High Rate Biological Filtration

AM van Niekerk • WG Rudert

Report to the Water Research Commission
by
Wates, Meiring and Barnard (Pty) Ltd

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HIGH RATE BIOLOGICAL FILTRATION

Report to the

WATER RESEARCH COMMISSION

on the Project " Investigation into Application of High Rate Biological Filtration Processes to Municipal Wastewater Treatment"

by

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EXECUTIVE SUMMARY

1. INTRODUCTION

Biofiltration is a widely used technology in the treatment of sewage and industrial effluent. The technology can be applied to large sophisticated wastewater treatment plants as well as to simple community-based systems. The process is, however, relatively inflexible and requires high capital expenditure to achieve an acceptable treated sewage effluent quality, especially in winter. Suspended culture processes such as activated sludge have become more popular in recent years, specifically in sensitive catchments which require nutrient removal.

Biofiltration, however, still holds promise as an attractive treatment technology. Many recent advances in the technology are actively pursued in North America and Europe. The application of biofiltration process innovations can result in substantial capital cost savings and in a high quality final treated effluent. Biofilters are relatively simple to construct and to operate with a low imported mechanical and electrical equipment content. Local materials can be used to construct biofilters, such as natural stone and labour-based construction techniques can be employed. Blocks and/or gabions can be used in the construction of biofilters in lieu of conventional reinforced concrete.

2. RESEARCH OBJECTIVES

The objectives of the research project were related to developing a better understanding of high rate biofiltration, aimed specifically at optimising the carbon removal characteristics. The specific aims of the project included:

- investigation of the hydrodynamic properties of high rate biofilters;
- assessment of the treatment performance of biofilters receiving a high organic loading rate and coupled with high recirculation;
- quantification of the solids production by biofilters;
- valuation of the influence of stone media size and media grading on biofilter performance.

The research work was conducted on a relatively large pilot plant to demonstrate the practical application of the technology.

3. MAIN RESULTS

3.1 Hydrodynamic Characteristics of Biofilters

The liquid retention, hydraulic residence time (HRT) and residence time distribution in biofilters were investigated at different hydraulic loading rates. In general, it was concluded that:

- The HRT of wastewater in biofilters is relatively short (several minutes) compared to the other bio-treatment processes, such as activated sludge (several hours).

- The HRT increases sharply at low hydraulic loading rates (< 5 $m^3/m^2_f/day$) and approaches a low asymtotic value at high loading rates (> 100 $m^3/m^2_f/day$).

- The HRT in a biofilter increases as the filter media size decreases.

The HRT is for a specific biofilter calculated on the basis of the liquid retention approach and on the basis of tracer migration will differ. The difference can be ascribed to diffusion of the tracer molecules into and from the biofilm. The HRT based on tracer information is, therefore, more representative of the actual residence time of the carbon substrate molecules. The HRT estimate based on liquid retention would underestimate the actual substrate retention time.

The small media size (29 - 45 mm stone) and the medium media size (46 - 63 mm stone) biofilters exhibited similar hydraulic residence time properties. The large media (64 - 81 mm) biofilters suffered from severe short circuiting as reflected by the short hydraulic residence times. This phenomena impacted negatively on the treatment performance of the latter filter.

The HRT on full scale installations, with intermittent dosing of sewage is much longer than the HRT on the pilot plant filters. The difference can be ascribed to the different dosing technique. The intermittent dosing of sewage results in a high local hydraulic application rate, which increases the local hydraulic retention time, resulting in a larger effective HRT. The non-steady state migration of flow through the full scale biofilter also contributes to the relatively long HRT's. Flow through the distribution pipework and collection drains contribute to the longer HRT's observed on full scale.

3.2 Carbon Removal Characteristics of Biofilters

The carbon removal of biofilters increases as the organic loading rate onto the filter increases. At high organic loading, a maximum carbon removal capacity is reached which depends on the strength of the feed sewage. Recirculation around a biofilter has limited benefit at high organic loading rates (> 2000 gCOD/m3f/day) due to the effective wetting of the biofilter media at these high organic loading rates.

The smaller media size biofilter was more effective in carbon removal per unit volume of filter compared to the larger media biofilter. All biofilters, irrespective of the media size, had similar carbon removal rate per unit surface area of filter media. The carbon removal rates per unit surface was 11 $gCOD/m^2_m/day$ in the organic loading range of 500 – 1 500 $COD/m_f^3/day$. Biofilters can effectively remove 50 - 70% of the carbon load, depending on the media size, at loading rates of 1000 - 1500 g $COD/m_f^3f/day$.

Very high recirculation rates (Qr/Q >7) can improve the performance of biofilters receiving an intermediate organic loading rate (±1 000 g $COD/m^3f/day$). The biomass appears to have improved flocculant characteristics at these high recirculation rates.

The biosolids yield is dependent on the biofilter media size. Smaller media sizes generates less solids per unit carbon removal (0,48 g SS/g COD removed) compared to the larger media sizes (1,09 g S/g COD removed). The difference in yield has an important implication to downstream polishing treatment processes.

Little nitrogen, apart from the biosynthesis requirements, is removed by high rate biofilters receiving organic loading rates in excess of 750 $gCOD/m_f^3/day$.

3.3 Evaluation of Full Scale Intermediate Rate Biofiltration

Two biofiltration plants operating at intermediate rates using natural stone filters, were monitored and evaluated.

In general, the carbon removal capacity of the full scale biofilters exceeded the design criteria of 250 gCOD/mf3/day. The traditional design criteria are, therefore, conservative, and even existing biofilters may have substantially underestimated treatment capacity in terms of carbon removal.

Nitrogen removal by nitrification and denitrification was also observed at intermediate organic loading rates (300 - 400 g COD/m_f^3/day). Partial nitrification (> 60%) was observed and a substantial fraction of the nitrate generated in the nitrification process was lost by denitrification (60 - 70%). The presence of available carbon compounds to drive the denitrification process in these intermediate rate biofilters was essential for the high degree of denitrification.

In general, the full scale intermediate rate biofilters require polishing treatment such as secondary biofilters or activated sludge before discharge of the final treated effluent to the public stream.

3.4 Economic Potential for Application of High Rate Biofiltration

An economic analysis of the high rate biofiltration process confirmed that it is an efficient and cost-effective approach to the removal of carbonaceous compounds from sewage. The capital construction/erection cost of high rate biofilters in combination with polishing activated sludge is marginally higher than the other process technologies. The operating and maintenance cost of high rate biofiltration is, however, substantially lower than other process technologies. The high rate biofiltration process would also require little attention from skilled operators.

In general, the application of high rate biofiltration is economically attractive, specifically in catchments which do not require nutrient removal. Plants with existing biofilters may be upgraded at relatively low cost to high rate applications, which can increase the reliable treatment capacity and the life of an existing plant.

4. FINAL CONCLUSIONS

The general performance of biological filters can be described in terms of three different situations:

- At low organic loading rates, less than 250 g COD/m_f^3/day, biofiltration is effective in carbon removal (> 80 %) and virtually complete nitrification (biofilter effluent containing $\leq$ 10 mg NH3-N/ℓ) is achieved. The biofilter effluent is typically well mineralised, containing low COD-concentrations and high nitrate concentrations.
- At intermediate organic loading rates, 250-750 g COD/m_f^3/day, biofiltration can still remove a substantial fraction of the organic load as well as nitrogen load. Nitrification as well as denitrification can take place in the same biofilter, due to the relative availability of carbon compounds to drive the denitrification process. The biofilter effluent will contain low COD, ammonia and nitrate concentrations, but may not always comply with the General Standard of the Water Act 54 of 1956.
- At high organic loading rates, 750 - 1 500 g COD/m_f^3/day, biofilters can still remove 50 - 70 % of the influent carbon load, depending on the biofilter media size. No significant nitrification can be anticipated, but some nitrogen removal, due to biomass synthesis will take place. The biofilter effluent will require further polishing treatment, before discharge to the public stream.

Economic analysis of the high rate biofiltration process confirmed that it is an efficient and cost-effective approach to the removal of carbonaceous compounds from wastewater. A comparison of the treatment cost of combined biofiltration/activated sludge versus conventional activated sludge indicated that the former has a lower unit treatment cost, specifically with respect to the operating and maintenance aspects.

5. RECOMMENDATIONS FOR FURTHER RESEARCH

This research project was successful in demonstrating the potential for high rate biofiltration technology in South African wastewater treatment. The further application of the technology will benefit from research into the following aspects:

- optimisation of the nitrogen removal capacity of a biofilter operated at intermediate organic loading rates. Many field observations are related to improved nitrogen removal by recirculation around the biofilter.

- the flocculation characteristics of biofilter solids changed substantially at high recirculation rates (Qr/Q >7). A very high quality biofilter effluent was produced at these high recirculation rates. High recirculation rates are expensive on a full-scale application, but may obviate the need for polishing treatment, downstream of a high rate biofilter.

- the extrapolation of the process performance by continuously-fed biofilters (pilot plant) to intermittently-fed biofilters (full scale plants) should be investigated.

- a further extension of the technology to aerated biofiltration is gaining popularity among international researchers. The local application of this new generation biofiltration process should be investigated.

A valuable biofiltration research facility was erected at the Pretoria, Baviaanspoort Water Care Works as part of this project. The Water Research Commission should consider the further use of this facility to advance biofiltration technology.

6. ACHIEVEMENT OF CONTRACT OBJECTIVES

The research work demonstrated the potential for high rate biological filtration processes in municipal sewage treatment. The performance of these processes under different operating and loading conditions was demonstrated.
Some aspects related to the nitrification and denitrification characteristics of the process were not adequately quantified and should be further researched.

7. TECHNOLOGY TRANSFER OF RESEARCH RESULTS

A technology transfer workshop was held on 5-6 November 1997 on the topic of high rate biological filtration. An internationally recognised biofiltration specialist, Dr DS Parker from Brown Caldwell Consultants, California, USA, was also invited to relate the American and international experience in this regard. The workshop was attended by 100 people and general favourable comments were received on the contents of the workshop.

A paper on the application of high rate biological filtration was presented at the Biennial Conference of the Water Institute of Southern Africa in May 1998.

ACKNOWLEDGEMENTS

We would like to thank the Water Research Commission for the support of the high rate biological filtration project. The research will hopefully stimulate new interest in and application of biofiltration technology. It is a simple technology which can be incorporated in modern sophisticated wastewater treatment plants as well as in simple community-based treatment systems.

We also appreciate the support of the Greater Pretoria Metropolitan Transitional Council for the use of the Baviaanspoort water care works facility. The City Engineer: Wastewater Treatment, the Chief Chemist and his staff and the plant management and operating staff assisted in the project.

The permission granted by the Witbank Transitional Local Council to use plant performance data from the full scale plants at Ferrobank and Riverview is also appreciated.

The members of the Project Steering Committee are thanked for their valuable contributions and advice on the project including:

Mrs APM Oelofse	-	Water Research Commission (Chairperson)
Dr SA Mitchell	-	Water Research Commission
Mrs AM du Toit	-	Water Research Commission (Committee Secretary)
Prof WA Pretorius	-	University of Pretoria
Prof TE Cloete	-	University of Pretoria
Mr GB Saayman	-	Greater Pretoria Transitional Metropolitan Council
Mr JS Terblanche	-	ERWAT
Mr A Louw	-	ERWAT
Dr P van Eeden	-	ERWAT
Mr J Joubert	-	Rand Water

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Θ	temperature correction coefficient
a	number of distributor arms (#)
As	total filter media surface (m^2/m^3)
Aw	wetted filter media surface (m^2/m^3)
C(z,t)	tracer concentration at time t and at location z (mg/l)
C_e	settled biofilter effluent COD-concentration (mg/l)
Ce	settled filter effluent BOD_5 concentration (mg/l)
C_o	settled sewage total COD-concentration (mg/l)
Co	total filter influent BOD_5 concentration (mg/l)
COD_e	biofilter effluent COD-concentration of settled sewage (mg/l)
COD_i	COD-concentration (mg/l)
C_s	constant
D	filter depth (m)
D	effective dispersion coefficient (m^2/sec)
De, Dw	diffusion coefficient (m^2/day)
E	initial tracer concentration (mg/l)
E	carbon removal (gCOD/m^3 filter/day)
F	effective number of filter passes
HRT	hydraulic retention time (mins)
k	maximum metabolic rate
K	filter constant
K_b	empirical rate constant
kf	mass transfer coefficient
Knrc	empirical constant
K_s	half saturation constant (mg/l)
K_r	rate constant (1/day)
L	thickness of biofilm (m)
M	microbial density (kg biomass/m^3) the area of the floor
n	rotational speed of distributor arms (r.p.m.)
n, m	empirical constants
n	filter media constant
N	substrate flux (kg/m^2/day)
N_e	biofilter effluent ammonia concentration (mgN/l)
N_{ef}	nitrification rate (gN/m^3/day)
N_{load}	nitrogen loading rate (gN/m^3/day)
$N_{o,e}$	biofilter effluent organic nitrogen concentration (mgN/l)
p	empirical weighing factor
q	metabolic rate (kg substrate/kg biomass/day)
q_m	maximum metabolic rate (kg subtrate/kg biomass/day)

Q	settled sewage feed rate (Ml/day)
Q	influent flow rate (m^3/day)
Q	settled sewage feed flow (m^3/day)
Q	influent hydraulic load (m^3/m^2 filter/hr)
Qs	hydraulic loading rate (m^3/m^2 filter/day)
r	recycle ratio (R/Q)
r	filter radius (m)
R	recirculation flow rate (Ml/day)
S	substrate concentration (kg/m^3)
S_b	substrate concentration of the bulk liquid (kg/m^3)
S_c	substrate concentration (kg/m^3)
SHLR	Volumetric Hydraulic Loading Rate (m^3/m_f^2 filter/d)
S_s	substrate concentration at the surface of the biofilm (kg/m^3)
SS_e	biofilter effluent suspended solids concentration (mg/l)
t	wastewater temperature (°C)
T	contact time (mins)
TKN	TKN concentration (mgN/l)
V	volume of biofilter media (m^3)
V	linear flow velocity (m/sec)
VHLR	Volumetric Hydraulic Loading Rate, (m^3/m^3 filter/d)
VOLR	Volumetric Organic Loading Rate (gBOD or gCOD/m^3 filter/d)
W/V	organic loading per unit biofilter volume (kg BOD/m^3/day)
Y	solids yield coefficient (gSS/gCOD removed)
z	dimension (m)
_	biofilm liquid cover thickness (m)
∀	volume of liquid draining from the biofilter after instantaneous termination of influent flow (m^3)

GLOSSARY OF TERMS

BOD_5	Biological Oxygen Demand (5 day)
BOD	Biological Oxygen Demand
COD	Chemical Oxygen Demand
N	Nitrogen
OA	Oxygen Absorbed
P	Phosphorus
SS	Suspended Solids
STP	Standard temperature (20°C) and pressure (1 atm)
TKN	Total Kjeldahl Nitrogen

1 INTRODUCTION

The use of biofiltration technology for the treatment of domestic sewage and industrial effluent is widespread, especially in the municipal sector in South Africa. A large number of sewage treatment plants use biological filters either as the core treatment process or in combination with other unit treatment processes. Biofiltration has been the work horse of wastewater treatment industry for many decades. The process is however relatively inflexible and requires large filter media volumes to achieve an acceptable effluent quality, especially during winter. The activated sludge process has become more popular due to better operational control and ability to remove nutrients (N & P) microbiologically. Recent experience has, however, indicated that integration of the biofiltration and activated sludge processes is frequently the most economical approach to upgrading an existing plant. Integration of the processes allows optimal use of the strong features associated with the individual processes.

Biofiltration has not received much research attention in South Africa. American and European researchers have, on the other hand, developed a renewed interest in fixed-film reactors (IAWQ Biofilm Conference, 1993). The biofilter solids contact (BFSC) process is an example of the recent innovations introduced to the conventional biofiltration process.

Biofiltration plants and periodic upgradings of these plants in South Africa still employ design criteria which were developed more than 20 years ago. Development of more realistic design approaches and criteria could result in substantial capital cost saving and more reliable production of a high quality effluent. Biofilters are relatively simple to construct and operate. Local materials can be used to construct biofilters, including natural stone and the labour-based construction techniques can be used. Blocks and/or gabions can be used in the construction in lieu of conventional reinforced concrete.

The following is a listing of common, but inaccurate perceptions, about biological filters:

- biofilters cannot produce a high quality effluent, low in Chemical Oxygen Demand (COD) and suspended solids (SS).
- biofilters cannot effectively nitrify and cannot compete with other technologies in this regard.
- biofilters require a lot of land and cannot be constructed as a compact plant.

Despite the fact that a biofilter contains a solid media, taking up a large fraction (typically 40 -50 % in the case of natural stone filters) of the reactor volume, the biofilter may still contain 5 - 7 kg/m^3 of biomass. This biomass concentration is therefore typically higher than in most suspended culture bioreactors, such as activated sludge containing 2 - 4 kg/m^3. The common observation however is that some micro-organisms in a conventional low rate biofilter are less viable compared to the micro-organisms in a suspended culture.

The production of excess (waste) biosludge from a biofilter is also relatively low compared to other types of reactors. This can be ascribed to the rich diversity of micro-organisms resident on a biofilter. The complex food chain includes the lower ranks of bacteria/algae to a variety of metazoa, including Rotatoria, Nematoda, Insecta, etc. A comparison of the typical solids yield coefficients (kg SS/kg COD removed) for a biofilter and an activated sludge reactor demonstrates this:

- low rate biofilter, treating domestic sewage:

  Y = 0,25 kg SS/kg COD removed

- activated sludge (sludge age = 5-10 days) treating domestic sewage:

  Y = 0, 35 kg SS/kg COD removed

The anaerobic degradation of biomass in the deeper parts of the biofilm may also contribute to the observed lower excess solids production rate.

Biofilter performance can however suffer in the event of shifts in the microbial population. Rapid increases in number of animals such as snails or *Daphnia* at the upper ranks of the food web could result in rapid loss of biomass by grazing. These animals may also excrete fine, colloidal and unsettleable particles to the biofilter effluent, which reflects in a poorer quality of effluent.

Fixed film processes, like biofilters typically have few controllable process parameters. The sludge age can for example not be adjusted as in the case of activated sludge to control nitrification. The lack of control has in general not been a serious problem in carbon removal from domestic sewage.

The objectives of this research project were related to developing a better understanding of high rate biofilters, aimed at optimising the carbon removal characteristics. High rate biofilters would typically find application in integrated biofiltration/activated sludge processes and in the treatment of high strength industrial effluents.

The specific aims of the high rate biofiltration research work included:

- to establish the hydrodynamic characteristics of high rate biofilters.
- to assess the performance of biofilters receiving high rate recirculation with respect to COD/BOD (Biological Oxygen Demand) removal, nitrification and denitrification.
- to investigate the degree of biofilm control which can be achieved, including the solids production from biofilters.
- to evaluate the influence of stone media size and grading on biofilter performance.

The research work was aimed at the practical application of the technology. Pilot scale work at the Pretoria Baviaanspoort Water Care Works was conducted using settled sewage without further augmentation or modification. Several full-scale plants using medium/high rate biofiltration were also analysed to investigate the practical application of the process. An economic evaluation of the high rate biofiltration process was also conducted to confirm the financial viability of the process.

2 REVIEW OF THE BACKGROUND TO EVOLUTION OF BIOFILTRATION

Application of biofiltration technology has evolved from the traditional core treatment process to several process configurations which employ biological filters in combination with other processes. The trend has been to identify and exploit the strong and attractive aspects of biofiltration and to supplement/augment the weaker features by combination/integration with other treatment processes. The following sewage treatment plant process configurations demonstrate the changing application of biofiltration technology in South Africa:

- conventional biofiltration process.
- biofiltration solids contact (BFSC) process.
- biofiltration with high rate recirculation.
- pond enhanced biofiltration (PETRO) process.
- integrated biofiltration activated sludge process.

2.1 Conventional biofiltration process

The conventional biofiltration process employs a combination of primary clarification, biofiltration and humus clarification to achieve both oxidation and removal of carbonaceous and nitrogenous compounds. The typical process configuration is shown on **Figure 2.1**.

The raw sewage is clarified in the primary settler from where the settled sewage would typically pass to a dosing siphon structure. The dosing siphon structure regulates the flow to the biological filter to ensure a minimum flow required to activate and drive the distributor arms. Biofilter effluent is clarified in a humus clarifier from where the effluent will be discharged to the public stream after disinfection. Traditionally, some recirculation of the final effluent would be practised. This recirculation was considered to be important to keep the biological filter wet during low flow periods. Recirculation was, however, not believed to be significant in enhancing the performance of the biological filter, apart from sustaining biological life on the filter during low flow periods.

Biological filters used in the conventional process configuration are still sized using conservative design criteria. These design criteria are based on unit loading rates of carbon (COD or OA) and nitrogen (NH_3-N). The loading rates are typically dictated by the nitrification capability of the filters during the colder winter months. The application of conservative design criteria resulted in biological filters becoming very capital cost intensive, due to the large size of the biofilter reactor.

In sensitive catchments, which require the discharge of effluent containing low levels of plant nutrients, phosphate has to be removed from the biofilter plant effluents using chemical means. Activated sludge processes have a competitive advantage in this respect, since the phosphate removal could be mediated by microbiological means.

The conventional biological filtration process configuration is, however, still employed in many parts of the country, where the simplicity of maintenance and minimum requirement for trained operating personnel make this process attractive.

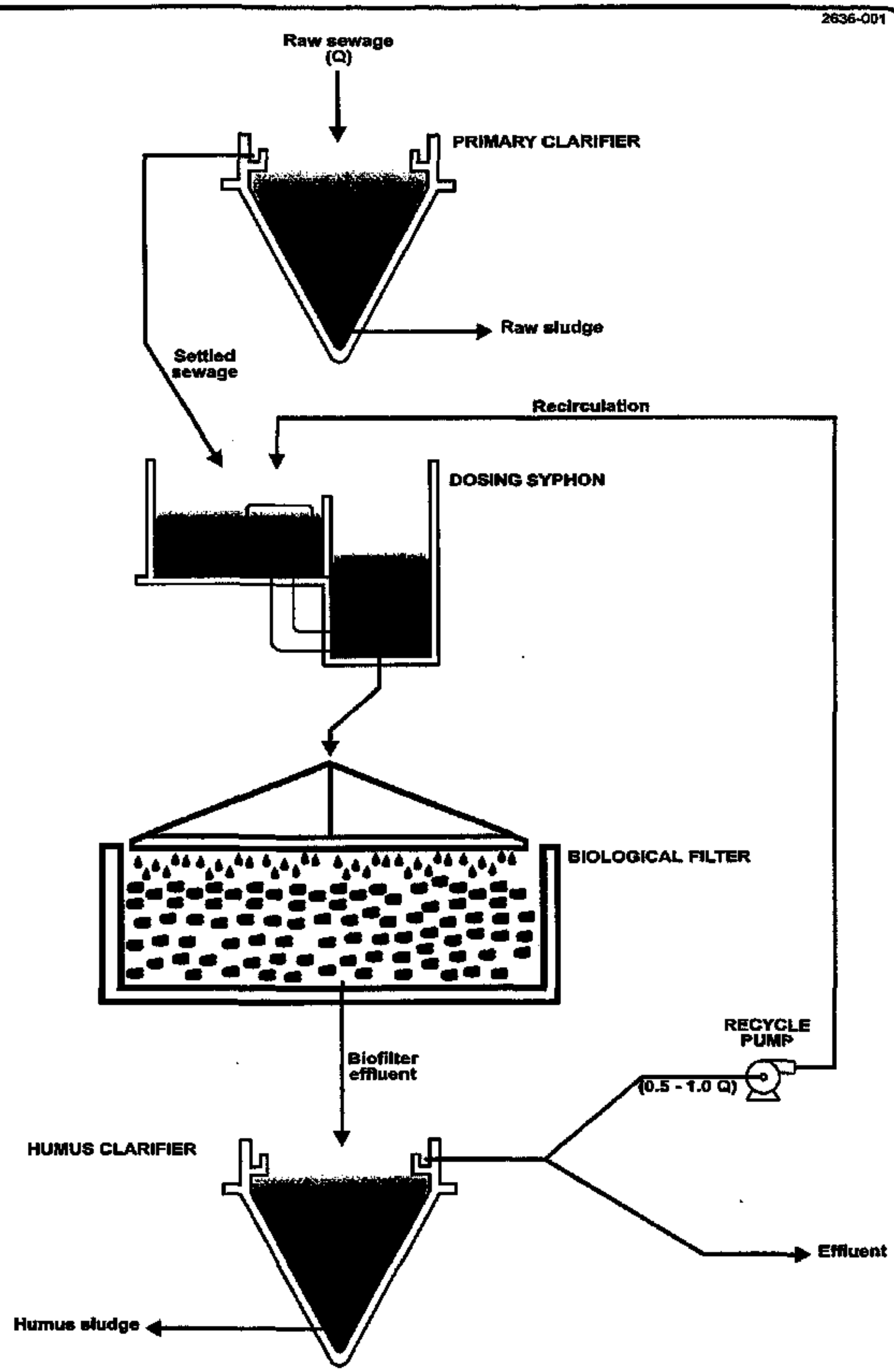

FIGURE 2.1 : PROCESS FLOW DIAGRAM OF CONVENTIONAL BIOFILTRATION PROCESS

2.2 Biofiltration solids contact process

The conventional biological filtration plant typically produces a relatively turbid effluent, albeit within the General Effluent Standard (Water Act 54 of 1956) of less than 25 mgSS/l . The effluent turbidity is ascribed to the presence of finely divided and colloidal particles contained in the effluent. The BFSC process attempts to remove the residual small and colloidal particle fraction by enhanced bioflocculation. The humus sludge itself is used as the bioflocculation agent and is recycled on a continuous basis from the final clarifier underflow to an aerated solids contactor. The biofilter effluent containing the residual humus solids is then contacted with the recycled humus sludge in an aerated environment. Provision for adequate contact time at an optimal level of mixing by diffused aeration is effective in flocculation of humus solids and enhances effective solids separation in the downstream final clarifier. The final effluent from this process modification then contains a clear effluent which resembles the typical effluent from an activated sludge plant. The generic BFSC process configuration is shown on **Figure 2.2.**

A sludge culture is effectively built up in the solids contact reactor and final clarifier with periodic wasting of excess sludge. Previous work on the application of the biofiltration solids contact process to high rate filters has also confirmed the additional removal of carbonaceous compounds in the solids contact reactor. The main benefit of the solids contact process under South African conditions is, however, related to the improved removal of suspended humus solids and the production of a very clear plant effluent.

The process has also found application in biological filtration plants which perform chemical phosphate removal. Plant scale information collected at the Krugersdorp Percy Stewart water care works indicated that the use of an iron salt could be decreased by 20 - 30 % after implementation of the biofiltration solids contact process (Duvenhage, 1994). The improved efficiency of chemical usage is ascribed to the recycling of available iron compounds from the clarifier underflow to the biofilter effluent.

In the South African context, the biofilter in the BFSC process would still have to be designed for oxidation and removal of carbonaceous and nitrogenous compounds. This would imply the use of conservative design criteria for the sizing of biological filters to achieve nitrification in the cold winter months.

2.3 Biofiltration with high rate recirculation process

The biofiltration process with a high rate recirculation is a relatively simple modification of the conventional biofiltration process. It involves the implementation of direct recirculation at relatively high rates around the biofilter. One of the first such full scale installations in South Africa was constructed at the Sundumbele plant in KwaZulu/Natal.

