

**ACTIVATED SLUDGE TREATMENT
OF PAPER MACHINE EFFLUENT
FOR MILL RE-USE**

BY

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SYNOPSIS

The SAPPI Ngodwana mill is the largest integrated pulp and paper mill in Africa and is situated in the Elands River catchment in the Mpumalanga province.

A need has arisen at the mill to reduce effluent volumes requiring discharge. The combined mill effluent is currently irrigated onto pastures and over the years percolation of attenuated effluent has resulted in elevated chloride levels in the Elands River. Elevated chloride levels in the river have in turn impacted on the tobacco farmers downstream of the mill.

Reclamation of Kraft Liner Board effluent was identified as a means of reducing the hydraulic load onto the irrigation pastures and at the same time reduce the intake of fresh water into the mill.

Two possible uses for the reclaimed effluent, namely washing of bleached or unbleached pulp, were identified. The major reclaimed water quality variables of concern for re-use are; biodegradable organic material, colour and suspended solids.

Approximately 9 months of pilot-scale activated sludge treatment of the effluent demonstrates that sufficient organic material can be removed for re-use, as wash water. Removal of the organic material was not influenced by sludge age in the range 2 to 8 days.

A high degree of colour removal was achieved, which is contrary to reports in the literature. Even with the high colour removal achieved, however, insufficient colour was removed to allow washing of bleached pulp.

Pulp and paper effluents are often reported to result in filamentous bulking activated sludges. This was confirmed in the testwork. Severe sludge settleability problems were experienced throughout the pilot-scale testwork. Filamentous bulking was identified as the cause of poor sludge settleability and preventative or control strategies would have to be implemented on full-scale.

OPSOMMING

Die Sappi Ngodwana Meule is die grootste geïntegreerde papier- en pulpmeule in Afrika en is in die Elandsrivier opvangsgebied in die Mpumalanga Provinsie geleë.

Die meule moet noodgedwonge die hoeveelheid uitvloeiende water wat weggedoen word verminder. Die gekombineerde meule uitvloeiende water word reeds vir verskeie jare en nog steeds op voergras besproei. Die syfering van die uitvloeiende water het verhoogde chloriedvlakke in die Elandsrivier tot gevolg. Die verhoogde chloriedvlakke in die rivier het verder stroomaf 'n impak op die tabakboerderybedryf.

Die herwinning van "Kraft Liner Board" uitvloeiende water is geïdentifiseer as 'n wyse waarop die hidrouliese lading op die besproeiingslande en die inname van vars water in die meule verminder kan word.

Potensiële gebruik van die herwonne uitvloeiende water vir die was van gebleikte en ongebleikte pulp is geïdentifiseer. Die watergehalte veranderlikes van spesifieke belang vir die hergebruik van water vir die doel is die bio-afbreekbare organiese verbindings, kleur en swewende stowwe.

Loodskaal geaktiveerde slykbehandeling van die uitvloeiende water het oor 'n periode van nege maande bewys dat voldoende organiese materiaal verwyder kan word, sodat die herwonne water as waswater gebruik kan word. Die verwydering van organiese verbindings is nie sensitief vir die slykouderdorm oor die interval 2 - 8 dae nie.

Hoë vlakke van kleurverwydering is ook behaal, ten spyte van teenstrydige verwysings in die literatuur. Alhoewel hoë kleurverwydering bereik is, was die kleurverwydering steeds onvoldoende om die herwonne water vir die was van gebleikte pulp te gebruik.

Dit word gereeld in die literatuur gemeld dat slykuitdying 'n probleem met die geaktiveerde slykbehandeling van papier- en pulpvloeiende water is. Dit is ook bevestig in hierdie eksperimentele werk. Draadvormige organismes is geïdentifiseer as die vernaamste rede vir die swak slykbesinking en voorkomende- en beheermaatreëls sal op volskaal toepassing van die tegnologie geïmplementeer moet word.

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1. INTRODUCTION

South Africa is a semi-arid country with limited water resources and few natural lakes. The country is thus forced to construct large storage dams in an attempt to reconcile water supply with demand for an ever increasing population.

Increased industrialisation is but one of the factors contributing to a continual increase in water demand and also a decrease in quality of the country's water resources (Department of Water Affairs and Forestry, 1991).

One of the industries contributing to this problem is the pulp and paper industry. The industry is highly energy intensive, a drain on natural resources, and a major source of pollution (CTS Consulting, 1991).

The South African Pulp and Paper Industry (SAPPI) is a major role-player in local and international pulp and paper markets and is the largest producer of pulp and paper in the country. The largest pulp and paper mill in South Africa owned by SAPPI is the Ngodwana mill. The mill is situated in the Elands River catchment in the Eastern Transvaal province. The mill is the largest integrated (producing bleached and unbleached pulp) pulp and paper mill in Africa and produces approximately 1 500 tons of pulp and paper daily.

Water used at the Ngodwana mill is abstracted from the Ngodwana river (a tributary of the Elands River) and approximately 25 megalitres of effluent is produced daily.

Since commissioning of the mill in the first half of the 1980's, the effluent has been irrigated onto pastures adjacent to the mill. Over the years attenuated effluent has percolated into the Elands River resulting in elevated chloride levels in the river. The elevated chloride levels have in turn impacted on downstream tobacco growers.

The high volumetric load onto the irrigation pastures has furthermore resulted in an elevated water table which in turn has increased the rate of effluent discharge into the Elands River.

The mill is thus faced with a two-pronged problem; chloride contamination of the Elands River and a high volume of effluent requiring disposal.

Numerous projects have been conducted by SAPPI Research and Development in an attempt to solve both of these problems.

The work presented in this thesis is the result of one such project which is aimed at reducing the volume of effluent discharged from the mill and concomitantly the contamination of the Elands River.

The effluent produced at the mill is made up of a large number of component streams but can broadly be classified into paper machine effluent and bleach plant effluent. Reclamation of paper machine effluent for re-use within the mill was identified as one means of reducing the total volume of effluent requiring disposal.

Re-use of the reclaimed water, to replace fresh-water make-up, as pulp wash-water was identified as a possible means of effluent volume reduction. The reclaimed water could then either be used for bleached pulp washing or unbleached pulp washing, each potential use requiring a certain quality of reclaimed water. To this end a project was initiated in order to achieve the following objectives:

- To determine the water quality objectives of reclaimed paper machine effluent to satisfy the identified uses.
- To review technologies available which could achieve the desired water quality objectives.
- To select the most effective and appropriate technology, and to test the effectiveness of the technology, on pilot-scale, in meeting the desired water quality objectives.
- To identify and investigate any operational problems which may impact on full-scale application.

This thesis summarises the results of approximately nine months of pilot scale testwork using completely mixed activated sludge technology for the reclamation of paper machine effluent.

2. LITERATURE REVIEW

2.1 INTRODUCTION

Unfavourable climatic conditions, uneven geographic distribution of water resources and upward spiralling demands, in step with rapidly multiplying population mean that water is becoming scarce in many parts of South Africa. Increasing population growth in most parts of South Africa is placing greater demands on the water resources available to satisfy the needs of industrialisation, urbanisation, agriculture and recreation. At the same time, all these water users can create both point and diffuse sources of pollution of inland and coastal waters.

The Department of Water Affairs and Forestry is the custodian of water resources in the country, and has, as its first goal in water quality management, the encouragement of (Department of Water Affairs and Forestry, 1991);

"Source reduction, recycling, detoxifying and neutralisation of wastes"

Industry is a major source of pollution in the country and the pulp and paper industry is no exception. There are no mills able to operate without producing a raw wastewater (Webb, 1991). The compositions and flows of effluent streams vary from mill to mill depending mainly on pulping and bleaching methods, however, the major effects on the environment are due to (Bonsor *et al*, 1988);

- suspended solids
- Biological Oxygen Demand (BOD)
- resin and fatty acids
- reduced sulphur compounds
- chlorates and chlorides
- chlorinated organics

The toxicity of pulp and paper mill effluents has been under close scrutiny over the past decade (Walden and Howard, 1981). In particular, the carcinogenic and mutagenic properties of chlorinated organics found in bleaching effluents have raised public awareness of pollution associated with the pulp and paper industry (Owens, 1991; Boman and Frostell, 1988; Lindström and Mohamed 1988)

Mills worldwide are being forced to comply with stricter environmental legislation (CTS Consulting, 1991). This is also the case in South Africa, and although recycling, detoxifying, source reduction and neutralisation are not yet law, these practices are encouraged by the Department of Water Affairs and Forestry (Department of Water Affairs and Forestry, 1991).

2.2 WATER QUALITY OBJECTIVES FOR RE-USE

The quality of water required for re-use depends on the eventual end use. In some cases the required water quality is more stringent than the statutory quality requirements and tertiary treatment of the water is necessary.

Re-use of water in the paper section of a mill results in a buildup of dissolved organic material in water circuits which may have a deleterious effect on the paper making process (Water Research Commission, 1991). It is likely that closing up of water circuits will increase the concentration of dissolved organic material but decrease the load (Webb, 1991).

Biodegradable organic material may, furthermore, cause the proliferation of bioslime which accelerates metallic corrosion, reduces flow rate and decreases heat exchange (Cloete, *et al*, 1989, Water Research Commission, 1991).

The **colour** of the recycled water is also of importance and, in particular, bleached papers are sensitive to colour. Brown (unbleached) grades of paper are most tolerant of recycled water, followed by newsprint and tissue paper (Water Research Commission, 1991).

Existing biologically treated effluents are generally of high quality for much of the time, however, variations in the **particulate** content of the water often necessitates filtration to ensure a constant quality (Webb, 1991).

The most important water quality parameters for re-use thus appear to be biodegradable organics, colour and suspended matter. No reference in the literature could, however, be found which indicates specific concentration limits for these parameters.

2.3 TECHNIQUES FOR ACHIEVING THE WATER QUALITY OBJECTIVES

The three major water quality parameters of concern for re-use of reclaimed water for pulp washing have been established above. These are:

- biodegradable organic material
- colour
- suspended solids

Although the actual water quality limits could not be established from the literature it is pertinent to investigate the technologies which are applicable in improving the levels of these parameters in the reclaimed water.

2.3.1 Biodegradable organic material removal

Several technologies are available, and have been used within the industry for the removal of biodegradable organic material. These technologies can be categorised into: aerobic, anaerobic, sequential anaerobic-aerobic, fixed film and fungal treatment.

Aerobic Treatment

Aerobic biological treatment of pulp and paper effluents has dominated the industry for many years (Lee *et al*, 1991, Shell and Hicks, 1993). Many variants of aerobic treatment technology have been applied to pulp and paper effluents, these include:

Aeration lagoons:

The aerated lagoon was the first treatment technology applied in the industry for the removal of biodegradable organic material (Liu *et al*, 1993). Aerated lagoons have the following advantages:

- very little sludge is generated compared to activated sludge systems (Lindström and Mohamed, 1988).
- are more resistant to organic, pH or temperature shocks than anaerobic treatment (Lee *et al*, 1989).

The disadvantages of aerated lagoons are, however:

- large land areas are required compared to all other treatment technologies (Lee *et al*, 1989).
- less effective at removing organic material than activated sludge systems (Lindström and Mohamed, 1988).
- require large amounts of energy for aeration and mixing compared to anaerobic and fixed film systems (Lee *et al*, 1991).
- are ineffective at removing colour (Erriksson, 1988).

Activated sludge systems:

Activated sludge systems are used most widely within the industry and many variants have been applied, namely: plug flow, completely mixed, step aeration, contact stabilisation, extended aeration and various hybrids of these (Webb, 1991; Welch, 1979; Lee *et al*, 1989). The major advantages of activated sludge systems include:

- require smaller land area than aerated lagoons (Lee *et al*, 1989)
- are capable of treating higher organic loads compared to aerated lagoons and anaerobic systems (Liu *et al*, 1993).
- are more effective at removing organic material than aerated lagoons or anaerobic systems (Liu *et al*, 1993).
- are more resistant to shock loads than aerated lagoons and anaerobic systems (Weeks and Oleszkiewicz, 1994; Cocci *et al*, 1982)
- are less sensitive to inhibitory toxic compounds than anaerobic treatment (Lee *et al*, 1989).

Activated sludge systems, however, have the following disadvantages:

- produce large amounts of sludge compared to anaerobic or aerated lagoon systems (Lee *et al*, 1989)
- require large amounts of energy compared to anaerobic or aerated lagoon systems (Lee *et al*, 1991).

Anaerobic treatment

Anaerobic digestion of municipal sewage sludge has been practised routinely since the 1930's. Until the previous decade, however, anaerobic treatment of industrial waste has been limited primarily to the poultry and red meat packing and vegetable industries. Research done in the 1970's and early 1980's resulted in significant advances in anaerobic treatment of pulp and paper effluents and led to the first application in the industry in 1978 (Lee *et al*, 1989).

Many variants of anaerobic treatment technology have been applied in the industry, including: anaerobic lagoons, biofilters, fluidised beds, anaerobic contact and upflow anaerobic sludge bed systems (Lee *et al*, 1989).

Anaerobic treatment technology has the following advantages over aerobic treatment systems (Liu *et al*, 1990, Lee *et al*, 1989);

- low sludge production
- low nutrient requirement
- low energy requirement
- energy recovery from methane produced
- operates effectively at high temperature
- the sludge can be left dormant without feed for a long time (12 - 18 months) and brought back into operation within a short time (1 - 3 days).

The following disadvantages are, however, inherent to anaerobic systems compared to aerobic systems:

- less resistant to shock loads (Rintala and Sierra-Alvarez, 1991)
- low removal of toxic compounds (Schnell *et al*, 1990)
- sensitive to inhibitory toxic compounds such as resin acids and hydrogen sulphide (Lee *et al*, 1989).
- malodorous and corrosive compounds are often formed (Lee *et al*. 1989).
- lower organic loads are treatable (Cocci *et al*, 1982)
- biosolids retention is a problem (Lee *et al*, 1989)
- requires long startup times, often requiring acclimation of the sludge (Hall and Cornacchio, 1988).
- anaerobic systems are best suited to the treatment of high strength wastewaters. The optimum COD (Chemical Oxygen Demand) concentration range is 1000 - 30 000 mg/ℓ (Hall and Cornacchio, 1988).

Sequential aerobic-anaerobic treatment

In many instances discharge limits cannot be reached by anaerobic treatment alone and sequential anaerobic-aerobic treatment becomes necessary, the aerobic step acting as a polishing step (Driessen and Habets, 1992; Garvie, 1992). Sequential treatment is reported to decrease sludge production and improve effluent quality compared to aerobic treatment alone (Rintala and Vuoriranta, 1988; Flammino *et al*, 1989).

Fixed film biological treatment

Fixed film biological treatment systems, such the biofilter and rotating biological contactor have been tested on pulp and paper wastewater on pilot scale. These systems are reported to have the

following advantages, over other treatment systems (Bennet *et al*, 1973; Gillespie *et al*, 1974, Fein *et al*, 1993);

- Simplicity of operation
- low maintenance
- low power consumption
- resistant to influent variations
- advantageous secondary sludge characteristics

No reference could, however, be found for full-scale application of this technology in the pulp and paper industry.

Fungal treatment systems

White rot fungi are the only known organisms to degrade polymeric lignin completely. They will also degrade industrially modified lignin, including chlorinated high molecular mass lignin from pulping and bleaching operations (Erriksson, 1988).

Fungal treatment systems are reported to achieve high organic, colour and toxicity removal (Pellinen *et al*, 1988; Boman and Frostell 1988; Roy-Arcand and Archibald 1991), however no reference could be found for full-scale application of this technology in the pulp and paper industry.

2.3.2 Colour removal

Several technologies are available, and have been used within the industry, for the removal of colour. These technologies are broadly classified into; internal process modifications and external, or "end-of-pipe" methods.

Internal process modifications

Numerous internal mill process modifications can be implemented to reduce colour in pulp and paper wastewaters. These methods

have little bearing on the project, however, and can be found in the literature (Gellman and Berger, 1974, Panchapakesan, 1991).

Adsorption

Several adsorption techniques have been tested including ion-exchange and activated carbon adsorption. Both methods have been shown to be technologically feasible, however, the high costs of regeneration and pretreatment are prohibitive (Rock *et al*, 1974; Panchapakesan, 1991; Gellman and Berger, 1974).

Oxidation

Ozone and chlorine have been investigated as a methods of oxidizing colour from pulp and paper effluents. Both methods, although technically feasible, have proven to be too costly for practical implementation (Gellman and Berger 1974).

Membrane separation

Membrane separation processes such as ultrafiltration, reverse-osmosis and electrodialysis have been tested on pilot-scale. These processes have, however, been shown to be economically inhibitive (Gellman and Berger, 1974, Panchapakesan, 1991).

Biological treatment

Little reference could be found to colour removal by biological treatment and the literature available appears to be conflicting.

One author (Davies and Wilson, 1990) reports that little or no colour is removed by conventional biological treatment, while another (Joyce *et al*, 1979) reports that colour is removed to some degree.

Two hypotheses for colour removal by conventional biological treatment have been put forward; the first is that colour is adsorbed onto and is discharged with the waste sludge. The second is that colour bodies are adsorbed onto bacterial surfaces and are altered to a non-coloured form (Joyce *et al*, 1979).

2.3.3 Suspended solids removal

There are numerous methods for removing suspended matter from waste streams, however, due to the blinding and plugging nature of pulp and paper wastes, three general methods are used, namely; sedimentation, flotation and screening (Bonsor *et al*, 1988).

Reclamation of paper machine effluent for re-use within a mill, however, requires the removal of not only suspended matter but also biodegradable organic material and colour. Conventional solids removal techniques will not remove sufficient biological oxygen demand (BOD) and colour for re-use. If conventional biological treatment methods are employed to remove, in particular, BOD, then some form of solids separation is required to remove the associated biosludge. The quality of the reclaimed wastewater is thus dependent on the effectiveness of this secondary clarification and is concomitantly dependent on the settling characteristics of the biosludge. This aspect is covered in more detail in **Section 2.4.3**

2.4 ACTIVATED SLUDGE TREATMENT OF PULP AND PAPER EFFLUENTS

Effluents may be generated from various points within a pulp and paper mill, for example; bleaching effluents, pulping effluents and paper machine effluents. Each of the effluents generated typically has a different chemical composition. Furthermore, different methods of operation, for example chemical versus mechanical pulping, will again produce effluents with different compositions. These changes in composition are often not only process-specific, but change from mill to mill, using the same processes (Bonsor *et al*, 1988).

The effluent under investigation in this study is paper machine effluent originating from a Kraft Liner Board (KLB) manufacturing machine. The effluent thus originates from a chemical pulping process, and more specifically, the Kraft pulping process. The production schedule at the SAPPI Ngodwana mill also provides for the manufacture of White Top Liner (WTL) on a batch basis, approximately once per month. During the manufacture of White Top Liner, a thin layer of bleached pulp is placed on top of the unbleached KLB. The effluent produced in this process is approximately five times more dilute than KLB effluent alone and comprises a blend of pulping and bleaching effluents.

Many authors have published results of activated sludge treatability studies, done either on pilot-, or full-scale. The majority of these studies have been conducted on either total mill effluent, mechanical pulping effluent or on chemi-mechanical pulping effluent. No reference could be found dealing specifically with activated sludge treatment of KLB effluent.

In addition to this, most studies have been done abroad and are aimed at eventual river discharge of the treated effluent. River discharge criteria, specific to the particular country, are thus generally used to define the treated water quality objectives.

In order to bridge the gap between the treatability of effluents originating from chemical pulping methods (such as KLB effluent) and mechanical pulping effluents it is necessary to explore the similarities and differences between these types of effluents.

2.4.1 Mechanical versus chemical pumping effluents

The pulping of wood or other cellulosic material, whether it is done mechanically or chemically, results in the solubilisation of organic materials such as lignin and various wood extractions. These include: carbohydrates, acetic and other organic acids, methanol and other low molecular weight alcohols, and a small amount of inorganic ash.

Lignin is refractory to biological degradation by bacteria. Carbohydrates, organic acids and alcohols are, however, easily metabolised. These compounds make up 40 to 60 percent of the total organics, irrespective of the pulping method (Lee *et al*, 1989).

Chemical characteristics of typical mechanical and chemical pulping effluents are shown in **Table 2.1**.

Table 2.1 : Chemical characteristics of typical mechanical and chemical pulping effluents (Lee *et al*, 1989)

Parameter	Pulping Process	
	Mechanical	Chemical
Total COD (mg/ℓ)	7 210	5 020
Total BOD ₅ (mg/ℓ)	2 800	1 600
BOD ₅ /COD	0.39	0.32
Carbohydrates (mg/ℓ)	2 700	610
Acetic acid (mg/ℓ)	235	54
Methanol (mg/ℓ)	25	9

The above discussion highlights the similarities, particularly with respect to biological treatability of mechanical and chemical pulping effluents. Any reference to activated sludge treatment of mechanical pulping effluents will thus also, in broad terms, be applicable to chemical pulping effluents.

2.4.2 Removal of organic material

Numerous studies have been conducted on various pulp and paper effluents in order to determine the efficiency of organic removal by activated sludge treatment. The results of some of these studies are summarised in **Table 2.2**

Consistently high BOD removal efficiencies (80 - 99%) are reported for a wide spectrum of pulp and paper effluents. As expected, the reported COD removal efficiencies are significantly lower.

The efficiency of activated sludge treatment systems in breaking down carbonaceous material is, however, known to be dependent on a number of operating parameters. These include (Marais and Ekama 1976);

Table 2.2 : Summary of organic removal results found in the literature for various pulp and paper effluents

Type of Effluent	Percentage Removal		Reference
	BOD ₅	COD	
Combined mill effluent	88-92	—	Welch, 1979
Mechanical, Newsprint and Kraft pulping effluent	95	—	Johnson and Chatterjee, 1993
Combined mill effluent	97	68	Simpura and Pakarinen 1993
Printing and magazine papers	96	—	Peterson and Gilbert, 1993
Mechanical pulping	80-85	—	Rintala and Vuoriranta, 1988
Bleach effluents	80-93	40-50	Nevalainen, <i>et al</i> 1991
Combined mill effluent	98-99	—	Mackay and Galloway, 1993

- sludge age
- temperature
- pH
- dissolved oxygen level
- organic load

Sludge age

The removal of organic material is dependent on sludge age and increases with increasing sludge age. This dependence is not as marked for biodegradable organics (measured as BOD) as it is for total organics (measured as COD). The rate at which COD is removed slows down rapidly for sludge ages in excess of 20 days (as the sludge age increases from 20 days to 40 days, the COD removal increases from 60% to 68%). BOD removal is less dependent on sludge age (as the sludge age is increased from 10 days to 40 days, the BOD removal increases from 95% to 97%) (Simpura and Pakarinen, 1993).

