand (COD) is used to estimate the total oxygen demand of organic matter in a wastewater solution. The carbonaceous biochemical oxygen demand (CBOD) is used to estimate the total amount of oxygen required to biochemically remove the organic matter from the wastewater solution within 5 days. Neither method directly measures the concentration of organic matter in the wastewater solution, as the fraction is too complex.

O'Donnell (1995) characterised the wastewater from the fellmongery slat-processors as a function of the processing step. Figure 2.3 was drawn from the data provided by that study. A rather unusual observation in the O'Donnell (1995) study is that the soluble COD discharged is less than the soluble BOD. Theoretically, this is incorrect, as compounds that are chemically oxidisable are not always biodegradable. No discussion on methodology or data analysis was included in this study so it is difficult to fully ascertain why this was the case.

On average the total BOD to COD ratio was 0.23 (Table 2.1). Metcalf *et al* (1991) suggested a typical BOD to COD ratio for domestic sewage will be within 0.4 to 0.8. So by comparison, the fellmongery wastewater is not very biodegradable.

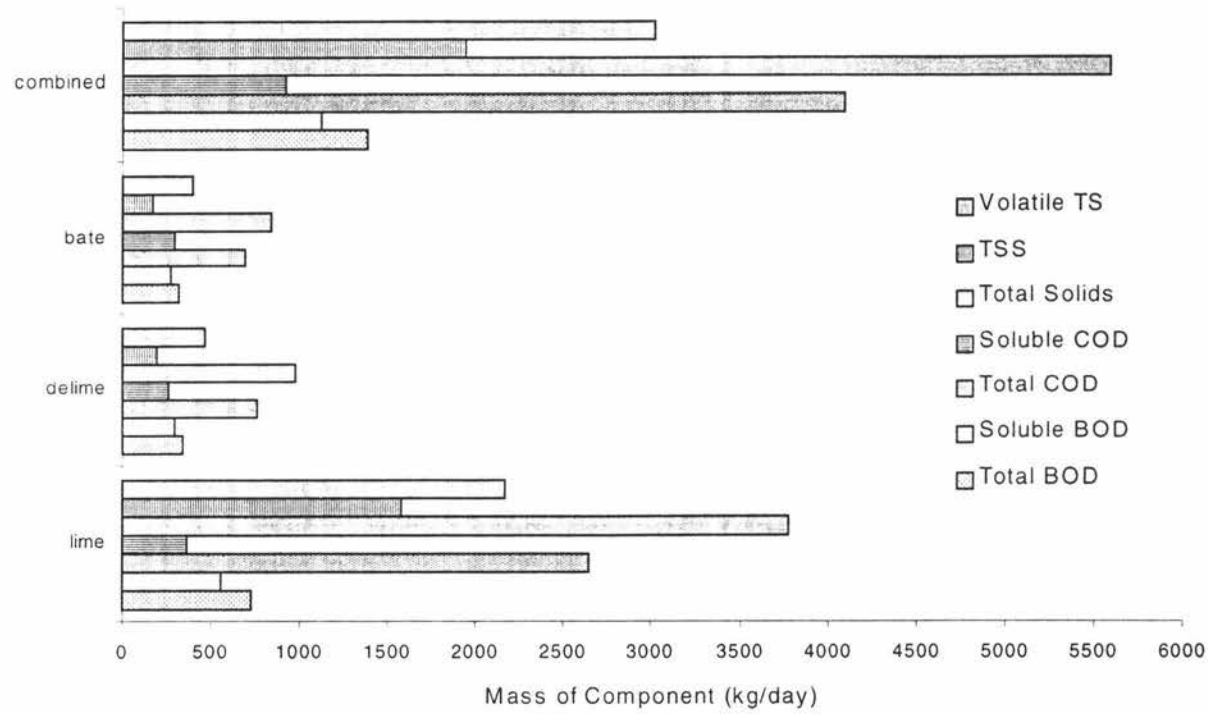

Figure 2.3: Masses of specific wastewater components produced from each step of the slat processing stage for the fellmongery. (Drawn from data provided by O'Donnell, 1995).

The fellmongery wastewater has a total COD concentration of approximately 8900 g/m³ (O'Donnell, 1995) making it a high strength wastewater. Almost 37 % (4000 kg/d) of the total COD in fellmongery wastewater is produced during the liming-step, according to data from O'Donnell (1995). A study comparing two different slat-processing methods also concluded that a significant amount of the total COD in fellmongery wastewater came from the liming-step (Cooper *et al*, 1982). Yet, from the O'Donnell (1995) data the BOD to COD ratio was 0.38 for this step. Thus, the liming-step produces an extremely high amount of organic matter that may not be suitable for the activated sludge plant, ie. it may not be readily or slowly biodegradable.

2.2.2 Suspended Solids

The mass of suspended solids (SS) in the combined wastewater of the slat- processing stage is extremely high, with an average of 3000 kg/d discharged (O'Donnell, 1995). The liming-step produces over 66 % of this amount alone (according to data from O'Donnell, 1995), which explains why the total COD mass is so large from this stage.

There is no primary suspended solids removal included in the pretreatment operation so most of the solids load is discharged directly to the activated sludge process. In most situations, primary sedimentation would be used to reduce the mass of suspended solids in the raw wastewater because they may not be readily biodegradable (Jenkins *et al*, 1993). Orhon *et al* (1999) measured an average TSS concentration of 2026 g/m³ for raw tannery wastewater and 853 g/m³ for primary settled tannery wastewater in Istanbul. O'Donnell (1995) suggests an average TSS concentration of approximately 3686 g/m³ for the fellmongery wastewater.

Russell (1980) presented a least squares relationship (Equation 2.6) for the fellmongery wastewater total COD with the fat and organic nitrogen concentrations.

$$COD = 106 + 3 * FAT + 9 * (TKN - Ammonia)$$

COD	= The chemical oxygen demand (g/m³)
FAT	= The fat concentration (g/m³)
TKN	= The total kjeldahl nitrogen concentration (g/m³)
Ammonia	= The ammonia concentration (g/m³)

Equation 2.6: Proposed relationship between total COD, fat, TKN and ammonia concentrations for fellmongery wastewater (Russell, 1980).

A regression coefficient of 98% was achieved for predicting the total COD from the fat and organic nitrogen concentrations. Russell (1980) concluded that the total COD is dependent on both the concentration of fat and organically bound nitrogen in the fellmongery wastewater.

2.2.3 Nitrogen

The total kjeldahl nitrogen (TKN) is used is estimate the total concentration of organic nitrogen in the wastewater solution. The TKN at each step of the slat-processing stage is far higher than the ammonia (NH_3-N) as shown in Figure 2.4. In the combined wastewater, the TKN-mass produced 450 kg/d (200 g/m³) in comparison the ammonia is only 20 kg/d (7 g/m³). This difference can only be due to the significant concentration of organically bound nitrogen in the wastewater. Such a trend should occur if the slat process is performing well, because all the collagen, protein, keratin and other detritus is supposed to be washed out of the system during the liming-step and the initial part of the delime-step.

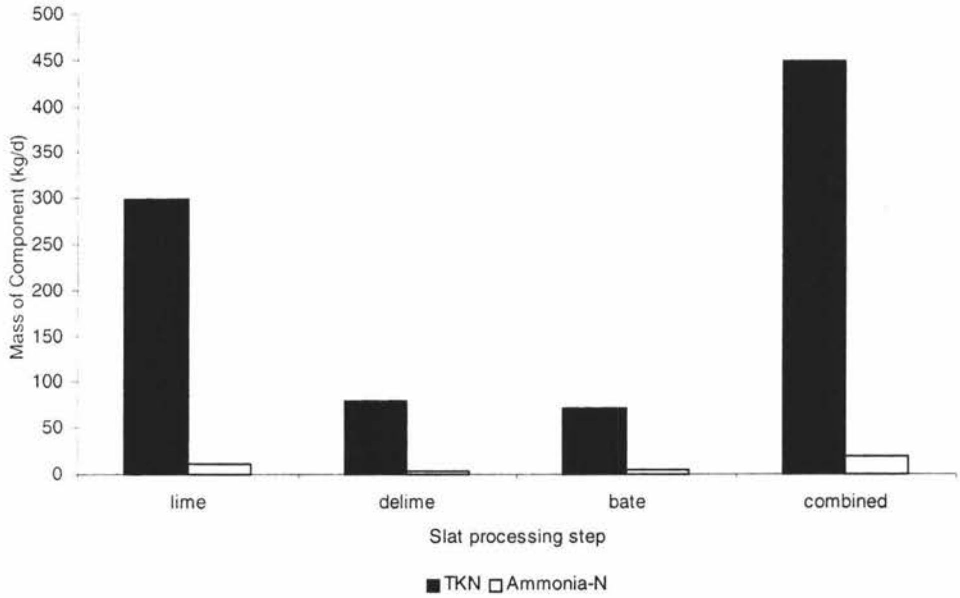

Figure 2.4: Masses of TKN and ammonia (NH_3-N) discharged from each step in the slat-processing stage (drawn from data provided by O'Donnell, 1995).

Process changes during the last 5 years at the fellmongery have seen the elimination of ammonium chloride use in the delime-step, which is another reason why there is little ammonia produced in the O'Donnell (1995) study.

2.2.4 Grease and Sulphide

The grease and fat concentration of pretreated fellmongery wastewater is significant and is approximately 679 g/m³ or 817 kg/d (O'Donnell, 1995) which is mainly sourced from the slat-processing stage. Approximately 90% of the total mass of grease produced from the slat-processing stage is generated during the liming-step (according to data from O'Donnell, 1995).

The combined mass flow of sulphide is approximately 200 kg/day (

Figure 2.5). The fellmongery wastewater pretreatment-plant (see section 2.3.2) is designed to reduce this loading prior to the activated sludge plant, therefore sulphide is not of primary concern in this project.

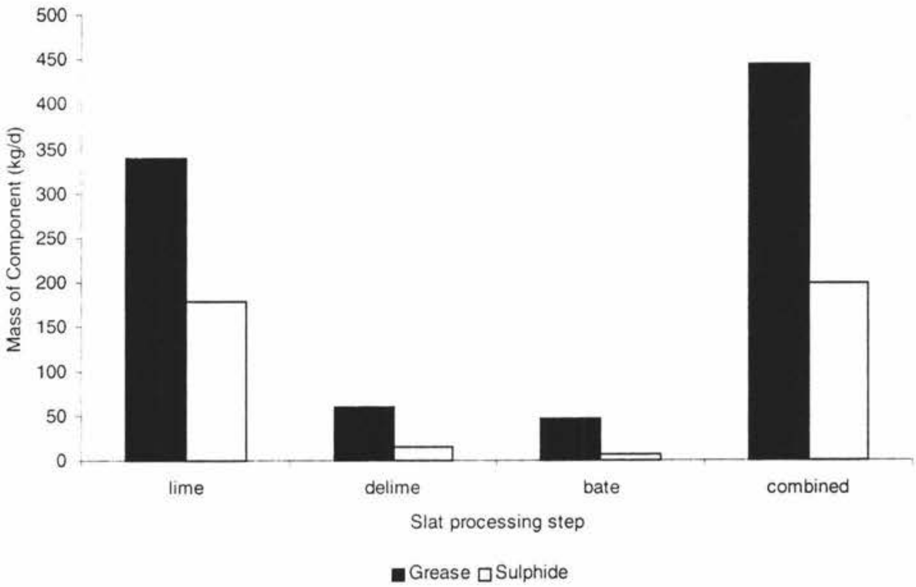

Figure 2.5: Masses of sulphide and grease produced from each step of the slat processing stage (Drawn from data provided by O'Donnell, 1995).

2.2.5 Phosphorous

Neither Cooper (1982) nor O'Donnell (1995) considered the phosphorous concentration of the fellmongery wastewater, possibly because the component is not present in significant quantities. However, Orhon *et al* (1999) reported that the total phosphorous concentration of tannery wastewater is about 1.8-11.5 g/m³.

Orhon *et al* (1999) concluded that the tannery wastewater was phosphorous limited with a COD:N:P ratio of approximately 100:9.3:0.3. Eckenfelder *et al* (1995) suggested that this ratio be maintained at 100:5:1. Nutrient deficiencies can lead to process failure if the BOD:N:P ratio is not checked regularly (Metcalf *et al*, 1993 and Jenkins *et al*, 1993). From this point of view, there is sufficient nitrogen in proportion to BOD, but not enough phosphorous for the Istanbul wastewater. From data presented by O'Donnell (1995) on the fellmongery wastewater, the BOD:N ratio is 100:43 implying that there is more than enough nitrogen.

Rawlings *et al* (1987) said that beamhouse (a fellmongery processing cattle hides) wastewater they studied had sufficient nutrients for balanced growth. Their argument was based on a few arbitary determinations of the nitrogen and phosphorous balances indicating an average

COD:N:P ratio of 100:4.2:0.2. According to the suggested proportions discussed earlier, the beamhouse wastewater appears to contain insufficient nitrogen and phosphorous to sustain balanced microbial growth.

2.3 PRETREATMENT OF FELLMONGERY WASTEWATER

2.3.1 Introduction

Wastewater pretreatment is designed to remove or reduce any wastewater characteristics that are not compatible with optimal performance of the activated sludge process (Ekenfelder *et al*, 1995). Fellmongery wastewater is usually pretreated to remove sulphide, grease and fatty material because these characteristics are known to reduce activated-sludge performance. If a tannery process discharges wastewater on the same site as the fellmongery then pretreatment to remove chromium is also required.

2.3.2 Sulphide removal

The sulphide-rich wastewater streams are reacted in sulphide oxidation tanks. The contents are continuously aerated for 8 hours with a Manganese sulphate ($MnSO_4$) catalyst. The suggested concentration of Mn^{2+} is 50-100 g/m³ (Hayward, 1990). The aeration period should last at least 5-10 hours at pH 10-12 (Hayward, 1990). Optimisation is required to meet the effluent quality target.

Other methods of sulphide removal include (Hayward, 1990):

1. Precipitation with ferrous or ferric salts with addition of lime. The sulphide sludge is settled and removed.
2. Acidification to pH 2-3 and aeration, with adsorption of the resultant hydrogen sulphide gas in caustic soda solution within packed tower scrubbers.
3. Addition of chlorine to form sulphate and chloride ions. At least 9 kg Cl_2/kgS^{2-} is required to avoid generating colloidal sulphur.
4. Hydrogen peroxide dosing, with sulphate being the end product when the reaction is carried out in alkaline conditions. Requires at least 8 kg H_20_2/kgS^{2-}.

Sulphide concentrations of around 50-200 g/m3 can be tolerated in biological plants following a period of acclimatisation (Hayward, 1990). Higher concentratins become problematic as they can reduce sludge quality (Hayward, 1990).

The treatment of chrome tannery wastewaters in Italy usually consists of physio-chemical pretreatment followed by biological treatment (Genschow *et al*, 1996). During pretreatment ferrous salts are added to induce flocculation and settling of the colloidal solids and removal of sulphides (Genschow *et al*, 1996). Aluminium or iron salts may be added if the wastewater has previously been treated to remove sulphide (Genschow *et al*, 1996).

A Slovenian tannery use a physio-chemical pre-treatment system that includes aluminium sulphate with anionic polyelectrolyte flocculation and coagulation (Ros *et al*, 1998). Pretreatment of the raw wastewater removes about 60 % of the total COD and over 95 % of the sulphide and chromium (Ros *et al*, 1998).

One extremely interesting comment made during the Rawlings (1987) investigation was sulphide pretreatment might not be required. An observation recorded that the sulphide concentration within the activated-sludge reactor was always zero, even when the influent sulphide concentration was 937 g/m^3 (Rawlings, 1987). This indicated to Rawlings (1987) and his colleagues that pre-aeration to remove sulphide is not essential if there is sufficient aeration capacity in the completely mixed reactor to both oxidise the sulphide and provide for substrate removal.

2.3.3 Gross Solids Removal

Fellmongery wastewater contains significant quantities of suspended solids and colloidal matter as discussed in section 2.2. In most overseas tanneries the suspended solids are removed prior to biological treatment processes using chemical settling pretreatment operations which are successful in removing sulphide and chromium simultaneously (Orhon *et al*, 1999). If suspended solids are present in the wastewater the active biomass fraction in the floc will be reduced which will make the sludge difficult to thicken and de-water (Ekenfelder *et al*, 1995).

2.3.4 Grease and Fat removal

Grease, fat and other small floatables are removed to a certain extent using dispersed air flotation tanks. Grease, fat and related organic compounds float on the reactor surface and reduce aeration efficiency and thus the activated sludge flocs become deprived of oxygen.

These pretreatment processes generate substantial quantities of sludges that need to be dewatered and disposed. Szpyrkowicz *et al* (1991) looked at the possibility of treating fellmongery wastewater without pretreatment using a single-sludge nitrification/denitrification process. The objective was to reduce sludge production. The lack of pretreatment did not appear to cause any reduction in treatment efficiency during biological oxidation. In fact, nitrogen and COD removals increased, and the final effluent quality was improved. This study used a pilot plant simulation of a full-scale plant. It was fed with the same wastewater, which arrived at the full-scale treatment plant. The pilot plant was run for 6 months in which four runs were carried out. Runs 2 and 4 were fed with wastewater that was characterised by a high contribution of lime wastewater. Whilst runs 1 and 3 were low in lime wastewater. Each run lasted for 25-30 days and no mention of steady state operation was included.

2.4 CONTROL METHODS FOR THE ACTIVATED SLUDGE PROCESS

2.4.1 Introduction

To produce effluent quality that is acceptable it is necessary to incorporate an operation-strategy with an effective control objective (Corder *et al*, 1986 and Busby *et al*, 1975). The control objective for an activated-sludge plant is simply:

"Control the biomass generation and substrate removal rates using a suitable control parameter in order to reduce organically bound energy in the effluent to a level where it can no longer sustain heterotrophic growth in the receiving environment, and reduce nutrient concentration of the effluent, which in turn reduces the capacity of the receiving environment to sustain autotrophic growth". (Marais *et al*, 1976).

The control objective outlined above is achieved by manipulating a control parameter, and this is usually actioned at one or more of the critical-control points in an activated-sludge plant (WPCF, 1987). The critical-control points in most activated-sludge plants are:

1. The return sludge point (return activated sludge (RAS) control),
2. The waste sludge point (waste activated sludge (WAS) control),
3. The aeration rate (dissolved oxygen (DO) and oxygen uptake rate (OUR) control),
4. The wastewater feed pattern (equalisation control), and
5. Other methods including ATP monitoring. (WPCF, 1987)

The choice as to which control-point is the most critical for process control, depends on the individual plant characteristics and operator preference (Cakici *et al*, 1995). Busby *et al* (1975) considered the aeration rate and wastewater feed pattern control points. Both are difficult to control in reality (Busby *et al*, 1975), and will not be considered in this review. Kabouris *et al* (1990) discovered that regulating activated-sludge using WAS-control methods produces less effluent-quality variability. Thus, this method was considered more reliable. In contrast, the recycle ratio method (RAS-control) resulted in highly variable effluent quality (Kabouris *et al*, 1990).

Controlling the activated sludge process using WAS control methods is the most common. Wasting activated sludge effects the process more than any other control method because the WAS rate has been found to influence effluent quality, the biomass generation rate, aeration requirements, sludge settling characteristics and other important parameters (WPCF, 1987). WAS control can be performed using three main control parameters which are discussed below with major emphasis on the preferred solids retention time (SRT).

2.4.2 Food-to-Microorganism Ratio Control (F/M-control)

The food-to-microorganism ratio (F/M) was originally developed as a control parameter by McKinney (1962), and is based on

Equation 2.7.

$$F/M = \frac{S_0}{(HRT)X_V}$$

F/M = Food-to-microorganism ratio (g CODorBOD/g VSS.day)
S_0 = Influent organic substrate concentration (usually expressed as either g CODorBOD/m³)
HRT = Hydraulic retention time (days)
X_V = Mixed liquor volatile suspended solids concentration (g VSS/m³)

Equation 2.7: The food-to-microorganism ratio.

The control objective is to maintain the F/M value within a certain range (Metcalf *et al*, 1993). The range is carefully chosen based on experience and what has been found to produce acceptable effluent-quality and process performance for the particular system. The method is usually applied in industrial situations where the influent organic substrate concentration varies between defined levels (WPCF, 1987). In these cases, the RAS and WAS rates can be adjusted to maintain the required biomass concentration (X_v) in order to keep the F/M ratio within the stipulated range (WPCF, 1987).

Burchett *et al* (1974) reported that this method usually results in consistent plant operation and effluent quality even for highly variable wastewaters. Chapman (1990) reported otherwise by saying that if a plant is operated at a constant F/M for an extended period, the plant will become destabilised. On some extended aeration plants in particular this can lead to fungal growths appearing as foam on the reactor surface (Chapman, 1990).

Heddle (1979) studied the F/M control method using laboratory scale activated-sludge plants treating slaughterhouse wastewater. Suspended solids removal was measured as 94.3 % (± 2.2 %) at the specified low F/M range of 0.25 to 1.2 g COD/g MLSS/day. The corresponding value at the high F/M range of 1.2 to 2.8 g COD/g MLSS/day was only slightly lower at 92.0 % (± 4.6 %). In fact, removal efficiencies for most of the parameters monitored were best when the system was operated in the low F/M range. Low F/M is related to a long solids retention time, so most of the ammonia removal was attributed to nitrification (Heddle, 1979).

For the extended aeration activated-sludge process, the suggested F/M range is 0.05 to 0.15 g BOD/g MLVSS/day for treating municipal wastewater (Metcalf *et al*, 1992). Typical systems treating tannery wastewater may aim to maintain an F/M within 0.10 to 0.18 g BOD/g MLVSS/day (Eckenfelder *et al*, 1995).

It has been shown that the F/M ratio can be related to the substrate removal rate using the process efficiency (Lawrence *et al*, 1970). Equation 2.8 adjusted from the equation given by Metcalf *et al* (1993) represents this relationship.

$$R_S = \frac{(F/M)E_S}{100} X_V$$

E_S = Organic substrate removal efficiency (%)
R_S = Organic substrate removal rate (g BODorCOD/d)

Equation 2.8: The substrate removal rate.

Equation 2.8 also shows that the indirect implication of controlling F/M is the manipulation of the substrate removal rate. Substrate removal is directly related to biomass generation (Equation 2.4), so low F/M-control will generate less biomass and thus less wastage is required. The biomass generation rate of a low F/M activated sludge process will be comparatively lower than that of a high F/M sludge because the organic loading is comparatively higher in the latter case.

Burchett (1974) discussed the F/M ratio as a control method and concluded that it was too labour intensive and too difficult to measure accurately. This is true; maintaining the F/M range is difficult when wastewater characteristics vary considerably, and requires daily measurements of the organic substrate concentration (WPCF, 1987).

2.4.3 Mixed Liquor Suspended Solids Concentration Control (MLSS-control)

The aim of using the mixed liquor suspended solids concentration (MLSS) as a control parameter, is to maintain a target MLSS level that has been found to produce consistent effluent quality (WCPF, 1987). The WAS rate is then calculated using

Equation 2.9 for the basic activated-sludge system. This calculates the excess suspended solids accumulated over the target value that must be wasted to maintain constant MLSS.

$$WAS = \frac{(X_{CURRENT} - X_{TARGET})V}{1000}$$

WAS = Waste activated sludge mass (kg TSS/d)
V = Volume of the reactor (m^3)
$X_{CURRENT}$ = Current mixed liquor suspended solids concentration (g TSS/m^3)
X_{TARGET} = Target mixed liquor suspended solids concentration (g TSS/m^3)

Equation 2.9: Waste activated sludge mass for the constant mixed liquor suspended solids concentration control strategy.

A further calculation is required to calculate Q_W, the WAS volume. This is done using Equation 2.10.

$$Q_W = \frac{WAS}{X_?}1000$$

Q_W = WAS volume (m^3)
$X_?$ = The concentration of volatile suspended solids of the stream from which the sludge is wasted. In the case of wasting from the recycle line, $X_?$ represents the clarifier underflow volatile suspended solids concentration.

Equation 2.10: The waste activated sludge volume for the constant mixed liquor suspended solids concentration control strategy.

This control parameter is best when used for systems treating a constant flow of wastewater with constant organic load (WPCF, 1987). Since the fellmongery process produces wastewater that is extremely variable in both volume and characteristics, this mode of control is not likely to be suitable.

Burchett *et al* (1974) stated that advantages of this method include the fact that it is relatively simple and less labour intensive. Operating preference was given to plants treating wastewater with a constant organic substrate (BOD or COD) concentration (Burchett *et al*, 1974). In this instance, the activated-sludge is effectively being controlled on a constant F/M basis, because MLSS concentration and the influent organic substrate concentration are constant.

The MLSS control parameter is weakly linked to responses in effluent quality and an example was given by Burchett *et al* (1970). If the influent wastewater organic load were to increase by 40 %, the biomass generation rate would increase as a result and thus more solids would need to be wasted to maintain the MLSS set point. The result of this action will be a 40 % higher F/M ratio; thus organic overload may occur, as the MLSS cannot increase instantaneously. This could ultimately lead to process problems and possibly process failure.

2.4.4 Solids Retention Time Control (SRT-control)

The solids retention time (SRT) estimates the average time biomass is held suspended in the reactor. SRT is usually based on the reactor volume (V) and the volatile suspended solids (VSS) concentrations for the mixed liquor and the waste sludge source, according to Equation 2.11 for the basic system (Metcalf *et al*, 1993).

The objective is to use the WAS rate (represented by $Q_wX_?$ in Equation 2.11), calculated from the daily measurements of the reactor MLVSS and effluent VSS to maintain the target SRT.

The target SRT is chosen based on previous experience as to what gives consistent effluent quality and acceptable process performance under the environmental and physical conditions.

$$SRT = \frac{X_V V}{Q_E X_E + Q_W X_?}$$

SRT = Solids retention time (days)
Q = Effluent flowrate (m³/d)

Equation 2.11: The solids retention time (SRT).

The beauty of using SRT as the control parameter lies in the fact that the operator is indirectly controlling the biomass generation rate. Equation 2.12, which has been derived from steady state mass balances in many studies represents this fact (Metcalf *et al*, 1992 and Burchett *et al*, 1974).

$$G_{VSS} = \frac{X_V V}{SRT} = YR_S - k_d X_V V$$

G_{VSS} = Net biomass generation rate (g VSS/d)
Y = Theoretical biomass yield coefficient (g VSS/g CODorBOD)
k_d = Combined coefficient for endogenous decay of microbial VSS and cellular maintenance energy requirements.

Equation 2.12: The volatile suspended solids generation rate.

By using the SRT as a control variable, the microbial population dynamics are being selected. For instance, the biomass generation rate when the activated sludge plant is controlled at 10 days SRT will be comparatively greater than that of the same process controlled at a 30 day SRT. In other words, the combined microbial growth rate of the 10 day SRT process is greater (faster) than the 30 day SRT.

Burchett *et al* (1974) also mentioned the link between the F/M ratio and the SRT and stated that if one of the two variables is controlled, the other will seek and find its own associated level. This statement is affectively embodied by Equation 2.13, which relates the SRT to the F/M ratio. Equation 2.12 is related to

Equation 2.7 because the substrate removal rate is correlated to the biomass generation rate.

$$\frac{1}{SRT} = Y(F/M)\frac{E}{100} - k_d$$

Equation 2.13: The relationship between the solids retention time and the food-to-microorganism ratio.

The SRT is known to effect the bio-kinetics of the activated sludge process. The Lovett (1984) study found that the settling characteristic (measured using the sludge volume index, SVI) of sludge treating meat-processing wastewater was influenced by the SRT. Reactors were maintained at an SRT level of 10 days for several months until steady state values of MLSS, effluent TSS and effluent COD were obtained. Response variables of interest were then measured for 6 weeks while at steady state.

The SVI for meat-processing wastewater tended to decrease as the SRT increased from 10 to 30 days. The SVI peaked at around 8 to 10 days and then dropped as SRT was decreased from 8 to 2 days (Lovett, 1984). As SRT was reduced, dispersion of the effluent (un-flocculated biomass) increased, thus the effluent suspended solids concentration increased. It appears from this study that SRT above 8 days are required to produce effluent with low suspended solids when treating meat-processing wastewater. Any higher than 10-12 days there appears to be no major increase in suspended solids concentration or SVI.

Bisogni *et al* (1971) produced similar results, observing that dispersion increased as the SRT decreased and settling generally improved as the SRT increased (glucose-yeast extract substrate). This study used the Ludzak-type reactor also used by Lovett (1987). Temperature was maintained constant at 20 °C whilst other environmental factors such as pH was neutral, DO (5-7 mg/L) and agitation were held relatively constant. Wasting was discrete and supernatant from the waste was returned to the reactor to reduce hydraulic disturbances. Steady state conditions were assumed to prevail once each reactor was operated for a period of 3 times the operating SRT.

Lovett (1984) studied the influence of SRT during activated sludge treatment of abattoir wastewater. Conclusions from that paper were similar to the previous study in that SRT levels of 5 to 20 days were found to produce reliable effluent quality. The effluent was low in phosphorous and TKN, and the sludge settled and dewatered satisfactorily.

Annachhatre (1995) observed that a longer SRT of 13 days for treating meat-processing wastewater produced a more stable effluent quality and resulted in near complete nitrification compared to a shorter SRT of 3 days.

Rawlings *et al* (1987) investigated the treatment of beamhouse effluent using activated sludge pilot plants operated at an SRT of 18 days over a period of twelve months. The beamhouse effluent used comprised of the liming and deliming wastewater fractions from the fellmongery operation. Acceptable steady state operation was achieved in three out of eight runs under varying operating conditions. The high strength wastewater (typical total COD greater than 20,000-g/m^3) required very high MLSS concentrations to achieve a suitable food-to-microorganism ratio. The pilot plant trials that did appear to reach a steady state required long run times, up to 70 days. Table 2.2 summarises the data collected from the three runs that reached steady state.

SRT days	HRT days	E_{sCOD} %	TSS_E g/m^3
18	2	88	100
9	2	82	100
9	1	55	1500

TSS_E = Effluent total suspended solids concentration (g TSS/m^3).
E_{sCOD} = Soluble COD removal (%).

Table 2.2: Data collected from activated sludge pilot plant trials treating South African fellmongery wastewater (Rawlings, 1987).

Notice that the HRT in all three cases is relatively low. The Richmond fellmongery activated-sludge plant in this study has an approximate HRT of 6 to 7 days. The shorter HRT levels could have been the cause of poor plant stability simply because of excessive organic loading. This comes back to the relationship between the SRT of the F/M ratio. The short HRT with an extremely high influent COD concentration will result in an increased F/M ratio.