The concept of high rate recirculation around a biofilter was motivated by the observation of poor flow distribution across the biofilter media and ineffective use of the available media surface area, especially in the case of natural rock media. High rate recirculation keeps the biofilter distribution mechanism in motion and thereby reduces the endogenous period between dosing events which could be quite long in the conventional biofilter process configuration. The typical process configuration for the high rate recirculation is shown on **Figure 2.3.**

Recirculation around a biological filter has also been claimed (du Toit, 1995) to improve the nitrification efficiency of the process. The improved nitrification is presumably due to the reduced concentration of carbonaceous compounds which produces a benefit to the nitrifying bacteria which are in competition for the available oxygen with the heterotrophic microbes.

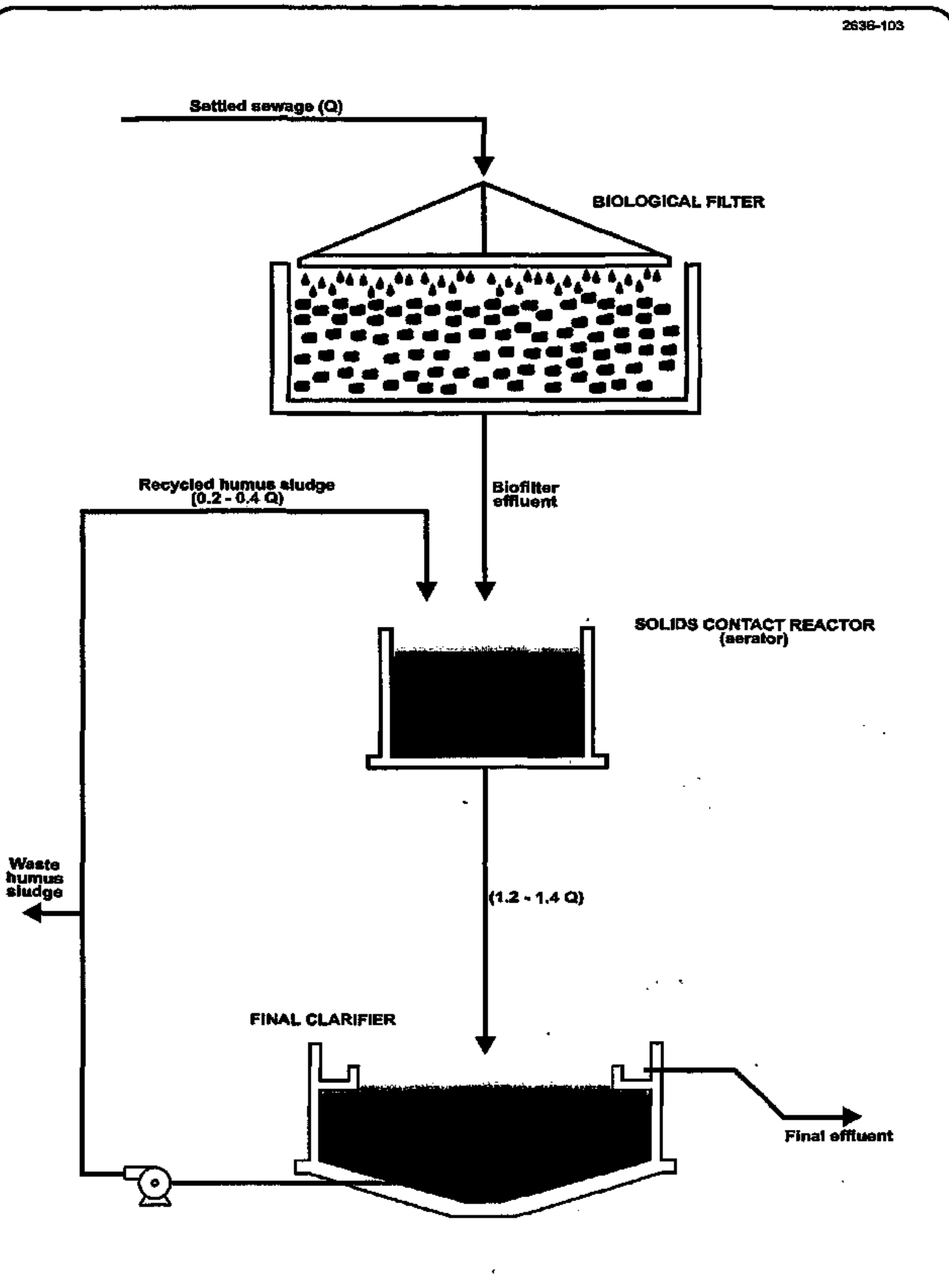

FIGURE 2.2 : PROCESS FLOW DIAGRAM OF BIOFILTRATION SOLIDS CONTACT PROCESS

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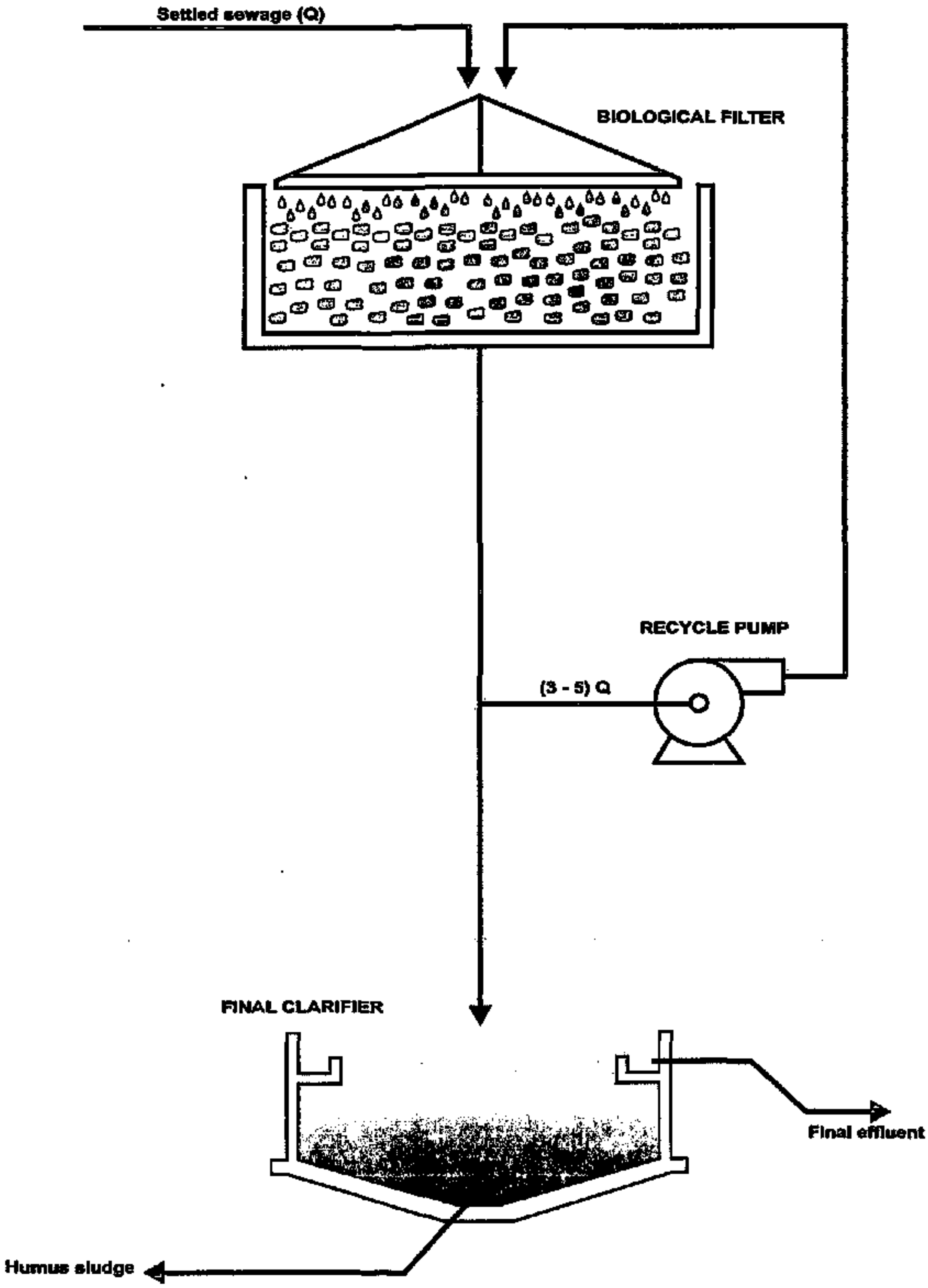


FIGURE 2.3 : PROCESS FLOW DIAGRAM OF BIOFILTRATION WITH HIGH RATE RECIRCULATION

2.4 Pond enhanced biological filtration (PETRO) process

The PETRO process typically involves the use of an anaerobic pond for the removal of the bulk of suspended solids and a substantial part of the carbonaceous compounds in the influent raw sewage. Some nitrogen removal can also be achieved depending on the pond configuration. The anaerobic pond effluent flow is then typically split between downstream oxidation ponds and a biological filter. The algal rich oxidation pond effluent is blended back with a fraction of the anaerobic pond effluent before biofiltration. The PETRO process can achieve a final effluent quality which reliably meets the General Standard of the Water Act 54 of 1956.

Pond systems have found widespread use in especially rural parts of the country serving smaller communities. Pond systems are attractive from a low maintenance and low operational cost perspective and produce a high-quality effluent. The high algal content, as reflected in elevated suspended solids concentrations in pond effluents, may however restrict the discharge of effluent to a public stream. Pond systems also operate well in the relatively warm South African climatic conditions. The pond enhanced biological filtration process integrates the biological filtration and oxidation pond processes. Numerous process configurations have been applied in the upgrading of pond systems using biological filtration. **Figure 2.4** shows a typical process configuration which integrates an anaerobic pond, an oxidation pond and biological filter.

Current research is continued into the further enhancement of the biological filtration system to remove suspended algal cells, enhance residual carbonaceous compound removal and to achieve reliable nitrification (Meiring *et al*, 1995). The work is conducted to find the optimal combination of pond size and biological filter capacity. The research specifically attempts to optimise the bioflocculation of algal cells which takes place in a biological filter with the correct blend of oxidation pond effluent and carbon rich anaerobic pond overflow. Several full scale PETRO process plants have been installed in South Africa and the potential for future application is significant. The PETRO process has been patented by the original developer.

2.5 Integrated biological filtration activated sludge process

The integrated biological filtration activated sludge process attempts to find an optimal combination of carbon removal in a biofiltration process with nitrogen removal in a downstream activated sludge process. The combination therefore enhances and optimises the strong features of the biofiltration and activated sludge processes respectively. Fixed film processes are in general very effective and economically attractive for the removal of the carbonaceous compounds contained in domestic sewage and industrial effluent. Fixed film processes are, however, less reliable in achieving nitrogen removal, due to the inability to control the nitrifier growth rate. The activated sludge process, on the other hand, is much more flexible in this regard and can be effectively controlled to achieve reliable nitrogen removal.

The carbon removal capacity of biological filters has in general been under-utilized in the conventional biofiltration process. The conventional biofiltration process employs carbon loading rates in the range of 250 - 300 $gCOD/m^3/day$. This loading rate is among other things dictated by the need to achieve nitrification in the same biofilter. A biological filter specifically designed for carbon removal can achieve 75 - 85 % carbon removal at loading rates in the range 750 - 1000 $gCOD/m^3/day$. **Figure 2.5** shows a typical process configuration for the integrated process.

The downstream activated sludge process acts as a polishing step to remove any residual carbon and to remove nitrogen by nitrification and denitrification. A fraction of the settled sewage may be bypassed to the activated sludge process to provide sufficient carbon for effective denitrification. The downstream activated sludge process is relatively small, since the carbon load is low and field observations on full scale plants have indicated that the sludges generated in these systems settle very well and do not suffer from bulking problems.

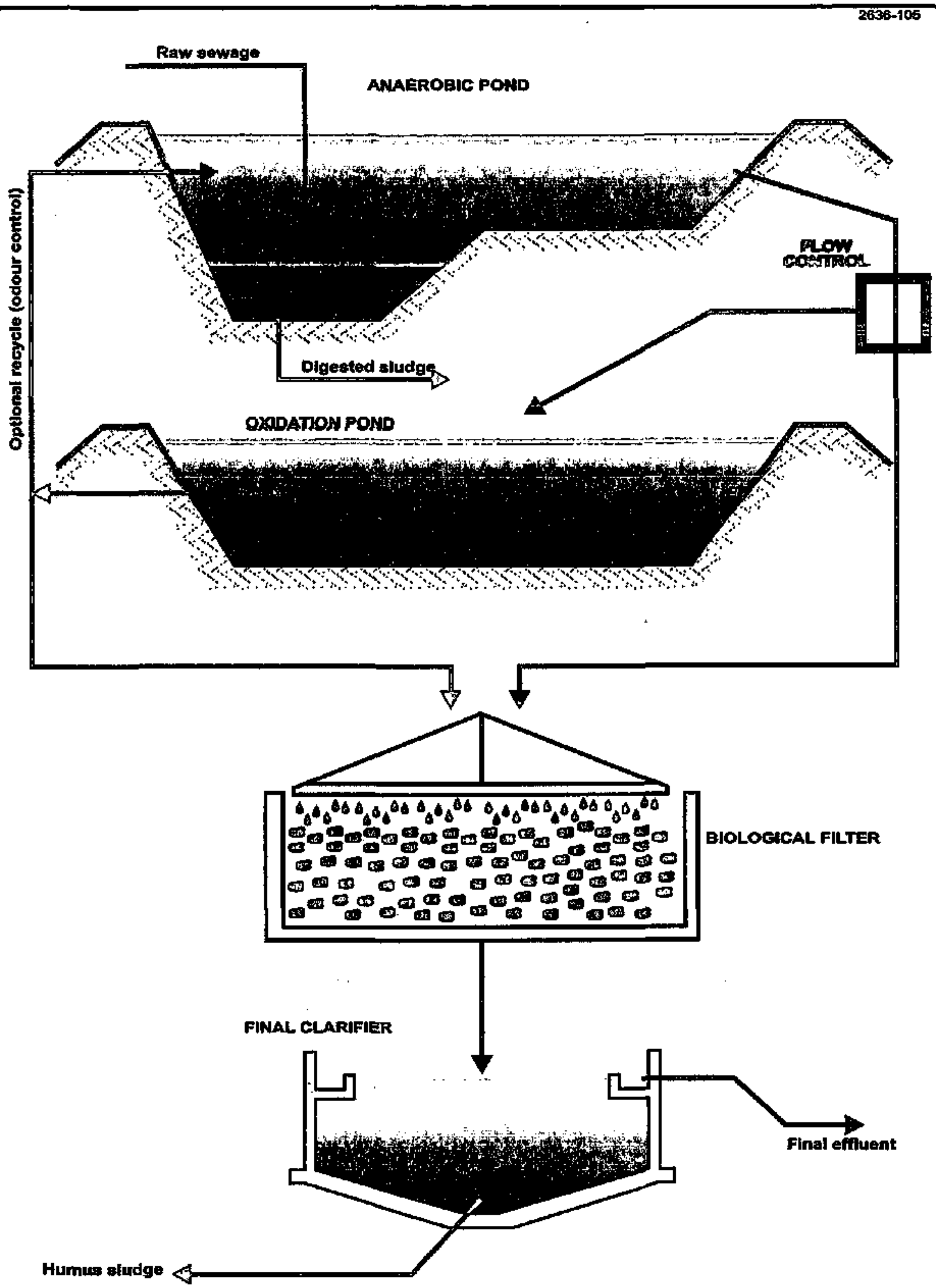


FIGURE 2.4 : PROCESS FLOW DIAGRAM OF POND ENHANCED BIOLOGICAL FILTRATION (PETRO) PROCESS

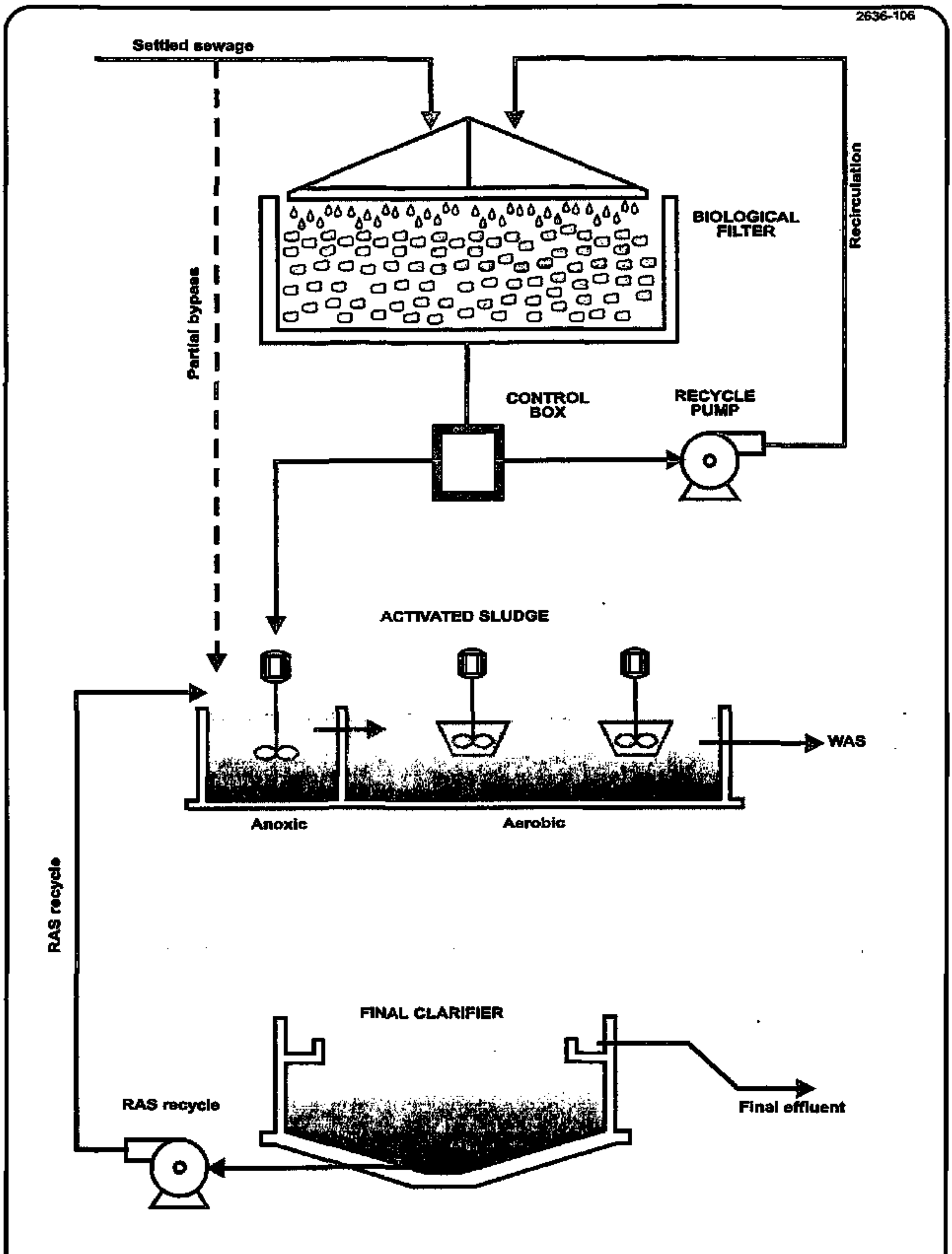


FIGURE 2.5 : PROCESS FLOW DIAGRAM OF INTEGRATED BIOFILTRATION ACTIVATED SLUDGE PROCESS

3 LITERATURE REVIEW

3.1 General process description

The general term biological filter refers to a large number of different reactor types which incorporate a fixed biological film growing on a stationary medium/support. Compounds in wastewater are modified in the migration across the fixed film by processes of adsorption, absorption and biological oxidation.

Biological filters are typically classified (Metcalf & Eddy, 1991) as low rate, intermediate rate or high rate:

- Low rate filters receive a hydraulic load of 1 - 4 m^3/m_f^2/day and an organic load of 120 - 480 $gCOD/m_f^3$/day. Rock media filters are commonly used. Low rate filters can produce a well stabilised and nitrified effluent. The filter is typically used as the main treatment process to achieve a low COD (≤ 75 mg/ℓl) and ammonia effluent (≤ 10 mg N/ℓ).
- Intermediate rate filters receive a hydraulic load of 4-10 m^3/m_f^2/day and an organic load of 480-960 $gCOD/m_f^3$/day. It is popular to use natural rock filter media or packed synthetic filter media. Intermediate rate filters remove the bulk of the organic carbon compounds, but do not reliably produce nitrification. The intermediate rate filters can be used in applications where a nitrified final effluent is not required or a further downstream treatment process oxidizes the residual ammonia.
- High rate filters receive a hydraulic load of typically 10-40 m^3/m_f^2/day and a corresponding organic load of 800-9600 $gCOD/m_f^3$/day. Synthetic media filters are almost exclusively used in high rate applications. High rate filters are typically employed to remove a substantial part of the wastewater organic load. The high rate filter effluent will however require further downstream treatment, before discharge to a public stream.

3.2 Hydrodynamic aspects of biofiltration

Recirculation is commonly employed to improve the performance of biological filters. The increased effective hydraulic load due to recirculation improves the liquid distribution and reduces the likelihood of dry or partially wetted filter media surfaces. It also helps to slough excess biogrowth due to the increased shear action and recycles some biomass to assist in the microbial stabilisation of the influent flow.

In general, it would appear that the biofilter carbon removal per unit media volume (m^3) will improve as the depth of the filter increases. This phenomenon is linked to the improved hydrodynamics and better flow distribution at the high surface loading rates associated with deeper filters. For vertical fully corrugated (VFC) media, the minimum depth for optimal performance was 3,2 m (hydraulic loading rate of 44 m^3/m_f^2/day) in a study conducted by Dow Chemical Company (1964).

Galler and Gotaas (1964) found that recirculation in excess of 4 : 1 does not materially increase the filter efficiency and is not generally considered to be economical. Recirculation of biofilter effluent could improve the biofilter performance due to one or a combination of factors:

- organic compounds come into contact with the active biofilm more than once, although the contract time may be shortened by increased recirculation.
- the bioreactor is also continuously reseeded by micro-organisms contained in the filter effluent. The biological action of the fixed film is therefore augmented by a suspended biomass.

- recirculation can dampen organic concentration peaks and can dilute very concentrated feed concentrations. Peak loads and high concentrations may be detrimental to the biofilter performance, especially in the upper media layers.
- increased hydraulic load on a filter will result in more effective wetting of the biofilter media and more active wetted surface will be able to support biolife.

The hydrodynamic conditions in a packed bed biofilter have an influence on the process performance. Kong (1979) demonstrated that the organic and hydraulic loading rates on a biofilter determined the solids retention and by implication the sludge age of a biofilter culture. Optimum carbon removal was achieved at an effective biomass sludge age in excess of 12 days.

The wastewater dosing frequency also has a significant impact on biolife and the composition of the microbial population in a biofilter. Tomlinson and Hall (1955) demonstrated that rock biofilters perform better at lower frequency of dosing. The improved performance may also be related to improved flushing, thus removing excess biomass and maintaining a healthy and thin biofilm (Albertson, 1989).

The optimum dosing rate is defined in terms of a German concept of "Spülkraft":

$$SK = Q(1 + r)\ 1000/(60\ a.n) \qquad (3.2.1)$$

where:

Q	=	influent hydraulic load ($m^3/m^2/hr$)
r	=	recycle ratio (R/Q)
a	=	number of distributor arms (#)
n	=	rotational speed of distributor arms (r.p.m.)

SK-factors of 20 - 50 mm/pass are now recommended for optimal functioning of natural rock biofilters.

The hydrodynamic regime in a rock medium filter determines the wetting efficiency. The wetting efficiency is defined as:

$$Aw/As \qquad (3.2.2)$$

where:

Aw	=	wetted media surface (m^2/m_f^3)
As	=	total media surface (m^2/m_f^3)

Crine *et al.* (1990) indicated that the wetting efficiency of randomly packed rock media may be as low as 0,2 - 0,6.

The benefits of recirculation on synthetic biofilter media were observed up to a hydraulic rate of 44 m^3/m_f^2/day. The carbon removal in the filter did not improve much beyond this surface hydraulic load. The threshold hydraulic loading rate is also sensitive to the specific type of synthetic media. The threshold value for effective and optimal wetting of natural rock media biofilters is not well known.

3.3 Filter media

A large variety of substances can be used in the construction of filter media, including gravel, stone, bricks, slag, shells, tin cans, wooden slats, moulded plastic and plastic sheets.

In South Africa, natural stone is readily available and will, in most cases, still be the most economical.

Typical rock media properties from the WEF Design Manual (1992) are summarised hereunder in Table 3.1.

Table 3.1 : Typical biofilter rock media properties

Size (mm)	Density (kg/m_r^3)	Specific surface area (m^2/m_r^3)	Porosity (m^3/m_r^3)
25 - 75	1 440	60	0,50
50 - 100	1 600	45	0,60

3.4 Removal of carbonaceous compounds in biofilters

Many different empirical expressions have been developed to predict the carbon removal capacity of rock biofilters. These expressions are usually based on analysis of experimental data to include a number of variables which may affect biofilter performance. Expressions are also typically based on limited calibration for different types of wastewater, operating conditions and biofilter media types, and cannot universally predict the actual performance of any biofilter.

A number of mathematical expressions have in the past been used to predict the carbon removal performance of biofilters. These traditional formulae are, however, typically expressed in terms of total BOD or the 5-day BOD concentrations. The different formulae take the organic loading and hydraulic loading aspects into account to varying degrees:

- **NRC (1948) formula for stone media:**

$$Ce/Co = 1/[1 + Knrc\,(W/VF)^{0,5}] \quad (3.4.1)$$

where:

Ce	=	settled filter effluent BOD_5 concentration (mg/l)
Co	=	total filter influent BOD_5 concentration (mg/l)
W/V	=	organic loading per unit biofilter volume (kg BOD/m_r^3/day)
F	=	effective number of filter passes
	=	$(1 + r) / [1 + (1 - p)\,r]^2$
r	=	recycle ratio = R/Q
p	=	empirical weighing factor (0,9)
Knrc	=	empirical constant

The NRC formula is specific to relatively high strength domestic sewage (research was conducted on US military installations) and no temperature dependency was considered.

- **British Manual of Practice formula (1988):**

$$Ce/Co = 1/[1+K_b.\Theta^{(t-15)}.As^m/Qs^n] \quad (3.4.2)$$

where:

K_b	=	empirical rate constant

Θ	=	temperature correction coefficient
t	=	wastewater temperature (°C)
As	=	specific filter media area (m^2/m_f^3)
Qs	=	*hydraulic loading rate* (m^3/m_f^2/day)
n, m	=	empirical constants

The expression was specifically developed for strong domestic sewage, with settled BOD_5 = 360 mg/l and the original researchers stressed the importance of slow biofilter distributor rotational speeds (high SK-factors)

- **Velz equations and variations thereof:**

Velz (1948) was the first researcher to attempt the use of a more fundamental approach to describing the carbon removal in a biological filter. He developed the expression:

$$\ln [Ce/Co] = -K_v.D \quad (3.4.3)$$

where:

K_v	=	first order rate constant (1/day)
D	=	filter depth (m)

The rate constant is however sensitive to a number of hydrodynamic factors, wastewater properties and operational conditions. A rate constant of K_v = 0,150/day at 20°C is commonly used in practice. The maximum recorded organic load according to the Velz equation is approximately 10 kgCOD/m_f^2/day at 30° C (Velz, 1948).