Temperature

The rate at which carbonaceous material is biologically degraded is temperature dependent and increases with increasing temperature (Marais and Ekama, 1976). Temperatures in excess of 40°C are, however, reported to cause a deterioration in performance (Lo *et al*, 1990, Liu *et al*, 1993).

pH

Effective pH control is critical to the performance of the activated sludge process (Keays *et al*, 1993). Operation at pH's as close to neutral (6.5 to 7.5) are reported to be optimal (Lo *et al*, 1990, Liu *et al*, 1993).

Dissolved oxygen

The effect of dissolved oxygen concentration on the performance of activated sludge systems above a value of 2 mg/l is reported to be small (an increase in COD removal from 70% to 80% for an increase in dissolved oxygen concentration from 2.5 mg/l to 8.2 mg/l) (Lo *et al*, 1990). A low dissolved oxygen concentration (< 0.1 mg/l), however, causes a deterioration in performance (Peterson and Gilbert, 1993).

Organic load

Organic load is expressed as the mass of substrate (for example, COD) which is fed to a reactor per unit volume of the reactor, and can be expressed as:

$$\text{Organic load} = \frac{\text{Feed substrate concentration}}{\text{Hydraulic retention time}} \quad (1)$$

The hydraulic retention time (HRT) is defined as the volume of reactor divided by the feed flow rate.

Another parameter which is often used and which is related to organic load and hydraulic retention time is the Food : Microorganism (F/M) ratio. The F/M ratio is expressed as the mass of substrate removed per unit mass of solids (either total or volatile solids) in the reactor, or;

$$F/M = \frac{(\text{Feed} - \text{Effluent})_{\text{substrate concentration}}}{(\text{Reactor solids concentration}) (\text{hydraulic retention time})} \quad (2)$$

This parameter, is however dependent on sludge age and no additional information can be obtained from it that cannot be derived from the sludge age. Unfortunately the F/M is widely used as the basis for design, particularly in North America and Europe (Ekama *et al*, 1984).

A summary of the parameters discussed above which have been applied in pilot- and full-scale applications for various pulp and paper effluents is summarised in **Table 2.3**.

Table 2.3 : Summary of operational parameters found in the literature for various pulp and paper effluents

Type of Effluent	Organic Load		FM		HRT hrs	Reference
	kg BOD/m ³ /d	kg COD/m ³ /d	kg BOD/kg MLSS/d	kg COD/kg MLSS/d		
Mechanical, Newsprint and kraft pulping	0.5	—	0,2	—	17	Johnson and Chatterjee, 1993
Mechanical pulping	—	2-5	—	—	—	Rintala and Vuoriranta, 1988
Combined mill effluent	0.5	—	0.05 - 0.08	—	24	Simpura and Pakarinen, 1993
Combined mill effluent	0.1 - 0.2	—	0.1	—	36 - 48	Mackay and Galloway, 1993

2.4.3 Colour removal

As mentioned in **Section 2.3.2** the literature appears to be conflicting regarding colour removal by biological treatment systems. One author (Davies and Wilson, 1990) states that little or no colour removal is achieved, while another (Joyce *et al*, 1979) gives two hypotheses on how colour is removed during biological treatment.

No reference could be found, however, giving actual removal efficiencies.

2.4.4 Suspended solids removal

Two basic operations determine the performance of an activated sludge process; the conversion of organic matter into microbial mass, and the physical separation of the resulting mass from the liquid by settling. The efficiency of most activated sludge systems depends on the separation of the solids, and this operation is controlled by the settling characteristics of the sludge (Ekama *et al*, 1984).

Poor sludge settleability is a common problem in the activated sludge treatment of pulp and paper effluents and is mostly attributed to filamentous bulking (Webb, 1991; Grau 1991, Richard 1991).

An extensive survey conducted on 29 paper mills in the USA showed that filamentous bulking was the cause for 90% of the bulking episodes. The major filamentous bacteria identified and the causes are summarised in **Table 2.4**.

Table 2.4 : Occurrence of filament types as a cause of papermill activated sludge bulking (Richard, 1991)

Filament Group	Cause(s)
0675, 1851, 0041	low FM
<i>Thiothrix I and II</i> , <i>N. limicola II</i> and Type 021N	nutrient deficiency sulfides/septicity
<i>S. Natans</i> and Type 1701	oxygen deficiency

The factors reported to cause or impact on filamentous bulking episodes include: substrate type and load, dissolved oxygen, temperature and nutrients:

Substrate type and load

Activated sludge systems treating streams containing high concentrations of starch, sulphur compounds or significant concentrations of pulping liquors are prone to the development of filamentous organisms (Biörnstad *et al*, 1993, Grau 1991). High

organic loading of soluble, readily biodegradable organic material is also reported to promote filament overgrowth (Richard 1991).

Several authors report that a too low or too high FM ratio may lead to filamentous bulking (Rintala and Sierra-Alvarez, 1991, Richard 1991). None of these authors have, however, quantified "high" and "low".

Dissolved oxygen

Low dissolved oxygen concentrations are reported to promote filament overgrowth (Richard 1991, Lo *et al*, 1990), however, "low" is again not quantified.

Temperature

Temperatures in excess of 40°C are reported to be a cause of filamentous bulking (Lo *et al*, 1990).

Nutrients

Pulp and paper effluents are generally deficient in nutrients, particularly nitrogen and phosphorus, for sustaining bacterial growth (Gostick 1990, Vaananen and Hynninen 1993). Nutrients are thus generally added as urea and phosphoric acid and the dosage is typically controlled by monitoring the treated water nutrient concentrations (Möbius 1991). Nutrient deficiency is often cited as a cause for filamentous bulking (Doepke 1991, Richard 1991, Björnstad *et al* 1993).

2.5 SUMMARY AND PROJECT MOTIVATION

The major motivation for this project stems from the need, by the Ngodwana mill, to reduce effluent volumes requiring disposal. Paper machine effluent reclamation was identified as a means of achieving this. Review of the available literature indicates that BOD, colour and suspended solids are the most important water quality parameters regarding re-use of the treated effluent. The secondary objectives of the project are thus summarised as follows:

Water quality objectives

No reference could be found as to the quality of water required for re-use as wash water. An aim of the project is thus to determine the required quality of reclaimed effluent, particularly with respect to BOD, colour and suspended solids.

Appropriate technology

The KLB effluent targeted for reclamation is highly variable in flow and quality and has a low concentration of organic material (approximately 1900 mg COD/ℓ - **Section 4.1**) which makes it unsuitable for anaerobic treatment. The high reported organic removal efficiency of activated sludge systems and lower land area required also make them more attractive than aerated lagoon systems.

Application of the technology

Activated sludge treatment has been applied to the treatment of many different types of pulp and paper effluents.

No reference is, however, made to its application for reclamation of effluents. Furthermore, optimal operational conditions for achieving the desired water quality are not sufficiently reported to allow accurate full-scale design. It was thus decided that pilot-scale testwork would be necessary to evaluate whether the desired water quality could be achieved and to determine under what conditions this occurs.

Poor sludge settleability is widely reported to be a problem with pulp and paper effluents. It was thus decided that if bulking occurs, its causes should be investigated in order to limit its effects in large-scale application.

3. MATERIALS AND METHODS

3.1 PROCESS DESCRIPTION

A flow diagram of the pilot plant is shown in **Figure 3.1**. Kraft Liner Board effluent was piped to the pilot plant from the paper machine section of the mill. The pH of the effluent was adjusted on a batch basis in a mechanically stirred, 2 000 ℓ mixing tank. Hydrated lime and sulphuric acid were used for pH adjustment. Macro-nutrients were added to the mixing tank in the form of ammonium nitrate and phosphoric acid.

Batches of effluent were pumped to a 5 000 ℓ feed tank. The primary settler at the activated sludge reactor was fed continuously from the feed tank. Flow control was achieved by an in-line rotameter and a recycle line and valve over the feed pump.

Removal of settled material from the primary settler was done manually every 2 hours by opening the drain valve on the settler.

The overflow stream from the primary settler discharged into the aeration tank (5 400 ℓ). Coarse bubble diffuse aeration was achieved by injecting compressed air into the aeration basin through a single outlet.

Mixed liquor from the aeration basin discharged into the secondary clarifier where solids separation was achieved. Settled solids were returned to the aeration basin by means of a return sludge pump. The flow rate of the return sludge stream was controlled by means of an in-line rotameter and a recycle line and valve over the return sludge pump.

The overflow stream from the secondary clarifier was returned to the mill general effluent stream.

The sludge age was controlled by manually wasting sludge directly from the aeration basin. Sludge was abstracted every 2 hours into a graduated waste activated sludge tank.

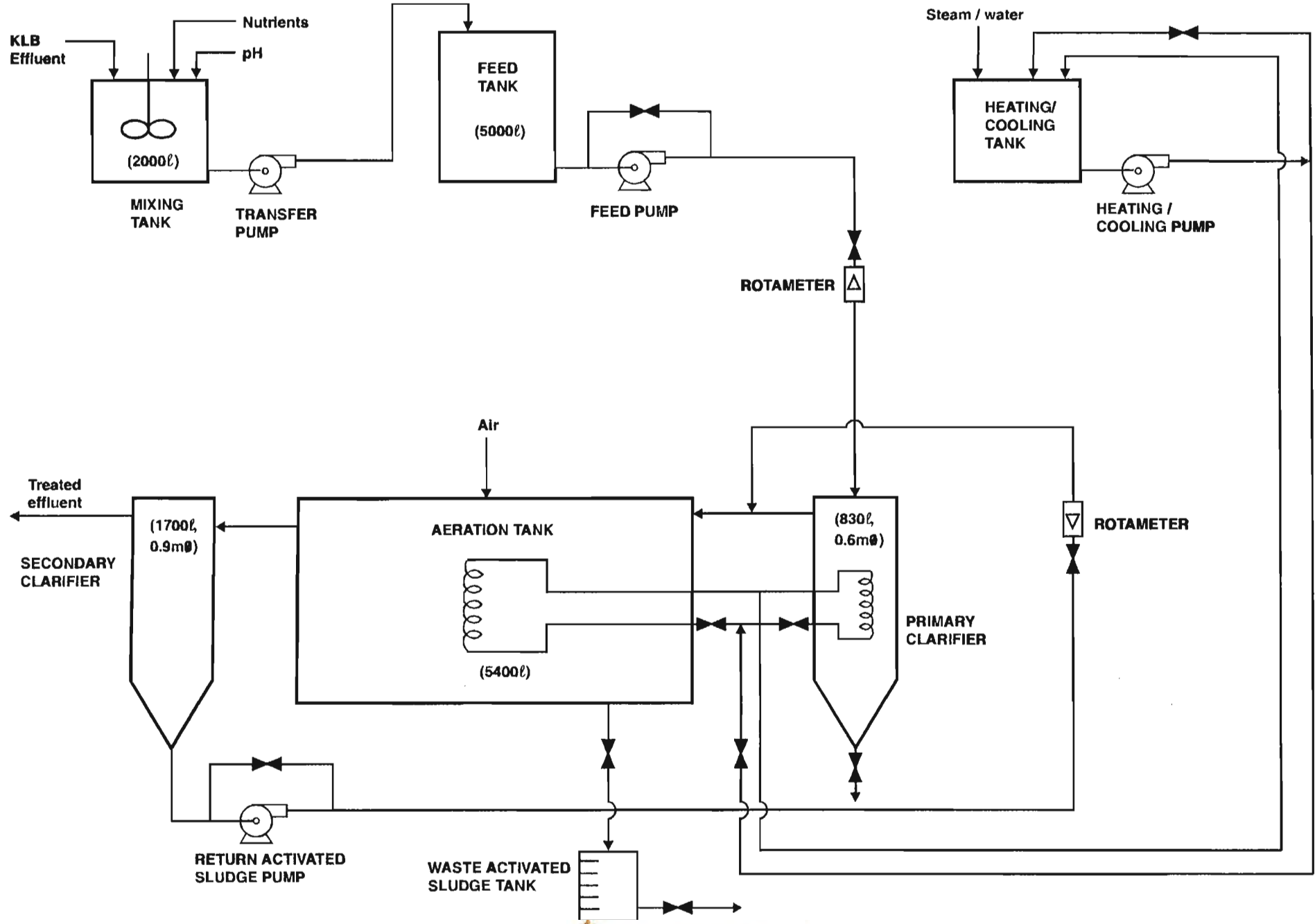


FIGURE 3.1 : SCHEMATIC FLOW DIAGRAM

The average temperature of the raw KLB effluent from the paper machines was 30°C. During the storage of the effluent in the mixing and feed tanks, the temperature of the effluent decreased. In order to simulate full-scale continuous operation, the effluent had to be re-heated. Heating and cooling were achieved by injecting live-stream or cold water into a heating/cooling tank and pumping into a ring-main. Heating/cooling coils in the primary sedimentation tank and aeration basin were then fed from the ring-main in order to achieve the necessary heating or cooling.

3.2 OPERATING AND ANALYTICAL SCHEDULES

3.2.1 Operating

The pilot plant was operated continuously (7 days a week, 24 hours per day) for a period of 259 days. The following parameters were monitored and manually controlled on a two-hourly basis;

Sludge age

Sludge age was controlled by wasting a known volume of sludge directly from the aeration tank. The influence of sludge age on the performance of pilot-plant was evaluated at three different sludge ages, namely 8, 4 and 2 days.

Load

The variability in KLB effluent quality made it impractical to control the organic load imposed onto the plant. The feed flow rate was, however, controlled. The rate at which the plant was fed was determined, in the end, by the poor sludge settleability. High feed rates resulted in higher organic loads and, concomitantly higher mixed liquor suspended solids concentrations and high carry-over of suspended solids (even at high sludge recycle ratios).

pH

The pH was controlled by dosing either lime or sulphuric acid into the mixing tank. In keeping with reported optimal pH values, it was endeavoured to maintain the pH in the aeration basin between 6.5 and 7.5.

Temperature

The average temperature of the KLB effluent generated at the mill is 30°C. During storage of the effluent in the mixing and feed tanks, however, the temperature dropped and had to be reheated to 30°C in order to simulate full-scale conditions. This was done by heating/cooling coils as indicated in **Figure 3.1**.

Dissolved oxygen

It was endeavoured to maintain the dissolved oxygen (DO) concentration in the aeration tank between 1.0 and 2.0 mg/l. It was, however, found that between these DO concentrations, the air distribution system was such that insufficient mixing occurred and the sludge settled in the aeration tank. The DO concentration was thus maintained at approximately 5 mg/l to achieve sufficient mixing.

Nutrients

Nitrogen and phosphorus was dosed into the mixing tank in the form of ammonium nitrate and phosphoric acid. The dosages were controlled based on the nitrogen and phosphorus concentrations in the treated effluent. It was endeavoured to maintain a small residual (≤ 1 mg/l) of nitrogen and phosphorous in the treated effluent.

A summary of the operating schedule is given in **Table 3.1**. All measurements or actions were carried out on a 2 hourly basis, 24 hours per day.

Table 3.1 : Summary of operating schedule

Position	Measurement				
	Temperature	pH	Flowrate	Concentration	On/Off
Feed	*	*	*		
Primary settled overflow	*	*			
Reactor	*	*			
Reactor D.O.				*	
Secondary settler overflow	*	*			
Recycle			*		
Waste Sludge			*		
Heating/Cooling					*



3.2.2 Analytical

An intensive monitoring program was initiated in order to characterise the KLB effluent quality. Monthly grab samples were taken over a period of approximately one year. Standard methods were used to analyse the effluent. The monitoring program was initiated in order to evaluate the following:

- the variability in quality in general
- the availability and variability of nutrients (macro- and micro)
- the presence and quantity of possible inhibitory compounds

On the pilot plant samples were taken of the feed, product and mixed liquor once per shift and refrigerated. The samples were then composited and analysed daily for the following variables:

COD

The total and filtered COD concentrations of the feed and product were measured in order to determine the treated effluent quality with respect to organic material. Paired data is used to statistically evaluate the influence of various operating parameters (such as sludge age and organic load) on the treated effluent COD concentration and to evaluate whether the water quality objectives could be met.

Suspended Solids

Suspended solids concentration of the feed, product and mixed liquor was measured to determine the treated effluent quality with respect to suspended solids, and to enable calculation of the sludge age. Paired data is used to statistically evaluate the influence of various operating parameters on the treated effluent suspended solids concentration and to evaluate whether the treated effluent quality could be met.

Absorbance

Absorbance was used as a measure of colour and was monitored in order to determine whether the treated water colour could be reduced sufficiently to enable washing of bleached pulp.

The effect of residual colour on bleached pulp brightness was evaluated by firstly measuring the brightness of fully bleached pulp and then measuring the brightness after repulping with treated effluent.

Nitrogen and Phosphorus

Phosphate, nitrate and ammonia were measured in the product in order to enable nutrient dosage control.

Sludge settleability

Sludge settleability was measured by determining the Sludge Volume Index (SVI) daily. Paired data could be used to statistically evaluate the influence of various operating parameters on the sludge settleability.

Microscopical observations

The sludge was examined microscopically on a weekly basis in order to establish the presence and abundance of filamentous organisms which may cause bulking.

The analytical methods used are given in **Appendix A**.

Calculations and presentation of results

The results are mainly presented as probability (or frequency) distribution plots. These plots are often used to facilitate comparison of large data sets and have been used to summarise influent and effluent characteristics of municipal sewage treatment plants. The characteristics of these distributions may conveniently be used to describe both the level and variability of treatment performance.

The efficiency of the process is interpretable from the median (50 percentile) and range of the distribution. The variability or stability of the treatment system performance can be interpreted from the slope and range of the distribution. The slope can be characterised by the standard deviation of the observations (EPA 1979).

A spreadsheet software package (Quattro Pro, Version 3) was used to calculate the probability distributions and their associated statistical parameters. The normal and log

correlation coefficient for each distribution. Only the distributions showing the best fit (highest correlation coefficient) are shown in the results.

The best-fit, or regression lines, are shown on some of the probability distributions. This was done only when one or two distributions are given on one figure in order to prevent cluttering of the figure where three or more distributions are presented.

Normal- and log-normal distributions are used, depending on which give the highest correlation coefficient.

4. RESULTS AND DISCUSSION

4.1 CHARACTERISATION OF THE KLB EFFLUENT

A summary of the results of the KLB effluent monitoring program are shown in Table 4.1.

Table 4.1 : Summary of KLB effluent quality

Water Quality Parameter	Units	Minimum	Average	Maximum
Temperature	° C	28	30	43
pH	-	4.22	5.26	6.55
Alkalinity	mg/l as CaCO ₃	0	40	80
Absorbance	-	0.030	0.097	0.160
Hazen colour	HCU	40	112	150
Total Phosphorus	mg P/l	1.07	12.7	47.4
Free and saline ammonia	mg N/l	0.14	1.12	1.1
Nitrate	mg N/l	0.1	1.13	6.3
Total COD	mg/l	400	1887	2760
Filtered COD	mg/l	560	1198	2120
Suspended solids	mg/l	46	801	2982
Total Dissolved Solids	mg/l	1156	3132	5402
Organic Solids	mg/l	745	2001	4772
Chloride	mg/l	15.4	30.7	46.4
Sulphate	mg/l	12	1038	2802
Sulphide	mg/l	0	24.8	72
Volatile Fatty Acids	mg/l	30	91	207
Sodium	mg/l	5	259	760
Magnesium	mg/l	9	18	31
Potassium	mg/l	4.2	43	67
Cobalt	mg/l	0	0.04	0.18
Nickel	mg/l	0	0	0
Manganese	mg/l	0.7	3.8	6.4
Iron	mg/l	0.19	1.14	3.50
Chromium	mg/l	0	0.03	0.11
Copper	mg/l	0	0.04	0.08
Calcium	mg/l	7	20	46
Aluminium	mg/l	0	9	30



Suspended solids, hazen colour, absorbance and COD of the KLB was measured daily for monitoring the performance of the pilot plant. Probability distribution plots for these variables are given in **Appendix B**.

The KLB effluent is considerably more dilute than typical mechanical and chemical pulping effluents (**Table 2.1**). This is due to the fact that unbleached pulp is dewatered and stored prior to being used. During the manufacturing process the pulp is washed with clean water which dilutes the pulping effluent entrapped in the pulp.

The high variability in constituent concentrations is evident from the probability plots given in **Appendix B**. This is partly due to the manufacture of White Top Liner as described in **Section 2.4**.

4.2 TREATED WATER QUALITY OBJECTIVES

The major water quality parameters of concern for reclamation and re-use of the KLB effluent were identified as being: biodegradable organic material, colour and suspended solids (**Section 2.2**). The required reclaimed water quality with respect to these variables is discussed below;

Biodegradable organic material

Biodegradable organic material results in the proliferation of bioslime in pipe networks resulting in reduced flow, accelerated corrosion and reduced heat exchange. In order to minimize these effects the biodegradable, and not necessarily the total, organic material content of the effluent must be minimized. Pulp and paper effluents comprise a wide range of different organic compounds ranging from very readily biodegradable to non-biodegradable. It is thus difficult to determine the actual concentration of organic material which must be achieved for re-use. The philosophy adopted was to vary the treatment conditions and evaluate the effect on the removal of organic material.

Colour

The Ngodwana mill is required to produce bleached pulp with a certain brightness to satisfy market demands. Washing of bleached pulp with coloured water results in a decrease in the pulp brightness. The effect of colour on bleached pulp was determined by washing bleached pulp with treated KLB effluent and measuring the effect on brightness. The results are shown in **Figure 4.1**.