In runs in which steady state could not be achieved, reactor stability was thought to be effected adversely by poor settling and excessive foam generation (Rawlings *et al*, 1987). These factors caused high effluent solids concentrations, which reduced the reactor mixed liquor suspended solids concentrations dramatically. The MLSS continued to drop thus reducing reactor performance even further. Rawlings *et al* (1987) recommendation was to avoid using the activated sludge process for treating beamhouse effluent.

McFarlane (1979) identified the need for investigation into suitable operating conditions and long term stability of activated sludge systems treating fellmongery wastewater. McFarlane (1979) reported results from several other laboratory scale experiments that indicated short SRT (0.74 to 0.96 days) and short retention times (10 hours) can be used to achieve significant reductions in COD (83 % in some cases), and suspended solids (94 %) for tannery wastewater.

Rawlings *et al* (1976) investigated the use of a 5 day SRT with a 2 day hydraulic retention time. They found that the COD could be reduced by more than 72 % despite the sulphide concentrations.

2.5 EXPERT SYSTEMS FOR OFF-LINE PROCESS CONTROL AND OPERATION OF ACTIVATED SLUDGE

2.5.1 Introduction

In many ways, treatment plant operation becomes an information-management problem (Lai *et al*, 1990). It is widely believed that plant performance can be improved if the operator is equipped with convenient and effective methods for using his data (Ozgur *et al*, 1994). An expert system (ES) is such a tool that can be adapted for the specific situation (Berthouex *et al*, 1987).

2.5.2 Structure of an expert-system

Lai *et al* (1990) defined an expert system as an information-data management system, which could be used in conjunction with the human expert, the operator and the information database. Figure 2.6 taken from Lai *et al* (1990) shows the relationships between these individual areas of wastewater treatment-plant operation.

The knowledge base contains the codified expertise (heuristic rules) extracted from the human expert (Ozgur *et al*, 1994). The inference engine assesses the knowledge-base with the database when an inquiry is made by the user. The expert system is then able to output suggestions for control decisions to the user (Lai *et al*, 1990). Therefore the expert system can be used by non-expert people to make expert control decisions (Ozgur *et al*, 1994).

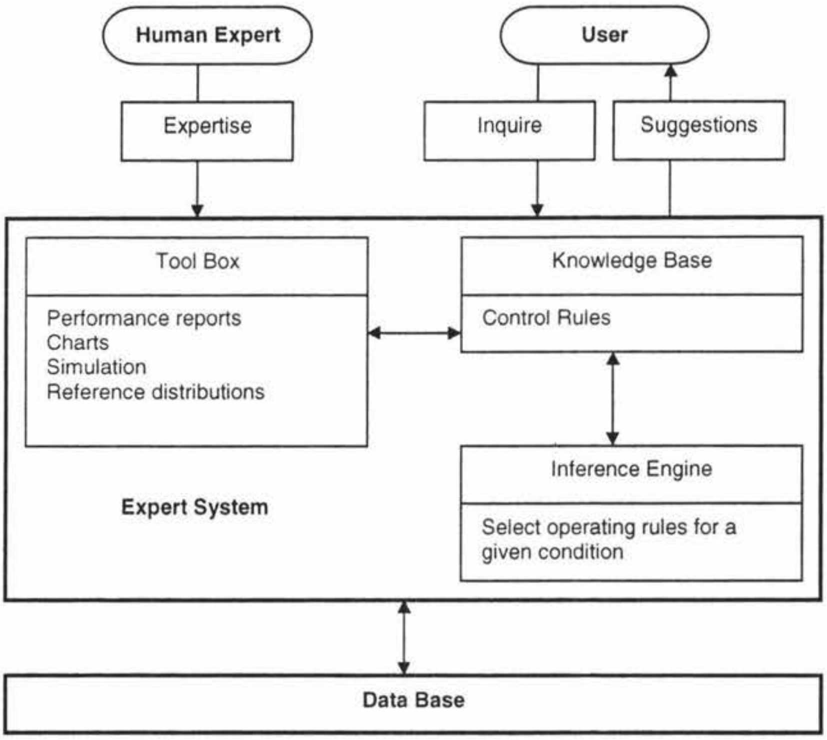

Figure 2.6: Relationships of the human expert, the user and the database to the expert system (Lai *et al*, 1990).

Ladiges *et al* (1994) developed a Windows based off-line expert system for a biological-nutrient-removal plant in Germany. The system was developed primarily for solving process problems using knowledge-base that contained extensive expert information on biochemical and physical processes occurring in the plant (Ladiges *et al*, 1994). Figure 2.7 illustrates the expert system developed in the Ladiges *et al* (1994) project.

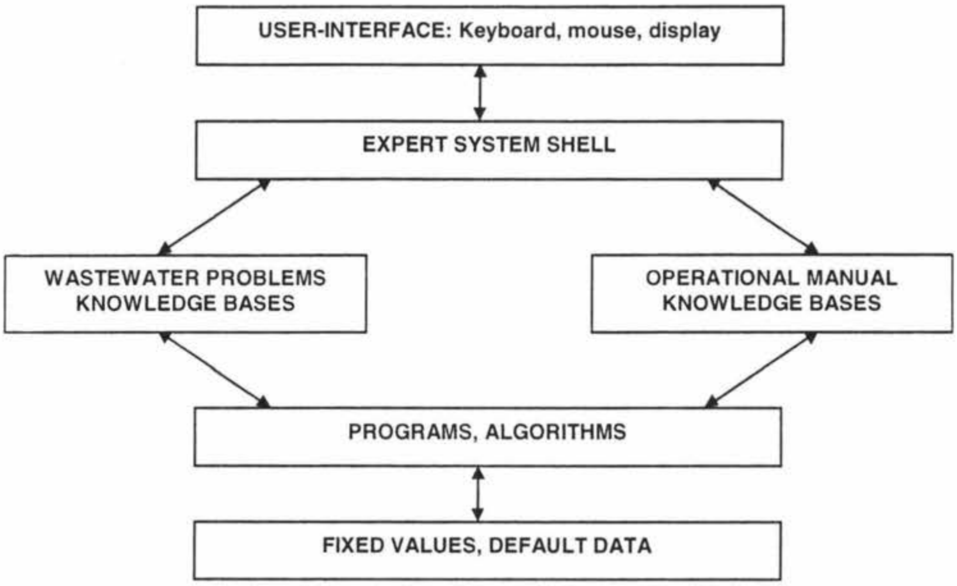

Figure 2.7: Structure of the expert system (Ladiges *et al*, 1994).

2.6 SUMMARY

2.6.1 Wastewater Characteristics

Diagnosis of the observed process problems will require knowledge of the wastewater characteristics. Therefore, a wastewater-characterisation study is required and will need to include the phosphorous concentration of the secondary fellmongery-wastewater in addition to COD, BOD, TKN, NH_3-N, TSS and VSS and the soluble counter-parts.

2.6.2 Process Control and Operation of the Activated Sludge Plant

Bench-scale simulations are required to obtain data under solids retention time (SRT) control for full-scale operation and design purposes. A relatively simple, user-friendly system is required to embody the new process control and operation strategy.

3 MATERIALS AND METHODS

3.1 BENCH-SCALE ACTIVATED SLUDGE SIMULATION PLANTS

3.1.1 Construction

Two bench-scale activated sludge plants were operated in the Institute of Technology and Engineering, environmental engineering laboratory at Massey University (Palmerston North). A scale down factor of 3.10^{-6} from the full-scale plant was used, and both plants were operated at 20°C. Figure 3.1 is a schematic diagram of one of the bench-scale plants.

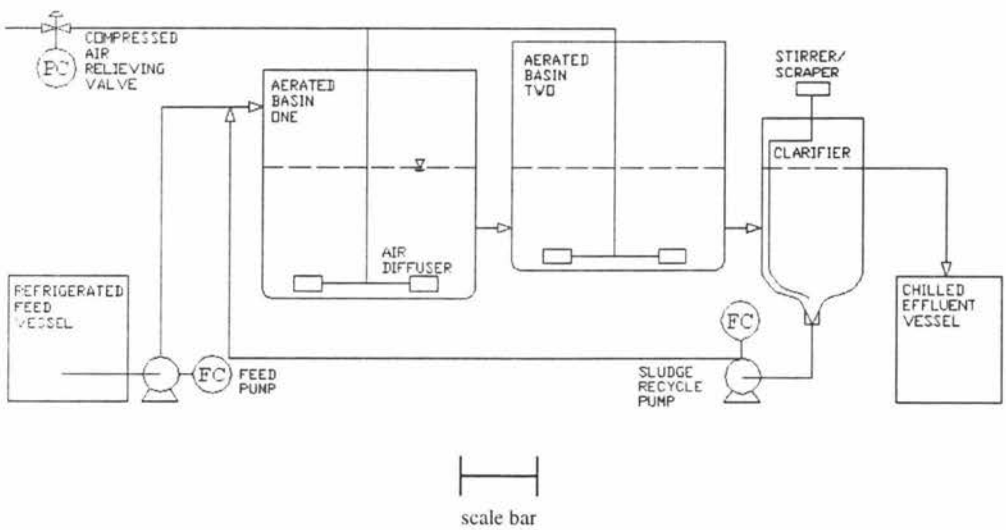

Figure 3.1: A schematic/ instrumentation diagram of the bench-scale activated sludge plant (scale bar = 8.8 cm).

The refrigerated feed vessel and the aerated basins were constructed from 20 litre plastic containers. Inlets and outlets were positioned so that static pressure maintained constant volume. Influent was fed to basin one using a Masterflex peristaltic pump (Cole Parmer, model 7013) and a Masterflex pump controller unit, on a 6 minute off, 6 minute on intermittent basis to control hydraulic residence time. Basin one was maintained at 10 litres and basin two was elevated so that it could be maintained at 7.5 litres as shown in Figure 3.1.

The clarifier was constructed from a 2 litre transparent plastic bottle, which when turned upside down, formed good sludge collection space and 0.0095 m^2 of surface area. Mixed liquor from basin two flowed into the clarifier under the influence of static pressure. Thickened sludge was withdrawn constantly from the central outlet at the bottom using a Masterflex peristaltic pump (Cole-Parmer, model 7014) with a Masterflex pump controller unit.

The thickened sludge was returned to basin one and contacted with the influent wastewater prior to entering the reactor. The supernatant overflowed into the outlet and was collected in a chilled 10 litre bucket. A specially designed stirrer/ scraper was inserted into the clarifier as shown Figure 3.1. The stirrer was driven with a Singer electric motor (model 416 504 20) at 0.4 rpm. It consisted of a 1 mm diameter wire shaped to the inner surface of the clarifier and connected to a drive shaft.

3.1.2 Activated Sludge Seed

The bench-scale basins were initially seeded with activated sludge from basin one of the Richmond fellmongery activated sludge plant.

3.1.3 Aeration and Sludge Wasting

The basins were continuously aerated with compressed air at a constant pressure of 12 psi. Aeration was controlled using a relieving valve (Norgren, model R06) with an oil trap attached. Air was diffused into the bottom of the basins through aeration stones. Sludge was wasted directly from basin one and replaced with an equal volume of tap water. The tap water was gentling stirred over night to reduce the residual chlorine concentration.

3.2 ANALYTICAL METHODS

3.2.1 Total Suspended Solids

The mixed liquor suspended solids (MLSS) and the total suspended solids concentrations were measured according to the Standard Method (APHA, 1995). Whatman GF/C filter paper (70 mm diameter) was used for filtering the samples (Bickers, 1995). Mixed liquor samples were taken from each basin directly using a 10 ml plastic pipette. Influent and effluent samples were taken from the respective composite sample using a 50 ml glass pipette. Equation 3.1 was used to calculate the total suspended solids concentration.

$$\text{TSS or MLSS} = \left(\frac{(F+R_1)-F}{V_S} \right) \times 10^6$$

F = Initial filter dry weight (g).
$(F+R_1)$ = Filter plus primary residue dry weight after evaporation at 105°C (g).
V_S = Sample volume (ml).

Equation 3.1: Total suspended solids concentration.

3.2.2 Volatile Suspended Solids Concentration

The mixed liquor volatile suspended solids (MLVSS) and the volatile suspended solids concentration were measured using the Standard Method (APHA, 1995). Residue from the total suspended solids concentration method was ignited in a 550°C furnace for 20 minutes and weighed.

Equation 3.2 was used to calculate the volatile suspended solids concentration.

$$\text{VSS or MLVSS} = \left(\frac{(F+R_1)-(F+R_2)}{V_S} \right) \times 10^6$$

$(F+R_2)$ = Dry weight of the filter and the residue left after ignition at 550°C (g).

Equation 3.2: The volatile suspended solids concentration.

3.2.3 Fixed Suspended Solids Concentration

The fixed suspended solids concentration was measured using the Standard Method (APHA, 1995). Equation 3.3 was used to calculate the FSS based on data collected from the VSS and TSS methods.

$$FSS = \left(\frac{(F + R_2) - F}{V_S} \right) \times 10^6$$

Equation 3.3: The fixed suspended solids concentration.

3.2.4 Carbonaceous Biochemical Oxygen Demand

Carbonaceous biochemical oxygen demand (CBOD) was measured using the Standard Method (APHA, 1995). Soluble BOD was measured by filtering the sample through Whatman GF/C filter paper (70 mm diameter). Hach BODTrak apparatus was used along with Hach nutrient buffer pillows and Hach lithium hydroxide powder pillows for BOD measurement. The BODTrak apparatus logged BOD data for the entire 5 day incubation period so that the 5 day BOD value could be read directly from the data and then adjusted for dilutions.

3.2.5 Chemical Oxygen Demand

Chemical oxygen demand (COD) was measured using the closed reflux method (APHA, 1995). Soluble COD was measured by filtering the sample through 70 mm diameter Whatman GF/C filter paper (Orhon *et al*, 1999). Influent samples required diluting to be within the calibration range (0-500 g COD/ m^3). The samples were reacted in 7.5 ml Hach glass reactor tubes. The tubes were placed in a Hach COD heating block for 2 hours. Absorbance was measured at 600 nm using a Shimadzu UV-vis spectrophotometer (model UV-1201) with a light path of 1 cm. Equation 3.4 was used to calculate the COD.

$$COD = AF_{COD}D$$

A = Digested sample absorbance at 600 nm/cm (Absorbance units)
F_{COD} = COD standardisation constant (g COD/ m^3/ Absorbance units)
D = Dilution ratio

Equation 3.4: The chemical oxygen demand concentration.

3.2.6 Sludge Volume Index

The sludge volume index (SVI) was measured according to Standard Methods (APHA, 1995). One litre of mixed liquor from basin two was placed in a one litre measuring cylinder and the sludge volume read after 30 minutes (Jenkins *et al*, 1995). The SVI was then calculated using Equation 3.5.

$$SVI = \frac{SSV_{30}}{MLSS_2}1000$$

SSV_{30} = Settled sludge volume after 30 minutes (ml).
$MLSS_2$ = Mixed liquor suspended solids concentration in basin two (g TSS/m^3).
SVI = Sludge volume index (ml/g TSS).

Equation 3.5: The sludge volume index.

3.2.7 Total Phosphorous Concentration

Influent total phosphorous concentration (TP) was measured using the nitric acid- sulphuric acid digestion method followed by the ascobic acid colourmetric method as given in the Standard Methods (APHA, 1995). Samples and standards were prepared according to Table 3.1, and the standardisation range was set 0 to 2.3 g P/ m^3 for a light path of 1 cm. Absorbance was measured using the same spectrophotometer used in the COD method, but set at a wavelength of 880 nm. The digestion step was carried out in a Tecator Digestion System (model 1007), using six digestion tubes.

Sample	g P/ m³	Sample Volume (ml)	DDW Volume (ml)	Total Volume (ml)
Duplicate 1	-	1	20	21
Duplicate 2	-	1	20	21
Standard 1	0	0	20	20
Standard 2	0.6	0.25	20	20.25
Standard 3	1.2	0.5	20	20.5
Standard 4	2.4	1	20	21

DDW = Distilled water

Table 3.1: Dilution table for total phosphorous method[3].

Equation 3.6 was used to calculate the total phosphorous concentration.

$$TP = AF_{TP}D$$

A = Digested sample absorbance at 880 nm/cm (Absorbance units).
F_{TP} = TP standardisation constant (g TP/ m³/ Absorbance units).
D = Dilution ratio.

Equation 3.6: The total phosphorous concentration.

3.2.8 Total Kjeldahl Nitrogen Concentration

The influent total kjeldahl nitrogen (TKN) concentration was measured according to the Standard Method (APHA, 1995). Soluble TKN was measured by filtering the sample through Whatman GF/C filter paper. Samples and standards were prepared according to

Table 3.2, and the standardisation range used was set 0 to 100 g N/ m³.

[3] Sample volumes for standards 1-4 were taken from a 50 g P/m³ stock standard solution.

Sample	g N /m³	Sample Volume (ml)	DDW Volume (ml)	Total Volume (ml)
Duplicate 1	-	5	45	50
Duplicate 2	-	5	45	50
Dupli 1 (soluble)	-	5	45	50
Dupli 2 (soluble)	-	5	45	50
Standard 1	50	25	25	50
Standard 2	100	50	0	50

Table 3.2: Total kjeldahl nitrogen dilution table for preparing samples and standards[4]

Samples and standards were digested using a Buchi digestion unit (model 435) set at heating level 7. Digested samples were distilled according to the standard method with a Buchi distillation unit (model 323) set at 60 ml DDW and 30 ml of NaOH with 5 seconds delay and 6 minutes distillation time. Nitrogen concentration was determined using the NaOH- boric acid titration method (APHA, 1998) with a Mettler auto-titrator (model DL 25).

3.2.9 Ammonia Concentration

The influent ammonia concentration was measured using the Standard Method (APHA, 1995). Samples were prepared by diluting 20 ml of wastewater sample to 50 ml using DDW. The solution was distilled using the same distillation unit used for the TKN method but set to add 0 ml water and 20 ml NaOH prior to distillation. Distillate was recovered and the NaOH-boric acid method was used (Mettler auto-titrator, DL5) to measure ammonia concentration.

3.3 WASTEWATER SAMPLING AND FLOW RECORDING METHODS

Influent wastewater samples were collected using a flow-composite sample-collection system. Flowrate was recorded by an ultrasonic flowmeter fixed to a Parshall flume. A programmable ISCO portable sampler (model 3700) was connected to the flowmeter for composite sampling. A 50 ml sub-sample would be taken 20 times per day to make up one 1 day flow

[4] Sample volumes were taken from a 100 g N/m³ stock standard solution.

composite sample (total volume of 1000 ml), which was used for wastewater characterisation. The sample was chilled during the 1 day collection period.

4 RESULTS AND DISCUSSION

4.1 WASTEWATER CHARACTERISATION AND DIAGNOSIS OF PLANT PROBLEMS

4.1.1 Introduction

Each unit process of the fellmongery plant produces a unique waste that contributes to the combined fellmongery wastewater. Because each unit process is operated separately, different volumes of wastewater may be produced from any one unit-process, which produces variable wastewater characteristics.

The chemical mixes used by the slat-processors depend on the day of the week and the type of slat, therefore the wastewater characteristics can vary within a wide range as shown in Table 4.1. This makes operating the activated-sludge plant difficult, especially without equalisation tanks, which are common in industrial applications to control wastewater variability (Ekenfelder *et al*, 1995).

Table 4.1 shows the characteristics of the fellmongery primary wastewater measured during this task. The characteristics measured were those, which were known to be important for activated-sludge operation and resource-consent compliance.

4.1.2 Organic Matter

The chemical oxygen demand (COD) was used to measure the oxygen demand of the non-soluble and soluble organic matter fractions of the fellmongery wastewater. The soluble fraction was that which passes through a Whatman GF/C (0.45 μm pore size) filter. The total COD was 4412 (± 369) g/m³, and 69 % or 3032 g/m³ was measured as soluble COD, as shown in Figure 4.1. The total COD for tannery wastewater is 6622 g/m³, where 85 % is soluble COD (Orhon *et al*, 1999). The lower percentage of soluble COD was caused by the significant concentration of volatile suspended solids (VSS, g/m³) in the fellmongery wastewater, which increases the non-soluble COD.

Characteristic	Units	Average	Standard Error (±)	Minimum	Maximum	Samples
COD	g/m³	4412	369	2104	7591	21
COD (soluble)	g/m³	3032	318	1090	6234	21
BOD	g/m³	1408	171	718	2242	8
BOD_U	g/m³	1703	301	807	3644	8
BOD (soluble)	g/m³	491	94	286	1031	8
BOD_U (soluble)	g/m³	578	88	297	998	8
TSS	g/m³	1976	361	378	6970	20
VSS	g/m³	1637	306	260	5880	20
TKN	g/m³	384	45	80	730	17
TKN (soluble)	g/m³	277	48	57	524	11
Ammonia	g/m³	88	12	27	200	17
Total P	g/m³	16	2	5	37	15
Total P (soluble)	g/m³	12	1	9	15	5

Table 4.1: Fellmongery wastewater characteristics after pretreatment to remove sulphide, grease and gross solids.

The 5-day carbonaceous biochemical oxygen demand (BOD) was used to measure the oxygen required to biologically remove organic matter from the wastewater. The method cannot be used to directly estimate the concentration of biodegradable organic matter. The total BOD load (kg/d) of the wastewater discharge is usually restricted by local authorities in order to minimise oxygen depletion in the receiving waters.

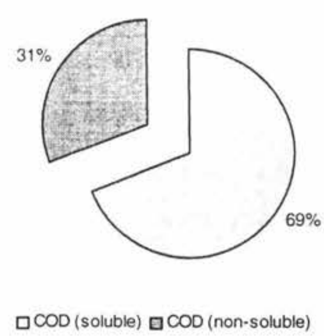

Figure 4.1: Distribution of the total chemical oxygen demand between the soluble and non-soluble phases for fellmongery wastewater.

Therefore, biological treatment plants are traditionally designed on a BOD removal basis. The average total BOD of the fellmongery wastewater was 1408 (± 171) g/m^3, and the average soluble BOD was 491 (± 94) g/m^3. Therefore, most of the total BOD (65 %) was attributed to the non-soluble fraction of the fellmongery wastewater as shown in
Figure 4.2. This indicates that the volatile suspended solids component may exert a large proportion of the total BOD.

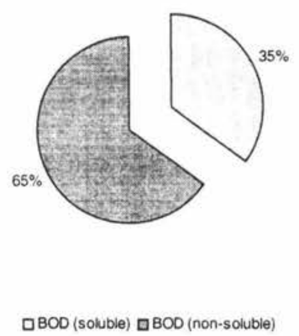

Figure 4.2: Distribution of the total biochemical oxygen demand between the soluble and non-soluble fractions of fellmongery wastewater.

The ultimate BOD (BOD_U) estimates the total oxygen demand required to completely remove the biodegradable organic matter. Like the 5-day BOD measurement, BOD_U underestimates the energy of the organic matter in a wastewater (Marais *et al*, 1976). The total BOD_U for fellmongery wastewater was 1703 (± 301) g/m^3, and the soluble BOD_U was 578 (± 88) g/m^3. The significant difference reinforces the inference made earlier that most of the BOD appears to be distributed in the non-soluble fraction.

The total BOD rate expression for the fellmongery wastewater is shown as
Equation 4.1.

$$BOD_t = 1703(1 - e^{-0.74t})$$

Equation 4.1: Fellmongery wastewater total biochemical oxygen demand (BOD) rate expression.

The rate constant for removal of total BOD (k) at 20 °C is 0.74 day^{-1}. A typical value of k for municipal wastewater is 0.23 day^{-1} (Metcalf *et al*, 1991). Therefore, oxygen uptake will be comparatively rapid during the initial contact period with the activated sludge microbes as they metabolise the soluble organic matter and hydrolyse the volatile suspended solids.

The total BOD to total COD ratio was 0.32. Domestic sewage BOD to COD ratio will usually lie within 0.4 to 0.8 (Metcalf *et al*, 1991). O'Donnell (1995) suggested 0.23 for fellmongery wastewater. Eckenfelder *et al* (1995) suggested a typical BOD to COD ratio for domestic sewage of about 0.37.

4.1.3 Suspended Solids

The average total suspended solids concentration (TSS) for the pretreated fellmongery wastewater was 1976 (± 361) g/m^3. This is a very high concentration to be treated in the activated sludge process. Normally, TSS is reduced by 50 to 65 % prior to any secondary treatment process using primary solids removal (Metcalf *et al*, 1993). The current strategy (prior to this study) for operating the activated-sludge plant was closely related to the Constant MLSS-control strategy discussed in section 2.4.3. However, the MLSS concentration could not be controlled to a target set point, due to the large variations in the influent volume and TSS. Instead, the operator used the secondary clarifier feed pump to control the basin volumes. This usually resulted in solids overload as the sludge blanket would frequently rise until only centimetres from the overflow weir.

The volatile suspended solids concentration (VSS) was used to estimate the concentration of organic suspended solids. The VSS for the fellmongery wastewater was (1637 ± 306) g/m^3. Therefore, 83 % of the total suspended solids are organic and the remaining 17 % or 339 (± 63 g/m^3) are inorganic (fixed). The fixed suspended solids will pass through the activated sludge system unchanged (Ekenfelder *et al*, 1995), unless they are removed in the waste sludge.

4.1.4 Nitrogen

Nitrogen is a required nutrient for microbial metabolism and must be supplied in sufficient quantities to avoid process problems related to nitrogen limitation and in a form that is readily available to the cell. The total concentration of organic nitrogen in the wastewater was estimated using the total kjeldahl nitrogen (TKN) method. This includes organically bound and ammonical nitrogen forms. The average TKN concentration was 384 (± 45) g/m³. The soluble TKN for the pretreated fellmongery wastewater was measured as 277 (± 48) g/m³. Therefore, 72 % of the total organic nitrogen is distributed in the soluble fraction. Approximately 88 (± 12) g/m³ of the soluble nitrogen is ammonia.

The pretreated fellmongery wastewater has a very high organically bound nitrogen concentration of 296 (± 38 g/m³). Typical organic nitrogen concentrations for meat processing wastewater range from 70 to 250 g/m³ (Bickers *et al*, 1998). Approximately 15 to 50 % of the organic nitrogen in domestic wastewater can be removed by the activated sludge process (Metcalf *et al*, 1993), and it is converted into ammonia by hydrolysis.

4.1.5 Phosphorous

Phosphorous is another nutrient required for microbial metabolism. The total concentration of phosphorous forms (soluble and total) in the fellmongery wastewater was measured using the total phosphorous (TP) concentration. TP was 16 (± 2) g/m³ for the fellmongery wastewater, and 12 (± 2) g/m³ was distributed in the soluble fraction.

The fellmongery activated-sludge plant exhibits non-filamentous bulking during the spring and summer seasons. Non-filamentous bulking in the secondary clarifier is linked to the high BOD concentration, and the lack of phosphorous supply in the influent wastewater. In such a situation the microbial population needs a readily metabolisable source of phosphorous and nitrogen (Jenkins *et al*, 1995).

Under these conditions of high influent BOD (high F/M) and low phosphorous supply, microbial metabolism shifts to what is referred to as "shunt metabolism" (Jenkins *et al*, 1993). Shunt metabolism or unbalanced growth occurs when the microbial cell cannot maintain a high biomass generation rate as the rate of supply of nutrients limits the process of anabolism (refer to Figure 1.3). The net result, being the over production of extracellular polymers, which makes the floc highly water retentive and the mixed liquor becomes very slimy. Reduced settling, poor compaction rates and viscous foaming on the aeration basin surface occurs. The mixed liquor of the fellmongery activated-sludge plant is slimy and the sludge does not settle well, despite the absence of filamentous bacteria. Both basin one and two surfaces of the fellmonger activated sludge plant are always covered with a thick, light brown, viscous foam that is sticky to feel. Shunt metabolism is thought to be the cause of these problems.

4.1.6 High Grease Load

There is approximately 679 g/m^3 (817 kg/d) of grease present in the secondary fellmongery wastewater (O'Donnell *et al*, 1995). It appears to exaserbate foaming problems on the basin surface. The compounds that make up the group termed "Grease" have a relatively large molecular weight and are therefore not effectively removed from the wastewater solution by activated sludge (Metcalf *et al*, 1993). Grease tends to float on the basin surface and increase the resistance to oxygen transfer across the liquid-film boundary layer. Thus the aeration equipment must work harder to maintain the dissolved oxygen set point concentration. This will increase operation costs, which could be avoided by optimising pretreatment to reduce the grease load.

Grease removal in the fellmongery pretreatment plant is performed by two air flotation tanks (approximately 10 m^3 each). A revolving impeller introduces air directly into the liquid phase, which is slightly different from dissolved air flotation (DAF) which uses compressed air. Wastewater is discharged to the dispersed air flotation tanks by static head from the previous gross-solids removal process. The average hydraulic retention time is between 12 and 20 minutes. Air flotation using a short hydraulic retention time is usually not warranted (Metcalf *et al*, 1993).

It is unknown as to whether the dispersed air flotation tanks are operating below expected performance. It is recommended that an investigation into pretreatment plant control, operation and performance is initiated with the aim of optimising the process.

4.1.7 Poor Aeration Control

An investigation is also required to optimise the aeration control because the existing strategy does not provide efficient control of the mechanical aerators. Optimising the aeration control strategy should reduce the cost (power usage) of aeration in some instances. The strategy should aim to maintain 1 to 2 g/m^3 of dissolved oxygen in both basins consistently (Metcalf *et al*, 1993).

4.1.8 Coloured Effluent

Coloured wastewaters are frequently encountered from industrial applications after biological treatment. This is usually remedied with addition of chemicals to improve clarification (Ekenfelder *et al*, 1995). The fellmongery activated-sludge effluent is coloured golden-brown, which is caused by the high proportion of soluble COD in the influent.

The fellmongery secondary clarifier is dosed with polyelectrolyte to enhance clarification of the supernatant, but this does not remove colour. However dosage rates are not monitored and additional problems such as floating clumps of polyelectrolyte are experienced. Addition of polyelectrolyte may also exacerbate the non-filamentous bulking problem mentioned earlier. The combined effect reduces the sludge thickening capacity of the clarifier and sludge de-waterability. Reducing the colour will depend on removal of the soluble COD fraction.

It is recommended that the secondary clarifier be optimised for the fellmongery activated-sludge. An investigation should include generating SVI operating charts.

4.1.9 Shock Sulphide Loads

Pretreatment is designed to remove those wastewater characteristics that cannot be handled by the activated-sludge process (Ekenfelder *et al*, 1995). The lack of an effective operation-strategy allows shock sulphide loads to frequently discharge to the activated-sludge plant. Activated-sludge flocs are capable of eliminating sulphide ions from the wastewater solution, provided that the floc contains sulfide-oxidising bacteria (Sengul *et al*, 1991). However, the sulfide oxidising bacteria that predominate in phosphorous limited environments are of the filamentous type (Jenkins *et al*, 1995) and filamentous bulking may occur.

