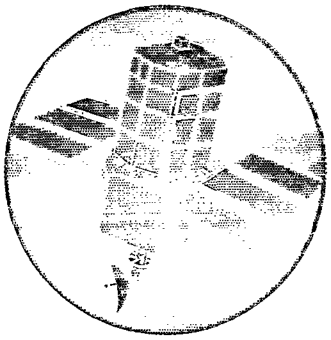
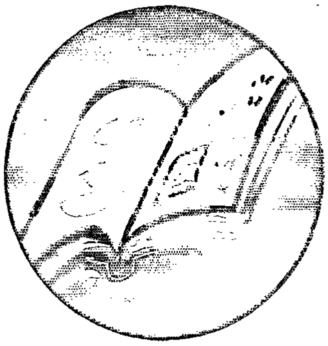
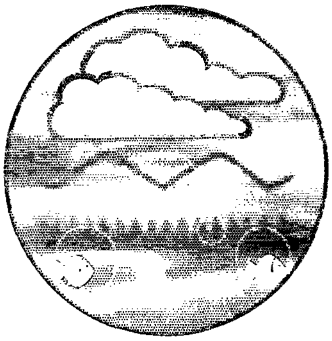
Land-Based Landfill Leachate Treatment

Research and Development

Technical Report
P228

ENVIRONMENT AGENCY

Land-Based Landfill Leachate Treatment

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R&D Technical Report P228

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Research Contractor:

Cranfield University and Shanks & McEwan Ltd

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Statement of use
This R&D report details the treatment processes responsible for the removal of ammoniacal nitrogen from landfill leachate irrigated onto vegetated treatment planes. Irrigation schedules, application methods, vegetation selection/management, treatment plane preparation and appropriate treatment plane technologies are recommended. The report will be of interest to landfill operators, regulators, consultants and anybody with an interest in landfill leachate management.

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EXECUTIVE SUMMARY

An investigation of the treatment processes responsible for the removal of ammoniacal nitrogen from leachate irrigated onto vegetated treatment planes was undertaken by the Department of Water Management, Silsoe College, Cranfield University.

Treatment planes are a widely used leachate treatment technology within Shanks & McEwan (Southern Waste Services) Ltd. Leachate is irrigated onto vegetated sloping land and returned to a recirculation lagoon by overland flow. Recirculation continues until the lagoon contents meet the discharge consent conditions at which point discharge can take place. Past operational experience has shown that the readily biodegradable organic components of the leachate are reduced to levels suitable for discharge within a few days of treatment, whereas ammoniacal nitrogen may take weeks to reach the discharge consent condition.

Despite the widespread use of treatment planes, the processes responsible for the removal of ammoniacal nitrogen on treatment planes were not well understood. Similarly, approaches to the design and operation of treatment planes were ill-defined.

A programme of experiments was undertaken with the aim of developing the scientific understanding of treatment plane processes and translating this into improved approaches to treatment plane design and management. Preliminary experiments were carried out at Silsoe College, in which leachate was recirculated on troughs (2m long x 0.4m wide x 0.2m deep) filled with soil and seeded with grass. The results of these preliminary experiments were used as guidance in the development of the experimental design of the principal field-scale experiments using purpose-built plots (25m long x 1m wide x 0.3m deep).

During 1994, three field-scale plot experiments were undertaken, supported by three trough experiments. Each experiment was of approximately 1 month duration. The principal variable tested was the hydraulic loading rate (leachate volume applied (*l*) per unit area of treatment plane (m^2) per day). Hydraulic loading rates were tested within the range 17 - 217 *l*/m^2/d. This range extended below and above rates of application at operational landfill sites.

The results confirmed that treatment planes can effectively reduce the volume of leachate within the treatment system and reduce COD, BOD and colour. The most significant results concerned the ability of the treatment plane to remove ammoniacal nitrogen. The daily mass removal of ammoniacal nitrogen per unit area of treatment plane varied from < 1 g/m^2/day to 45 g/m^2/day. Analysis of pooled data from the Silsoe College experiments demonstrated a relationship between the ammoniacal nitrogen removal capacity of the treatment plane (mass NH_3-N / m^2/d) and the leachate NH_3-N concentration. In simple terms, the treatment plane removed more ammoniacal nitrogen per unit area per day at high concentrations than at low concentrations. The relationship between ammoniacal nitrogen concentration and the treatment plane removal capacity was quantified and forms the basis of a model for sizing treatment planes and predicting treatment times. The finding that a treatment plane has a limited capacity to remove ammoniacal nitrogen, largely independent of hydraulic loading rate has implications for the running costs of treatment planes. It would appear that at operational sites, more leachate may be pumped onto treatment planes than can be effectively treated.

As a result of the Silsoe College experiments and the investigation of operational treatment planes, recommendations have been made regarding leachate irrigation schedules, leachate application methods, vegetation selection / management, treatment plane preparation and appropriate application of treatment plane technology. In particular, the use of treatment planes as a pre-treatment prior to conventional biological treatment systems is highlighted. This application of treatment plane technology is worthy of further consideration in the context of leachate treatment requirements associated with accelerated stabilisation of landfill.

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1. INTRODUCTION

1.1 CONTRACT DETAILS

This work was commissioned by Wastes Technical Division of the Department of the Environment under Contract no. PECD 7/10/252. The work was undertaken by staff of the Water Management Department at Silsoe College, Cranfield University and by staff of Shanks & McEwan (Southern Waste Services). The work was undertaken over the period 01-01-92 until 31-03-95.

1.2 BACKGROUND

1.2.1 Leachate production

Landfill leachate is produced at all landfill sites. In addition to the initial moisture-content of the solid waste and any liquid waste inputs, water may enter the landfill site as a result of the ingress of precipitation, surface water or groundwater. As the water passes through the waste, leaching of various organic and inorganic materials occurs and if the site has accepted a significant proportion of degradable material the result can be a highly polluted liquor.

In the past, landfill sites relied on natural attenuation processes (soil physicochemical processes such as ion exchange and precipitation), dispersion and dilution to reduce the polluting effects of the leachate seeping from the fill into surrounding ground. Concerns about the protection of groundwater resources (Edworthy, 1989; Palmer and Young, 1991; Robinson and Gronow, 1992) and the prevention of landfill gas migration have resulted in legislation and codes of practice (notably the Environmental Protection Act of 1990, the Water Resources Act 1991 and Waste Management Paper 27) which demand that landfill sites are designed in such a way that environmental pollution is minimised, hence the trend toward so-called containment. This may be achieved by lining the base and sides of a site with very low permeability material, diverting surface water and dewatering where necessary (Philpott *et al*, 1992). Leachate generation may be minimised if the operational area is kept as small as reasonably possible until each part of the site is completed and a low permeability cap is installed over the waste. It is extremely difficult to predict leachate production rates however, as they depend upon variables such as site characteristics, operational practices, climatic conditions and the types of wastes deposited. Several models (Blakey and Young, 1991; Blakey and Craft, 1991) of leachate production rates based on water balances have been produced but they lack transferability.

More recently, emphasis has shifted from leachate minimisation towards the aim of rapid stabilisation of landfill sites through the recirculation of leachate and possibly additional freshwater. This means maintaining wet, anaerobic conditions within the fill leading to the production of greater volumes of landfill gas and, if no additional freshwater is recirculated, stronger leachate over a shorter active period. The low permeability cap prevents the uncontrolled release of landfill gas in such situations. A build up of leachate at the base of a site develops a hydraulic head over the liner which may result in leakage (Seymour and Peacock, 1989). In addition, concentration gradients across the liner will result in diffusion of pollutants. To prevent pollution of groundwater, streams and rivers the leachate must be extracted and treated prior to discharge to the environment, normally a surface water course or sewer. Any discharge must be in compliance with discharge consent conditions as set out by the National Rivers Authority (NRA) in England and Wales, in the case of a watercourse, or HMIP and/or the sewerage undertaker in the case of a sewer.

The extraction of leachate from older sites has proved difficult, due to the physical properties of compacted waste. In new sites, an underdrainage system may be installed before filling operations begin but this in itself can have no effect on the physical nature of the waste and problems of compaction can still restrict efficient drainage (Ramke, 1989). The leachate is often stored in lagoons on the landfill site prior to treatment.

1.2.2 Leachate composition

For the purpose of this document, leachate may be regarded as that arising from household and other degradable wastes. Leachate composition is highly variable, being a function of the types and ages of the waste, the prevailing chemical conditions and the microbiology and water balance of the landfill. Leachate quality and quantity therefore varies between sites, with the seasons, and as the site ages. Landfilled waste will continue to produce leachate for years after the filling operations have ceased. It is impossible to predict leachate composition accurately at a given site or time.

Broadly speaking, leachates from recently filled waste contain high levels of organic acids and ammoniacal nitrogen. In older landfills, as degradation of the waste continues, these acids are broken down to methane and carbon dioxide so that older leachates contain even higher concentrations of ammoniacal nitrogen but much lower levels of organic material. Chloride concentrations tend to remain high throughout the leachate production phase reflecting the high solubility of the chloride ion.

Leachate is unsuitable for direct discharge into freshwater courses. The high Biochemical Oxygen Demand (BOD) and ammoniacal nitrogen concentrations would have a severe impact on the ecology of the receiving water. Strict controls imposed by regulatory authorities dictate the permissible volumes of leachate and concentrations of various substances within the leachate discharged from site. Several studies (Chian and Dewalle, 1977a; Chian and Dewalle, 1977b; Robinson and Maris, 1979; Robinson and Luo,1991) address the issue of leachate composition and the factors which influence it. This information can then be used to evaluate treatment methods.

1.2.3 Leachate treatment

In almost all cases, some form of treatment is required before leachate can be discharged to sewer or surface water. The landfill operator selects the most cost-effective treatment to enable the leachate to meet the required quality (as laid down in the Surface Water or Trade Effluent Discharge Consent). Various treatment options exist, ranging from intensive, high technology methods to extensive low technology methods (Robinson *et al,* 1992; Robinson and Maris, 1983; Harrington and Maris, 1986; Knox, 1987).

Many operators have shown resistance to high technology, intensive, leachate treatment systems, due to their high capital costs, high management and maintenance requirements. Extensive systems require less management input and are usually considered to be cheaper to install. They also have the potential advantage of providing a low cost method of leachate treatment after the site has closed. Further, extensive systems may be less sensitive than intensive biological treatments to changes in leachate quality and volume.

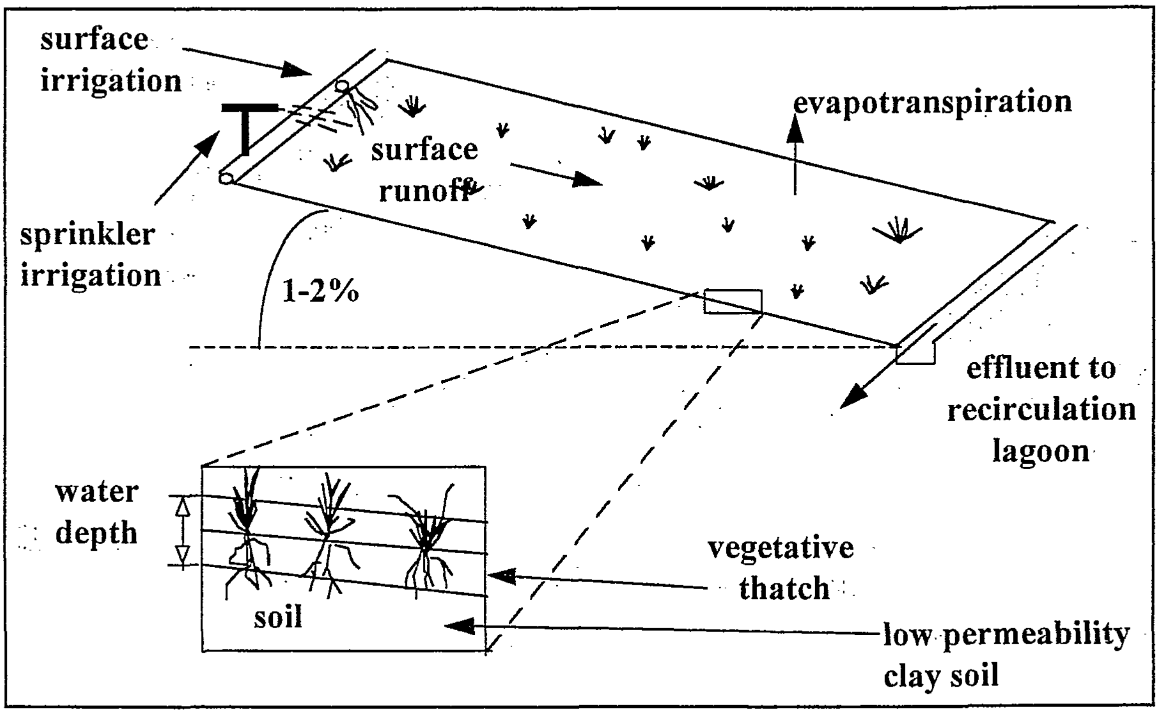
Land-based systems such as constructed wetlands (Robinson, 1990; Hammer, 1989; Robinson *et al,* 1991) and overland flow systems(Perry *et al,* 1982; Wightman *et al,* 1983; Glide *et al,*1971; Schelinger and Clausen, 1992) have been used to treat sewage and other wastewaters for many decades and some of the methods have been applied to leachate treatment (Bennet *et al,* 1975; Norstedt *et al,* 1975). They have commonly been used as a final polishing stage, just prior to discharge to a water course or, in a few cases, as a pre-treatment before some other process. Shanks & McEwan Ltd have used overland flow as their principal treatment process on several of their landfill sites over a number of years. This treatment method may be considered as low technology and requires a relatively low investment. Overland flow methods are an attractive option as they make use of existing resources such as land, pipework and pumps.

1.2.4 Overland flow

Overland flow systems involve the application of wastewater onto a vegetated slope, on low permeability clay soils (Metcalf and Eddy, 1991). The leachate passes over the surface of the slope (with minimal infiltration) and is collected at the base of the slope. It is then recirculated through the system until the target quality is achieved. The main features of overland flow systems are shown in Fig. 1.2.1.

Treatment occurs by the interaction of the wastewater with soil, vegetation and micro-organisms (Chan *et al,* 1978). Whilst these systems have been shown to be able to treat leachate to meet discharge consent requirements, little was known of the treatment mechanisms involved or factors affecting efficiency. As a result, treatment planes have often been designed and managed on an *ad hoc* basis and little was known of the importance of operational variables such as land area requirements, gradient of site, soil requirements, suitable vegetation, irrigation rate and schedule. Much has been written on the subject of constructed wetland design and factors affecting their efficiency, but less is known about overland flow systems. Existing knowledge of overland flow systems is mainly confined to the treatment of municipal wastewaters (Tucker and Vivado, 1983; Smith and Schroeder, 1983). A few studies have dealt specifically with landfill leachate (Wong and Leung, 1989; Johnstone *et al*, 1988; Menser *et al*, 1983; Khalid *et al*, 1982; . Bennett *et al*, 1975; Norstedt *et al*, 1975). However, these have tended to concentrate on the impact of leachate on vegetation growth rather than on descriptions/quantification of treatment processes.

Fig. 1.2.1 Main hydrological features of overland flow treatment systems



1.3 EVOLUTION OF THE PROJECT

Experience at Shanks & McEwan sites has shown that of all of the potential pollutants in leachate ammoniacal nitrogen is the most difficult constituent to treat. The high levels of ammoniacal nitrogen typically found in leachate are not easily amenable to biological treatment due to inhibition of the nitrification process.

However, experience with overland flow at operational sites had shown that rates of ammoniacal nitrogen removal could be significant, although the extent and efficiency of removal had not been quantified.

It was originally intended to carry out experimental work to study the operational factors affecting these processes at an operational landfill site. However, this proved to be impossible owing to constraints placed upon the research by the operational requirements of the site. Also the size and layout of the operational plane did not lend itself to the precise leachate distribution and monitoring needed. It was subsequently agreed therefore that the experiments should be conducted at Silsoe College where an experimental treatment plane would be constructed. Data from large scale experiments on this plane have been supplemented by smaller laboratory experiments and the monitoring data from operational sites.

1.4 STATEMENT OF AIMS AND OBJECTIVES

1.4.1 Aim

The aim of the research was to develop an improved methodology for leachate treatment plane design and management.

1.4.2 Objectives

The primary objective of the research was to derive a quantitative model of ammoniacal nitrogen (NH_3-N) removal within the leachate treatment plane system that might be used as a basis for sizing treatment planes.

Secondary objectives of the research were:

- to determine and if possible, quantify the processes responsible for the removal of ammoniacal nitrogen (NH_3-N).

- to quantify the effect of varying hydraulic loading rate, initial ammoniacal nitrogen concentration, intermittent leachate irrigation and season on the ammoniacal nitrogen (NH_3-N) removal process.

- to quantify the effect of treatment upon a range of secondary chemical determinants, particularly chemical oxygen demand (COD).

- to monitor the ability of the chosen grass species, *Agrostis stolonifera*, to survive under a variety of leachate irrigation and concentration regimes.

2. METHODOLOGY

2.1 EXPERIMENTAL APPROACH

Operational treatment planes usually have an area of several hectares and as such, it was considered desirable to conduct the research on a scale as large as practically possible. An experimental treatment plane (16 m x 25 m) was constructed at Silsoe College that consisted of ten 25 m long x 1 m wide plots plus a range of supply and collection tanks. However, while this was being built, the opportunity was taken to provide preliminary information on the operation of the plane by conducting interim experiments using small soil-filled troughs 2 m long x 0.4 m wide over which leachate was discharged.

2.2 PRELIMINARY TROUGH EXPERIMENTS

2.2.1 Construction

The troughs were constructed from mild steel sheet and were 2 m long x 0.4 m wide x 0.2 m deep (Fig. 2.2.1). They were partially filled to a depth of approximately 0.1 m with the clay loam soil (Wicken series) found at the experimental site at Silsoe College. This was then covered with turf, taken from an operational treatment plane, in which the predominant grass species present was *Agrostis stolonifera*. The troughs were positioned such that they had a 2% down-slope gradient and a 0% cross-slope gradient. Leachate was applied to each trough from its own 220 l reservoir that discharged its contents via a control valve to a transverse distributor (Fig. 2.2.2) positioned at the upper end of the trough. At the lower end of the distributor, residual leachate was collected in an identical 220 l polypropylene barrel.

Fig. 2.2.1 Trough design

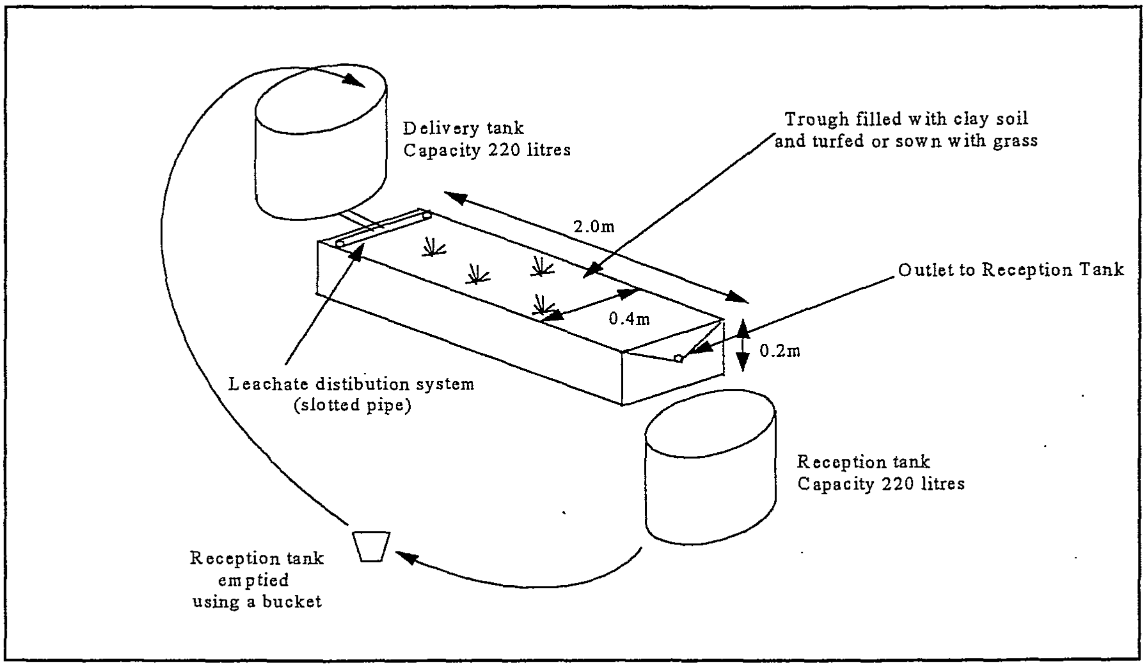
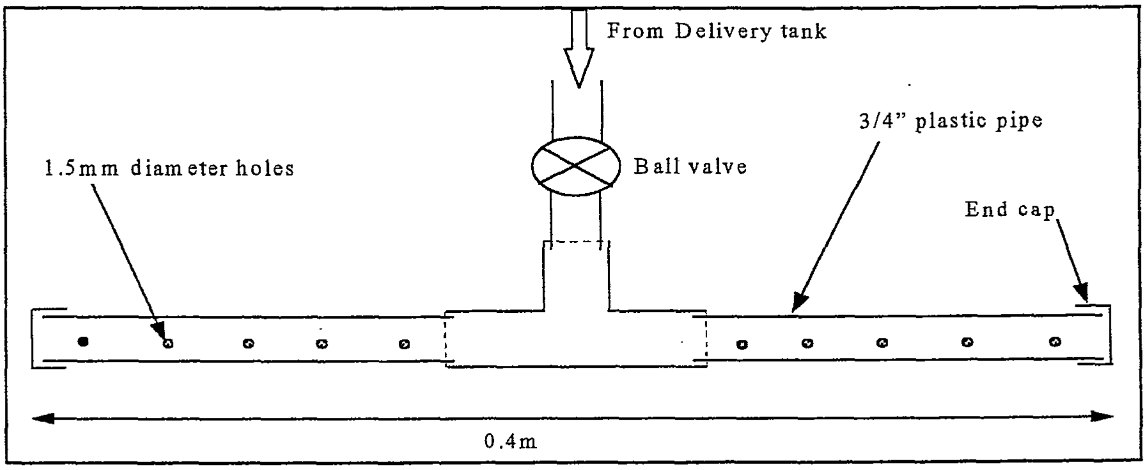


Fig. 2.2.2 Leachate distributor



2.2.2 Operational procedure

The troughs were operated on a 24 hour cycle. Leachate application began at 10 am. and continued for 5 hours. The soil was then allowed to drain and dry for 19 hours until the next application period began the following day. Research in the United States with overland flow systems for the treatment of domestic wastewater has shown that an application period followed by a drying period improved treatment efficiency (Smith and Schroeder, 1985). The troughs were operated on weekdays only. The required hydraulic loading rate was set by adjusting the ball valve on the leachate distributor and was subsequently checked and adjusted as required at hourly intervals. Runoff from the trough outlet collected in the reception tank, the contents of which was sampled and then returned to the delivery tank. The volume lost by evaporation during the previous 24 hour period calculated on the basis of the volume remaining.

2.3 PLOT EXPERIMENTS

2.3.1 Construction

Plot construction began in the spring of 1993 and continued until late summer of the same year. 10 separate plots of 25 m length, 1 m width and 0.4 m depth were constructed. Each plot had its own dedicated 1.25 m^3 delivery tank and two linked 1.25 m^3 reception tanks. The plots were lined to prevent seepage out of the system.