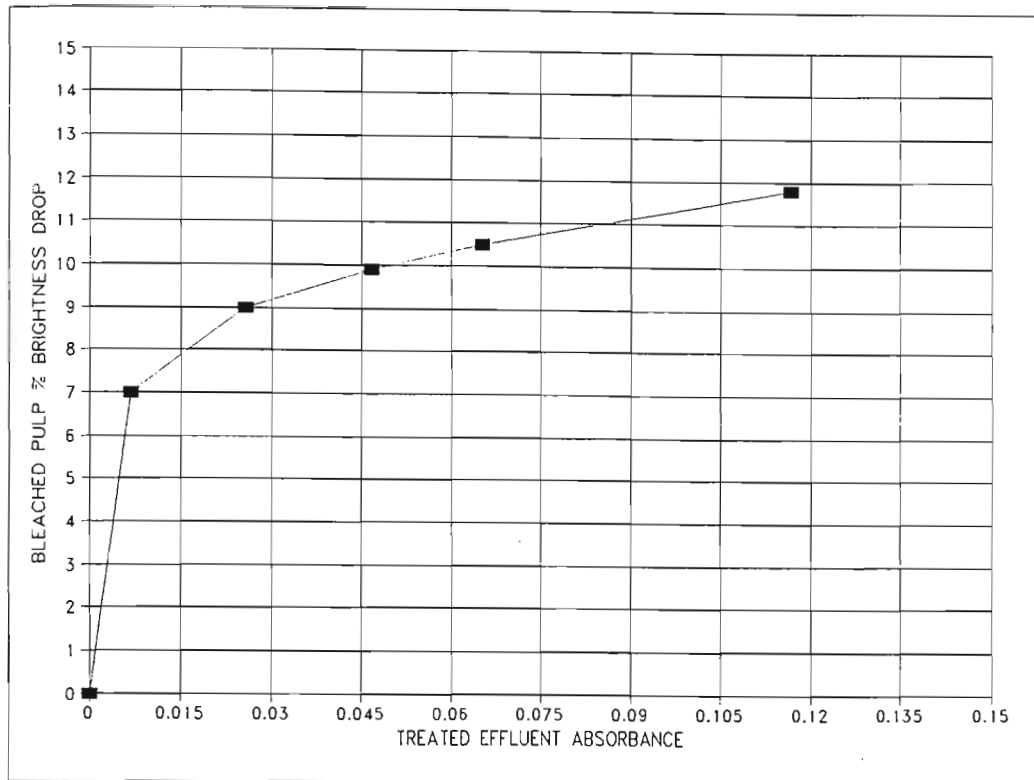


Figure 4.1 : Effect of treated effluent colour on bleached pulp brightness

The mill is required to produce bleached pulp with a brightness of at least 88 ISO to satisfy market demands. The mill, however, currently struggles to achieve this level of brightness and any decrease in brightness would exacerbate this situation.

There are no brightness constraints for unbleached pulp, however, and thus the colour of the treated effluent is not important.

Suspended solids

The major motivation for achieving low suspended solids concentrations in the treated effluent are blockages of wash-water spray nozzles and increased pulp dirt-counts. No formal testwork was conducted to determine the suspended solids limit, however, from past experience by the mill staff a limit of 10 mg/ℓ was set.

4.3 PILOT PLANT PERFORMANCE

The performance of the pilot plant with respect to organics, colour and suspended solids removal is discussed in the following sections.



Reference is made to plant operating conditions which are presented, in the form of statistical probability plots, in **Appendix C**.

4.3.1 Organic removal

The probability distribution of COD removal efficiency for the entire operating period is shown in **Figure 4.2**.

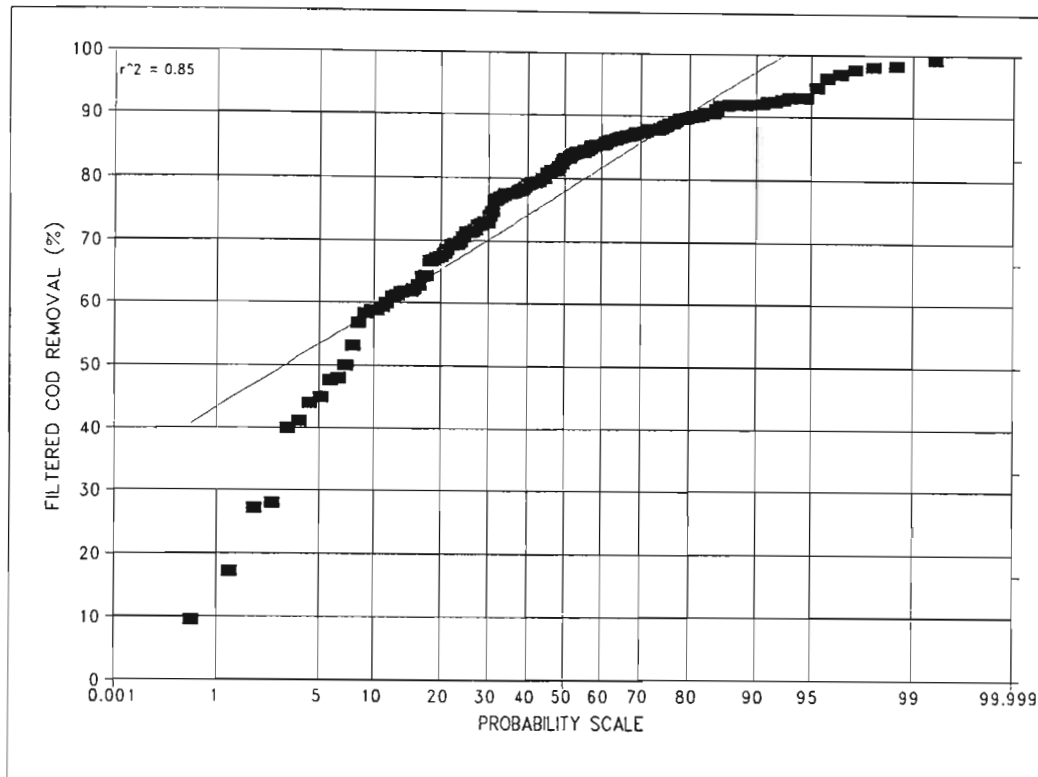


Figure 4.2 : COD removal efficiency distribution for the entire operating period

An average (50 percentile) removal of 83% was achieved over the entire operating period. The average filtered feed COD concentration was 860 mg/l and was highly variable ($\sigma = 437$, **Figure B1** in **Appendix B**). The average removal efficiency is significantly higher than the reported values (40 - 68%; Simpura and Pakarinen 1993, Nevalainen *et al* 1991).

In terms of reclamation and re-use of the effluent, however, **Figure 4.2** does not give any valuable information. The major question which must be answered is; is the biodegradable organic material removed, and by how much? Secondary to this, the conditions under which biodegradable material is **not**

removed must be established in order to prevent these conditions from occurring on full-scale.

To answer these questions it is pertinent to first examine the effect that the feed COD concentration has on the product COD concentration. **Figure 4.3** shows this relationship.

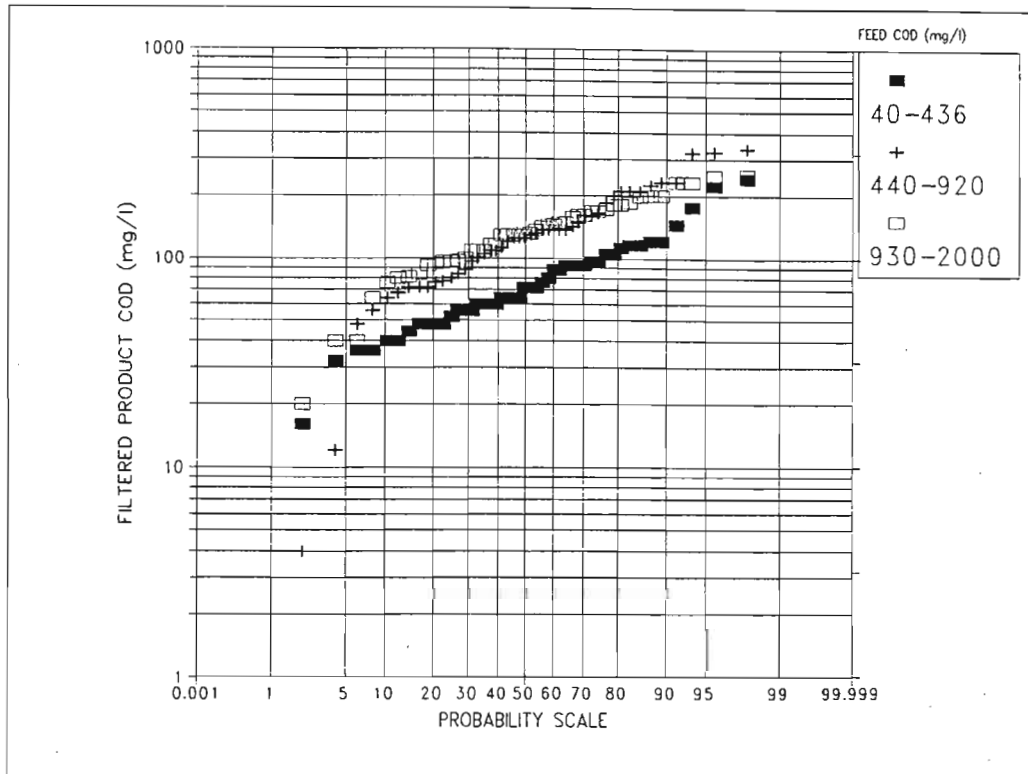


Figure 4.3 : Probability distribution showing the treated effluent COD concentrations achieved for various ranges of feed COD concentrations (paired data)

It is evident that the product COD concentration increases with increasing feed COD concentration. This may mean one of two things;

- either the fraction of readily biodegradable organic material in the feed remains constant and the process is ineffective at removing this fraction
- or
- the process is effective in removing the biodegradable fraction but this fraction increases with increasing feed COD concentration.

If the former is true then it would be expected that an increase in sludge age would cause the effluent COD concentration to drop significantly since more time will be available for degradation. Alternately, if the latter is true then sludge age should not have a significant effect. This is investigated below;

Figures 4.4 to 4.6 show the feed and product filtered COD concentration distributions for the three set sludge ages at which the plant was operated.

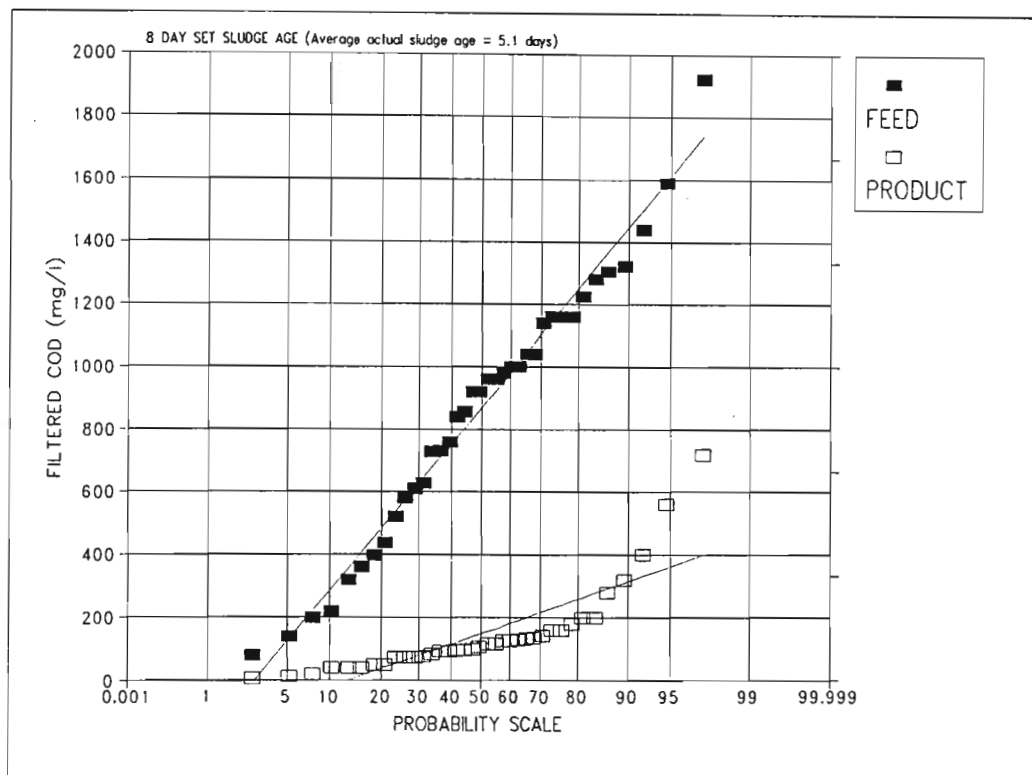


Figure 4.4 : Feed and product COD concentration probability distributions for the 8-day sludge age operating period (unpaired data)

It can be seen from Figures 4.4 to 4.6 that the actual sludge ages are significantly different to the set sludge ages tested. This was due to poor sludge settleability which resulted in a high loss of sludge from the secondary clarifier. The actual sludge age is thus reduced. This is discussed in more detail in Section 4.3.3.

Relevant statistical parameters pertaining to Figures 4.4 to 4.6 are summarised in Table 4.2.

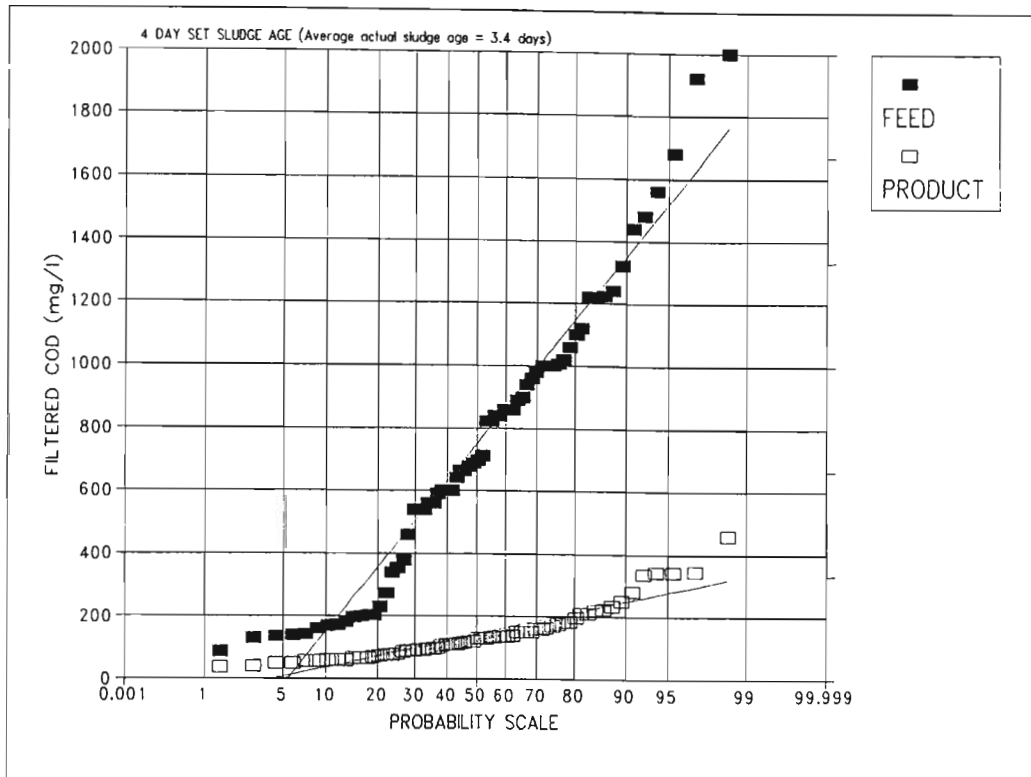


Figure 4.5 : Feed and product COD concentration probability distributions for the 4-day sludge age operating period (unpaired data)

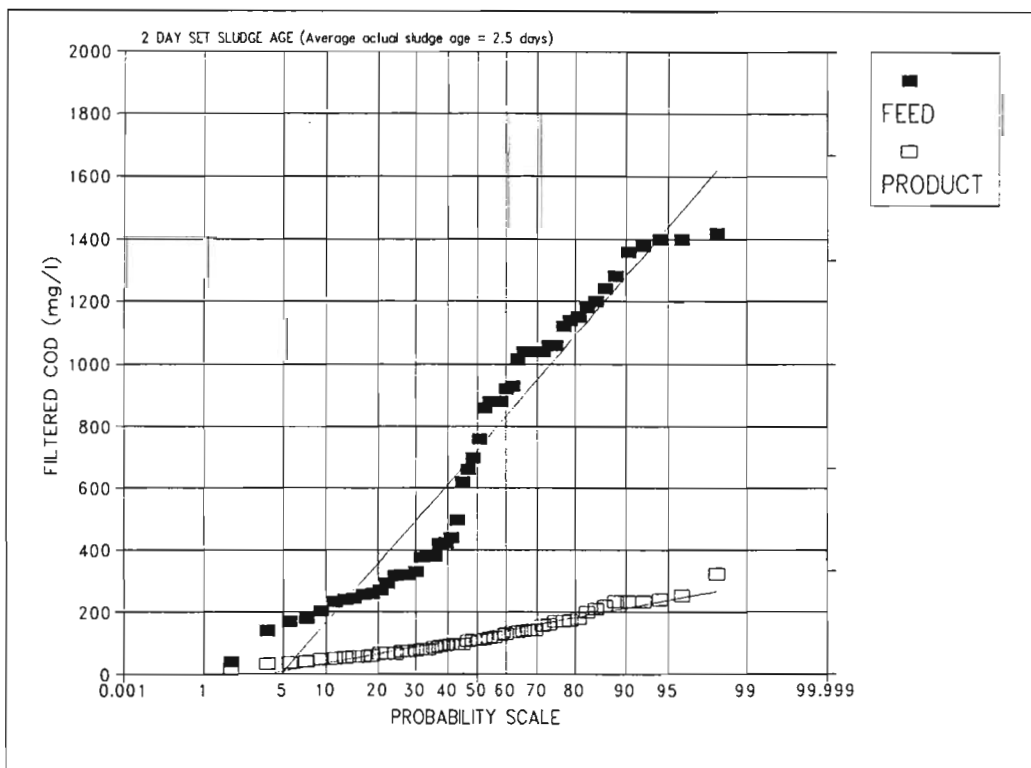


Figure 4.6 : Feed and product COD concentration probability distributions for the 2-day sludge age operating period (unpaired data)

Table 4.2 : Summary of statistical parameters describing the influence of feed on product COD concentration at the set sludge ages tested

Set sludge age (days)	Feed			Product		
	Correlation Coefficient	Slope	Standard Deviation	Correlation Coefficient	Slope	Standard Deviation
8	0.98	453	418	0.69	131	144
4	0.96	468	452	0.85	83	85
2	0.93	435	420	0.94	70	67

The low standard deviations and slope values for the product compared to the feed COD concentration distributions demonstrates that sludge age had little impact on the product COD concentration. This is seen more clearly in **Figure 4.7** which shows iso-concentration lines for the product COD at the various sludge ages tested.

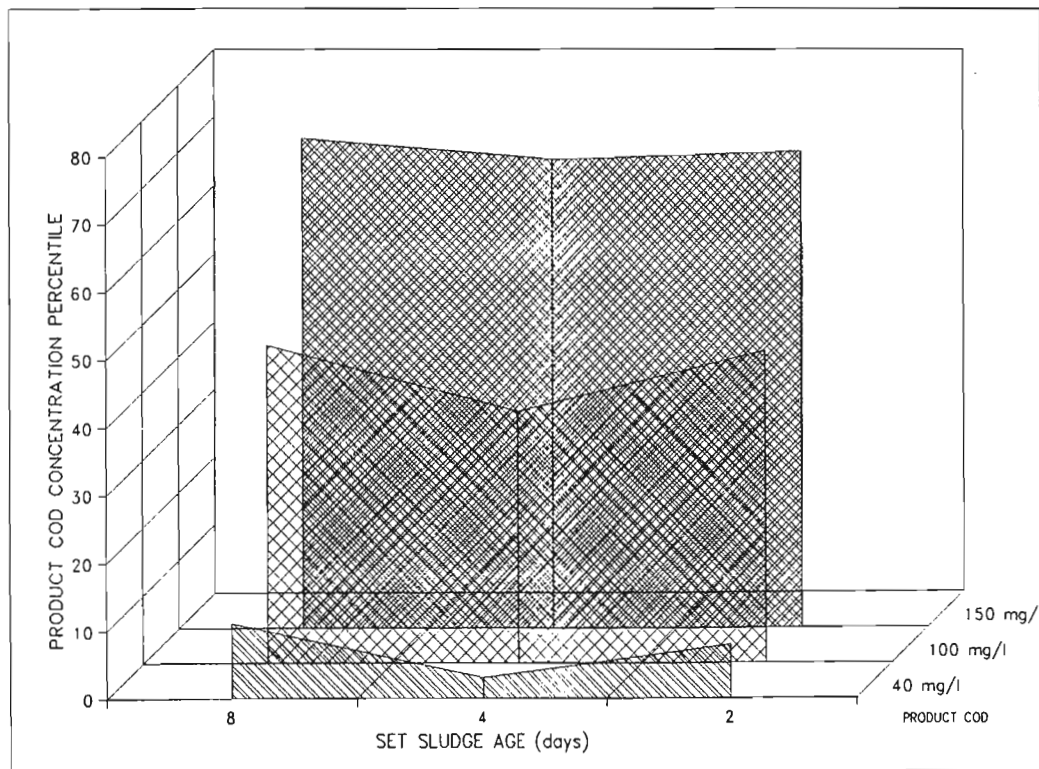


Figure 4.7 : Iso-product concentration lines showing the percentage of time a product COD concentration equal to or less than the indicated values are achieved, at the various set sludge ages

The effect of sludge age is clearly insignificantly small (with a percentile increase of only 3 from a 2-day to 8-day sludge age, for a pr ion of 40 mg/l).



Sludge age thus appears to have little effect on COD removal, indicating that the process is effective in removing the readily biodegradable organic fraction. The behaviour of the feed and product COD concentrations shown in **Figure 4.3**, however, still needs to be explained. This can be done by examining **Figure 4.8** which shows the fraction of the feed COD which is not removed for various ranges of feed COD concentrations.

A higher feed COD concentration result in a lower fraction of this COD which remains after treatment and thus the fraction of biodegradable organic material increases with increasing feed COD concentration.