Improved pretreatment operation is required to prevent shock sulphide loads. The sulphide removal process needs to be monitored and its performance measured regularly. Equalisation would be advantageous, because shock loads that do manage to escape pretreatment could be contained and recycled if necessary.

4.1.10 Mass Flows of Organic Matter, Nutrients and Suspended Solids

For the period of analysis (01/10/98 to 30/06/99), an average of 925 m^3/d of effluent was discharged to the receiving environment. During the same period, 2,435,260 skins were processed through the fellmongery, and the wastewater-production to skins-processed ratio was (0.09 ± 0.01) m^3/skin. So approximately 90 L of wastewater was discharged to the activated-sludge plant per skin processed. Table 4.2 lists specific pollutant loads in the pretreated fellmongery-wastewater calculated using the wastewater characteristics data in Table 4.1 and the average daily-discharge volume. Figure 4.3 shows the specific pollutant loadings in the pretreated fellmongery-wastewater per skin processed.

Characteristic	Units	Average	Standard Error (±)
COD	kg/d	4081	341
COD (soluble)	kg/d	2805	294
BOD	kg/d	1302	158
BOD_U	kg/d	1575	278
BOD (soluble)	kg/d	454	87
BOD_U (soluble)	kg/d	535	81
TSS	kg/d	1828	334
VSS	kg/d	1514	283
TKN	kg/d	355	42
TKN (soluble)	kg/d	256	44
Ammonia	kg/d	81	11
Total P	kg/d	15	2
Total P (soluble)	kg/d	11	1

Table 4.2: Specific pollutant loadings in fellmongery wastewater.

The fellmongery produces approximately 400 g COD, 127 g BOD and 178 g of TSS per skin, as shown in Figure 4.3. The COD is thought to be made up of dissolved albumin, mucoids, mucopolysaccharides, keratin, dissolved and emulsified fats (M^{c}Farlane, 1979).

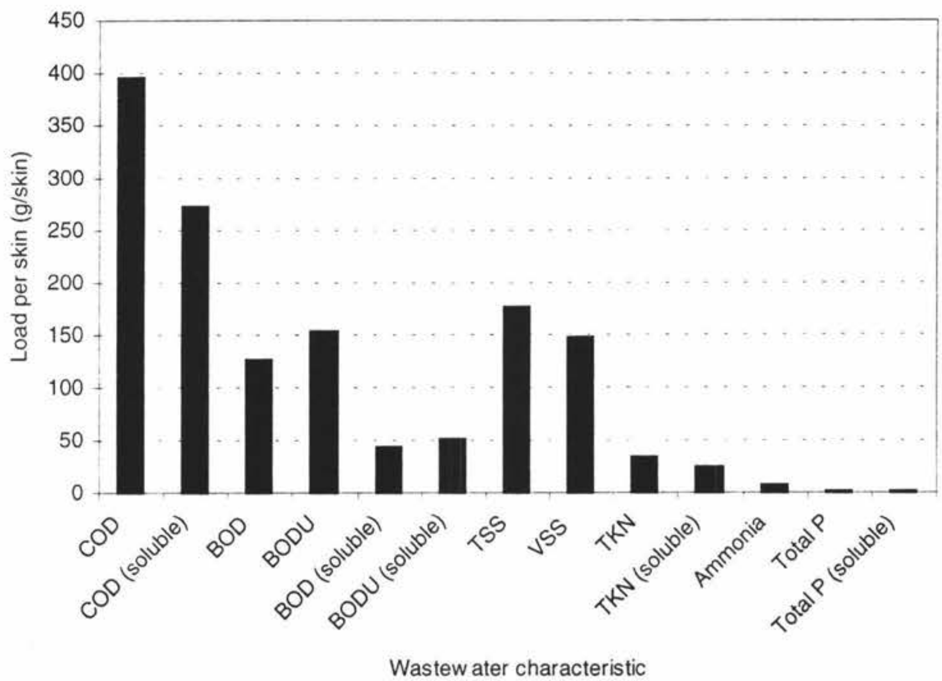

Figure 4.3: Average wastewater characteristic loading per skin processed for fellmongery wastewater.

4.1.11 Nutrient Control Requirements

The BOD:N:P ratio should be checked regularly to ensure that nitrogen and phosphorous concentrations are maintained in relation to the biodegradable organic matter concentration (WPCF, 1987). In most cases the BOD:N:P ratio should be maintained at 100:5:1 (Ekenfelder *et al*, 1995). If the BOD proportion increases above 100 then supplementary addition of nutrients will be required to maintain balanced growth. Similarly, if the N or P proportions decrease in relation to the BOD then nutrient addition will be required to maintain the generally accepted BOD:N:P ratio. Table 4.3 shows the BOD:N:P range for fellmongery wastewater.

load range	BOD	N	P
average	100	27.27	1.14
minimum	100	11.14	0.70
maximum	100	32.56	1.65

Table 4.3: The BOD:N:P ratio for average, minimum and maximum load condition for fellmongery wastewater.

The proportion of phosphorous appears to be satisfied, and there is more than enough nitrogen during average and maximum loading conditions. During minimum loading conditions, the phosphorous proportion may not be satisfied in terms of the generally accepted BOD:N:P ratio.

4.1.12 Effluent Quality Targets and the Full-scale Activated Sludge Plant

4.1.12.1 Total Suspended Solids (TSS) Target

To cope with the suspended solids load and meet the effluent target, the activated sludge plant must have a suspended solids removal efficiency of 64 % (for a 10 day SRT). As inferred in section 4.1.3 a large proportion of the suspended solids are volatile (organic), and it was also inferred that this volatile suspended solids fraction exerts most of the total BOD in fellmongery wastewater.

Activated sludge is capable of removing 80 to 90 % of the total suspended solids (Metcalf *et al*, 1993). This depends on the nature of the sludge and its settleability and is only the case for primary settled wastewater. The sludge from the full-scale plant settles poorly, with usual 30 minute settled sludge volume (SSV_{30}) of 900 to 1000 ml/1. The poor settling rate is caused by extremely high concentrations of mixed liquor suspended solids (MLSS) in basin two of the full-scale plant. The MLSS usually lies between 6000 to 8000 g/m^3, and has been observed to increase to 10,000 g/m^3. The typical range for extended aeration is 3000 to 6000 g/m^3 (Metcalf *et al*, 1991). So, it appears that solids management within the activated sludge plant coupled with the significant load of suspended solids in the influent may be the major cause of poor solids removal.

Solids management within an activated sludge plant is usually performed by operating the secondary clarifier to maintain a stable sludge blanket. Stable clarifier operation is extremely important for successful activated-sludge operation (Cakici *et al*, 1993). The clarifier of the full-scale plant frequently appears to be in a state of washout, because billowing solids have been observed in the clarifier, and the solids load is usually greater than the combined solids extraction rate. The recommendation is to isolate basin two so that its volume remains constant, and to eliminate the present surges in suspended solids that carry through the activated sludge basins into the clarifier. The process control and operation strategy presented in section will discuss how the clarifier is to be operated to attain stability in the sludge blanket.

4.1.12.2 Biochemical Oxygen Demand (BOD) Target

The BOD effluent quality target is 450 kg/d. The average effluent total BOD load from the activated sludge plant was 6.1 (± 0.2) kg/d for a hydraulic retention time (HRT) of 6.8 days during the period analysed. So the current BOD removal efficiency for the full-scale plant is therefore 98.6 %.

load range	BOD removal efficiency required (%)
average	65
minimum	32
maximum	78

Table 4.4: BOD removal efficiencies required for average, maximum and minimum influent BOD loads in order to achieve the effluent quality BOD target of 450 kg/d.

The BOD removal efficiencies required under various influent BOD load ranges are listed in Table 4.4. In general, the activated sludge process is capable of 80 to 95 % BOD removal (Metcalf *et al*, 1993). This indicates that the current BOD removal efficiency compares well to most activated sludge plants and it is more than acceptable for meeting the effluent quality target under various influent BOD loads.

4.1.12.3 Ammonia Target

The effluent target ammonia load is 540 kg/d. The influent ammonia load is only 81 kg/d. It would therefore appear that the effluent quality target can be met without treatment. However, the average-effluent ammonia load from the activated sludge plant during the period of analysis was 117 (± 2) kg/d. The ammonia concentration of the effluent is greater than that of the influent, because of the large amount of organic nitrogen that has been hydrolysed to ammonia by the activated sludge microbes.

Loads as high as 560 kg/d were recorded and the effluent quality target was therefore exceeded, but this was out of the operator's control. Greater control over the ammonia load is required considering that it is a resource consent compliance parameter. Reducing the influent organic nitrogen load will reduce effluent ammonia. This could be achieved by increasing the primary suspended solids removal-efficiency, as discussed in section 4.1.12.1. Enhancing nitrification will also reduce the ammonia concentration and could be achieved by increasing the solids retention time (SRT) in the activated sludge plant so that nitrifying bacteria are selected. Although, a 10 day SRT should be sufficient for nitrification.

Enhanced nitrification will increase the nitrate concentration in the effluent and may cause related problems in the secondary clarifier such as clumping and rising sludge due to denitirification. The fellmongery activated sludge plant already exhibits denitrification problems. Nitrate is monitored by resource consent, but has no specified limit. The future consent may require that nitrate discharge be restricted, the activated sludge plant may need upgrading to add denitirification facilities if this eventuates.

4.1.12.4 Sulphide Target

The effluent quality target for sulphide depends on the river flow (Q_{RIVER}, m^3/s) of the receiving environment. When Q_{RIVER} is above the critical flow ($Q_{CRITICAL}$, m^3/s), the sulphide target is 3.6 kg/d. When Q_{RIVER} is below $Q_{CRITICAL}$ the sulphide target is calculated using Equation 4.2.

$$\text{Sulphide} = \frac{3.6Q_{RIVER}}{13.5} \qquad \text{for } \left(0 \le Q_{RIVER} \le 13.5\right)$$

Equation 4.2: The sulphide load, effluent quality target when the river flow is below the critical river flow. ($Q_{CRITICAL}$ = 13.5 m^3/s)

For a river flow of 10 m^3/s, the effluent quality target becomes 2.7 kg/d of sulphide. The sulfide concentration in the pretreated wastewater is 30 g/m^3 (O'Donnell *et al*, 1995) which translates to a load of 28 kg/d. So, for river flows above the critical flow the activated sludge plant must be capable of removing 87 % of the influent sulphide. If the river flow drops below critical, then the removal efficiency becomes a function of the river flow as shown in Equation 4.3.

$$E_{SUL} = -0.95Q_{RIVER} + 100 \qquad \text{for } (0 \le Q_{RIVER} \le 13.5)$$

E_{SUL} = The sulphide removal efficiency (%)

Equation 4.3: The sulphide removal efficiency required once the river flow drops below critical.

For a river flow of 10 m^3/s (which is below critical), the required removal efficiency is 90.5 %. Removal of sulphide in the activated sludge plant will be mainly by aeration, biochemical processes will not play an important role. So improvements to the fellmongery pretreatment plant (mentioned in section 4.1.9) should be considered so that the effluent-quality target is achieved prior to the activated-sludge plant.

4.2 EVALUATION OF SOLIDS-RETENTION-TIME CONTROL (SRT) USING BENCH-SCALE SIMULATIONS

4.2.1 Introduction

The bench-scale simulations were used to test solids retention time (SRT) control prior to full-scale application. The aim was find a suitable SRT level for maintaining stable activated sludge performance under the variable wastewater characteristics presented by fellmongery wastewater. A suitable level was defined as that which would produce acceptable and reliable plant response in terms of the effluent quality targets mentioned in the previous section. The typical SRT range for activated sludge treating domestic wastewater is 5 to 20 days for extended aeration plants (Metcalf *et al*, 1995).

Previous related studies had indicated that the lower SRT range (below 10 to 15 days) might be appropriate for fellmongery wastewater. McFarlane (1979) also suggested that SRT levels below 10 days could produce acceptable process responses. However, one study by Rawlings *et al* (1987) recommended that activated sludge be avoided for fellmongery wastewater because steady state operation was difficult too attain.

The bench-scale investigation was divided into two independent experiments, both operated at 20 °C. Experiment 1 used a 5 day SRT (case 1A) and a 15 day SRT (case 1B). Experiment 2 was set up in response to the results and lessons from experiment 1 and used a 5 day SRT (case 2A) alongside a 10 day SRT (case 2B). Both experiments will be discussed in terms of their respective process responses to establish the most appropriate SRT level for fellmongery wastewater.

4.2.2 Hydraulic Retention Times (HRT)

The full-scale plant has an average HRT of 6.8 days.

4.2.2.1 Experiment 1

Case 1A and 1B were operated with an average HRT of 3.2 (± 0.6) days.

4.2.2.2 Experiment 2

The steady state average HRT for both cases of experiment 2 was 6.4 (± 0.1) days.

4.2.3 The Steady State Condition

Usually an activated sludge plant needs 3 to 5 SRT time periods to reach a steady state (Marais *et al*, 1976, and Jenkins *et al*, 1993). A steady state is difficult to achieve in reality expecially for biological systems, due the dynamic nature of microbial metabolism and variations in the influent COD. But in activated sludge a pseudo-steady state condition can be achieved if the effluent total suspended solids concentration (TSS_E) remains relatively constant for an extended period.

4.2.3.1 Experiment 1

The TSS_E for both cases of experiment 1A and 1B appeared to stabilise after day 28 of operation as shown in Figure 4.4. After day 49, the TSS_E from case 1B increased dramatically. The increase was linked to a sample of wastewater pumped into the bench scale plants one hydraulic retention time (HRT) period prior to day 49 (day 46). Figure 4.5 shows that this wastewater sample was the first in a series of samples with extremely high total suspended solids concentrations. The shock load of suspended solids was not processed effectively by case 1B, so the apparent steady state was lost.

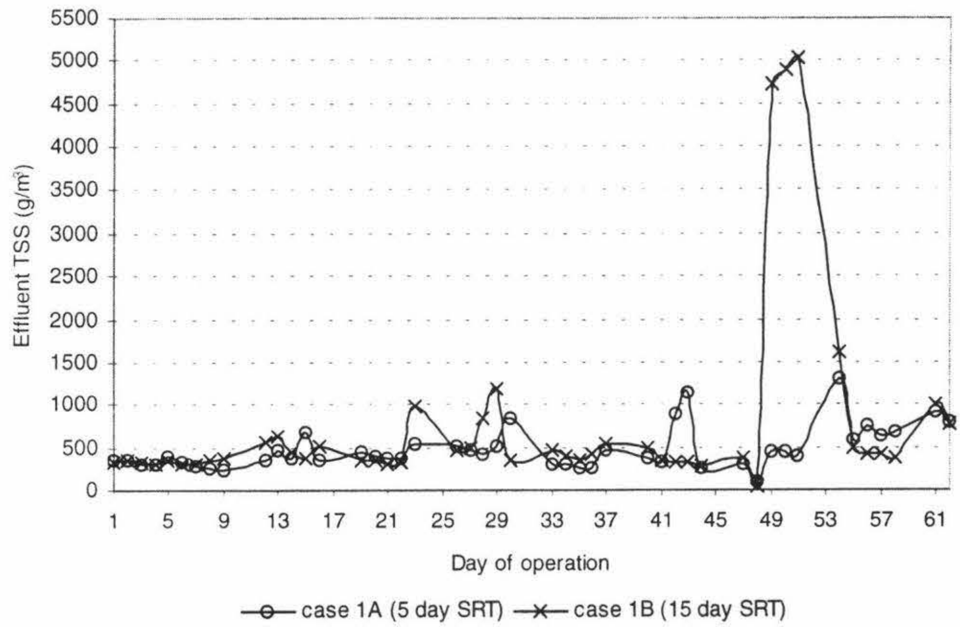

Figure 4.4: Experiment 1 effluent total suspended solids concentrations for the entire operating period.

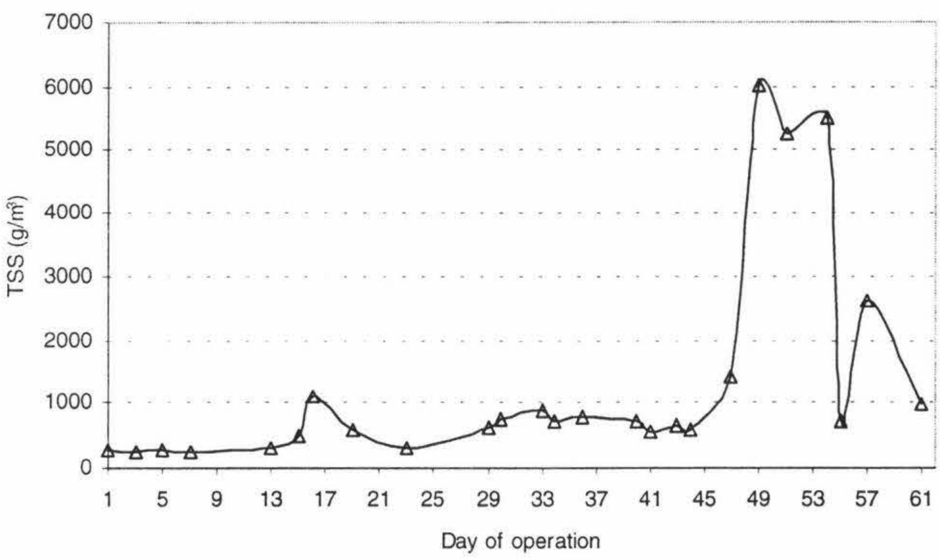

Figure 4.5: Experiment 1 influent total suspended solids concentrations for the entire operating period.

4.2.3.2 Experiment 2

The steady state period was taken as 3 times the 10 day SRT plant (case 1B), so day 30 marked the beginning of the steady state period, shown in Figure 4.6.

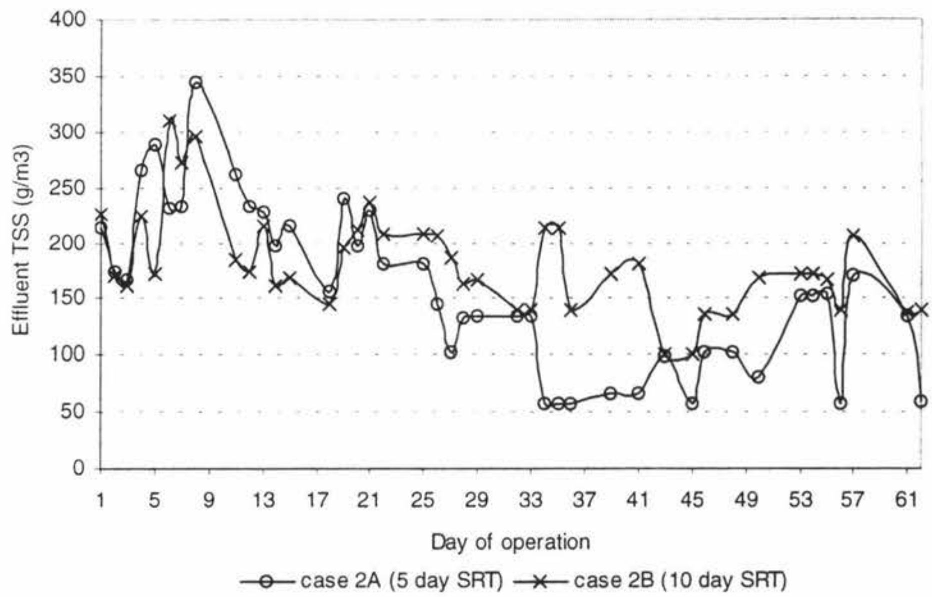

Figure 4.6: Experiment 2 total effluent suspended solids concentrations (TSS_E) for the entire operating period.

4.2.4 The Biodegradable Organic Loading Rates

The food-to-microorganism ratio (F/M) was used to measure the biodegradable organic loading rate.

Equation 2.7 in the literature review defines the F/M ratio and its units. Typical systems treating tannery wastewater may aim to maintain an F/M within 0.10 to 0.18 g BOD/g MLVSS/day (Eckenfelder *et al*, 1995). For extended aeration plants, the F/M typically lies between 0.2 to 0.6 g BOD/g MLVSS/day (Metcalf *et al*, 1991).

4.2.4.1 Experiment 1

Case 1A was operated with an average F/M ratio of 0.098 g BOD/g MLVSS/day and case 1B operated with an average F/M of 0.083 g BOD/g MLVSS/day. Therefore, the organic loading rate was comparatively low. This was because of the high overall mixed liquor volatile suspended solids concentration (MLVSS) which was maintained in both plants during the steady state period.

4.2.4.2 Experiment 2

Case 2A had a steady state average F/M ratio of 0.20 g BOD/g MLVSS/day, and case 2B had a steady state average of 0.25 g BOD/ g MLVSS/day. These are both high organic loading rates, but the plant responses appeared to improve in comparison to experiment 1.

4.2.5 Effluent Suspended Solids (TSS_E)

4.2.5.1 Experiment 1

The hypothesis concerning effluent suspended solids concentration for experiment 1 was that case 1A would produce a lower average TSS_E than case 1B. Case 1A produced TSS_E that averaged 451 (± 74) g/m³ compared to case 1B that produced an average of 452 (± 68) g/m³ for the steady state data shown in Figure 4.4. Hypothesis testing (z-test using a significance level of 0.05) indicated that there was not enough statistical evidence to reject the hypothesis for experiment 1. Therefore in terms of effluent suspended solids concentration, there is no significant difference between 5 and 15 day SRT control on a bench scale.

The effluent quality target for suspended solids load ($Q_E TSS_E$) discharged to the receiving environment is 900 kg/d. Under 5 day SRT control, the full-scale activated sludge plant would produce a steady state average $Q_E TSS_E$ of 417 kg TSS/d. By comparsion, 15 day SRT control would produce 418 kg/d under the required usual full-scale effluent discharge of 925 m³/d. When the influent total suspended solids concentration increased on day 46, the 15 day SRT $Q_E TSS_E$ increased to a peak of 4371 kg TSS/d. This is over 4 times the effluent quality target. It therefore appears that in order to achieve the effluent $Q_E TSS_E$ target consistently, shock loads of high influent suspended solids concentrations must be eliminated. This again stresses the need for increased primary suspended solids removal and flow equalisation prior to the activated sludge plant.

4.2.5.2 Experiment 2

The hypothesis for experiment 2 concerning effluent suspended solids was that the 10 day SRT (case 2B) would produce less TSS_E on a regular basis compared to the 5 day SRT (case 2A). Case 2A produced effluent suspended solids concentrations that averaged 100 (± 9) g/m³ compared to case 2B that produced an average of 157 (± 8) g/m³, for the period of steady state operation. Hypothesis testing (z-test using a significance level of 0.05) indicated that enough statistical evidence existed to assume that the 5 day SRT will produce lower effluent suspended solids concentrations than the 10 day SRT. However, from a qualitative point of view the activated sludge process is a biological one and is thus very complex. Statistical inferences such as these are helpful for characterising process response under different conditions, but they should not necessarily be taken literally.

Assuming the TSS_E concentrations above were produced at the full-scale activated sludge plant. The steady state average effluent suspended solids load ($Q_E TSS_E$) produced under 5 day SRT control would be approximately 93 kg/d. This is considerably lower than the corresponding load calculated for case 1A, which is more than likely due to the poor stability of case 1A. This is shown by the large standard error in the effluent suspended solids concentration from case 1A.

$Q_E TSS_E$ from case 2B would average 145 kg/d during steady state operation. If stable operation can be maintained under 5 or 10 day SRT control, the effluent quality target for TSS will be achieved without the use of chemical settling. Judging from experiment 1, maintaining stable operation will depend on managing the influent total suspended solids load, its fluctuations and solids management within the full-scale activated sludge plant.

4.2.6 Sludge Settleability

The settleability of activated sludge is important for maintaining acceptable effluent suspended solids concentrations. Sludge settleability was quantified using the sludge volume index (SVI). Sludge with an SVI between 50 and 150 ml/g TSS is generally accepted as a sludge with good settleability (Metcalf *et al*, 1993).

4.2.6.1 Experiment 1

The average steady state SVI for case 1A (5 day SRT) was 232 (± 23) ml/g, and the average for case 1B (15 day SRT) was 204 (± 11) ml/g, as shown in

Figure 4.7. The hypothesis test on these means (using 0.05 significance level) suggested that there was enough statistical evidence to suggest that 15 day SRT and 5 day SRT control will produce sludge with similar SVI. However, in terms of the generally accepted SVI range, both sludges do not settle very well.

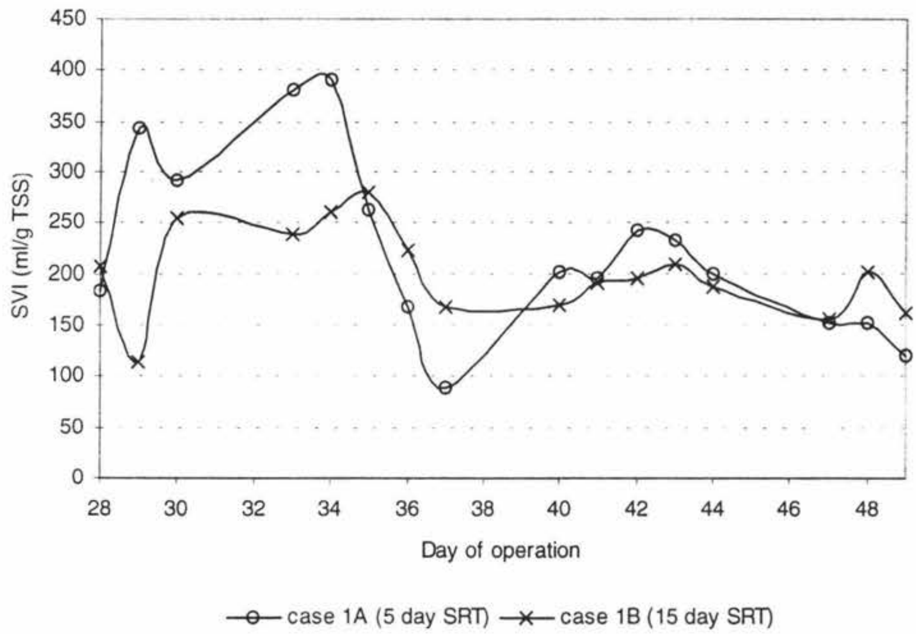

Figure 4.7: The sludge volume index trends for both cases of experiment 1.

4.2.6.2 Experiment 2

Case 2A (5 day SRT) sludge had a steady state average SVI of 67 (± 6) ml/g TSS compared to case 2B (10 day SRT) sludge, which had a steady state average of 119 (± 7) ml/g TSS, as shown in Figure 4.8. The hypothesis test on these means (using 0.05 significance level) suggested that there was enough statistical evidence to suggest that the 5 day SRT (case 2B) sludge will settle better than the 10 day SRT (case 2A) sludge.

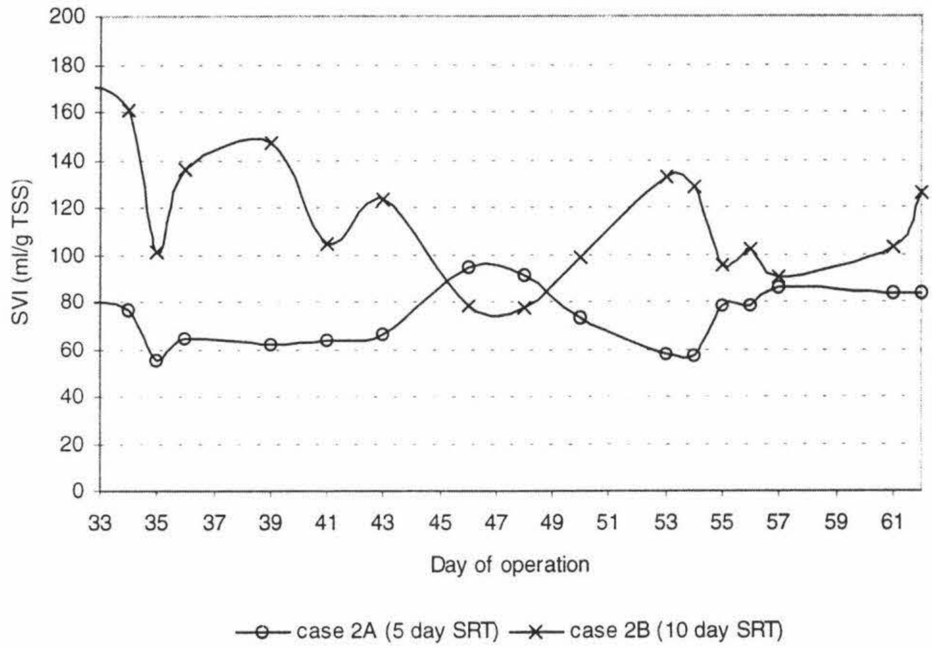

Figure 4.8: The steady state sludge volume index trend for both cases of experiment 2.

The 5 day SRT (case 1A) generated sludge with more filamentous bacteria than in case 2B, which is why the SVI is higher for case 1A. Filamentous growth in experiment 1 was linked to poor activated sludge seed, and problems with aeration. These problems were eliminated in experiment 2.

4.2.7 Organic Matter Removal Efficiency

4.2.7.1 Experiment 1

The total chemical oxygen demand removal efficiency (E_{COD}) was estimated from the influent and effluent total COD concentrations (COD_O and COD_E). Case 1A had an average E_{COD} of 58 (± 11) %, as shown in Figure 4.9. Case 1B (15 day SRT) had a steady state average E_{COD} of 64 (± 11) % as shown in Figure 4.10.