The first stage of construction was to excavate a pit (approximately 16 m long x 2.5 m wide x 2 m deep) to hold the reception tanks for collecting runoff from the plots. A reinforced concrete base was laid and tied to reinforced hollow block retaining walls.

Treatment plane preparation began on completion of the pit. 0.4 m of topsoil across the 25 m x 16 m treatment plane site was removed and stockpiled. The site was then graded to give a 2% down-slope gradient and a 0% cross-slope gradient with the lower end of the slope meeting the edge of the pit retaining wall. Ten plots were then marked out in five pairs, each pair separated by a 1 metre wide pathway for access

(Fig. 2.3.1). A light timber frame was erected on each plot. A singe piece of polyethylene damp-proof membrane was positioned over each pair of plots as shown in Fig. 2.3.2. The stored topsoil was broken up with a power harrow and carefully replaced inside the polythene lined plots. The soil was then irrigated with water to help break down the large clods into smaller aggregates. Seed of the grass *Agrostis stolonifera* was sown on the completed plots in early autumn, at a rate of 50g / m^2. *Agrostis stolonifera* was selected for the trials because it had been observed growing well on existing treatment planes and had performed well in pot trials (Bradford, 1992). At the lower end of each plot, connected to a 2 inch outlet pipe that discharged to a reception tank located in the pit. The end of the pipe was protected by a sheet of wire mesh and the trap half-filled with puddled clay (Fig. 2.3.3). Finally, a 1.25 m^3 delivery tank was placed on a bund at the upper end of each of the plots.

Fig. 2.3.1 Layout of the field-scale experimental treatment plane

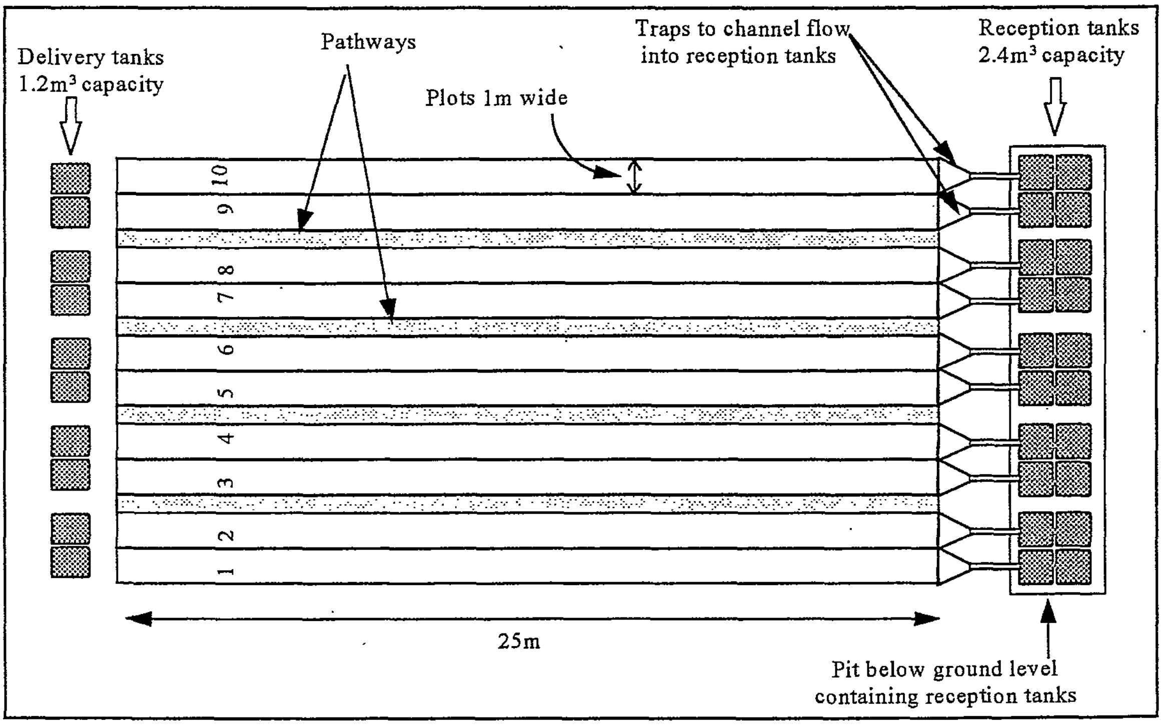


Fig. 2.3.2 Cross section of a pair of plots

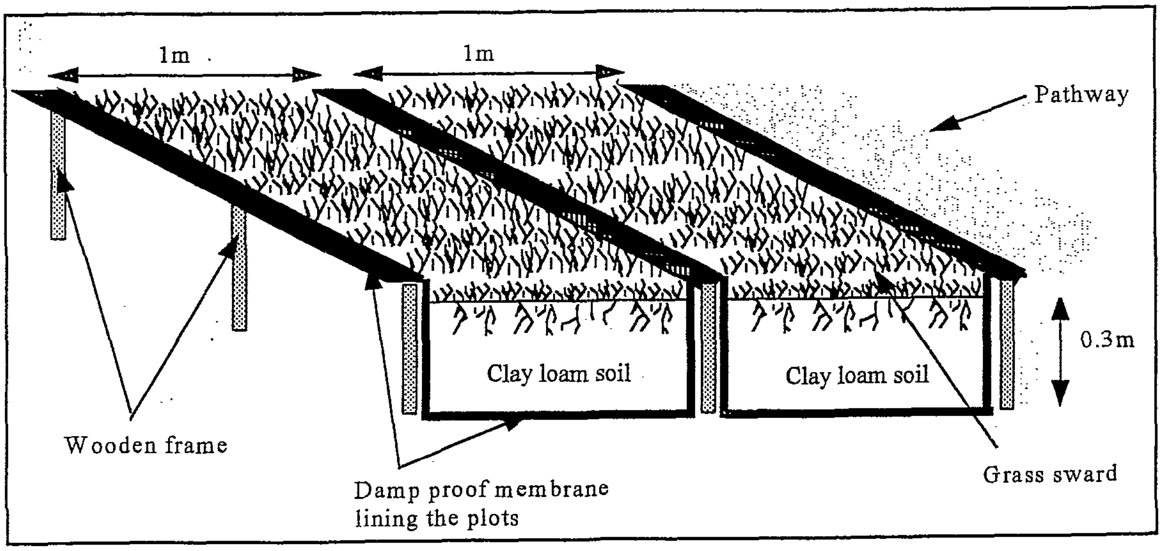
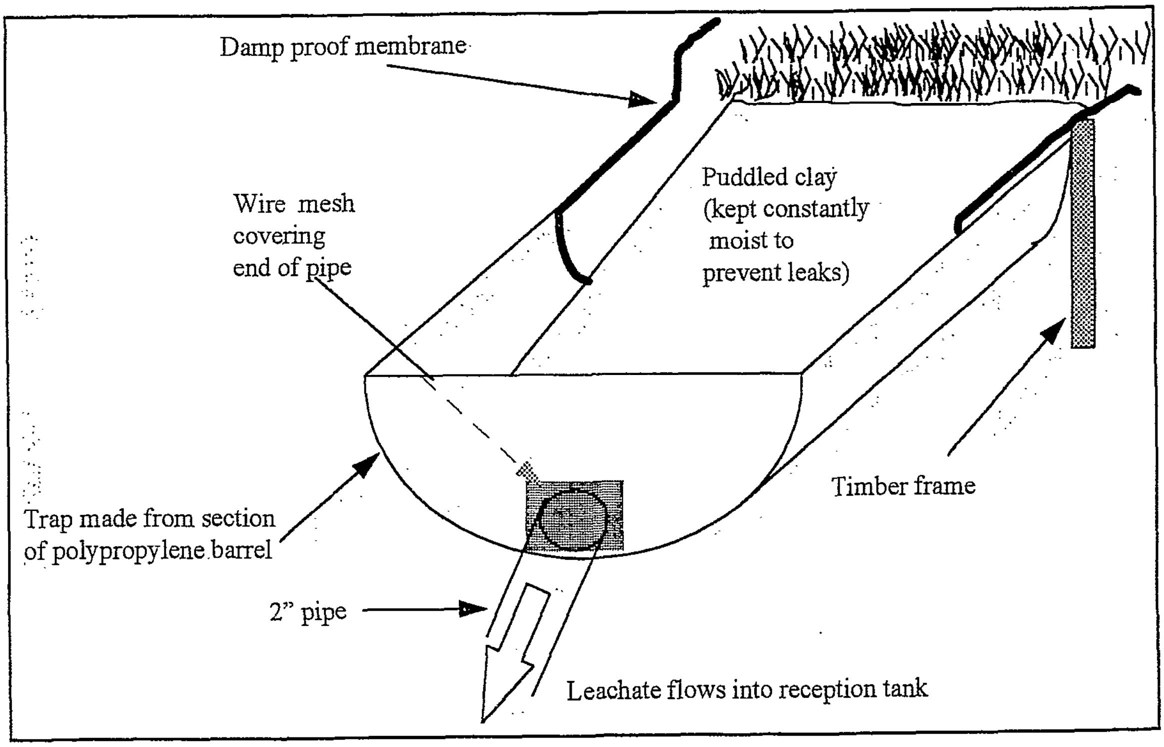


Fig. 2.3.3 Trap design



2.3.2 Operational Procedure

The plots were operated on a 24 hour cycle in a similar manner to the earlier trough experiments ie. 5 hours of leachate application typically beginning at 10 am and followed by a 19 hour drain and dry period. As with the trough experiments, the plots were operated on weekdays only. The hydraulic loading rates were set by adjusting the ball valve at the base of the delivery tank and calibrated by using a stopwatch and bucket to collect and measure the flow. This procedure had to be repeated at hourly intervals due to the combined effects of insensitive tank outlet valves and the falling head in the delivery tank. Therefore the target hydraulic loading rates were superseded by average measured hydraulic loading rates. In order to ensure uniform discharge across the 1 m width of the plot, the leachate was fed initially to a trough positioned transversely across the top of the plot. This was aligned horizontally so that it functioned as a side discharge weir over which the leachate could trickle out.

The volume of leachate collected in the reception tanks was measured each morning using the calibrated dipstick. It was then pumped back into the delivery tanks. Once the reception tank had been pumped dry the pump was switched off and any leachate remaining in the hoses drained back down under gravity to the reception tank. As a result between 50-100 litres were not returned to the delivery tank each morning but instead remained in the reception tank until the following day to be incorporated into the next batch to be recirculated. The volume of leachate in the delivery tank was measured each day by calibrated dipstick before and after the addition of the recirculated leachate. A sample of the mixed leachate in the delivery tank was taken as soon as irrigation onto the plots began.

2.4 LEACHATE SAMPLING AND ANALYSIS

Leachate samples were taken every weekday morning from delivery tanks following the return and mixing of the treated leachate with any untreated leachate. This mimics the operational situation where treated leachate running off the treatment plane mixes with the leachate remaining in the recirculation lagoon. Therefore a sample taken from the recirculation lagoon is a composite sample of leachate that has been treated recently and leachate that has not. All leachate samples were analysed by Shanks &

McEwan at the Stewartby Landfill Site Waste Input Monitoring Facility. Wherever possible, ammoniacal nitrogen (NH_3-N), nitrate nitrogen (NO_3-N), nitrite nitrogen (NO_2-N) and COD were measured daily by colorimetry using a Hydrocheck 600C spectrophotometer. Chloride was measured daily initially and then weekly by colorimetry. pH was measured daily using a pH electrode.

2.5 EXPERIMENTAL PROGRAMME

Six experiments were conducted between January and September 1994 comprising three trough experiments (Experiments A, B, E) and three plot experiments (Experiments C, D, F). The initial trough experiments (A and B) each lasted about 1 month and provided useful information regarding the management of the full-scale plane and in particular, the range of hydraulic loading rates that should be applied to the plot trials. The initial plot trial (C) was of limited duration (13 days) but served to draw attention to the practical problems associated with the larger-scale experiment. It was found that the 1.25 m^3 capacity of the delivery tanks was insufficient to sustain an experimental run of longer than 2 weeks on a 25 m^2 plot due to water loss by evapotranspiration. This problem was overcome in two ways. Firstly, plot length (and therefore area) was reduced by moving the distributor trough down the plot. The standard plot length became 20 m and in some cases a 10 m plot length was used to increase the hydraulic loading rate (ie. by halving the surface area of a plot the hydraulic loading rate can be doubled). Secondly, the delivery tank volume to each plot was increased by linking the delivery tanks for two plots together to feed a single plot. Although this move halved the number of plots available, it coincided with the discovery that plots 7 and 8 were losing water faster than the other plots because of damage to the polyethylene liner. Thus, plots 7 and 8 had to be rejected for further use. Out of the 10 plots installed, only four were successfully adapted for experimental study (Plots 2,4,6 and 9). Summary information about the experiments is presented Table 2.5.1.

Table 2.5.1 Summary of the experimental programme

Experiment	Dates	Days duration	Type	Initial NH_3-N concentration mgl^{-1}	Hydraulic Loading Rates (H) $l/m^2/d$
A	17/01/94-18/02/94	32	Troughs	T1 573 T2 573	T1 H=87 T2 H=217
B	23/02/94-25/03/94	30	Troughs	T1 119 T2 136 T3 412 T4 379	T1 H=90 T2 H=44 T3 H=90 T4 H=44
E	13/06/94-01/07/94	18	Troughs	T1 507 T2 511 T3 523	T1 H=78 T2 H=43 T3 H=17
C	26/04/94-09/05/94	13	Plots	Various	Various (commissioning site)
D	23/05/94-28/06/94	36	Plots	P2 113 P6 128 P9 134	P2 H=70 P6 H=24 P9 H=37
F	01/08/94-05/09/94	35	Plots	P2 218 P4 264 P6 330 P9 247	P2 H=75 P4 H=45 P6 H=23 P9 H=45

NB: The hydraulic loading rate refers to the volume of leachate applied per square metre of treatment plane surface area during the 5 hours in the daily cycle that leachate was being applied.

3. RESULTS AND DISCUSSION

3.1 REMOVAL OF AMMONIACAL NITROGEN ON EXPERIMENTAL TREATMENT PLANES

3.1.1 Rate of removal of ammoniacal nitrogen

The experiments demonstrated that irrigation of leachate onto a treatment plane results in the removal of ammoniacal nitrogen (NH_3-N). The pattern of removal of NH_3-N was similar in each of the six experiments (A,B,E on troughs and C,D,F on plots) in that a curve resulted from the plot of NH_3-N concentrations against time. These curves are presented in Appendix 1. Fig. 3.1.1 illustrates a typical curve for one of the plots in experiment D. The best-fit curve plotted on the graph conforms to a first-order model, suggesting that the rate of NH_3-N removal is directly proportional to the NH_3-N concentration:

$$\mathbf{C = C_o exp(kt)}$$

Equation 3.1.1

Where:

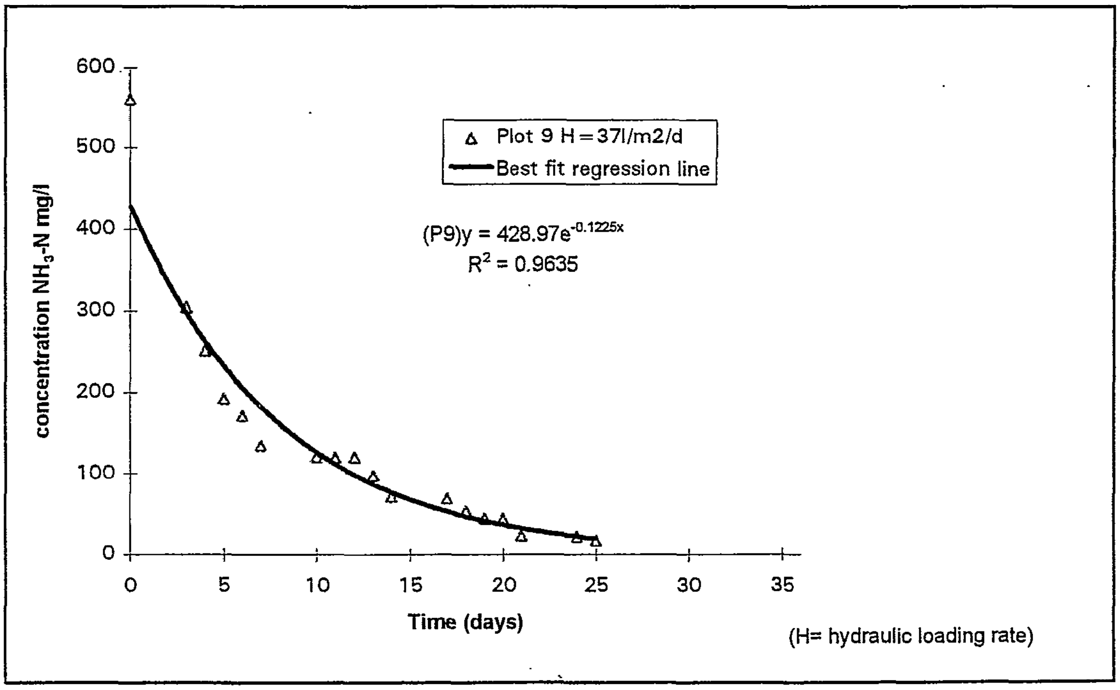
C = NH_3-N concentration (mg/l) at time t

C_o = NH_3-N concentration (mg/l) at t = 0

k = reaction rate constant (d^{-1})

t = time (d)

Fig. 3.1.1 Change in NH_3-N concentration for Plot 9 Experiment D with best fit line plotted



The best-fit equations (using least squares regression analysis) for each of the treatments are presented in Table 3.1.1 along with the respective coefficient of determination (r^2). The r^2 values suggest that a first-order model can account for the majority of variation in the experimental data.

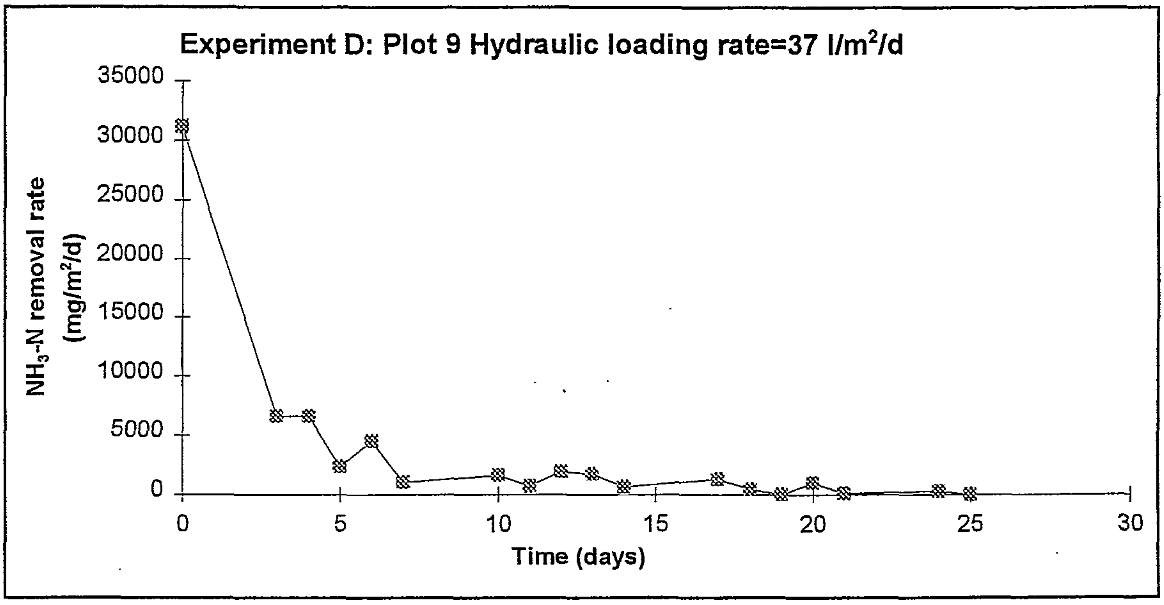
Table 3.1.1 Best-fit equations and coefficients of determination for each of the experimental treatments

Experiment	Trough (T) / Plot (P) Number[#]	Best-fit equation	r^2
A	T1	$y = 495.48e^{-0.0535x}$	0.9829
A	T2	$y = 454.47e^{-0.0479x}$	0.9690
B	T1	$y = 149.71e^{-0.0787x}$	0.9498
B	T2	$y = 142.59e^{-0.053x}$	0.9662
B	T3	$y = 438.09e^{-0.0575x}$	0.9574
B	T4	$y = 346.82e^{-0.0273x}$	0.9627
D	P2	$y = 387.82e^{-0.071x}$	0.8246
D	P6	$y = 486.63e^{-0.0985x}$	0.9057
D	P9	$y = 428.97e^{-0.1225x}$	0.9635
E	T1	$y = 491.14e^{-0.0644x}$	0.9878
E	T2	$y = 478.35e^{-0.0612x}$	0.9903
E	T3	$y = 496.74e^{-0.0338x}$	0.9825
F	P2	$y = 139.68e^{-0.0412x}$	0.8508
F	P4	$y = 195.81e^{-0.0335x}$	0.9169
F	P6	$y = 249.56e^{-0.0382x}$	0.8989
F	P9	$y = 237.48e^{-0.0463x}$	0.904

[#]Experimental treatment corresponding to each trough/plot given in Table 2.4.1

The general shape of the experimentally-derived NH_3-N removal curves has implications in terms of the dynamics of NH_3-N removal. The NH_3-N removal curves demonstrate that NH_3-N is removed rapidly during the first few days of the treatment of a leachate batch with the rate of removal slowing considerably towards the end of the treatment period. This effect may be quantified in terms of the change in mass NH_3-N removal (mg NH_3-N / m^2 /d) with time. A typical example of the change in mass NH_3-N removal with time is given in Fig. 3.1.2. In this case, mass removal on day 1 is 31 147 mg NH_3-N / m^2 /d falling to 235 NH_3-N / m^2 /d, by day 24. Thus the treatment plane is much more efficient during the first few days of a batch than at the end. This would be expected if the reaction is first-order as the rate of reaction is proportional to the reactant concentration. As the treatment system works on a batch recirculation basis, the concentration is highest on day one and lowest on the final day of treatment. Consequently, the rate of removal will be highest on day one and lowest on the final day of treatment.