Schlutze (1960) modified the Velz equation by postulating that the retention (contact) time in a filter is proportional to the hydraulic loading rate:

$$T = C_s.D/Q_s^n \quad (3.4.4)$$

where:

T	=	contact time (mins)
C_s	=	constant
D	=	filter depth (m)
Qs	=	hydraulic loading rate (m^3/m_f^2/day)
n	=	filter media constant

The contact time expression was then incorporated into the Velz equation to yield:

$$\ln [Ce/Co] = - K_v.D/Q_s^n \quad (3.4.5)$$

The rate constant would still be a function of wastewater characteristics, filter depth, media type, media configuration, temperature, ventilation, operating conditions, etc.

Eckenfelder (1963) further modified the Velz equation to account for recirculation across the filter:

$$Ce/Co = \exp[- K_v.D/Q_s^n]/[(1 + r) - \exp(-K_v.D/Q_s^n)] \quad (3.4.6)$$

where:

K_v = rate constant

- **Galler and Gotaas** (1964) developed a multiple regression equation between biofilter carbon removal and a number of physical and operating variables:

$$Ce = [K(Q.Co + R.Ce)^{1,19}]/[(Q + R)^{0,78}(1 + D)^{0,67}\, r^{0,25}] \qquad (3.4.7)$$

where:

Q = influent flow rate

R = recirculation flow rate

r = filter radius

t = temperature

K = filter constant

= $[0,464(43560)/\pi]^{0,13}/[Q^{0,28}\, t^{0,15}]$

The multiple regression equation was developed for stone biofilters, treating predominantly domestic wastewater. They further indicated that the practical upper limit to recirculation was R/Q = 4, beyond which little further improved carbon removal was observed.

In general, below a certain minimum wetting rate, it was found for **synthetic media** filters that the carbon removal rate constant varies with depth as:

$$k_1/k_2 = [D_2/D_1]^{0,5} \qquad (3.4.8)$$

Extrapolation of rate constant, k, determined at one filter depth to another filter depth should be done with correction for the different depth.

At higher hydraulic loading rates (≥ 1 m^3/m^3 filter/day) and organic loading rates (≥ 500 gCOD/m_f^3/d) it would appear that the carbon removal per unit volume of filter media (gCOD removed/m_f^3/day) is independent of depth (WEF Design Manual, 1992). This observation was confirmed for synthetic media filters, but the application to rock filters is not confirmed (Bruce and Merkens, 1970). The kinetic constant, k, determined on one filter configuration can therefore be extrapolated to a different depth (D) and waste strength (C) by the expression:

$$k_2 = k_1\,(D_1/D_2)^{0,5}(C_1/C_2)^{0,5} \qquad (3.4.9)$$

The normalised value for domestic wastewater at a synthetic media biofilter depth of 6,1 m and an influent COD concentration of 300 mg/l is (WEF Design Manual, 1992):

$$k = 0,203\ (l/sec)^{0,5}/m^2 \qquad (3.4.10)$$

This kinetic constant applies to the situation where a minimum wetting rate of 44 m^3/m_f^2/day is achieved. The information could be applied to rock filters, but the minimum wetting rates for different types of rock filters are not well documented. Honoso (1980) has confirmed that the wetting efficiency increases with decreasing specific surface area. The minimum wetting rate for rock media filters should therefore be lower than for synthetic media filters.

Rumpf (1956) suggested a minimum surface loading rate of 19,2 m^3/m_f^2/day for effective biofilm control and regular flushing of excess humus solids from natural stone filters. He mentioned that this hydraulic loading rate must effectively be achieved at least once a day during peak flow hours.

It would appear from the literature that the fundamental variable to employ in analysing a biofilter performance is volumetric loading. The carbon removal (per unit volume of a filter) can best be related to the carbon loading rate (per unit volume of a filter) and this relationship is not dependant on the filter surface loading rate, provided that a certain minimum wetting rate is achieved - refer to **Figure 3.1** (Bruce and Merkins, 1970).

3.5 Biofilter/biofilm models

The theoretical prediction of carbon removal in biofilm reactors has mainly concentrated on low molecular mass compounds. The removal of macromolecules and particulate substrate depends on several intermediate steps of attachment, hydrolysis and decomposition to simpler lower molecular mass compounds, before final microbial metabolism. The available and proven biofilm models do not address the fate of complex substrates, but concentrates on simple soluble substrates.

The available biofilm models describe the fate of a substrate as a number of sequential process:

- transfer of substrate from the liquid film in contract with the biofilm;
- diffusion of substrate into the biofilm;
- metabolism (conversion) of the substrate;
- transfer of metabolic end products from the biofilm.

One of these sequential steps is typically the overall rate limiting step, depending on the relative rates of diffusion and metabolism. It must also be kept in mind that oxygen must be available for aerobic metabolism and the same considerations apply to the mass transfer of oxygen into a biofilm.

The mass transfer across the liquid boundary layer (**Figure 3.2**) can be described as follows:

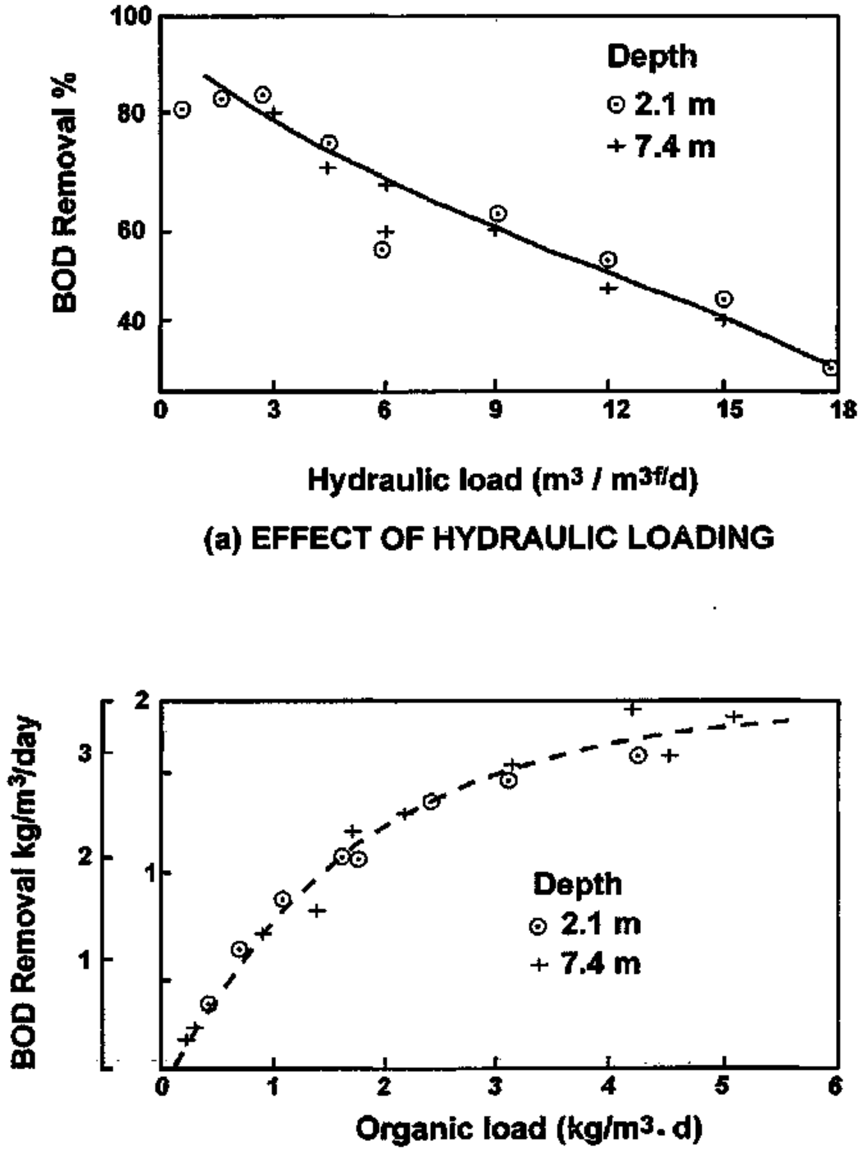
$$N = -Dw.\partial S/\partial z = -Dw/\Delta.(S_b - S_s) \quad (3.5.1)$$

$$= -k_f.(S_b - S_s)$$

where:

N	=	substrate flux ($kg/m_m^2/day$)
Dw	=	diffusion coefficient (m^2/day)
S	=	substrate concentration (kg/m^3) with subscript b referring to the bulk liquid and subscript s referring to the liquid and biofilm interface
z	=	dimension (m)
Δ	=	biofilm liquid cover thickness (m)
k_f	=	mass transfer coefficient (m/day)

A number of empirical relationships have been developed to compute the mass transfer coefficient in terms of the hydrodynamic properties of a packed bed reactor.



(b) EFFECT OF ORGANIC LOADING

FIGURE 3.1 : CARBON REMOVALS VERSUS HYDRAULIC AND ORGANIC LOADINGS OF VFC MEDIA AT TWO MEDIA DEPTHS

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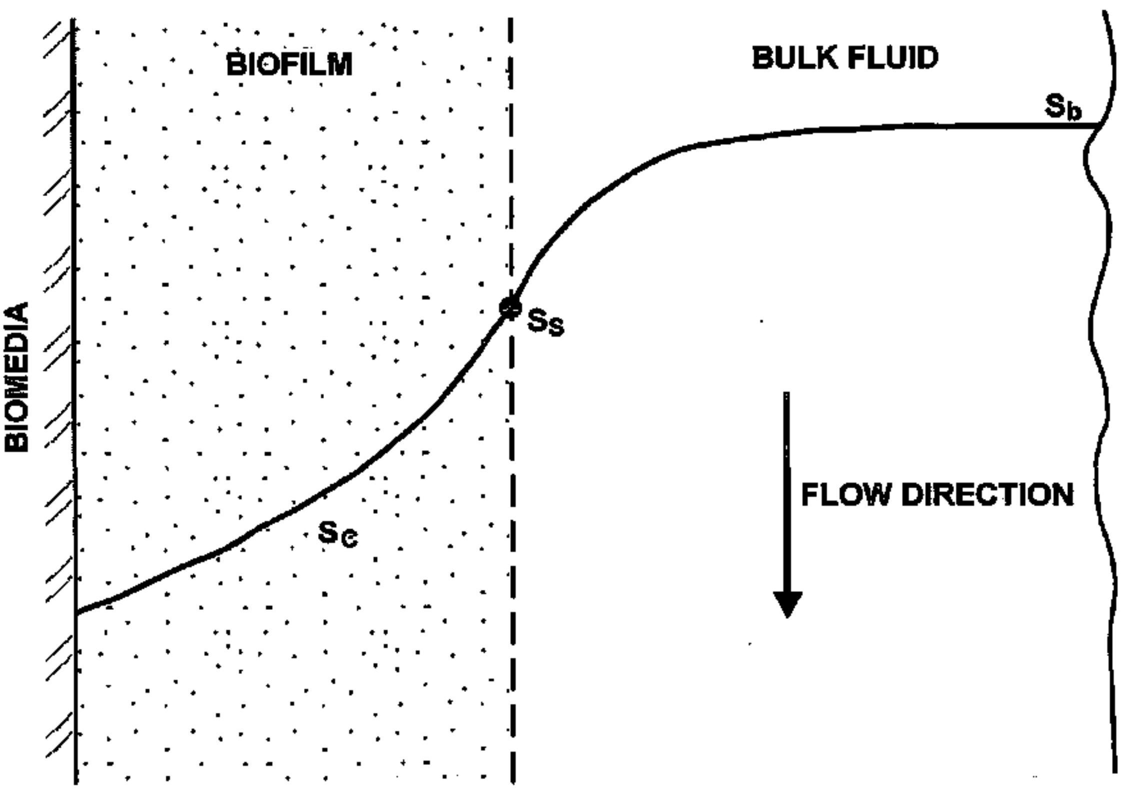


FIGURE 3.2 : PROFILE OF SUBSTRATE CONCENTRATION IN BIOFILM

The substrate diffusion into the biofilm can in general be described by the equation (Iwai and Kitao, 1994):

$$\frac{\partial S_c}{\partial t} = De. \frac{\partial^2 S_c}{\partial z^2} - M.q. \qquad (3.5.2)$$

where:

S_c	=	substrate concentration (kg/m³) with subscript c referring to the interior of the biofilm
M	=	microbial density (kg biomass/m³)
q	=	metabolic rate (kg substrate/kg biomass/day)
De	=	diffusion coefficient (m²/day)

The metabolic rate of substrate breakdown is frequently expressed in terms of the Monod equation and for **steady state conditions** then:

$$\frac{\partial^2 S_c}{\partial z^2} = M.q_m.S_c/[De(K_s + S_c)] \qquad (3.5.3)$$

where:

K_s	=	half saturation constant (mg/l)
q_m	=	maximum metabolic rate

The differential equation can be simplified for the following two cases:

for $S_c >> K_s$

$$\frac{\partial^2 S_c}{\partial z^2} = q_m.M/De \qquad (3.5.4)$$

for $S_c << K_s$

$$\frac{\partial^2 S_c}{\partial z^2} = q_m.M.S_c/(De.K_s) \qquad (3.5.5)$$

The substrate flux rate, N, can be solved for the same two cases:

- for $S_c >> K_s$, with full substrate penetration of the microbial film:

$$N = q_m.M.L. \qquad (3.5.6)$$

where:

L	=	thickness of biofilm

- for $S_c >> K_s$, with partial substrate penetration of the microbial film:

$$N = [2De.q_m.M.S_c]^{½} \qquad (3.5.7)$$

which is approximately equal to $[2De.q_m.M.S_b]^{½}$

- for $S_c << K_s$, and with full substrate penetration of the biofilm:

$$N = \frac{[De.q_m.M/K_s]^{½}.S_b}{1 + [De.q_m.M/K_s]^{½}/k_f} \qquad (3.5.8)$$

In general then, the substrate flux (uptake) is a varying function of substrate concentration. At higher bulk substrate concentrations, the substrate uptake rate is zero order (independent) of substrate concentration. At the other extreme of low substrate concentration, the substrate uptake rate becomes sensitive to the substrate concentration, at first as a partial order and later as a first order dependence.

The model developments have important implications to the substrate removal in a biofilter - refer to **Figure 3.3**. In generic terms, the substrate removal rate (per unit biofilm area) should be insensitive to substrate concentration in the upper parts of the biofilter. As the liquid becomes depleted of substrate, removal rate does become sensitive to the ambient substrate concentration in the lower parts of the biofilter.

Recirculation of the biofilter effluent would result in a more uniform and lower substrate concentration throughout the biofilter. The substrate uptake rate should however also decrease due to the relatively lower ambient substrate concentration. Overall improved substrate removal with recirculation is, therefore, the result of longer effective contact time between the wastewater and biofilm.

Iwai and Kitao (1994) have indicated that dissolved oxygen may be the rate-limiting substrate for aerobic biofilm reactors under most practical conditions. Assuming for example a bulk DO concentration of 3 mg/l, it is predicted that oxygen would be the rate-limiting substrate as long as the biodegradable COD concentration is more than 30 mg/l, or the ammonia concentration is more than 1 mgN/l.

In general the fundamental biofilm models have been useful in developing a better understanding of the fundamental aspects of biofilter operation and performance. The complex hydrodynamic conditions in a natural rock biofilter have prevented the extrapolation of the available biofilm models to reliable design models, except for simple fixed-film type reactors. Logan *et. al.* (1987) took the practical application of theoretical models a step further by integrating (with some simplifying assumptions) the mathematical description of biofilm hydro-dynamics and substrate metabolism. He confirmed his model for a relatively simple hydro-dynamic situation of vertical cross-flow moulded plastic synthetic media.

The designers and operators of biofilter treatment systems are therefore still largely dependant on quasi-empirical expressions and pilot scale investigation for specialised applications of biofiltration.

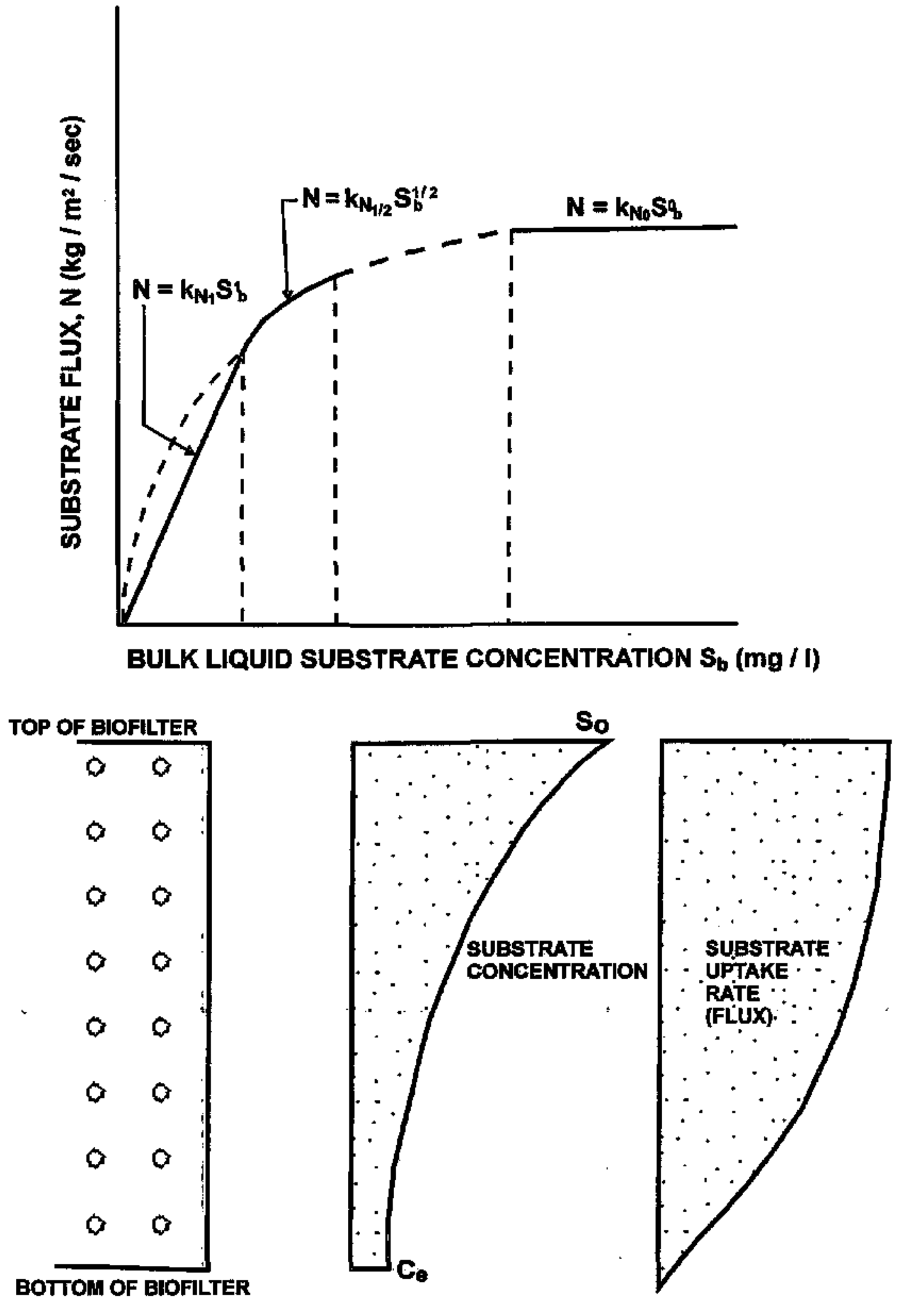


FIGURE 3.3 : SUBSTRATE FLUX DEPENDANCE ON SUBSTRATE CONCENTRATION IN THE BULK LIQUID OF A BIOFILTER

4 MATERIALS AND METHODS

The pilot scale biological filtration plant was erected at the Baviaanspoort Water Care Works, Pretoria. The motivation for the selection of Baviaanspoort was the availability of predominantly domestic sewage with a reasonable carbon concentration of 500 - 700 mg COD/ℓ. All experimental work was conducted on settled sewage of a predominantly domestic nature.

4.1 Location of pilot plant within the water care works

Raw sewage of a predominantly domestic nature enters the Baviaanspoort Water Care Works from the eastern residential suburbs of Pretoria. The pre-treatment (inlet works) consists of maceration, screening and grit removal. The pre-treated raw sewage is then treated in Dortmund-type primary clarifiers for suspended solids removal. The settled sewage quality in terms of COD concentration varied during the day as reflected in **Figure 4.1**.

The settled sewage was abstracted from a point downstream of the primary clarifiers for use in the pilot plant facility.

4.2 Pilot plant infrastructure

The biofiltration pilot plant consisted of three parallel biotowers, filled with different natural rock media sizes. The overall pilot plant process flow diagram is shown on **Figure 4.2**. The following components were utilized:

- **the inlet/division box** received the settled sewage and distributed the influent flow to each individual biofilter. The box was equipped with adjustable weirs to set the flow rate to individual filters. The box also had an emergency overflow to cater for excess flow.
- **the dosing box**, which could be used to regulate the dosing frequency to each individual filter. A control valve can be fitted to the box to accumulate and release the feed flow in a pre-determined fashion to the filters. Any recirculation of the filter effluent would enter the feed stream at the dosing box.
- **the distribution trough**, which sprayed the influent flow via 25 drilled holes (12 mm dia) onto the filter top surface (415 cm^2/hole). Each drilled hole was also equipped with an adjustable uPVC sleeve to ensure the even distribution of flow.
- **the biofilter towers** were 3,42 m high, 1,22 m diameter (1,17 m^2) and contained 4,0 m^3 stone filter media. The towers were constructed of galvanised mild steel ventilation pipes. Sampling ports were installed at three intermediate depths from the top of the filters (750 mm, 1 650 mm and 2 520 mm respectively). The sampling ports were equipped with retractable 50 mm diameter half-pipes, installed at a slight angle to allow convenient interception of samples at intermediate depths.
- **the biofilter sumps** (0,58 m^3) were conical-shaped containers, collecting the biofilter effluent flow. Each sump was equipped with a bottom outlet to the recirculation pump suction intake. The sump overflow discharged to a wastewater drain on the site of the Baviaanspoort Water Care Works.

Detailed construction drawings of the pilot plant are also contained in Appendix 1 to this report. Photographs (Appendix 2) show the general appearance of the individual components of the pilot plant infrastructure.

All experimental work on the pilot scale biofilters was conducted after an initial period of acclimatisation. The biofilters were typically operated for at least one month before any experimental data was collected.

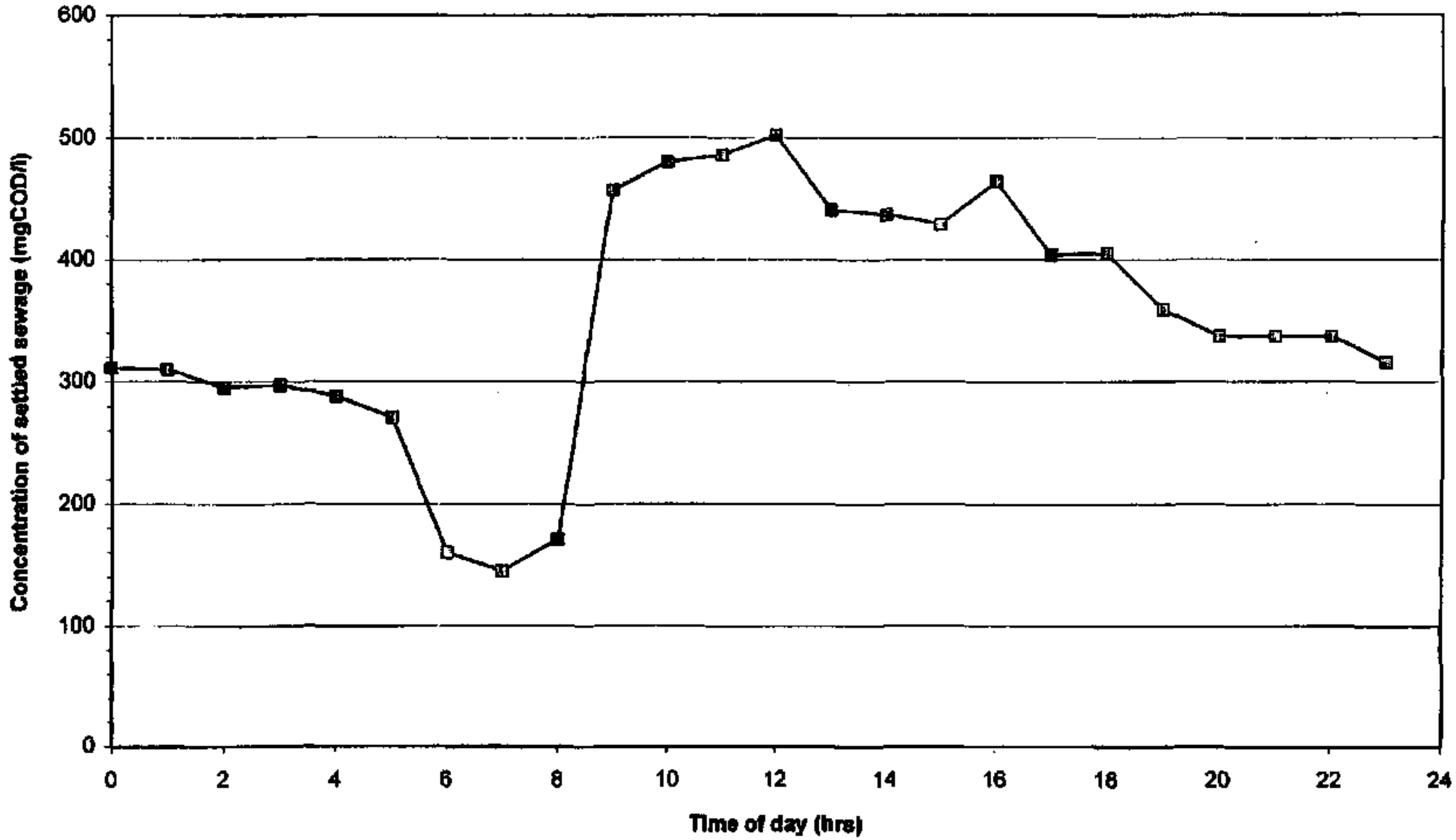


Figure 4.1 : Typical diurnal variation in settled sewage quality at Baviaanspoort Water Care Works

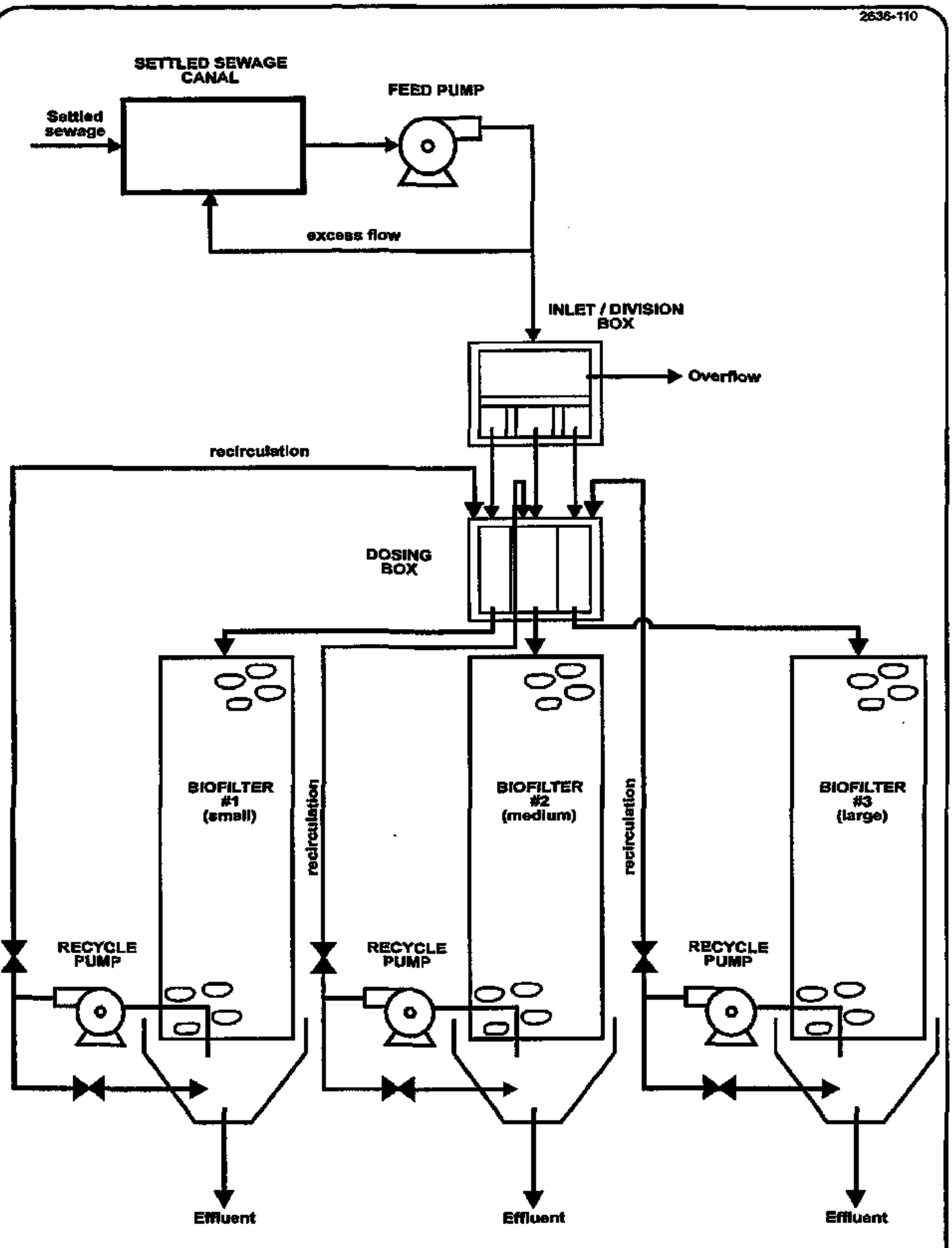


FIGURE 4.2 : PILOT BIOFILTRATION PLANT PROCESS CONFIGURATION

4.3 Filter media

The pilot plant biofilters were packed with felsite stone taken from the Derdepoort rock quarry, north of Pretoria. The filter media was washed and split into three different size fractions:

- small media size (S) = 29 - 45 mm
- medium media size (M) = 46 - 63 mm
- large media size (L) = 64 - 81 mm

The three biofilters were packed with the different size fractions. The porosity (voids fraction) of the different media size fractions was determined to all be in the range 46 – 48 %.