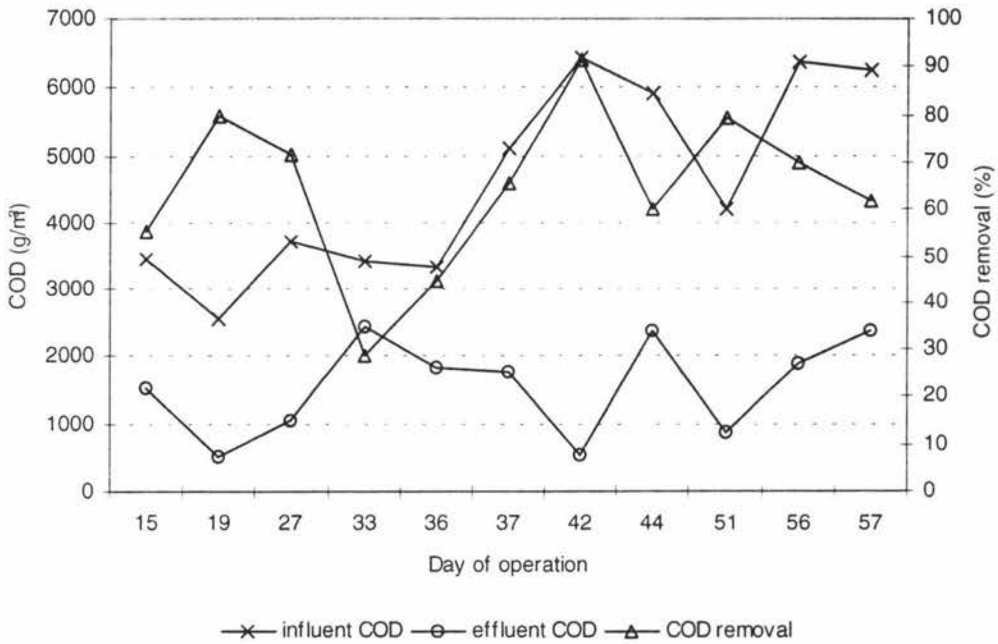

Figure 4.9: Influent and effluent chemical oxygen demand concentrations (COD) and total COD removal efficiency steady state trends for case 1A (5 day SRT) of experiment 1.

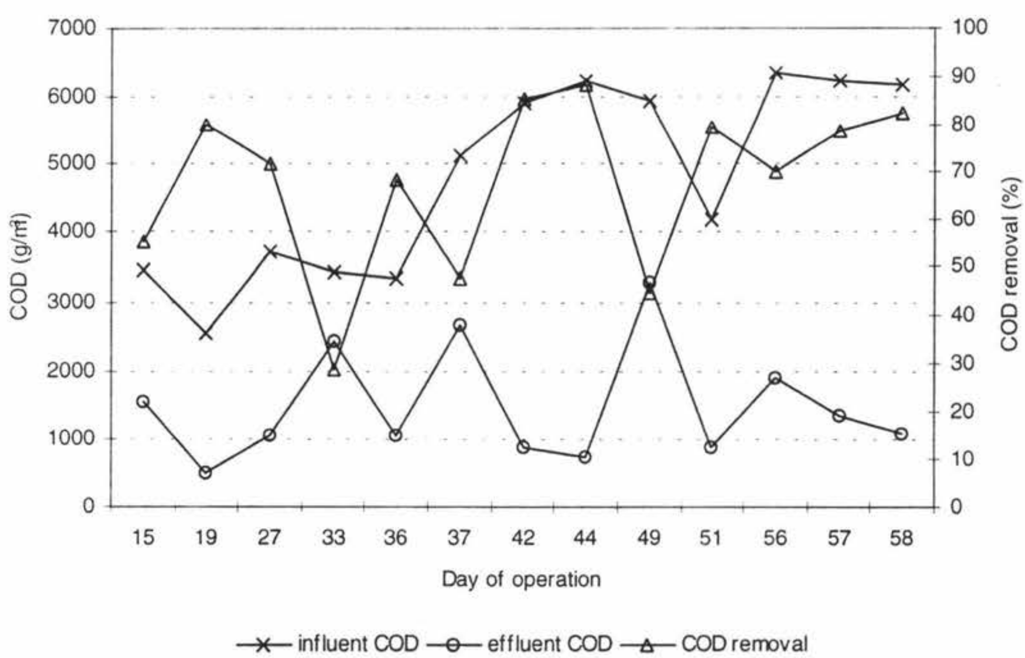

Figure 4.10: Influent and effluent COD concentrations and total COD removal efficiencies for case 1B (15 day SRT) of experiment 1.

Effluent total COD concentration from the 5 day SRT case averaged 1676 (± 300) g/m^3 and 1523 (± 413) g/m^3. The high effluent total COD in both cases was caused by the large effluent suspended solids concentrations.

The soluble COD removal efficiency for both cases of experiment 1, and the respective influent and effluent soluble COD concentrations are shown in Figure 4.11 and Figure 4.12.

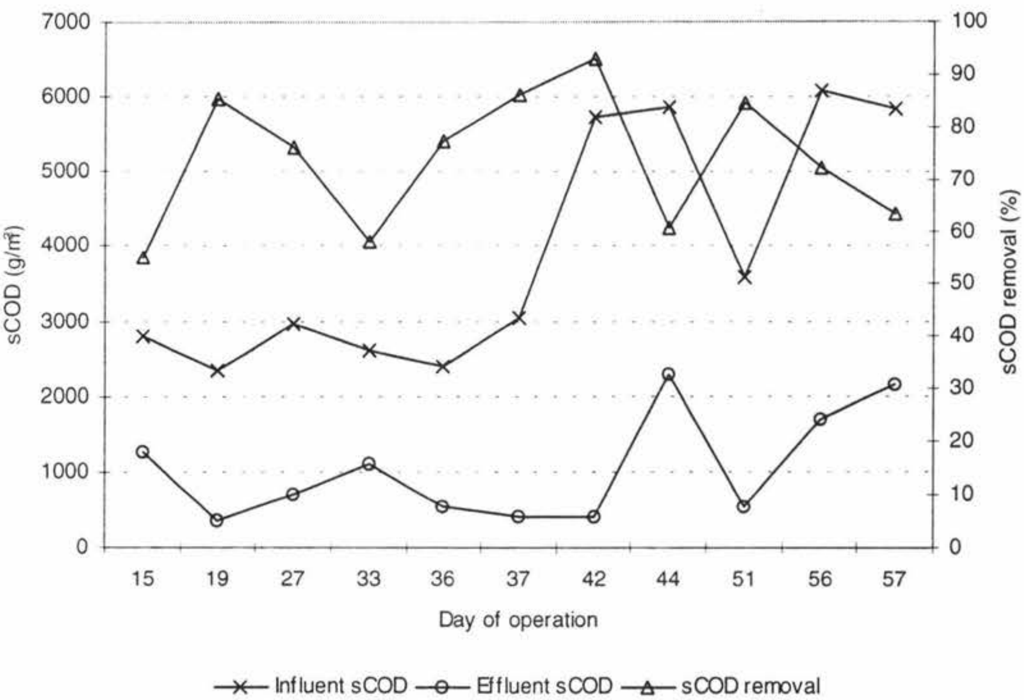

Figure 4.11: Influent and effluent soluble COD concentrations and soluble COD removal efficiencies for case 1A (5 day SRT) of experiment 1.

The steady state average effluent soluble COD concentration for 5 day SRT control (case 1A) was 915 (± 296) g/m^3. The corresponding average for 15 day SRT control (case 1B) was 755 (± 96) g/m^3.

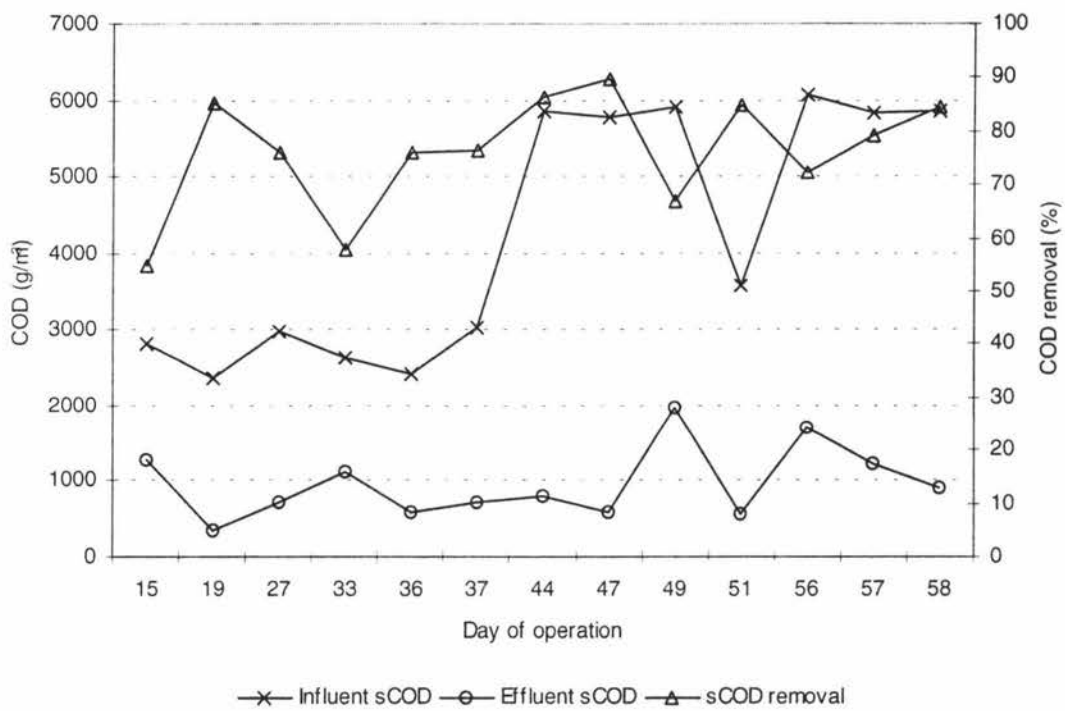

Figure 4.12: Influent and effluent soluble COD concentrations and soluble COD removal efficiencies for case 1B (15 day SRT) of experiment 1.

In section 4.1.2, it was concluded that the soluble fraction of fellmongery wastewater exerted a lower percentage of the total BOD than the non-soluble fraction. The high effluent soluble COD concentrations here show that the influent soluble organic matter in fellmongery wastewater may not be totally biodegradable.

4.2.7.2 Experiment 2

Case 2A (5 day SRT) achieved a steady state average biochemical oxygen demand removed (E_{BOD}) of 99 %, and case 2B (10 day SRT) achieved a steady state average of 98 %. Both are more than acceptable for meeting the estimated effluent quality goal of 40 % BOD removal, which was discussed in section 4.1.12.2. Hypothesis testing of this data using a significance level of 0.05 suggests that there was not a statistically significant difference between these removal efficiencies. This means that the 5-day (case 2A) and the 10-day (case 2B) SRT control are capable of maintaining similar and relatively high process performance in terms of BOD removal. In terms of total chemical oxygen demand removal (E_{COD}, %) there was no statistical evidence of a difference between case 2A and 2B. Case 2A managed an E_{COD} of 88

(± 2) % (Figure 4.13), and case 2B managed 82 (± 3) % (Figure 4.14) using an HRT of 6.4 days during the steady state period.

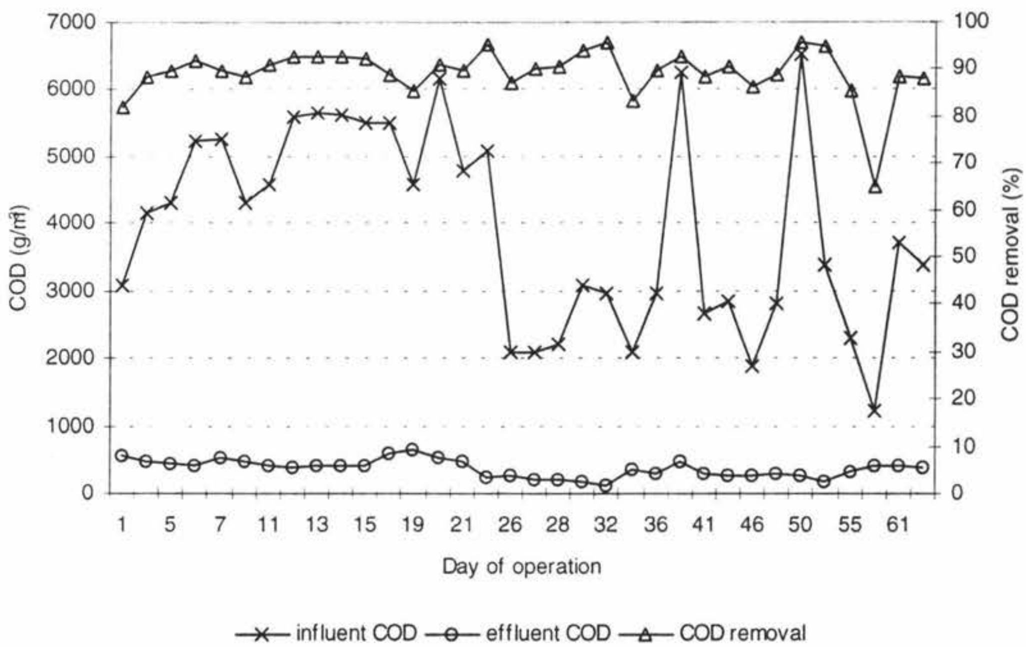

Figure 4.13: Influent and effluent total COD concentrations and total COD removal efficiencies for case 2A (5 day SRT) in experiment 2.

The steady state average effluent total COD concentration from the 5 day SRT (case 2A) was 323 (± 25) g/m^3, and 460 (± 25) g/m^3 from the 10 day SRT (case 2B).

The lower total COD concentrations in experiment 2 in comparison to experiment 1 were due to the lower effluent volatile suspended solids concentrations obtained in experiment 2.

The average effluent soluble COD concentration from the 5 day SRT was 265 (± 25) g/m^3 at steady state (Figure 4.15). The corresponding value for the 10 day SRT was 349 (± 22) g/m^3 (Figure 4.16). These are relatively high soluble COD concentrations, and indicate that the influent soluble COD has a siginificant proportion of organic matter that may not be biodegradable. The steady state average soluble COD removal efficiency for the 5 day SRT was 85 (± 2) %, and 80 (± 2) % for the 10 day SRT. Rawlings *et al* (1987) found that they could achieve a soluble COD removal of 72 % using an HRT of 2 days and an SRT of 5 days.

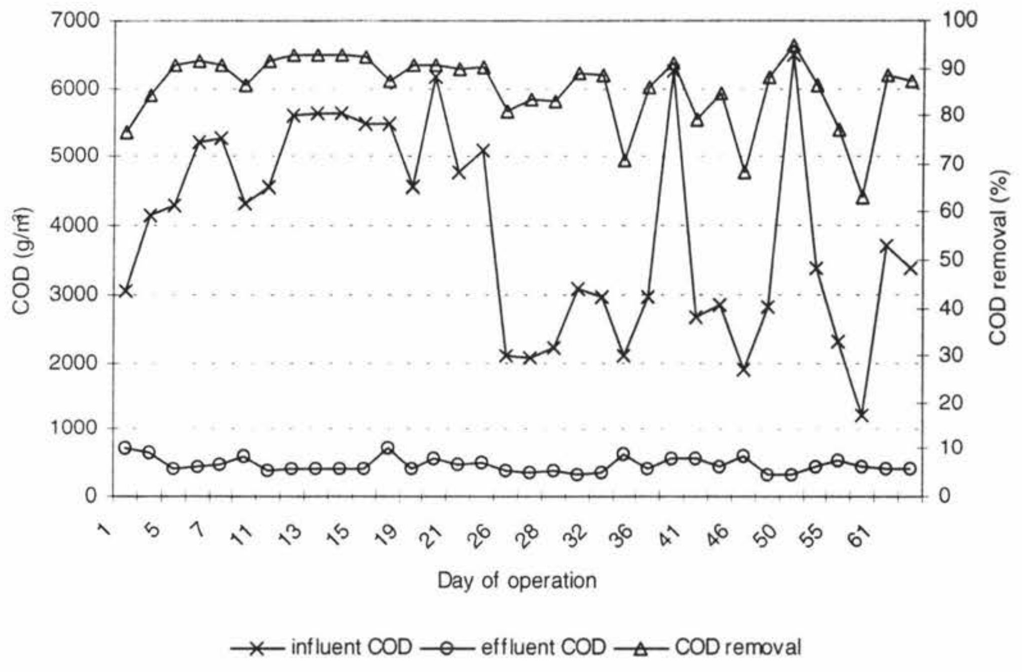

Figure 4.14: Influent and effluent total COD concentrations and total COD removal efficiencies for case 2B (10 day SRT) in experiment 2.

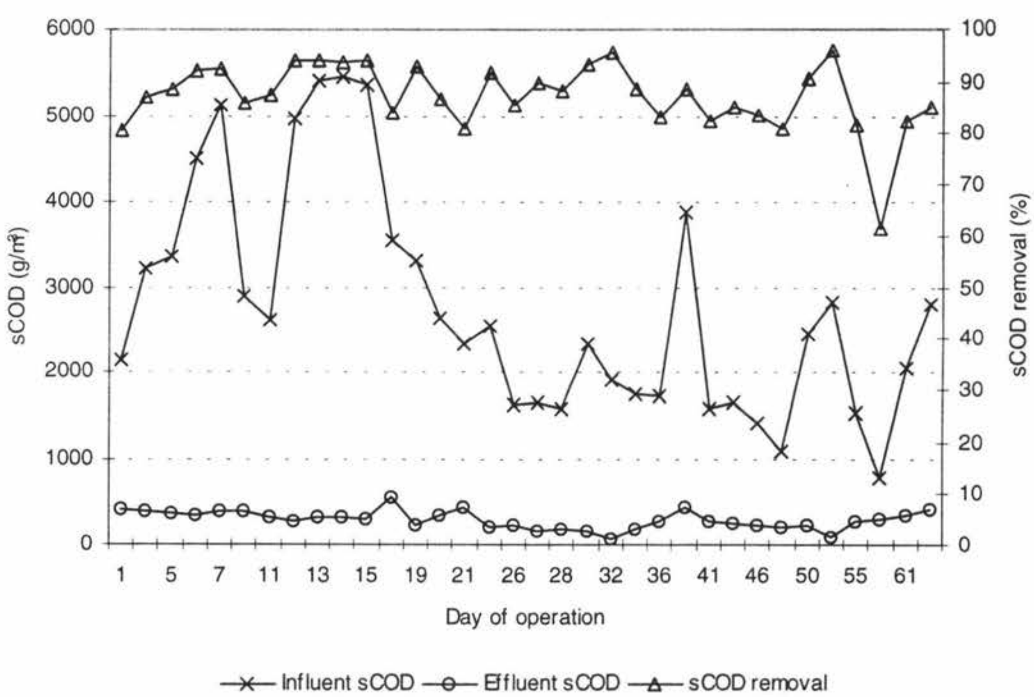

Figure 4.15: Influent and effluent soluble COD concentrations and soluble COD removal efficiencies for case 2A (5 day SRT) of experiment 2.

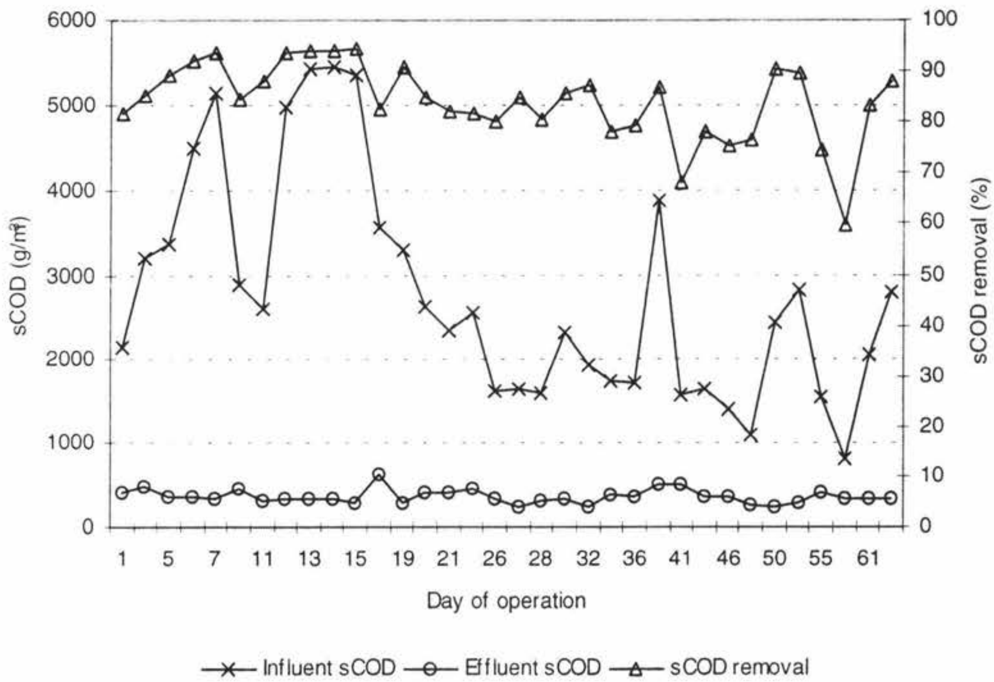

Figure 4.16: Influent and effluent soluble COD concentrations and soluble COD removal efficiencies for case 2B (10 day SRT) of experiment 2.

Therefore, soluble organic matter removal by the activated sludge process treating fellmongery wastewater appears to decrease as the hydraulic retention time decreases. This is not a major finding but does present an important design and operation consideration for fellmongery wastewater treatment.

4.2.8 Qualitative Observations

There are several influences on the settleability of a particular sludge, but most can be linked to the microbial population and its apparent state. This section discusses some qualitative observations made during the course of both experiments that can be used to characterise the microbial populations.

4.2.8.1 Experiment 1

Investigations using the microscope included evaluating floc structure and presence of filamentous bacteria. Floc structure can be divided into two parts, microstructure and macrostructure. Microstructure is formed by bioflocculation, which is casued by extracellular polyelectrolytes. Macrostructure is formed by filamentous bacteria (Jenkins *et al*, 1995). If the microbial population contains too much filamentous bacteria then the floc macrostructure becomes too extensive producing very large flocs that do not settle well.

The case 1A (5 day SRT) floc macrostructure appeared to be better than case 1B because filamentous bacteria were not dominating the floc macrostructure. Filamentous growth dominated case 1B sludge microbial population, which caused failure of the floc macrostructure. Failure of the floc macrostructure in this case is the reason for the poor sludge settleability and thus the unacceptable SVI for case 1B sludge.

4.2.8.2 Experiment 2

Case 2A (5 day SRT) sludge formed small flocs and dispersed bacteria remained in the wastewater solution giving rise to the high effluent suspended solids concentration. Case 2B (10 day SRT) sludge formed well-shaped (spherical-type) flocs that settled together thus minimising dispersion.

4.2.9 Summary

Experiment 1 was not successful for evaluating SRT control because the microbial population in both cases was dominated by filamentous bacteria. However, several important inferences can be made from experiment 1. Firstly, experiment 1 showed that during shock suspended solids loads, the effluent suspended solids load did not meet the effluent quality target. It is not known why case 1A remained unaffected by the sudden increase of influent suspended solids. High influent total suspended solids concentrations, especially shock loads should not be avoided if possible. The need for increased primary suspended solids removal efficiency is revisited. Table 4.6 compares the effluent suspended solids data attained from a similar study by Rawlings *et al* (1987) with the data from this study.

SRT days	HRT days	Effluent TSS g/m³	Source
5	6.4	117	This study
9	2	100	Rawlings *et al*, 1987
10	6.4	172	This study
18	2	100	Rawlings *et al*, 1987

Table 4.5: Effluent suspended solids concentrations with respective hydraulic retention time and solids retention for comparison.

By comparsion, the effluent suspended solids concentrations for an SRT between 5 and 9 days are lower than those produced with an SRT of 10 days. An SRT of 18 days also produced low effluent suspended solids concentrations. More research is required to investigate the higher SRT range (15 days and over) for fellmongery wastewater treatment. For this project, the 10 day SRT is recommended as it will produce stable process response with less sludge wastage volume than a 5 day SRT. This will also help minimise sludge handling costs.

4.3 STEADY STATE ANALYSIS OF THE ACTIVATED SLUDGE PLANT

4.3.1 Introduction

A mathematical model of the activated sludge plant will provide the designer and operator with a tool to investigate plant responses under different conditions so that control decisions can be made before problems arise (Patry *et al*, 1989). The objective of this section was to generate a simple steady-state mathematical model for describing the biochemical and physical operations occurring in the fellmongery activated-sludge plant. The model was to be based on mass balances of biomass and organic substrate so that process performances could be calculated. The control parameter was the solids retention time (SRT).

4.3.2 Conceptualisation of the fellmongery activated sludge plant

Influent wastewater from the pretreatment plant is contacted with the recycled sludge in the contact chamber (2-3 mins hydraulic retention time) and then discharged to basin one as shown in Figure 4.17. The combined volumes of basin one (V_1, m³) and two (V_2, m³) provide a hydraulic retention time (HRT, days) of 4 to 7 days depending on the influent wastewater volume (Q_O, m³/d). Mixed liquor from basin two ($MLSS_2$, g/m³) is pumped into the clarifier using a variable-speed pump (P_2, Hz). The solids loading rate (SLR, kg TSS/m²/h) for the clarifier can be controlled by adjusting the speed of the clarifier-influent pump.

Thickened sludge is pumped from the bottom of the clarifier using the underflow pump (P_U, Hz). The speed of this pump (P_U) can be used to control the sludge blanket height (SBH, m) in the clarifier and the volume of recycled sludge (Q_R, m³/d). Sludge is wasted from the underflow line using the waste pump (P_W, %[5]).

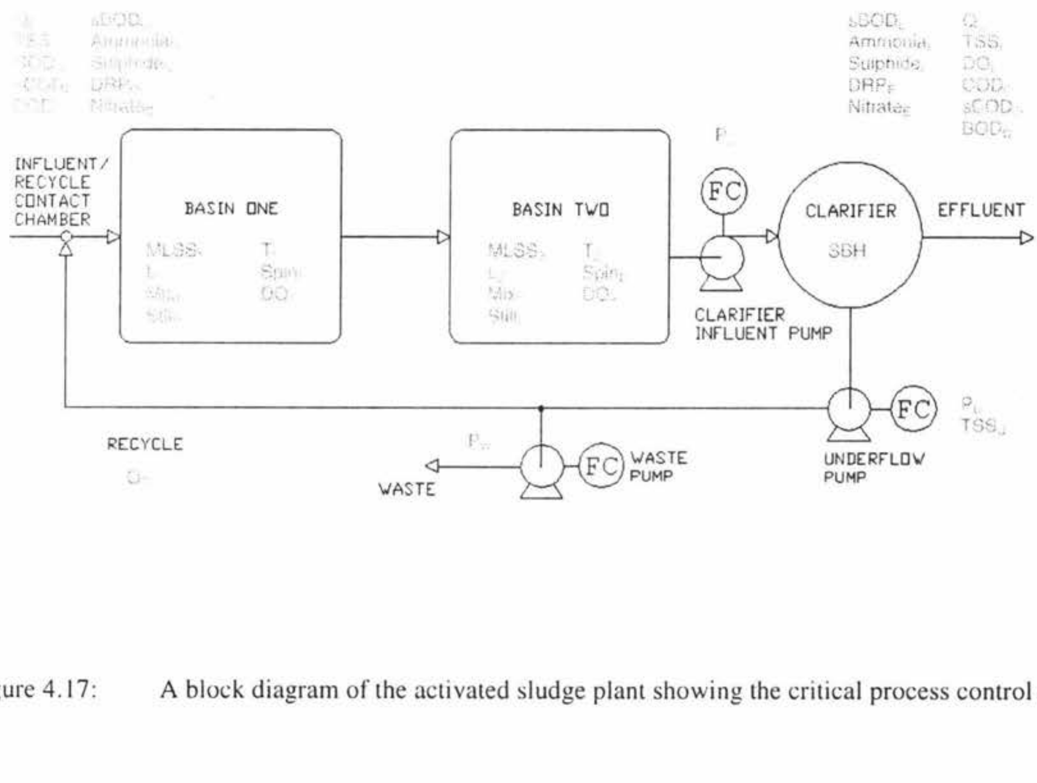

Figure 4.17: A block diagram of the activated sludge plant showing the critical process control points.

The critical process control points in the fellmongery activated sludge plant are therefore:

1. The clarifier-influent pump,
2. The underflow pump, and
3. The waste pump, shown in Figure 4.17.

The clarifier-influent pump is a critical control point for stable clarifier operation as the stability of the clarifier will effect the overall stability of the activated sludge plant and

[5] P_W is controlled from a PLC in conjunction with operation of the sludge dewatering plant.

therefore the effluent quality. The chosen speed for this pump must reflect the settleability of the mixed liquor from basin two and the capacity of the clarifier to maintain stable clarifier operation.

The underflow pump is important for withdrawing sludge from the clarifier at an appropriate rate, and maintaining an acceptable recycle sludge volume. Its speed should be a function of the clarifier-influent pump speed to avoid accumulation of suspended solids.

The current process control, strategy failed to recognise the importance of the waste pump, and provided only a crude estimate of the waste sludge volume. This method was neither accurate nor was it acceptable for monitoring sludge handling costs. The waste pump is of particular importance for solids retention time (SRT) control and hence it is the point for control of the combined biomass growth rate (r_g, g VSS/m^3/d) (WPCF, 1987).

One operating day was divided into 24 hours, so that each 24 hour duration would have its own data for a particular set of targets such the pump speeds. This method was required because the plant does not have an automated supervisory control and data aquistion (SCADA) system.

Some of the control parameters are given target values that must be achieved during a particular 24 hour period. Others have target values that should not be exceeded. This was the basis of the target-achievement idea that was to bind the new process control and operation strategy. Further discussion on this idea can be found in section 4.4, but for now the reader should realise that the system input (SI) values are given new values daily (or as otherwise stated). So the consequential variables (CV) calculated daily, are acheivements for the previous 24 hour period, or targets for the next 24 hour period. This is the downside of offline monitoring as there is a delay time of one 24 hour operating period before updated information is used for calculating new targets.

4.3.3 Assumptions

The following assumptions were made in order to simplify the model:

1. The activated sludge basins are being maintained at a pseudo steady-state, which means that there is no net accumulation of biomass or substrate. This assumption was made to

eliminate the accumulation term of volatile suspended solids (VSS), chemical oxygen demand (COD) and soluble biochemical oxygen demand (BOD) from the respective mass balance equations.

2. The volatile suspended solids concentration (VSS) estimates the concentration of biomass for any process stream in the activated sludge plant. This is a very general assumption considering the recent advances in measuring biomass concentration and viability (Aitken *et al*, 1994). The amount of active biomass is in fact only a fraction of the total volatile suspended solids concentration (Henze *et al*, 1987, Ekenfelder *et al*, 1995)). However the volatile suspended solids concentration is still the most rapid, easily performed and inexpensive method for quantifying biomass in activated sludge to date (WPCF, 1987). Its use here is justified for simplistic control measurements.
3. There are no reactions occurring in the clarifier to change the concentration of organic substrate in the supernatant after it leaves basin two. In reality, aerobic-respiration on the organic substrate in the aerated basins will continue in the clarifier but not to the same extent.
4. The aerated basins are completely mixed so the dissolved oxygen concentration is the same at any point (Metcalf *et al*, 1993). This is not currently the case in reality as discussed in section 4.1.7. But once recommendations for improved aeration performance are implemented this assumption should hold for the full-scale plant. However, even under the current aeration strategy, BOD removal is still more than adequate.
5. Samples of wastewater taken for measurement of process variables are representative.
6. A combined mixed liquor volatile suspended solids concentration (MLVSS) can be used to estimate the overall concentration of biomass in the fellmongery activated sludge basins. This assumption was made in order to simplify the mass balances.
7. The influent wastewater volatile suspended solids, contains no biomass.