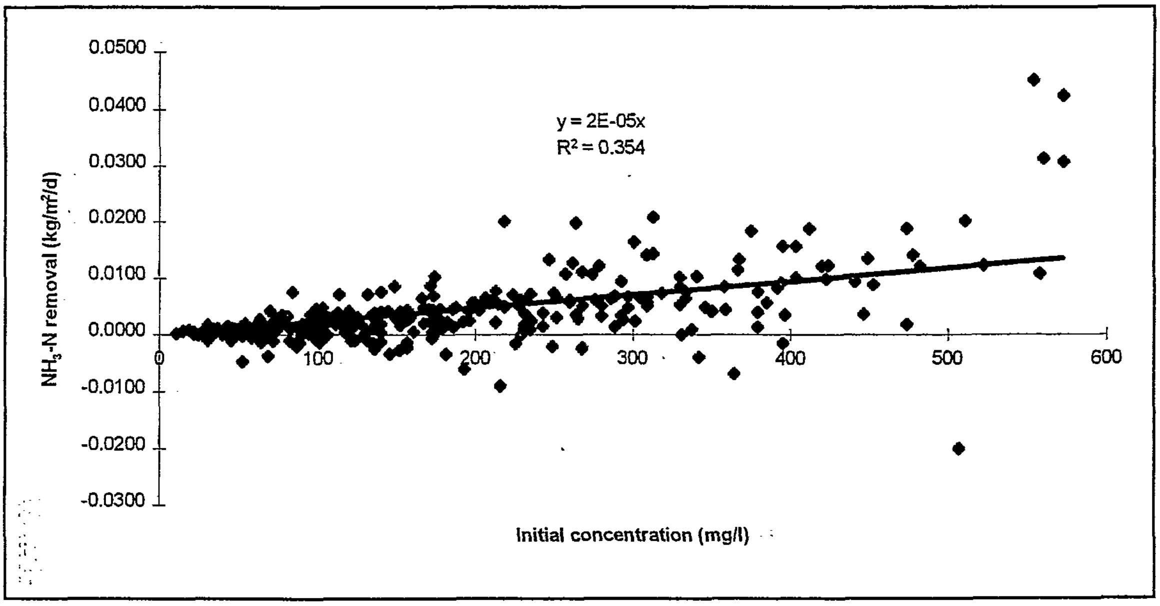
Fig. 3.1.2 Relationship between mass removal (mg NH_3-N / m^2 /d) and time for Plot 9 Experiment D



3.1.2 Effect of concentration on rate of removal of ammoniacal nitrogen

The pattern of NH_3-N removal observed suggests that there is a relationship between NH_3-N concentration and the mass removal rate. To test this idea, the data from the three plot experiments and two plot experiments were pooled to derive a generalised relationship between the rate of NH_3-N removal (kg NH_3-N / m^2 /d) and the leachate NH_3-N concentration. For each day of each of the experiments, the NH_3-N mass removed was calculated and plotted against the leachate NH_3-N concentration at the start of the day (Fig. 3.1.3). The figure demonstrates a significant ($p<0.99$) positive correlation (although there is considerable variation around the regression line) between NH_3-N removal rate and NH_3-N concentration *ie.* the higher the NH_3-N concentration at the start of each day of treatment, the greater the mass of NH_3-N removed per square metre. The relationship derived from this analysis can be used to predict the treatment rate per square metre on any day if the starting concentration is known and as such can be used for treatment plane sizing (see Section 4).

Fig. 3.1.3 Relationship between NH_3-N removal rate and concentration for pooled data



This relationship between NH_3-N removal rate and NH_3-N concentration could have implications for future utilisation of leachate treatment planes. Land-based treatment systems are often promoted as tertiary or 'polishing' systems with the role of bringing pre-treated effluent to the discharge consent level. However, this research implies that treatment planes may be working relatively less effectively at the low NH_3-N concentrations associated with polishing systems. A further implication is that treatment planes could have a role as pre-treatment systems for leachates with high NH_3-N concentrations prior to conventional biological processes such as Rotating Biological Contactors or Aerated Lagoons.

A further practical implication of the relationship between NH_3-N removal rate and NH_3-N concentration is the effect on the practice of dilution. Leachate often has to be diluted with fresh water in order to meet the discharge condition for chloride. At certain sites, this is carried out prior to irrigation onto the leachate treatment plane. This could be counter-productive because reducing the leachate concentration by dilution will reduce the rate of NH_3-N removal. An alternative approach would be to treat the undiluted leachate using the treatment plane to the point at which the NH_3-N concentration will meet the discharge condition after it has been diluted to the level required to meet the chloride discharge consent. For example:

leachate volume	1000 m^3
leachate NH_3-N post-treatment plane	20 mg/l
leachate Cl^- post-treatment plane	1600 mg/l
NH_3-N discharge condition	10 mg NH_3-N/l
Cl^- discharge condition	800 mg/l

In this simple example, the discharge condition for both NH_3-N and Cl^- could be met by a 1:1 dilution with freshwater. However, this approach may not be acceptable to the NRA as it could be construed that chloride dilution is being used as a means of treating ammoniacal nitrogen.

Pre-treatment plane dilution is sometimes carried out because there is concern that high chloride concentrations will kill the leachate treatment plane vegetation. There was only limited evidence of localised grass damage at the point at which the leachate discharged onto the experimental treatment planes. The vast majority of the experimental treatment plane grass appeared very healthy. In fact grass growth was promoted on the top few metres of each of the plots, probably because of the nitrogen content of the leachate. Chloride concentrations were as high as 3700 mg/l, which is considered to be a relatively high chloride value (Robinson and Maris, 1979). The continued good health of *Agrostis stolonifera* under leachate irrigation would suggest that pre-treatment plane dilution is unnecessary. However, it should be noted that the Silsoe experiments were of short duration (4-5 weeks) in comparison to the continuous usage of operational treatment planes. The issue of vegetation management will be considered further in Section 5 of this report.

3.1.3 Effect of hydraulic loading rate on rate of removal of ammoniacal nitrogen

The principal variable tested in the six experiments conducted was the hydraulic loading rate, i.e. the volume of leachate applied per unit treatment plane area per unit time ($l/m^2/d$). During the course of the experimental period, hydraulic loading rate was tested within the range 17 - 217 $l/m^2/d$ (17-217 mm/d). This compares to estimated hydraulic loading rates of 52 $l/m^2/d$ (52 mm/d) for Shanks & McEwan's Calvert Landfill and up to an estimated 72 $l/m^2/d$ (72mm/d) at Brogborough Landfill.

Graphs of NH_3-N removal against time at different values of H are given in Appendix 1 for both trough experiments A,B,E and plot experiments D,F.

To determine the effect of hydraulic loading rate on treatment efficiency, the experiments conducted (plots and troughs) were classed within definable hydraulic loading rate ranges i.e. <20, 20-50, 51-100, >100 ($l/m^2/d$). Values of the ammoniacal nitrogen rate removal constant, k, for each of the experimental treatments were derived from the gradient of the best fit lines given in Table 3.1.1. The k value for each experimental treatment corresponding to one of the hydraulic loading rate ranges and the mean k value (and standard error) for each range is given in Table 3.1.2. There is considerable variation in values of k across the range of hydraulic loading rates tested and there is similarity between the mean k values for the hydraulic loading rate classes. This analysis suggests that within the experimental range, hydraulic loading rate has little effect on treatment performance. The finding that treatment appears to proceed independently of the hydraulic loading rate can be linked to the concept that the treatment plane has the capacity to remove an amount of NH_3-N per day (gNH_3-$N/m^2/d$) and that on any one day, this capacity is linked to the starting NH_3-N concentration. Thus, for a given soil type, it is the leachate concentration which controls the daily removal capacity, not the rate at which leachate is applied (assuming that enough leachate is applied to meet the daily removal capacity). Proposed mechanisms of NH_3-N removal which support this contention are given in Section 3.2.

Table 3.1.2 Relationship between the hydraulic loading rate (H) and the ammonia removal rate constant k

Experiment	Trough (T) or Plot (P) Number	Hydraulic loading rate by class ($l/m^2/d$)	Actual H	k	Std Error
E	T3	<25	17	-0.034	
F	P6	<25	23	-0.038	
D	P6	<25	24	-0.099	
		Class Average	**21**	**-0.057**	**0.021**
D	P9	25-50	37	-0.123	
E	T2	25-50	43	-0.061	
B	T2	25-50	44	-0.053	
B	T4	25-50	44	-0.027	
F	P4	25-50	45	-0.034	
F	P9	25-50	45	-0.046	
		Class Average	**43**	**-0.057**	**0.014**
D	P2	51-100	70	-0.071	
F	P2	51-100	75	-0.041	
E	T1	51-100	78	-0.064	
A	T1	51-100	87	-0.054	
B	T1	51-100	90	-0.079	
B	T3	51-100	90	-0.058	
		Class Average	**82**	**-0.061**	**0.006**
A	T2	>100	217	-0.048	
		Class Average	**217**	**-0.048**	

In operational terms, the finding that hydraulic loading rate has a small effect upon the rate of NH_3-N removal is significant. The volume of leachate to be pumped each day affects the cost of pumping which is the principal element of the running costs of a treatment plane. The cost of diesel for pumping leachate on to the treatment plane at Shanks & McEwan's Calvert Landfill site is £18 000 per annum. Any reduction in pumping requirement would be associated with a saving in fuel costs.

The real significance of the hydraulic loading rate is that it controls the NH_3-N loading rate. To avoid underloading the system, enough leachate must be applied to the leachate treatment plane to meet the plane's capacity for treatment on a daily basis. However, the research has demonstrated that there is no point in overloading the system as the treatment plane has a finite capacity to remove leachate at a given NH_3-N concentration. Any additional pumping over and above this value is wasteful.

3.1.4 Effect of season on rate of removal of ammoniacal nitrogen

NH_3-N removal in biological wastewater treatment systems is usually temperature dependent. This is because of the temperature sensitivity of nitrifying bacteria, the bacteria responsible for NH_3-N and NO_2^-N oxidation. As such, NH_3-N removal in conventional biological wastewater treatment systems is often best in summer months and worst in winter months.

However, by contrast, our experiments did not demonstrate any clear difference between winter and summer treatment plane NH_3-N removal performance. Experiments A and B were conducted during the winter months of 1994 (January-March). Winter values of k were of a similar order to those derived from the summer experiments. This finding suggests that treatment planes are equally reliable in summer or winter conditions. This is in part corroborated by the fact that operational treatment planes continue to operate effectively throughout the winter months. This suggests that treatment planes are not solely dependent upon nitrification for NH_3-N removal and as such are fundamentally different from conventional biological NH_3-N oxidation systems.

3.2 MECHANISMS OF AMMONIACAL NITROGEN REMOVAL

3.2.1 Adsorption of ammonium ions to cation exchange sites

It is well established that clay minerals possess a negative surface charge as a result of ion substitution within the clay crystal structure and pH dependent dissociation of surface hydroxyl (OH) groups (Gast, 1977). In addition, pH dependent negative charges originate in soil organic matter from the dissociation of carboxyl (COOH) and phenolic OH groups (Nommik and Vahtras, 1982). The negative charge associated with clay minerals and organic matter attracts cations from the soil solution. These cations are subject to replacement by other cations through the process known as cation exchange. The strength of cation adsorption at exchange sites is dependent upon factors such as the valency, the size of the cation and the relative concentration of the different ions in the system. The relative replacing power has been found to increase in the order corresponding to the lyotropic series (Nommik and Vahtras, 1982). ie:

$Li^+ < Na^+ < K^+ = NH_4^+ < Rb^{2+} < Cs^{2+} < Mg^{2+} < Ca^{2+} < Sr^{2+} < Ba^{2+}$

Cation exchange obeys the mass action law. In simple terms, this means that when NH_4^+ is in high concentration in soil solution, it will be able to displace cations that would have had a greater replacing power if concentrations had been equal in soil solution. For example, if the concentration of Ca^{2+} is equal to the concentration of NH_4^+ in soil solution, Ca^{2+} will be adsorbed at exchange sites in preference to NH_4^+ due to its greater binding strength. However, if the NH_4^+ concentration is significantly greater than the Ca^{2+} in the soil solution, the greater abundance of NH_4^+ will outweigh the greater binding power of Ca^{2+} leading to preferential adsorption of NH_4^+. The cation exchange equilibrium for any pair of cations in the lyotropic series is governed by an equilibrium constant which may be quantified using the Gapon analysis (Wild, 1988).

This mechanism provides one explanation for the observed concentration-dependent performance of the experimental treatment planes. The soils used in the experiments were of a clay loam texture (32% sand, 20% silt, 48% clay). The predominant clay mineral, smectite, is derived from the underlying Gault; it is calcium saturated and has a cation exchange capacity (CEC) of 36 meq / 100 g. Such a soil would be expected to retain leachate NH_4^+. However, it should be noted that as the clay mineral content of soil varies, so does the cation exchange capacity of different clay minerals, so one should expect retention of ammoniacal nitrogen to vary depending upon the prevailing soil type. For example, at the Brogborough landfill site in Bedfordshire's Marston Vale, the clay minerals are derived from the Lower Oxford Clay (predominantly illite and illite-smectite)(Milodowski and Wilmot, 1985) and have CEC values of 9 - 20 meq / 100 g.

One would expect there to be displacement of cations commensurate with the amount of NH_4^+ adsorbed as cation exchange reactions are considered to be stoichiometric (Gast, 1977). However, full cation balances were not carried out and this cannot be verified. Calcium and magnesium determinations were conducted on leachate before and after treatment for experiment F. The results showed that both calcium and magnesium concentrations were greater after the leachate had been treated. This suggests that there was displacement from the clay surface but the increase was not sufficient to account for the loss of several hundred mg NH_4^+/l. At the beginning of an experiment, the high NH_4^+ concentration would cause displacement of soil-bound cations. It is possible that as NH_4^+ was removed from exchange sites, the soil cations could reattach at the vacated sites. Thus the difference in leachate calcium and magnesium concentration between the beginning and end of a batch should not be great. Daily cation balances are required to provide reliable evidence of the magnitude of the cation exchange reaction.

A leachate treatment plane would be generically termed an overland flow system due to the predominant flow route for water. This would suggest that leachate only interacts with the cation exchange sites in a thin surface layer of soil. The depth of interaction of leachate and soil has not been determined. However, it is conceivable that diffusion of NH_4^+-N from the surface and some throughflow of water permits deeper layers to contribute to treatment. This is probably more likely in the experimental plots and troughs than in operational treatment planes as there is potential for water to follow a preferential flow path at the of soil/liner boundary.

The apparent effectiveness of treatment planes during the colder months of the year when biological activity is retarded supports the idea that a physico-chemical mechanism of NH_3-N removal such as cation exchange could be significant.

3.2.2 Volatilisation of ammonia

Volatilisation can occur whenever un-ionised ammonia is present near the soil surface (Nelson, 1982). The loss of ammonia from the aqueous to the gaseous phase can be described by the equations:

$$NH_4{}^+{}_{(aq)} \Leftrightarrow H^+ + NH_{3(aq)}$$

Equation 3.2.1

$$NH_{3(aq)} \Leftrightarrow NH_{3(g)}$$

Equation 3.2.2

It can be seen from the equations above that volatilisation of NH_3 from an $NH_4{}^+$ source will leave residual acidity (Wild, 1988). The proportion of NH_3 present at equilibrium will increase as pH increases. At pH values of 5,7 and 9, approximately 0.0036, 0.36 and 36% respectively of the total ammoniacal N in the soil solution is present as $NH_{3(aq)}$. At equilibrium, the amount of $NH_{3(aq)}$ is related to the partial pressure of NH_3 in the atmosphere (pNH_3) by the Henry Constant (K_H) according to:

$$[NH_{3(aq)}] = K_H \, pNH_3$$

Equation 3.2.3

An increase in the $NH_{3(aq)}$ concentration by adding $NH_4{}^+$ or increasing the pH will lead to a change in the equilibrium between $[NH_{3(aq)}]$ and pNH_3 resulting in loss of NH_3 to the atmosphere. Therefore, as the NH_3 concentration in the air is relatively low, NH_3 volatilisation is controlled by the $NH_{3(aq)}$ concentration.

The bulk cation exchange capacity (CEC) of the surface layers of the soil may also have an impact on volatilisation. Fine textured soils such as the clays used for leachate treatment planes tend to have a high CEC. With a high CEC, a greater proportion of added $NH_4{}^+$ would be present on the exchange complex and less $NH_{3(aq)}$ would be present in the soil solution (Nelson, 1982)

$$NH_4{}^+{}_{(exch)} \Leftrightarrow NH_4{}^+{}_{(aq)} \Leftrightarrow NH_{3(aq)}$$

Equation 3.2.4

It is impossible to make a definitive statement regarding the relative importance of volatilisation as an NH_3-N removal process as no measurements of gaseous losses to atmosphere were carried out. The relationship between NH_3-N volatilisation and pH is well known. Ammonia stripping processes involve raising alkalinity to > pH 11 to push the equilibrium towards unionised ammonia in order to promote gaseous loss.

The pH of the leachate used in this research was relatively alkaline, with batches typically starting off at around pH 8.2-8.5 and finishing around pH 7.6-7.8 after a typical 4 week experimental run (graphs of pH variation during the course of experiments trough experiments A,B,E and plot experiments D,F are presented in Appendix 1). Theoretically, volatilisation would be enhanced at the beginning of a batch but would slow during the course of treatment. The fall in pH during the course of a batch may be evidence of volatilisation but it could also be explained by nitrification (see section 3.2.3).

In their studies of ammonia volatilisation from surface applied sewage sludge, Ryan and Keeney (1975) found that between 11% and 60% of applied ammoniacal nitrogen (initial [NH_3-N] = 950 mg/l) was lost, with the variation being dependent upon soil type. The figure of 11% corresponded to a clay soil (24% sand, 44% silt, 32% clay). As previously explained, the cation exchange process will reduce volatilisation losses, therefore it would be expected that percentage losses would be relatively low on soils which contain minerals and organic matter with high cation exchange capacities. As stated previously, the clay mineral content is 48% of the bulk soil used in the Silsoe experiments. The exact percentage of nitrogen lost to the atmosphere due to volatilisation cannot be quantified. However, the experimental conditions, in terms of soil type, starting ammoniacal nitrogen concentration and pH, are comparable to those in Ryan and Keeney's experiments with clay soils. Therefore an estimated value for volatilisation losses for the Silsoe experiments would be approximately 10% of the NH_3-N applied.

Treatment plane operators often hope to volatilise NH_3-N by spraying leachate into the air. Spray droplets have good contact with the atmosphere and as there is no competing process such as cation exchange occurring before the droplets hit the ground, this approach appears to have merit. However, the desirability of encouraging volatilisation should be questioned. Excessive NH_3-N in the atmosphere can cause smell nuisance and must ultimately be deposited elsewhere.

3.2.3 Nitrification of ammoniacal nitrogen and nitrite to nitrate

There is evidence to suggest that the adsorption of NH_4^+ ions is the principal mechanism by which ammoniacal nitrogen is removed from leachate irrigated onto vegetated treatment planes. However, exchange sites are a finite resource. For a treatment plane to be sustainable, exchange sites must be regenerated. Nitrification is one means by which adsorbed ammoniacal nitrogen may be removed from exchange sites. Nitrification refers to the sequential bacterial oxidation of ammoniacal nitrogen to nitrite (via hydroxylamine) and on to nitrate (Prosser, 1989).

$$NH_3 + O_2 + 2H^+ + 2e^- \rightarrow NH_2OH + H_2O$$

Equation 3.2.5

$$NH_2OH + H_2O \rightarrow NO_2 + 5H^+ + 4e^-$$

Equation 3.2.6

$$NO_2 + H_2O \rightarrow NO_3 + 2H^+ + 2e^-$$

Equation 3.2.7

In theory, this process would transform adsorbed NH_4^+ ions into highly soluble forms of oxidised nitrogen that would readily be leached from clay surfaces into the passing treated leachate. Thus, evidence for the occurrence of nitrification would ultimately be an increase in nitrate concentration as a batch proceeded.

Changes in nitrite and nitrate concentration for plot experiments D,F and trough experiments A,B,E are given in Appendix 1. NO_3-N concentrations in the Calvert leachate used for the experiments varied considerably (2-95 mg/l NO_3-N). No consistent trend in NO_3-N removal or production could be identified from the experiments with final NO_3-N concentrations comparable with initial NO_3-N concentrations in the three experiments A,B, and F, whilst increasing during the course of experiments D and E, from 2-5 mg/l NO_3-N to 19-51 mg/l NO_3-N. It has been assumed that any increase in NO_3-N concentration can be attributed to nitrification.

Evidence that nitrification has played a part in leachate nitrogen transformation is the change in NO_2-N concentration during the course of an experiment. Initial nitrite concentrations were higher than would normally be expected in landfill leachate (up to 450 mg NO_2-N /l) because a pilot experimental aeration plant at Calvert (the source of the leachate for the Silsoe research) was suffering from the problem of incomplete nitrification. NO_2-N concentrations always declined during the course of treatment. NO_2-N concentrations fell to < 5 mg/l in experiments A,B, and D (>95% reduction) although the removal was less dramatic in experiments E and F (20-85%).

Nitrite oxidation, being the second step of the nitrification process, is prone to inhibition by sub-optimal pH (optimum pH 7.5) and by substrate inhibition (Prosser, 1989). Thus, conditions for nitrite oxidation improve during batch treatment as pH falls towards optimum and NH_3-N levels decline due to cation exchange and volatilisation. The bacteria responsible for nitrification are obligately aerobic, natural soil-dwelling organisms (Schmidt, 1982). Recent research has shown that they tend to inhabit the larger pores of soil aggregates where oxygen concentrations are at their highest (Fair *et al*, 1994).

Research has been conducted in the United States on the use of vegetated overland flow systems for the treatment of municipal sewage (Smith and Schroeder, 1985). These results have emphasised the advantages of intermittent application of wastewater onto vegetated treatment areas (5 hours continuous application each day). During the period of non-application, the soil dries due to drainage and evaporation thus creating conditions favourable for oxidation reactions, including nitrification. The Silsoe research programme adopted this intermittent sequence of application of leachate for this reason. This is in contrast to the operational use of treatment planes that often operate 24 hours a day. However, short-term experiments at Silsoe College have suggested that there is little difference in NH_3-N removal or NO_3- N accumulation between those with continuous (24 hours per day application) and those with intermittent application (5 hours on, 19 hours off) (Wellsbury, 1994). This finding is at odds with the concept that drying conditions promote nitrification.

A significant conclusion drawn from these data is that NO_3-N concentrations either remain unchanged or increase marginally during the course of the experimental treatment batches. The mass of NO_3-N present in the treated leachate at the end of an experiment does not account for the mass of NH_3-N and NO_2-N removed. Table 3.2.1 sets out the initial and final mass of nitrogen in the leachate (kgN) in each of the experimental treatments and the percentage of the initial nitrogen remaining at the end of each experimental run. The percentage of inorganic nitrogen remaining at the end of an experiment varies considerably between 1% and 43% and no single factor has been found to explain this variation.

Table 3.2.1 Percentage loss of nitrogen from leachate in experiments A-F

Experiment	Trough (T) / Plot (P) Number	Total mass of inorganic N (kg) in leachate		Percentage remaining at end
		Start	End	
A	T1	0.1422	0.0263	18%
A	T2	0.1422	0.0291	20%
B	T1	0.0293	0.0073	25%
B	T2	0.0334	0.0107	32%
B	T3	0.0925	0.0105	11%
B	T4	0.0852	0.0268	31%
D	P2	1.587	0.0111	1%
D	P6	1.631	0.0512	3%
D	P9	1.5379	0.0441	3%
E	T1	0.1342	0.0341	25%
E	T2	0.1351	0.0392	29%
E	T3	0.1401	0.0606	43%
F	P2	1.5668	0.0409	3%
F	P4	1.7058	0.3877	23%
F	P6	1.7699	0.5063	29%
F	P9	1.5096	0.2408	16%

The fate of the inorganic nitrogen apparently lost from the system is another area of uncertainty. A component of the deficit is accounted for by assimilation into vegetation biomass. The mean measured value for above ground N uptake by the grass as a percentage of the deficit is approximately 10%. A further possible component of the deficit could be the accumulation of nitrogen within the soil. A limited amount of soil sampling was undertaken but the results were extremely variable and inconclusive. It is suggested that changes in soil N storage should be negligible in the long term as NH_4^+ should accumulate in the soil at the start of a treatment batch due to adsorption at exchange sites but be progressively lost as exchange sites are regenerated, with the soil returning to its pre-treatment state by the end of a batch.