The estimated media surface area per unit of media volume was:

- small media size (S) = 65 m^2/m^3_f
- medium media size (M) = 55 m^2/m^3_f
- large media size (L) = 45 m^2/m^3_f

4.4 Filter feed and recirculation capacity

The settled sewage feed pump had a capacity of 125 m^3/day. At an average COD concentration of 400 mg/ℓ, if evenly distributed, this corresponds to a maximum organic load of 50 kg COD/day (4 100 gCOD/m^3/day for each filter when evenly distributed).

The recirculation pump capacities varied among the different biofilters as follows:

- small media size (S) = 265 m^3/day
- medium media size (M) = 329 m^3/day
- large media size (L) = 371 m^3/day

High recycle rates (up to R/Q of approximately 9:1) were therefore possible and feasible.

4.5 Description of tracer experiments

Tracer experiments were performed to compare the flow patterns at various depths of one filter (filter M), as well as between the different biofilter types.

The tracer (70 gNaCl/l solution) was introduced rapidly (3 seconds to pour 667 ml of tracer solution) via a ring with 8 holes in it, onto the top of the filter medium at time zero. The electrical conductivity of the biofilter effluent was measured for a period of time. The background electrical conductivity of the influent flow was subtracted from the effluent measurements, so as to develop a tracer curve.

The average hydraulic residence time (HRT) on a biofilter was determined from the equation:

$$HRT = Q/\forall \qquad (4.5.1)$$

where

Q = steady state flow to the biofilter (m^3/min)

∀ = volume of liquid draining from the biofilter after termination of influent flow (m^3)

4.6 Standard analytical techniques

Indirect measurement of the COD was employed in some of the experimental work. A correlation was developed between the spectrophotometer (at 420 nm wave length) reading and conventional COD measurement. This correlation was developed for:

- settled sewage
- settled biofilter effluent.

Figure 4.3 shows the correlation between the COD-concentration and the spectrophotometer readings for settled sewage.

Standard analytical techniques were applied to the determination of Chemical Oxygen Demand, suspended solids, ammonia, total Kjeldahl nitrogen, nitrate and nitrite (Standard Methods, 1985). The conductivity was measured using a Labotec WTW instrument. Dissolved oxygen concentrations were measured using Labotec WTW field instrument.

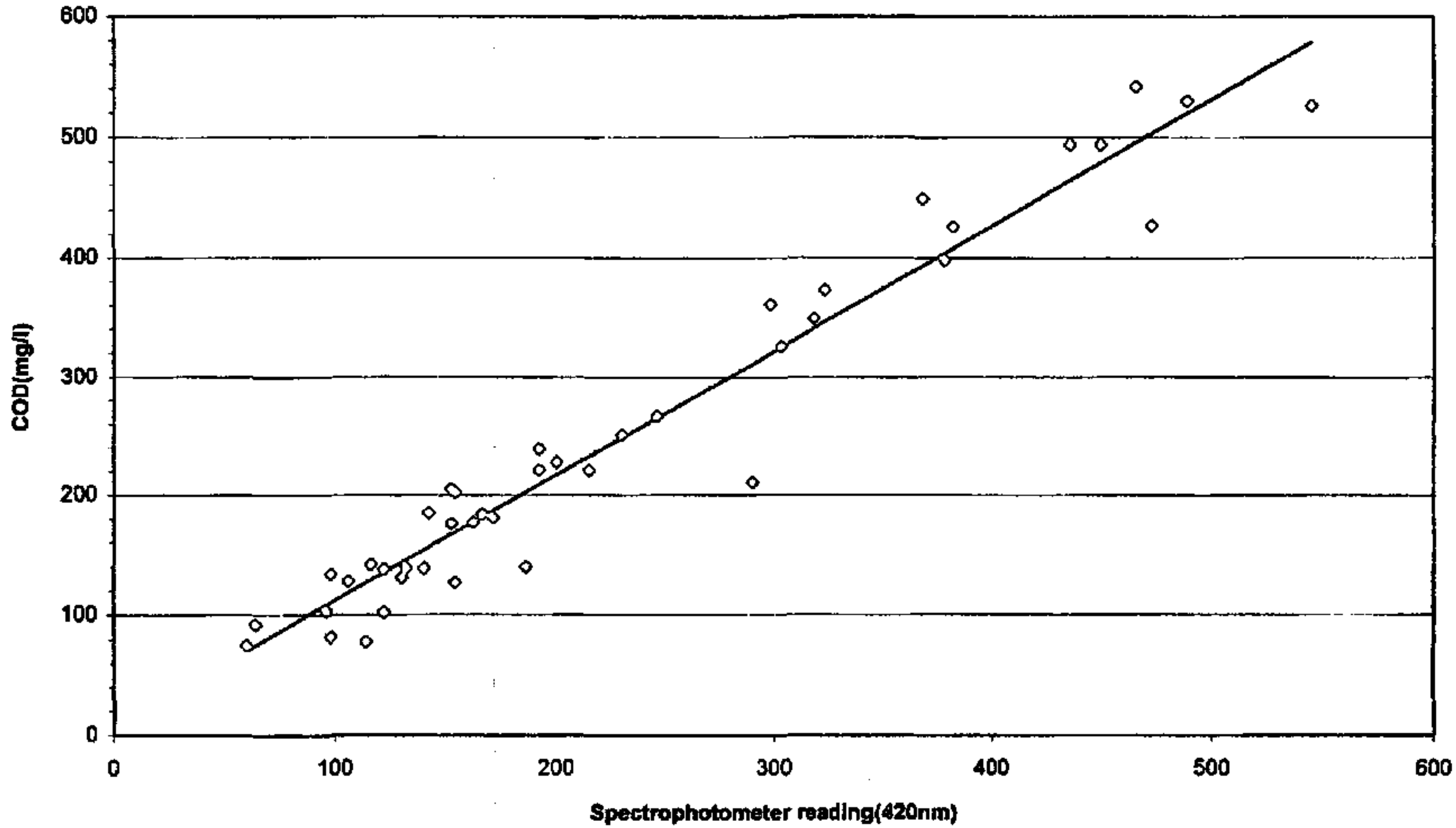


Figure 4.3: Correlation between Spectrophotometer reading and COD-concentration

5 RESULTS AND DISCUSSION - HYDRODYNAMIC CHARACTERISTICS OF BIOFILTERS

The hydrodynamic properties of a biofilter are important in determining the carbon removal efficiency. The hydrodynamic properties include the flow patterns within the filter media; short circuiting without effective wetting of the entire media surface; stagnant zones within the filter without effective flushing of the local stagnant area and advective and dispersive phenomena that influence the effective contact time between wastewater and biofilm. Collectively the hydrodynamic properties of a biofilter determine the effective contact between the wastewater and biomass (biofilm) and, therefore, play an important role in the removal/stabilisation of carbon compounds.

The pilot plant biofilters received a continuous application of wastewater and a steady state situation was, therefore, approached. This experimental arrangement allowed the convenient and simple determination of the hydrodynamic properties such as residence time distribution, liquid retention etc.

The experimental arrangement must be distinguished from the more complex full-scale situation which normally involves the intermittent dosing of wastewater to the biofilter surface. A non steady-state situation, therefore, exists on full-scale biofilters as opposed to the steady-state situation in the pilot plant biofilters. The extrapolation of pilot scale observations to full scale biofilters must, therefore, be done with caution.

5.1 Hydraulic retention time

The liquid retention (hold-up) in the biofilter was determined at several different hydraulic loading rates for each of the biofilters. The experimental results are expressed in terms of hydraulic loading rate (expressed as $m^3/m^2_f/day$) versus hydraulic residence time - refer to **Figure 5.1**. The range of hydraulic loading rates of 10 - 100 $m^3/m^2_f/day$ is high and appropriate to high rate biological filtration.

In general for a continuously fed pilot scale biofilter, it can be concluded that:

- the hydraulic residence time (HRT) is relatively short (1 - 5 minutes) compared to other biological treatment processes such as activated sludge.
- the HRT decreases as the hydraulic loading rate increases.
- the HRT increases rapidly at low hydraulic loading rates (< 5 $m^3/m^2_f/day$) and appears to approach an asymptotic value at high hydraulic loading rates (> 50 $m^3/m_f^2/day$).
- the HRT in the biofilter increases as the filter media size decreases.

The information related to liquid retention in the biofilters also gives some indication of the average liquid thickness covering the biofilm. For example, at a hydraulic loading rate (HLR) of 40 $m^3/m_f^2/day$, the corresponding average liquid film thickness, assuming 40 % wetting of the filter media, is summarised below:

Table 5.1 : Estimated liquid film thickness on pilot plant biofilters (HLR = $40 m^3/m^2_f/day$)

Stone media size	HRT (secs)	Liquid retention ($m^3 \times 10^3$)	Liquid film thickness (mm)
Small	193	105	1,0
Medium	105	57	0,7
Large	88	48	0,7

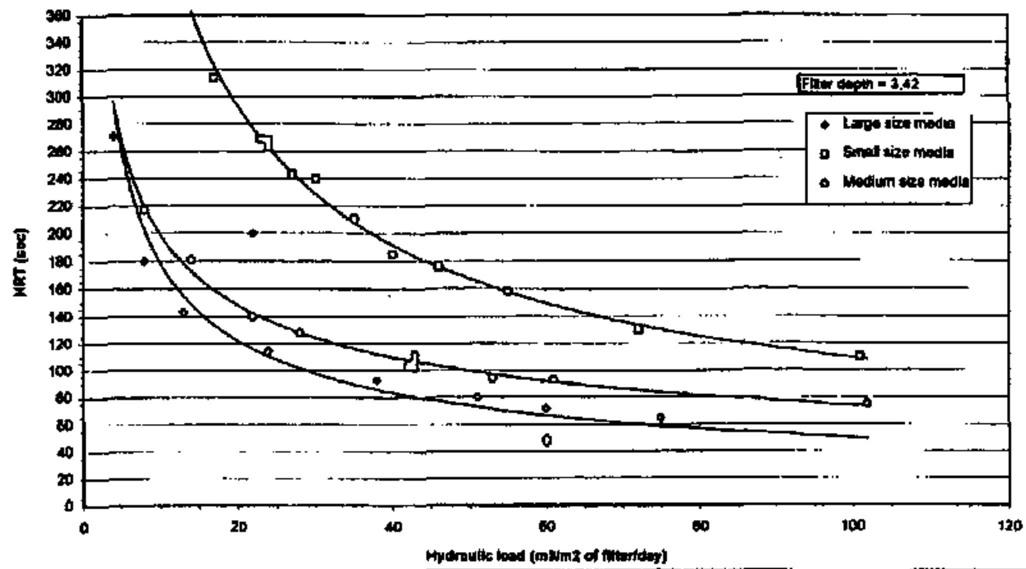


Figure 5.1: Hydraulic retention time as a function of hydraulic loading rate

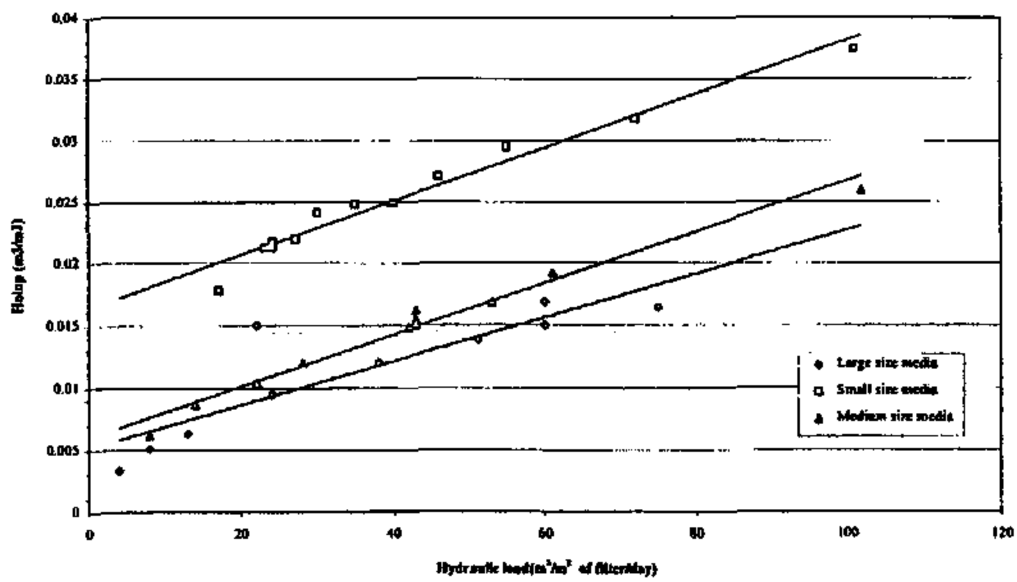


Figure 5.2 : Liquid retention in biofilter as a function of hydraulic loading rate

The average liquid thickness covering the biofilm is, therefore, very small and the mass transfer across the liquid layer should not be a limiting factor in the removal of carbon compounds.

The HRT on most filter installations in South Africa is much longer than the pilot plant biofilters, due to the lower hydraulic loading rates. The difference between pilot plant and full scale biofilter HRTs was investigated further. The measured HRTs at the Riverview Plant, Witbank and at Rondebult Plant, Germiston were compared to pilot scale observations under similar hydraulic loading rates:

Table 5.2 : Hydraulic retention time in pilot and full scale biofilters

Filter	Hydraulic loading (m^3/m^2 filter/day)	Hydraulic loading (m^3/m^3 filter/day)	HRT (mins)
Baviaanspoort pilot plant (3,4 m high)	6,0	1,75	5
Riverview, full scale (35 m dia, 3,6 m high)	6,6	2,07	15
Rondebult, full scale (31 m dia, 4,3 m high)	6,2	1,45	13

The difference in HRT between the pilot plant and the full scale biofilters can be ascribed to the different dosing techniques. The continuous, even application of wastewater to the pilot plant biofilter requires a high hydraulic loading rate to achieve effective wetting of the filter media. At the low hydraulic loading rate of 6,0 m^3/m^2 of filter/day, it is conceivable that short-circuiting and inefficient wetting can take place. This will result in a relatively short effective retention time. The intermittent application of wastewater on full scale biofilters results in a localised high hydraulic application rate, thus increasing the local liquid hold-up and resulting in a longer effective HRT. The non-steady migration of flow through the biofilter on full-scale plants, receiving intermittent dosing also contributes to the observed relatively long effective HRT. Flow through the distribution pipework and collection canals on full-scale biofilters also contributes to the observed longer HRTs.

The observation that the liquid retention (hold-up) increases with higher hydraulic loading rates is shown on **Figure 5.2**. The highest liquid retention (hold-up) for a specific hydraulic loading rate was observed for the small media biofilter. This corresponds to the longest HRT also observed for the small media biofilter. The liquid retention does, however, not compensate for the more rapid migration of liquid at higher hydraulic loading rates. The HRT therefore still decreases at higher hydraulic loading rates.

5.2 Tracer studies

Tracer studies were also conducted to further investigate the hydrodynamic nature of flow through the biological filters. A tracer study can give information on the residence time distribution in the biofilter reactor and on the dispersion phenomena associated with flow through a packed bed bioreactor.

The tracer studies on pilot plant were conducted at a hydraulic loading rate of approximately 35 m^3/m_f^2/day. The tracer patterns in the biofilter effluents are shown on **Figure 5.3** for the small size media, medium size media and large size media biofilters respectively. The residence time distribution is markedly different among the different filters. The flow through the biofilter containing large size media resembles a plug flow situation with a relatively short tracer wash-out period. The tracer flow pattern through the biofilter containing the small size media is very different. The tracer is retained in the bioreactor for a longer period of time and the wash-out takes place over a much longer period of time.

Dispersion phenomena therefore become more important as the biofilter media size decreases.

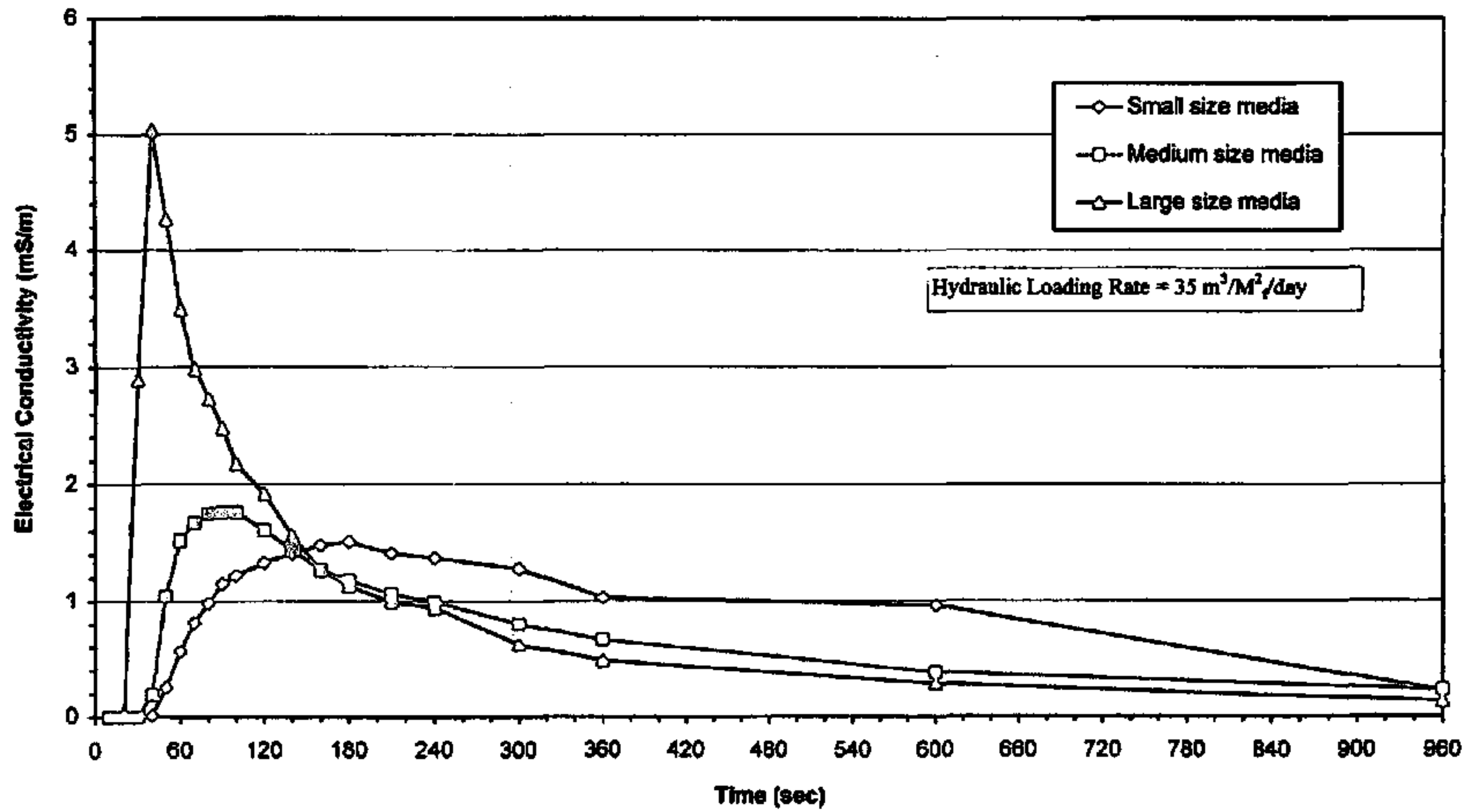


Figure 5.3: Tracer studies on pilot scale biofilters

Analysis of the tracer information was conducted using the generalised tracer equation (Huang, 1991):

$$\frac{\partial C(z,t)}{\partial t} = \frac{D\partial^2 C(z,t)}{\partial z^2} - \frac{V\partial C(z,t)}{\partial z} \qquad (5.2.1)$$

with analytical solution

$$C(z,t) = E/(\sqrt{4\pi Dt}).\exp[-(z - V.t)^2/4Dt] \qquad (5.2.2)$$

where:

$C(z,t)$ = tracer concentration at time t and at location z (mg/l)

E = initial tracer concentration (mg/l)

D = effective dispersion coefficient (m^2/sec)

V = linear flow velocity (m/sec)

The analysis of the tracer studies results using the general analytical solution revealed that the following parameters apply to the different experimental filters:

Table 5.3 : Tracer migration parameters for different pilot scale biofilters

	Small media	Medium media	Large media
D (m^2/sec)	0,014	0,009	0,007
V (m/sec)	0,010	0,025	0,049

The smaller media size resulted in a higher effective dispersion of the tracer molecules, presumably due to the more tortuous flow path and the more effective retention and subsequent slow release from stagnant pore spaces.

The **median** residence time in each filter was calculated from the tracer information and compared with the derived residence time, based on liquid hold-up information (refer to Section 5.2 of this report). The calculated residence times apply to a hydraulic surface loading rate of 35 m^3/m^2/day:

Table 5.4 : Comparison of residence time estimates on the basis of liquid hold-up and tracer measurements

Biofilter	Residence time (sec)	
	Liquid hold-up	Tracer movement
Small size media	210	300
Medium size media	115	270
Large size media	95	180

The residence times for a specific biofilter calculated using the liquid retention approach and using the tracer movement approach differed. The residence time calculated on the basis of the tracer information reflects the diffusion into and out of the biofilm. This is something which is not reflected in a residence time calculated on the basis of purely hydrodynamic considerations. The latter approach would therefore show a shorter residence time.

The information based on liquid hold-up indicated that the medium size media biofilter and the large size media biofilter have similar hydrodynamic properties. The tracer studies however indicated that significant shortcircuiting takes place in the large media size biofilter. The tracer migration patterns for the medium size and small size media biofilters were similar.

It must be kept in mind that the tracer information can mainly be interpreted in terms of the migration of soluble carbon compounds and may not apply to colloidal and particulate matter.

The effective residence time in a biofilter reactor is very short compared to other suspended growth reactors. There is, however, a wide distribution of actual residence times, depending on the specific flow path followed and the effect of diffusion into and from the biofilm covering the filter media.

The tracer movement pattern also changes over the biofilter depth as shown on **Figure 5.4**. The specific tracer study work on the medium size stone biofilter was conducted at a hydraulic loading rate of 20 m^3/m^2/day. The increasing influence of dispersive phenomena with increasing depth of biofilter is shown clearly on the tracer washout curve.

Tracer studies were also conducted at full scale on the Riverview Water Care Works, Witbank. The full scale filters were 35 m diameter, contained a 3,6 m high filter media bed and received a hydraulic load of 6,6 m^3/m^2/day. The SK-factors or the two filters were in the range 2 - 3 mm/pass. The filters contained a natural rock media in the size range 50 mm to 70 mm - refer to **Figure 5.5**.

The full scale tracer results reflect the combined influence of flow through the distribution pipework, migration through the biofilter media and flow through the biofilter effluent collection system. The residence time in the distribution pipework and in the effluent collection system is, however, short compared to the flow through the biofilter itself. The shape of the residence time distribution curve on the full scale filter is similar to the pilot plant medium media size. The reasons for the relatively long hydraulic residence time observed on the full scale biofilters are presented in **Section 5.1** of this report.

5.3 General conclusions

In general, the tracer studies confirmed the complex flow pattern through a natural rock media biofilter. The complex hydrodynamic characteristics have to be taken into account in any attempt to model or predict biofilter performance and behaviour. The conclusions based on the investigation into the hydrodynamic properties can be summarised as follows:

- the HRT in biofilters is relatively short compared to other types of biological reactors. The available information can be related to the migration of soluble substrate compounds. The situation with respect to colloidal and particulate substrates may be even more complex and cannot be deducted from the available tracer information.
- dispersion due to the tortuous nature of biofilter flow paths plays an important role in soluble substrate migration. This has to be taken into account in any attempt to model biofilter performance.
- the HRT in biofilters receiving an intermittent dose of wastewater is substantially longer compared to a biofilter receiving a continuous, even application of wastewater. The difference can be ascribed to the transient nature of liquid application and the increased liquid hold-up at high local hydraulic loading rates.