4.3.4 Nomenclature and Model Development

4.3.4.1 Introduction

The following tables list all the major nomenclature for the model alongside their respective descriptions. Each variable in the model has been categorised as a system input (SI) or a consequential value (CV). A SI variable cannot be controlled from within the activated sludge plant and thus cannot be altered within the model. A CV is defined as a variable that depends on one or more other variables according to a known equation or logic expression.

4.3.4.2 The Influent Wastewater

The influent wastewater is defined using the variables listed in Table 4.6. There are 9 SI variables and 2 CV variables. The SI variables are given values regularly as new information on the influent characteristics is collected. The two CV variables, BOD_O and VSS_O are estimated from their specific expressions.

Variable	Units	Type	Description
Q_O	m^3/d	SI	Influent volume
$SCOD_O$	g/m^3	SI	Influent soluble COD
COD_O	g/m^3	SI	Influent COD
$SBOD_O$	g/m^3	SI	Influent soluble BOD
BOD_O	g/m^3	CV	Influent BOD
BOD/COD_O		SI	Influent BOD/COD ratio
TSS_O	g/m^3	SI	Influent TSS
VSS_O	g/m^3	CV	Influent VSS
VSS/TSS_O		SI	Influent VSS/TSS ratio
$Ammonia_O$	g/m^3	SI	Influent Ammonia
SP_O	g/m^3	SI	Influent soluble phosphate

Table 4.6: Nomenclature of the influent variables.

The 5 day carbonaceous biochemical oxygen demand (BOD) is a standard method for estimating the oxygen required to bio-oxidise the organic substrate. However for process control decisions involving aeration requirements and the BOD effluent quality target, information concerning biodegradable organic matter is required on a more frequent basis than 5 days, which is the typical time required for evaluating the BOD. The chemical oxygen demand (COD) is a Standard Method for measuring the total organic matter concentration in the wastewater solution (biodegradable and unbiodegradable) and results can be obtained within 2 to 3 hours. Historical data can be used to generate the BOD to COD ratio. As discussed in section 4.1.2, the BOD/COD ratio was found to be approximately 0.34. This can be used in Equation 4.4 to estimate the daily influent BOD concentration from the daily COD concentration.

$$BOD_O \approx 0.34(COD_O)$$

Equation 4.4: Estimated biochemical oxygen demand for the influent wastewater using the corresponding total chemical oxygen demand concentration.

This equation is known to be applicable to many different wastewaters as most have a relatively constant BOD/COD ratio. For instance, Eckenfelder *et al* (1995) published a range of BOD/COD ratio for various wastewaters including pure synthetic wastewaters.

The wastewater characterisation study established that the volatile suspended solids to total suspended solids ratio (VSS/TSS_O) is approximately 0.81 for the pretreated fellmongery wastewater. Thus, Equation 4.5 was incorporated into the model to estimate the VSS concentration of the influent using the VSS/TSS_O ratio and the measured influent total suspended solids concentration (TSS_O).

$$VSS_O = 0.81(TSS_O)$$

Equation 4.5: Estimated volatile suspended solids concentration for the influent using the corresponding total suspended solids concentration.

This equation was included to reduce data collection costs and in light of the current lack of appropriate analysis equipment.

4.3.4.3 The Aerated Basins

Each basin has 7 SI vaiables and 2 CV variables each, as shown in Table 4.7 and Table 4.8.

Variable	Units	Type	Description
$MLSS_1$	g/m^3	SI	Mixed liquor suspended solids
$MLVSS_1$	g/m^3	CV	Mixed liquor volatile suspendeds solids
L_1	mm	SI	Basin level
V_1	m^3	CV	Basin volume
$Spin_1$	%	SI	Centrifuge solids
T_1	C	SI	Basin temperature
DO_1	g/m^3	SI	Basin dissolved oxygen concentration
$still_1$	cm	SI	30 minute settlometer reading
mix_1	ml	SI	30 minute settling column reading

Table 4.7: Nomenclature of basin one.

The mixed liquor volatile suspended solids concentration (MLVSS) is estimated from the mixed liquor total suspended solids concentration (MLSS) with the VSS/TSS ratio for both basins using Equation 4.6 and Equation 4.7.

Variable	Units	Type	Description
$MLSS_2$	g/m^3	SI	Mixed liquor suspended solids
$MLVSS_2$	g/m^3	CV	Mixed liquor volatile suspended solids
L_2	mm	SI	Basin level
V_2	m^3	CV	Basin volume
$Spin_2$	%	SI	Centrifuge solids
T_2	°C	SI	Basin temperature
DO_2	g/m^3	SI	Basin dissolved oxygen concentration
$still_2$	ml	SI	30 minute settleometer reading
mix_2	cm	SI	30 minute settling column reading

Table 4.8: Nomenclature of basin two.

$$MLVSS_1 = {}^{VSS}\!/_{TSS}\,(MLSS_1)$$

Equation 4.6: Estimated mixed liquor volatile suspended solids concentration for basin one.

$$MLVSS_2 = {VSS}/{TSS}(MLSS_2)$$

Equation 4.7: Estimated mixed liquor volatile suspended solids concentration for basin two.

Typical values of the mixed liquor VSS/TSS ratio lie between 0.7 and 0.8 (Metcalf *et al*, 1991) for the usual solids retention time range of 5 to 15 days. For this model, a value of 0.75 was used.

The volume of each basin was estimated using the associated mixed liquor level and Equation 4.8 and Equation 4.9.

$$V_1 = 2(L_1) + 3600$$

Equation 4.8: Estimated total volume of basin one.

$$V_2 = 1.5(L_2) + 2700$$

Equation 4.9: Estimated total volume of basin two.

The combined basin variables are listed in

Table 4.9.

Variable	Units	Type	Description
VSS/TSS		SI	Mixed liquor VSS/TSS ratio for basin one two
MLVSS	g/m³	CV	Average MLVSS
V	m³	CV	Total volume for biological reaction

Table 4.9: Nomenclature of the combined basin variables.

The weighted-MLVSS concentration is calculated using Equation 4.10, which is important for calculating the solids retention time (SRT) and biomass mass balance.

$$MLVSS = \frac{MLVSS_1 V_1 + MLVSS_2 V_2}{V}$$

Equation 4.10: The weighted mixed liquor volatile suspended solids concentration.

Assumption 6 explains why the weighted-MLVSS was included in the steady state model.

4.3.4.4 The Clarifier

There are 8 SI variables and 4 CV variables for the clarifier as shown in Table 4.10 and Table 4.11. The clarifier influent pump is controlled using a speed controller (P_2, Hz) rated from 0 to 50 Hz (0 to 2515 m³/d). The total volume of basin two mixed liquor discharged to the clarifier is calculated using the sum of each pump speed (P_2^i, Hz) for each hour of the 24 hour period, and the pump conversion factor (k_2, m³/ h.Hz), as shown in Equation 4.11.

Variable	Units	Type	Description
Q_2	m^3/d	CV	Clarifier influent volume
P_2	Hz	SI	Clarifier influent pump speed
k_2	$m^3/h.Hz$	SI	Clarifier influent pump conversion factor
t	h/d	SI	A one hour division of the 24 hour period
SVI	ml/gTSS	CV	Sludge volume index
SSV_T	ml/l	SI	Settled sludge volume after T mintues
SBH	m	SI	Sludge blanket height
d_C	m	SI	Clarifier sidewall depth
A_C	m^2	SI	Clarifier surface area
OFR	$m^3/m^2/d$	CV	Overflow rate
SLR	kg $TSS/m^2/h$	CV	Solids loading rate

Table 4.10: Nomenclature of the clarifier influent related variables.

Variable	Units	Type	Description
Q_U	m^3/d	CV	Underflow volume
P_U	Hz	SI	Underflow pump speed
k_U	$m^3/h.Hz$	SI	Underflow pump conversion factor
TSS_U	g/m^3	SI	Underflow TSS
VSS_U	g/m^3	CV	Underflow VSS
$Spin_U$	mm	SI	Underflow centrifuge solids

Table 4.11: Nomenclature of the clarifier underflow variables.

$$Q_2 = k_2 t \sum_{i-1}^{24} (P_2^{\,i})$$

Equation 4.11: Total clarifier influent flowrate.

Under the current process-control strategy, the value of P_2 was chosen based on qualitative observations of the level of mixed liquor in basin one and two (L_1 and L_2) and the quantity of skins being processed in the fellmongery (skins). This method takes no account of the sludge settleability, and does not consider the possibility of hydraulic overload. Consequently, the clarifier is frequently unstable and the sludge blanket (SBH) is frequently very close to the top of the clarifier as discussed in section 1.1. The sludge blanket should be kept below 25 % of the side wall depth (d_c, m) (WPCF, 1987).

The variable chosen for controlling the clarifier-underflow pump speed was the settled sludge concentration (SSC_T, %) that corresponds to the optimal settling time (SST_T, mins). This value is obtained from the settling curve formed by plotting the settled sludge concentration (y-axis) against the associated settling time (x-axis). The optimal SCC_T is taken as the point where the curve slope begins to decrease, indicating that settling rate is decreasing or is close to completion. The underflow pump speed (P_U, Hz) is calculated using Equation 4.12.

$$P_U = \frac{Spin_2 P_2}{SSC_T}$$

Equation 4.12: The minimum underflow pump speed for the next 24 hour period.

The clarifier-influent pump speed (P_2, Hz) is calculated by steady state solids balance over the clarifier to give Equation 4.13.

$$P_2 = \frac{24k_U P_U TSS_U + Q_E TSS_E}{24k_2 MLSS_2}$$

Equation 4.13: The maximum clarifier-influent pump speed for the next 24 hour period.

The solids loading rate (SLR, $kg/m^2/d$) which is calculated using Equation 4.14 and is used as check that the clarifier influent pump speed is not causing solids overload.

$$SLR = \left(\frac{Q_2 MLSS_2}{1000 A_C} \right)$$

Equation 4.14: The clarifier solids loading rate.

The target SLR is set according to previous experience as to what provides stable clarifier operation. In this case, a suitable target SLR was not known. Thus, the target SLR is an additional SI that can be changed according to practical experience. The current target SLR was set to an arbitrary value 70 kg/m²/d, which is within the suggested range of 23 to 117 kg/m²/d (Metcalf *et al*, 1991).

The clarifier overflow rate (OFR, m³/m²/d) was also incorporated into the model as a check that the clarifier is not subjected to hydraulic overload.

$$OFR = \frac{Q_2}{A_C}$$

Equation 4.15: The clarifier overflow rate.

At the maximum flow of 2515 m³/d, the overflow rate is 22.26 m³/m²/d. The suggested range is from 8.14 to 16.28 m³/m²/d (Metcalf *et al*, 1991), therefore the clarifier may become hydraulically overloaded at peak influent flowrates. However, the average pretreated wastewater volume is only 925 m³/d which translates to an OFR of 8.19 m³/m²/d. During average wastewater flows the clarifier should not experience hydraulic overload. This assumes that the clarifier influent pump speed is not changed by more than 5 to 10 % daily.

The sludge volume index (SVI, ml/ g) is calculated from the settled sludge volume after 30 minutes ($still_2$, ml) and basin two mixed liquor suspended solids concentration ($MLSS_2$, g/m³) using Equation 4.16.

$$SVI = \frac{still_2}{MLSS_2} 1000$$

Equation 4.16: The sludge volume index for basin two mixed liquor.

The clarifier underflow pump is the second critical control point and is controlled using the pump speed, P_U (Hz). The pump is rate from 0 to 50 Hz (0 to 786 m^3/d). The underflow volume achieved during a 24 hour period (Q_U, m^3/d) is calculated using Equation 4.17 and the sum of the 24 underflow pump speeds used during the 24 hour period.

$$Q_U = k_U t \sum_{i=1}^{24} (P_U^{\,i})$$

Equation 4.17: The total underflow volume.

For example, when $MLSS_2$ is 6000 g/m^3, Q_2 is 1000 m^3/d, Q_E is 925 m^3/d and TSS_U is 10000 g/m^3. The target P_U is 38 Hz, which translates to a total underflow volume of 597 m^3/d.

4.3.4.5 Sludge Wasting and Solids Retention Time Control

Sludge wasting and SRT-control have 2 SI variables, 1 CV variable and two variables that interchange between CV and SI status, as shown in Table 4.12.

Variable	Units	Type	Description
SRT	d	SI/CV	Solids retention time
k_W	$m^3/h.\%$	SI	Waste pump conversion factor
Q_W	m^3/d	CV	Waste sludge volume
P_W	%	SI/CV	Waste pump speed

Table 4.12: Nomenclature of the waste activated sludge control variables.

SRT is either the target solids retention time to be maintained by setting the waste pump speed to the target value P_W (%). Or SRT is the solids retention time achieved for the previous 24 hour period. The target P_W is calculated using Equation 4.18, and assuming that each 1 hour duration of the 24 hour period uses the same pump speed.

$$P_W = \frac{\left(\frac{MLVSS(V)}{SRT} - Q_E TSS_E\right)}{24 k_W TSS_U}$$

Equation 4.18: Target waste pump speed to be maintained during a 24 hour period in order to maintain the target solids retention time..

Q_W (m^3/d) is the target waste activated sludge volume that needs to be wasted from the plant during the 24 hour period to maintain the target SRT. Equation 4.19 is used to calculate Q_W, which was derived from the SRT equation (Equation 4.21).

$$Q_W = \left(\frac{MLVSS(V)}{SRT} - Q_E VSS_E\right) \Big/ VSS_U$$

Equation 4.19: The waste activated sludge volume to maintain the solids retention time.

Q_W (m^3/d) can also be the waste activated sludge volume achieved from the previous 24 hour period. In that case, it is a summation function of the 24 waste pump speeds used for each 1 hour duration of the 24 hour operating period. The conversion factor k_W is used to convert the waste pump speeds to a volume using Equation 4.20.

$$Q_W = k_W t \sum_{i=1}^{24} (P_W{}^i)$$

Equation 4.20: The total waste sludge volume.

The waste sludge volume achieved and other system input data collected for the previous 24 hour period is used to calculate the SRT achieved for that period, as shown in Equation 4.21.

$$SRT = \frac{MLVSS(V)}{Q_E VSS_E + Q_W VSS_U}$$

Equation 4.21: The solids retention time.

4.3.4.6 Sludge Recycle

A simple balance of flow around the waste point on the underflow line (Figure 4.17) was used to derive Equation 4.22 to calculate the recycle activated sludge volume (Q_R, m^3/d).

$$Q_R = Q_U - Q_W$$

Equation 4.22: The recycle sludge volume during a 24 hour period.

Variable	Units	Type	Description
R		CV	Recycle ratio
Q_R	m³/d	CV	Recycle sludge volume

Table 4.13: Nomenclature for the recycle line.

The total volume of sludge recycled to basin one can be calculated from the underflow and waste volumes. The recycle ratio is calculated for future reference, but is not used as a control parameter in this model.

$$R = \frac{Q_R}{Q_O}$$

Equation 4.23: Recycle ratio.

4.3.4.7 Effluent Discharge

The effluent has 9 SI variables and 2 CV variables as shown in Table 4.14.

Variable	Units	Type	Description
Q_E	m³/d	SI	Effluent volume
COD_E	g/m³	SI	Effluent total COD
$sBOD_E$	g/m³	SI	Effluent soluble BOD
BOD_E	g/m³	SI	Effluent total BOD
BOD_{E^*}	g/m³	CV	Effluent total BOD, estimated
BOD/COD_E		SI	Effluent BOD/COD ratio
TSS_E	g/m³	SI	Effluent TSS
VSS_E	g/m³	CV	Effluent VSS
VSS/TSS_E		SI	Effluent VSS/TSS ratio
$Ammonia_E$	g/m³	SI	Effluent Ammonia
$Sulphide_E$	g/m³	SI	Effluent Sulphide

Table 4.14: Nomenclature of the effluent variables.

The effluent BOD concentration (BOD_E^*, g/m³) is estimated using Equation 4.24, which has similar structure to Equation 4.1.

$$BOD_E^* = \left[BOD / COD_E \right] (COD_E)$$

Equation 4.24: Estimated biochemical oxygen demand concentration for the effluent using the corresponding total chemical oxygen demand concentration.

It was important to distingush the estimated effluent BOD from the weekly BOD measurement (BOD, g/m^3) for resource consent reporting. The resource consent stipulates that the effluent total and soluble BOD be measured once a week. But for monitoring of BOD removal performance the daily estimate of the effluent BOD was required.

The effluent volatile suspended solids concentration is estimated using a similar equation to Equation 4.5, and is shown as Equation 4.25.

$$VSS_E = \left[\frac{VSS}{TSS_E} \right] TSS_E$$

Equation 4.25: The estimated effluent volatile suspended solids (biomass) concentration.

4.3.4.8 Process Performance Measures

Operation of the fellmongery activated sludge plant is primarily to treat the wastewater and meet the effluent quality targets discussed in section 1.1.1. To do this the activated sludge plant must maintain certain process performances.

The total BOD removal efficiency is an important process performance measure because the resource consent is concerned with the total BOD and soluble BOD effluent loads. Knowledge of the current BOD removal efficiency (Equation 4.26) is valuable for predicting the total and soluble BOD loads in the effluent from influent data.

$$E_{BOD} = 100\left(1 - \frac{Q_E BOD_E}{Q_O BOD_O}\right)$$

Equation 4.26: The total biochemial oxygen demand removal efficiency

The TSS removal efficiency is another important process performance measure because the TSS load is specified by the resource consent (Equation 4.27). The effluent TSS load can be predicted from the influent data.

$$E_{TSS} = 100\left(1 - \frac{Q_E TSS_E}{Q_O TSS_O}\right)$$

Equation 4.27: The total suspended solids removal efficiency

The effluent ammonia load is also restricted by the resource consent, with the ammonia removal efficiency given by Equation 4.28.

$$E_{AMM} = 100\left(1 - \frac{Q_E Ammonia_E}{Q_O Ammonia_O}\right)$$

Equation 4.28: The ammonia removal efficiency

4.3.4.9 Sludge De-watering

The sludge de-watering plant is not the focus of this research project. However, because consistent SRT-control requires the continuous operation of the sludge de-watering plant, it was found necessary to include the two SI variables listed in

Table 4.15.

Variable	Units	Type	Description
Dry solids	%	SI	Dewatered sludge percent dry solids
Truckloads		SI	Truck loads

Table 4.15: Nomenclature of the sludge de-watering plant variables.

4.3.4.10 Mass Balances and Kinetic Equations

A steady state biomass (volatile suspended solids) balance across the entire activated sludge system shown in Figure 4.17 can be used to derive an equation for the biomass growth rate. The derivation is shown in Equation 4.29 and Equation 4.30, and uses the waste activated sludge volume achieved (Q_W, m³/d), as this value determines the SRT achieved and thus the biomass growth rate (r_g) at steady state.

$$0 = Q_O VSS_O - Q_E VSS_E - Q_W VSS_U + Vr_g$$

Equation 4.29: A steady state (zero accumulation) biomass balance across the entire activated sludge plant (basis = g VSS/m³).

Rearranging to make r_g (g VSS/m³/d) the subject gives Equation 4.30, which mathematically describes the steady state biomass growth rate for the fellmongery activated sludge system.

$$r_g = \frac{Q_W VSS_U + Q_E VSS_E - Q_O VSS_O}{V}$$

Equation 4.30: The biomass growth rate at steady state for the fellmongery activated sludge system.

Equation 4.30 can be used to demonstrate the principle of waste activated sludge control. An example situation can be set up: the activated sludge plant is at steady state, meaning no change in either the effluent or underflow TSS mass flow and minimal change in the influent TSS load. As the operator increases the WAS flowrate (Q_W, m³/d) to maintain a new lower SRT target set point, the biomass growth rate (r_g, g/m³/d) should increase to a new steady state after a period of 3 to 5 times the target SRT. This is why the SRT level can be related to so many process responses such as floc morphology and population dynamics (Jenkins *et al*, 1995), effluent suspended solids concentration (Lovett *et al*, 1987), and sludge settleability (Jenkins *et al*, 1995).

A steady state organic matter balance can be used to derive an equation for the organic substrate removal rate (r_{BOD}, g/m³/d). The balance is made across the entire fellmongery activated sludge plant if assumption 4 holds (section 4.3.3), and is shown as Equation 4.31.

$$0 = Q_O BOD_O - Q_E BOD_E + V(-r_{BOD})$$

Equation 4.31: The steady state organic substrate balance across the entire fellmongery activated sludge plant (basis = g BOD/m³).

Rearranging in terms of the substrate removal rate ($-r_{BOD}$) gives Equation 4.32.

$$-r_{BOD} = \frac{Q_E BOD_E - Q_O BOD_O}{V}$$

Equation 4.32: The substrate removal rate for the fellmongery activated sludge plant.

The aeration requirement can be computed from the BOD substrate removal rate and the rate of biomass generation using a steady state oxygen balance, as shown in Equation 4.33.

$$M_{AIR} = \frac{\left(\frac{V(-r_{BOD})}{f} + 4.57Q_O(TKN_O - TKN_E) - 1.42Q_W TSS_U\right)}{0.21n}$$

Equation 4.33: Estimated air requirement for carbonaceous biochemical oxygen demand removal and nitrogen oxidation. The variable 'n' is the overall oxygen transfer efficiency achieved. A value of 0.10 was used in this model.

The current process control strategy does not include aeration control. Consequently the aeration equipment is not optimised as discussed in section 4.1.7. Equation 4.33 may be useful in the future as it could become another addition to the target-achievement control-strategy, to further optimise the activated sludge plant in terms of operating costs.

4.4 DEVELOPMENT OF THE NEW PROCESS CONTROL AND OPERATION STRATEGY

4.4.1 Introduction

The process control and operation strategy presented here is a computer program designed specifically for the fellmongery situation and the conclusions drawn from the previous tasks. The existing operation strategy for the fellmongery activated sludge plant did not include an effective information-management system. The operator[6] simply entered information into an aging database and failed to make any important inferences about trends in specific process parameters. Control decisions were therefore virtually independent of most the information collected by the operator. Decisions tended to be made in response to problems, rather than made to predict and avoid potential problems.

Careful planning and information analysis must be used over a significant period to operate the activated sludge plant. For a 10 day SRT, data from as far back as 30 days should analysed to decide if the plant is responding consistently. The operator needs an effective and convenient method for using the information, to identify appropriate control decisions (Lai *et*

[6] Operator: any person that operates some part of the activated sludge plant

al, 1990). The Activated Sludge Operation Program (ASOP) developed here was constructed using the Microsoft Office database development tool, Microsoft Access.

An expert-system is an information-management system (Lai *et al*, 1995) that transforms information from the activated sludge plant into outputs that can be used to make control decisions. ASOP embodies a very simple expert-system developed as a consequence of this research, which is shown schematically in Figure 4.18.

4.4.2 The Knowledge-Base

A knowledge-base holds rules and conditions that are set by an expert in the field. The ASOP knowledge-base is comparatively simple and contains a set of conditions based on specific process variables and their values. These rules will be discussed in the following sections.

4.4.3 The Inference-Engine

The inference-engine distinguishes an expert system from a basic computer program (Giles *et al*, 1989). It examines the conditions (rules) set in the knowledge-base and compares them to the output from the calculation-engine to make suggestions to the ASOP-user[7]. The inference-engine helps the operator to work through a structured procedure to prevent process problems from occurring. The expert system presented by Lai *et al* (1990) included an inference-engine in the expert system box.

For ASOP, the inference-engine was split between the ASOP-user box and the expert-system box. The idea behind this was to allow the ASOP-user to maintain most of the inference making power coupled with the operation manual. The ASOP inference-engine was designed to produce simple suggestions based on the values of important process variables using basic heuristic rules set in the knowledge-base. For instance, one rule designed to output a suggestion to the ASOP-user for clarifier control uses the following code:

If (SVI > 140) (SVI = sludge volume index)

THEN ("PROBLEM: Sludge settleability has deteriorated, alterations are required to avoid increase in sludge blanket height. ACTION: (1) Trend analysis to ascertain whether a general rise in SVI is occuring, if YES then (2) Examine the activated

[7] ASOP-user: any person that enters data into ASOP, and uses the outputs and suggestions to make control decisions for the operator. The ASOP-user may be the operator on some days.

sludge floc for major increases in filamentous bacteria. (3) Analyse the influent BOD:solubleN:solubleP ratio to ensure it is at least 100:5:1 for sufficient nutrient supply. (4) Refer to the "Clarifier Operation" section of the operation manual for further direction.")

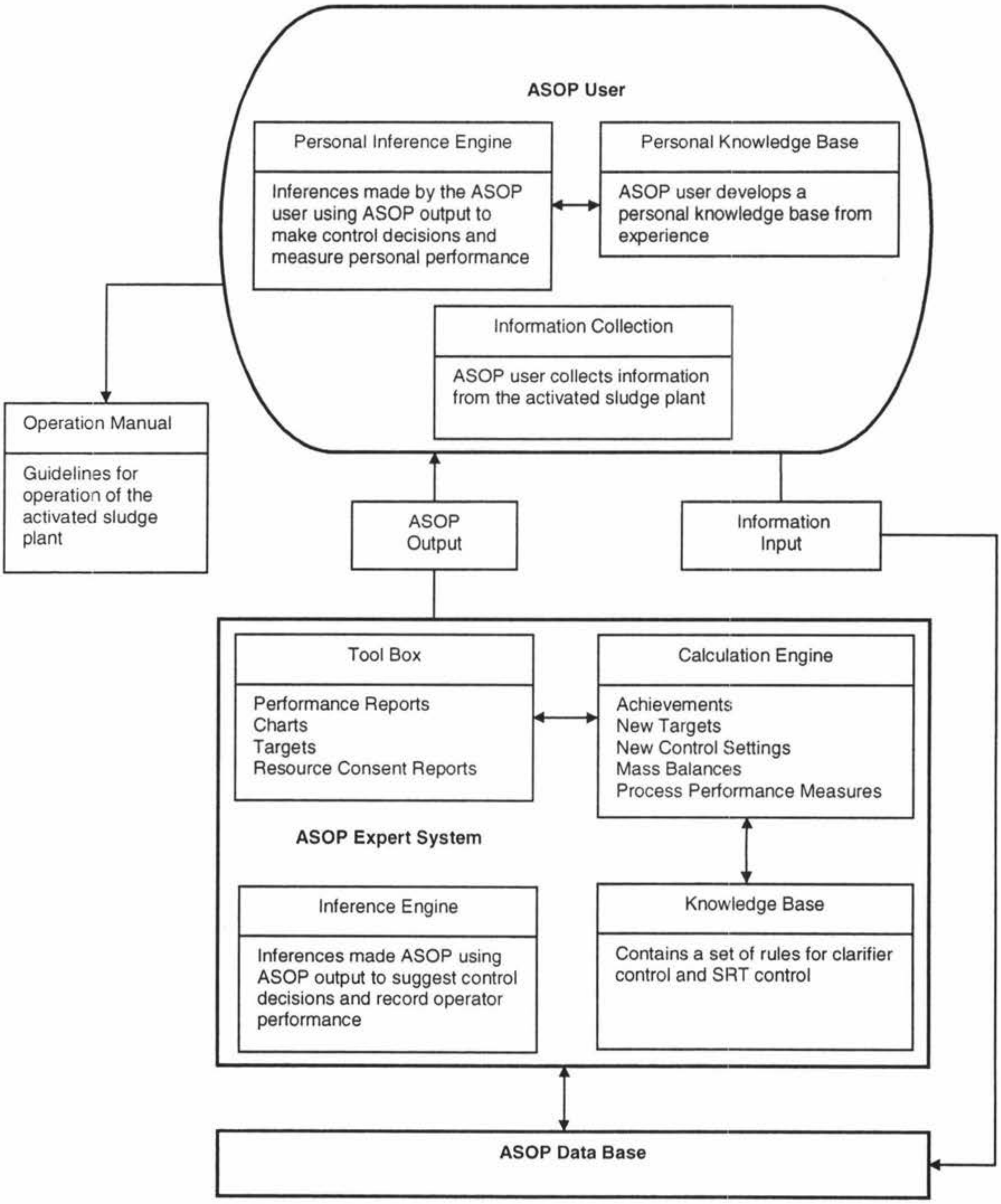

Figure 4.18: Structure of the activated sludge operation program (ASOP).

Based on this suggestion the ASOP-user will analyse historical sludge volume index (SVI, measure of sludge settleability) data with the appropriate charts, which can be generated automatically in ASOP. They decide, using their personal inference-engine whether there is a general increasing SVI trend. If there is an increasing trend, the ASOP-user is given three suggestions for further diagnosis and then directed to the related area in the operation manual, which considers the diagnosis of settling problems.

4.4.4 The Calculation-Engine

Control instructions are set by the calculation-engine, which uses the steady state model derived in the previous section for the fellmongery activated sludge plant. The ASOP-user takes the quantitative targets output from the calculation-engine to set the manipulated control variables for the next day of operation.

For SRT-control the manipulated control variable is the waste activated sludge volume (Q_W, m^3/d) as discussed in the literature review. Q_W is controlled directly using the waste activated sludge pump speed controller (P_W, %). The most important target output by ASOP is P_W, the waste pump speed that needs to be maintained to achieve the target Q_W and thus maintain the SRT.

It is important during SRT control that the target SRT is met within ± 5 % to maintain consistent plant operation. This will result in stability if all other external disturbances can be reduced. The idea of operating under a target-acheivement regime is advantageous for both simplicity and consistency. If the SRT achieved for the particular day is not within ± 5 % of the target SRT, the ASOP inference-engine suggests control action using the following code:

If (SRT achieved < 0.95*Target SRT)
OR (SRT achieved > 1.05*Target SRT)
THEN ("PROBLEM: Target SRT for the day did not lie within the 5 % threshold
region!!!! ACTION: (1) Ensure the Target WAS volume is achieved for the next day and (2) Refer to the "Waste Activated Sludge Control" section of the operation manual for further direction").

The operator then knows that the WAS volume was not controlled properly, and an important target was not achieved within the acceptable range. During the next day, the Q_W target will be achieved with more concern for maintaining plant stability. The operator is also referred to the operation manual to determine further action.

4.4.5 The Tool-Box

The tool-box generates reports and charts that compare the targets with the actual achieved values (achievements), and shows trend data and summarises plant performance. The ASOP user can view both the outputs and the targets to make the necessary control decisions or alterations. Further discussion on reports and charts follows in the next sections.