Therefore, the majority of the nitrogen deficit is still unaccounted for and may be explained by unmeasured losses to the atmosphere. A component of this would be volatilisation. A crude estimate for volatilisation loss of 10% was proposed in section 3.2.2., the remainder of the deficit being attributed to denitrification. If nitrification is the principal means of regenerating cation exchange sites on treatment planes it is paradoxical that a corresponding mass of nitrate does not accumulate. However, this paradox may be explained if nitrate is converted to a gaseous form of nitrogen as is the case in denitrification. Nitrate (and the subsequent reduction products of nitrate) may be used by a number of facultatively anaerobic bacteria as an alternative electron acceptor to molecular oxygen (Stevenson, 1982), thus allowing respiration to continue under anaerobic conditions. The end products of denitrification reactions are the gases N_20 and N_2. Denitrification will proceed in soil where there is an organic carbon source; where there are anaerobic conditions (such as in waterlogged soil or even in a well-drained soil at the centre of an aggregate); and where there is a source of nitrate (Stevenson, 1982). All of these conditions are met within the leachate treatment plane system (i.e. the plane itself and the recirculation lagoon which may provide ideal conditions for denitrification). Therefore, it is suggested that linked nitrification/denitrification is responsible for the shortfall in the nitrogen budget. An annual nitrogen loss from field soils of <20% has been reported under normal levels (approximately 250 kgN/ha) of agricultural fertiliser application (Colbourn and Dowdwell, 1984; Ryden, 1983). If volatilisation accounts for 10% of the deficit; plant uptake accounts for 10%; and residual inorganic nitrogen in the treated leachate accounts for 1% to 43%, then a crude estimate of denitrification losses in the Silsoe experiments would be in the range 37-79%. Higher levels of denitrification would be expected on a leachate treatment plane in comparison to agricultural soils due to the higher nitrogen application rates (up to 6000 kgN/ha) and the high moisture content of the treatment plane soils.

The possibility of linked nitrification/denitrification on treatment plane systems is of significance as it reduces the mass of nitrate discharged to the water environment. Increasing attention is being focused on point-source nutrient discharges to surface waters due to the high cost of nitrate removal at potable water treatment works and the contribution to eutrophication in the receiving waters. The results of this research suggest that the treatment plane system differs from conventional biological treatment systems in that it discharges/emits nitrogen to the atmosphere rather than to the water environment.

3.3 CHEMICAL OXYGEN DEMAND AND COLOUR REDUCTION

The emphasis of the research has been on the removal of ammoniacal nitrogen as this is considered to be the critical, treatable, water quality parameter affecting discharge consent compliance. However, monitoring of the organic component of the leachate has been undertaken to determine treatment plane capabilities.

Changes in chemical oxygen demand (COD) were monitored in each of the experiments. The COD of the raw leachate used in the Silsoe experiments varied from 700-5064 mg/l. In all of the experiments, COD concentrations decreased but COD was never eliminated completely (never falling below 210 mg/l). Removal ratios ranged from 11% to 85%. The nature of the oxidisable compounds being removed by the experimental treatment planes is unknown. Components may be particulate organic matter, readily oxidisable organic matter, relatively recalcitrant organic matter and oxidisable inorganic matter. Any particulates would be removed by settlement and filtration processes on the treatment plane. Readily oxidisable matter should biodegrade within a few days of treatment (NB. the BOD of raw Calvert leachate varies between 80 and 800 mg/l and by the end of experiment F, a one-off measurement gave a treated BOD value of < 20 mg/l).

Another noticeable change resulting from treatment was the marked change in colour. The colour was found to survive filtration through a 0.45 μm filter and as such may be classified as soluble. Such colour compounds may frequently contribute to the raw COD. The reduction in colour may be due to adsorption of colour compounds on to soil particles. Colour analysis demonstrated that colour fell by a maximum of 43% (from 474 units PtCo to 272 units PtCo) after only 6 days of treatment.

4. DEVELOPMENT OF A MODEL FOR SIZING LEACHATE TREATMENT PLANES

In order to model the treatment plane process successfully, a general function describing the removal rate of NH_3-N from the leachate needs to be derived. We have demonstrated that the key controls over removal are the concentration of the leachate applied and the area to which it is applied. The hydraulic loading rate appear to have little effect on the process.

It is shown in section 3.1.1 that the treatment plane experimental data always gives a good fit to an exponential decay function which implies a first order process having the general form of equation:

$$\frac{dC}{dt} = kC$$

Equation 4.1.1

where k is a rate constant which has units of days^{-1}

The form of the fitted equation is:

$$C = C_o \exp(kt)$$

Equation 4.1.2

which has allowed values of k to be estimated from the experimental data. Equations of this form are presented for all the experiments in Table 3.1.1 from which values of the coefficient k can be found.

In finite difference form equation 4.1.1 may be written as:

$$\frac{\Delta C}{\Delta t} = k\overline{C}$$

Equation 4.1.3

where ΔC is the change in concentration in time Δt

The mass of solute removed in unit time per unit area of the treatment plane, M_r, is given by:

$$M_r = \Delta C.\frac{V}{A}\frac{1}{\Delta t}$$

Equation 4.1.4

where V is the volume of the reservoir and A is the area of the treatment plane. Typical units for M_r are mg of solute per m^2 per day

Thus:

$$M_r = \beta.\overline{C}$$

Equation 4.1.5

where the value of:

$$\beta = \frac{V}{A}.k$$

Equation 4.1.6

which is a straight line relationship with an intercept at zero as expected. The best-fit linear regression line for the pooled experimental data confirms that there is indeed such a relationship (Fig. 3.1.3).

The slope of the function is a scaled value of k. Table 4.1.1 shows values for k and the scaled value of this slope term, β. As expected scaling reduces the spread of the values.

This process has been modelled using the above approach as shown in the simple flow chart in Fig. 4.1.1. The model is for a batch process similar to that investigated where the leachate is irrigated from the reservoir onto the leachate treatment plane each day and recirculated on a daily basis until discharge consents are achieved.

The hydraulic loading rate is constrained to be larger than a set minimum value (20 l/m^2/d) because at very low rates it was observed that the distribution of water on the treatment plane was non-uniform leading to an under-exploitation of the treatment area.

Table 4.1.1 Scaled values of the ammonia removal rate constant *k*

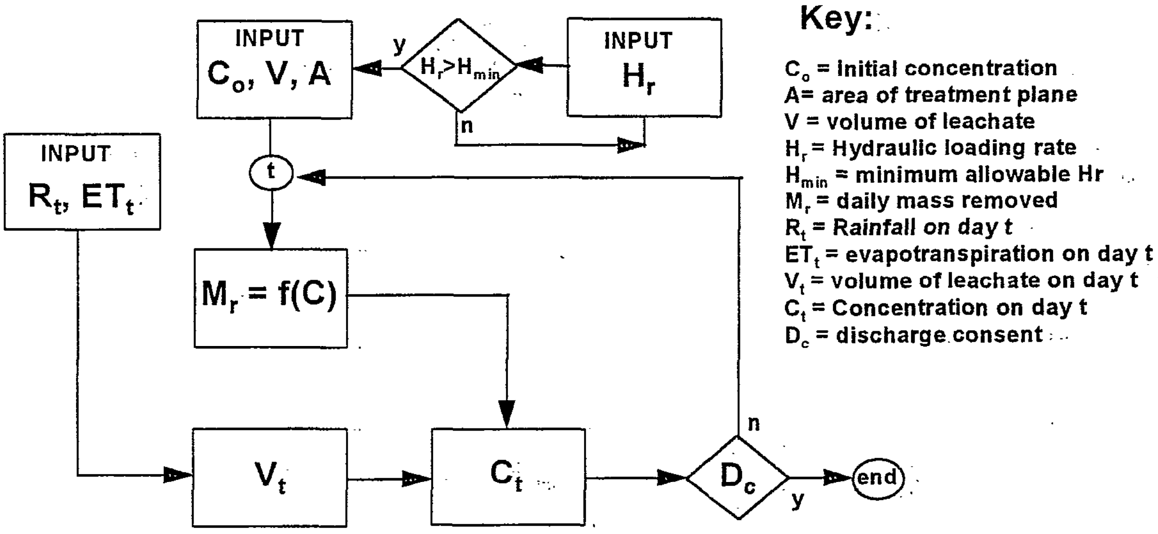
Experiment & Plot / Trough Number.	Rate constant *k* (d^{-1})	V/A (lm^{-2})	β ($lm^{-2}d^{-1}$)
AT1	-0.054	250.0	-13.5
AT2	-0.048	250.0	-12.0
BT1	-0.079	250.0	-19.8
BT2	-0.053	250.0	-13.3
BT3	-0.058	250.0	-14.5
BT4	-0.027	250.0	-6.8
DP2	-0.071	237.0	-16.8
DP6	-0.099	118.5	-11.7
DP9	-0.123	110.0	-13.5
ET1	-0.064	262.5	-16.8
ET2	-0.061	262.5	-16.0
ET3	-0.034	268.8	-9.1
FP2	-0.041	235.0	-9.6
FP4	-0.034	240.0	-8.2
FP6	-0.038	235.0	-8.9
FP9	-0.046	230.0	-10.6

Input data required are the daily rainfall and evapotranspiration, the starting concentration, the volume of the reservoir and the treatment plane area. The controlling function is that shown in Equation 4.1.5. The average value of β, calculated from our experimentallly-derived values of k (Table 4.1.1) is used in the model.

The model calculates a daily mass balance for water and NH_3-N and so calculates the end of day concentration. This is compared to the required discharge consent concentration. If the concentration is too high the routine loops and the calculations are repeated for subsequent days until the discharge consent is reached.

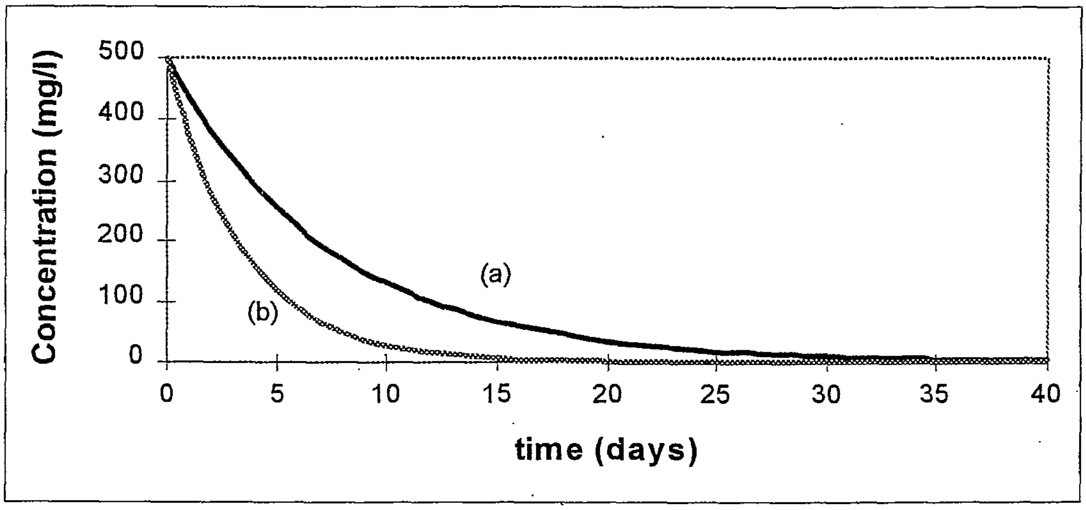
The model is written in a 'Windows' environment and a graphical representation of daily concentration is output to the screen. All input parameters and the value of β can be changed so that the model can be used to investigate the relationship between the size of the batch reservoir, the treatment plane area and the starting concentration of the leachate. A future development of the model will include an energy budget for the system.

Fig. 4.1.1 Leachate Treatment Plane Model



The model has been used to simulate the reduction in concentration of a leachate applied to a clay treatment plane. Fig. 4.1.2 shows output from the model as leachate concentration against time of treatment. In this simulation a 2000 m^3 re-circulation lagoon with treatment on a 2 ha plane with a starting concentration of leachate of 500 mg NH_3-N/l is considered. It is seen that daily irrigation and recirculation of the leachate from the lagoon onto the treatment plane gives the expected exponential decay in concentration; treatment to a discharge consent level of 5 mg NH_3-N/l takes 36 days which would be typical of observations at Brogborough and Calvert. Doubling the treatment area to 4 ha theoretically reduces the time to reach discharge consent to 16 days. It should be noted that the equation 4.1.4 predicts an inverse relationship between the area of the treatment plane and the time required for a given mass removal of ammonia, so doubling the area of treatment halves the time required for treatment.

Fig. 4.1.2 Output from the model showing the fall in ammonia concentration in a 2000 m^3 lagoon with time for (a) a 2 ha treatment plane and (b) a 4 ha treatment plane



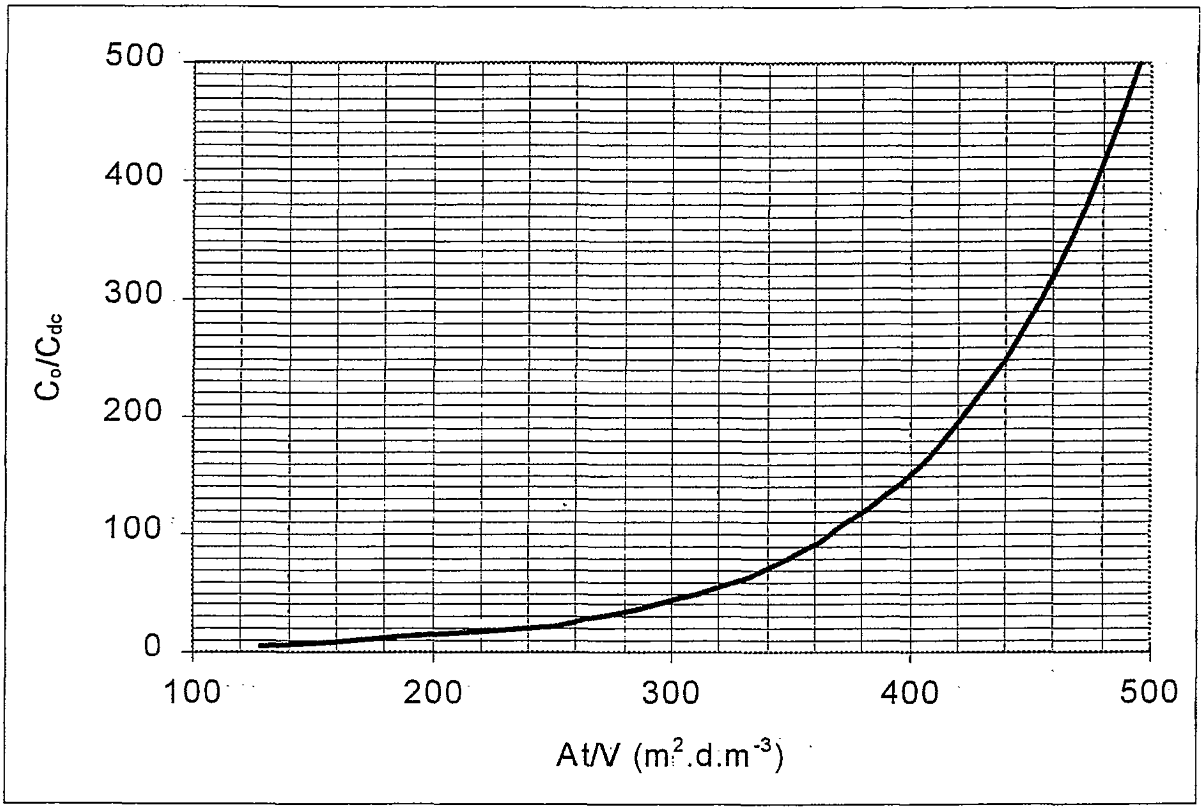
A general form of the mass removal relationship may be developed as shown in Fig. 4.1.3. Here the relationship between the ratio of the starting concentration to the discharge consent concentration is shown as a function of the area of the treatment plane (A), the volume of the recirculation lagoon (V) and the time of treatment (t). This relationship can be used to size the treatment plane.

As an example, assume that the starting concentration of the leachate is 500 mg/l and the discharge consent is 5 mg/l. The ratio, C_o/C_{dc}, is therefore equal to 100. Using the graph we can read from the vertical axis at a value of 100 to the curve and find a value of A.t/V which in this case has a value of 367. If we assume that we want the treatment to discharge to take no more than 20 days and the volume of the re-circulation lagoon is 2000 m^3 then the required area of the treatment plane is found as:

367 x 2000/20 = 36,700 m^2 or 3.67 ha

If we allow 36 days for treatment then the area required may be reduced to 2 ha as shown by the model results. It is suggested that this approach could be used as a first stage in sizing a clay treatment plane and that the model, which can also take account of rainfall and evapotranspiration, can be use for fine tuning the system.

Fig. 4.1.3 The relationship between C_o/C_{dc} and At/V



5. RECOMMENDATIONS FOR THE DESIGN AND OPERATION OF LEACHATE TREATMENT PLANES

This final report marks the end of six years of treatment plane research at Silsoe College, initially in the form of MSc student projects and, more recently, full-time research supported by Shanks & McEwan (Southern Waste Services) Ltd. and the Department of the Environment. In that time, much has been learned about the science of the treatment process and about current design and operational practices. Below is a set of practical recommendations stemming from the work.

(a) Current approaches to treatment planes sizing can be improved by the adoption of the new sizing model. The model may aid treatment plane managers by estimating the time for batch treatment completion.

(b) Evenly distributed overland flow will result from shallow downslope gradients (the Silsoe research utilised a 2% downslope) with no cross-slope gradient. This is often not practised because of the cost of earthworks. Nonetheless, it is recommended that treatment planes are graded as evenly as possible to promote uniform distribution of leachate over the available area. Observation of the Brogborough treatment plane suggests that poor distribution and channelling result in <25% of the available area coming into contact with leachate. Low-rate sprinklers may be used to promote the even distribution of leachate over the treatment plane.

(c) The current practice of 24 hour continuous leachate application is considered to be disadvantageous and intermittent application is recommended for the following reasons. Firstly, intermittent application should promote the regeneration of exchange sites through nitrification. Secondly, treatment plane grass will benefit from intermittent periods of drying. Finally, the research suggests that leachate is often over-applied with no added treatment benefit. Reducing the daily period of pumping will result in a proportional saving in fuel costs. For example, the Silsoe experiments operated on the basis of 5 hours of continuous irrigation per day which is equivalent to a 79% reduction in pumping from the standard continuous approach.

(d) The practice of pre-treatment plane dilution should be reconsidered. In fact, because NH_3-N mass removal is related to NH_3-N concentration, dilution may in fact slow the NH_3-N removal process. Dilution is sometimes considered a precaution against 'chloride-burn' of grass. This is a well-founded concern. The authors have witnessed dead grass on treatment planes, although the cause of death was unknown. Chloride is usually blamed for poor vegetation performance, but it may not be the major stress factor. It is suggested that waterlogging is the principal cause of ill-health in treatment plane grass. In our experiments, surface irrigated undiluted leachate up to 3700 mg/l chloride applied intermittently had no ill-effect on *Agrostis stolonifera*, the favoured grass species for the treatment plane research. In fact, experiments have shown that grass growth is stimulated by the plentiful nitrogen supply. Longer-term trials of intermittently applied, undiluted leachate is recommended before changing current practices. The current practice of acclimatising grass to leachate by gradually increasing the concentration is supported.

(e) Hardy grass species should be sown on treatment planes. Salt-tolerance is the characteristic normally sought. However, ability to form a close turf quickly, waterlogging resistance, and ability to grow on unstructured clay are all favourable characteristics. Pot trials and field-scale experiments have demonstrated that *Agrostis stolonifera,* possesses the necessary attributes (Bradford, 1992). Experimental evidence is supported by the botanical survey of the Brogborough treatment plane (Appendix IV) which supports a thriving self-sown population of *A. stolonifera.*

To prevent erosion, a period of grass establishment following seeding is essential prior to overhead irrigation (Millichip, 1989). The grass on the Silsoe plots was sown in late summer and did not receive any leachate until the following spring. Thus, the recommended period of grass establishment would be several months. The minimum period between sowing and active tillering (branching) of the grass would be 6 weeks minimum, depending on the grass species. At this stage the grass has established a healthy root system and can cope better with adverse conditions.

Treatment plane grass is not normally mown, with summer vegetation dying back naturally in the autumn. Vegetation at Shanks & McEwan's Brogborough treatment plane is grazed by geese. An alternative would be to permit sheep to graze on the treatment plane (sheep are commonly used for grass management on landfill caps). Treatment planes have landscape value and could be managed in order to provide a habitat for wildlife. This aspect of site management may be worth considering as part of a waste management company's environmental policy.

6. THE FUTURE FOR LEACHATE TREATMENT PLANES

Leachate treatment planes have been in use at landfill sites for many years. Experience of operating these systems has demonstrated that they are a reliable and sustainable means of achieving 100% compliance with surface water discharge consent conditions with respect to ammoniacal nitrogen and BOD, something that is rarely achieved with single pass treatment systems. This research supports this operational experience and proposes ways of improving existing design and management practices.

The dynamics of NH_3-N removal have been determined. This new-found knowledge will no doubt confirm some of the anecdotal knowledge that exists about treatment plane performance such as the ability of treatment planes to remove NH_3-N in the winter months. In addition it is hoped that some existing ideas will be challenged. The confirmation that treatment efficiency is greatest at high concentrations has implications for the proposed use of treatment planes. If used as ammonia polishing systems, they will not be operating within their most efficient range. However, they may continue to be operated for this purpose purely out of convenience. This research suggests that a new application may be as a pre-treatment system prior to a conventional biological system such as an aerated lagoon or Rotating Biological

Contactor. (The research team have encountered interest in a pre-RBC system that would considerably reduce RBC running costs by reducing NH_3-N loading onto it).

It is highly likely that landfill operators such as Shanks & McEwan will continue to use treatment planes as the sole treatment system at sites wherever there is sufficient land available. In such situations, the change to a highly land-efficient, "small footprint" system will not be necessary until the land area available for the treatment plane is reduced due to the needs of filling coupled with the inevitable increase in leachate production as the site nears full capacity.

A further application of treatment plane technology is the idea of using the restored landfill cap as a treatment area. This is not a new idea and some landfill operators already recirculate water through the fill by irrigation onto temporary cap. This approach has clear benefits for sites where there is no unfilled land available for treatment. In such a case, the restored cap could potentially be used as a long-term, sustainable, means of leachate treatment following completion of the site.

The future of treatment planes is assured, perhaps due more to their convenience and robustness rather than their efficiency or low-cost. Treatment planes make full use of existing resources: land and equipment. Once established they can continue to run with minimum management input.