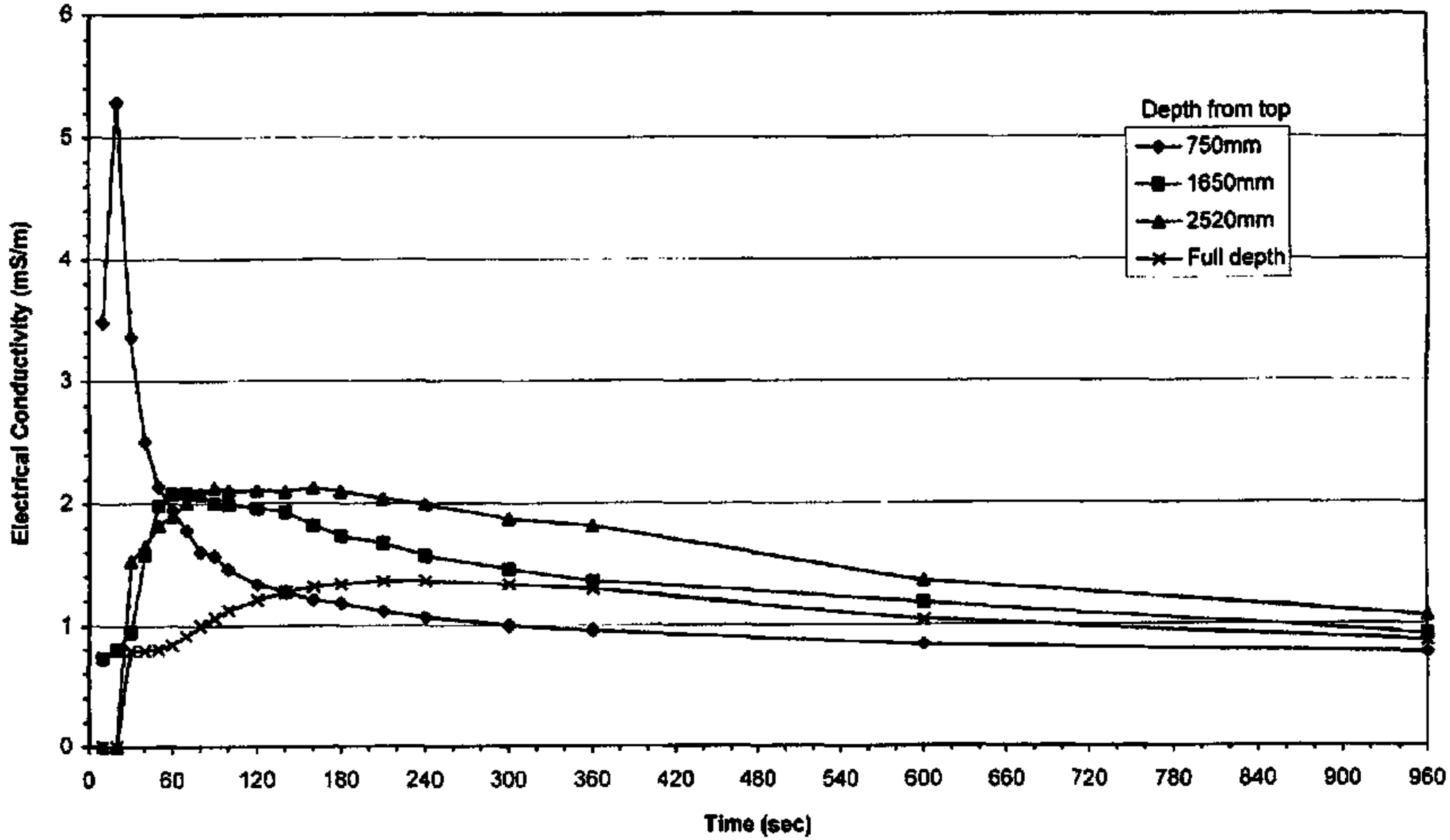


Figure 5.4 : Tracer studies on medium size biofilter at different depths

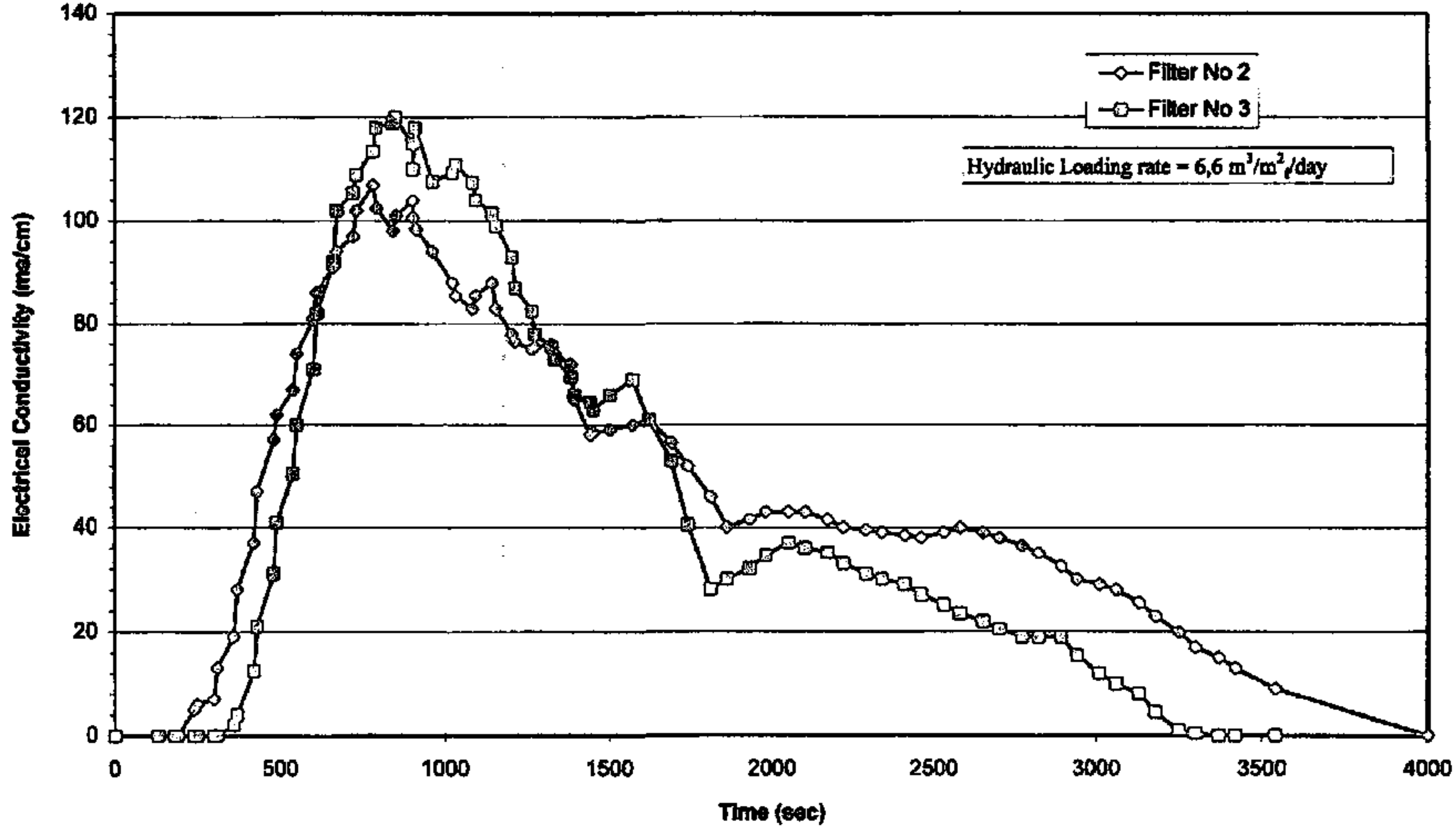


Figure 5.5 : Tracer curves on full scale Biofilters at Riverview Sewage Treatment Plant,Witbank

6 RESULTS AND DISCUSSION - CARBON REMOVAL IN HIGH RATE BIOLOGICAL FILTERS

The removal of carbonaceous compounds in a high rate biofilter was of primary interest to this research project. It must be kept in mind that the pilot plant biological filters received a continuous wastewater application, unlike full scale biofilters which receive an intermittent dose of wastewater. The extrapolation of the pilot plant results to full-scale biofilters must be done with caution.

Removal of carbonaceous compounds by the biofilter was based on the following equation:

$$E = Q.[C_o - C_e]/V \quad (6.1)$$

where:

E = carbon removal ($gCOD/m_f3/day$)

Q = settled sewage feed flow (m^3/day)

C_o = settled sewage total COD-concentration (mg/l)

C_e = settled (30 mins) biofilter effluent COD-concentration (mg/l)

V = biofilter volume (m^3)

6.1 Carbon removal at high loading rates

The hydraulic load on the biofilters was kept fairly constant within the range of 30 – 40 $m^3/m^2f/d$, while the organic load (in units of $gCOD/m^3/d$) was allowed to vary as the influent wastewater COD-concentration varied. The general carbon removal properties of each type of biofilter are depicted on **Figure 6.1 to 6.3**. The range of experimental carbon loading was substantially higher than the conventional application for natural stone biofilters. The biofilters were operated with and without recirculation and the recirculation ratio (R/Q) was typically in the range of 3 - 5.

The carbon removal by the biofilters increased as the carbon loading on the biofilters increased. In general, the carbon removal ($gCOD/m_f^3/d$) by the small media biofilter was highest, with lowest carbon removal achieved by the large media biofilter. It would also appear that moderate recirculation of biofilter effluent did not improve/enhance the carbon removal at the specific high loading rates employed. It must be kept in mind that the hydraulic loading on the biofilters was already high, and increased recirculation probably did not improve the hydrodynamics in terms of better wetting, biofilm control and more even wastewater distribution.

The small media size biofilter did not clog or pond at these high organic loading rates as one would expect under normal circumstances. The hydraulic loading rate (30 - 40 $m^3/m^2/day$) was apparently sufficient to control the biofilm thickness and to maintain adequate flow distribution with flow patterns conducive to carbon removal.

Carbon removal increased with the increasing carbon load, despite very high loading rates. This points to the fact that the influent wastewater contains a carbon fraction which must be readily biodegradable. The biofilm must, however, be kept in a viable and healthy state to remove this fraction, even at high loading rates.

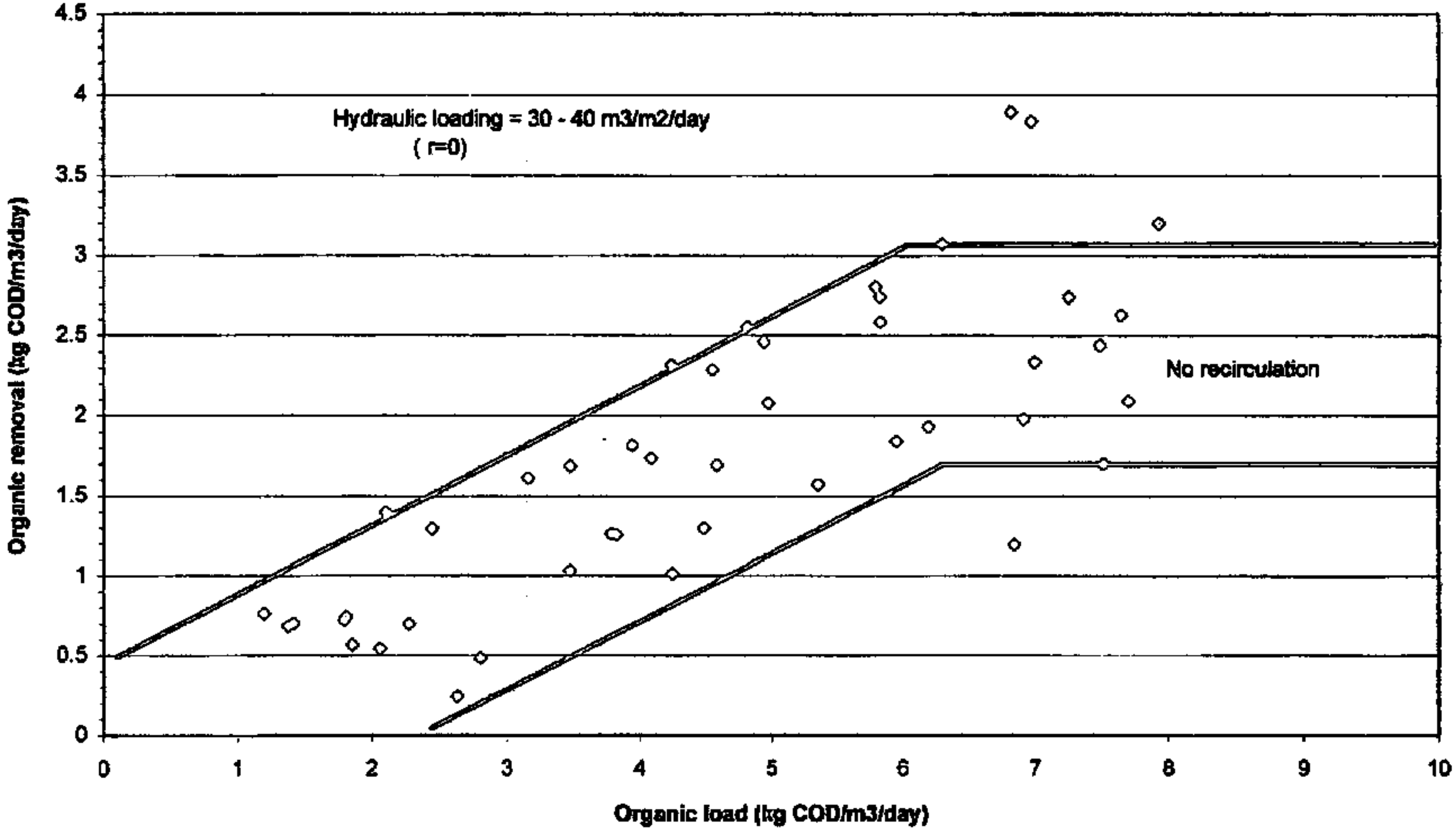


Figure 6.1 : Organic loading and removal on small media size biofilter

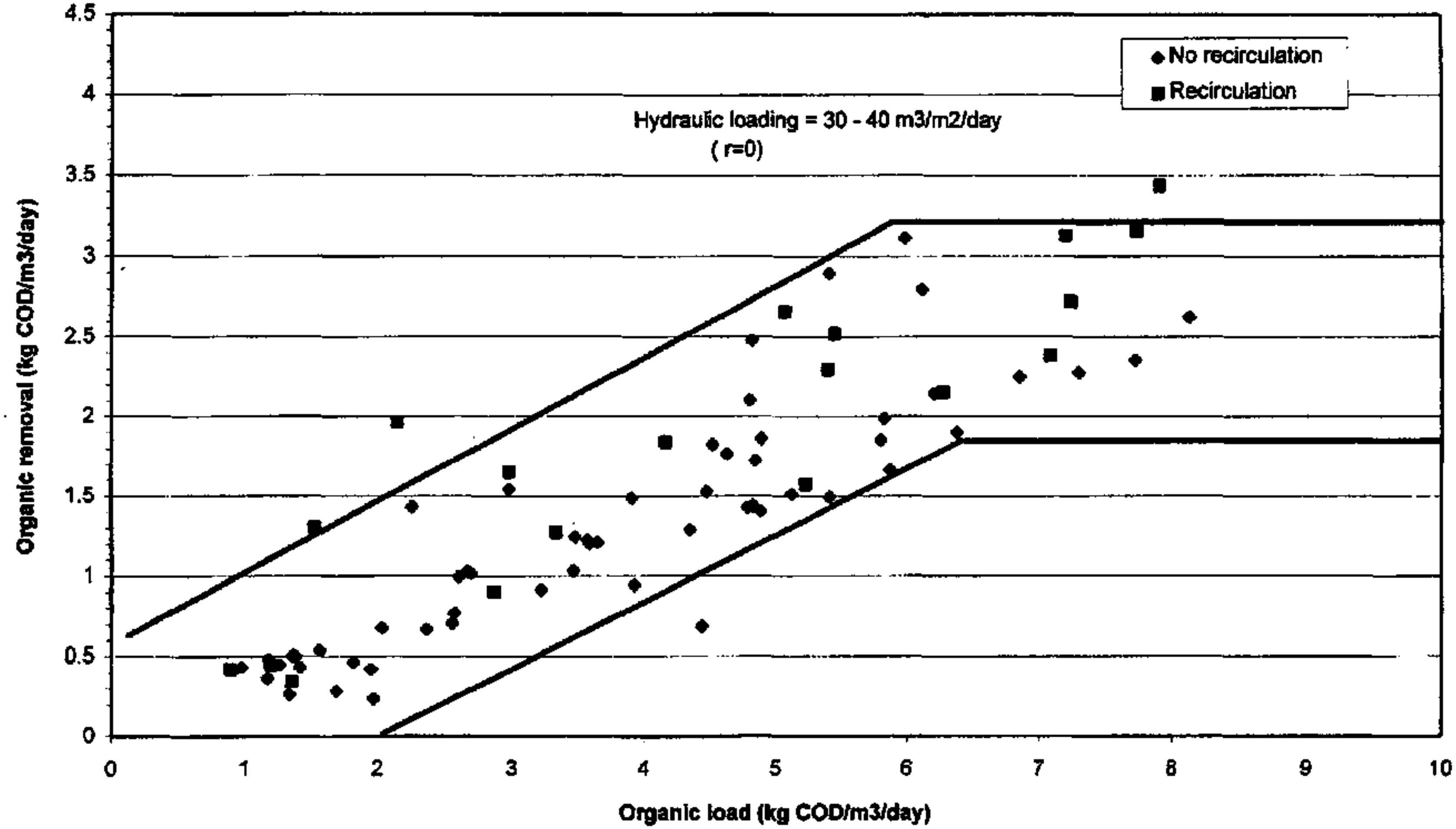


Figure 6.2 : Organic loading and removal on medium media size biofilter

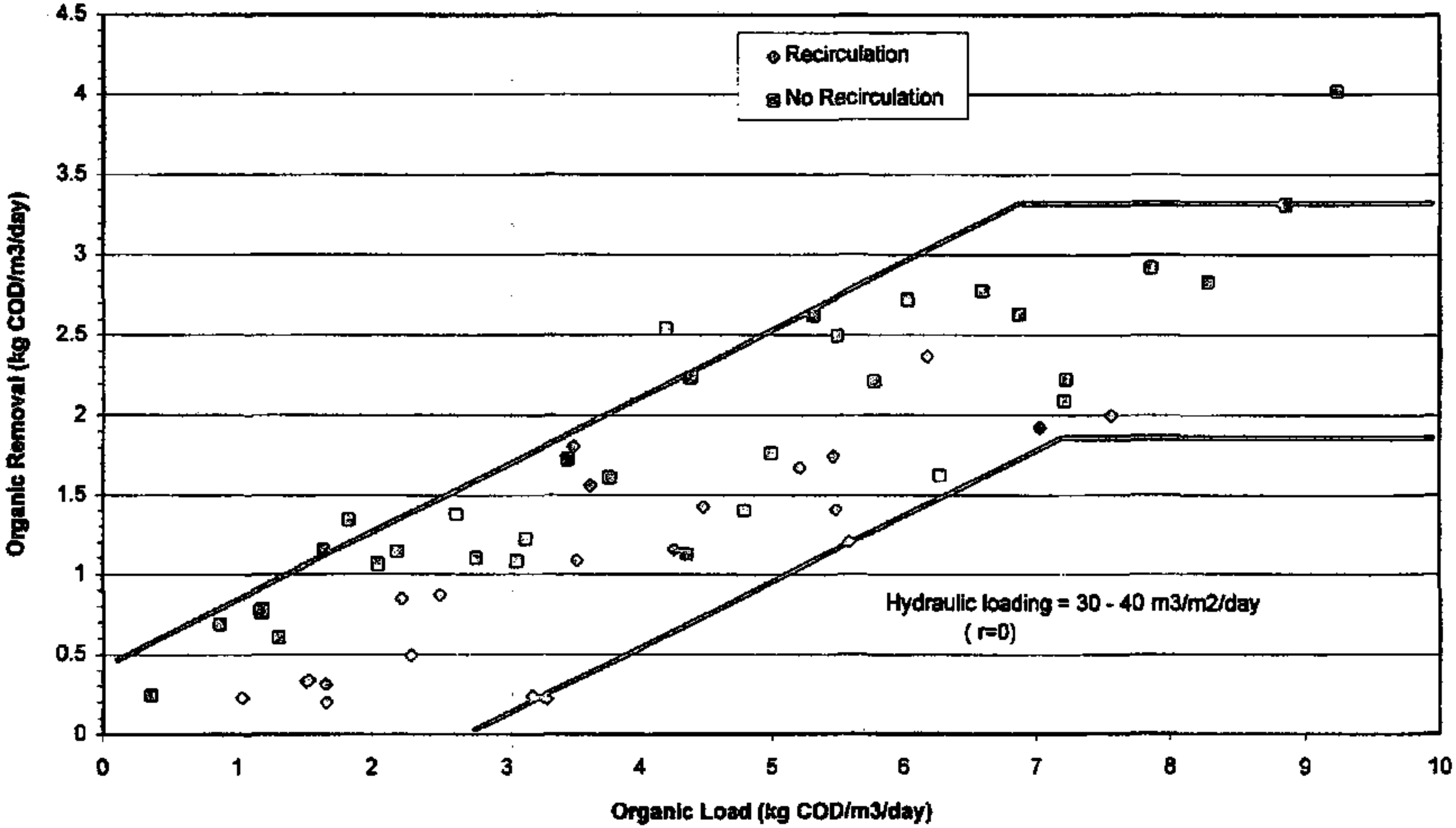


Figure 6.3 : Organic loading and removal on large media size biofilter

The carbon removal capacity did appear to approach a maximum level at high organic loading rate in excess of 6 - 7 kgCOD/m^3/day. The absolute maximum carbon removal capacity was not confirmed for any of the experimental biofilters and the conclusions in this regard must be considered as tentative. The maximum carbon removal rates corresponded to a 40-45% removal of the influent COD load. This fraction can be interpreted as the readily biodegradable and readily flocculated fraction of the influent sewage carbon source.

The carbon removal characteristics of biofilters receiving a high organic loading rate could also be expressed in a fashion which better demonstrates the concept of a carbon removal capacity **Figure 6.4** shows a graphical presentation for the small media biofilter carbon removal on the following basis:

- the biofilter was operated at three different hydraulic loading rates (10,6 m^3/m$_f^2$/day; 36 m^3/m$_f^2$/day and 98 m^3/m$_f^2$/day) with no recirculation.
- the feed sewage COD concentration varied between 150 mg/l and 600 mg/l for each of the individual hydraulic loading rates.
- a fairly constant percentage COD removal was observed for a specific hydraulic loading rate, irrespective of the feed sewage COD concentration.

The conclusion can be drawn that the maximum carbon removal capacity depends on the feed sewage COD-concentration. The maximum carbon removal capacities derived from the experimental results are summarised in **Table 6.1**.

Table 6.1 : Maximum carbon removal capacity as a function of feed sewage COD-concentration (Small media biofilter)

Feed sewage COD-concentration (mg/l)	Maximum carbon removal capacity (gCOD/m$_f^3$/day)
300 mg/l	1 300
400 mg/l	1 900
500 mg/l	2 550

It is also significant to note that the maximum carbon removal capacity is only reached at a relatively high hydraulic loading rate (36 m^3/m^{2}f/day) which corresponds to relatively high organic loading rates (>2 000 gCOD/m$_f^3$/day). At these high organic loading rates, the continuously-fed biofilters were adequately wetted and moderate recirculation would not be of much benefit.

6.2 Dissolved oxygen profiles in the biofilter

It was also interesting to note that the biofilter effluent contained substantial dissolved oxygen (DO) concentrations, even at high organic loading rates - refer to **Figure 6.5**. The settled sewage feed typically contained DO levels of approximately 1,0 mg/l. The biofilter effluent typically contained DO concentrations of 3-4 mg/l. The biofilter effluent contained even higher DO concentrations when recirculation was practised. It must be kept in mind that the biofilters received a continuous application of settled sewage, with no rest periods to ventilate and to re-aerate the biofilm. The practical implication of this observation is that full-scale biofilters do not necessarily need long rest periods between the intermittent dosing of wastewater.