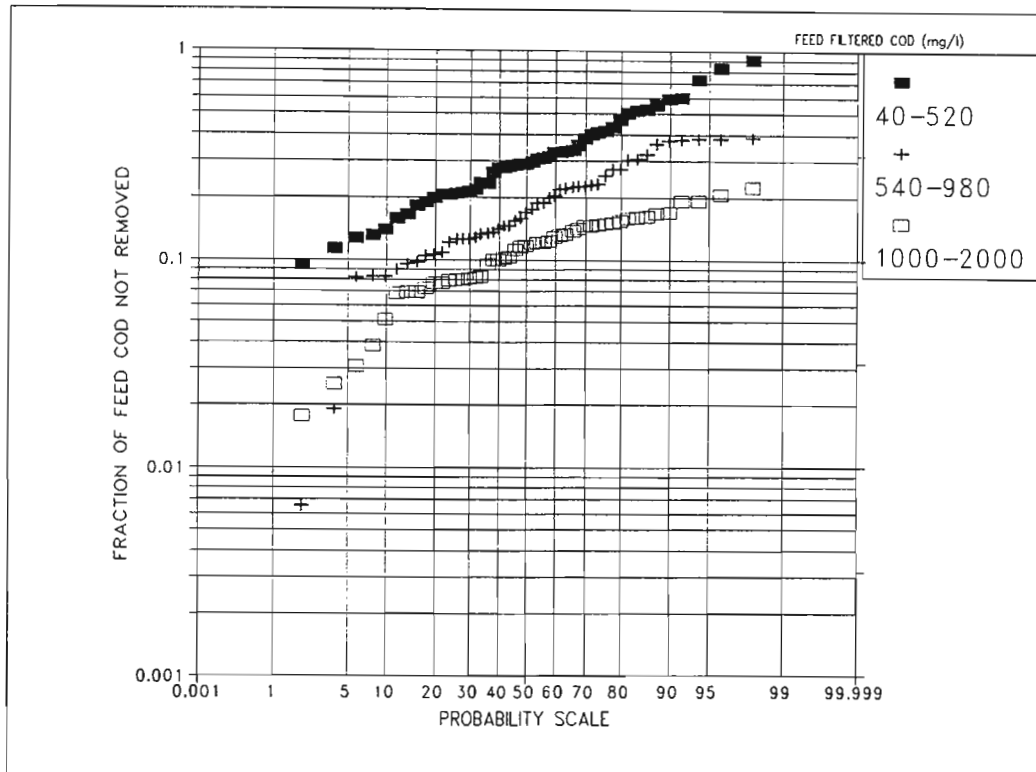


Figure 4.8 : Probability distribution for the fraction of the feed COD which is not removed by treatment for various ranges of feed COD concentrations (paired data)

It thus appears that the process was effective at removing the readily biodegradable organic material from the KLB effluent, but that this fraction increases with increasing feed COD concentration.

The increase in standard deviation (**Table 4.2**) for the product COD with increasing sludge age (for a relatively constant and

high feed COD variability, $\sigma = 435 - 468$), however, suggests that the performance of the plant was more stable at lower sludge ages. This is contrary to what is generally accepted (Ekama *et al* 1984), however, the variability of other operating parameters, discussed below, are a possible cause.

Temperature

The aeration tank temperature had little effect on the product COD concentration (Figure D1 in Appendix D), as demonstrated in Table 4.3.

Table 4.3 : Summary statistical parameters describing the effect of aeration tank temperature on the treated effluent COD concentration

Temperature range (°C)	Product filtered COD (mg/l)			Correlation coefficient	Standard Deviation	Slope
	10 Percentile	50 Percentile	90 Percentile			
25.5 - 28.4	40	120	344	0.93	131	0.4
28.5 - 29.5	56	126	228	0.93	82	0.3
29.5 - 31.5	50	104	232	0.99	70	0.3

No apparent increase in performance was observed at higher operating temperatures, however, the temperature was controlled to within a narrow range (25.5 - 31.5). The temperature never exceeded 40°C and thus no deterioration in performance due to temperature is expected (Lo *et al* 1990).

pH

The aeration tank pH had a significant effect on the product COD concentration (Figure D3 in Appendix D), as demonstrated in Table 4.4.

Table 4.4 : Summary statistical parameters describing the effect of aeration tank pH on the treated effluent COD concentration

pH range	Product filtered COD (mg/l)			Correlation coefficient	Standard Deviation	Slope
	10 Percentile	50 Percentile	90 Percentile			
6.99 - 7.32	137	376	1120	0.87	410	410
7.33 - 7.51	240	960	1320	0.96	397	417
7.51 - 7.93	500	888	1480	0.97	389	409



Lower product COD concentrations were achieved at the lower, and closer to neutral, aeration tank pH values.

These results confirm that effective pH control is critical to performance (Keays *et al*/ 1993) and that pH's as close to neutral are optimal (Lo *et al*/ 1990). The pH control was, inadvertently, better during the 2 day sludge age operating period (**Figure D4** in **Appendix D**). It is therefore expected that the performance during the 8-days sludge age, discussed above, would have been better if stricter pH control was achieved.

Organic load

The organic load applied onto the system had a significant effect on the product COD concentration (**Figure D5** in **Appendix D**), as demonstrated in **Table 4.5**.

Table 4.5 : Summary of statistical parameters describing the effect of organic load on the treated effluent COD concentration

Organic load range (kg COD/m ³ /day)	Product filtered COD (mg/l)			Correlation coefficient	Standard Deviation	Slope
	10 Percentile	50 Percentile	90 Percentile			
0.11 - 1.22	40	72	192	0.85	55	0.29
1.24 - 2.24	72	128	332	0.90	119	0.28
2.25 - 3.84	76	158	302	0.92	93	0.26

The product COD concentration achieved is lower for the lower range (0.11 - 1.22 kg COD/m³/day) of organic load, and is highest at the higher (2.25 - 3.84 kg COD/m³/day) organic load range.

The organic load during the 8-day sludge age period was, however, lower than during the 4- and 2-day sludge age periods (**Figure D6** in **Appendix D**). This was done intentionally in order to maintain a sufficient concentration of sludge in the aeration tank (**Figure C11** in **Appendix C**).

Hydraulic retention time and Food : Microorganism ratio (**Figure D7** to **D10** in **Appendix D**) show similar behaviour.

Furthermore, the range of organic loads at which the pilot plant was operated compares well to values reported in the literature (2 - 5 kg COD/m³/day : Rintala and Vuoriranta 1988).

4.3.2 Colour removal

The distribution of colour (measured as absorbance) removal efficiency for the entire operating period is shown in **Figure 4.9**.

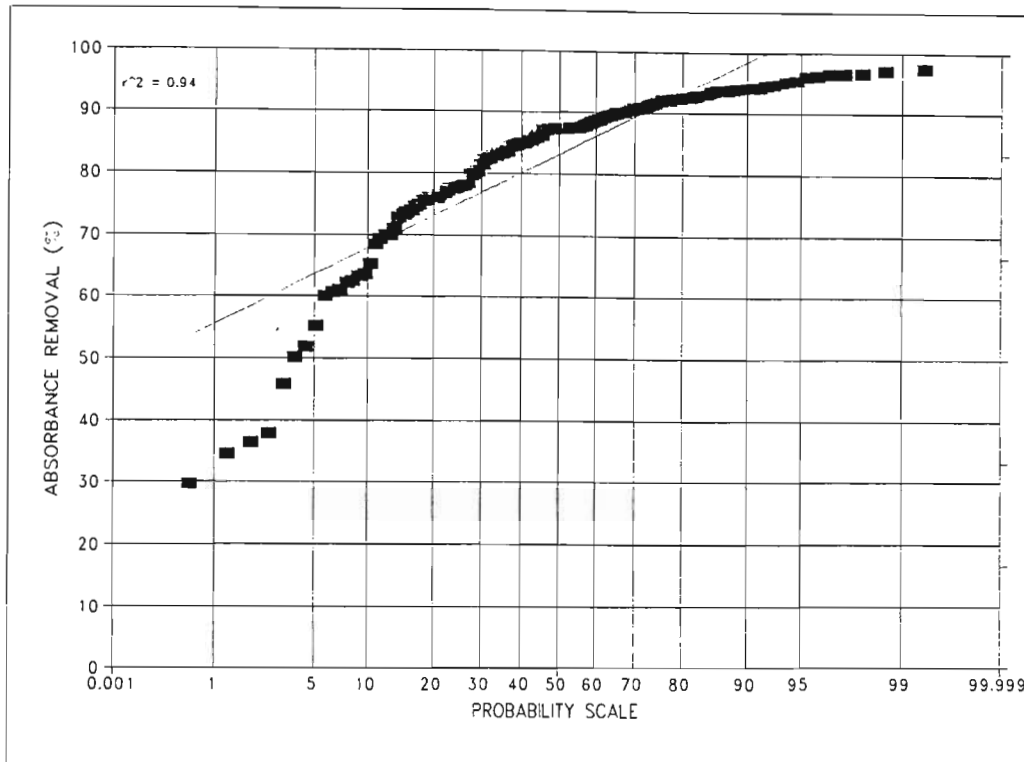


Figure 4.9 : Efficiency Probability distribution colour removal for the entire operating period

An average (50 percentile) removal of 87% was achieved over the entire operating period. The average feed absorbance was 0.48 and was highly variable ($\sigma = 0.30$, **Figure B2** in **Appendix B**).

No reference could be found in the literature regarding actual colour removal efficiencies by activated sludge treatment of pulp and paper effluents. A high degree of colour removal was, however, observed which is contrary to indications given in the literature (Davies and Wilson, 1990).

For reclamation of the effluent for washing of bleached pulp, the actual colour of the treated effluent is more important than the removal which can be achieved. The effect of residual colour on bleached pulp brightness is shown in **Figure 4.1** and the product absorbance achieved throughout the entire operating period is given in **Figure 4.10**. The effect of treated effluent colour on bleached pulp brightness is thus summarised in **Table 4.6**.

Table 4.6 : Effect of treated effluent colour on the brightness of bleached pulp

Percent of time	Residual absorbance	Drop in pulp brightness (%)
5	0.014	7.8
50	0.052	10.0
90	0.147	12.5

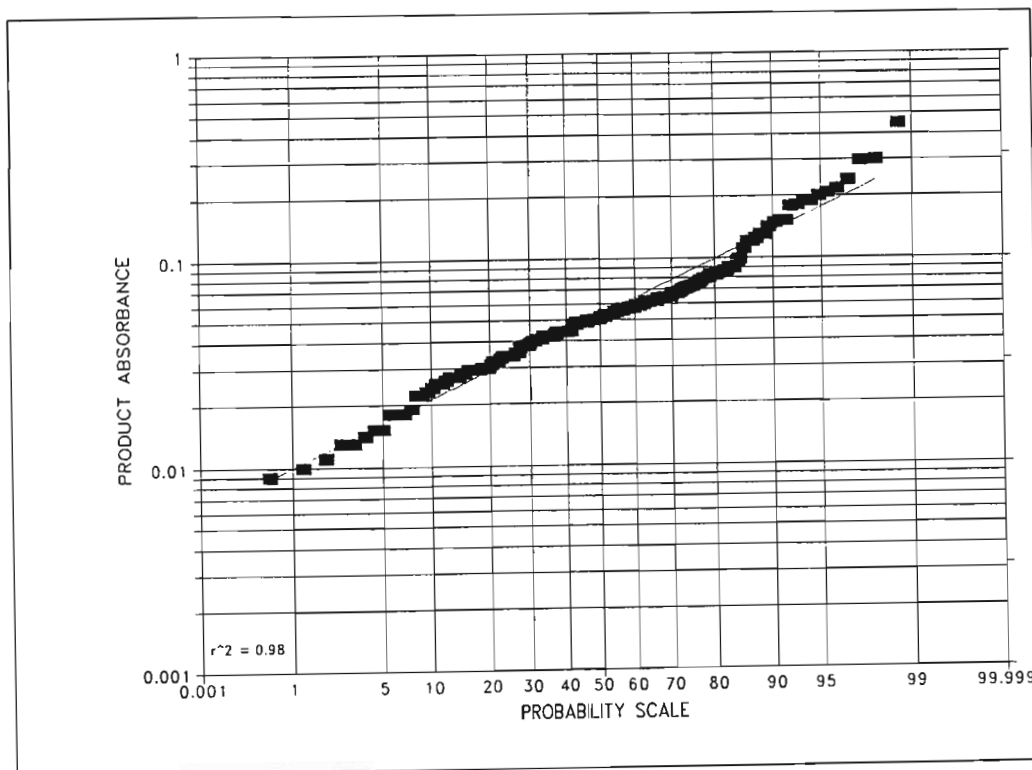


Figure 4.10 : Probability distribution for product absorbance for the entire operating period

A treated effluent absorbance of ≤ 0.052 was only achieved for half of the measured values. This would result in a 10% drop in bleached pulp brightness (from 88 ISO to 79 ISO) and thus

market demands would not be met. The cost of improving bleaching methods at the mill were considered to be too high to warrant reclamation of the effluent for washing of bleached pulp.

Washing of unbleached pulp could, however, be practised since the colour criteria for washing are less stringent (Webb 1991).

4.3.3 Solids Removal

A suspended solids limit of 10 mg/ℓ was set for re-use of the treated effluent as wash water. **Figure 4.11** shows the distribution of suspended solids concentrations measured in the treated effluent.

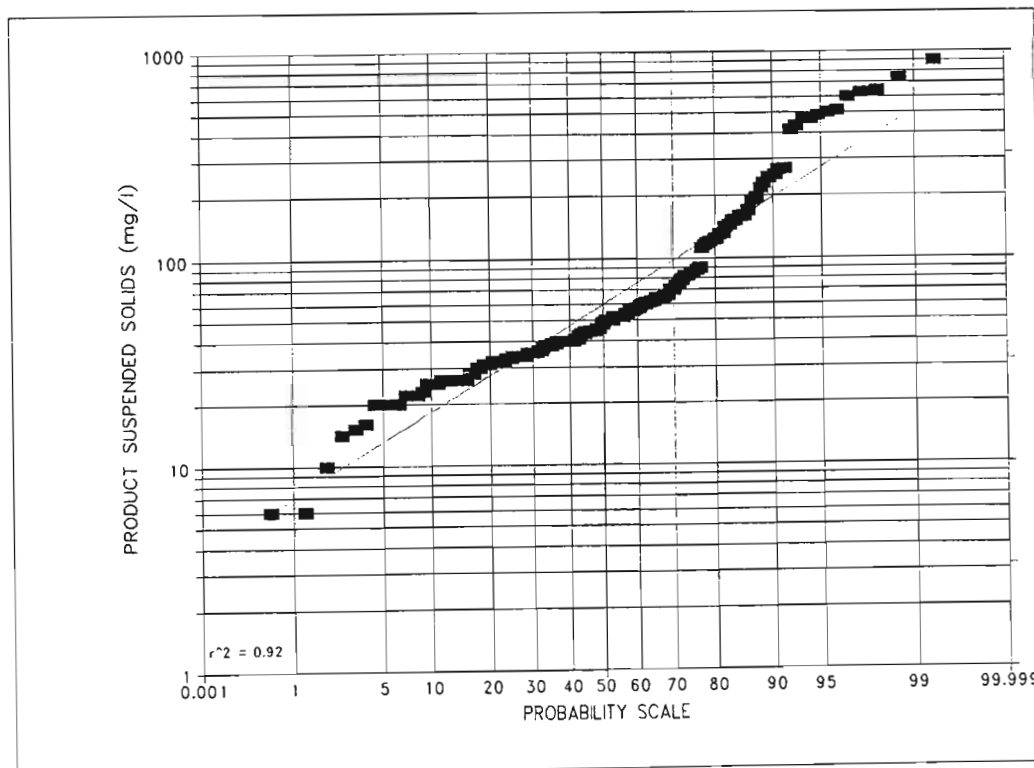


Figure 4.11 : Probability distribution of suspended solids concentration in the treated effluent

The required limit of 10 mg/ℓ was only achieved for 2% of the measured values.

Severe sludge settling problems were experienced throughout the test period. This is demonstrated by the high sludge volume

index shown in **Figure 4.12**, particularly during the 8-day sludge age operating period.

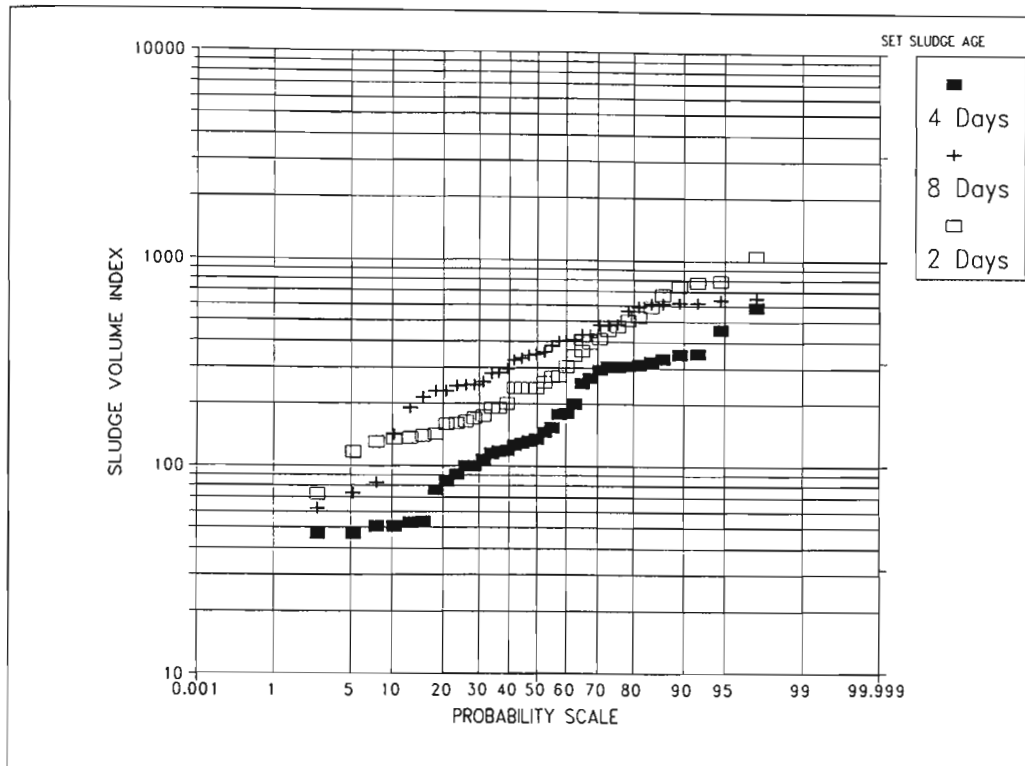


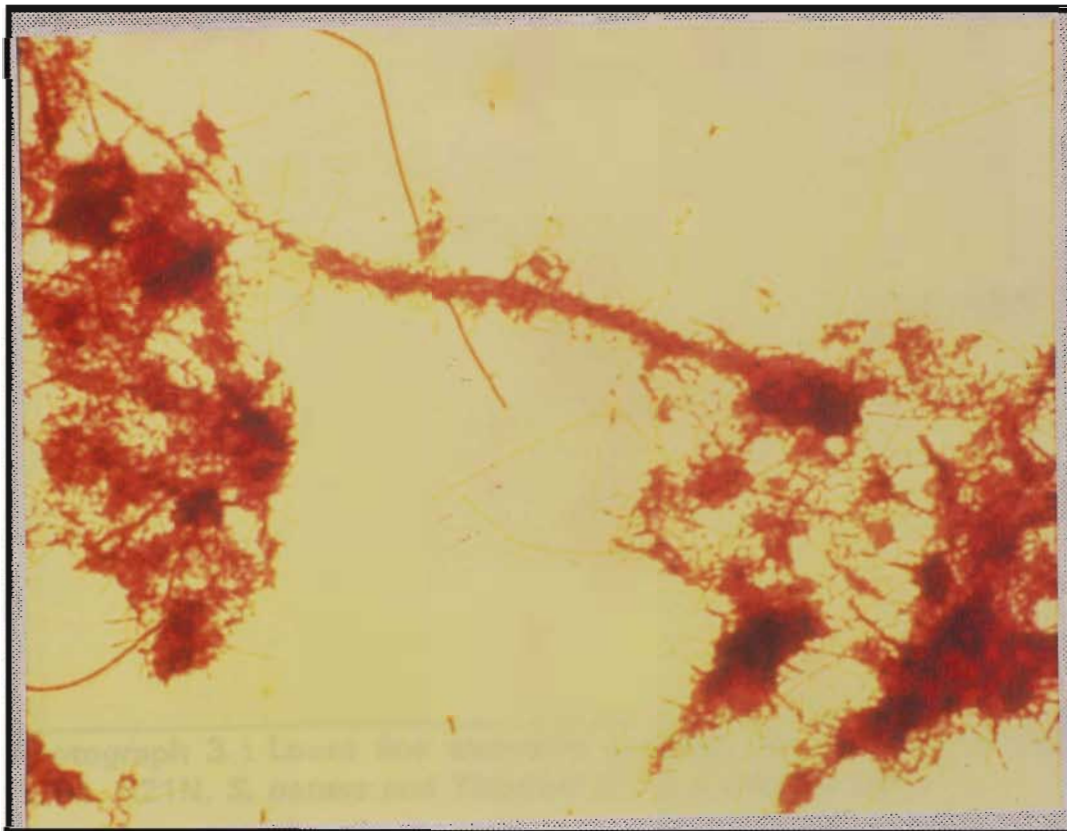
Figure 4.12 : Probability distributions of sludge volume index for the different set sludge age operating periods (unpaired data)

The presence of filamentous bacteria in the sludge were often detected during routine microscopic examination. A sample was taken during the 8 day set sludge age operating period and microscopically evaluated in order to identify the major filamentous organisms. The floc morphology and filament types identified are shown in **Photographs 1 to 4**. A summary of the microscopic evaluation results is shown in **Table 4.7**.