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9. APPENDIX 1 - DATA FROM TREATMENT PLANE EXPERIMENTS

9.1 LIST OF TABLES AND CHARTS

Experiment A

Experiment B

Experiment C

Experiment D

Experiment E

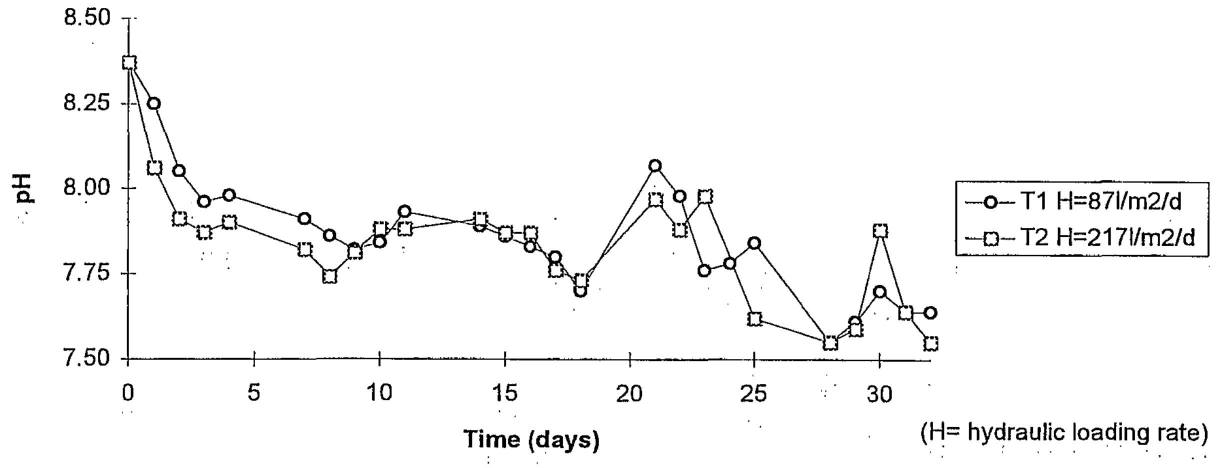
Experiment F

EXPERIMENT A Table A1: pH, Chemical Oxygen Demand (COD), and Chloride (Cl^-) data

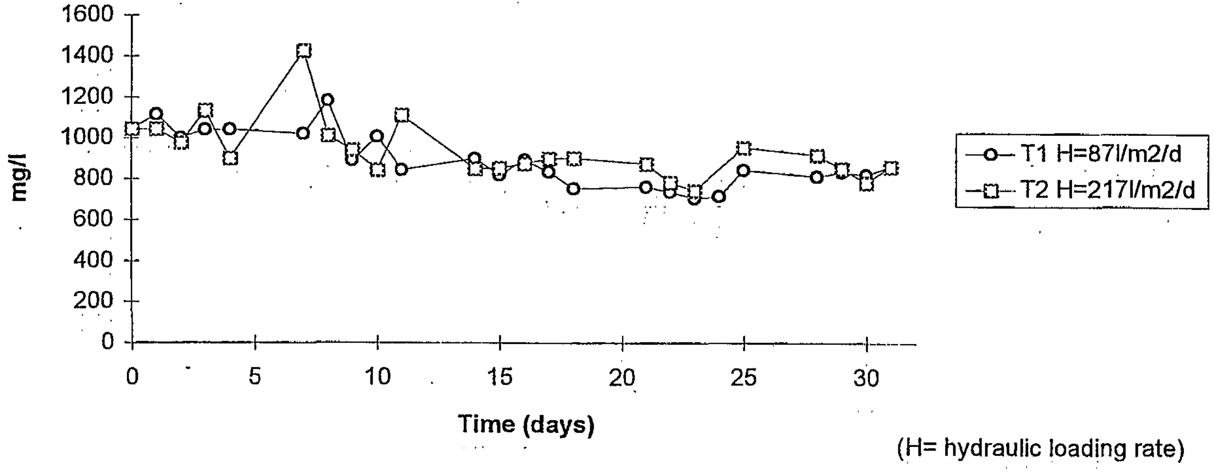
Dates:	17/01/94-18/02/94
Trough 1 (T1)	Hydraulic loading rate (H)=87l/m^2/d	Treatment plane surface area=0.8m^2
Trough 2 (T2)	Hydraulic loading rate (H)=217l/m^2/d	Treatment plane surface area=0.8m^2

		pH			COD conc. (mg/l)			Cl^- conc. (mg/l)			Leachate volume (l)		Cl^- total mass in leachate (kg)		Loading rate of Cl^- (kg/m^2)		Cl^- removal rate (kg/m^2/d)	
Day	Date	T1	T2	Ctrl	T1	T2	Ctrl	T1	T2	Ctrl	T1	T2	T1	T2	T1	T2	T1	T2
0	17/01/94	8.37	8.37	8.37	1043	1043	1043	3345	3345	3345	200	200	0.6690	0.6690	0.8363	0.8363	0.1356	0.1463
1	18/01/94	8.25	8.06		1115	1045		2950	2905		190	190	0.5605	0.5520	0.7006	0.6899	0.0251	0.0436
2	19/01/94	8.05	7.91	8.4	1000	975	1080	2890	2765	2370	187	187	0.5404	0.5171	0.6755	0.6463	0.0222	-0.0093
3	20/01/94	7.96	7.87		1040	1135		2810	2820		186	186	0.5227	0.5245	0.6533	0.6557	-0.0242	0.0081
4	21/01/94	7.98	7.9	8.5	1040	900	1145	2930	2800	2980	185	185	0.5421	0.5180	0.6776	0.6475	0.0304	0.0138
7	24/01/94	7.91	7.82	8.47	1020	1425	1155				184	184						
8	25/01/94	7.86	7.74		1180	1010					184	184						
9	26/01/94	7.82	7.81		885	940					184	184						
10	27/01/94	7.84	7.88	8.51	1005	840	1635	2590	2510	2710	153	180	0.3963	0.4518	0.4953	0.5648	0.0029	-0.0044
11	28/01/94	7.93	7.88		840	1110					150	175						
14	31/01/94	7.89	7.91		895	845					150	175						
15	01/02/94	7.86	7.87		815	850					150	168						
16	02/02/94	7.83	7.87	8.6	890	870	1300	2550	2815	3060	150	168	0.3825	0.4729	0.4781	0.5912	0.0053	0.0149
17	03/02/94	7.8	7.76		830	895					150	168						
18	04/02/94	7.7	7.73		750	900					149	168						
21	07/02/94	8.07	7.97		760	870					149	168						
22	08/02/94	7.98	7.88		735	780					146	166						
23	09/02/94	7.76	7.98	8.7	705	740	1200	2435	2360	2920	145	165	0.3531	0.3894	0.4413	0.4868	-0.0005	0.0031
24	10/02/94	7.78			715						145	165						
25	11/02/94	7.84	7.62		840	950					145	165						
28	14/02/94	7.55	7.55		810	915		2450	2285		145	165	0.3553	0.3770	0.4441	0.4713		
29	15/02/94	7.61	7.59		830	850					145	165						
30	16/02/94	7.7	7.88		820	780					142	162						
31	17/02/94	7.64	7.64		860	860					138	160						
32	18/02/94	7.64	7.55	8.61						3045	138	160						

EXPERIMENT A: Chart A1(i)
pH of leachate

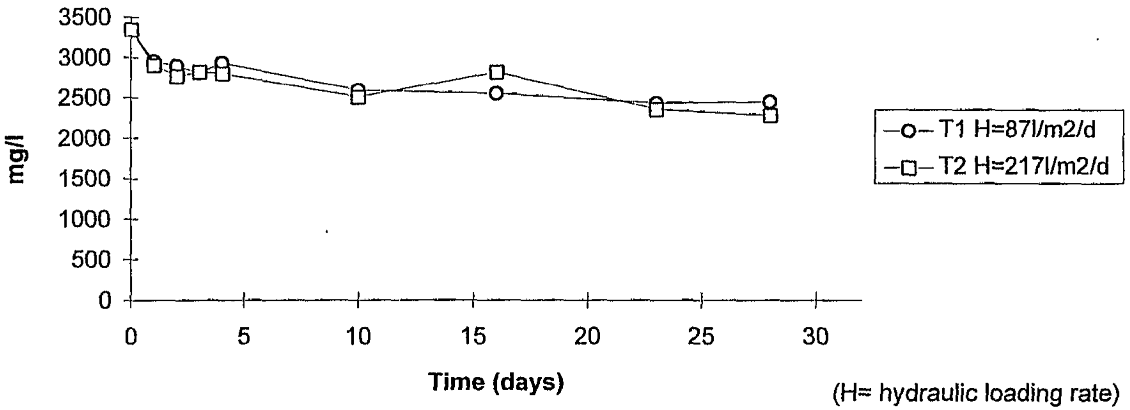


EXPERIMENT A: Chart A1(ii)
COD Concentration of leachate



EXPERIMENT A: Chart A1(iii)

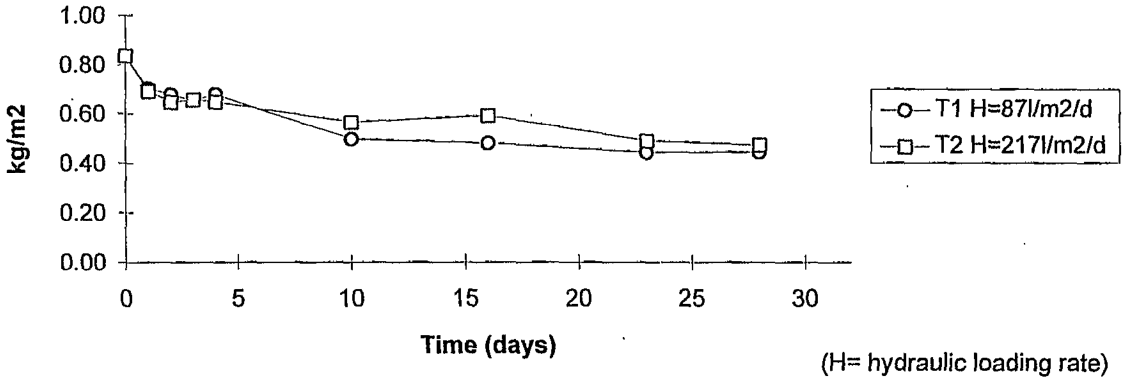
Cl⁻ Concentration of leachate



(H= hydraulic loading rate)

EXPERIMENT A: Chart A1(iv)

Mass of Cl⁻ in leachate per square metre of treatment area



(H= hydraulic loading rate)

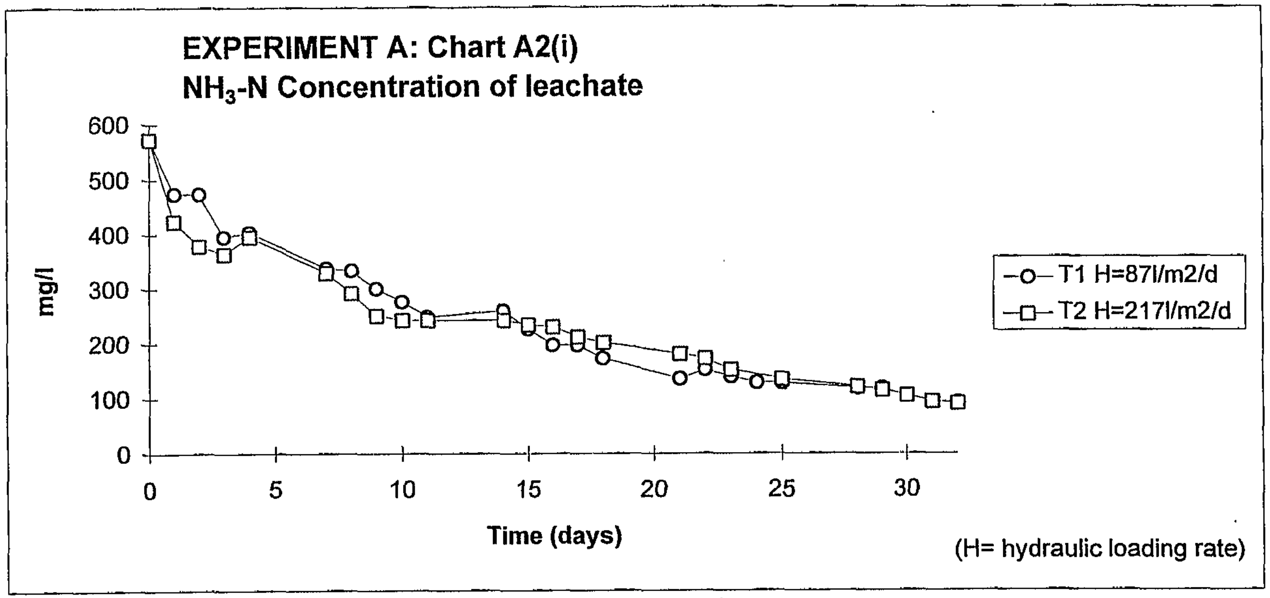
EXPERIMENT A Table A2: Ammonia (NH_3) data

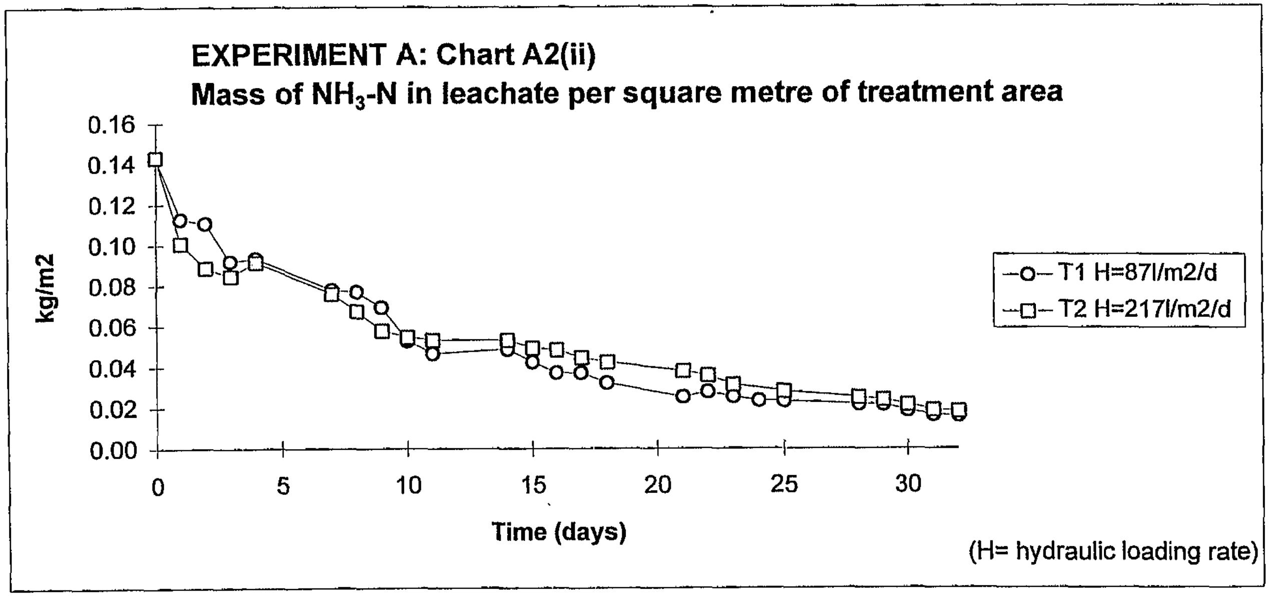
Dates: 17/01/94-18/02/94

Trough 1 (T1) Hydraulic loading rate (H)=87l/m^2/d Treatment plane surface area=0.8m^2

Trough 2 (T2) Hydraulic loading rate (H)=217l/m^2/d Treatment plane surface area=0.8m^2

		NH_3 conc. (mg/l)			NH_3-N conc. (mg/l)			Leachate volume (l)		NH_3-N total mass in leachate (kg)		Loading rate of NH_3-N (kg/m^2)		NH_3-N removal rate (kg/m^2/d)	
Day	Date	T1	T2	Ctrl	T1	T2	Ctrl	T1	T2	T1	T2	T1	T2	T1	T2
0	17/01/94	695	695	695	573	573	573	200	200	0.1145	0.1145	0.1432	0.1432	0.0306	0.0424
1	18/01/94	575	515		474	424		190	190	0.0900	0.0806	0.1125	0.1008	0.0018	0.0122
2	19/01/94	575	460	630	474	379	519	187	187	0.0886	0.0709	0.1108	0.0886	0.0188	0.0039
3	20/01/94	480	442		396	364		186	186	0.0736	0.0677	0.0920	0.0847	-0.0014	-0.0068
4	21/01/94	490	480	655	404	396	540	185	185	0.0747	0.0732	0.0934	0.0915	0.0157	0.0157
7	24/01/94	410	400	640	338	330	527	184	184	0.0622	0.0606	0.0777	0.0758	0.0009	0.0085
8	25/01/94	405	355		334	293		184	184	0.0614	0.0538	0.0768	0.0673	0.0076	0.0095
9	26/01/94	365	305		301	251		184	184	0.0553	0.0462	0.0692	0.0578	0.0164	0.0031
10	27/01/94	335	295	570	276	243	470	153	180	0.0422	0.0438	0.0528	0.0547	0.0061	0.0015
11	28/01/94	302	295		249	243		150	175	0.0373	0.0425	0.0467	0.0532	-0.0020	0.0000
14	31/01/94	315	295		260	243		150	175	0.0389	0.0425	0.0487	0.0532	0.0062	0.0039
15	01/02/94	275	285		227	235		150	168	0.0340	0.0395	0.0425	0.0493	0.0054	0.0009
16	02/02/94	240	280	640	198	231	527	150	168	0.0297	0.0388	0.0371	0.0485	0.0000	0.0038
17	03/02/94	240	258		198	213		150	168	0.0297	0.0357	0.0371	0.0446	0.0049	0.0022
18	04/02/94	210	245		173	202		149	168	0.0258	0.0339	0.0322	0.0424	0.0069	0.0043
21	07/02/94	165	220		136	181		149	168	0.0203	0.0305	0.0253	0.0381	-0.0025	0.0022
22	08/02/94	185	210		152	173		146	166	0.0223	0.0287	0.0278	0.0359	0.0024	0.0045
23	09/02/94	170	185	595	140	152	490	145	165	0.0203	0.0252	0.0254	0.0314	0.0019	0.0017
24	10/02/94	157			129			145	165	0.0188		0.0234		0.0001	
25	11/02/94	156	165		129	136		145	165	0.0186	0.0224	0.0233	0.0280	0.0016	0.0029
28	14/02/94	145	148		119	122		145	165	0.0173	0.0201	0.0217	0.0252	0.0001	0.0012
29	15/02/94	144	141		119	116		145	165	0.0172	0.0192	0.0215	0.0240	0.0029	0.0024
30	16/02/94	127	129		105	106		142	162	0.0149	0.0172	0.0186	0.0215	0.0022	0.0026
31	17/02/94	115	115		95	95		138	160	0.0131	0.0152	0.0163	0.0190	0.0003	0.0007
32	18/02/94	113	111	595	93	91	490	138	160	0.0128	0.0146	0.0161	0.0183		


EXPERIMENT A: Chart A2(i)
NH_3-N Concentration of leachate


EXPERIMENT A: Chart A2(ii)
Mass of NH_3-N in leachate per square metre of treatment area

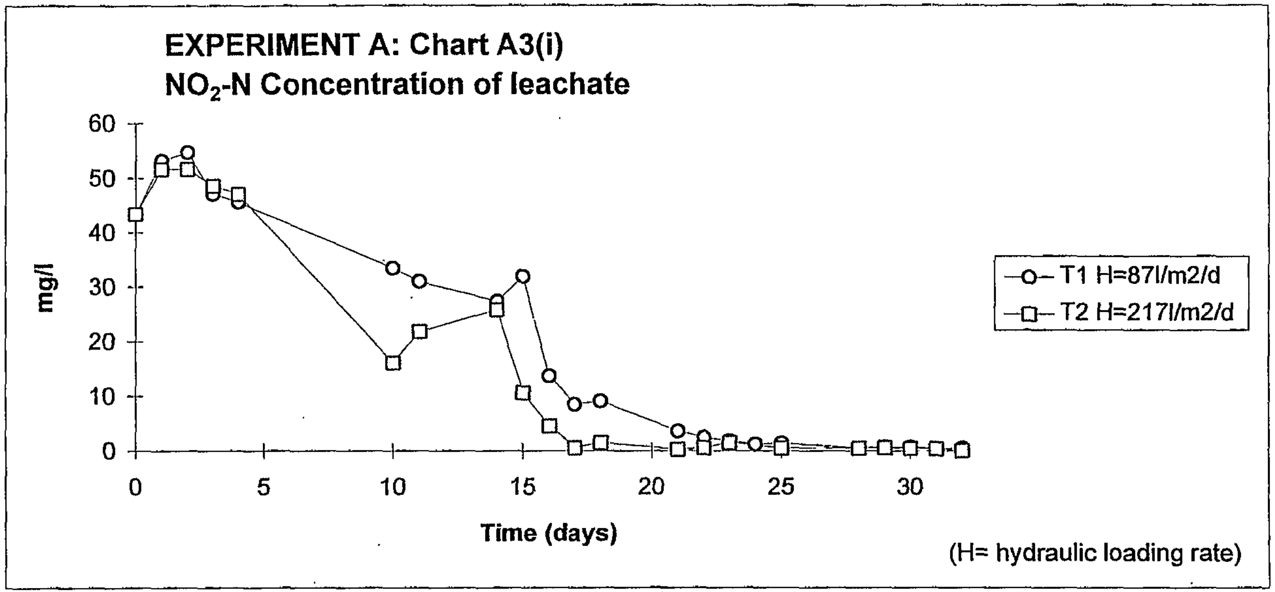
EXPERIMENT A Table A3: Nitrite (NO_2^-) data

Dates:	17/01/94-18/02/94
Trough 1 (T1)	Hydraulic loading rate (H)=87l/m^2/d
Trough 2 (T2)	Hydraulic loading rate (H)=217l/m^2/d