4.4.6 The User Interface

Ozgur *et al* (1994) found that it was necessary to include an easy-to-use interface due to the lack of computer experience by the user. In this case, computer illiteracy was not a problem for most of the users, so a user-interface was developed primarily to provide a visual link between ASOP and the activated sludge plant.

The control panel shown in Figure 4.19 was developed as the user-friendly interface. The central diagram is a basic schematic of the fellmongery activated sludge process. The ASOP user can click (using the mouse) on any section of the plant diagram to generate a form listing the process parameters used to measure the state of that section. For example, the form generated for basin two is shown in Figure 4.20.

Once a specific form is generated, the user can compare the current data with historical data stored in the ASOP database to develop their personal knowledge base. By developing their knowledge base using the ASOP output, the user becomes empowered to make educated process control inferences as they themselves gain knowledge about how the activated sludge plant is operating.

The mass flows of BOD and total suspended solids (TSS) are important for maintaining the effluent quality targets. The effluent quality targets were discussed in section 4.1.12. The control panel outputs the BOD and TSS mass flows for each section of the plant to help the ASOP-user visualise solids inventory and the rate of BOD removal.

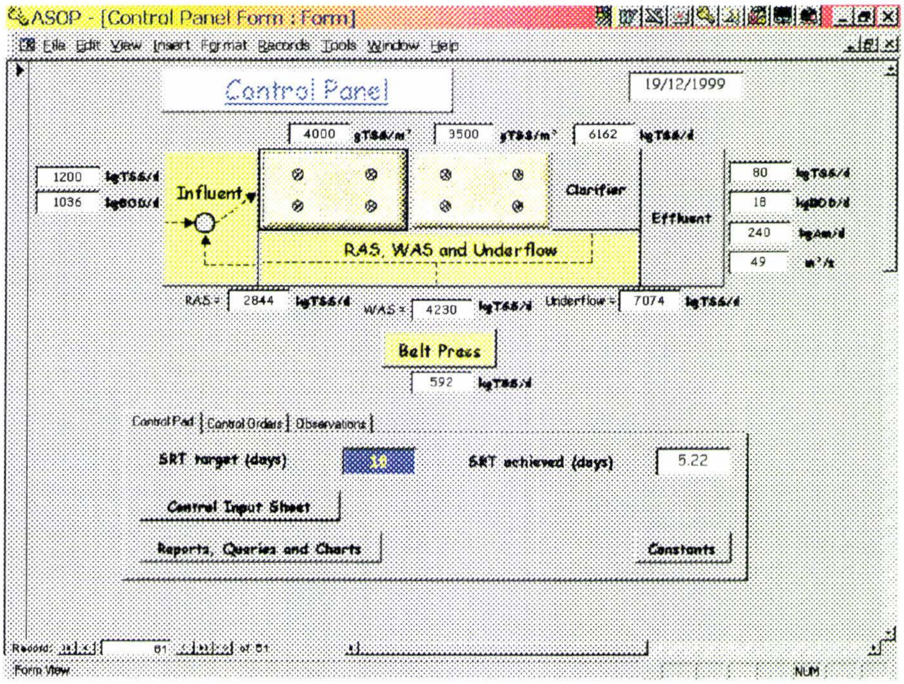

Figure 4.19: The Activated Sludge Operation Program (ASOP) user-expert system interface.

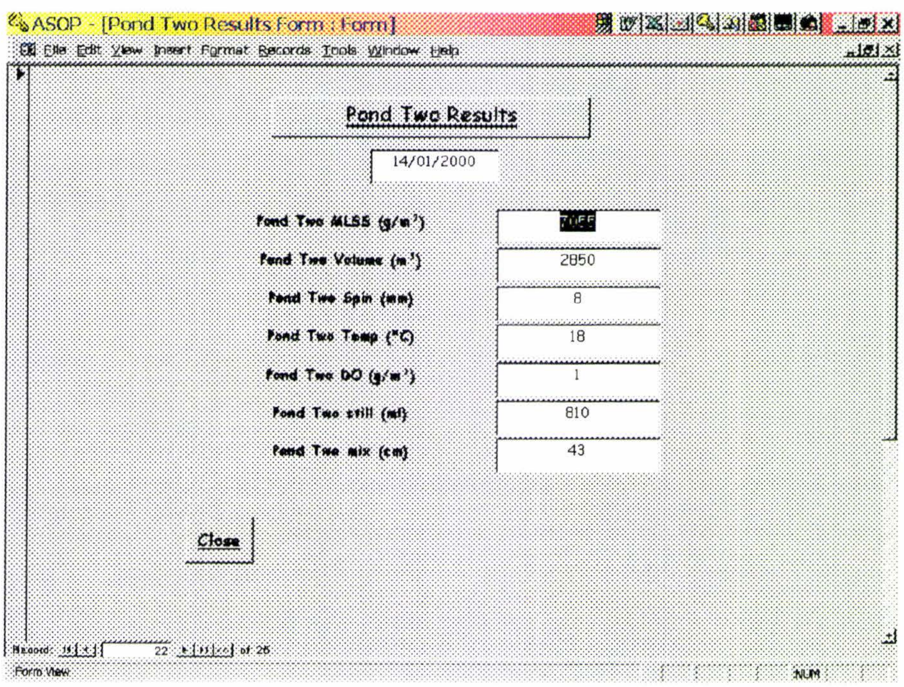

Figure 4.20: Basin two data display form in the activated sludge operation program (ASOP).

For instance, the ASOP user can compare the mass flow of TSS entering the clarifier to the sum of the effluent and the underflow TSS mass flows. In the case shown in Figure 4.20, there is more TSS mass entering the clarifier than there is leaving. This can only result in accumulation of suspended solids in the clarifier, which will increase the sludge blanket height. The ASOP inference-engine has a coded condition for this situation also, but it is based on the clarifier TSS ratio given by Equation 4.34.

$$R_{TSS} = \frac{\text{clarifier influent TSS (kg/d)}}{\text{effluent TSS (kg/d)} + \text{underflow TSS (kg/d)}}$$

Equation 4.34: The clarifier, influent suspended solids load ratio to the total suspended solids load withdrawn.

Equation 4.34 shows that if the clarifier influent TSS (kg/d) is large enough to be greater than the combined TSS withdrawal rate then R_{TSS} will be greater than unity.

The following code was set:

If (R_{TSS}>1)

THEN ("PROBLEM: Clarifier influent TSS load is greater than the combined

withdrawal of TSS from the clarifier, the TSS effluent quality target is at risk. ACTION: (1) Reduce the clarifier influent pump speed by 10 % daily until the TSS load is reduced below the combined withdrawal rate. (2) Monitor the sludge blanket height throughout the day, is it rising appreciably? if YES then (3) Increase the underflow pump speed by 10 % daily until the sludge blanket stabilises. (3) Refer to the "Clarifier Operation" section of the operation manual for further direction.")

The operator is warned of clarifier overloading when this message appears and will be able to adjust the appropriate settings to compensate.

The inference-engine is also capable of alerting the ASOP-user to the effluent quality targets. For instance the effluent BOD load (kg/d) has an effluent quality target of 450 kg/d. If the calculated value equals or exceeds 90 % of the BOD target then the inference-engine displays a control suggestion with the following code:

If (effluent BOD load > 0.90*Target effluent BOD load)

THEN ('PROBLEM: Effluent BOD load is in danger of exceeding the associated effluent quality target of 450 kg/d. ACTION: (1) Check that the aeration system is functioning properly and maintaining adequate dissolved oxygen concentration. (2) Analyse influent wastewater for shock loads of BOD. (3) Refer to the "BOD Removal" section of the operation manual for further direction.")

Similar sets of code exist to make automatic inferences about the other effluent quality targets. For the effluent TSS load the following code is used:

If (Effluent TSS load > 0.90*Target effluent TSS load)

THEN ("PROBLEM: Effluent TSS load is in danger of exceeding the associated effluent quality target of 900 kg/d. ACTION: (1) Check that the clarifier settings are feasible (ie. Is the clarifier overloaded?). If YES then (2) Reduce the clarifier influent pump speed immediately. (3) Increase the underflow pump speed by 10 % daily until the sludge blanket is reduced. (4) Refer to the "Clarifier Operation" section of the operation manual for further direction.").

If the effluent total suspended solids load (TSS) is in danger of exceeding the associated target, then the operator is immediately referred to clarifier operation. Firstly ASOP asks the user whether the current TSS load is due to an overloaded clarifier. The previous set of code discussed for the clarifier TSS ratio (R_{TSS}) would have already warned the ASOP-user when the clarifier had become overloaded. So the apparent senario might have been avoided if the appropriate alterations to the clarifier settings had been made days earlier.

4.4.7 Inputting Information

The ASOP-user collects information from the activated sludge plant and enters it directly to the ASOP-database using the Central Input Sheet (CIS). Part of which is shown in Figure 4.21. CIS is opened by clicking on the appropriate button located on the control pad in control panel.

Historical data can be analysed by the ASOP-user from CIS if the need arises by using the arrow buttons located in the bottom left hand corner of CIS (shown in Figure 4.21). This adds to the visual appeal of ASOP, and gives the user flexibility to change or add information. But, CIS is primarily for data and information aquisition rather than data analysis.

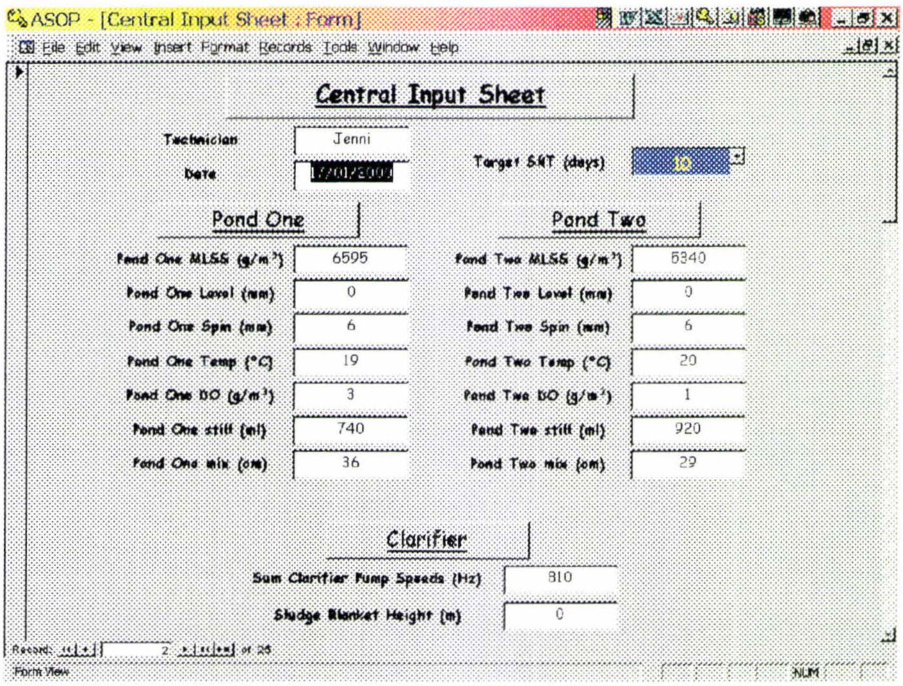

Figure 4.21: The central input sheet (CIS) for the activated sludge operation program (ASOP).

4.4.8 Daily Operation Sheet

To help the operator use the targets set by the expert system, the Daily Operation Sheet (DOS) was developed (Figure 4.22). DOS lists important targets such as the SRT, Q_W and P_W for the next day of operation. A table for recording the next day's pumping data makes up the rest of DOS.

The operator takes the target WAS pump speed (P_W, %) and attempts to maintain that speed over the next day of operation. Operator performance can only be measured in terms of target achievement if the external influences are reduced. Several external factors can effect the operator performance in this case including pump breakdowns and the sludge de-watering plant performance.

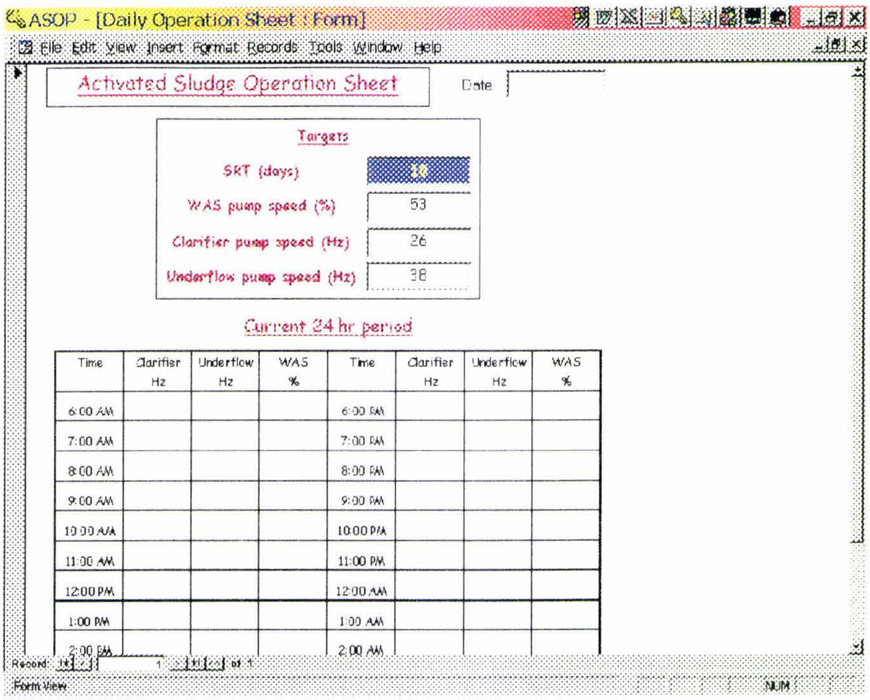

Figure 4.22: Daily operation sheet (DOS).

The fellmongery sludge de-watering plant has no back up plan in case of breakdown, therefore when breakdowns occur, no sludge wasting can be achieved. This means the target SRT cannot be maintained and thus plant stability may be adversely effected. The lack of a back up plan will mean the operator needs to plan maintenance of critical equipment such as the WAS pump and the belt filter press to reduce the frequency of breakdowns.

An auxiliary WAS pump would be a cheap solution because an additional belt filter press will be very expensive. If the operator is given the means (ie. sufficient financial support) to maintain the critical equipment then achievement of the targets should be consistent. Again, the idea is not to make changes in response to problems, it is to make educated decisions to prevent problems from occurring. Therefore, planned preventative maintenance plays a very important role in this area.

4.4.9 Reporting Information, Communication and Team-work

ASOP has been designed so that the user can generate reports from any major section of the activated sludge plant and these can be printed as required. It was envisaged that all three activated sludge team members (the operator, the ASOP-user and the information collector[8]) would, on a daily basis discuss and report information about the activated sludge plant. Operation of the plant would become a team effort and not (as it currently is) a set of independent people with little communication between them.

The activated sludge team (AST) meets daily around the ASOP control panel. The first point discussed is the solids retention time (SRT) control target. The ASOP-user enters the "Report, Charts and Queries" form in ASOP by clicking on the appropriate button on the control pad in control panel. The following form is displayed (Figure 4.23).

From this form, the ASOP-user can view any of several reports, charts and queries. To view the SRT target-achievement performance, the user clicks on the "Generate SRT chart" button and a chart like the one shown in Figure 4.24 is displayed.

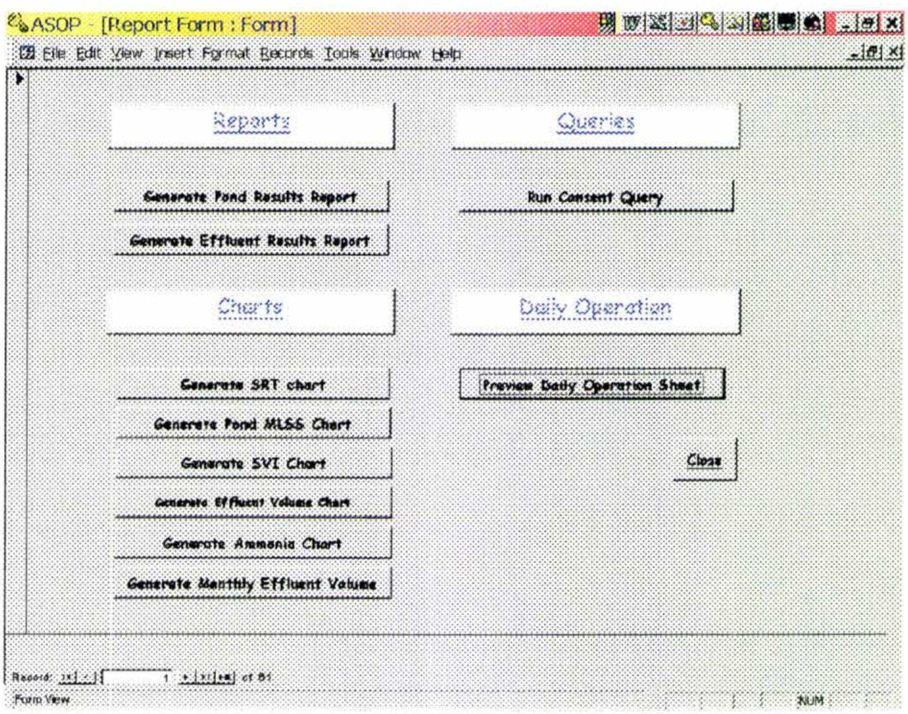

Figure 4.23: Reports, Charts and Queries form for the activated sludge operation program (ASOP).

For consistent plant operation (which will lead to stable plant performance) the SRT needs to be maintained constant. It is easy to see from the first set of bars Figure 4.24 that the target

[8] Information collector: person who manages daily data and information collection

SRT of 10 days was not met for the 10/01/2000. In fact the SRT achieved was close to 20 days and would be looked upon as a very important item for the day. The AST would need to discuss the reason behind the poor performance and then make sure it does not happen during the current day. On the other hand, the set of bars for the 12/01/2000 are very close together and the SRT achieved was within 5 % of the target SRT, ultimately this would be a normal day.

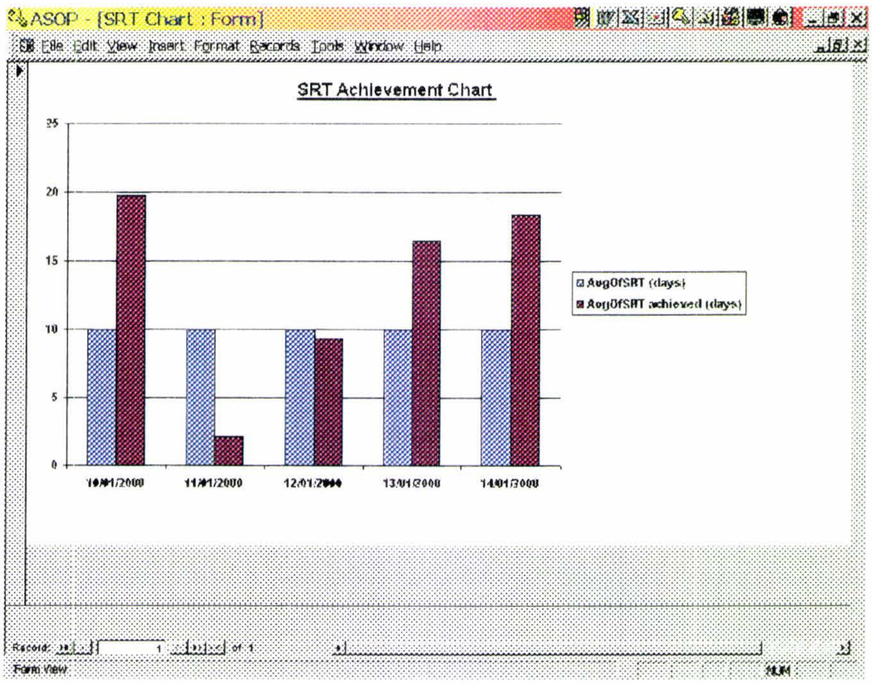

Figure 4.24: The solids retention time (SRT) achieved compared to the target SRT. A chart in the activated sludge operation program (ASOP).

After analysing the SRT chart as a team, the ASOP-user can generate a report for the operator, which lists the current day's waste activated sludge targets that need to be met to maintain the SRT. AST can then go about performing their individual tasks until the next meeting. The communication within the team needs to be effective and each member needs to know that they have an important role to play for maintaining overall plant stability and thus process performance in terms of the effluent quality targets.

5 CONCLUSIONS AND RECOMMENDATIONS

5.1 CONCLUSIONS

5.1.1 Recap

The primary aim of this project was to provide the fellmongery with a refined process control and operation strategy and knowledge of their activated sludge plant to improve plant reliability. The project scope was set in a series of tasks that were presented in section 1.2. The following conclusions summarise the main outcomes for each of these tasks.

5.1.2 Task 1: Characterisation of the fellmongery wastewater and diagnosis of observed process problems in the activated sludge plant

The pretreated fellmongery wastewater may occasionally have insufficient soluble phosphorous. This causes shunt-metabolism, which leads to non-filamentous sludge bulking, frequently experienced in the fellmongery clarifier.

The influent suspended solids concentration is too high. The additional suspended solids coupled with sludge settleability problems reduces clarifier performance.

The influent organic nitrogen load is extremely high. The organic nitrogen is hydrolysed to ammonia during the activated sludge process so the ammonia load in the effluent is higher than that in the influent.

Poor aeration control is causing deadspots and highly variable dissolved oxygen concentrations.

5.1.3 Task 2: Evaluation of solids retention time control (SRT) using bench-scale simulations

A solids retention time (SRT) between 5 and 10 days will produce effluent quality that will more than satisfy the associated targets.

5.1.4 Task 3: Steady state modelling of the activated sludge plant

The critical process control points in the fellmongery activated sludge plant are the clarifier-influent pump, the underflow pump and the waste pump shown in Figure 4.17. The waste pump flow controller is of particular importance for maintaining stable solids retention time (SRT) control.

5.1.5 Task 4: Development of the new process control and operation strategy

Consistent control of the SRT is required to ensure the success of such as control method. The current situation does not cater for this, because there is little in the way of preventative maintenance nor is there much communication between the operator and data collector.

5.2 RECOMMENDATIONS

5.2.1 Task 1: Characterisation of the fellmongery wastewater and diagnosis of observed process problems in the activated sludge plant

The influent suspended solids load is too high. Increased primary suspended solids removal efficiency is recommended for two main reasons:

1. The secondary clarifier is currently the critical point of control to maintain the effluent quality suspended solids load target. Reducing the influent suspended solids concentration is reccomended to help improve clarifier operation.
2. Reduce the influent organic nitrogen load to improve control over the effluent ammonia load.

Phosphorous addtion may be required during minimum influent flows to maintain the BOD:N:P ratio around the ideal value.

It is recommended that an investigation into using basin one as a pseudo-equalisation basin/ aeration basin be carried out. This will reduce the volume fluctuations currently experienced in basin two, which will be advantageous for improving secondary clarifier operation. This can be actioned by isolating basin one from basin two with a variable speed pump to control flow and maintain a constant level in basin two.

5.2.2 Task 2: Evaluation of solids retention time control (SRT) using bench-scale simulations

It is recommended that the 10 day SRT be implemented for control of the fellmognery activated sludge plant under the existing conditions. The smaller volume of waste sludge should offset sludge handling costs.

Increased nitrification at higher SRT levels may be advantageous for meeting resource consent limits, but the associated increase in nitrate concentration may introduce additional clarifier operation problems related to denitrification. Further work is required to investigate the use of a higher SRT level above 15 days for these reasons.

5.2.3 Task 3: Steady state modelling of the activated sludge plant

It is recommended that further work is carried out to continually upgrade the steady state model. Certain parameters should be updated regularly and the equations themselves should be replaced if a superior version is preferred.

5.2.4 Task 4: Development of the new process control and operation strategy

Current communication between the data collector and activated sludge plant operator is unsatisfactory and will not achieve improved plant operation. It is recommended that the new process control and operation strategy presented in this thesis be implemented by a team.

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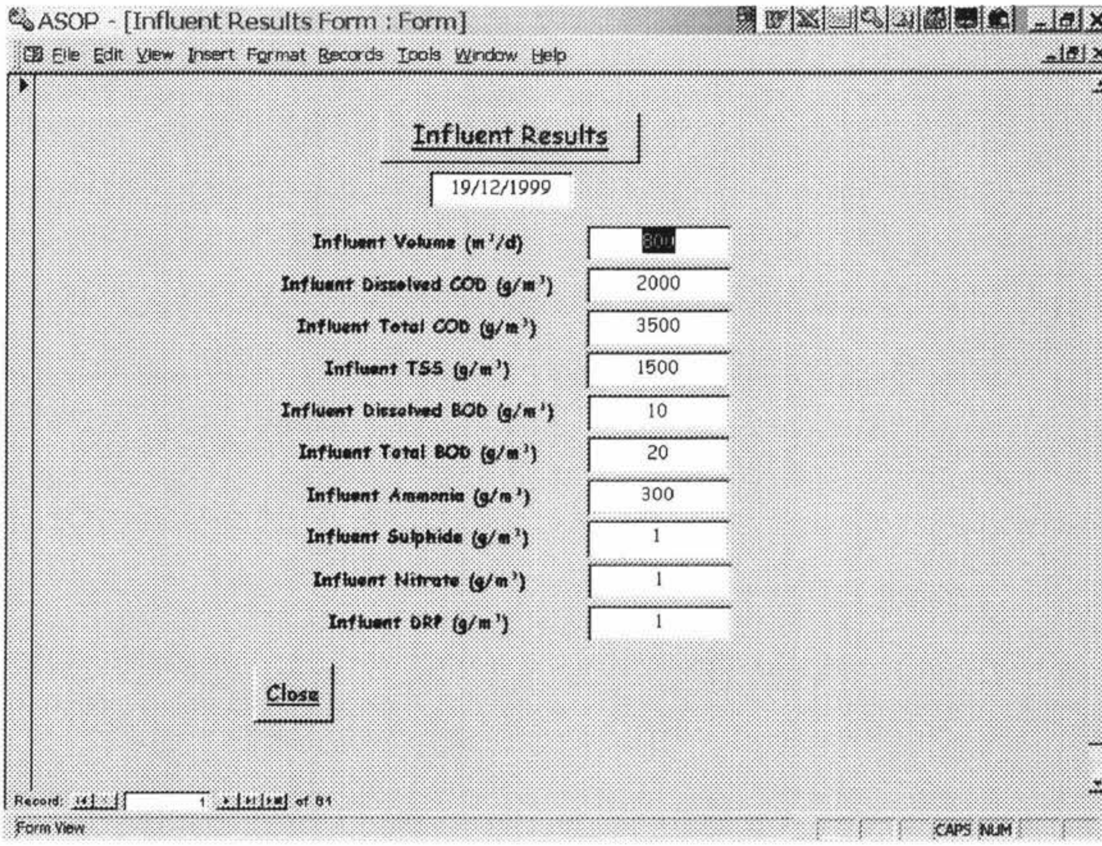
APPENDIX



ASOP - [Influent Results Form : Form]

File Edit View Insert Format Records Tools Window Help

Influent Results

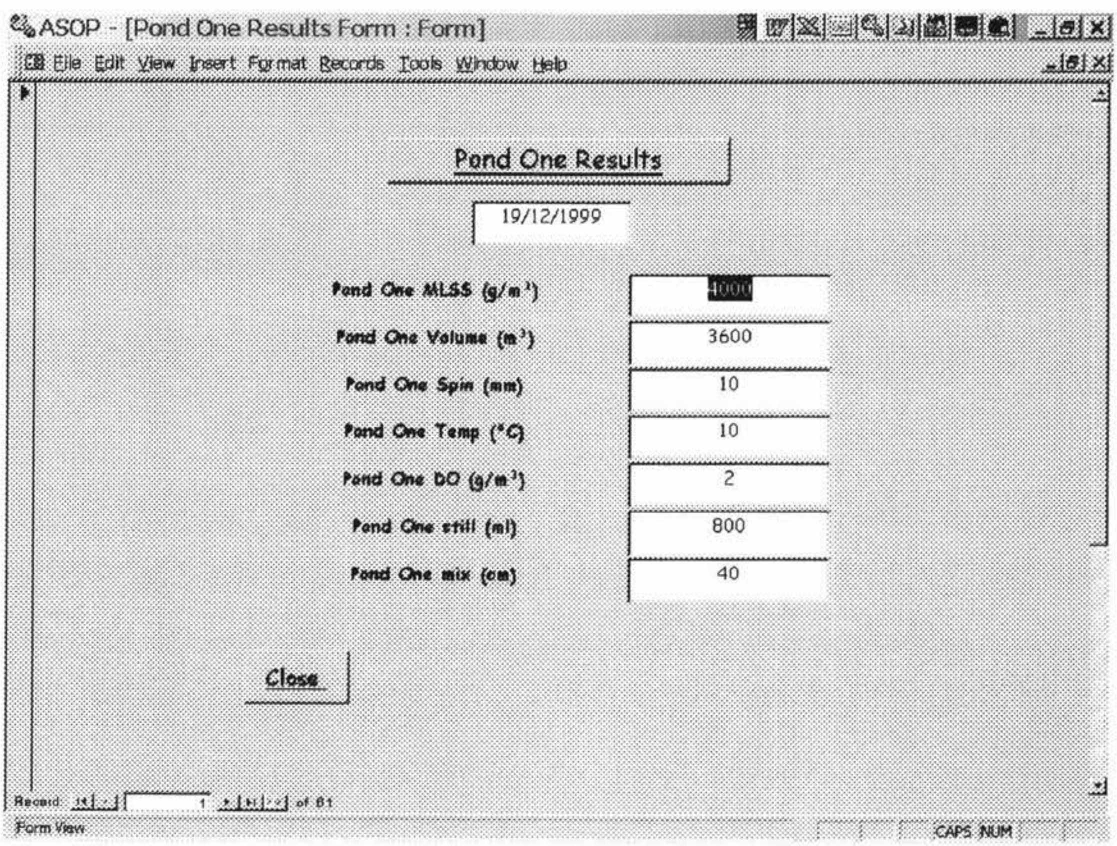
19/12/1999

Influent Volume (m^3/d)	800
Influent Dissolved COD (g/m^3)	2000
Influent Total COD (g/m^3)	3500
Influent TSS (g/m^3)	1500
Influent Dissolved BOD (g/m^3)	10
Influent Total BOD (g/m^3)	20
Influent Ammonia (g/m^3)	300
Influent Sulphide (g/m^3)	1
Influent Nitrate (g/m^3)	1
Influent DRP (g/m^3)	1