6.3 Carbon removal at moderate loading rates

An intensive investigation of carbon removal by biofilters in the moderate organic loading rate range of 500 - 1500 gCOD/m$_f^3$/day was conducted. This investigation confirmed that the smaller media size was more effective in carbon removal per unit filter volume - refer to **Figure 6.6**. The COD removal at an organic loading rate of 1 000 gCOD/m$_f^3$/day is contrasted in **Table 6.2** for the different biofilter media sizes:

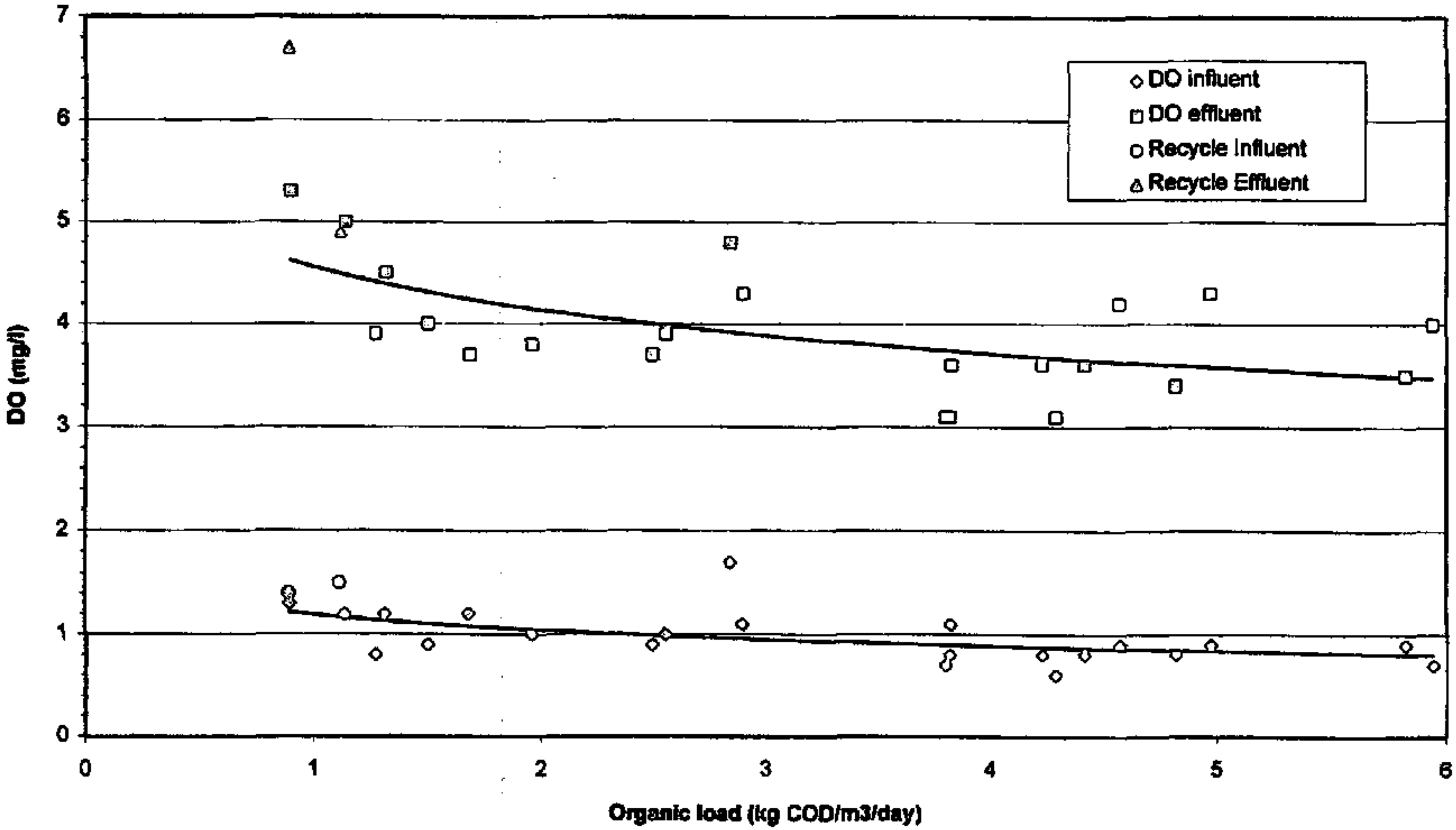


Figure 6.4: Dissolved oxygen in biofilter feed and biofilter effluent (small media size)

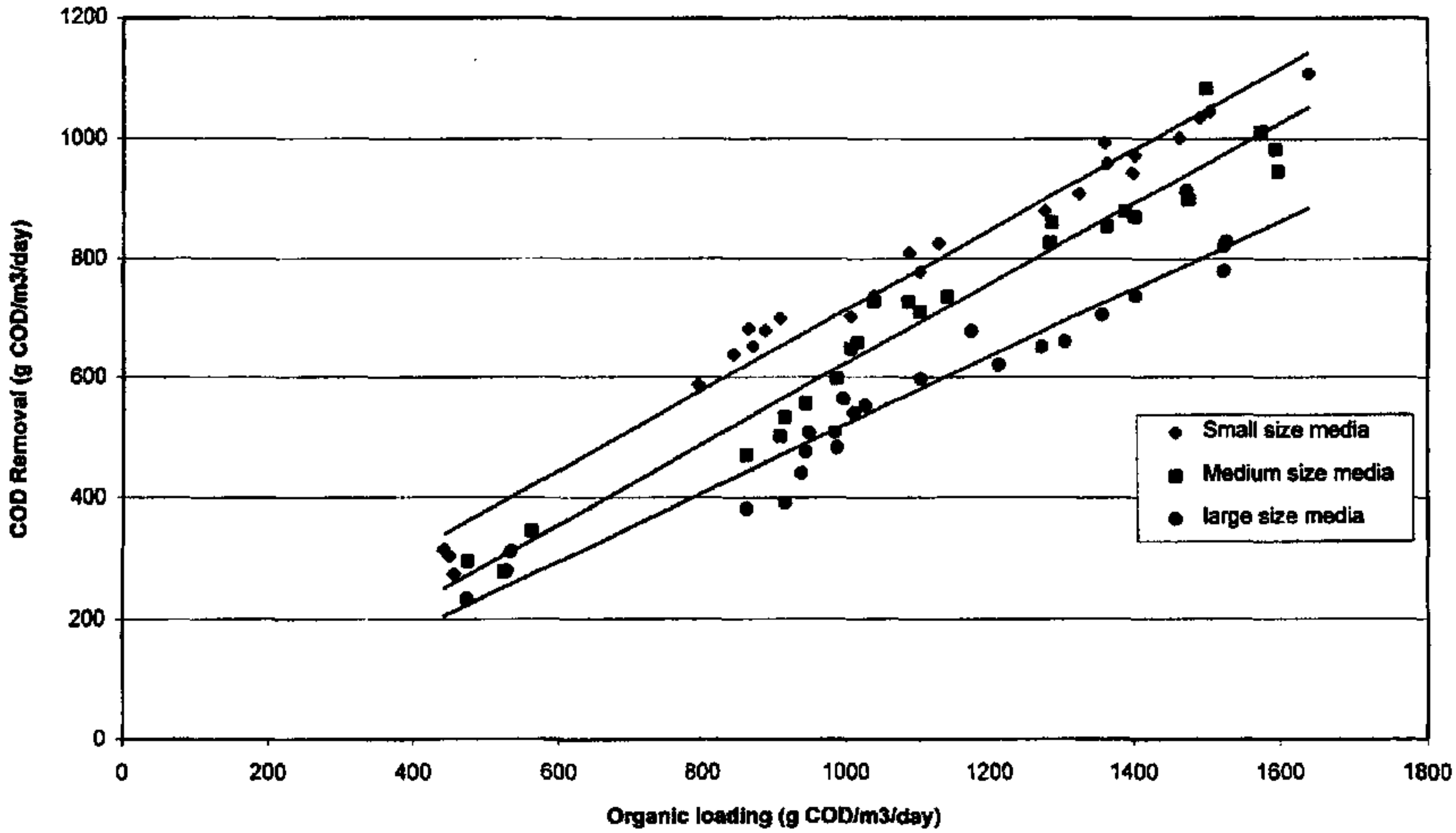


Figure 6.5: Comparative carbon removal for different biofilters.

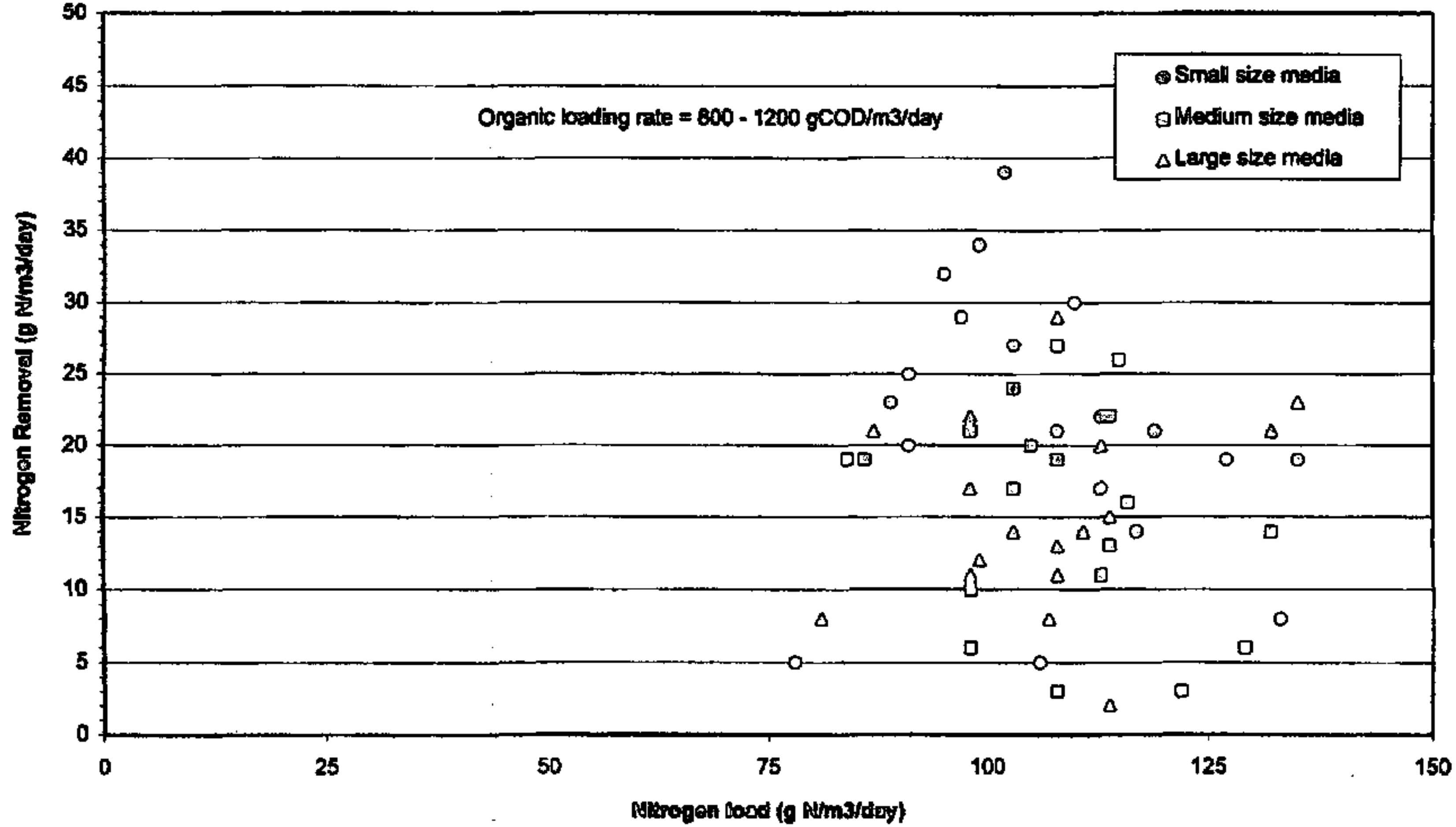


Figure 6.6: Nitrogen removal from high rate biofilters

Table 6.2 : comparison of carbon removal for different biofilter media sizes (loading = 1000 gCOD/m_f^3/day)

Biofilter media	Carbon removal	
	gCOD/m_f^3/day	gCOD/m^2_m/day
Small	710	11
Medium	630	11
Large	520	11

The carbon removal per unit surface area of biofilter media is comparable, indicating that the smaller biofilter media supports more biomass per unit volume. In general, the improved carbon removal ability of the smaller biofilter media can be ascribed to:

- longer contact time between wastewater and biomass attached to media.
- the larger biomass (per unit biofilter volume) attached to more biofilter media surface.

The potential benefits of recirculation around a biofilter were investigated at moderate carbon loading rates. The small media biofilter was operated at an average carbon loading rate of 1 000 gCOD/m_f^3/day and at an average hydraulic loading rate of 10 m^3/m_f^2/day. The carbon removal by the biofilter for different recirculation rates is depicted in **Table 6.3.**

Table 6.3 : Carbon removal for different recirculation rates (carbon loading = 1000 gCOD/m^3/day)

Recirculation Ratio (Qr/Q)	Carbon Removal Rate (gCOD/m^3/day)
0	772
1,7	287
6,2	455
7,3	973

The experimental observations indicated that recirculation influenced the carbon removal performance in the following manner:

- low recirculation rates (Qr/Q <6) did not benefit the carbon removal performance, but actually resulted in a poorer quality biofilter effluent. The poorer quality biofilter effluent may be attributed to the presence of more colloidal and fine particulate matter in the effluent. The higher level of turbulence created by recirculation may be detrimental to effective flocculation and removal of the colloidal and particulate carbon fraction.
- high recirculation rates (Qr/Q >7) did result in an improvement in carbon removal performance. The biofilter effluent was well flocculated and the settled effluent was very clear. The nature of the biofilter solids appeared to change and to be more amenable to flocculation at the high recirculation rates.

It would therefore appear that some recirculation at moderate carbon loading rates does not improve the biofilter performance. Very high and probably uneconomical recirculation rates may improve the biofilter performance. The higher the organic carbon load, the more recirculation is required to achieve a high quality effluent.

6.4 Nitrogen removal at moderate organic loading rates

The nitrogen removal across the biofilters was determined on the basis of ammonia concentrations in the biofilter feed and effluent streams respectively. The nitrogen removal observations were done in a range of organic loading rates of 800 - 1200 g COD/m^3/day.

The nitrogen removals are shown on **Figure 6.7**. A wide scatter of nitrogen removal rates was observed, varying between 5 and 40 % removal of the influent nitrogen load. It was not anticipated that any significant nitrification would take place at these high organic loading rates. The observed nitrogen removal can therefore be ascribed to:

- volatilization loss of ammonia
- nitrogen uptake to satisfy the synthesis of new biomass

6.5 Biosolids generation

Biosolids are synthesised from the carbon compounds contained in the feed sewage to the biofilters. The biosolids generation is expressed in terms of a solids yield (kg SS) per unit mass of carbon removed (kg COD).

Substantial variations in the day to day biosolids yield were observed on the experimental biofilters. The typical observations are summarised in **Table 6.4**.

Table 6.4 : Biosolids yield observed on experimental biofilters

Biofilter	Carbon loading rates (g COD/m_f^2/day)	Biosolids yield (kg SS/kg COD removed)	
		Range	Average
Small media	1300-8800	0,23-0,98	0,48
Medium media	1300-5900	0,29-1,58	0,86
Large media	1300-8100	0,43-2,30	1,09

The biosolids yield was sensitive to the size of the biofilter media. The yield increased with larger biofilter media size. The biomass inventory in the biofilter containing the larger media size is relatively small (due to the smaller specific surface area). The conclusion can be made that the effective biomass age (solids residence time in the biofilter) in the small media biofilter is relatively long and that the biomass age in the large media biofilter is relatively short. This could have an implication with respect to the viability of biomass and the treatment performance of a biofilter.

6.6 Conclusions

Biofilters have a high capacity to remove a substantial fraction of the carbon load onto a filter. The carbon removal capacity (gCOD/m^3/day) increases as the biofilter organic loading rate (gCOD/m^3/day) increases. Recirculation of biofilter effluent does not improve the biofilter carbon removal capacity at high loading rates. The hydraulic loading rates at the high organic loading rates were in the range 30 - 40 m^3/m^2/day and further recirculation apparently did not improve the hydrodynamic characteristics of the biofilters. High rate biofilters do have a maximum carbon removal capacity which depends on the feed sewage strength.

In the moderate organic loading range of 500 - 1 500 gCOD/m^3/day, the experimental biofilters removed 50 - 70 % of the influent carbon load, depending on the biofilter media size. Smaller biofilter media maintained a higher volumetric carbon removal rate (gCOD/m^3/day) compared to the large biofilter media. The carbon removal capacity of the different biofilter media sizes could be related to the available media surface area. The carbon removal capacity of intermediate rate biofilters can be improved by very high rates of recirculation.

Some nitrogen removal, presumably due to biomass synthesis, was also observed in the high rate biofilters.

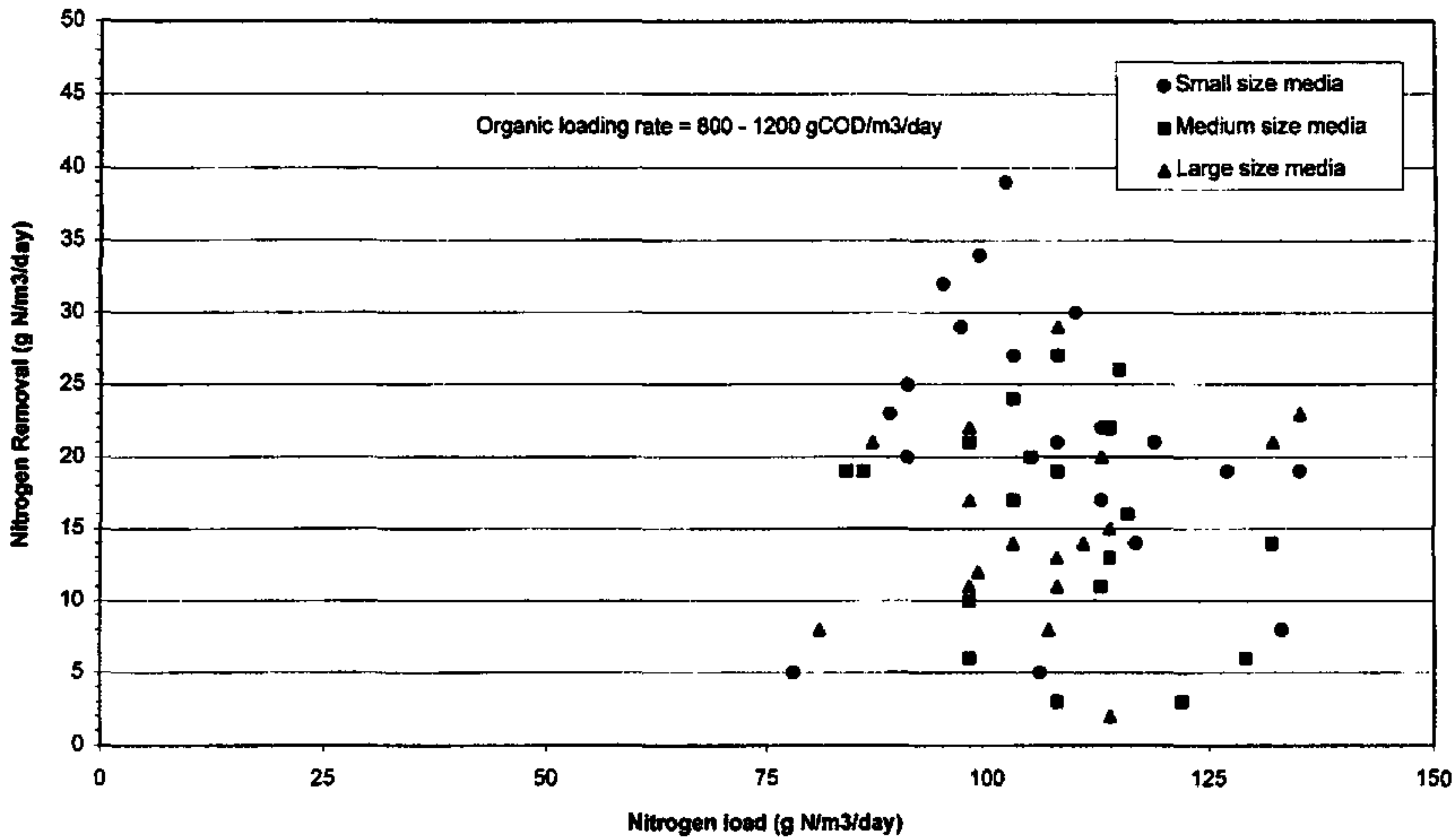


Figure 6.7: Nitrogen removal by high rate biofilters

The biomass yield (kg SS/kg COD) removed is sensitive to the biofilter media size. The smaller media size biofilter generated relatively small amounts of biomass compared to the larger media size biofilter.

7 APPLICATION TO FULL SCALE HIGH RATE BIOLOGICAL FILTERS

A number of full-scale sewage treatment plants, which incorporate biological filters operated at relatively high organic loading rates were surveyed and their performances were analysed. Full-scale observations can add to the understanding of performance and future potential application of high rate biofiltration. It must, however, be kept in mind that the high-rate biofilters surveyed in South Africa, are still operated at relatively low rates compared to world standards.

The sewage treatment plants were surveyed and the available biofiltration performance data was analysed. An economic analysis was also conducted of the high rate biological filtration process to confirm the financial viability of the process.

7.1 Ferrobank Water Care Works

Ferrobank Water Care Works is a conventional single stage biofiltration plant. The plant receives predominantly domestic sewage with some industrial effluent contribution. The raw sewage is settled to remove solids (primary clarification) prior to biofiltration. Four biological filters are operated in parallel to achieve carbon and nitrogen removal. The biofilter effluent is settled in final clarifiers to remove humus solids. Recirculation across the biofilters is also provided to maintain a certain minimum wetting rate. The plant receives approximately 20 Ml/day of raw sewage.

The biological filters are 3,4 m high with a diameter of 35 m. The filter media is a natural stone in the size range 40 - 70 mm. The average hydraulic load on the biofilters is 4,9 m^3/m_f^2/day. The humus clarifier effluent is partially recirculated, especially at night, to maintain a minimum wetting rate. The average recirculation rate is 5,0 Ml/day, which corresponds to a recirculation ratio of r = Q:R = 1:0,25.

The carbon removal performance of the plant is reflected on **Figure 7.1**, which shows an average biofilter loading of 489 g COD/m_f^3/day. It is interesting to observe that the carbon *removal capacity* increases at the carbon *loading rate* increases. The biofilters were removing 300 - 400 g COD/m_f^3/day (72% of influent carbon load), which is significantly higher than the typical design criterion of 250 g COD/m_f^3/day used for conventional low-rate biofilters.

The nitrogen loading rate on the biological filter was calculated using the expression:

$$N_{load} = Q.[TKN]/V \qquad (7.1)$$

where:

N_{load}	=	loading rate (gN/m^3/day)
Q	=	settled sewage flow rate (Ml/day)
TKN	=	settled sewage TKN concentration (mgN/l)
V	=	volume of biofilter media (m^3)

The nitrogen removal ability of the biofilters is reflected on **Figure 7.2**. The ammonia loading rate was in excess of the conventional design criterion of 20 - 25 gNH_3-N/m_f^3/day. At the high ammonia loading rates, the following average removals were still achieved:

FERROBANK SEWAGE TREATMENT PLANT

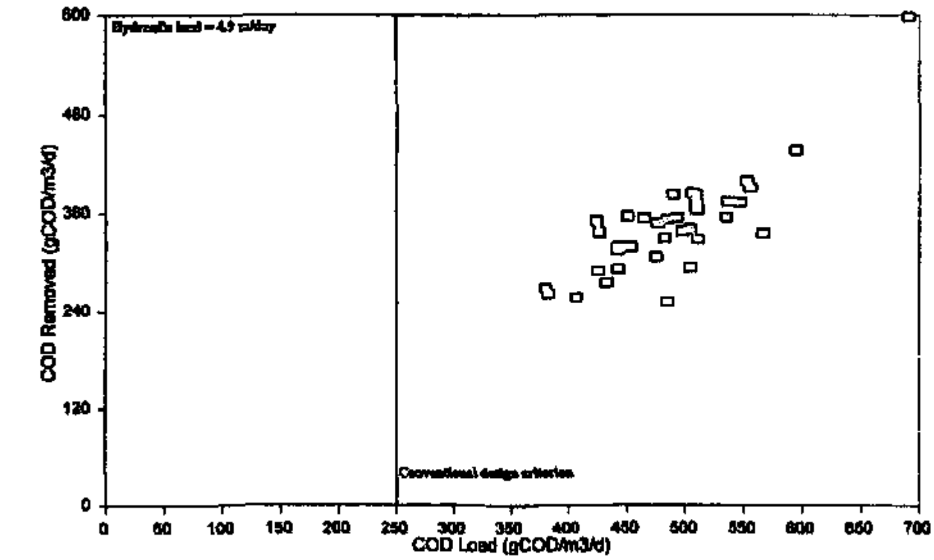


FIGURE 7.1: Biofilter COD removal

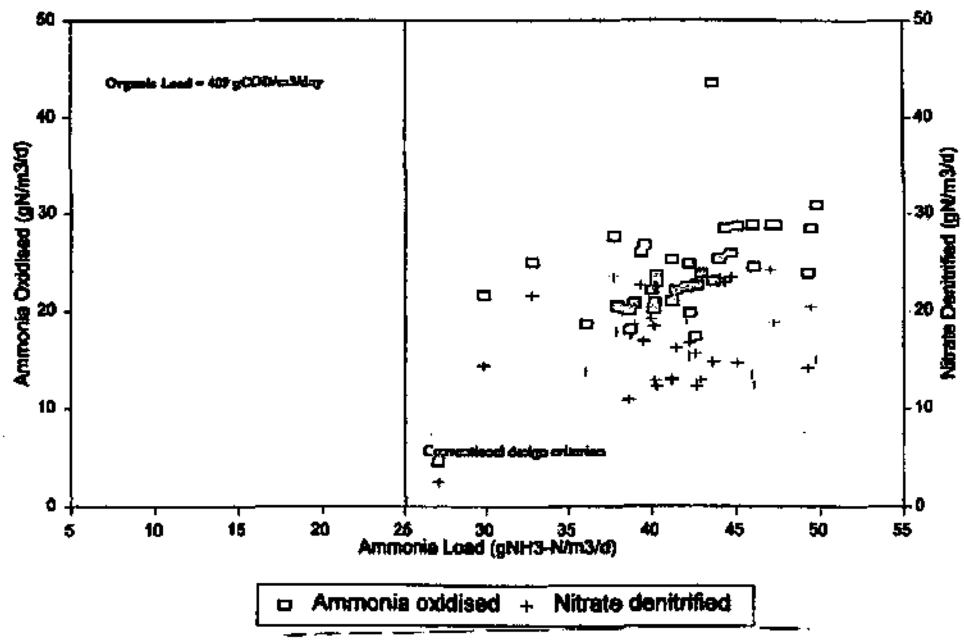


Figure 7.2 : Biofilter Nitrogen Removal

- ammonia oxidation = 24 gNH_3-N/m³/day (61% of influent nitrogen load)
- nitrate denitrification = 17 gNO_3-N/m³/day (43% of influent nitrogen load)

The Ferrobank Water Care Works performance demonstrates that the carbon removal capacity of biofilters operated at traditional loading rates may be underutilized. Ammonia oxidation rates may not necessarily be reduced in biofilters operated under relatively high carbon loading rates. Denitrification of nitrate is also significant in biological filters which operate at high carbon loading rates and with recirculation.

7.2 Riverview Water Care Works

Riverview Sewage Treatment Plant receives an average raw sewage flow of 6,5 Ml/day. The sewage is predominantly of domestic origin with some industrial (abattoir) effluent contribution. The plant employs high rate biological filtration as a pretreatment step, before final polishing in an activated sludge process. The plant performance with respect to biofiltration was analysed over the period March 1994 to March 1995. Two biological filters, which operate in parallel were analysed in some detail.

The biological filters are 3,2 m high and 35 m diameter. The filter media is a natural rock in the size range 40 - 70 mm. The biofilters do not receive any recirculation and the average hydraulic loading rate is 6,6 m^3/m_f^2/day. The biofilters were operated at an SK-factor of 2 - 3 mm/pass.

The carbon (COD) removal performance of the biofilters is shown on **Figure 7.3**. The plant performance was not sensitive to the season and similar COD removals were observed in both filters for winter and summer conditions. The average COD-loading on the biofilters was 370 gCOD/m_f^3/day. The filters are therefore still operated substantially below the design loading rate of 600 gCOD/m_f^3/day. The COD removal rate varied depending on the loading rate. In general, the carbon removal rate increased as the carbon loading rate increased. Extrapolation of the carbon removal observations indicated that the influent settled sewage contained on unbiodegradable fraction of approximately 50 mgCOD/l. The average COD removal rate was 220 gCOD/m_f^3/day (approximately 60% removal) over the period of observation.

The nitrogen loading on the biofilter was variable with an average of 46 gN/m_f^3/day. The nitrification efficiency of the biofilters are shown on **Figure 7.4** for biofilters 2 and 3 respectively. The nitrification rate was calculated using the expression:

$$N_{ef} = Q[TKN - N_e - N_{o,e}]/V \quad (7.2)$$

where:

N_{ef} = nitrification rate (gN/m_f^3/day)

N_e = biofilter effluent ammonia concentration (mgN/l)

$N_{o,e}$ = biofilter effluent organic nitrogen concentration (mgN/l)

The nitrification rates also varied with an average of 28 gN/m_f^3/day over the year. This is relatively high, considering the high organic loading rate of 370 gCOD/m_f^3/day. The nitrification rate was also not sensitive to the organic loading rate over the range 250 - 450 gCOD/m_f^3/day. In general the nitrification rate was not sensitive to the season of the year, and comparable nitrification rates were observed in winter and in summer.