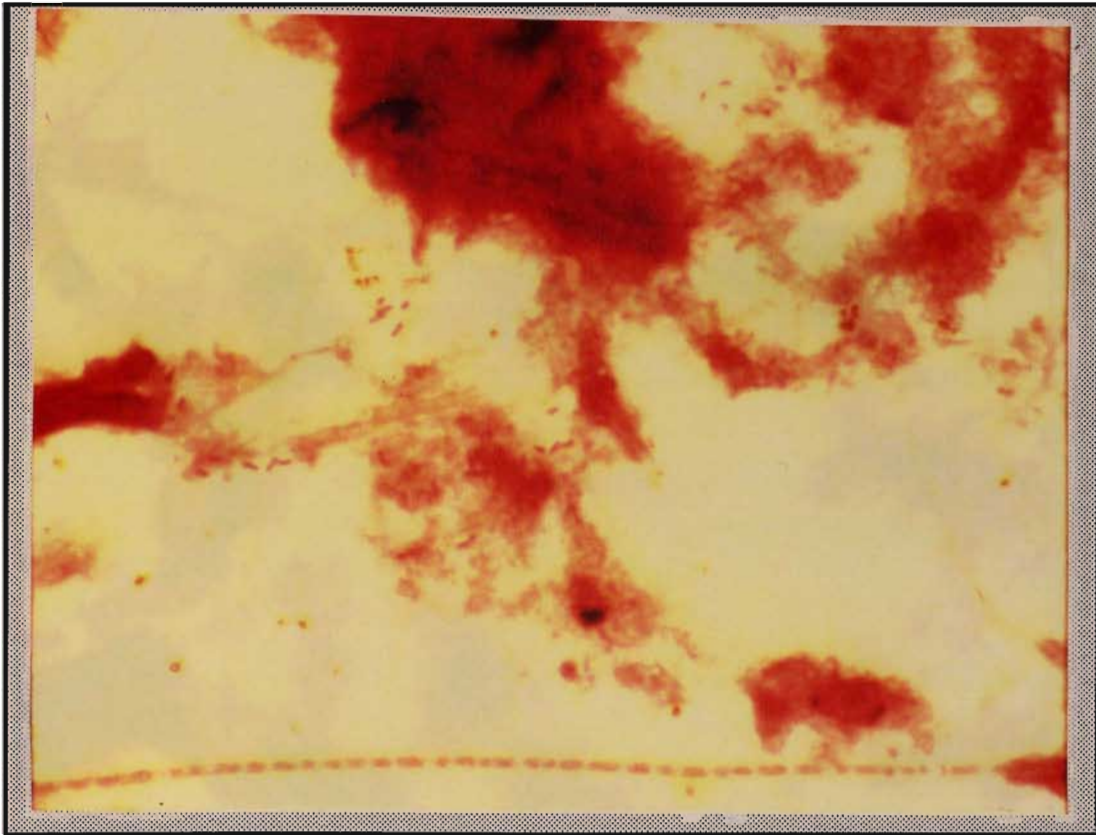
The most dominant type of filamentous organism observed was Type 1701. *Thiothrix II* was also observed but were less abundant.

Table 4.7 : Summary of sludge microscopic evaluation results

Observations	Comments
Floc form	round, diffuse
Floc size	small
Floc morphology	diffuse but fairly firm
Loose cells	+
Higher organisms	+ / -
Zoogloea	-
Spirochetes	-
Inorganic particles	+ +
Filament quantity	abundant
Effect of filaments on floc structure	loose structure
Organisms identified	Type 1701 (dominant) Type 0675, 021N, <i>H. hydrossis</i> and <i>S. natans</i> in smaller quantities
+ present (5 - 10 per microscopic field)	
+ / - present (< 1 per microscopic field)	
- absent	



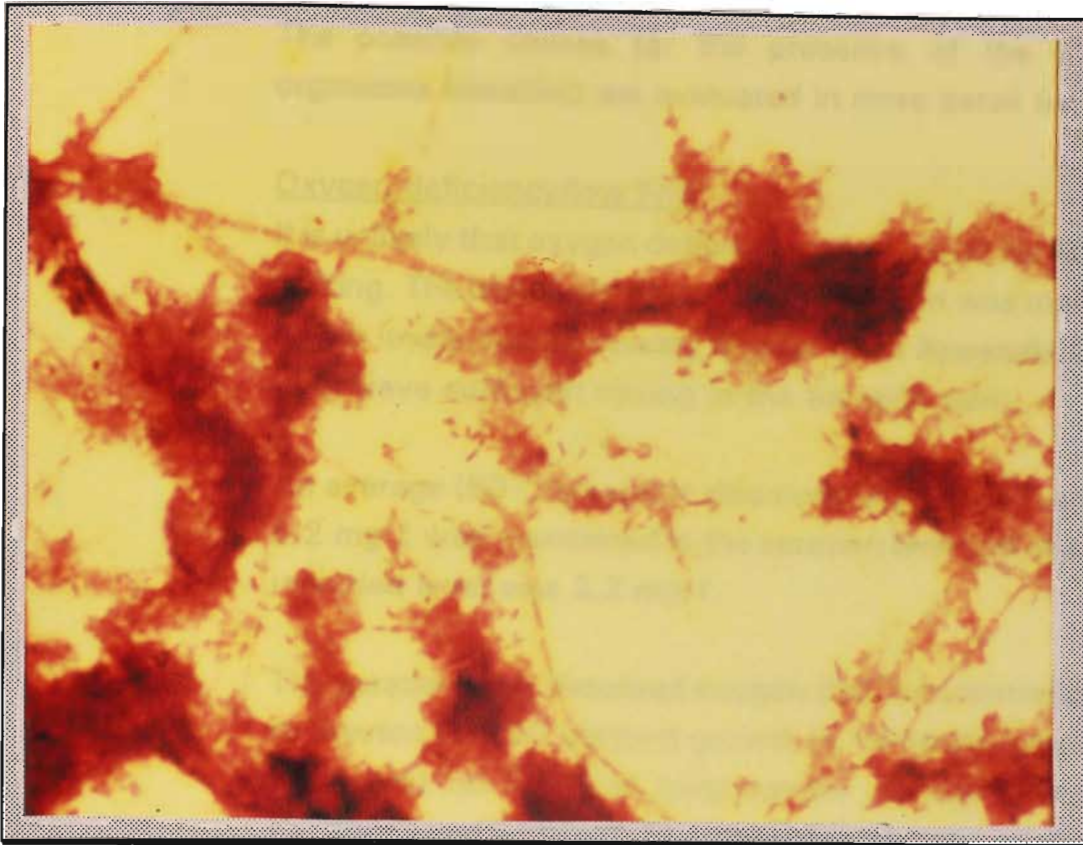
Photograph 1 : Loose floc structure with bridging of flocks by filaments. Types 1701 and 0675 present (40 x magnification)



Photograph 2 : Firm floc structure showing the presence of Type 021N and *S. natans* (100 x magnification)



Photograph 3 : Loose floc structure showing the presence of Types 1701, 021N, *S. natans* and *Thiothrix II* (40 x magnification)



Photograph 4 : Flocs are diffuse and small, showing an abundance of Type 1701 (100 x magnification)

The presence of the filamentous organisms identified are compared to the possible causes for their growth (refer to Table 2.4) in Table 4.8.

Table 4.8 : Summary of filament types identified and possible causes

Filamentous organisms identified	Possible cause
Type 1701	oxygen deficiency
Type 0675	low FM
Type 021 N	septicity nutrient deficiency
<i>H. hydrossis</i>	oxygen deficiency low FM nutrient deficiency
<i>S. natans</i>	oxygen deficiency
<i>Thiothrix</i>	septicity nutrient deficiency

The possible causes for the presence of the filamentous organisms identified are evaluated in more detail below.

Oxygen deficiency/low F/M

It is unlikely that oxygen deficiency was a cause for filamentous bulking. The dissolved oxygen concentration was maintained at higher levels than necessary (**Figure C3 in Appendix C**) in order to achieve sufficient mixing in the aeration tank.

An average (50 - percentile) dissolved oxygen concentration of 5.2 mg/ℓ was maintained in the aeration tank and the minimum recorded level was 2.2 mg/ℓ.

The aeration tank dissolved oxygen (DO) concentration needed to prevent low DO filament growth is, however, reported to be dependent on F/M and temperature. At higher temperature (> 25°C) and F/M (> 0.5) a dissolved oxygen concentration of greater than 2 mg/ℓ may be required to prevent bulking (Richard 1991, Jenkins *et al* 1986).

The effect of F/M on the sludge volume index is shown in **Figure 4.13**.

The statistical parameters describing the distributions given in **Figure 4.13** are shown in **Table 4.9**.

Table 4.9 : Statistical parameters describing the effect of the food : Microorganism ratio on the sludge volume index

F/M Range (kg COD/kg MLSS/d)	SVI at 50 percentile	Correlation coefficient	Slope	Standard deviation
0.03 - 0.75	331	0.99	0.33	11.8
0.76 - 1.55	296	0.97	0.41	11.8
1.57 - 3.44	444	0.97	0.41	11.5

The high F/M range (1.57 - 3.44) results in the highest SVI values, followed by the low F/M range (0.03 - 0.75). The intermediate F/M range (0.76 - 1.55), however, results in the lowest SVI values.

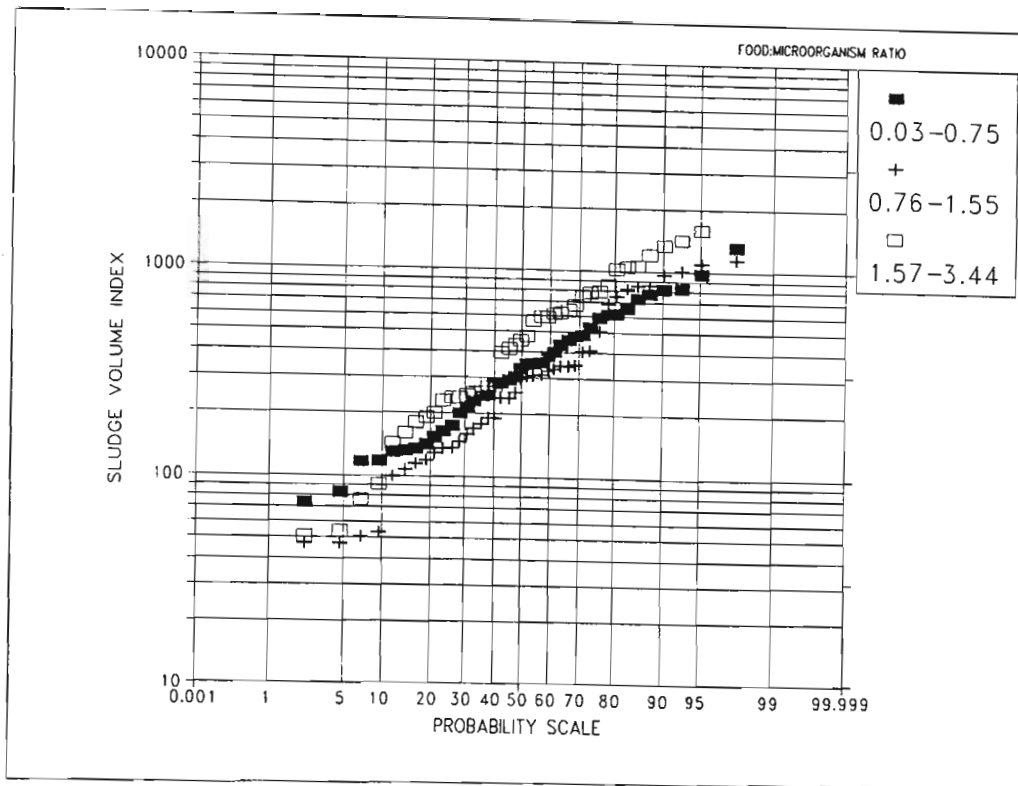


Figure 4.13 : SVI probability distributions for various ranges of F/M (paired data)

It thus appears that a "too low" F/M reported in the literature falls within the 0.03 - 0,75 kg COD/kg MLSS/day range and a "too high" F/M falls within the range 1.57 - 3.44 kg COD/kg MLSS/day range (Rintala and Sierra-Alvarez 1991, Richard 1991).

Nutrient deficiency

It is unlikely that nutrient deficiency was a cause for filamentous bulking. Inadequate nutrient dosing control resulted in high residual nitrogen and phosphorus concentrations (**Figures C12 to C14 in Appendix C**).

Substrate type and load

High sulphide and volatile fatty acid concentrations are reported to promote filamentous bulking (Jenkins *et al* 1986). No reference could, however, be found as to the actual concentration that "high" represents. The average sulphide and volatile fatty acid concentrations in the untreated KLB effluent were 28.4 mg/l and 91 mg/l respectively.

Septic conditions in the primary clarifier were observed to occur (bad odour and dark colour of the sludge). A sample of the

primary clarifier sludge was microscopically examined and the dominant organisms identified were:

- *Kiebsiella oxycota*
- *Clostridium innocuum*
- *Clostridium fallax*

The domination of microbes such as *Clostridia* confirm that anaerobic conditions prevailed in the primary clarifier.

It has been established (**Section 4.3.1**) that the KLB effluent has a high fraction of soluble, readily biodegradable organic material (approximately 80% of soluble COD). High organic loading of soluble, readily biodegradable organic material is also reported to promote filament overgrowth. "High" is, however, not quantified (Richard 1991).

The effect of organic loading on the sludge volume index is shown in **Figure 4.14**.

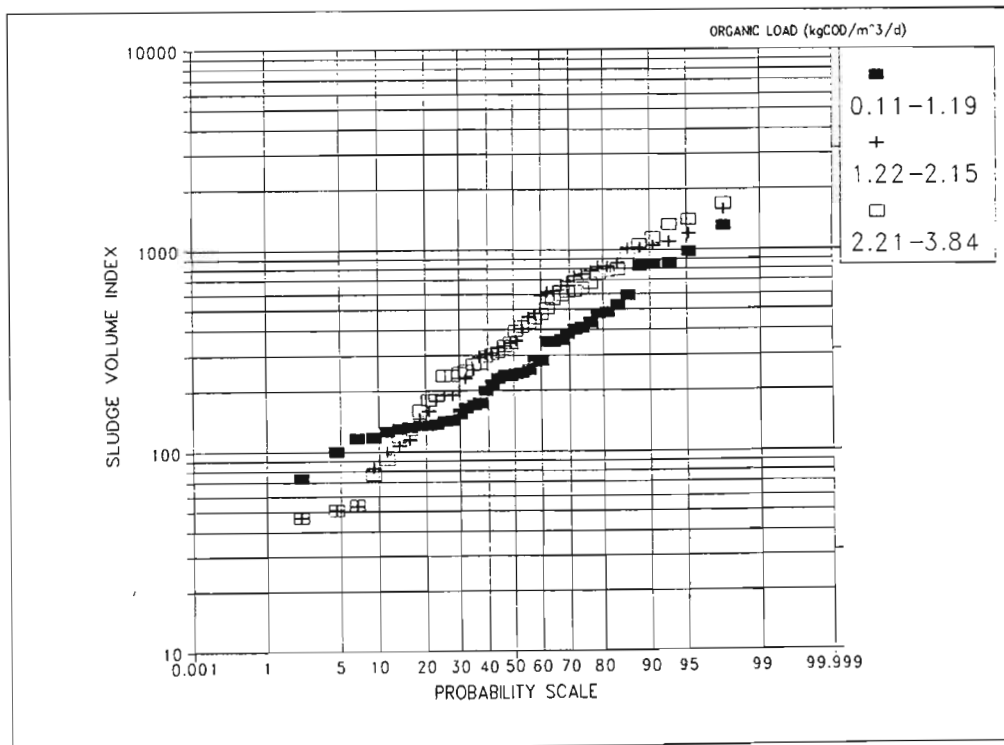


Figure 4.14 : Probability distributions showing the effect of organic load on SVI

Lower SVI values were measured at the lower organic load range (0.11 - 1.19 kg COD/m³/day). The effect is less pronounced, however, at higher organic loads (with equal 50-percentile values for the two higher load ranges).

In summary, the high treated effluent suspended solids concentrations observed are due to the occurrence of filamentous bulking, which appears to have been caused mainly by a combination of the following factors;

- Operation at low (0.03 - 0.75 kg COD/kg MLSS/day) and high (1.57 - 3.44 kg COD/kg MLSS/day) Food : Microorganism ratios
- High (1.22 - 3.84 kg COD/m³/day) organic loads
- Septic conditions in the primary clarifier.

5. CONCLUSIONS AND RECOMMENDATIONS

5.1 ORGANIC REMOVAL

Removal of biodegradable and not total organic material is important for the reclamation of the effluent in order to prevent bioslime from forming in pipe networks. From the pilot plant results the following conclusions can be made regarding the removal of organic removal;

- The KLB effluent contains a high fraction (approximately 80% of the soluble COD) of soluble, readily biodegradable material.
- The fraction of biodegradable material does not remain constant but increases with increasing organic concentration.
- Activated sludge treatment is effective in removing the soluble, readily biodegradable organic material content of the KLB effluent
- Removal of the soluble, readily biodegradable organic fraction is independent of sludge age (in the range 2 days to 8 days).
- The performance of the treatment system is sensitive to pH in the range 6.99 to 7.93 and better performance is achieved at near neutral pH (6.99 - 7.32).
- The performance of the treatment system is not sensitive to temperature in the range 25.5 to 31.5°C.

Activated sludge treatment of the KLB effluent is thus recommended for the removal of organic material. Strict pH control (7 ± 0.2) is, however, recommended in order to optimise performance.

Nutrient control was inadequate during the pilot studies. It is recommended that stricter control be achieved on full-scale in order to further limit the growth of bioslime in pipe networks. It is, furthermore, recommended that disinfection of the treated effluent be practised in order to kill any pathogens which may be present and to further limit the growth of bioslime.

5.2 COLOUR REMOVAL

Removal of colour is important for re-use of the reclaimed water for bleached pulp washing. Although a high degree (87%, on average) of colour removal was achieved, the effect of this colour on bleached pulp brightness was considered to be too severe to allow washing of bleached pulp with reclaimed KLB effluent. It is recommended that the reclaimed effluent only be used for washing of unbleached pulp.

5.3 SOLIDS REMOVAL

Removal of solids is important in order to prevent blockages of spray nozzles and to prevent the deterioration in quality of bleached pulp.

Severe sludge settleability problems were experienced and the suspended solids concentration limit of 10 mg/ℓ could only be met for 2% of the time.

Filamentous bulking was observed to be the cause of poor sludge settleability. Filamentous bulking was in turn caused by a combination of the following factors;

- Operation at low (0.03 - 0.75 kg COD/kg MLSS/day) and high (1.57 - 3.44 kg COD/kg MLSS/day) Food : Microorganism ratios.
- High loading of readily biodegradable organic material
- Septic conditions in the primary clarifier.

It is recommended that the following be investigated in order to prevent or control filamentous bulking;

- Bulking prevention strategies such as employing anaerobic or aerobic selectors.
- Bulking control strategies such as dosing of oxidants
- Prevention of septic conditions by, for example, reducing the residence time in the primary clarifier

- Tertiary treatment such as sand filtration or dissolved air flotation.

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APPENDIX A

ANALYTICAL METHODS

Standard methods (Greenburg *et al* 1992) were used for the determination of all water quality variables. The variables measured and references are listed in **Table A.1** below.

Table A.1 : Summary of standard analytical methods used

Water quality variable	Standard methods reference	Comments
Suspended solids	2540 D	Using glass fibre filter paper
Volatile suspended solids	2540 E	Using Whatman 114 filter paper
Total dissolved solids	2540 C	
Total volatile solids (organic solids)	2540 E	
Hazen colour	2120	Using colour disks. Filtered on 0.45 μm membrane
Absorbance	2120 C	At 480 μm filtered on 0,45 μm membrane
Free and saline ammonia	4500 - NH_3	
Nitrate	4500 - NO_3	
Phosphorus	4500 - P (c)	
pH	4500 - H^+	
Alkalinity	2320 (B)	
Chloride	4500 - Cl (B)	
Sulphate	4500 - SO_4^{2-} (D)	
Sulphide	4500 - S^{2-} (D)	
Volatile fatty acids	5560 (C)	
Metals	3110	
BOD	5210 (B)	
Sludge Volume Index	2710 (C and D)	Not stirred. Diluted

APPENDIX B

UNTREATED KLB EFFLUENT QUALITY

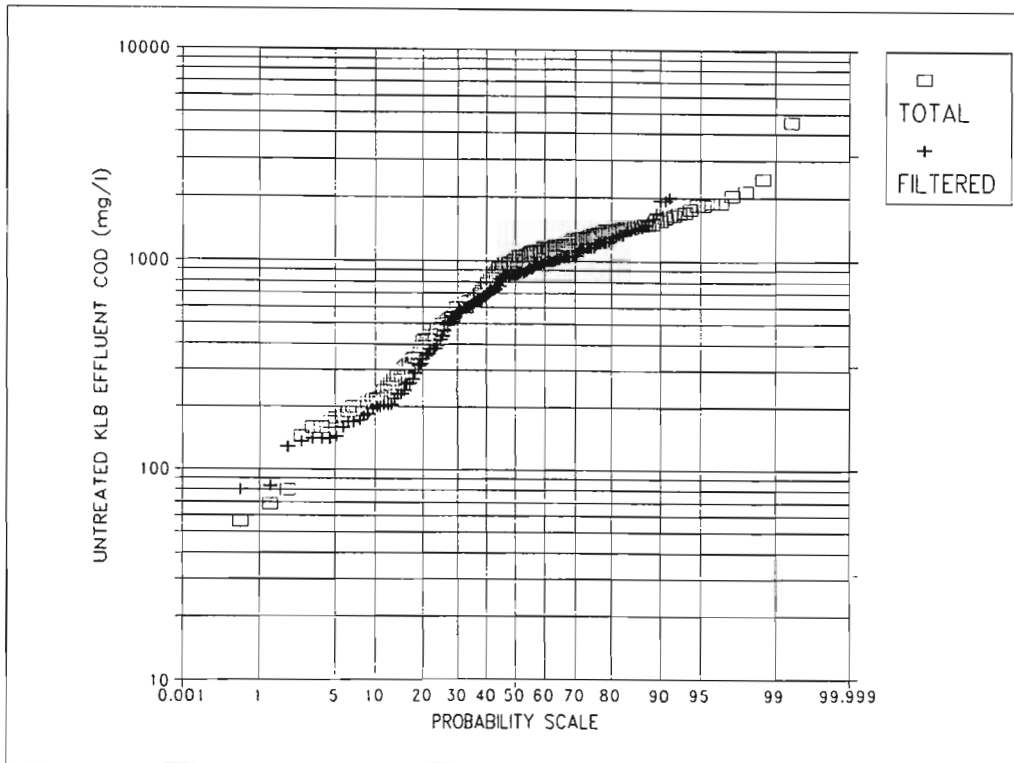


Figure B1 : Probability distribution for untreated KLB effluent COD concentration for the entire operating period