Close

Record: 1 of 81

Form View CAPS NUM



ASOP - [Pond One Results Form : Form]

File Edit View Insert Format Records Tools Window Help

Pond One Results

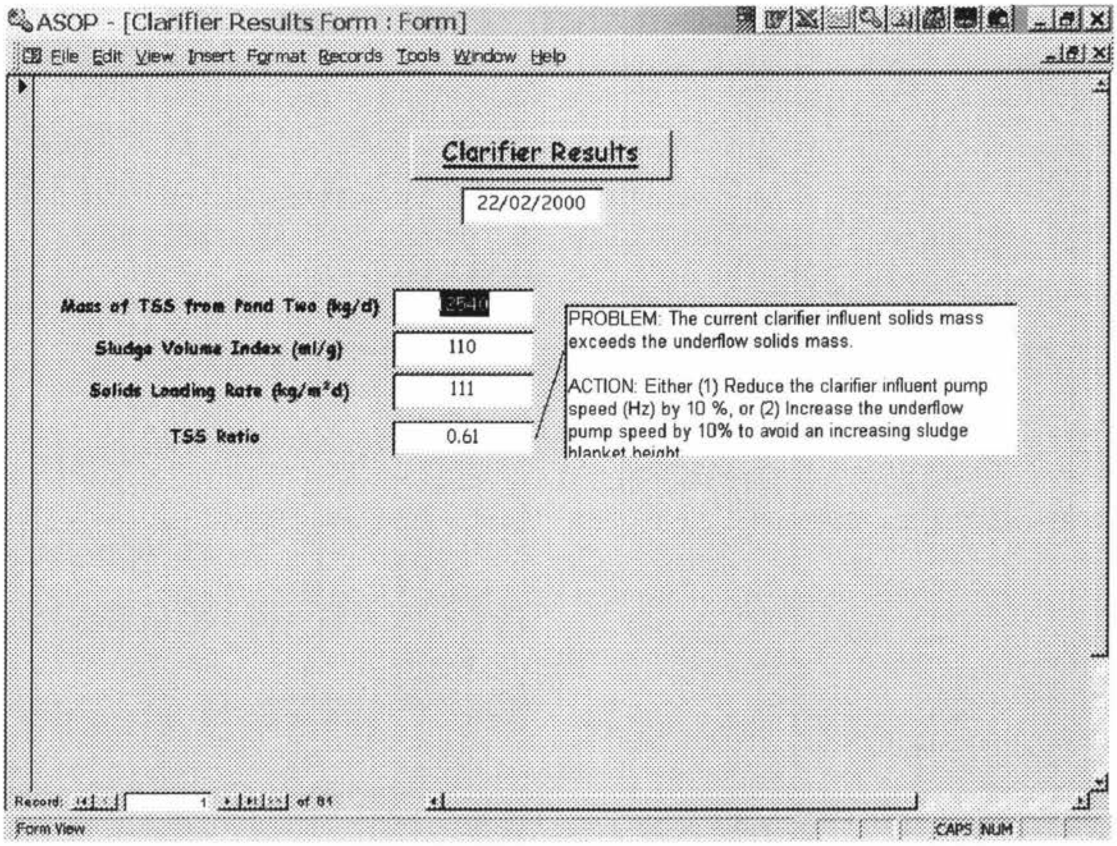
19/12/1999

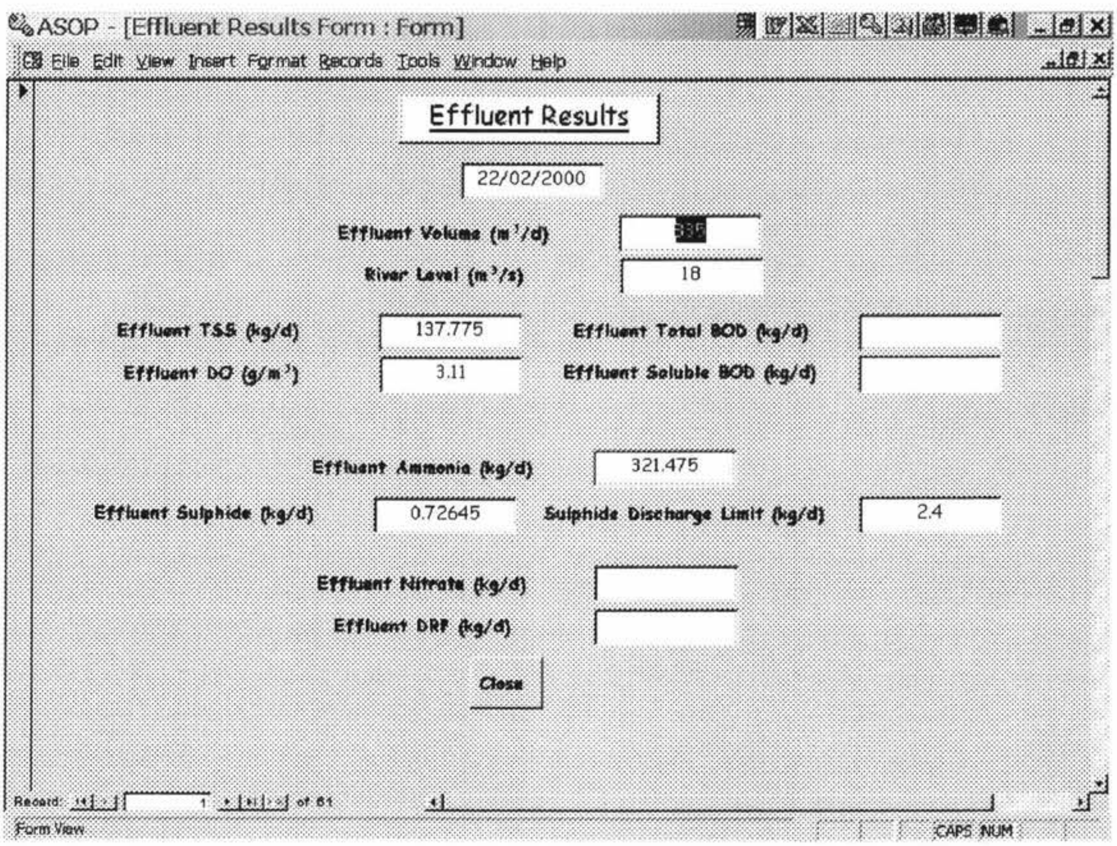
Pond One MLSS (g/m^3)	4000
Pond One Volume (m^3)	3600
Pond One Spin (mm)	10
Pond One Temp (°C)	10
Pond One DO (g/m^3)	2
Pond One still (ml)	800
Pond One mix (cm)	40

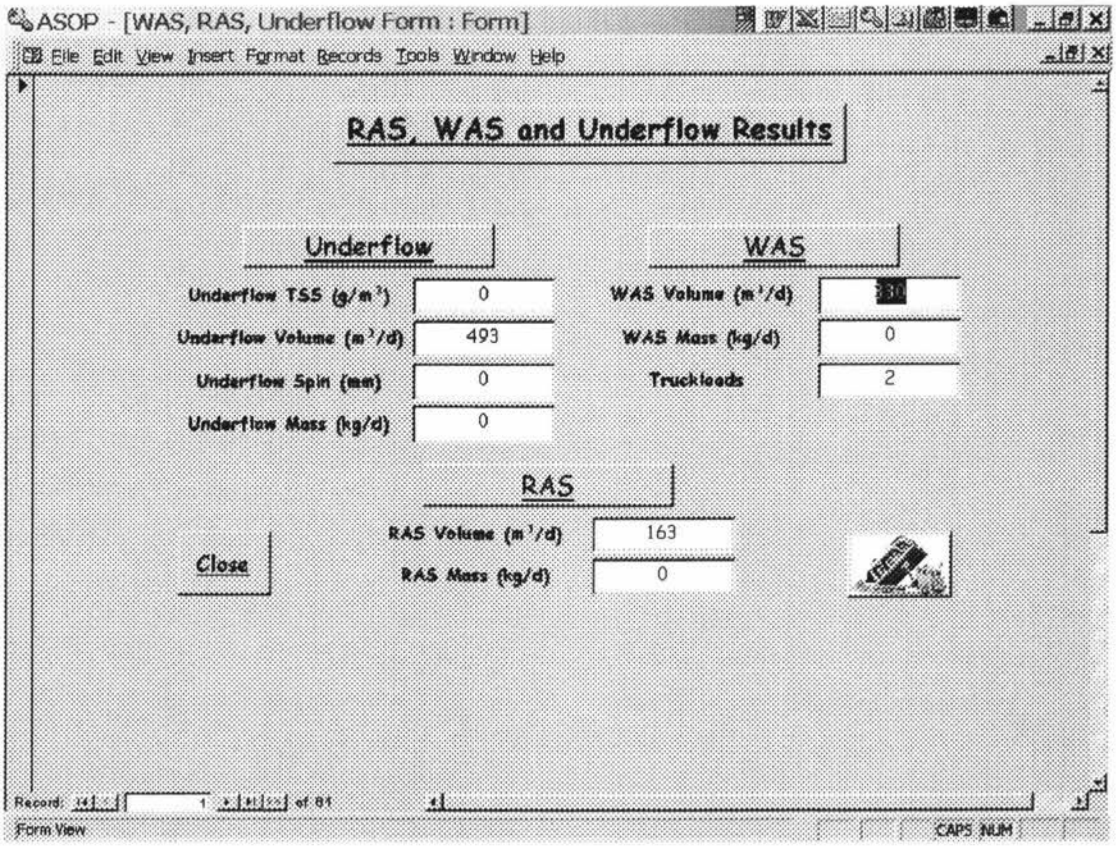
Close

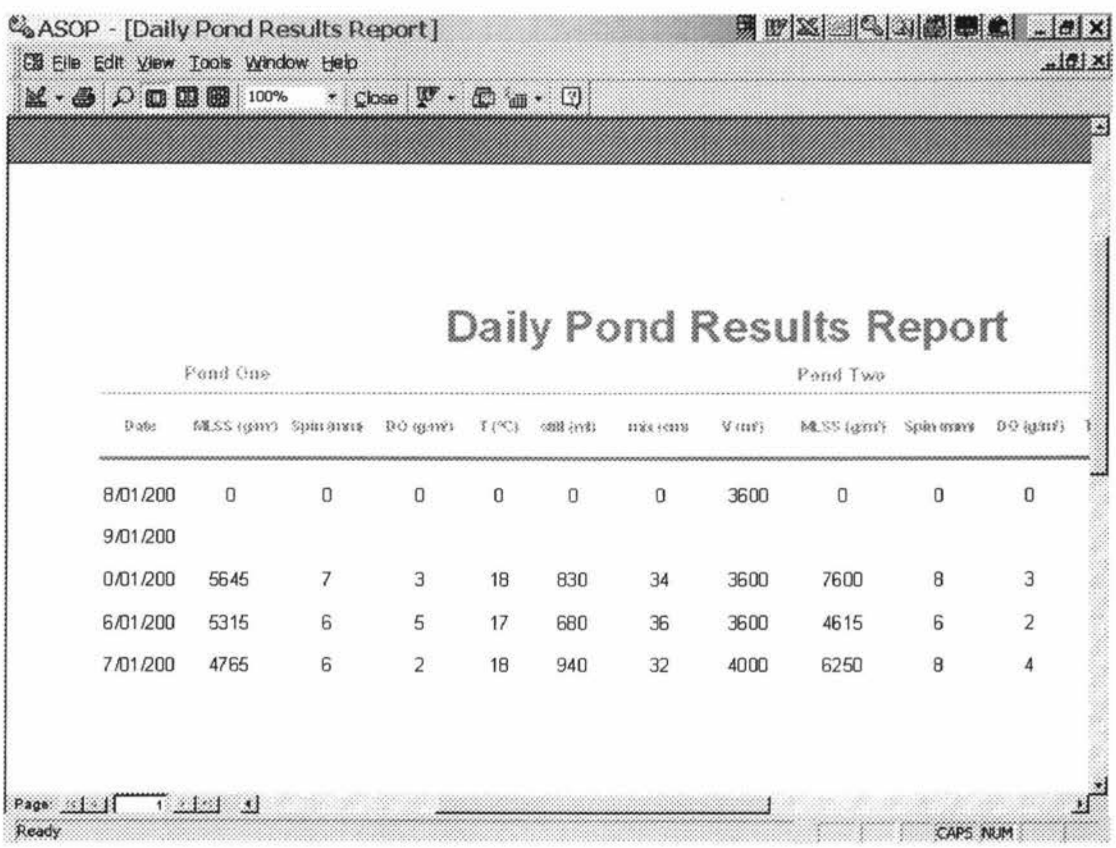
Record: 1 of 81

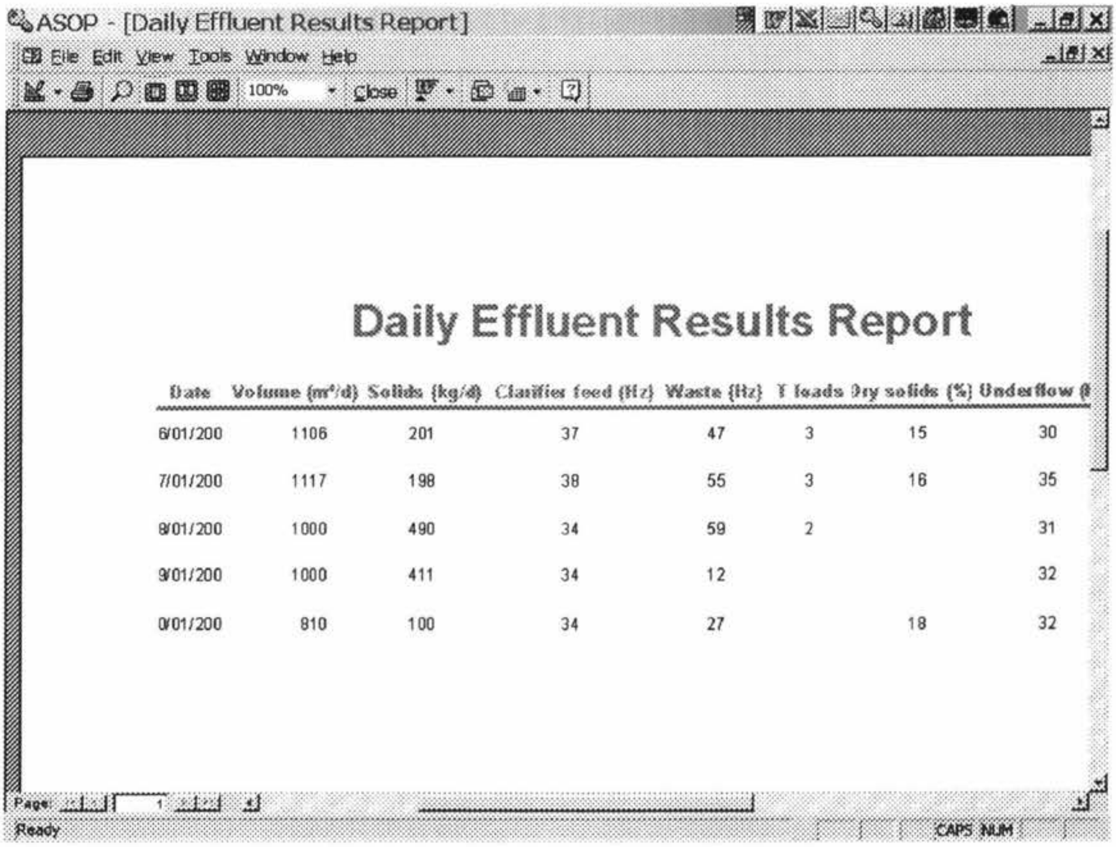
Form View CAPS NUM


ASOP - [Clarifier Results Form : Form]
File Edit View Insert Format Records Tools Window Help
Clarifier Results
22/02/2000
Mass of TSS from Pond Two (kg/d)
2540
Sludge Volume Index (ml/g)
110
Solids Loading Rate (kg/m²d)
111
TSS Ratio
0.61
PROBLEM: The current clarifier influent solids mass exceeds the underflow solids mass.
ACTION: Either (1) Reduce the clarifier influent pump speed (Hz) by 10 %, or (2) Increase the underflow pump speed by 10% to avoid an increasing sludge
Form View
CAPS NUM


ASOP - [Effluent Results Form : Form]
File Edit View Insert Format Records Tools Window Help
Effluent Results
22/02/2000
Effluent Volume (m³/d)
335
River Level (m³/s)
18
Effluent TSS (kg/d)
137.775
Effluent Total BOD (kg/d)
Effluent DO (g/m³)
3.11
Effluent Soluble BOD (kg/d)
Effluent Ammonia (kg/d)
321.475
Effluent Sulphide (kg/d)
0.72645
Sulphide Discharge Limit (kg/d)
2.4
Effluent Nitrate (kg/d)
Effluent DRP (kg/d)
Close
Form View
CAPS NUM

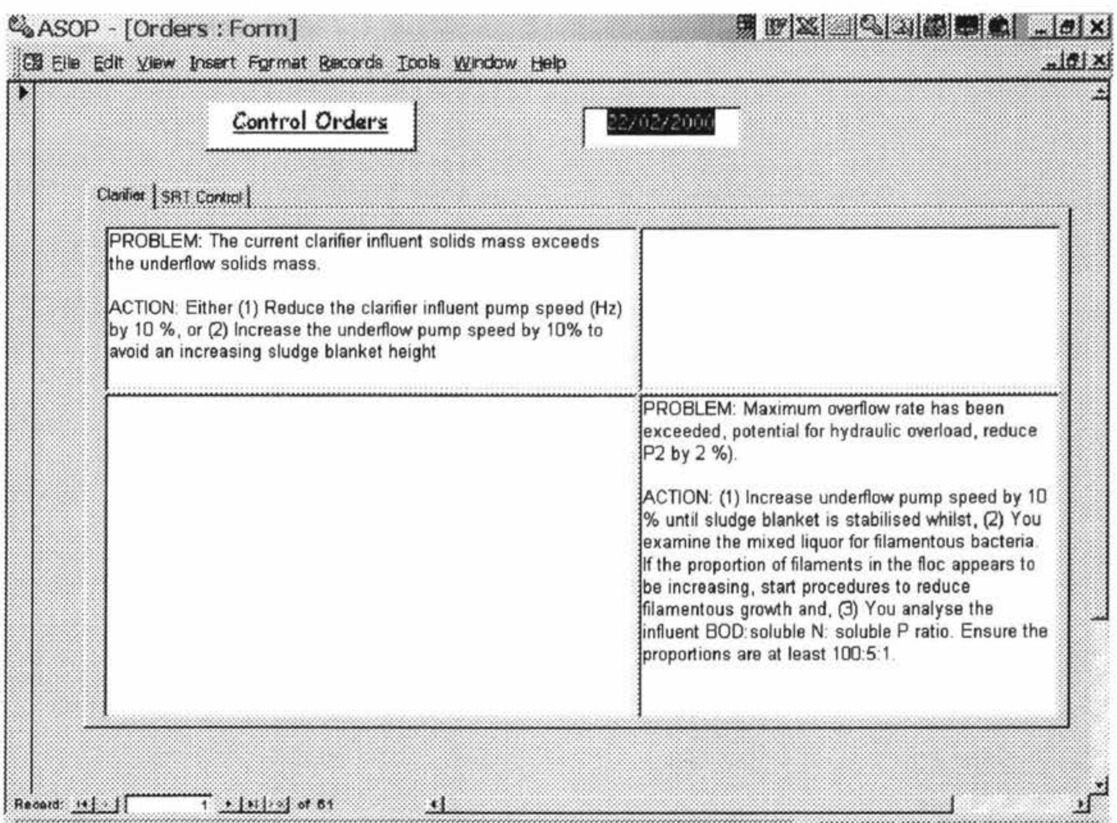

ASOP - [WAS, RAS, Underflow Form : Form]
File Edit View Insert Format Records Tools Window Help
RAS, WAS and Underflow Results
Underflow
Underflow TSS (g/m³) 0
Underflow Volume (m³/d) 493
Underflow Spin (mm) 0
Underflow Mass (kg/d) 0
WAS
WAS Volume (m³/d)
WAS Mass (kg/d) 0
Truckloads 2
RAS
RAS Volume (m³/d) 163
RAS Mass (kg/d) 0
Close
Form View
CAPS NUM


ASOP - [Daily Pond Results Report]
File Edit View Tools Window Help
100%
Close
Daily Pond Results Report
Pond One
Pond Two
Date
T (°C)
8/01/200 0 0 0 0 0 0 3600 0 0 0
9/01/200
0/01/200 5645 7 3 18 830 34 3600 7600 8 3
6/01/200 5315 6 5 17 680 36 3600 4615 6 2
7/01/200 4765 6 2 18 940 32 4000 6250 8 4
Page: 1
Ready
CAPS NUM



Daily Effluent Results Report

Date	Volume (m³/d)	Solids (kg/d)	Clarifier feed (Hz)	Waste (Hz)	T loads	Dry solids (%)	Underflow (
6/01/200	1106	201	37	47	3	15	30
7/01/200	1117	198	38	55	3	16	35
8/01/200	1000	490	34	59	2		31
9/01/200	1000	411	34	12			32
0/01/200	810	100	34	27		18	32



Fellmongery wastewater characterisation results

Date	Total P g/m^3	Total P (soluble) g/m^3	TKN g/m^3	TKN (soluble) g/m^3	TKN (VSS)	Ammonia g/m^3	BOD_U g/m^3	BOD_5 g/m^3	k_{20} g/m^3	BOD_U (soluble) g/m^3	BOD_5 (soluble) g/m^3
16/09/99	9.01		522.20			146.78					
20/09/99	8.31		249.05			88.97					
23/09/99	5.34		146.30			137.59					
28/09/99	7.17		79.67	57.13	22.53	46.16					
30/09/99			540.70			85.82					
4/10/99							1530	1292	0.56	825	700
7/10/99							1463	1222	0.52	665	561
13/10/99			235.67			88.65	1342	1148	0.84	542	434
14/10/99	8.28		256.19			199.98	1777	1715	1.23	998	1031
18/10/99	36.51		108.78	96.86	11.91	60.25	3644	2242	0.19	595	291
20/10/99							807	718	0.69	323	290
26/10/99	22.59		542.96	473.20	69.76	68.33	1860	1815	1.05	297	286
28/10/99							1201	1112	0.81	377	334
29/10/99	21.69		494.42	206.64	287.78	109.99					
3/11/99	16.65		372.28	259.38	112.91	49.43					
5/11/99	23.39		730.29	523.97	206.32	138.50					
11/11/99	14.81	9.27	461.04	443.91	17.14	47.04					
12/11/99	16.46	8.85	632.39	82.13	550.25	121.50					
15/12/99	16.27	13.24	373.47	302.58	70.90	26.69					
17/12/99	15.91	12.61	399.87	320.65	79.22	34.57					
21/12/99	17.59	14.47	375.23	284.37	90.86	38.24					
Mean	16	12	384	277	138	88	1703	1408	0.74	578	491
Std. Er	1	1	21	28	22	6	209	118	0.08	61	65

k_{20} (soluble) g/m^3	COD g/m^3	COD (soluble) g/m^3	COD (VSS) g/m^3	TSS g/m^3	VSS g/m^3	FSS g/m^3
	4780	2342	2439	3510	2810	700
	5087	2552	2536	1090	683	407
	2213	1595	618	588	544	44
	2951	1926	1026	1065	950	115
	2104	1740	363	608	497	111
0.69	6266	3884	2382	3120	2390	730
0.47	2661	1587	1074	1190	1000	190
0.71	2814	1090	1724	1498	1386	112
1.30	6508	2447	4062	6970	5880	1090
0.18	3375	2830	545	4326	3582	744
0.58	2309	1542	767	378	260	118
1.02	3702	2047	1655	3645	3405	240
0.63	3480	3109	371	2145	1620	525
	3480	3109	371	1450	1340	110
	4038	2487	1550			
	7591	5443	2148	1988	1412	576
	4780	3924	856	840	700	140
	6460	6234	226	1667	1440	227
	6525	5491	1034	1035	900	135
	5281	3472	1809	955	890	65
	6250	4829	1421	1460	1060	400
0.70	4412	3032	1380	1976	1637	339
0.08	158	136	89	158	134	55

Case 1A (5 day SRT) of the Bench-scale simulations

Date	Day	VSS_O (g/m^3)	TSS_O (g/m^3)	$MLVSS_1$ (g/m^3)	$MLSS_1$ (g/m^3)	$MLVSS_2$ (g/m^3)	$MLSS_2$ (g/m^3)
10/06/99	1	225	270	3340	4085	3300	4250
11/06/99	2			3320	3980	3305	3970
12/06/99	3	160	245	3225	3815	3025	3715
13/06/99	4			2750	3340	2775	3370
14/06/99	5	140	270	2350	2950	2235	2795
15/06/99	6			1855	2455	1920	2565
16/06/99	7	135	265	1970	2575	1805	2360
17/06/99	8			1525	2120	1475	2080
18/06/99	9			1450	2090	1335	1915
21/06/99	12			1240	1705	1130	2005
22/06/99	13	175	300	1190	1735	1320	2810
23/06/99	14			1440	2160	1265	2110
24/06/99	15	360	502	1100	2180	820	1895
25/06/99	16	840	1104	1215	1685	1360	2005
28/06/99	19	290	595	885	1425	910	1850
29/06/99	20			870	1355	1105	1805
30/06/99	21			740	1265	910	1595
1/07/99	22			920	1310	1090	1650
2/07/99	23	200	315	1920	2725	1820	2485
5/07/99	26			3000	3680	2735	3465
6/07/99	27			1820	2360	1820	2615
7/07/99	28			2255	3310	2285	2870
8/07/99	29	436	616	2500	3195	1870	2455
9/07/99	30	584	764	3115	3910	2800	3695
12/07/99	33	872	887	2360	2960	2625	3210
13/07/99	34	446	732	1940	2440	2480	3105
14/07/99	35			2905	3960	3080	4225
15/07/99	36	504	778	4535	5970	3740	5130
16/07/99	37			4175	5295	4270	5430
19/07/99	40	482	716	4760	5685	4855	7610
20/07/99	41	474	566	5040	6575	6105	8575
21/07/99	42			3970	4930	4105	5100
22/07/99	43	551	654	3390	4720	3730	4725
23/07/99	44	476	596	3815	4455	3915	4605
26/07/99	47	930	1432	5595	7370	5135	6645
27/07/99	48			5560	7525	4890	7205
28/07/99	49	3910	6020	7480	9440	7550	9710
29/07/99	50			9110	12420	9350	11820
30/07/99	51	3940	5260	8040	10680	7750	10470
2/08/99	54	3530	5510	5930	8020	6630	8930
3/08/99	55	446	714	7510	9690	8500	11030
4/08/99	56			7590	10030	8080	10730
5/08/99	57	1675	2620	6000	7490	4130	5250
6/08/99	58			6430	8180	6770	8680
9/08/99	61	594	986	7350	9560	8040	10110
10/08/99	62	594		6100	7900	6950	9020

	VSS_O (g/m^3)	TSS_O (g/m^3)	$MLVSS_1$ (g/m^3)	$MLSS_1$ (g/m^3)	$MLVSS_2$ (g/m^3)	$MLSS_2$ (g/m^3)
Steady State Mean	879	1251	3962	5109	3965	5268
Std. Er	182	285	184	235	184	262

VSS$_E$ (g/m^3)	TSS$_E$ (g/m^3)	SSV$_{30}$ (ml/l)	SVI (ml/g)	COD$_O$ (g/m^3)	sCOD$_O$ (g/m^3)	COD$_E$ (g/m^3)	sCOD$_E$ (g/m^3)
232	340						
234	356						
220	306						
306	398						
212	316						
166	282						
152	266						
196	234						
228	356						
310	462						
244	378						
424	674			3460	2800	1544	1264
162	360						
302	440			2555	2351	512	346
258	406						
218	384						
220	364						
336	548						
322	504						
284	464			3726	2966	1056	706
266	432	415	184				
364	512	860	344				
608	836	910	292				
190	296	900	381	3425	2625	2438	1104
176	302	760	392				
90	258	760	262			1103	733
80	246	765	169	3338	2401	1843	543
68	468	370	89	5117	3033	1758	417
254	372	960	202				
162	334	980	194				
596	890	960	242	6437	5737	545	399
894	1148	790	233				
152	266	760	199	5923	5865	2369	2294
176	310	850	152				
78	88	850	153				
264	436	900	120				
302	454	935	103				
224	408	940	117	4197	3588	868	547
858	1304	975	164	3385	2968	0	0
440	584	900	120				
506	752	920	121	6363	6072	1905	1684
478	640	940	157	6237	5845	2387	2141
474	678	870	135				
720	916	950	129				
472	786	960	157	2993	1793	2956	2777

276	450	799	225	4848	3932	1676	915
29	34	22	11	556	675	240	237

E_{COD} (%)	sE_{COD} (%)	Q_E (m^3/d)	Q_W (m^3/d)	Q_R (m^3/d)	SRT (days)	HRT (days)	F/M (g COD/g TSS/d)
		0.00850	0.00343	0.00425	4.92	2.06	
		0.00850	0.00341	0.00425	4.96	2.06	
		0.00850	0.00281	0.00425	5.76	2.06	
		0.00900	0.00283	0.00450	6.21	1.94	
		0.00650	0.00284	0.00325	5.50	2.69	
		0.00850	0.00229	0.00425	6.85	2.06	
		0.01000	0.00255	0.00500	6.13	1.75	
		0.00875	0.00288	0.00438	5.59	2.00	
		0.00790	0.00286	0.00395	5.38	2.22	
		0.00950	0.00300	0.00475	5.01	1.84	
		0.00600	0.00290	0.00300	5.33	2.92	
		0.00800	0.00291	0.00400	5.09	2.19	
55	55	0.00450	0.00332	0.00225	3.95	3.89	0.43
		0.00800	0.00288	0.00400	5.83	2.19	
80	85	0.00750	0.00286	0.00375	4.95	2.33	0.68
		0.01000	0.00290	0.00500	5.56	1.75	
		0.00800	0.00390	0.00400	4.56	2.19	
		0.00800	0.00370	0.00400	4.72	2.19	
		0.00650	0.00287	0.00325	5.29	2.69	
		0.00050	0.00310	0.00025	5.10	35.00	
72	76	0.00650	0.00350	0.00325	4.69	2.69	0.56
		0.00650	0.00350	0.00325	4.79	2.69	
		0.00550	0.00333	0.00275	4.38	3.18	
		0.00200	0.00280	0.00100	5.20	8.75	
29	58	0.00790	0.00295	0.00395	5.89	2.22	0.50
		0.01000	0.00295	0.00500	6.25	1.75	
		0.00710	0.00360	0.00355	4.93	2.46	
45	77	0.00800	0.00360	0.00400	4.47	2.19	0.27
66	86	0.00780	0.00320	0.00390	5.47	2.24	0.43
		0.00800	0.00350	0.00400	4.93	2.19	
		0.00750	0.00350	0.00375	5.38	2.33	
92	93	0.00800	0.00320	0.00400	5.13	2.19	0.59
		0.00550	0.00330	0.00275	4.88	3.18	
60	61	0.00800	0.00318	0.00400	5.44	2.19	0.60
		0.00710	0.00348	0.00355	4.79	2.46	
		0.00850	0.00333	0.00425	4.95	2.06	
		0.00725	0.00330	0.00363	5.23	2.41	
		0.00850	0.00346	0.00425	5.04	2.06	
79	85	0.01000	0.00350	0.00500	4.87	1.75	0.23
100	100	0.00850	0.00350	0.00425	4.95	2.06	0.20
		0.00800	0.00346	0.00400	5.21	2.19	
70	72	0.00600	0.00362	0.00300	4.85	2.92	0.21
62	63	0.00900	0.00350	0.00450	4.19	1.94	0.49
		0.00650	0.00287	0.00325	5.92	2.69	
		0.00900	0.00287	0.00450	5.92	1.94	
1	-55	0.00850	0.00350	0.00425	5.13	2.06	0.17