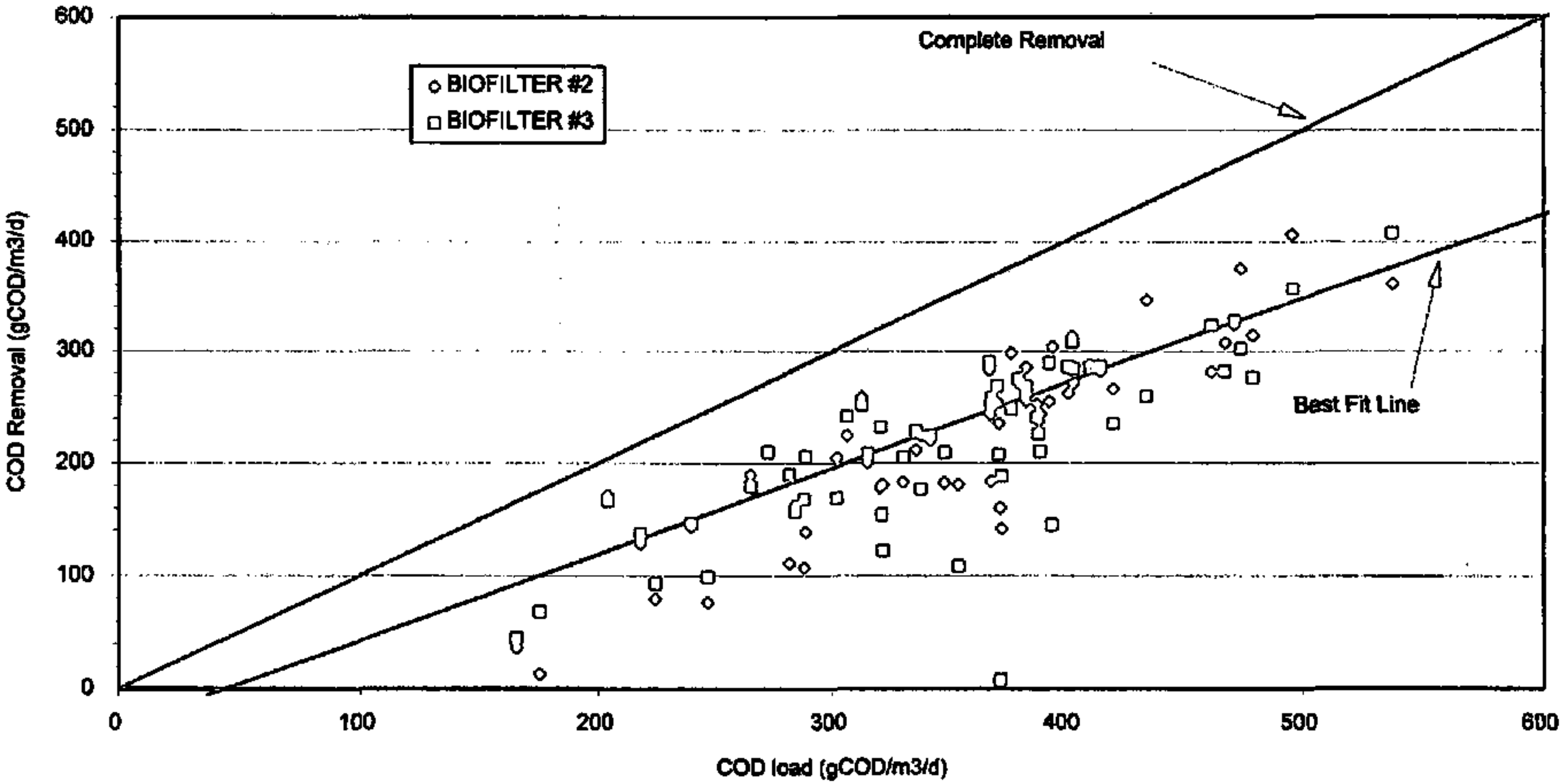


Figure 7.3: High Rate Biofiltration Project - Plant Carbon Removal

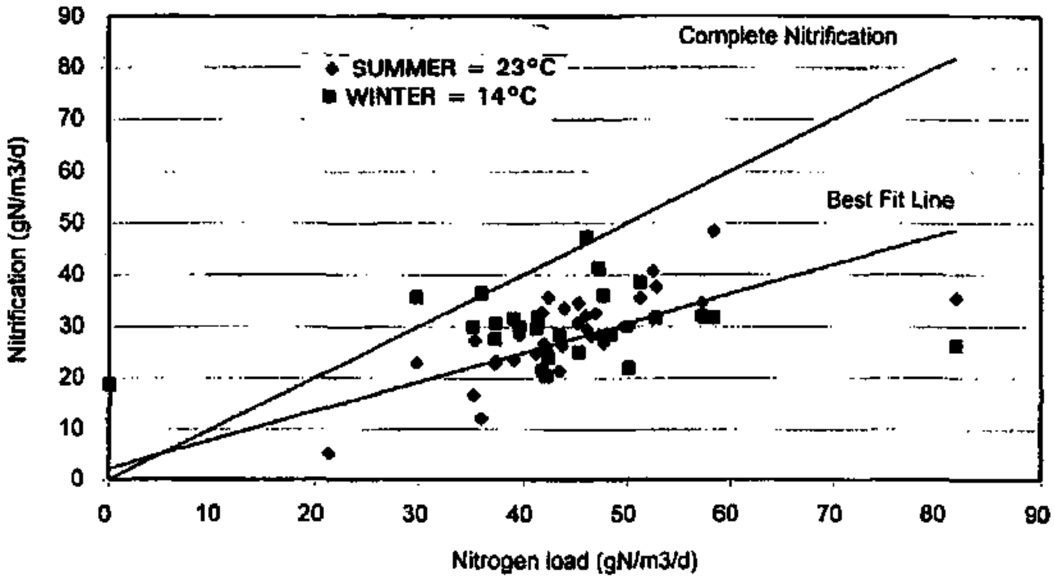


Figure 7.4(a): High Rate Biofiltration Project - Biofilter # 2 Nitrification

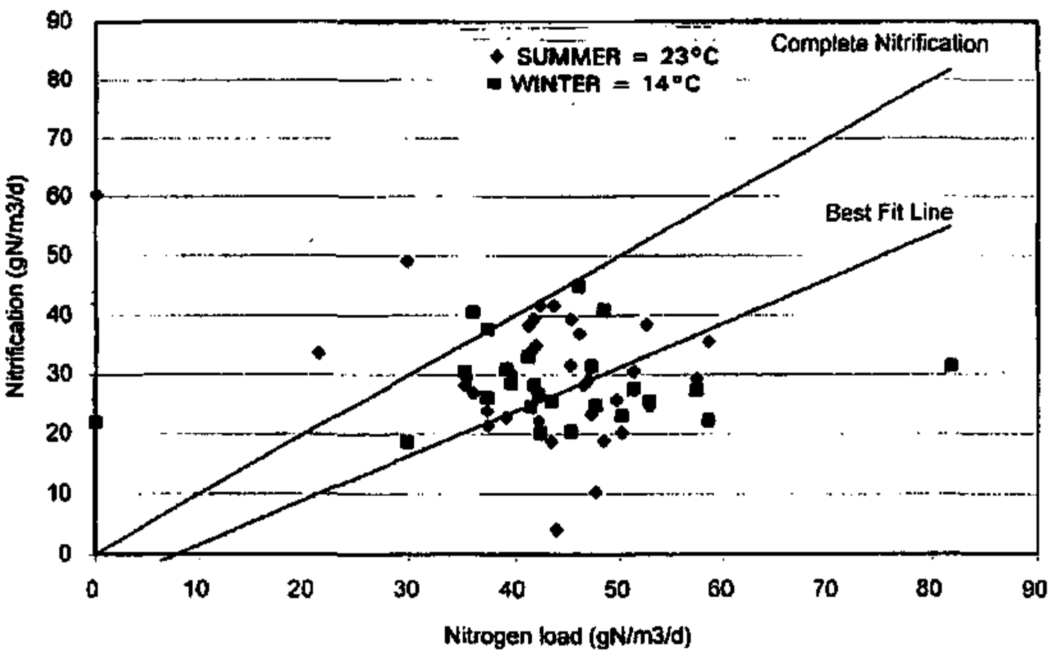


Figure 7.4(b): High Rate Biofiltration Project - Biofilter # 3 Nitrification

Partial denitrification was also observed in the two biological filters as reflected in **Figure 7.5**. The relatively high organic load, created an environment within the filter where carbon compounds would be available to drive the denitrification process. The average denitrification rate was 16 gN/m_f^3/day which corresponds to approximately 60 % of the available nitrate generated by the nitrification process. The observed denitrification was also not sensitive to seasonal influences.

In general the observed nitrification and denitrification rates were insensitive to the carbon loading rate (over the range 250 to 450 $gCOD/m_f^3$/day) and to the nitrogen loading rate (over the range 35 to 55 gN/m_f^3/d).

The humus solids production by the biofilters was also monitored over a year (1984) and a solids yield coefficient was calculated on the basis of the following expression:

$$Y = Q.SS_e / [Q(COD_i - COD_e)] \quad (7.3)$$

where:

Y	=	solids yield coefficient (gSS/gCOD removed)
Q	=	settled sewage feed rate (Ml/day)
SS_e	=	biofilter effluent suspended solids concentration (mg/l)
COD_i	=	COD-concentration of settled sewage (mg/l)
COD_e	=	settled biofilter effluent, COD-concentration (mg/l)

The observed nett yield coefficient was 0.32 gSS/gCOD removed.

7.3 Economic implication of high rate biofiltration

The economic implications and potential application of high rate biofiltration were investigated for a specific plant. The economic analysis was based on the following premises:

- the plant design flow was 6 500 m^3/day with an influent raw sewage COD concentration of 1 050 mg/l and TKN concentration of 85 mgN/l.
- the plant contained an inlet works and primary clarifiers for the initial pre-treatment of raw sewage.
- the effluent had to comply to the General Standard of the Water Act 54 of 1956 in terms of COD, SS and ammonia concentrations.

Two alternative process options were identified to achieve the treatment objectives on the settled sewage (refer to **Figure 7.6**):

- Option 1 - Conventional activated sludge
- Option 2 - High rate biofiltration with downstream polishing activated sludge

The settled sewage flow and load were characterised by an average daily flow rate of 6500 m^3/day, COD-concentration of 500 mg/l and TKN-concentration of 75 mgN/l.

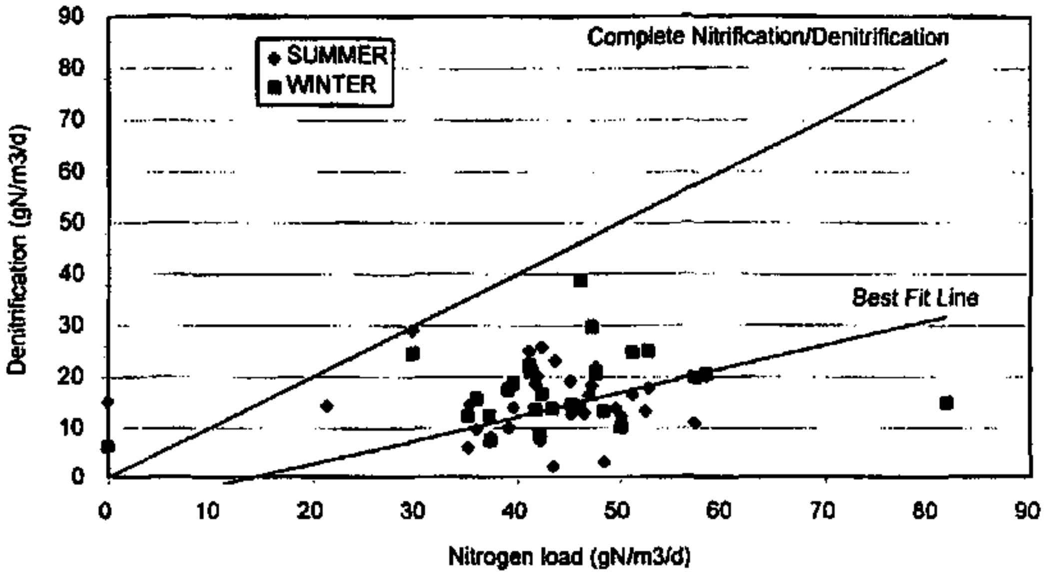


Figure 7.5(a): High Rate Biofiltration Project - Biofilter # 2 Denitrification

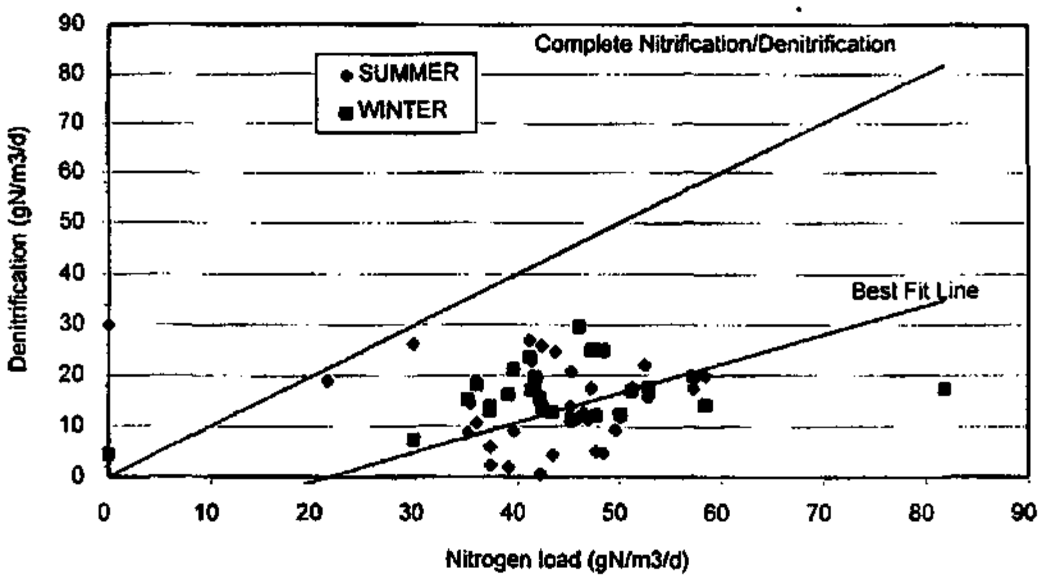
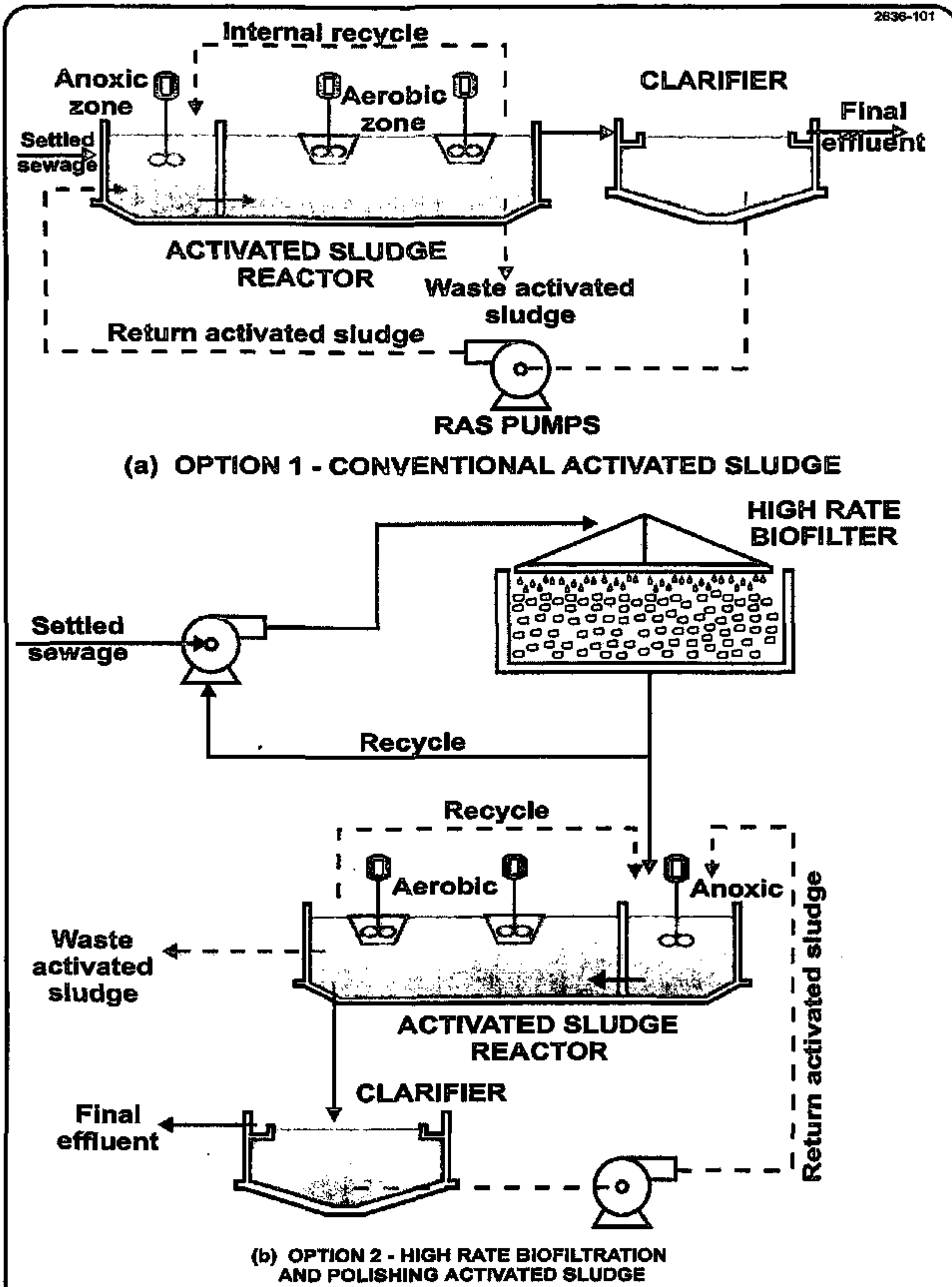


Figure 7.5(b): High Rate Biofiltration Project - Biofilter # 3 Denitrification



WMB FIGURE 7.6 : ALTERNATIVE PROCESS CONFIGURATION FOR FINANCIAL ANALYSIS

The conventional activated sludge process (Option 1) requires the following infrastructure:

- Activated sludge reactor = 4 620 m^3 (including a 1 020 m^3 anoxic compartment)
- Peak oxygen requirement = 8 590 kgO_2/day (at STP)
- Final clarifiers (2 off) = 17 m diameter
- RAS pump station capacity = 7 800 m^3/day (max)

The high rate biofiltration and polishing activated sludge (Option 2) requires the following infrastructure:

- Biofilter feed pump station capacity = 19 500 m^3/day
- High rate biofilters (2 off) = 2 290 m^3 each
- Activated sludge reactor = 1 190 m^3 (including a 270 m^3 anoxic compartment)
- Peak oxygen requirement = 3 730 kgO_2/day (at STP)
- Final clarifiers (2 off) = 17 m dia
- RAS pump station capacity = 7 800 m^3/day (max)

7.3.1 Capital cost estimates

This economic analysis focussed on the necessary further treatment of the settled sewage. The complete sewage treatment plant would obviously require an inlet works, primary clarifiers, final disinfection and sludge handling and disposal facilities. These other plant components were considered to be common to both options for treating the settled sewage and were therefore not included in the analysis.

Capital cost estimates were prepared for the two alternative process options. The estimates are summarised in **Table 7.1** in terms of April 1995 construction price indices. The combined biofiltration/ activated sludge option is more capital intensive than a conventional activated sludge plant.

Table 7.1 : Capital construction cost estimates for treatment options

	Biofiltration/ Activated Sludge	**Conventional Activated Sludge**
Biofilter pump station		
- Civil construction	R 124 000	-
- Mechanical equipment	R 90 000	-
- Electrical supply & controls	R 65 000	-
Biological filters		
- Civil construction	R1 023 000	-
- Mechanical equipment	R 135 000	-
- Electrical supply & controls	R 0	-
Activated sludge reactor		
- Civil construction	R 353 000	R 710 000
- Mechanical equipment	R 346 000	R 750 000
- Electrical supply & controls	R 245 000	R 520 000
Final clarifiers		
- Civil construction	R 433 000	R 433 000
- Mechanical equipment	R 220 000	R 220 000
- Electrical supply & controls	R 75 000	R 75 000
Total Construction Cost	**R3 109 000**	**R2 708 000**
Capital Redemption/Interest (15% over 20 yrs)	**R 497 000**	**R 432 000**

7.3.2 Operating and maintenance costs

Maintenance costs

The annual cost associated with maintenance of the plant was estimated based on the following approach:

- Civil/building construction work = 0.5 % of capital cost
- Mechanical equipment = 4 % of capital cost
- Electrical equipment = 2 % of capital cost

The estimated total annual maintenance costs were:

- R6 400 (Option 1 - Conventional activated sludge)
- R48 800 (Option 2 - Biofiltration/activated sludge)

Electrical power costs

The estimates of electrical power costs were based on the following municipal rates:

- Demand charge = R27.50/kVA/month
- Consumption charge = R12.24 c/kWhr
- Fixed charge = R270/month

A summary of the estimated electrical power demand is shown in **Table 7.2**:

Table 7.2 : Estimated Electrical power demand and usage

Equipment Item	Installed power (kW)	Operating hours (hr/d)	Power consump-tion (kWhr)
Biofiltration/Activated sludge			
- Biofilter feed/recycle pumps	13,5	18	343
- Mechanical Mixers	2,4	24	57,6
- Mechanical Aerators	88	24	2112
- A-recycle pumps	2,2	15	26,4
- RAS pumps	30	18	540
- Clarifier bridges	1,1	24	26,4
TOTAL	**137,2**		**3105,4**
Conventional Activated Sludge			
- Mechanical Mixers	9	24	216
- Mechanical Aerators	198	24	4752
- A-recycle pumps	2,2	12	26,4
- RAS pumps	30	18	540
- Clarifier bridges	1,1	24	26,4
TOTAL	**240,3**		**5560,8**

The annual electrical power costs were estimated as follows:

- R331 000 (Option 1 - Conventional activated sludge)
- R183 800 (Option 2 - Biofiltration/activated sludge)

Personnel costs

The plant would require the following minimum operating personnel contingent to operate/control both treatment options:

- 1 x trainee operator
- 1 x class I operator
- 1 x class II operator

The estimated total annual personnel cost for both treatment options was R67 200. No distinction is therefore made in the operating personnel requirements for the two process options. The conventional activated sludge plant would, however, typically require more operator attention and more skilled operation.

7.3.3 Total operating and maintenance costs

The estimated total annual operating and maintenance costs are summarised in **Table 7.3**. The unit costs were based on a design flow of 6 500 m^3/day.

Table 7.3 : Summary of operating and Maintenance Costs

Operating and Maintenance Cost	Biofiltration / activated sludge	Conventional activated sludge
•Maintenance	R 48 800	R 56 400
•Electrical power	R183 800	R331 000
•Personnel	R 67 200	R 67 200
TOTAL	R299 800	R454 600
Unit cost (c/m^3)	**12,6**	**19,2**

7.3.4 Total treatment cost

The total estimated settled sewage treatment costs, including capital expenditure, operating and treatment costs, are summarized hereunder in **Table 7.4**.

Table 7.4 : Total estimated treatment cost for two options

Cost Element	Biofiltration/ activated sludge	Conventional activated sludge
• Capital redemption and interest		
- R/year	R497 000	R432 000
- c/m^3	21	18,2
• Operating and maintenance		
- R/year	R299 800	R454 000
- c/m^3	12,6	19,1
• Total cost		
- R/year	R796 800	R886 000
- c/m^3	33,6	37,3

The high rate biofiltration/activated sludge process is, therefore, more economical, compared to the conventional activated sludge process. The capital expenditures for the two process options are comparable, but the combined biofiltration/activated sludge process has a much more attractive operating/maintenance cost. This would make the high rate biofiltration/activated sludge process more attractive over the life of a project.

8 CONCLUSIONS AND RECOMMENDATIONS

High rate biological filtration has potential for application to sophisticated large wastewater treatment plants and to small community-based treatment installations. The application potential is based mainly on the efficiency of carbon removal and the attractive economy of the process. Worldwide, renewed interest is shown in attached growth and immobilized culture technology for wastewater and effluent treatment. High rate biological filtration is an example of a process from this range of technology.

The hydrodynamic properties of a biofilter are important in determining the carbon removal efficiency. The hydrodynamic properties include the flow patterns within the filter media; short circuiting without effective wetting of the entire media surface; stagnant zones within the filter without effective flushing and adjective and dispersive phenomena that influence the effective contact time between wastewater and biofilm. Collectively the hydrodynamic properties of a biofilter determine the effective contact between the wastewater and biomass (biofilm) and, therefore, play an important role in the removal/stabilisation of carbon compounds.

The conclusions based on the investigation into the hydrodynamic properties of high rate biofilters can be summarised as:

- The hydraulic residence time in biofilters is relatively short compared to other types of biological reactors. The available information can be related to the migration of soluble substrate compounds. The situation with respect to colloidal and particulate substrates may be even more complex and cannot be deducted from the available tracer study information.
- Dispersion due to the complex nature of biofilter flow paths plays an important role in substrate migration. This fact has to be taken into account in any attempt to model biofilter performance.
- The residence time in biofilters receiving an intermittent dose of wastewater is substantially longer compared to a biofilter receiving a continuous, even application of wastewater. The difference can be ascribed to the transient nature of liquid application and the increasing liquid hold-up at high local application rates.

Optimal functioning of biofilters requires attention to the hydrodynamic aspects. Experimental work conducted at hydraulic loading rates of 30 - 40 $m^3/m^2{}_f/day$ indicated that recirculation of biofilter effluent, to enhance the hydrodynamic properties of the filter, was not essential. The literature quotes recommended minimum hydraulic loading rates of 20 $m^3/m^2f/day$ for natural rock biofilters. There is also growing consensus on the proper intermittent application of wastewater to full-scale biofilters. The trend is towards achieving a high local wastewater application rate, as reflected by a SK-factor of 10 - 20 mm/pass.

Biofilters are very efficient processes for the removal of carbonaceous compounds from wastewater. A maximum carbon removal capacity may be reached at high organic loading rates. This capacity is sensitive to the feed sewage strength. The carbon removal capacity increases as the carbon loading rate increases. Biofilters packed with a small size media (relatively high surface area per unit volume) were more effective than biofilters packed with large size media. High rate biofilters do, however, produce a substantial mass of biosolids per unit mass of carbon removed.

The general performance of biological filters can be described in terms of three different situations:

- At low organic loading rates, less than 250 $gCOD/m_f^3/day$, biofiltration is effective in carbon removal (> 80 %) and virtually complete nitrification (biofilter effluent containing $\leq$ 10 mg NH_3-N/l) is achieved. The biofilter effluent is typically well mineralised, containing low COD-concentrations and high nitrate concentrations.

- At intermediate organic loading rates, 250-750 gCOD/m_f^3/day, biofiltration can still remove a substantial fraction of the organic load as well as nitrogen load. Nitrification as well as denitrification can take place in the same biofilter, due to the relative availability of carbon compounds to drive the denitrification process. The biofilter effluent will contain low COD, ammonia and nitrate concentrations, but may not always comply with the General Standard of the Water Act 54 of 1956.
- At high organic loading rates, 750 - 1 500 gCOD/m_f^3/day, biofilters can still remove 50 - 70 % of the influent carbon load, depending on the biofilter media size. No significant nitrification can be anticipated, but some nitrogen removal, due to biomass synthesis will take place. The biofilter effluent will require further polishing treatment, before discharge to the public stream.