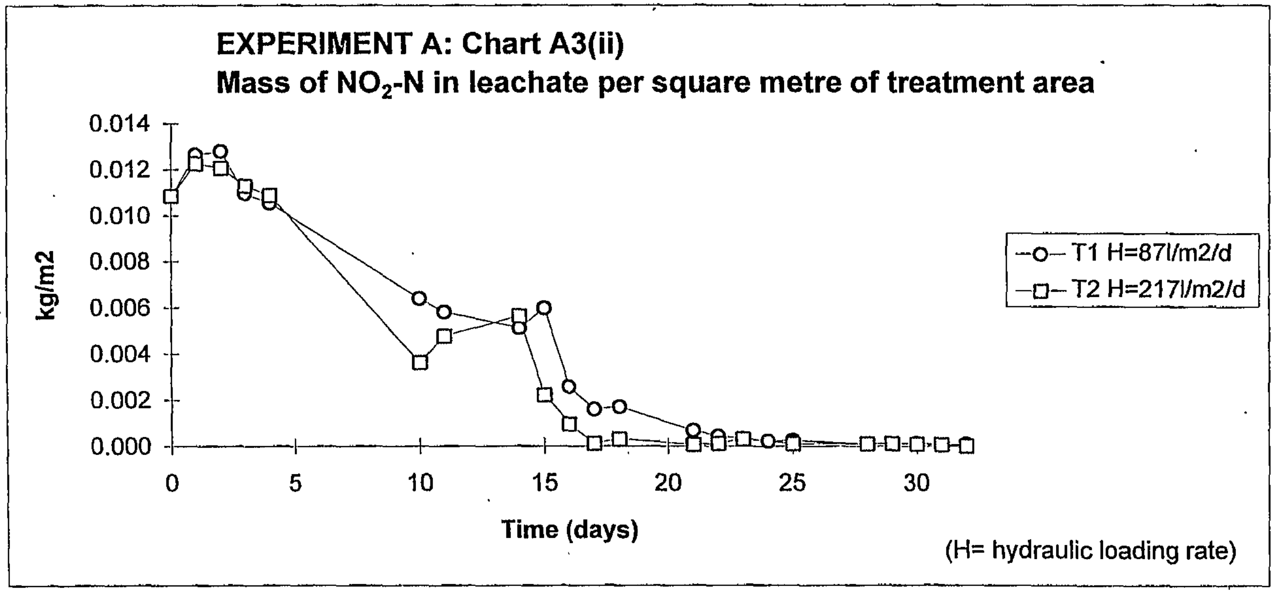
Treatment plane surface area=0.8m^2

Treatment plane surface area=0.8m^2

		NO_2^- conc. (mg/l)			NO_2-N conc. (mg/l)			Leachate volume (l)		NO_2-N total mass in leachate (kg)		Loading rate of NO_2-N (kg/m^2)		NO_2-N removal rate (kg/m^2/d)	
Day	Date	T1	T2	Ctrl	T1	T2	Ctrl	T1	T2	T1	T2	T1	T2	T1	T2
0	17/01/94	143	143	143	43	43	43	200	200	0.0087	0.0087	0.0109	0.0109	-0.0018	-0.0014
1	18/01/94	175	170		53	52		190	190	0.0101	0.0098	0.0126	0.0123	-0.0002	0.0002
2	19/01/94	180	170	140	55	52	43	187	187	0.0102	0.0097	0.0128	0.0121	0.0018	0.0008
3	20/01/94	155	160		47	49		186	186	0.0088	0.0090	0.0110	0.0113	0.0004	0.0004
4	21/01/94	150	155	190	46	47	58	185	185	0.0084	0.0087	0.0105	0.0109	0.0007	0.0012
7	24/01/94							184	184						
8	25/01/94							184	184						
9	26/01/94							184	184						
10	27/01/94	110	53	160	33	16	49	153	180	0.0051	0.0029	0.0064	0.0036	0.0006	-0.0012
11	28/01/94	102	72		31	22		150	175	0.0047	0.0038	0.0058	0.0048	0.0007	-0.0009
14	31/01/94	90	85		27	26		150	175	0.0041	0.0045	0.0051	0.0057	-0.0009	0.0034
15	01/02/94	105	35		32	11		150	168	0.0048	0.0018	0.0060	0.0022	0.0034	0.0013
16	02/02/94	45	15	155	14	5	47	150	168	0.0021	0.0008	0.0026	0.0010	0.0010	0.0008
17	03/02/94	28	2		9	1		150	168	0.0013	0.0001	0.0016	0.0001	-0.0001	-0.0002
18	04/02/94	30	5		9	2		149	168	0.0014	0.0003	0.0017	0.0003	0.0010	0.0003
21	07/02/94	12	1		4	0		149	168	0.0005	0.0001	0.0007	0.0001	0.0002	-0.0001
22	08/02/94	8	2		2	1		146	166	0.0004	0.0001	0.0004	0.0001	0.0001	-0.0002
23	09/02/94	6	5	152	2	2	46	145	165	0.0003	0.0003	0.0003	0.0003	0.0001	0.0001
24	10/02/94	4.1			1			145	165	0.0002		0.0002		0.0000	
25	11/02/94	4.6	1.7		1	1		145	165	0.0002	0.0001	0.0003	0.0001	0.0002	0.0000
28	14/02/94	1.7	1.7		1	1		145	165	0.0001	0.0001	0.0001	0.0001	0.0000	0.0000
29	15/02/94	2.1	2		1	1		145	165	0.0001	0.0001	0.0001	0.0001	0.0000	0.0000
30	16/02/94	2.3	1.6		1	0		142	162	0.0001	0.0001	0.0001	0.0001	0.0001	0.0000
31	17/02/94	1.4	1.4		0	0		138	160	0.0001	0.0001	0.0001	0.0001	0.0000	0.0001
32	18/02/94	1.8	0.2	160	1	0	49	138	160	0.0001	0.0000	0.0001	0.0000		



EXPERIMENT A: Chart A3(i)
NO_2-N Concentration of leachate



EXPERIMENT A: Chart A3(ii)
Mass of NO_2-N in leachate per square metre of treatment area

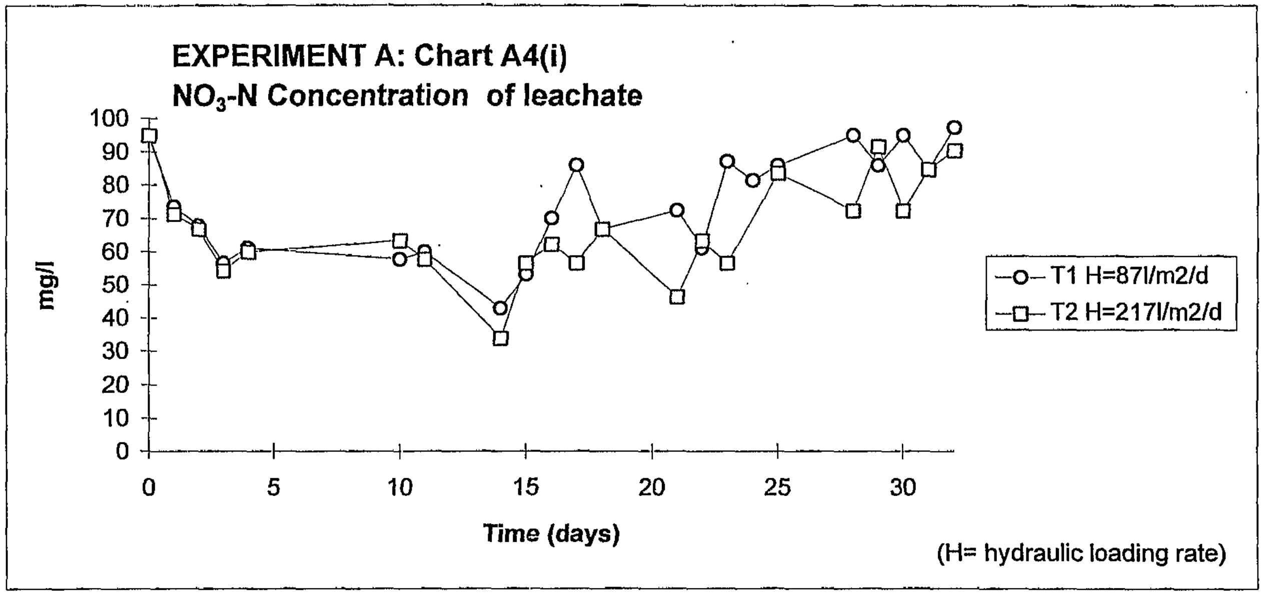
EXPERIMENT A Table A4: Nitrate (NO_3^-) data

Dates: 17/01/94-18/02/94

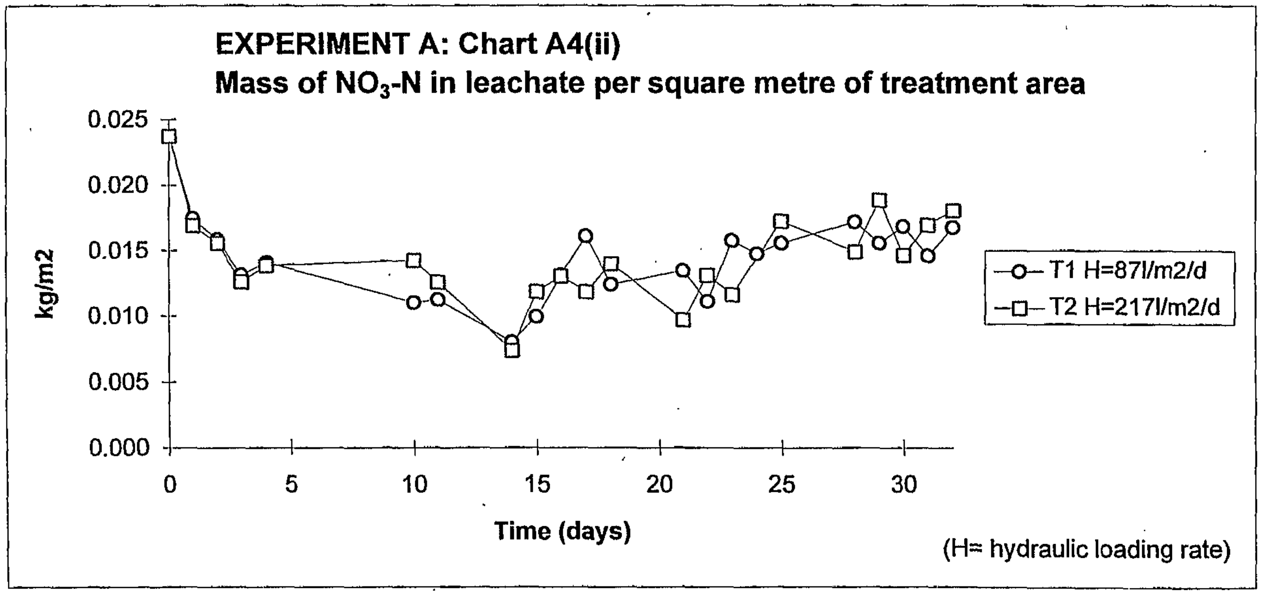
Trough 1 (T1) Hydraulic loading rate (H)=87l/m^2/d Treatment plane surface area=0.8m^2

Trough 2 (T2) Hydraulic loading rate (H)=217l/m^2/d Treatment plane surface area=0.8m^2

		NO_3 conc. (mg/l)			NO_3-N conc. (mg/l)			Leachate volume (l)		NO_3-N total mass in leachate (kg)		Loading rate of NO_3-N (kg/m^2)		NO_3-N removal rate (kg/m^2/d)	
Day	Date	T1	T2	Ctrl	T1	T2	Ctrl	T1	T2	T1	T2	T1	T2	T1	T2
0	17/01/94	420	420	420	95	95	95	200	200	0.0190	0.0190	0.0237	0.0237	0.0063	0.0068
1	18/01/94	325	315		73	71		190	190	0.0140	0.0135	0.0174	0.0169	0.0016	0.0013
2	19/01/94	300	295	350	68	67	79	187	187	0.0127	0.0125	0.0158	0.0156	0.0027	0.0030
3	20/01/94	250	240		57	54		186	186	0.0105	0.0101	0.0131	0.0126	-0.0010	-0.0012
4	21/01/94	270	265	295	61	60	67	185	185	0.0113	0.0111	0.0141	0.0138	0.0005	-0.0001
7	24/01/94							184	184						
8	25/01/94							184	184						
9	26/01/94							184	184						
10	27/01/94	255	280	265	58	63	81	153	180	0.0088	0.0114	0.0110	0.0142	-0.0002	0.0016
11	28/01/94	265	255		60	58		150	175	0.0090	0.0101	0.0112	0.0126	0.0032	0.0052
14	31/01/94	190	150		43	34		150	175	0.0064	0.0059	0.0081	0.0074	-0.0019	-0.0044
15	01/02/94	235	250		53	57		150	168	0.0080	0.0095	0.0100	0.0119	-0.0032	-0.0012
16	02/02/94	310	275	275	70	62	84	150	168	0.0105	0.0104	0.0131	0.0131	-0.0030	0.0012
17	03/02/94	380	250		86	57		150	168	0.0129	0.0095	0.0161	0.0119	0.0037	-0.0021
18	04/02/94	295	295		67	67		149	168	0.0099	0.0112	0.0124	0.0140	-0.0011	0.0043
21	07/02/94	320	205		72	46		149	168	0.0108	0.0078	0.0135	0.0097	0.0023	-0.0034
22	08/02/94	270	280		61	63		146	166	0.0089	0.0105	0.0111	0.0131	-0.0046	0.0015
23	09/02/94	385	250	220	87	57	67	145	165	0.0126	0.0093	0.0158	0.0117	0.0010	-0.0028
24	10/02/94	360			81			145	165	0.0118		0.0147		-0.0008	
25	11/02/94	380	370		86	84		145	165	0.0125	0.0138	0.0156	0.0172	-0.0016	0.0023
28	14/02/94	420	320		95	72		145	165	0.0138	0.0119	0.0172	0.0149	0.0016	-0.0040
29	15/02/94	380	405		86	92		145	165	0.0125	0.0151	0.0156	0.0189	-0.0013	0.0042
30	16/02/94	420	320		95	72		142	162	0.0135	0.0117	0.0168	0.0146	0.0022	-0.0023
31	17/02/94	375	375		85	85		138	160	0.0117	0.0136	0.0146	0.0170	-0.0021	-0.0011
32	18/02/94	430	400	235	97	90	71	138	160	0.0134	0.0145	0.0168	0.0181		



EXPERIMENT A: Chart A4(i)
NO_3-N Concentration of leachate



EXPERIMENT A: Chart A4(ii)
Mass of NO_3-N in leachate per square metre of treatment area

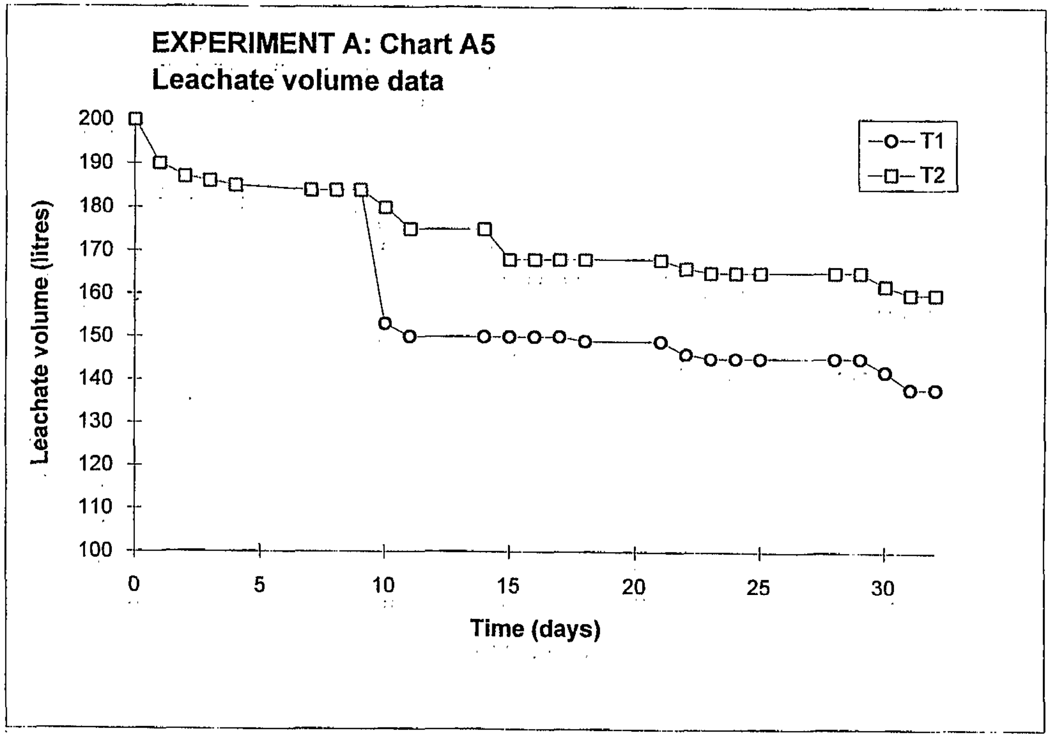
EXPERIMENT A

Table A5: Leachate volume and Hydraulic loading rate (H) data

Dates: **17/01/94-18/02/94**
Trough 1 (T1) **Hydraulic loading rate (H)=87l/m²/d** **Treatment plane surface area=0.8m²**
Trough 2 (T2) **Hydraulic loading rate (H)=217l/m²/d** **Treatment plane surface area=0.8m²**
Units: Volume (litres), Hydraulic loading rate (litres/m²/day)

		T1			T2		
Day	Date	Total	Applied	H	Total	Applied	H
0	17/01/94	200	67	83.75	200	200	250
1	18/01/94	190	70	87.5	190	190	237.5
2	19/01/94	187	70	87.5	187	187	233.75
3	20/01/94	186	70	87.5	186	186	232.5
4	21/01/94	185	70	87.5	185	185	231.25
7	24/01/94	184	70	87.5	184	184	230
8	25/01/94	184	70	87.5	184	184	230
9	26/01/94	184	70	87.5	184	184	230
10	27/01/94	153	70	87.5	180	180	225
11	28/01/94	150	70	87.5	175	175	218.75
14	31/01/94	150	70	87.5	175	175	218.75
15	01/02/94	150	70	87.5	168	168	210
16	02/02/94	150	70	87.5	168	168	210
17	03/02/94	150	70	87.5	168	168	210
18	04/02/94	149	70	87.5	168	168	210
21	07/02/94	149	70	87.5	168	168	210
22	08/02/94	146	70	87.5	166	166	207.5
23	09/02/94	145	70	87.5	165	165	206.25
24	10/02/94	145	70	87.5	165	165	206.25
25	11/02/94	145	70	87.5	165	165	206.25
28	14/02/94	145	70	87.5	165	165	206.25
29	15/02/94	145	70	87.5	165	165	206.25
30	16/02/94	142	70	87.5	162	162	202.5
31	17/02/94	138	70	87.5	160	160	200
32	18/02/94	138	70	87.5	160	160	200

Average actual H	87	217

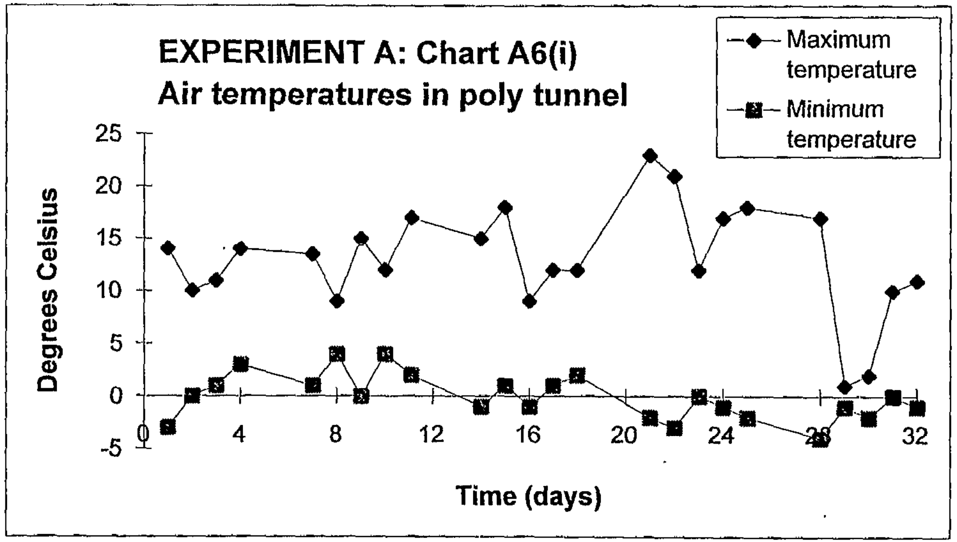


EXPERIMENT A **Table A6: Air and Soil temperature data**

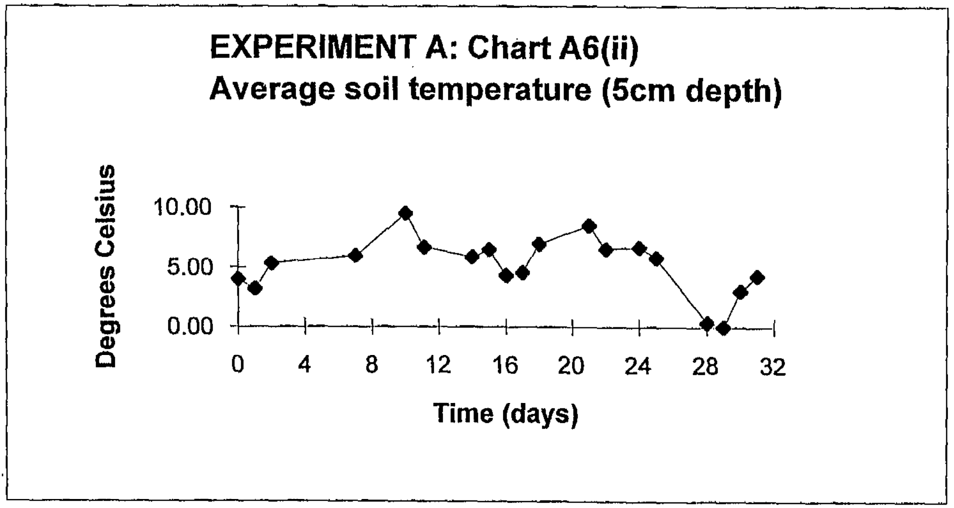
Dates: **17/01/94-18/02/94**

(Conducted in polytunnel)

		Air Temp. (°C)			Soil Temp. (°C)		
Day	Date	Max	Min	Ave.	10am	3pm	Ave.
0	17/01/94				3.00	5.00	4.00
1	18/01/94	14	-3	5.5	2.13	4.25	3.19
2	19/01/94	10	0	5	4.63	6.00	5.31
3	20/01/94	11	1	6	3.25		
4	21/01/94	14	3	8.5	6.50		
7	24/01/94	13.5	1	7.25	5.50	6.38	5.94
8	25/01/94	9	4	6.5	8.50		
9	26/01/94	15	0	7.5	6.25		
10	27/01/94	12	4	8	8.25	10.75	9.50
11	28/01/94	17	2	9.5	5.13	8.25	6.69
14	31/01/94	15	-1	7	4.50	7.25	5.88
15	01/02/94	18	1	9.5	6.00	7.00	6.50
16	02/02/94	9	-1	4	3.13	5.50	4.31
17	03/02/94	12	1	6.5	3.13	6.00	4.56
18	04/02/94	12	2	7	5.88	8.13	7.00
21	07/02/94	23	-2	10.5	6.75	10.25	8.50
22	08/02/94	21	-3	9	4.75	8.38	6.56
23	09/02/94	12	0	6	6.75		
24	10/02/94	17	-1	8	5.00	8.38	6.69
25	11/02/94	18	-2	8	5.13	6.50	5.81
28	14/02/94	17	-4	6.5	0.25	0.50	0.38
29	15/02/94	1	-1	0	0.13	0.00	0.06
30	16/02/94	2	-2	0	2.00	4.13	3.06
31	17/02/94	10	0	5	4.63	4.00	4.31
32	18/02/94	11	-1	5	4.00		
Average °C		13.06	-0.08	6.49	4.61	6.14	5.37



EXPERIMENT A: Chart A6(i)
Air temperatures in poly tunnel



EXPERIMENT A: Chart A6(ii)
Average soil temperature (5cm depth)

EXPERIMENT B

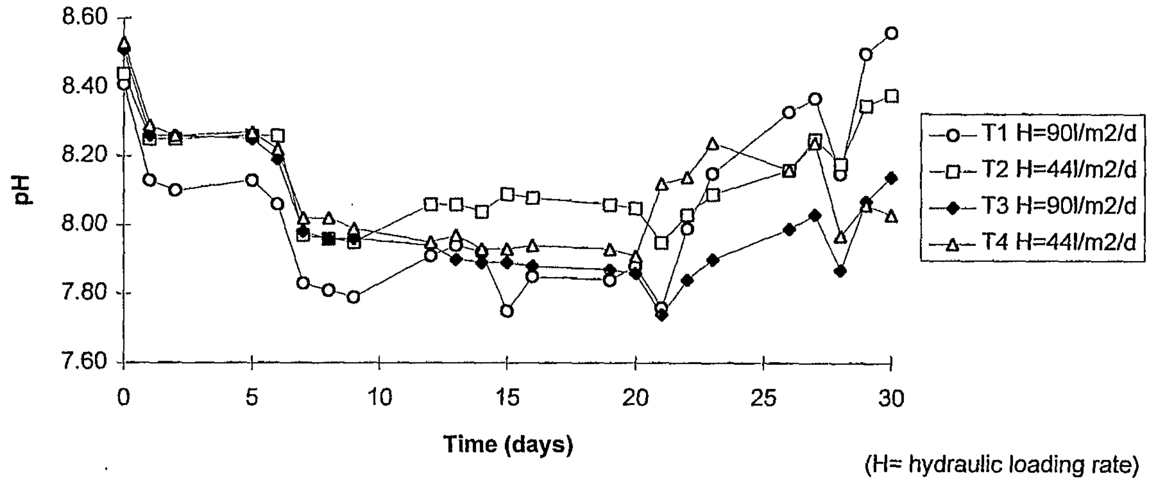
Table B1: pH, Chemical Oxygen Demand (COD), and Chloride (Cl^-) data