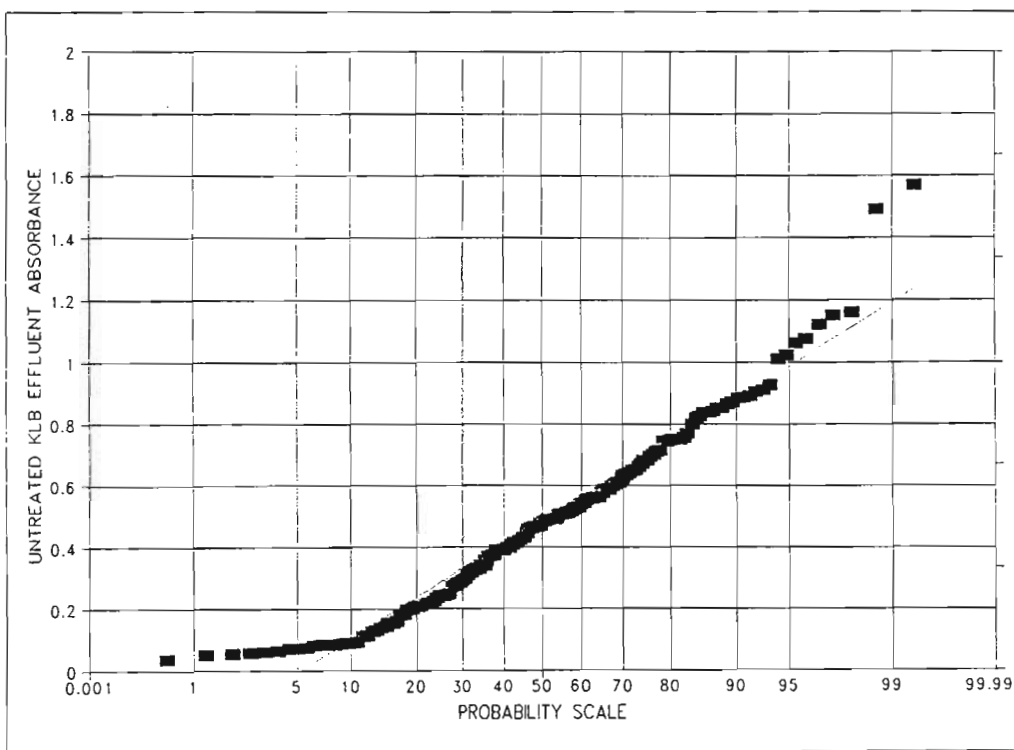


Figure B2 : Probability distribution for untreated KLB effluent absorbance for the entire operating period

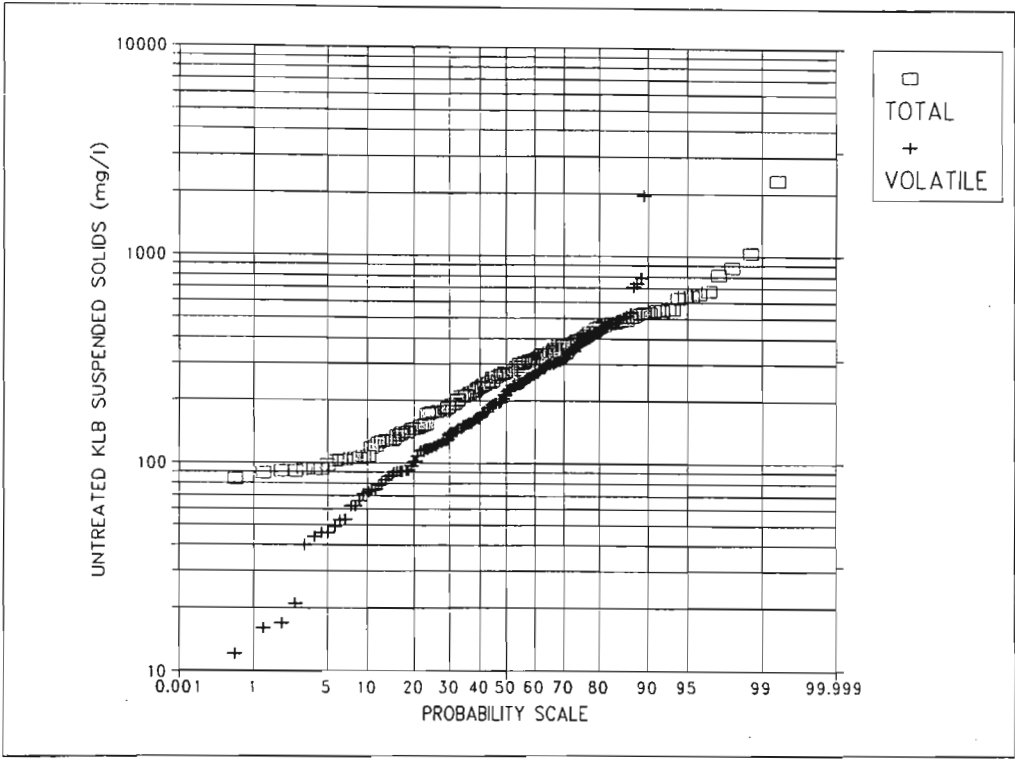


Figure B3 : Probability distribution for untreated KLB effluent suspended solids concentration for the entire operating period

APPENDIX C

PILOT PLANT OPERATING CONDITIONS



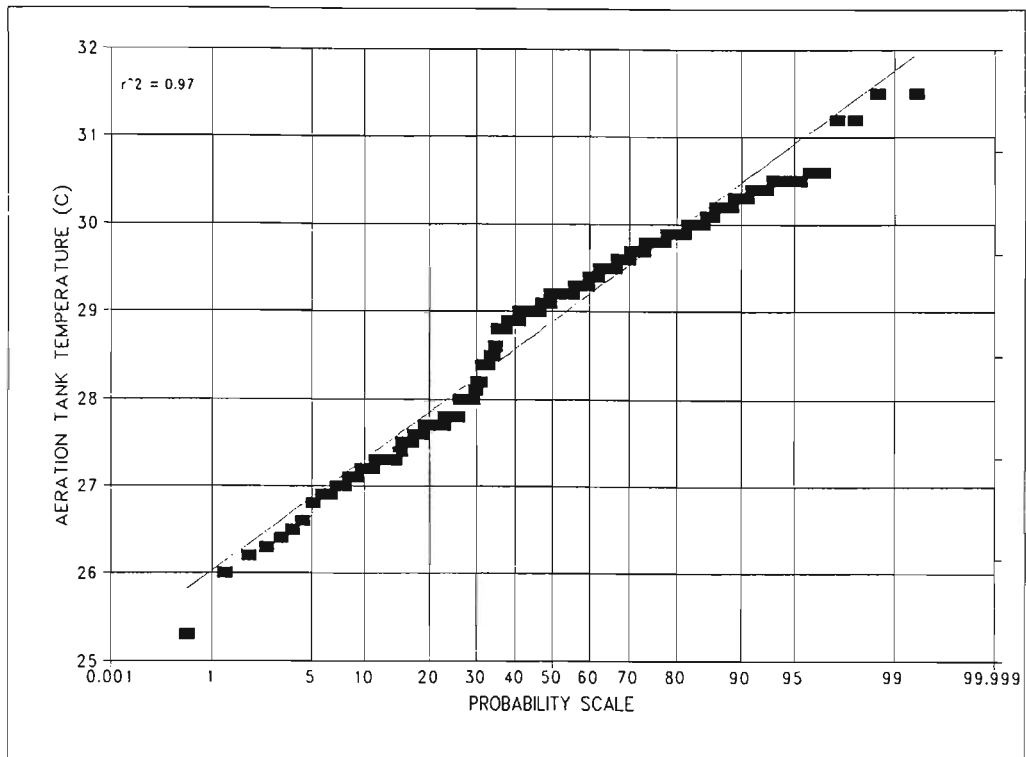


Figure C1 : Probability distribution of temperature maintained in the aeration tank

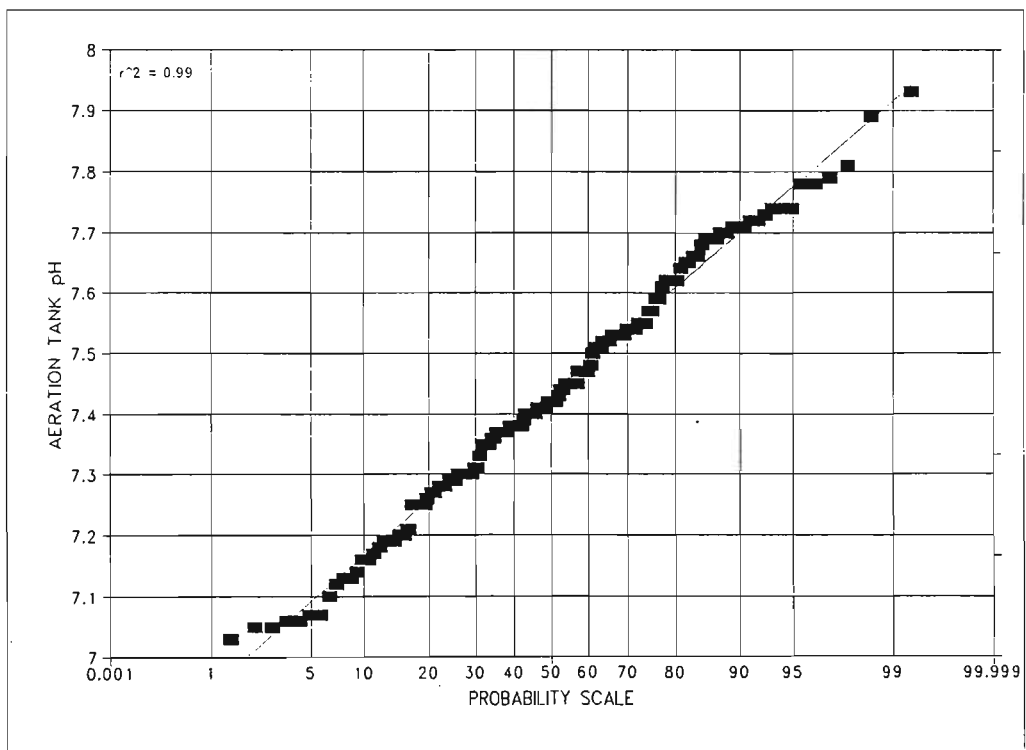


Figure C2 : Probability distribution of pH maintained in the aeration tank

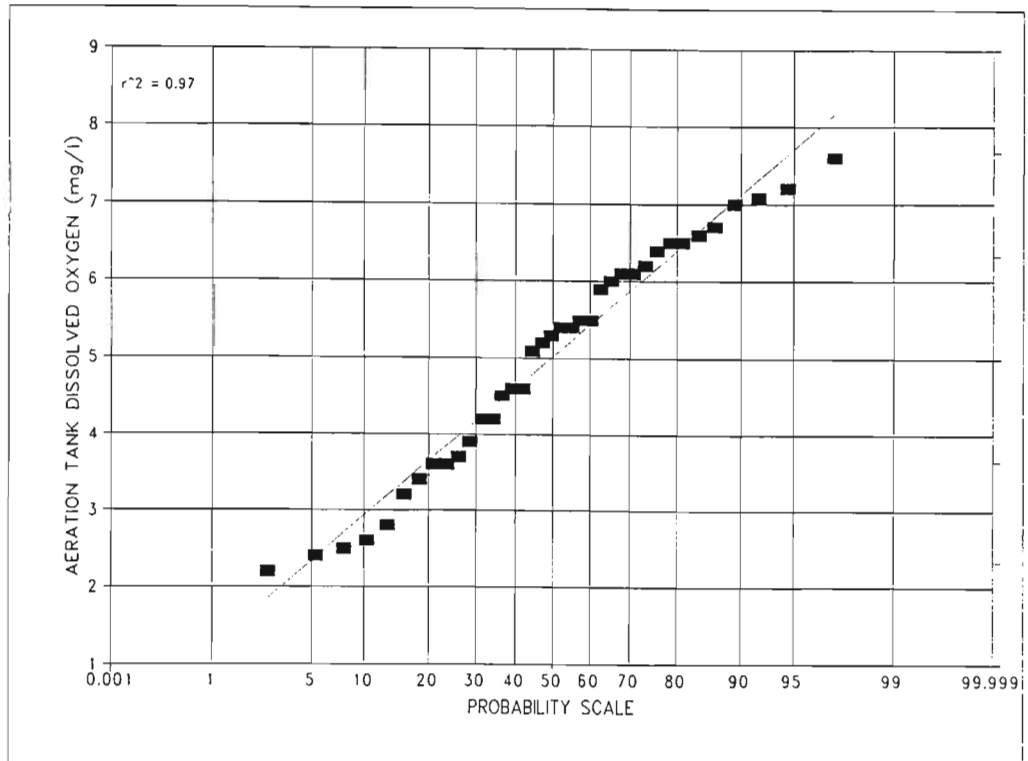


Figure C3 : Probability distribution of dissolved oxygen concentration maintained in the aeration tank

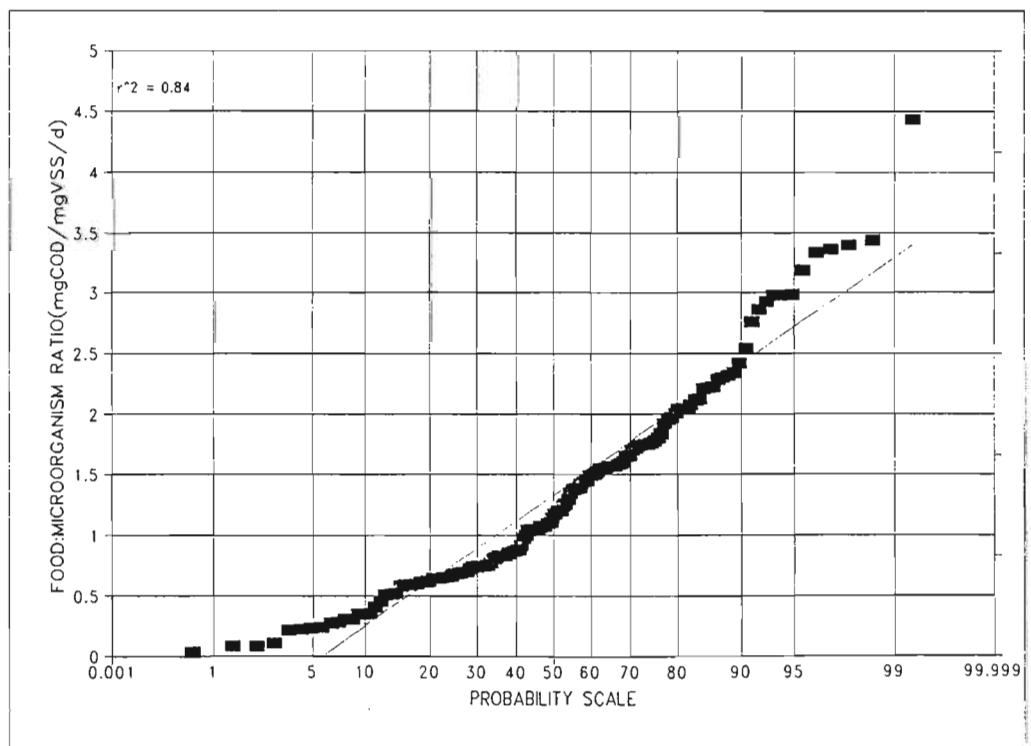


Figure C4 : Probability distribution of Food : Microorganism ratio

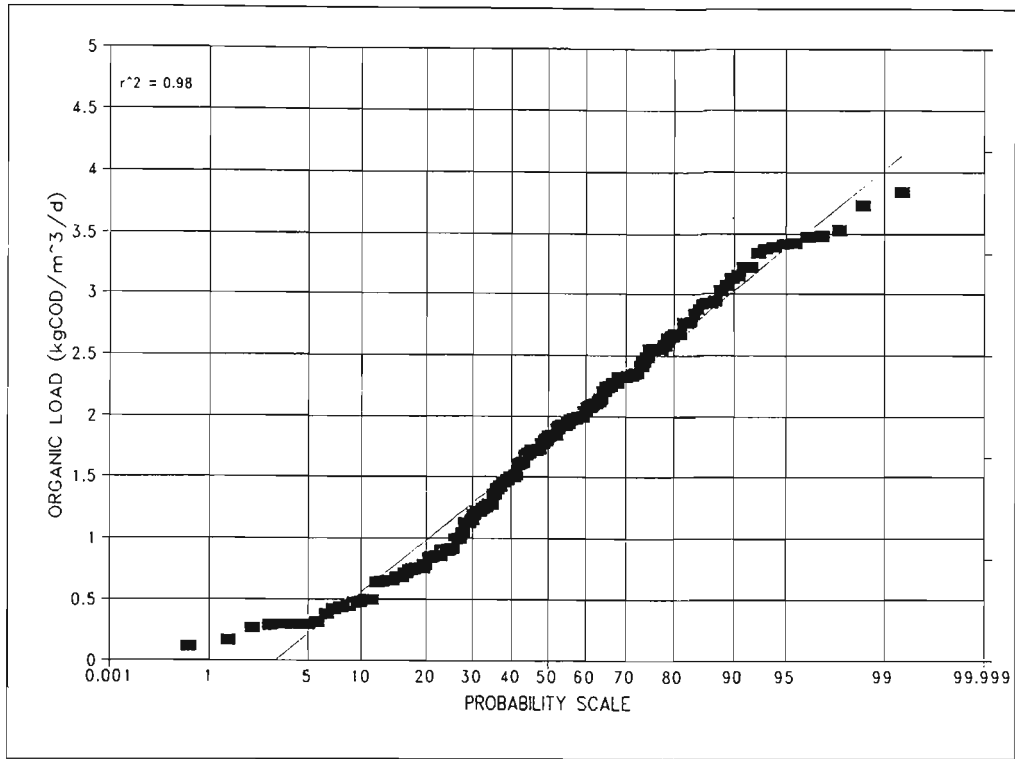


Figure C5 : Probability distribution of organic load

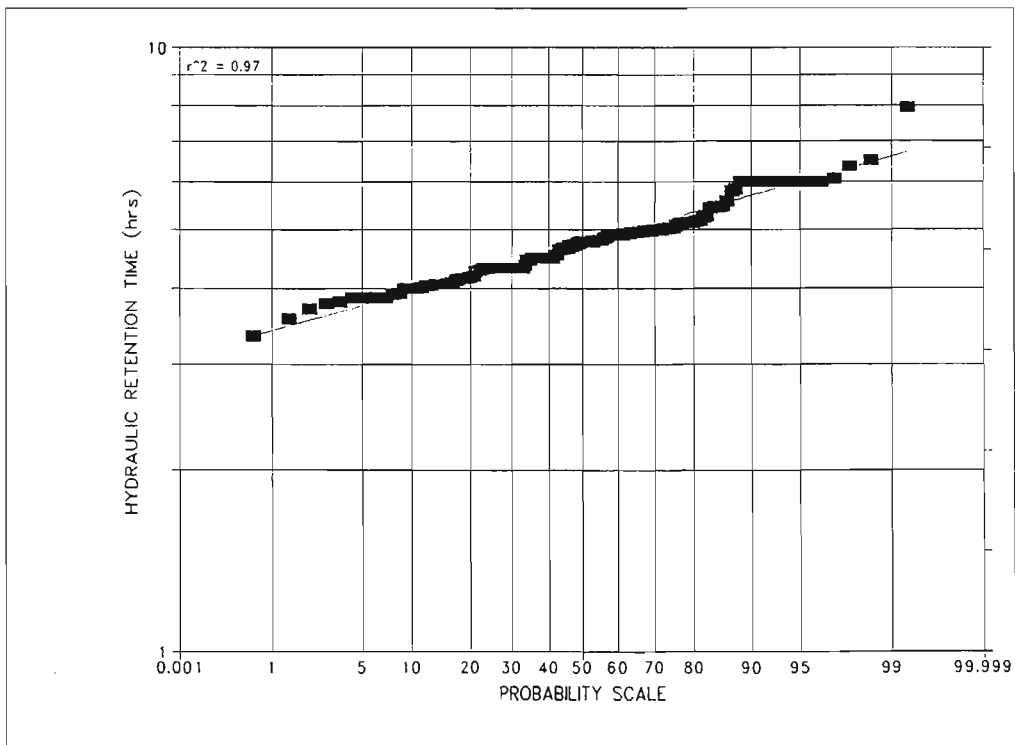


Figure C6 : Probability distribution of hydraulic retention time maintained in the aeration tank

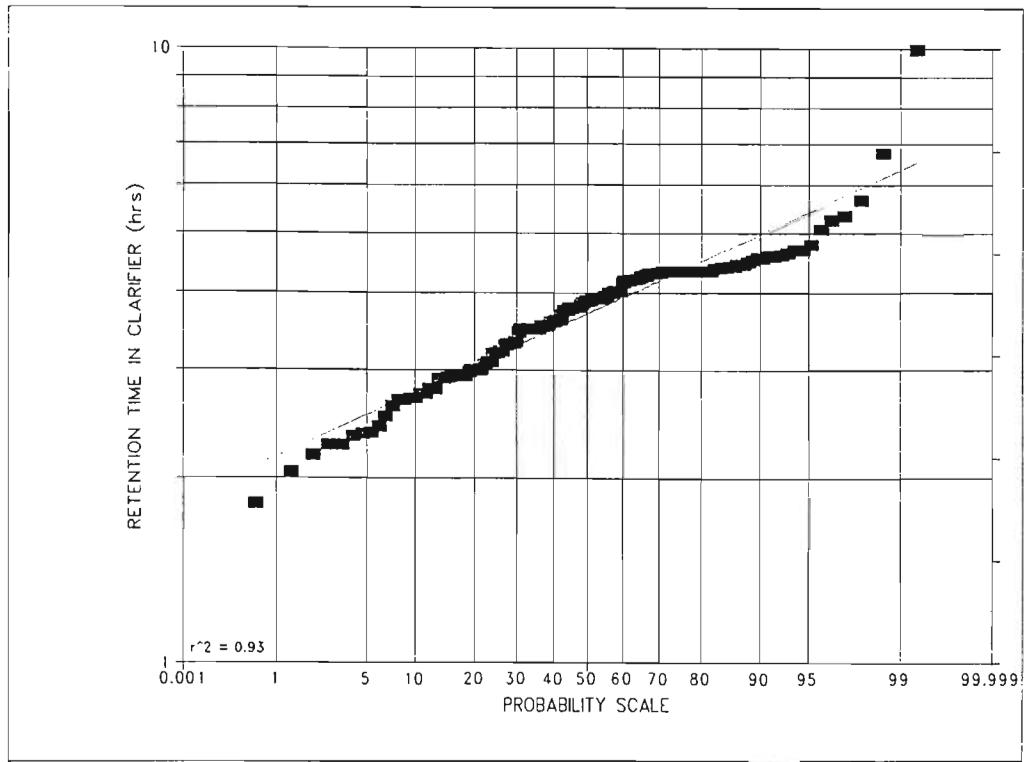


Figure C7 : Probability distribution of hydraulic retention time in the secondary clarifier