58	75	0.0072	0.00330	0.0036	5.13	2.8	0.48
9	6	0.0002	0.00003	0.0001	0.06	0.2	0.05

SLR (kg TSS/m^2/d)	r_g (g VSS/m^3/d)	$-r_{su}$ (g COD/m^3/d)	Remarks
0.95	658.04		
0.89	760.58		
0.83	546.99		
0.80	444.71		
0.48	443.03		
0.57	345.71		
0.62	304.77		
0.48	326.97		
0.40	325.45		
0.50	336.34		
0.44	243.49		
0.44	350.99		
0.22	225.14	199.50	
0.42	-109.99		Wasting target not met
0.37	149.78	791.88	
0.48	291.60		
0.34	264.57		
0.35	295.09		
0.43	365.39		
0.05	540.63		Feed pump malfunction
0.45	469.49	780.52	
0.49	549.80		Steady state period begins
0.36	453.09		
0.19	501.14		
0.67	89.95	34.89	
0.82	172.74		
0.79	634.11	-674.61	
1.08	739.09	304.78	
1.11	793.74	1175.33	
1.60	847.77		
1.69	874.29		
1.07	998.40	2593.68	
0.68	747.06		
0.97	545.13	1194.25	
1.24	806.70		
1.61	1095.87		Sudden increase in TSS_O
1.85	-99.97		
2.64	1947.86		Steady state period ends
2.76	-515.43	1728.88	
2.00	-111.83	1644.14	
2.32	1482.09		
1.69	1743.53	1134.51	
1.24	584.40	1502.67	
1.48	1230.58		
2.39	1270.20		
2.02	1160.74	-572.95	

1.01	609	771
0.06	40	373

Case 1B (15 day SRT) of the Bench-scale simulations

Date	Day	VSS_O (g/m³)	TSS_O (g/m³)	$MLVSS_1$ (g/m³)	$MLSS_1$ (g/m³)	$MLVSS_2$ (g/m³)	$MLSS_2$ (g/m³)
10/06/99	1	225	270	3100	3900	3135	4035
11/06/99	2			3070	3755	3205	3950
12/06/99	3	160	245	3060	3715	3070	3740
13/06/99	4			3065	3715	3000	3665
14/06/99	5	140	270	2865	3470	2845	3845
15/06/99	6			2475	3290	2620	3435
16/06/99	7	135	265	2255	3090	2375	3140
17/06/99	8			2180	3065	2225	3070
18/06/99	9			1985	2775	2235	3055
21/06/99	12			2080	2845	1970	2815
22/06/99	13	175	300	2220	3195	2120	2825
23/06/99	14			2330	3285	2310	3260
24/06/99	15	360	502	3050	3345	2920	3255
25/06/99	16	840	1104	2265	3085	2280	3200
28/06/99	19	290	595	2010	3080	2260	3470
29/06/99	20			1005	1460	1155	1640
30/06/99	21			850	1420	1250	1725
1/07/99	22			1870	2810	2185	3385
2/07/99	23	200	315	2715	3585	2585	3475
5/07/99	26			1200	2315	1175	2225
6/07/99	27			2450	3480	2510	3790
7/07/99	28			3125	3900	2605	3525
8/07/99	29	436	616	3115	3965	2825	4085
9/07/99	30	584	764	3850	4705	3315	4355
12/07/99	33	872	887	4130	4920	3765	4865
13/07/99	34	446	732	3750	4395	3955	4780
14/07/99	35			3500	4595	3995	4885
15/07/99	36	504	778	4375	5555	4020	5160
16/07/99	37			5810	7250	4175	5610
19/07/99	40	482	716	5800	7005	4965	6255
20/07/99	41	474	566	5185	6290	5850	7905
21/07/99	42			5065	6430	4835	5875
22/07/99	43	551	654	4665	5960	4680	6085
23/07/99	44	476	596	5220	6260	4985	6035
26/07/99	47	930	1432	6295	8960	5830	8020
27/07/99	48			4970	7095	4505	6120
28/07/99	49	3910	6020	6210	7900	6500	8490
29/07/99	50			6580	8270	7020	8750
30/07/99	51	3940	5260	6960	8900	6740	9210
2/08/99	54	3530	5510	8370	11130	8880	12340
3/08/99	55	446	714	5020	6390	5910	7580
4/08/99	56			4140	5960	5120	6540
5/08/99	57	1675	2620	5060	6510	2690	3820
6/08/99	58			5920	7080	5440	6490
9/08/99	61	594	986	7160	9360	6720	9060
10/08/99	62	594		5580	7350	5940	7660

Steady State Mean	879	1251	4692	5949	4425	5753
Std. Er	182	285	128	181	132	174

VSS_E (g/m³)	TSS_E (g/m³)	SSV_{30} (ml/l)	SVI (ml/g)	COD_O (g/m³)	$sCOD_O$ (g/m³)	COD_E (g/m³)	$sCOD_E$ (g/m³)	E_{COD} (%)
224	338							
248	352							
218	324							
208	300							
104	360							
158	298							
174	312							
186	344							
248	382							
366	560							
394	642							
280	434							
198	378			3460	2800	1544	1264	55
252	512							
168	346			2555	2351	512	346	80
190	342							
134	302							
130	336							
488	990							
256	462							
276	498			3726	2966	1056	706	72
470	848	645	206					
900	1192	355	114					
216	348	980	255					
264	466	985	238	3425	2625	2438	1104	29
234	394	980	261					
264	362	980	280					
210	426	975	223	3338	2401	1058	572	68
184	534	975	168	5117	3033	2667	717	48
234	498	990	171					
156	352	995	192					
154	330	985	194					
150	320	975	209					
134	280	980	188	5923	5865	875	792	85
234	380	980	156	6250	5783	725	592	88
36	50	1000	201					
3695	4725	1000	161	5950	5917	3283	1950	45
3645	4885	935	142					
3590	5025	940	135	4197	3588	868	547	79
1420	1612	995	119					
342	482	975	194					
218	430	970	234	6363	6072	1905	1684	70
174	416	570	113	6237	5845	1342	1217	78
226	372	940	159	6167	5850	1075	900	83
548	1002	960	134	2917	1783	2942	2950	-1
482	782	965	173	2993	1793	2956	2777	1

471	719	924	201	5001	4271	1841	954	61
108	135	21	5	428	571	355	171	8

sE_{COD} (%)	Q_E (m^3/d)	Q_W (m^3/d)	Q_R (m^3/d)	SRT (days)	HRT (days)	F/M (g COD/g TSS/d)	SLR (kg TSS/m^2/d)
	0.00850	0.00119	0.00425	12.03	2.06		0.90
	0.00850	0.00115	0.00425	12.23	2.06		0.88
	0.00850	0.00053	0.00425	20.73	2.06		0.84
	0.00900	0.00054	0.00450	20.65	1.94		0.87
	0.00650	0.00053	0.00325	25.26	2.69		0.66
	0.00850	0.00085	0.00425	16.13	2.06		0.77
	0.01000	0.00064	0.00500	18.39	1.75		0.83
	0.00850	0.00068	0.00425	16.90	2.06		0.69
	0.00800	0.00047	0.00400	17.90	2.19		0.64
	0.00800	0.00032	0.00400	15.06	2.19		0.59
	0.00600	0.00051	0.00300	13.21	2.92		0.45
	0.00800	0.00140	0.00400	9.54	2.19		0.69
55	0.00450	0.00116	0.00225	12.21	3.89	0.39	0.39
	0.00800	0.00053	0.00400	17.16	2.19		0.67
85	0.00750	0.00087	0.00375	15.21	2.33	0.20	0.68
	0.00750	0.00035	0.00375	15.25	2.33		0.32
	0.00750	0.00135	0.00375	10.96	2.33		0.34
	0.00750	0.00112	0.00375	13.53	2.33		0.67
	0.00650	0.00034	0.00325	14.65	2.69		0.59
	0.00100	0.00031	0.00050	13.33	17.50		0.06
76	0.00500	0.00118	0.00250	11.01	3.50	0.39	0.50
	0.00560	0.00125	0.00280	8.99	3.13		0.52
	0.00560	0.00040	0.00280	9.79	3.13		0.60
	0.00700	0.00050	0.00350	21.94	2.50		0.80
58	0.00790	0.00085	0.00395	15.13	2.22	0.27	1.01
	0.01000	0.00110	0.00500	13.36	1.75		1.26
	0.00710	0.00100	0.00355	14.29	2.46		0.91
76	0.00800	0.00100	0.00400	14.20	2.19	0.42	1.09
76	0.00580	0.00093	0.00290	14.55	3.02	0.44	0.86
	0.00800	0.00100	0.00400	14.16	2.19		1.32
	0.00750	0.00100	0.00375	16.50	2.33		1.56
	0.00800	0.00110	0.00400	14.10	2.19		1.24
	0.00550	0.00100	0.00275	15.55	3.18		0.88
87	0.00800	0.00100	0.00400	15.58	2.19	0.44	1.27
90	0.00900	0.00104	0.00450	14.29	1.94	0.33	1.90
	0.00720	0.00098	0.00360	16.65	2.43		1.16
67	0.00700	0.00109	0.00350	5.26	2.50	0.36	1.56
	0.00850	0.00109	0.00425	6.56	2.06		1.96
85	0.01000	0.00109	0.00500	6.75	1.75	0.21	2.42
	0.00850	0.00310	0.00425	5.26	2.06		2.76
	0.00800	0.00310	0.00400	5.84	2.19		1.60
72	0.00600	0.00200	0.00300	8.94	2.92	0.27	1.03
79	0.00900	0.00100	0.00450	12.31	1.94	0.41	0.90
85	0.00650	0.00079	0.00325	17.80	2.69	0.34	1.11
-65	0.00900	0.00079	0.00450	15.37	1.94	0.28	2.15
-55	0.00650	0.00082	0.00325	15.27	2.69	0.16	1.31

76	0.0073	0.00095	0.00366	14.0	2.5	0.38	1.12
4	0.0002	0.00003	0.00008	0.5	0.1	0.02	0.04

r_g (g VSS/m^3/d)	$-r_{su}$ (g COD/m^3/d)	Remarks
319.60		
322.20		
198.56		
201.55		
125.40		
196.96		
181.90		
175.05		
166.68		
205.35		
199.78		
314.40		
253.09	390.13	
183.80		Wasting target not met
171.93	850.13	
101.53		
123.00		
175.39		
234.01		
35.89		Feed pump malfunction
244.06	691.68	
373.61		Steady state period begins
359.20		
196.40		
319.78	327.39	
369.43		
307.11		
346.00	981.81	
369.74	670.29	
438.40		
363.14		
388.77		
313.71		
359.54	2257.81	
494.45	2798.34	
293.13		Sudden increase in TSS_O
1864.79	862.16	Effluent TSS increase
2180.27		Steady state period ends
2484.94	1848.35	
2172.40		
1045.60		
547.89	1310.86	
378.63	2440.76	
351.19	1842.66	
605.05	-145.65	
440.49	-124.57	

447	1316
47	320

Case 2A (5 day SRT) of the Bench-scale simulations

Date	Day	VSS_O (g/m^3)	TSS_O (g/m^3)	$MLVSS_1$ (g/m^3)	$MLSS_1$ (g/m^3)	$MLVSS_2$ (g/m^3)	$MLSS_2$ (g/m^3)
27/08/99	1	658	726	5880	6800	5970	7040
28/08/99	2	2084	2336	6060	7420	6580	7880
29/08/99	3	1432	1590	5980	7720	5660	7060
30/08/99	4	814	954	5720	6760	5540	7160
31/08/99	5	808	926	6040	8080	6020	7320
1/09/99	6	1212	1530	6060	7760	5580	7260
2/09/99	7	1298	1570	6120	8120	6020	7480
3/09/99	8	606	668	6040	8440	6080	8540
6/09/99	11	1014	1034	6340	8140	6080	7340
7/09/99	12	2467	2587	6140	7280	6300	7320
8/09/99	13	987	1047	6300	7820	6480	7740
9/09/99	14	917	957	6420	8020	6500	7940
10/09/99	15	910	953	6500	8280	6420	8220
13/09/99	18	3125	3725	6440	7600	6400	7460
14/09/99	19	1254	1775	5260	6480	6320	7540
15/09/99	20	2505	3260	5920	7540	6140	7480
16/09/99	21	2810	3510	6360	7440	6820	7720
17/09/99	22	1600	2660	4520	5800	4400	5180
20/09/99	25	683	1090	3640	4240	3700	4340
21/09/99	26	512	554	3380	4060	3340	3960
22/09/99	27	400	466	2740	3300	2720	2960
23/09/99	28	544	588	2540	2880	2440	2600
24/09/99	29	716	765	2180	3020	2140	2500
27/09/99	32	1145	1295	1700	2380	1660	1860
28/09/99	33	950	1065	1701	2378	1666	1864
29/09/99	34	590	725	1700	2540	1640	1820
30/09/99	35	497	608	1699	2535	1635	1830
1/10/99	36	1100	1300	1400	1820	1260	1540
4/10/99	39	2390	3120	1580	1860	1400	1440
6/10/99	41	1000	1190	1220	1380	1260	1180
8/10/99	43	895	1005	1160	1380	940	1060
10/10/99	45	1100	1300	700	910	630	770
11/10/99	46	142	282	920	950	840	850
13/10/99	48	1386	1498	800	800	790	770
15/10/99	50	5880	6970	690	730	650	680
18/10/99	53	3582	4326	980	1010	860	870
19/10/99	54	2405	3085	980	1010	860	870
20/10/99	55	260	378	700	720	640	640
21/10/99	56	700	1650	700	910	630	770
22/10/99	57	262	482	600	700	560	580
26/10/99	61	3405	3645	740	780	650	600
27/10/99	62	1620	2145	860	940	760	730
Steady State Mean		1543	1898	1096	1354	1017	1091
Std. Er		149	173	42	70	42	49

VSS_E (g/m³)	TSS_E (g/m³)	SSV_{30} (ml/l)	SVI (ml/g)	COD_O (g/m³)	$sCOD_O$ (g/m³)	COD_E (g/m³)	$sCOD_E$ (g/m³)	E_{COD} (%)
182	214			3069	2144	557	416	82
252	174							
184	166							
174	266			4151	3214	485	408	88
148	288			4312	3359	444	375	90
156	232			5233	4506	420	355	92
186	234			5265	5136	537	388	90
114	344			4320	2891	493	404	89
204	262			4579	2616	420	323	91
198	234			5604	4982	404	291	93
152	228			5644	5426	420	327	93
154	198			5628	5459	412	331	93
168	216			5491	5362	428	307	92
96	156	995	133	5491	3553	606	565	89
208	240	960	127	4570	3311	670	226	85
174	198	940	126	6169	2632	545	347	91
196	230	940	122	4780	2342	489	448	90
128	182	875	169	5087	2552	246	210	95
128	182	750	173					
144	146	560	141	2108	1623	271	234	87
98	102	400	135	2087	1651	206	170	90
126	132	320	123	2213	1595	206	186	91
130	134	250	100	3081	2330	186	157	94
114	134	150	81	2951	1926	129	81	96
114	134		0					
55	57	140	77	2104	1740	347	198	83
55	57	100	55					
50	57	100	65	2955	1724	303	287	90
56	67	90	63	6266	3884	468	436	93
58	66	75	64	2661	1587	303	279	89
74	98	70	66	2846	1651	271	246	90
50	57		0					
82	103	80	94	1886	1421	258	230	86
162	103	70	91	2814	1090	307	210	89
70	81	50	74	6508	2447	275	226	96
144	153	50	57	3375	2830	174	105	95
144	153	50	57					
146	154	50	78	2309	1542	331	283	86
50	57	50	78			424	311	
146	170	50	86	1215	803	424	311	65
126	135	50	83	3702	2047	432	359	88
50	60	50	83	3375	2802	404	412	88

92	100	75	66	3212	1964	323	265	88
4	4	4	3	209	112	13	13	1

sE_{COD} (%)	Q_E (m^3/d)	Q_W (m^3/d)	Q_R (m^3/d)	SRT (days)	HRT (days)	F/M (g COD/g TSS/d)	SLR (kg TSS/m^2/d
81	0.00580	0.00340	0.00290	4.92	3.02	0.15	1.075
	0.00400	0.00340	0.00200	5.09	4.38		0.829
	0.00350	0.00340	0.00175	4.87	5.00		0.650
87	0.00300	0.00340	0.00150	4.94	5.83	0.10	0.565
89	0.00300	0.00340	0.00150	5.03	5.83	0.10	0.578
92	0.00300	0.00340	0.00150	4.86	5.83	0.12	0.573
92	0.00300	0.00340	0.00150	4.98	5.83	0.12	0.591
86	0.00200	0.00340	0.00100	5.10	8.75	0.06	0.449
88	0.00200	0.00340	0.00100	4.96	8.75	0.07	0.386
94	0.00200	0.00340	0.00100	5.11	8.75	0.09	0.385
94	0.00100	0.00340	0.00050	5.17	17.50	0.04	0.204
94	0.00150	0.00340	0.00075	5.12	11.67	0.06	0.313
94	0.00200	0.00340	0.00100	5.04	8.75	0.08	0.433
84	0.00200	0.00340	0.00100	5.09	8.75	0.08	0.393
93	0.00100	0.00350	0.00050	5.37	17.50	0.04	0.198
87	0.00200	0.00310	0.00100	5.63	8.75	0.09	0.394
81	0.00200	0.00340	0.00100	5.21	8.75	0.07	0.406
92	0.00150	0.00330	0.00075	5.18	11.67	0.08	0.204
	0.00250	0.00350	0.00125	4.91	7.00		0.286
86	0.00150	0.00350	0.00075	4.89	11.67	0.04	0.156
90	0.00200	0.00350	0.00100	4.88	8.75	0.08	0.156
88	0.00200	0.00350	0.00100	4.78	8.75	0.09	0.137
93	0.00200	0.00350	0.00100	4.80	8.75	0.13	0.132
96	0.00200	0.00350	0.00100	4.77	8.75	0.16	0.098
	0.00200	0.00350	0.00100	4.77	8.75		0.098
89	0.00200	0.00350	0.00100	4.83	8.75	0.11	0.096
	0.00200	0.00350	0.00100	4.83	8.75		0.096
83	0.00200	0.00350	0.00100	4.69	8.75	0.20	0.081
89	0.00200	0.00350	0.00100	4.66	8.75	0.43	0.076
82	0.00200	0.00350	0.00100	4.94	8.75	0.23	0.062
85	0.00200	0.00350	0.00100	4.43	8.75	0.26	0.056
	0.00200	0.00350	0.00100	4.60	8.75		0.041
84	0.00200	0.00350	0.00100	4.58	8.75	0.24	0.045
81	0.00200	0.00350	0.00100	4.46	8.75	0.41	0.041
91	0.00200	0.00350	0.00100	4.61	8.75	1.05	0.036
96	0.00200	0.00350	0.00100	4.37	8.75	0.41	0.046
	0.00200	0.00350	0.00100	4.37	8.75		0.046
82	0.00200	0.00350	0.00100	4.30	8.75	0.38	0.034
	0.00200	0.00350	0.00100	4.60	8.75		0.041
61	0.00200	0.00350	0.00100	4.26	8.75	0.21	0.031
82	0.00200	0.00350	0.00100	4.32	8.75	0.60	0.032
85	0.00200	0.00350	0.00100	4.60	8.75	0.45	0.038

85	0.00200	0.00350	0.00100	4.58	8.75	0.37	0.057
1	0.00000	0.00000	0.00000	0.02	0.00	0.03	0.003

r_g (g VSS/m^3/d)	$-r_{su}$ (g COD/m^3/d)	Remarks
1203	724	
1235		
1199		
1141	534	
1199	577	
1204	743	
1221	706	
1187	342	
1255	394	
1216	516	
1233	217	
1261	367	
1282	495	
1262	441	Wasting initiated
1064	89	
1069	546	
1258	396	
863	368	
746		
688	103	
559	174	
522	188	
451	294	
353	297	
353		
346	131	
346		
286	243	
322	569	
251	209	
240	240	
146		
193	134	
179	225	
146	658	
212	331	
212		
157	160	
146		
137	6	
162	287	
178	259	

230	268
8	24

Case 2B (10 day SRT) of the Bench-scale simulations

Date	Day	VSS_O (g/m³)	TSS_O (g/m³)	$MLVSS_1$ (g/m³)	$MLSS_1$ (g/m³)	$MLVSS_2$ (g/m³)	$MLSS_2$ (g/m³)
27/08/99	1	658	726	5190	6200	5320	6340
28/08/99	2	2084	2336	5340	7020	5220	6240
29/08/99	3	1432	1590	5340	6800	5080	6260
30/08/99	4	814	954	5020	6580	4900	6220
31/08/99	5	808	926	5580	6900	5560	6520
1/09/99	6	1212	1530	5840	7180	5500	7100
2/09/99	7	1298	1570	5540	7800	5580	7000
3/09/99	8	606	668	5200	7500	5700	7500
6/09/99	11	1014	1034	5860	7280	5860	7060
7/09/99	12	2467	2587	5880	7020	5980	7140
8/09/99	13	987	1047	6300	7720	6360	7780
9/09/99	14	917	957	6420	7840	6900	8100
10/09/99	15	910	953	6460	8180	6160	8120
13/09/99	18	3125	3725	6020	7260	6040	7400
14/09/99	19	1254	1775	5820	7320	6140	7380
15/09/99	20	2505	3260	5520	7380	6320	7980
16/09/99	21	2810	3510	6540	7800	6940	8040
17/09/99	22	1600	2660	5300	6720	5600	6840
20/09/99	25	683	1090	4660	5520	4660	5400
21/09/99	26	512	554	4680	5800	4600	6000
22/09/99	27	400	466	4340	5460	4380	5380
23/09/99	28	544	588	4160	5100	4140	5160
24/09/99	29	716	765	3840	5040	3760	5240
27/09/99	32	1145	1295	3240	4340	3240	4460
28/09/99	33	950	1065	3240	4340	3240	4460
29/09/99	34	590	725	3280	4760	3280	4360
30/09/99	35	497	608	3280	4760	3280	4360
1/10/99	36	1100	1300	2800	3420	2780	3300
4/10/99	39	2390	3120	2540	3060	2520	2860
6/10/99	41	1000	1190	2260	2820	2160	2680
8/10/99	43	895	1005	1760	2820	1440	1940
10/10/99	45	1100	1300	1760	2820	1440	1940
11/10/99	46	142	282	1950	2210	2260	2560
13/10/99	48	1386	1498	1440	1690	1670	2330
15/10/99	50	5880	6970	1090	1360	1050	1370
18/10/99	53	3582	4326	1070	1310	1040	1320
19/10/99	54	2405	3085	1070	1310	1040	1320
20/10/99	55	260	378	1630	1860	1580	1780
21/10/99	56	700	1650	1400	1710	1390	1650
22/10/99	57	262	482	1150	1490	1130	1440
26/10/99	61	3405	3645	1070	1210	1080	1260
27/10/99	62	1620	2145	1040	1360	1010	1190

Steady State Mean	1543	1898	1951	2561	1928	2452
Std. Er	149	173	89	129	90	123

VSS_E (g/m³)	TSS_E (g/m³)	SSV_{30} (ml/l)	SVI (ml/g)	COD_O (g/m³)	$sCOD_O$ (g/m³)	COD_E (g/m³)	$sCOD_E$ (g/m³)	E_{COD} (%)
180	226			3069	2144	715	396	77
164	170					715	396	
184	162					715	396	
156	224			4151	3214	642	468	85
132	172			4312	3359	404	355	91
152	310			5233	4506	452	367	91
156	272			5265	5136	485	335	91
164	296			4320	2891	589	448	86
192	184			4579	2616	380	315	92
156	174			5604	4982	412	327	93
160	216			5644	5426	404	327	93
156	162			5628	5459	412	323	93
132	168			5491	5362	412	299	93
88	146	995	134	5491	3553	698	626	87
104	196	960	130	4570	3311	420	299	91
172	212	965	121	6169	2632	565	396	91
192	236	975	121	4780	2342	489	416	90
132	208	980	143	5087	2552	501	464	90
132	208	950	176					
192	206	950	158	2108	1623	400	323	81
112	186	940	175	2087	1651	347	250	83
148	164	930	180	2213	1595	371	311	83
168	166	900	172	3081	2330	335	331	89
110	140	770	173	2951	1926	343	242	88
110	140	770	173					
168	214	700	161	2104	1740	614	380	71
168	214	440	101					
122	140	450	136	2955	1724	412	359	86
94	172	420	147	6266	3884	549	505	91
96	182	280	104	2661	1587	549	505	79
42	100	240	124	2846	1651	432	359	85
42	100	241	124					
110	136	200	78	1886	1421	598	351	68
110	136	180	77	2814	1090	335	258	88
120	169	135	99	6508	2447	335	230	95
154	173	175	133	3375	2830	456	295	86
154	173	170	129					
100	166	170	96	2309	1542	525	396	77
122	140	169	102					
140	207	130	90	1215	803	448	323	63
146	139	130	103	3702	2047	424	339	89
162	140	150	126	3375	2802	424	339	87

119	157	312	120	3212	1964	460	349	82
4	3	23	3	209	112	13	12	1

sE_{COD} (%)	Q_E (m^3/d)	Q_W (m^3/d)	Q_R (m^3/d)	SRT (days)	HRT (days)	F/M (g COD/g TSS/d)	SLR (kg TSS/m^2/d
82	0.00100	0.00170	0.00050	10.20	17.50	0.03	0.17
	0.00150	0.00170	0.00075	9.93	11.67		0.25
	0.00200	0.00170	0.00100	9.69	8.75		0.33
85	0.00200	0.00170	0.00100	9.83	8.75	0.07	0.33
89	0.00100	0.00170	0.00050	10.14	17.50	0.04	0.17
92	0.00200	0.00170	0.00100	9.74	8.75	0.08	0.37
93	0.00200	0.00170	0.00100	9.99	8.75	0.08	0.37
84	0.00150	0.00170	0.00075	10.43	11.67	0.05	0.30
88	0.00250	0.00170	0.00125	9.82	7.00	0.09	0.46
93	0.00150	0.00170	0.00075	10.13	11.67	0.07	0.28
94	0.00200	0.00170	0.00100	10.04	8.75	0.08	0.41
94	0.00200	0.00170	0.00100	10.33	8.75	0.08	0.43
94	0.00200	0.00170	0.00100	9.85	8.75	0.08	0.43
82	0.00200	0.00170	0.00100	10.13	8.75	0.09	0.39
91	0.00200	0.00170	0.00100	10.32	8.75	0.07	0.39
85	0.00200	0.00170	0.00100	10.55	8.75	0.09	0.42
82	0.00200	0.00170	0.00100	10.21	8.75	0.07	0.42
82	0.00200	0.00170	0.00100	10.24	8.75	0.09	0.36
	0.00200	0.00170	0.00100	9.96	8.75		0.28
80	0.00200	0.00170	0.00100	9.75	8.75	0.04	0.32
85	0.00200	0.00170	0.00100	10.03	8.75	0.04	0.28
81	0.00200	0.00170	0.00100	9.86	8.75	0.05	0.27
86	0.00200	0.00170	0.00100	9.70	8.75	0.07	0.28
87	0.00200	0.00170	0.00100	9.90	8.75	0.08	0.23
	0.00200	0.00170	0.00100	9.90	8.75		0.23
78	0.00200	0.00170	0.00100	9.71	8.75	0.05	0.23
	0.00200	0.00170	0.00100	9.71	8.75		0.23
79	0.00200	0.00170	0.00100	9.76	8.75	0.10	0.17
87	0.00200	0.00170	0.00100	9.83	8.75	0.24	0.15
68	0.00200	0.00170	0.00100	9.62	8.75	0.11	0.14
78	0.00200	0.00170	0.00100	9.23	8.75	0.13	0.10
	0.00200	0.00170	0.00100	9.23	8.75		0.10
75	0.00580	0.00170	0.00290	9.22	3.02	0.26	0.39
76	0.00580	0.00170	0.00290	8.72	3.02	0.47	0.36
91	0.00580	0.00170	0.00290	7.37	3.02	1.58	0.21
90	0.00580	0.00170	0.00290	6.82	3.02	0.85	0.20
	0.00580	0.00170	0.00290	6.82	3.02		0.20
74	0.00580	0.00170	0.00290	8.40	3.02	0.42	0.27
	0.00580	0.00170	0.00290	7.91	3.02		0.25
60	0.00580	0.00170	0.00290	7.22	3.02	0.27	0.22
83	0.00580	0.00170	0.00290	7.05	3.02	1.00	0.19
88	0.00580	0.00170	0.00290	6.64	3.02	0.87	0.18

80	0.00400	0.00170	0.00200	8.58	5.73	0.46	0.21
1	0.00020	0.00000	0.00010	0.13	0.30	0.06	0.01

r_g (g VSS/m^3/d)	$-r_{su}$ (g COD/m^3/d)	Remarks
514	65	
533		
540		
505	339	
550	184	
585	502	
556	499	
519	263	
597	563	
585	405	
630	560	
641	556	
643	540	
595	480	Wasting initiated
577	434	
556	586	
657	443	
530	476	
468		
477	156	
434	165	
421	174	
392	281	
327	265	
327		
338	111	
338		
286	251	
257	600	
231	188	
176	234	
176		
226	369	
176	789	
146	2013	
155	923	
155		
191	540	
176		
158	211	
152	1045	
155	937	

218	605
7	72