Dates:	23/02/94-25/03/94	
Trough 1 (T1)	Hydraulic loading rate (H)=90l/m^2/d	Treatment plane surface area=0.8m^2
Trough 2 (T2)	Hydraulic loading rate (H)=44l/m^2/d	Treatment plane surface area=0.8m^2
Trough 3 (T3)	Hydraulic loading rate (H)=90l/m^2/d	Treatment plane surface area=0.8m^2
Trough 4 (T4)	Hydraulic loading rate (H)=44l/m^2/d	Treatment plane surface area=0.8m^2

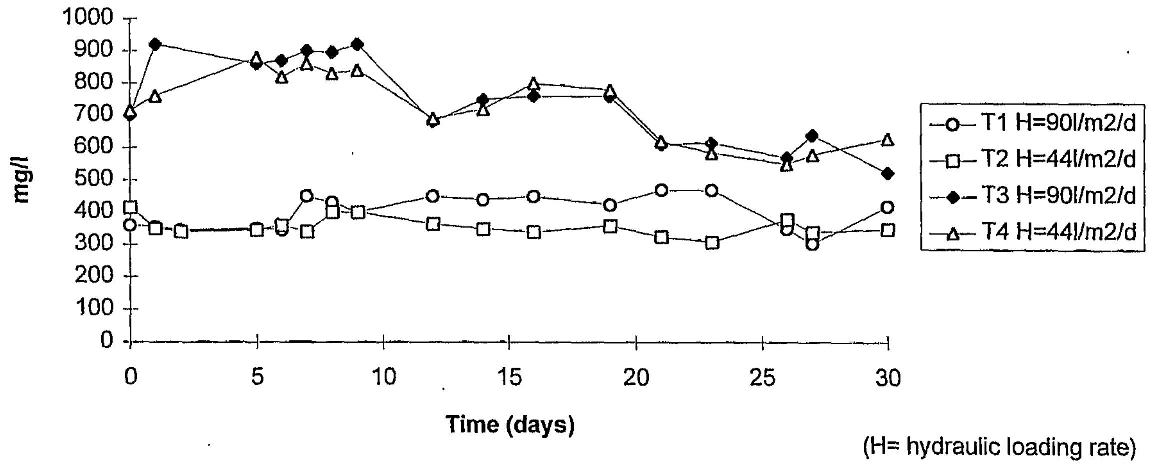
		pH				*COD conc.* (mg/l)				*Cl^- mg/l* (mg/l)			
Day	Date	T1	T2	T3	T4	T1	T2	T3	T4	T1	T2	T3	T4
0	23/02/94	8.41	8.44	8.51	8.53	360	415	700	715	990	180	2375	2115
1	24/02/94	8.13	8.25	8.26	8.29	355	350	920	760				
2	25/02/94	8.10	8.25	8.26	8.26	345	340						
5	28/02/94	8.13	8.26	8.25	8.27	350	345	860	880				
6	01/03/94	8.06	8.26	8.19	8.22	345	360	870	820				
7	02/03/94	7.83	7.97	7.98	8.02	450	340	900	860	870	840	1860	1915
8	03/03/94	7.81	7.96	7.96	8.02	430	400	895	830				
9	04/03/94	7.79	7.95	7.96	7.99	400	400	920	840				
12	07/03/94	7.91	8.06	7.94	7.95	450	365	680	690				
13	08/03/94	7.94	8.06	7.90	7.97								
14	09/03/94	7.92	8.04	7.89	7.93	440	350	750	720	900	930	1960	1950
15	10/03/94	7.75	8.09	7.89	7.93								
16	11/03/94	7.85	8.08	7.88	7.94	450	340	760	800				
19	14/03/94	7.84	8.06	7.87	7.93	425	360	760	780				
20	15/03/94	7.88	8.05	7.86	7.91								
21	16/03/94	7.76	7.95	7.74	8.12	470	325	610	620				
22	17/03/94	7.99	8.03	7.84	8.14								
23	18/03/94	8.15	8.09	7.90	8.24	470	310	615	585	1200	1165	2040	2095
26	21/03/94	8.33	8.16	7.99	8.16	350	380	570	550				
27	22/03/94	8.37	8.25	8.03	8.24	305	340	640	580	1240	1180	2090	2120
28	23/03/94	8.15	8.18	7.87	7.97								
29	24/03/94	8.50	8.35	8.07	8.06								
30	25/03/94	8.56	8.38	8.14	8.03	420	350	525	630	880	1350	2415	2240

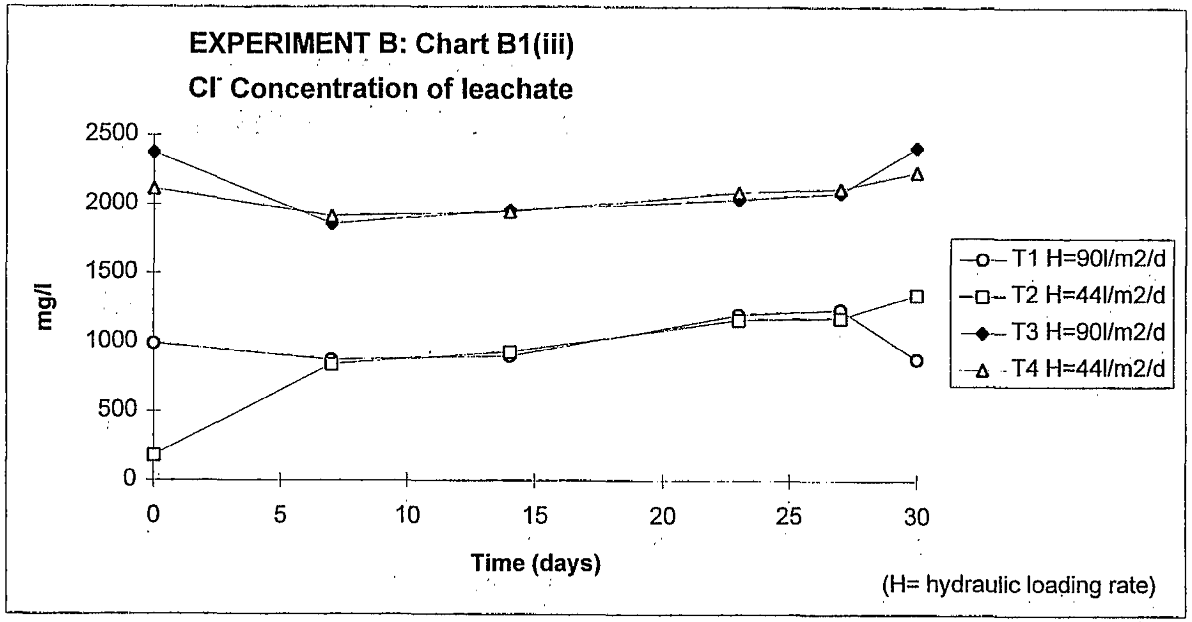
		Leachate volume (litres)				Cl^- total mass in leachate (kg)				Loading rate of Cl^- (kg/m^2)				Cl- removal rate kg/m^2/d			
Day	Date	T1	T2	T3	T4	T1	T2	T3	T4	T1	T2	T3	T4	T1	T2	T3	T4
0	23/02/94	200	200	200	200	0.1980	0.0360	0.4750	0.4230	0.2475	0.0450	0.5938	0.5288	0.0072	-0.0224	0.0217	0.0092
1	24/02/94	195	199	197	199												
2	25/02/94	195	199	197	199												
5	28/02/94	184	198	193	198												
6	01/03/94	182	195	192	195												
7	02/03/94	181	192	190	194	0.1575	0.1613	0.3534	0.3715	0.1968	0.2016	0.4418	0.4644	0.0013	-0.0018	0.0075	0.0012
8	03/03/94	176	191	186	193												
9	04/03/94	175	190	184	192												
12	07/03/94	171	189	165	190												
13	08/03/94	169	185	161	188												
14	09/03/94	167	184	159	187	0.1503	0.1711	0.3116	0.3647	0.1879	0.2139	0.3896	0.4558	-0.0035	-0.0033	0.0031	0.0038
15	10/03/94	166	182	157	185												
16	11/03/94	163	180	155	183												
19	14/03/94	159	178	150	175												
20	15/03/94	153	173	150	171												
21	16/03/94	151	171	148	169												
22	17/03/94	149	169	145	166												
23	18/03/94	146	167	142	161	0.1752	0.1946	0.2897	0.3373	0.2190	0.2432	0.3621	0.4216	0.0009	0.0022	0.0056	0.0014
26	21/03/94	143	165	136	160												
27	22/03/94	139	159	130	157	0.1724	0.1876	0.2717	0.3328	0.2155	0.2345	0.3396	0.4161	0.0271	-0.0090	0.0196	-0.0032
28	23/03/94	128	158	129	156												
29	24/03/94	126	157	128	155												
30	25/03/94	122	155	93	152	0.1074	0.2093	0.2246	0.3405	0.1342	0.2616	0.2807	0.4256				

EXPERIMENT B: Chart B1(i)
pH of leachate



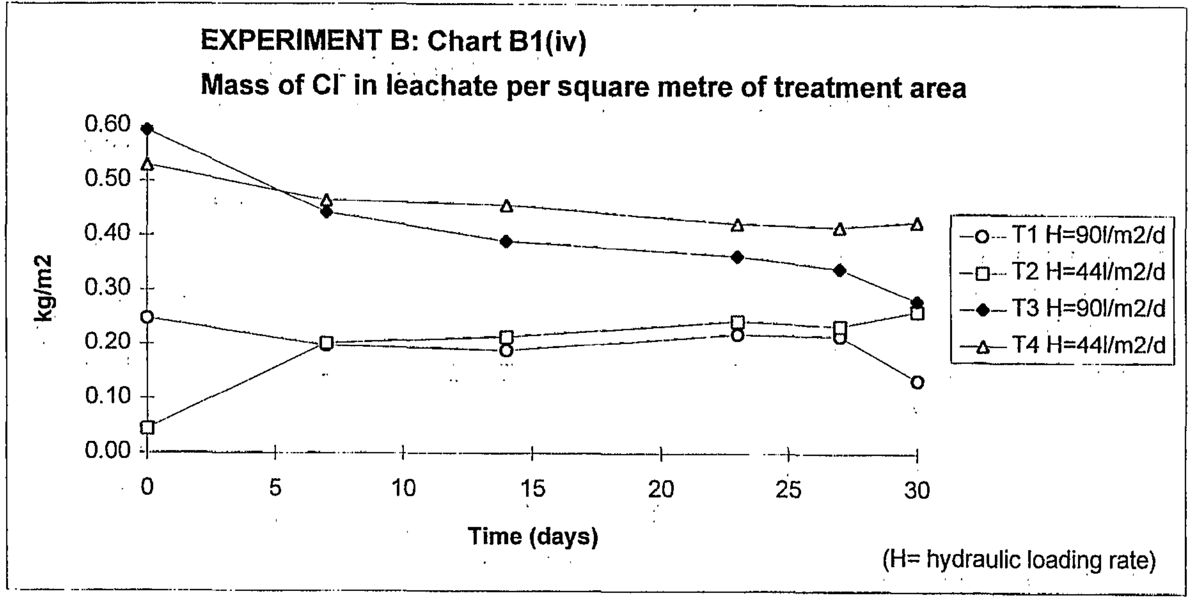
EXPERIMENT B: Chart B1(ii)
COD Concentration of leachate





EXPERIMENT B: Chart B1(iii)

Cl^- Concentration of leachate



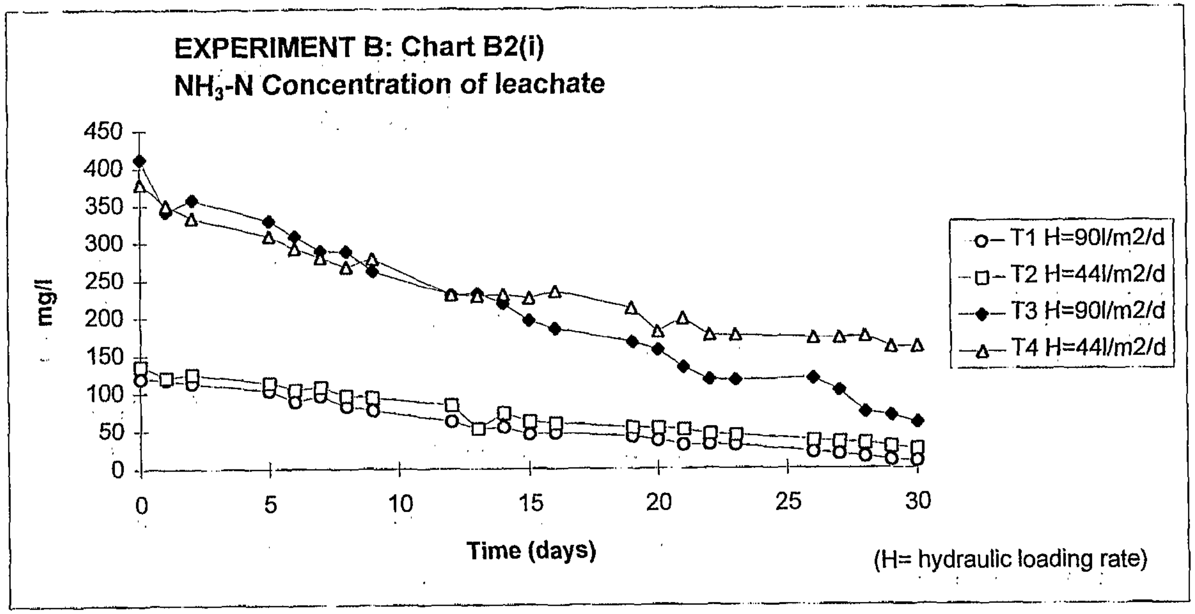
EXPERIMENT B: Chart B1(iv)

Mass of Cl^- in leachate per square metre of treatment area

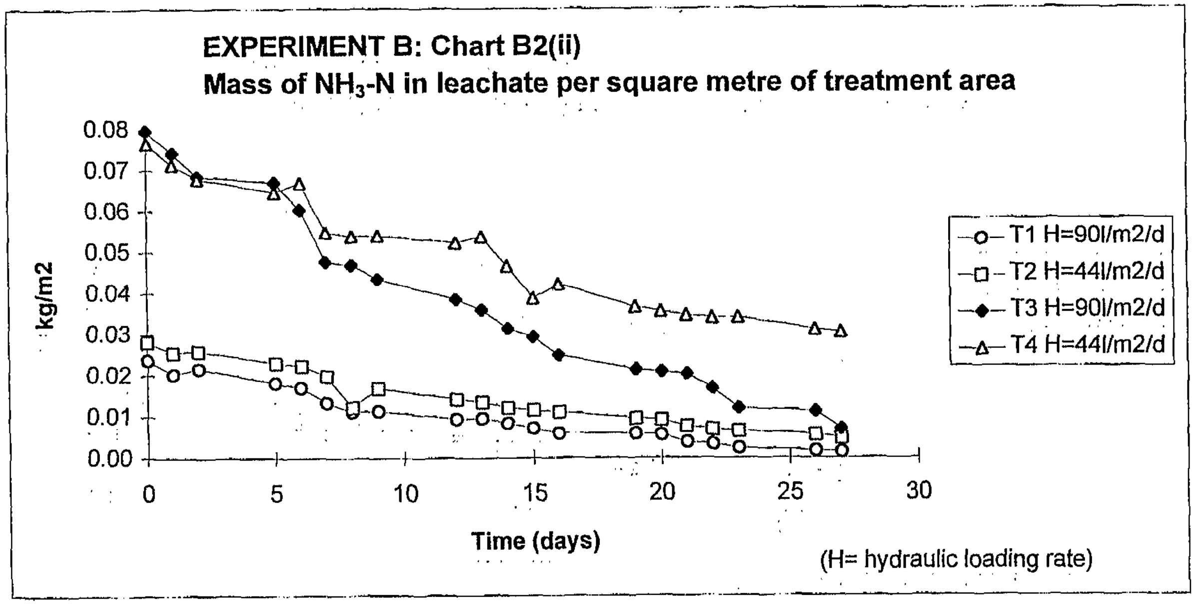
EXPERIMENT B Table B2: Ammonia (NH_3) data

Dates:	23/02/94-25/03/94	
Trough 1 (T1)	Hydraulic loading rate (H)=90l/m^2/d	Treatment plane surface area=0.8m^2
Trough 2 (T2)	Hydraulic loading rate (H)=44l/m^2/d	Treatment plane surface area=0.8m^2
Trough 3 (T3)	Hydraulic loading rate (H)=90l/m^2/d	Treatment plane surface area=0.8m^2
Trough 4 (T4)	Hydraulic loading rate (H)=44l/m^2/d	Treatment plane surface area=0.8m^2

		NH_3 conc. (mg/l)				NH_3-N conc. (mg/l)				Leachate volume (litres)				NH_3-N total mass in leachate (kg)				Loading rate of NH_3-N (kg/m^2)				NH_3-N removal rate (kg/m^2/d)			
Day	Date	T1	T2	T3	T4	T1	T2	T3	T4	T1	T2	T3	T4	T1	T2	T3	T4	T1	T2	T3	T4	T1	T2	T3	T4
0	23/02/94	145	165	500	460	119	136	412	379	200	200	200	200	0.0239	0.0272	0.0824	0.0758	0.0299	0.0340	0.1030	0.0948	0.0011	0.0039	0.0188	0.0076
1	24/02/94	143	147	415	425	118	121	342	350	195	199	197	199	0.0230	0.0241	0.0674	0.0697	0.0287	0.0301	0.0842	0.0871	0.0012	-0.0010	-0.0039	0.0041
2	25/02/94	137	152	434	405	113	125	358	334	195	199	197	199	0.0220	0.0249	0.0705	0.0664	0.0275	0.0312	0.0881	0.0830	0.0038	0.0030	0.0085	0.0065
5	28/02/94	125	138	400	375	103	114	330	309	184	198	193	198	0.0190	0.0225	0.0636	0.0612	0.0237	0.0281	0.0795	0.0765	0.0034	0.0026	0.0054	0.0052
6	01/03/94	108	127	375	355	89	105	309	293	182	195	192	195	0.0162	0.0204	0.0593	0.0570	0.0202	0.0255	0.0742	0.0713	-0.0014	-0.0004	0.0057	0.0034
7	02/03/94	116	131	350	340	96	108	288	280	181	192	190	194	0.0173	0.0207	0.0548	0.0544	0.0216	0.0259	0.0685	0.0679	0.0035	0.0029	0.0014	0.0033
8	03/03/94	100	117	350	325	82	96	288	268	176	191	186	193	0.0145	0.0184	0.0536	0.0517	0.0181	0.0230	0.0671	0.0646	0.0012	0.0007	0.0068	-0.0022
9	04/03/94	94	114	318	338	77	94	262	279	175	190	184	192	0.0136	0.0178	0.0482	0.0535	0.0169	0.0223	0.0603	0.0668	0.0036	0.0025	0.0127	0.0120
12	07/03/94	76	102	280	280	63	84	231	231	171	189	165	190	0.0107	0.0159	0.0381	0.0438	0.0134	0.0199	0.0476	0.0548	0.0022	0.0077	0.0008	0.0010
13	08/03/94	64	64	282	278	53	53	232	229	169	185	161	188	0.0089	0.0098	0.0374	0.0431	0.0111	0.0122	0.0468	0.0538	-0.0002	-0.0047	0.0034	-0.0001
14	09/03/94	66	89	265	280	54	73	218	231	167	184	159	187	0.0091	0.0135	0.0347	0.0431	0.0114	0.0169	0.0434	0.0539	0.0019	0.0026	0.0049	0.0017
15	10/03/94	55	76	238	274	45	63	196	226	166	182	157	185	0.0075	0.0114	0.0308	0.0418	0.0094	0.0142	0.0385	0.0522	-0.0002	0.0007	0.0026	-0.0015
16	11/03/94	57	73	225	285	47	60	185	235	183	180	155	183	0.0077	0.0108	0.0287	0.0430	0.0096	0.0135	0.0359	0.0537	0.0012	0.0014	0.0046	0.0072
19	14/03/94	51	66	203	258	42	54	167	213	159	178	150	175	0.0067	0.0097	0.0251	0.0372	0.0084	0.0121	0.0314	0.0465	0.0013	0.0005	0.0020	0.0078
20	15/03/94	45	65	190	220	37	54	157	181	153	173	150	171	0.0057	0.0093	0.0235	0.0310	0.0071	0.0116	0.0294	0.0387	0.0012	0.0005	0.0045	-0.0034
21	16/03/94	38	63	163	242	31	52	134	199	151	171	148	169	0.0047	0.0089	0.0199	0.0337	0.0059	0.0111	0.0248	0.0421	0.0001	0.0015	0.0035	0.0055
22	17/03/94	38	55	143	214	31	45	118	176	149	169	145	166	0.0047	0.0077	0.0171	0.0293	0.0058	0.0096	0.0214	0.0366	0.0003	0.0005	0.0006	0.0011
23	18/03/94	37	53	142	214	30	44	117	176	146	167	142	161	0.0045	0.0073	0.0166	0.0284	0.0056	0.0091	0.0208	0.0355	0.0017	0.0015	0.0005	0.0009
26	21/03/94	26	45	145	210	21	37	119	173	143	165	136	160	0.0031	0.0061	0.0162	0.0277	0.0038	0.0076	0.0203	0.0346	0.0005	0.0008	0.0036	0.0006
27	22/03/94	23	42	125	210	19	35	103	173	139	159	130	157	0.0026	0.0055	0.0134	0.0272	0.0033	0.0069	0.0167	0.0340	0.0009	0.0004	0.0048	-0.0001
28	23/03/94	18	40	90	212	15	33	74	175	128	158	129	156	0.0019	0.0052	0.0096	0.0273	0.0024	0.0065	0.0120	0.0341	0.0007	0.0008	0.0008	0.0029
29	24/03/94	13	35	85	195	11	29	70	161	126	157	128	155	0.0013	0.0045	0.0090	0.0249	0.0017	0.0057	0.0112	0.0311	0.0003	0.0009	0.0042	0.0006
30	25/03/94	11	30	73	195	9	25	60	161	122	155	93	152	0.0011	0.0038	0.0056	0.0244	0.0014	0.0048	0.0070	0.0305				