Economic analysis of the high rate biofiltration process confirmed that it is an efficient and cost-effective approach to the removal of carbonaceous compounds from wastewater. A comparison of the treatment cost of combined biofiltration/activated sludge versus conventional activated sludge indicated that the former has a lower unit treatment cost, specifically with respect to the operating and maintenance aspects.

This research project was successful in demonstrating the potential for high rate biofiltration technology in South African wastewater treatment. The further application of the technology will benefit from research into the following aspects:

- optimisation of the nitrogen removal capacity of a biofilter operated at intermediate organic loading rates. Many field observations are related to improved nitrogen removal by recirculation around the biofilter.
- the flocculation characteristics of biofilter solids changed substantially at high recirculation rates (Qr/Q >7). A very high quality biofilter effluent was produced at these high recirculation rates. High recirculation rates are expensive on a full-scale application, but may obviate the need for polishing treatment, downstream of a high rate biofilter.
- the extrapolation of the process performance by continuously-fed biofilters (pilot plant) to intermittently-fed biofilters (full scale plants) should be investigated.
- a further extension of the technology to aerated biofiltration is gaining popularity among international researchers. The local application of this new generation biofiltration process should be investigated.

A valuable biofiltration research facility was erected at the Pretoria, Baviaanspoort Water Care Works as part of this project. The Water Research Commission should consider the further use of this facility to advance biofiltration technology.

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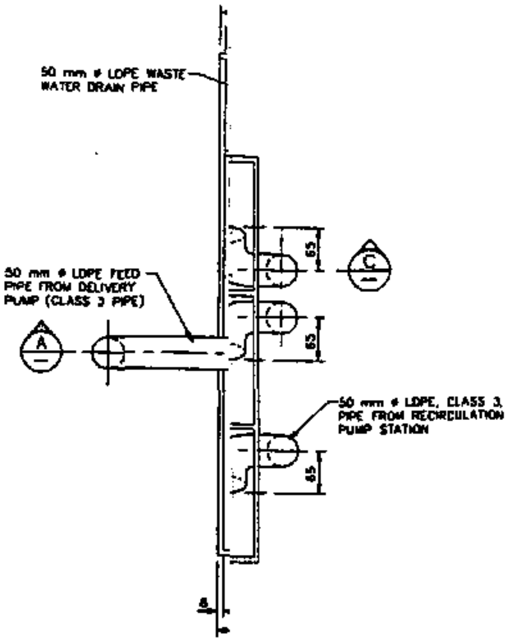
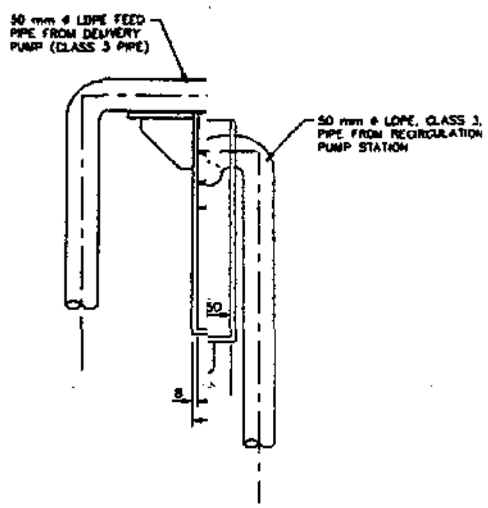
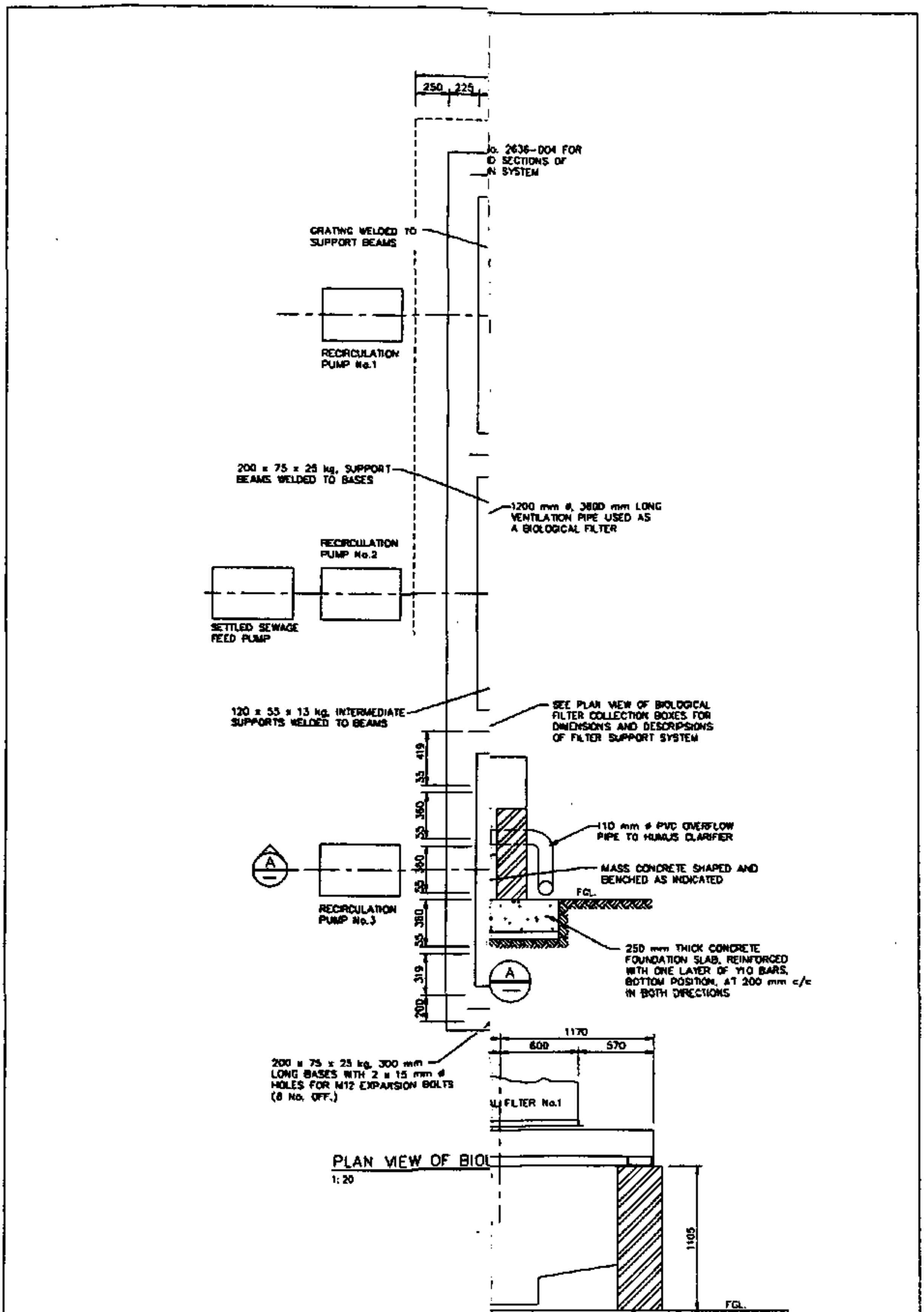
HIGH RATE BIOLOGICAL FILTRATION

APPENDIX 1

CONSTRUCTION DETAILS OF THE PILOT SCALE PLANT


50 mm ϕ LDPE WASTE WATER DRAIN PIPE
50 mm ϕ LDPE FEED PIPE FROM DELIVERY PUMP (CLASS 3 PIPE)
A
C
65
65
65
50 mm ϕ LDPE, CLASS 3, PIPE FROM RECIRCULATION PUMP STATION
8


50 mm ϕ LDPE FEED PIPE FROM DELIVERY PUMP (CLASS 3 PIPE)
50 mm ϕ LDPE, CLASS 3, PIPE FROM RECIRCULATION PUMP STATION
50
8



250
225
...o. 2636-004 FOR
...D SECTIONS OF
...N SYSTEM
GRATING WELDED TO SUPPORT BEAMS
RECIRCULATION PUMP No.1
200 x 75 x 25 kg. SUPPORT BEAMS WELDED TO BASES
1200 mm ø, 3800 mm LONG VENTILATION PIPE USED AS A BIOLOGICAL FILTER
RECIRCULATION PUMP No.2
SETTLED SEWAGE FEED PUMP
120 x 55 x 13 kg. INTERMEDIATE SUPPORTS WELDED TO BEAMS
SEE PLAN VIEW OF BIOLOGICAL FILTER COLLECTION BOXES FOR DIMENSIONS AND DESCRIPSIONS OF FILTER SUPPORT SYSTEM
419
55
360
55
360
55
380
55
319
200
110 mm ø PVC OVERFLOW PIPE TO HUMUS CLARIFIER
MASS CONCRETE SHAPED AND BENCHED AS INDICATED
FGL.
A
RECIRCULATION PUMP No.3
250 mm THICK CONCRETE FOUNDATION SLAB, REINFORCED WITH ONE LAYER OF Y10 BARS, BOTTOM POSITION, AT 200 mm c/c IN BOTH DIRECTIONS
200 x 75 x 25 kg. 300 mm LONG BASES WITH 2 x 15 mm ø HOLES FOR M12 EXPANSION BOLTS (8 No. OFF.)
1170
600
570
...FLTER No.1
PLAN VIEW OF BIOL...
1:20
1105
FGL.
900
338
250

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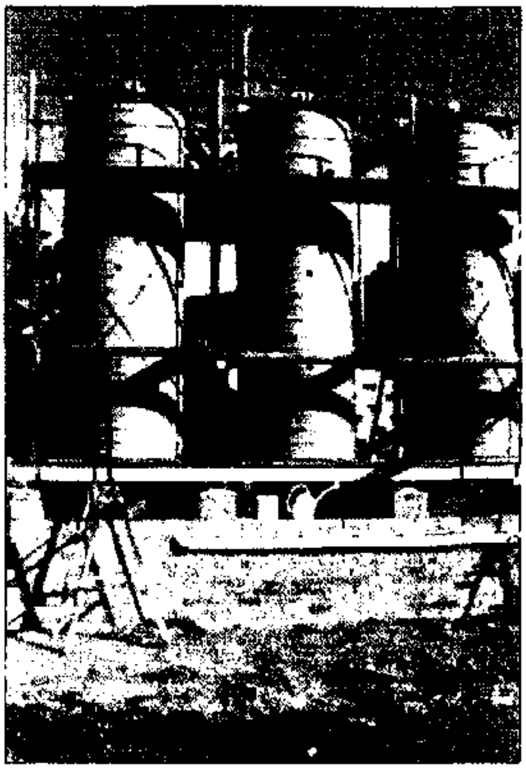
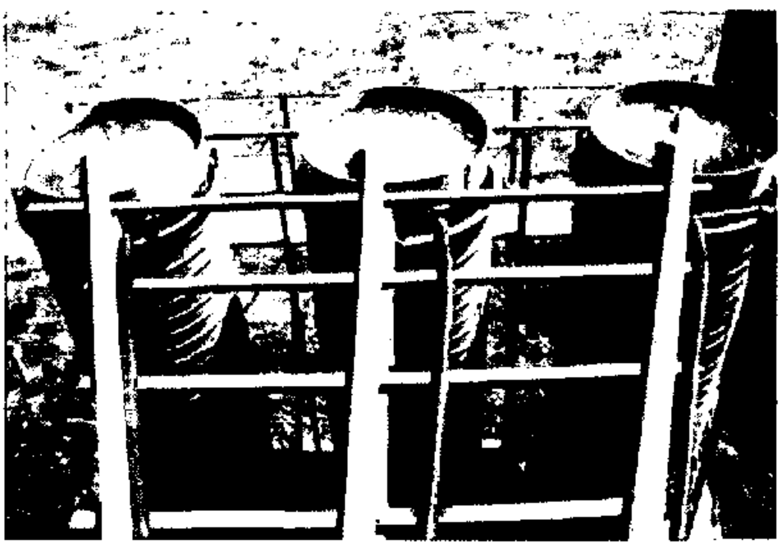
APPENDIX 2

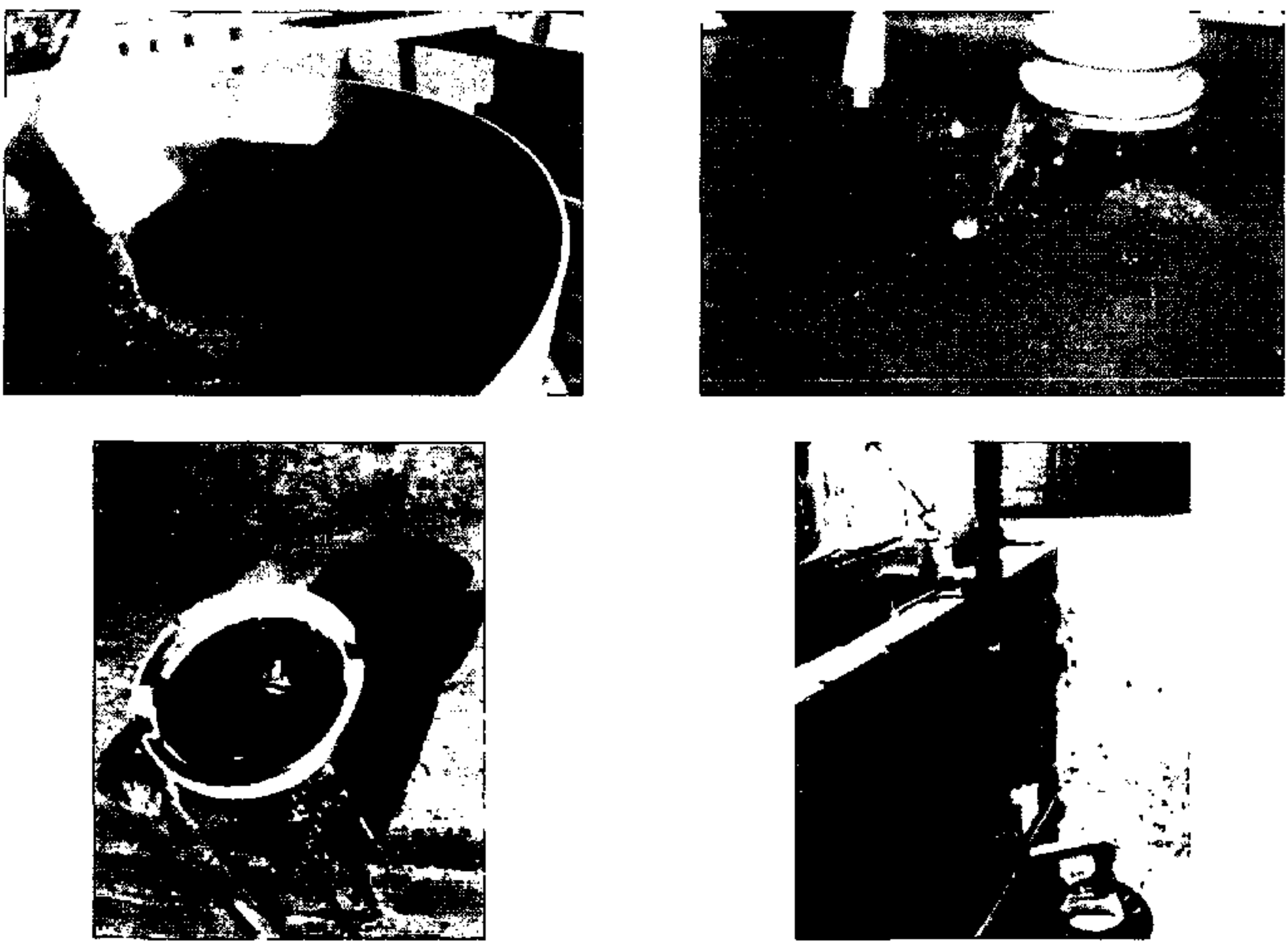
PHOTOGRAPHIC RECORD OF PILOT PLANT AND FULL SCALE BIOFILTERS



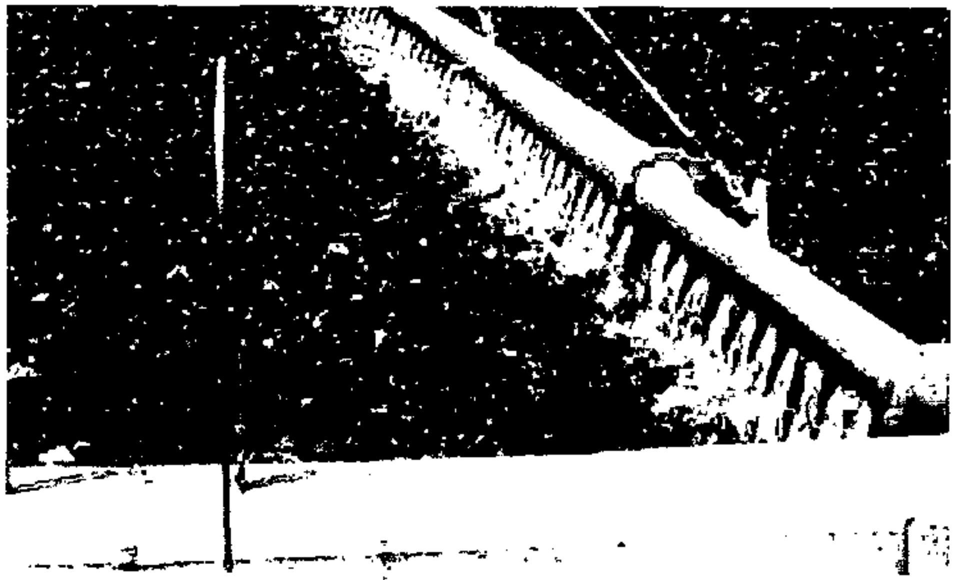


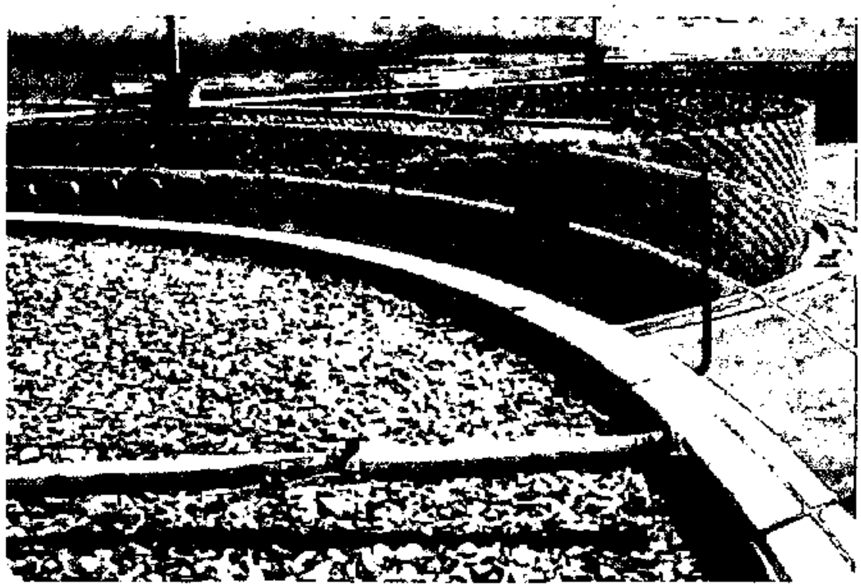
General View of the Biofilter Pilot Plant at the Baviaanspoort Water Care works

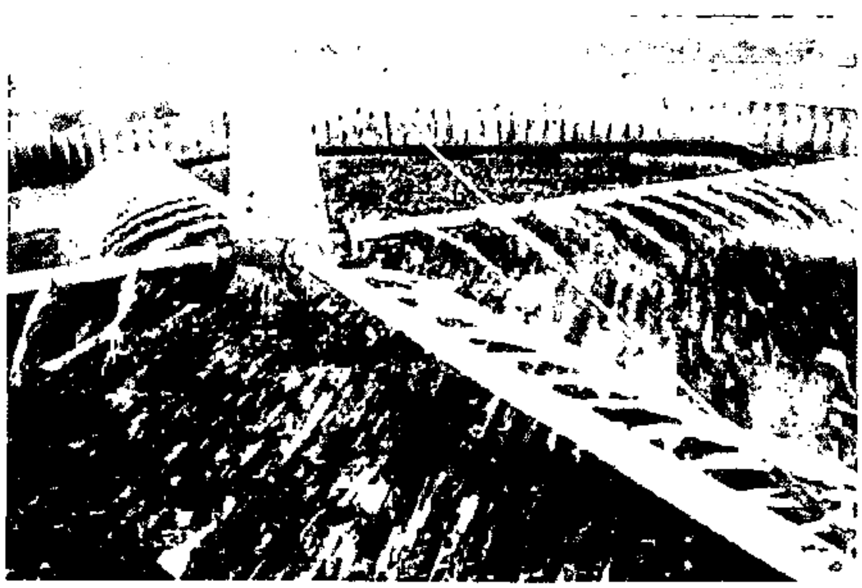
Flow distribution box on top of the Pilot Plant Biofilters



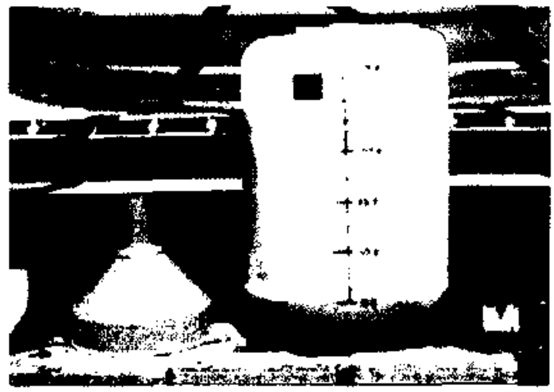
Recirculating Pump Installation



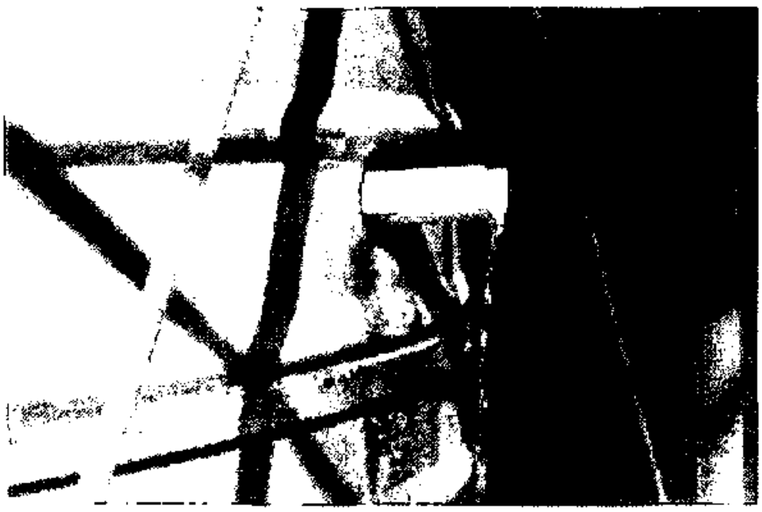




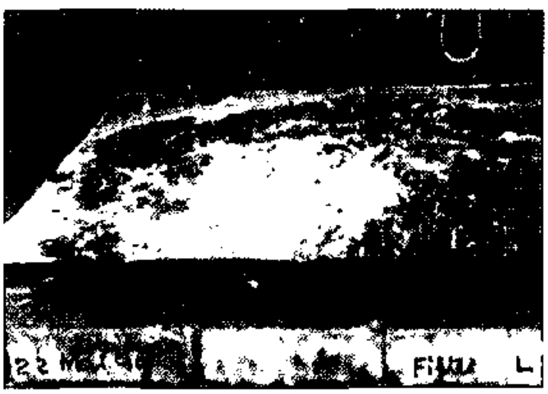
Flow distribution Mechanisms on Full-Scale Biofiltration Plants

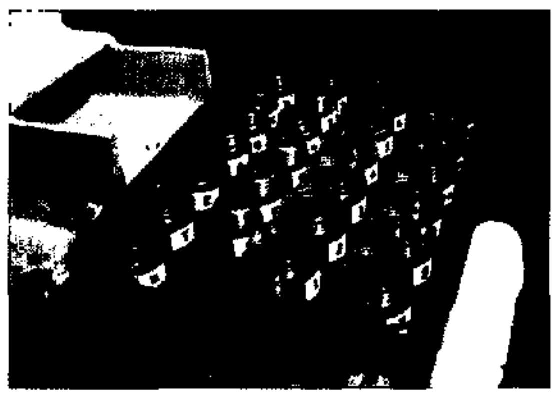


Pilot plant biofilter effluent dripping from bottom of pilot plant installation

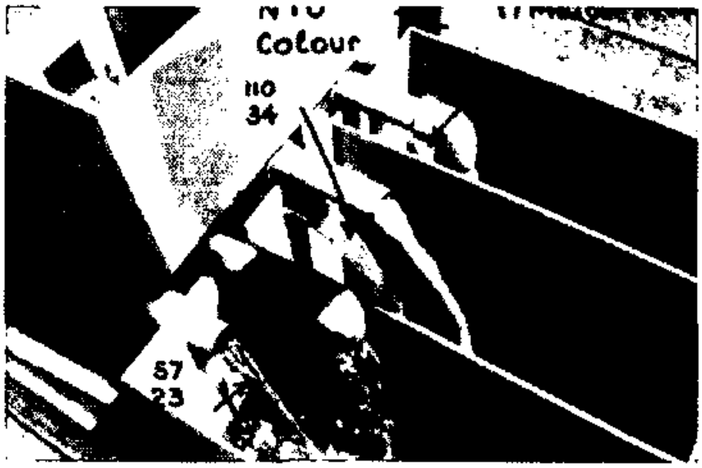


Sample post and sample tube on pilot plant biofilter

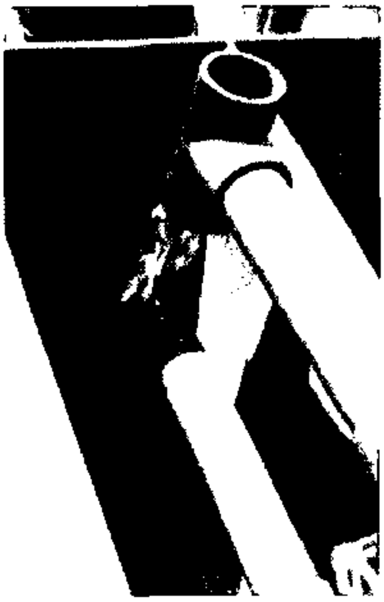


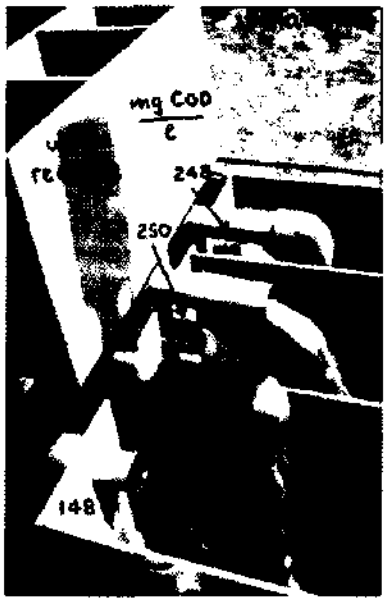


Pilot Plant Biofilter effluent and Sample Bottles



Pilot Plant biofilter Flow Splitting Box and Associated Pipework





Top View of Pilot Plant Flow Distribution Box