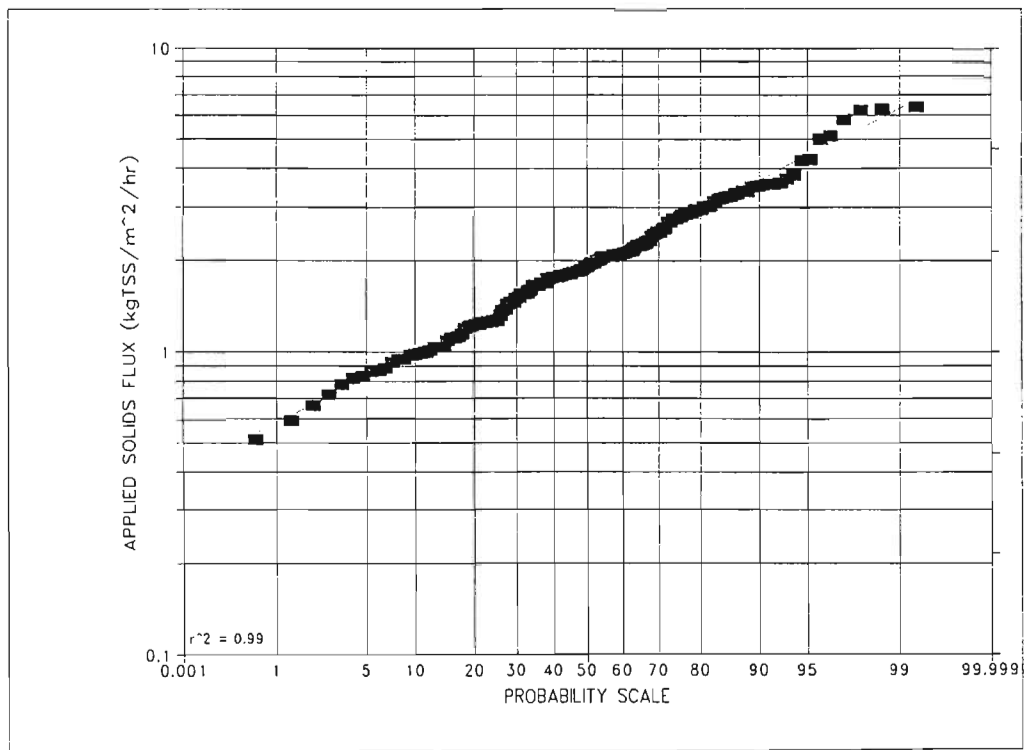


Figure C8 : Probability distribution of solids flux applied onto the secondary clarifier

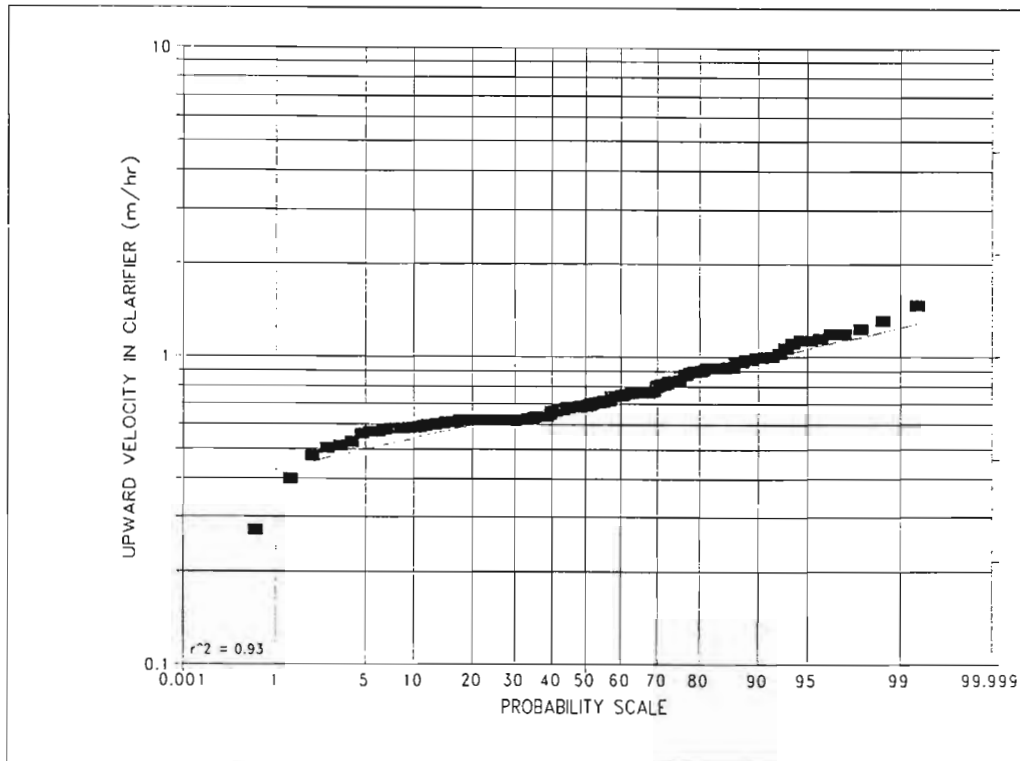


Figure C9 : Probability distribution of upward velocity in the secondary clarifier

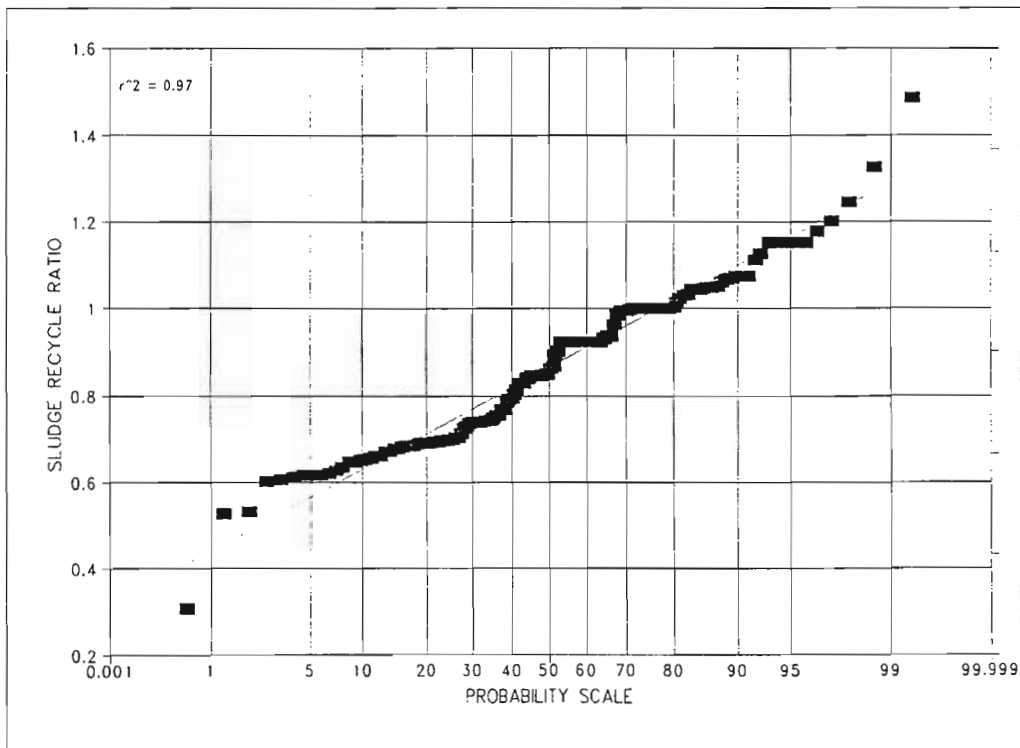


Figure C10 : Probability distribution of sludge recycle ratio

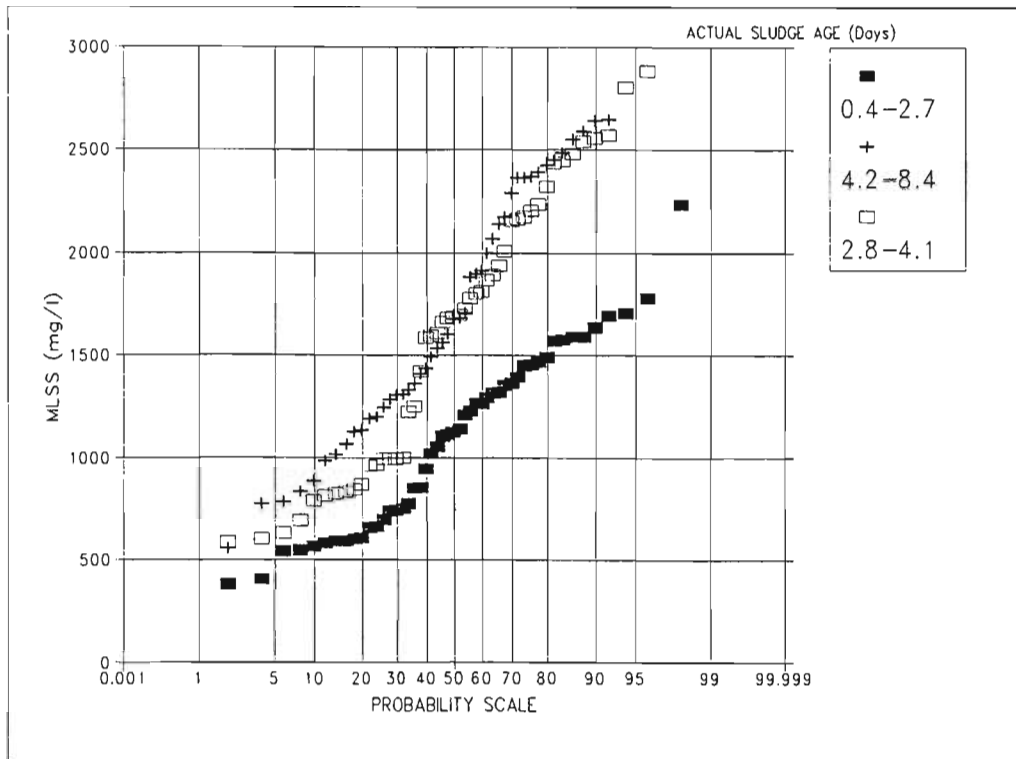


Figure C11 : Probability distribution of MLSS concentration measured as a function of actual sludge age

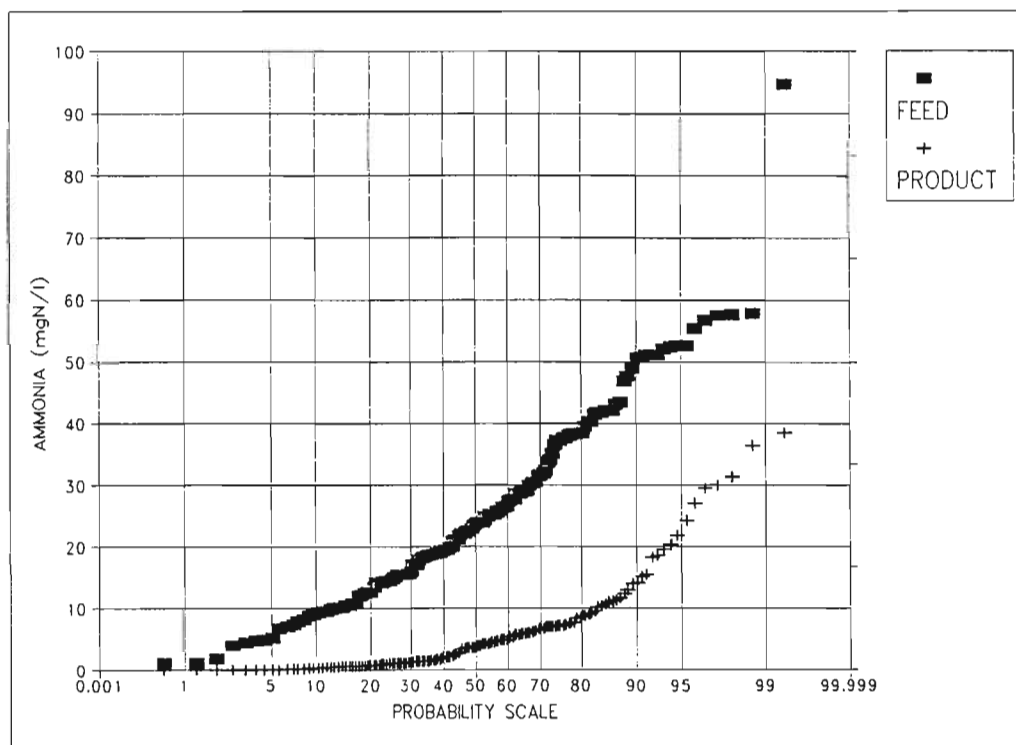


Figure C12 : Probability distributions of ammonia concentrations for the feed and product

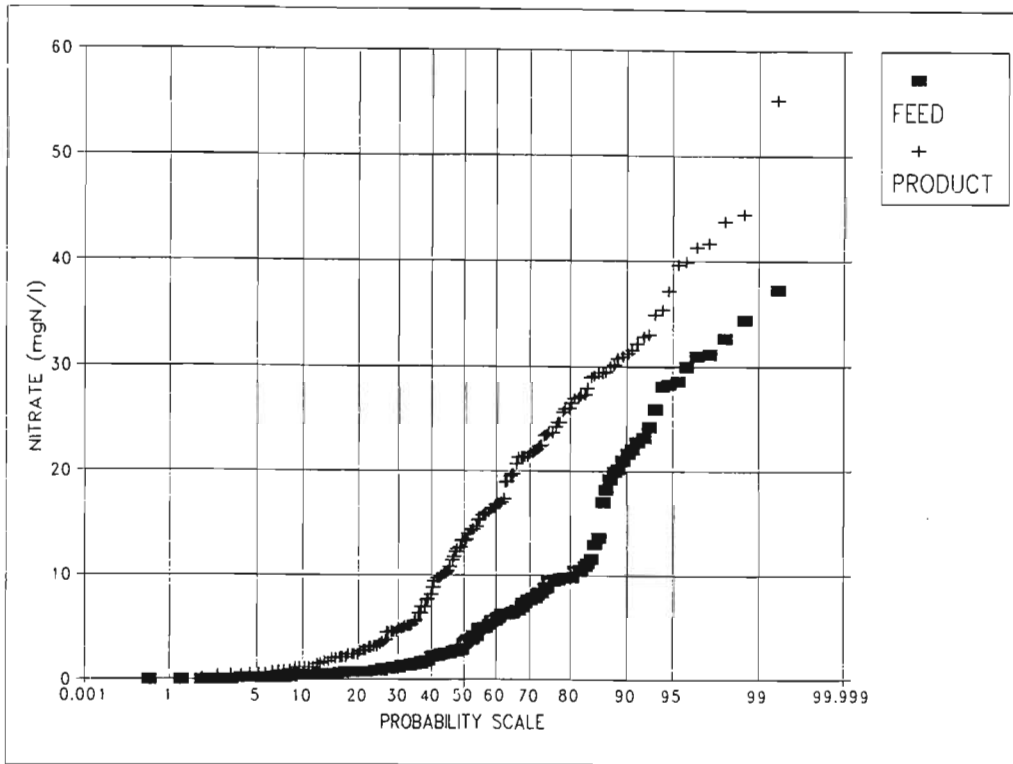


Figure C13 : Probability distributions for the nitrate concentrations in the feed and product

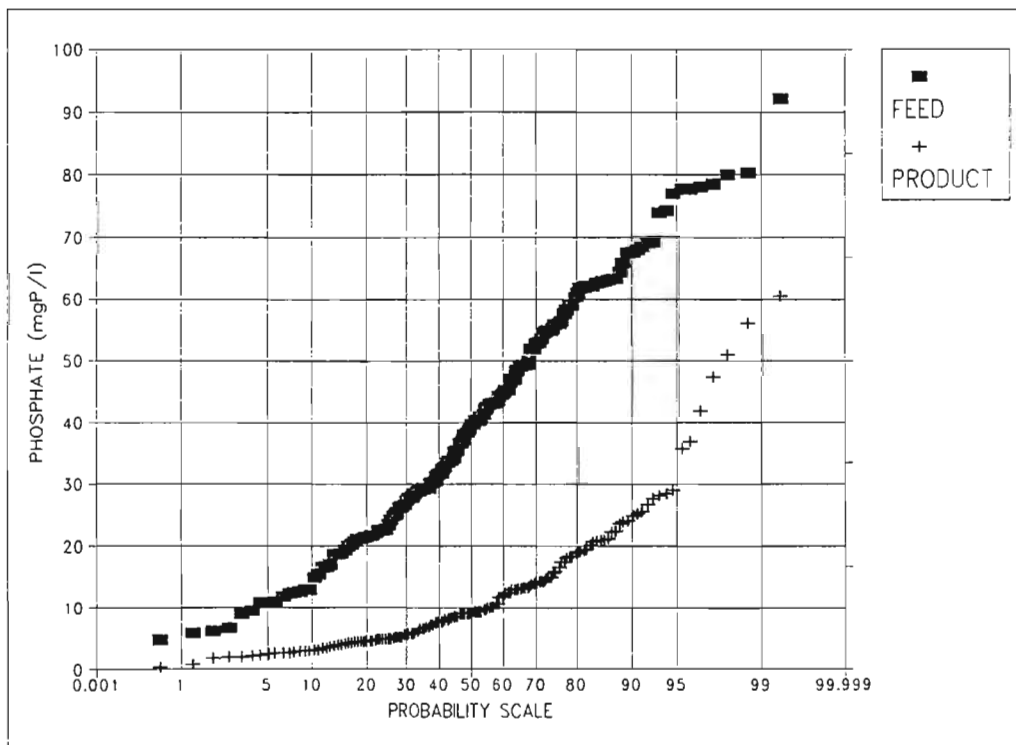


Figure C14 : Probability distributions for phosphate concentrations in the feed and product

APPENDIX D

MISCELLANEOUS PROBABILITY DISTRIBUTION PLOTS

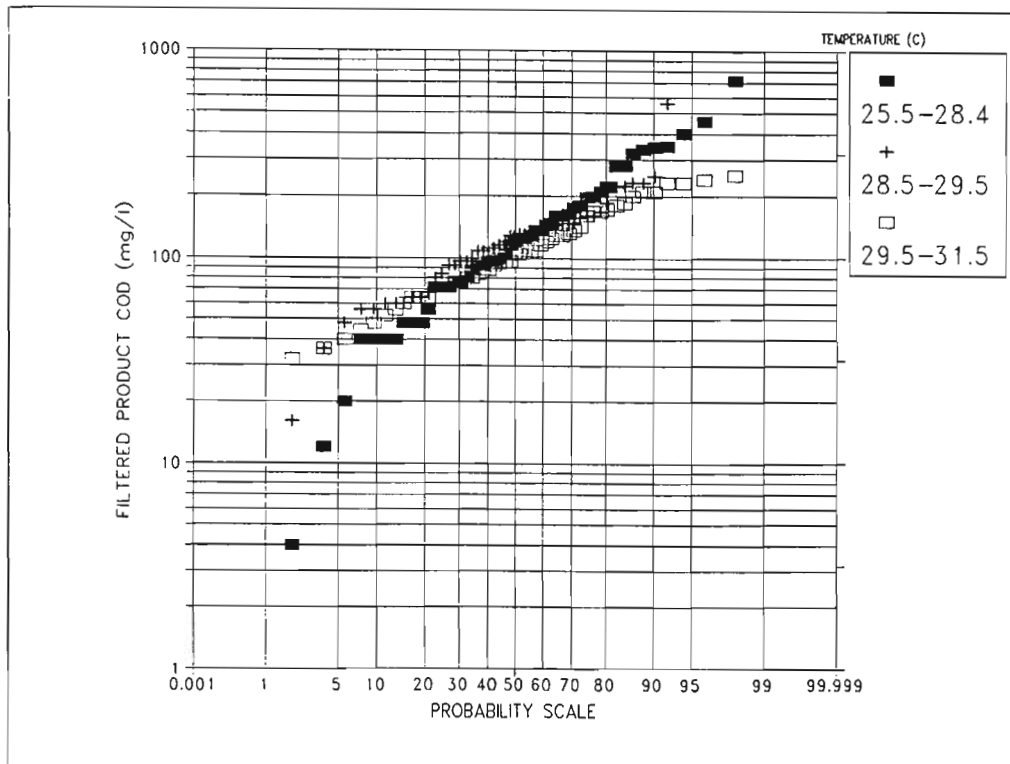


Figure D1 : Probability distributions showing the effect of temperature on the product COD concentration

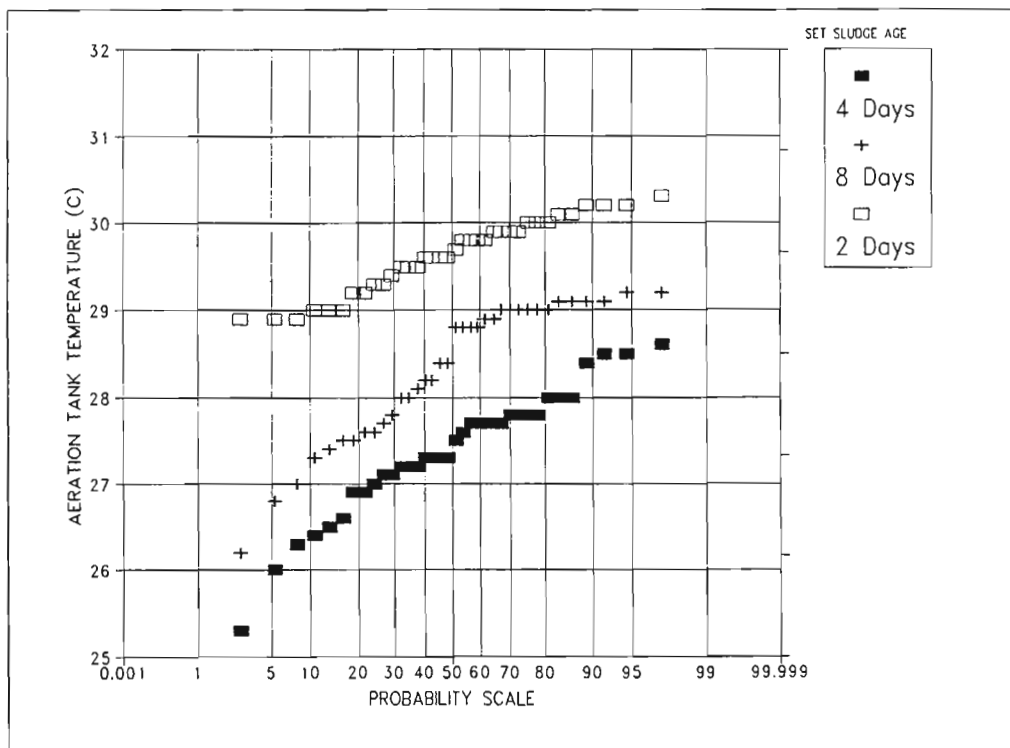


Figure D2 : Probability distribution of aeration tank temperature during the various set sludge age operating periods

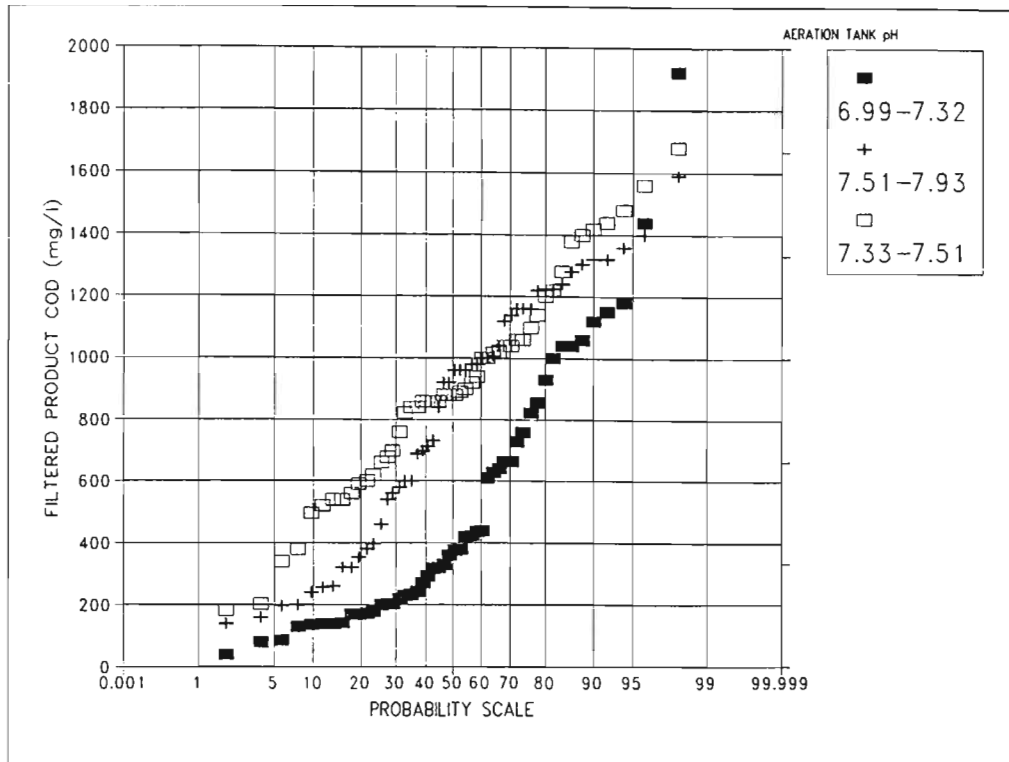


Figure D3 : Probability distribution of pH oxygen concentration maintained in the aeration tank

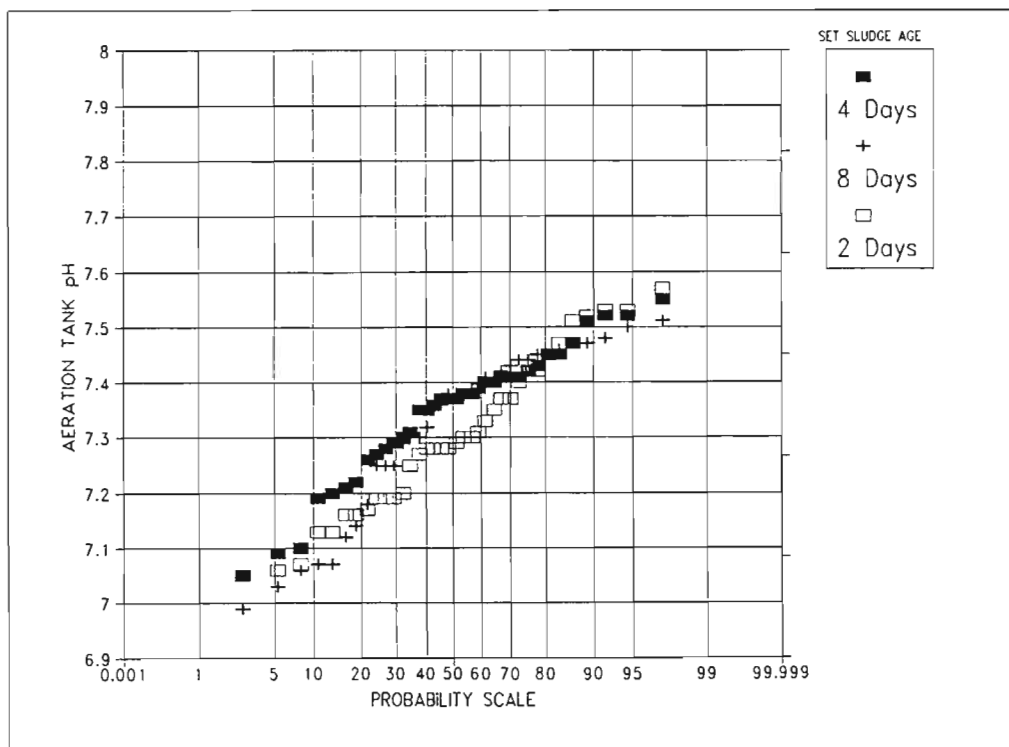


Figure D4 : Probability distribution of aeration tank pH during the various set sludge age operating periods

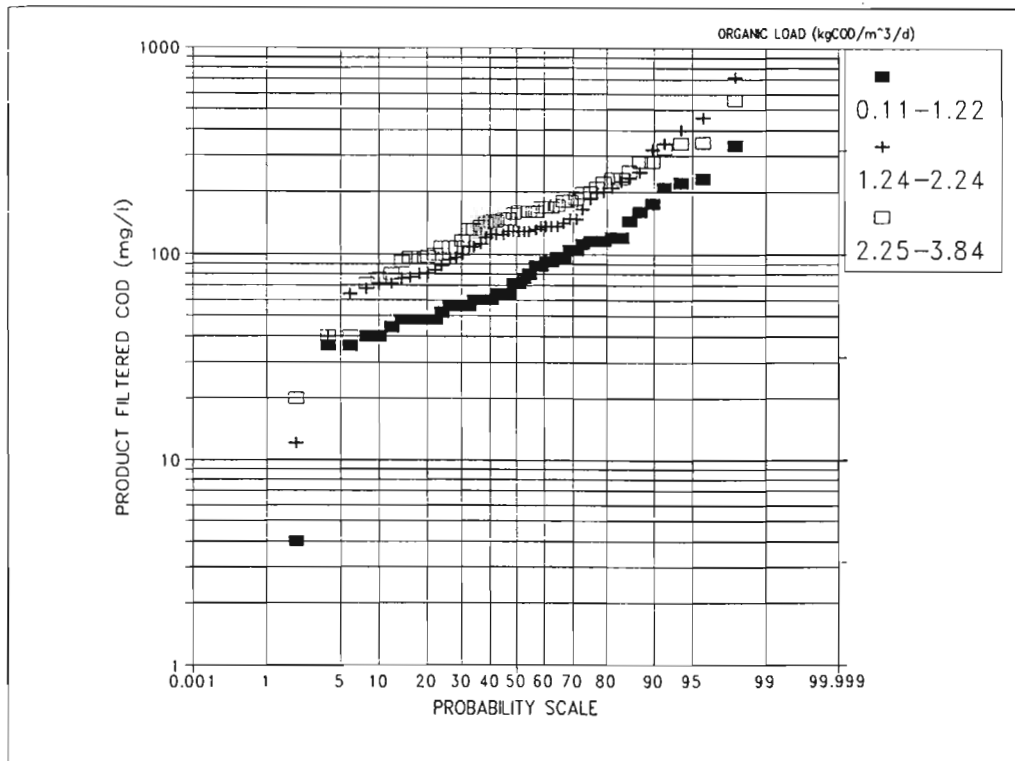


Figure D5 : Probability distribution showing the effect of organic load on the product DOC concentration

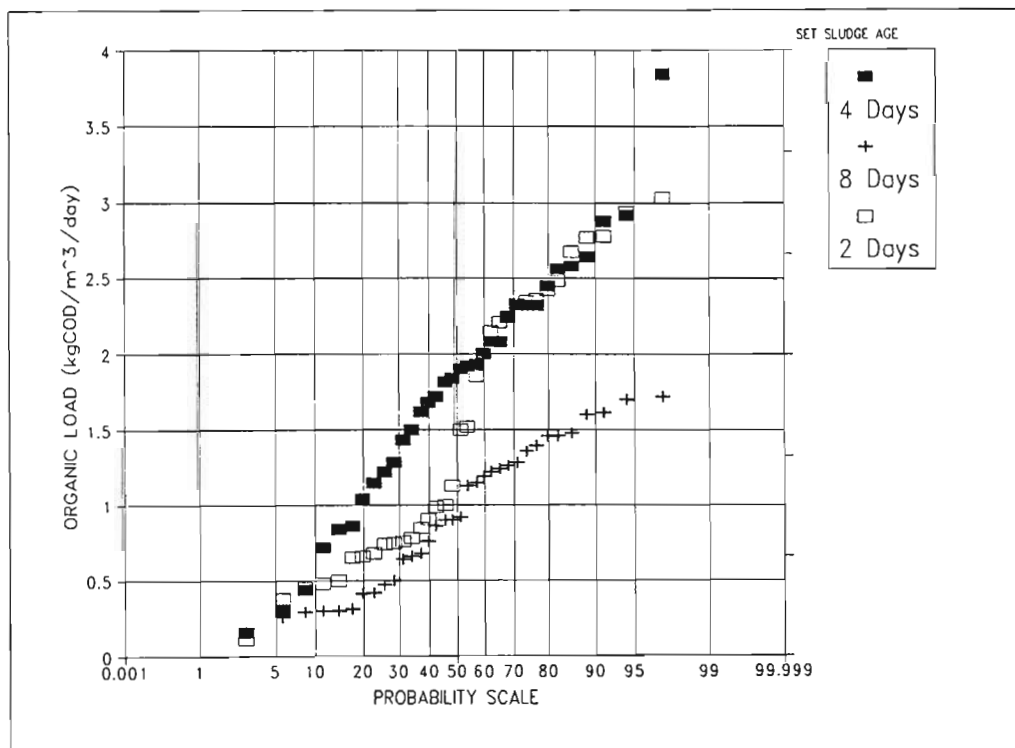


Figure D6 : Probability distribution of organic load during the various set sludge age operating periods

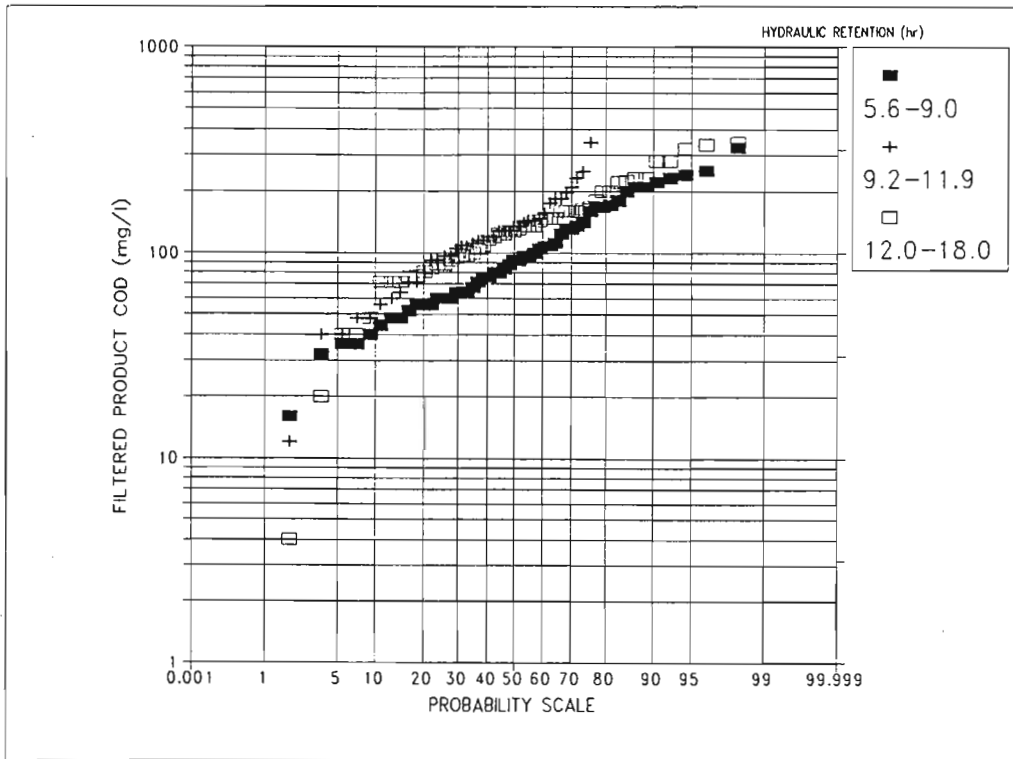


Figure D7 : Probability distribution showing the effect of hydraulic retention time on the product COD concentration

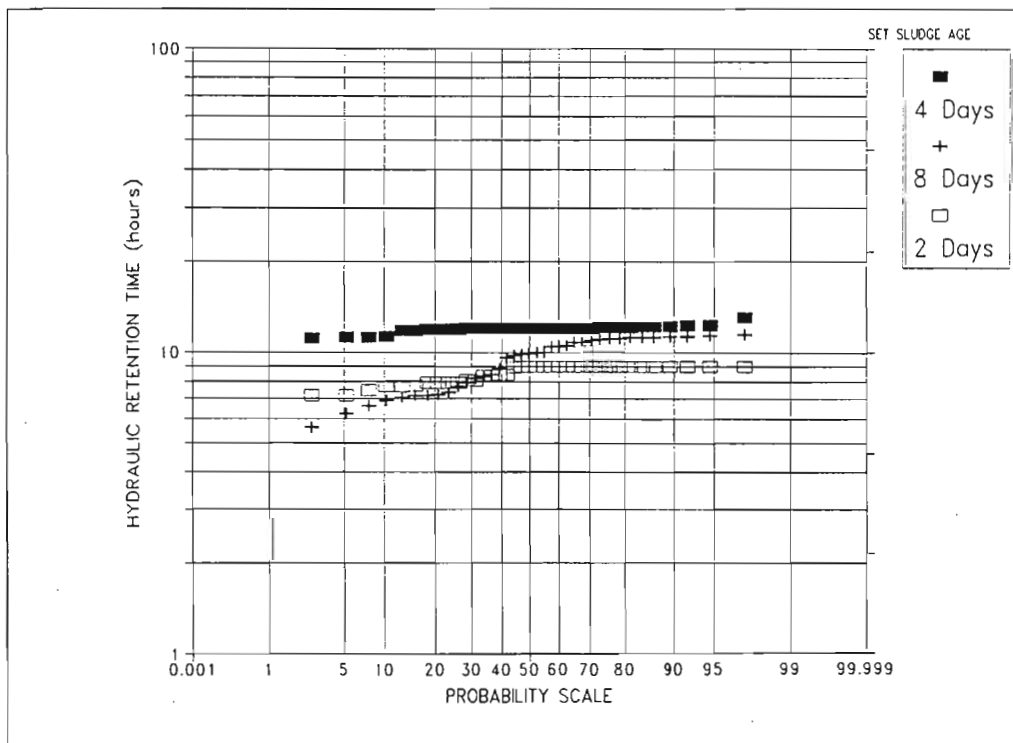


Figure D8 : Probability distribution of hydraulic retention time during the various set sludge age operating periods

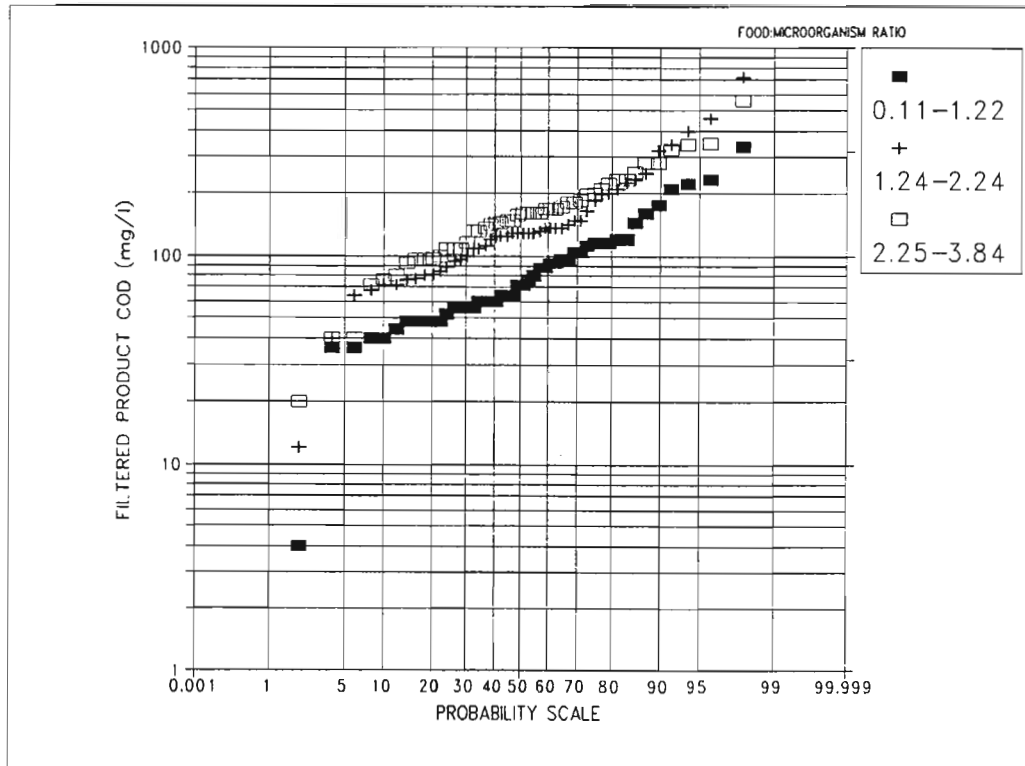


Figure D9 : Probability distribution showing the effect of Food : Microorganism ratio on the product COD concentration

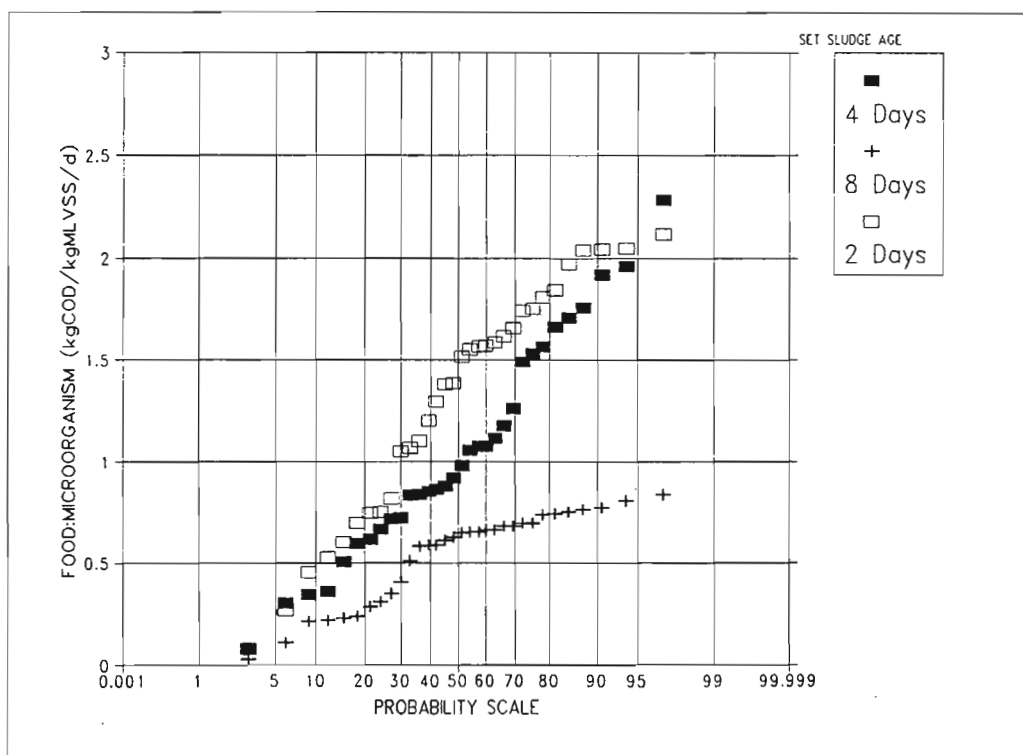


Figure D10 : Probability distribution of Food : Microorganism ratio during the various set sludge age running periods