EXPERIMENT B: Chart B2(i)
NH_3-N Concentration of leachate

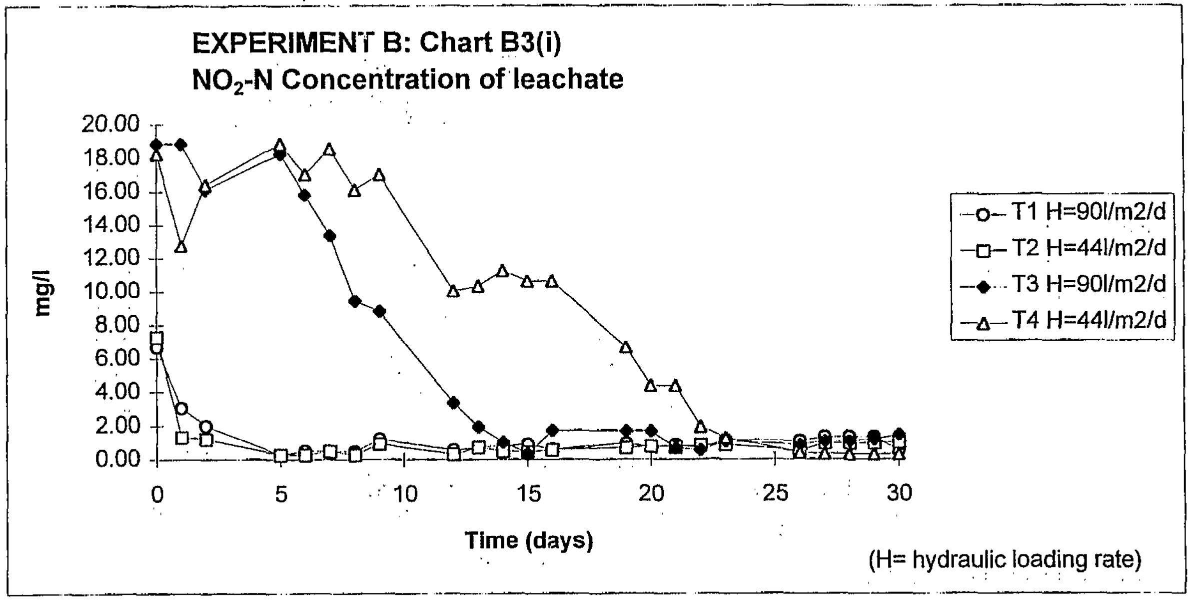


EXPERIMENT B: Chart B2(ii)
Mass of NH_3-N in leachate per square metre of treatment area

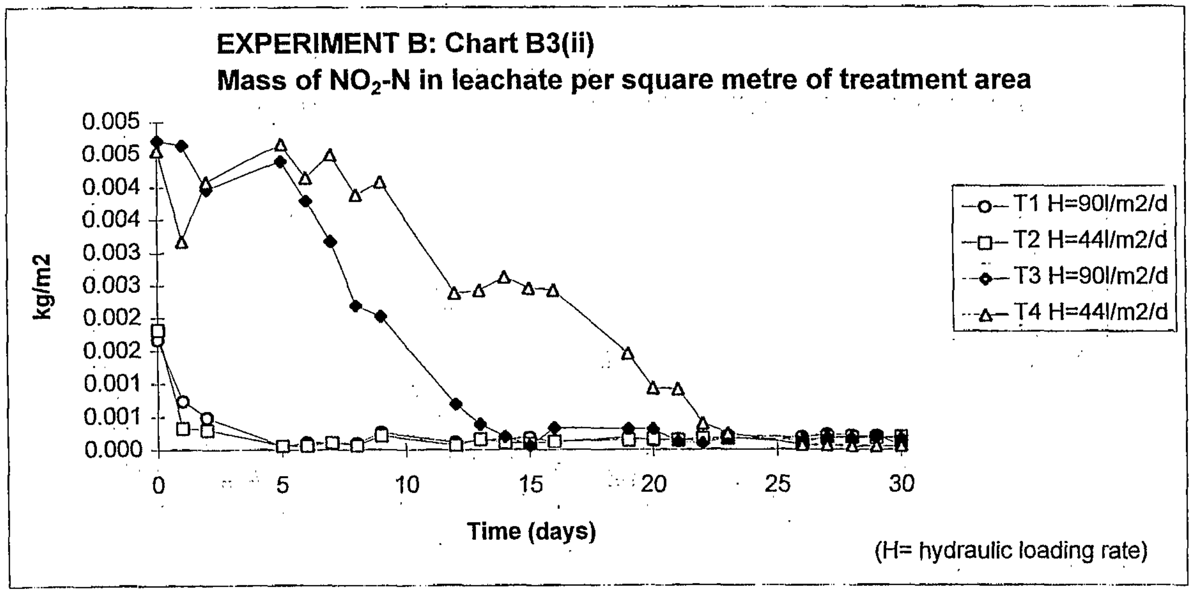
EXPERIMENT B **Table B3: Nitrite (NO$_2^-$) data**

Dates:	23/02/94-25/03/94	
Trough 1 (T1)	Hydraulic loading rate (H)=90l/m^2/d	Treatment plane surface area=0.8m^2
Trough 2 (T2)	Hydraulic loading rate (H)=44l/m^2/d	Treatment plane surface area=0.8m^2
Trough 3 (T3)	Hydraulic loading rate (H)=90l/m^2/d	Treatment plane surface area=0.8m^2
Trough 4 (T4)	Hydraulic loading rate (H)=44l/m^2/d	Treatment plane surface area=0.8m^2

		NO$_2^-$ conc. (mg/l)				NO$_2$-N conc. (mg/l)				Leachate volume (litres)				NO$_2$-N total mass in leachate (kg)				Loading rate of NO$_2$-N (kg/m^2)				NO$_2$-N removal rate (kg/m^2/d)			
Day	Date	T1	T2	T3	T4	T1	T2	T3	T4	T1	T2	T3	T4	T1	T2	T3	T4	T1	T2	T3	T4	T1	T2	T3	T4
0	23/02/94	22	24	62	60	7	7	19	18	200	200	200	200	0.0013	0.0015	0.0038	0.0036	0.0017	0.0018	0.0047	0.0046	0.0009	0.0015	0.0001	0.0014
1	24/02/94	10	4	62	42	3	1	19	13	195	199	197	199	0.0006	0.0003	0.0037	0.0025	0.0007	0.0003	0.0046	0.0032	0.0003	0.0000	0.0007	-0.0009
2	25/02/94	7	4	53	54	2	1	16	16	195	199	197	199	0.0004	0.0002	0.0032	0.0033	0.0005	0.0003	0.0040	0.0041	0.0004	0.0002	-0.0004	-0.0006
5	28/02/94	1	1	60	62	0	0	18	19	184	198	193	198	0.0001	0.0001	0.0035	0.0037	0.0001	0.0001	0.0044	0.0047	0.0000	0.0000	0.0006	0.0005
6	01/03/94	2	1	52	56	0	0	16	17	182	195	192	195	0.0001	0.0001	0.0030	0.0033	0.0001	0.0001	0.0038	0.0041	0.0000	-0.0001	0.0006	-0.0003
7	02/03/94	2	2	44	61	1	0	13	19	181	192	190	194	0.0001	0.0001	0.0025	0.0036	0.0001	0.0001	0.0032	0.0045	0.0000	0.0001	0.0010	0.0006
8	03/03/94	2	1	31	53	0	0	9	16	176	191	186	193	0.0001	0.0001	0.0018	0.0031	0.0001	0.0001	0.0022	0.0039	-0.0002	-0.0002	0.0002	-0.0002
9	04/03/94	4	3	29	56	1	1	9	17	175	190	184	192	0.0002	0.0002	0.0016	0.0033	0.0003	0.0002	0.0020	0.0041	0.0001	0.0002	0.0013	0.0017
12	07/03/94	2	1	11	33	1	0	3	10	171	189	165	190	0.0001	0.0001	0.0006	0.0019	0.0001	0.0001	0.0007	0.0024	0.0000	-0.0001	0.0003	0.0000
13	08/03/94	2	2	6	34	1	1	2	10	169	185	161	188	0.0001	0.0001	0.0003	0.0019	0.0002	0.0002	0.0004	0.0024	0.0000	0.0001	0.0002	-0.0002
14	09/03/94	3	2	3	37	1	0	1	11	167	184	159	187	0.0001	0.0001	0.0002	0.0021	0.0002	0.0001	0.0002	0.0026	0.0000	0.0000	0.0001	0.0002
15	10/03/94	3	2	1	35	1	0	0	11	166	182	157	185	0.0002	0.0001	0.0001	0.0020	0.0002	0.0001	0.0001	0.0025	0.0001	0.0000	-0.0003	0.0000
16	11/03/94	2	2	6	35	1	1	2	11	163	180	155	183	0.0001	0.0001	0.0003	0.0019	0.0001	0.0001	0.0003	0.0024	-0.0001	0.0000	0.0000	0.0010
19	14/03/94	3	2	6	22	1	1	2	7	159	178	150	175	0.0002	0.0001	0.0003	0.0012	0.0002	0.0002	0.0003	0.0015	0.0001	0.0000	0.0000	0.0005
20	15/03/94	2	3	6	14	1	1	2	4	153	173	150	171	0.0001	0.0001	0.0003	0.0007	0.0001	0.0002	0.0003	0.0009	0.0000	0.0000	0.0002	0.0000
21	16/03/94	3	2	2	14	1	1	1	4	151	171	148	169	0.0001	0.0001	0.0001	0.0007	0.0002	0.0002	0.0001	0.0009	0.0000	0.0000	0.0000	0.0005
22	17/03/94	2	3	2	6	1	1	1	2	149	169	145	166	0.0001	0.0001	0.0001	0.0003	0.0001	0.0002	0.0001	0.0004	-0.0001	0.0000	-0.0001	0.0001
23	18/03/94	4	3	4	4	1	1	1	1	146	167	142	161	0.0002	0.0001	0.0002	0.0002	0.0002	0.0002	0.0002	0.0003	0.0000	0.0001	0.0000	0.0002
26	21/03/94	4	2	3	1	1	1	1	0	143	165	136	160	0.0002	0.0001	0.0001	0.0001	0.0002	0.0001	0.0001	0.0001	0.0000	-0.0001	0.0000	0.0000
27	22/03/94	4	3	4	1	1	1	1	0	139	159	130	157	0.0002	0.0002	0.0001	0.0001	0.0002	0.0002	0.0002	0.0001	0.0000	0.0000	0.0000	0.0000
28	23/03/94	4	3	4	1	1	1	1	0	128	158	129	156	0.0002	0.0002	0.0001	0.0000	0.0002	0.0002	0.0002	0.0001	0.0000	0.0000	0.0000	0.0000
29	24/03/94	4	3	4	1	1	1	1	0	126	157	128	155	0.0002	0.0002	0.0002	0.0000	0.0002	0.0002	0.0002	0.0001	0.0001	0.0000	0.0000	0.0000
30	25/03/94	2	3	5	1	0	1	1	0	122	155	93	152	0.0001	0.0002	0.0001	0.0000	0.0001	0.0002	0.0002	0.0001				



EXPERIMENT B: Chart B3(i)
NO_2-N Concentration of leachate



EXPERIMENT B: Chart B3(ii)
Mass of NO_2-N in leachate per square metre of treatment area

EXPERIMENT B Table B4: Nitrate (NO$_3$) data

Dates: 23/02/94-25/03/94

Trough 1 (T1) Hydraulic loading rate (H)=90l/m^2/d Treatment plane surface area=0.8m^2

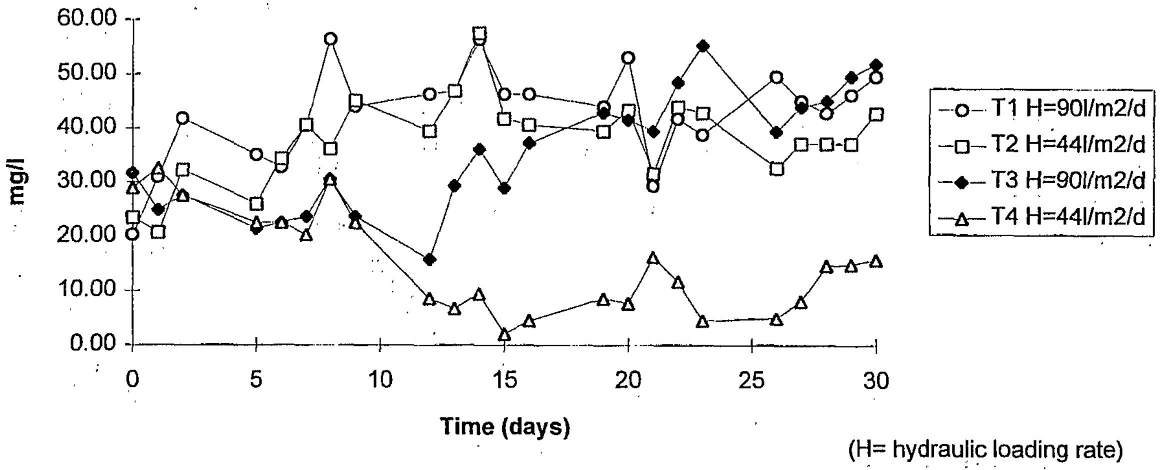
Trough 2 (T2) Hydraulic loading rate (H)=44l/m^2/d Treatment plane surface area=0.8m^2

Trough 3 (T3) Hydraulic loading rate (H)=90l/m^2/d Treatment plane surface area=0.8m^2

Trough 4 (T4) Hydraulic loading rate (H)=44l/m^2/d Treatment plane surface area=0.8m^2

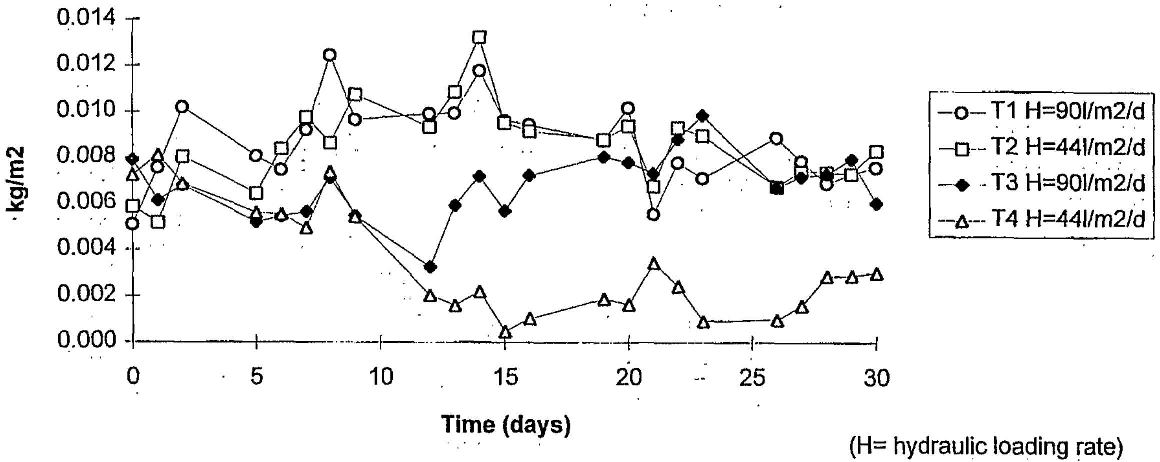
		NO$_3$ conc. (mg/l)				NO$_3$-N conc. (mg/l)				Leachate volume (litres)				NO$_3$-N total mass in leachate (kg)				Loading rate of NO$_3$-N (kg/m^2)				NO$_3$-N removal rate (kg/m^2/d)			
Day	Date	T1	T2	T3	T4	T1	T2	T3	T4	T1	T2	T3	T4	T1	T2	T3	T4	T1	T2	T3	T4	T1	T2	T3	T4
0	23/02/94	90	104	140	128	20	24	32	29	200	200	200	200	0.0041	0.0047	0.0063	0.0058	0.0051	0.0059	0.0079	0.0072	-0.0025	0.0007	0.0018	-0.0009
1	24/02/94	137	92	110	144	31	21	25	33	195	199	197	199	0.0060	0.0041	0.0049	0.0065	0.0075	0.0052	0.0061	0.0081	-0.0026	-0.0029	-0.0007	0.0012
2	25/02/94	185	143	122	122	42	32	28	28	195	199	197	199	0.0082	0.0064	0.0054	0.0055	0.0102	0.0080	0.0068	0.0069	0.0021	0.0016	0.0016	0.0013
5	28/02/94	155	115	95	100	35	26	21	23	184	198	193	198	0.0064	0.0051	0.0041	0.0045	0.0081	0.0064	0.0052	0.0056	0.0006	-0.0019	-0.0002	0.0001
6	01/03/94	145	152	100	100	33	34	23	23	182	195	192	195	0.0060	0.0067	0.0043	0.0044	0.0075	0.0084	0.0054	0.0055	-0.0017	-0.0014	-0.0002	0.0006
7	02/03/94	180	180	105	90	41	41	24	20	181	192	190	194	0.0074	0.0078	0.0045	0.0039	0.0092	0.0098	0.0056	0.0049	-0.0032	0.0011	-0.0015	-0.0024
8	03/03/94	250	160	135	135	57	36	31	31	176	191	186	193	0.0099	0.0069	0.0057	0.0059	0.0124	0.0086	0.0071	0.0074	0.0028	-0.0021	0.0016	0.0019
9	04/03/94	195	200	105	100	44	45	24	23	175	190	184	192	0.0077	0.0086	0.0044	0.0043	0.0096	0.0107	0.0055	0.0054	-0.0003	0.0014	0.0022	0.0034
12	07/03/94	205	175	70	38	46	40	16	9	171	189	165	190	0.0079	0.0075	0.0026	0.0016	0.0099	0.0093	0.0033	0.0020	0.0000	-0.0015	-0.0026	0.0004
13	08/03/94	208	208	130	30	47	47	29	7	169	185	161	188	0.0079	0.0087	0.0047	0.0013	0.0099	0.0109	0.0059	0.0016	-0.0019	-0.0024	-0.0013	-0.0006
14	09/03/94	250	255	160	42	57	58	36	9	167	184	159	187	0.0094	0.0106	0.0057	0.0018	0.0118	0.0133	0.0072	0.0022	0.0022	0.0037	0.0015	0.0017
15	10/03/94	205	185	128	9	46	42	29	2	166	182	157	185	0.0077	0.0076	0.0045	0.0004	0.0096	0.0095	0.0057	0.0005	0.0002	0.0004	-0.0015	-0.0006
16	11/03/94	205	180	165	20	46	41	37	5	163	180	155	183	0.0076	0.0073	0.0058	0.0008	0.0094	0.0092	0.0072	0.0010	0.0007	0.0004	-0.0008	-0.0008
19	14/03/94	195	175	190	38	44	40	43	9	159	178	150	175	0.0070	0.0070	0.0064	0.0015	0.0088	0.0088	0.0081	0.0019	-0.0014	-0.0006	0.0003	0.0002
20	15/03/94	235	192	184	34	53	43	42	8	153	173	150	171	0.0081	0.0075	0.0062	0.0013	0.0102	0.0094	0.0078	0.0016	0.0046	0.0026	0.0005	-0.0018
21	16/03/94	130	140	175	72	29	32	40	16	151	171	148	169	0.0044	0.0054	0.0059	0.0027	0.0055	0.0068	0.0073	0.0034	-0.0022	-0.0025	-0.0015	0.0010
22	17/03/94	185	195	215	52	42	44	49	12	149	169	145	166	0.0062	0.0074	0.0070	0.0020	0.0078	0.0093	0.0088	0.0024	0.0007	0.0003	-0.0010	0.0015
23	18/03/94	172	190	245	20	39	43	55	5	146	167	142	161	0.0057	0.0072	0.0079	0.0007	0.0071	0.0090	0.0098	0.0009	-0.0018	0.0022	0.0031	-0.0001
26	21/03/94	220	145	175	22	50	33	40	5	143	165	136	160	0.0071	0.0054	0.0054	0.0008	0.0089	0.0068	0.0067	0.0010	0.0010	-0.0007	-0.0004	-0.0006
27	22/03/94	200	165	195	36	45	37	44	8	139	159	130	157	0.0063	0.0059	0.0057	0.0013	0.0079	0.0074	0.0072	0.0016	0.0010	0.0000	-0.0001	-0.0013
28	23/03/94	190	165	200	65	43	37	45	15	128	158	129	156	0.0055	0.0059	0.0058	0.0023	0.0069	0.0074	0.0073	0.0029	-0.0004	0.0000	-0.0007	0.0000
29	24/03/94	205	165	220	66	46	37	50	15	126	157	128	155	0.0058	0.0059	0.0064	0.0023	0.0073	0.0073	0.0080	0.0029	-0.0003	-0.0010	0.0019	-0.0001
30	25/03/94	220	190	230	70	50	43	52	16	122	155	93	152	0.0061	0.0067	0.0048	0.0024	0.0076	0.0083	0.0060	0.0030				

EXPERIMENT B: Chart B4(i)
NO_3-N Concentration of leachate



(H= hydraulic loading rate)

EXPERIMENT B: Chart B4(ii)
Mass of NO_3-N in leachate per square metre of treatment area



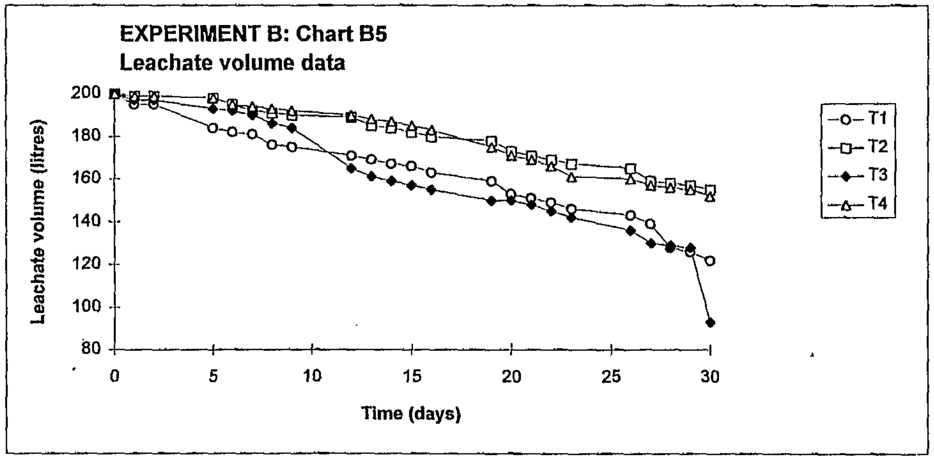
(H= hydraulic loading rate)

EXPERIMENT B Table B5: Leachate volume and Hydraulic loading rate (H) data

Dates:	**23/02/94-25/03/94**	
Trough 1 (T1)	**Hydraulic loading rate (H)=90l/m^2/d**	**Treatment plane surface area=0.8m^2**
Trough 2 (T2)	**Hydraulic loading rate (H)=44l/m^2/d**	**Treatment plane surface area=0.8m^2**
Trough 3 (T3)	**Hydraulic loading rate (H)=90l/m^2/d**	**Treatment plane surface area=0.8m^2**
Trough 4 (T4)	**Hydraulic loading rate (H)=44l/m^2/d**	**Treatment plane surface area=0.8m^2**
Units:	Volume (litres), Hydraulic loading rate (litres/m^2/day)	

		T1			T2			T3			T4		
Day	Date	Total	Applied	H	Total	Applied	H	Total	Applied	H	Total	Applied	H
0	23/02/94	200	70	87.5	200	35	43.75	200	70	87.5	200	35	43.75
1	24/02/94	195	70	87.5	199	35	43.75	197	70	87.5	199	35	43.75
2	25/02/94	195	70	87.5	199	35	43.75	197	70	87.5	199	35	43.75
5	28/02/94	184	70	87.5	198	35	43.75	193	70	87.5	198	35	43.75
6	01/03/94	182	70	87.5	195	35	43.75	192	70	87.5	195	35	43.75
7	02/03/94	181	70	87.5	192	35	43.75	190	70	87.5	194	35	43.75
8	03/03/94	176	70	87.5	191	35	43.75	186	70	87.5	193	35	43.75
9	04/03/94	175	70	87.5	190	35	43.75	184	70	87.5	192	35	43.75
12	07/03/94	171	70	87.5	189	35	43.75	165	70	87.5	190	35	43.75
13	08/03/94	169	70	87.5	185	35	43.75	161	70	87.5	188	35	43.75
14	09/03/94	167	70	87.5	184	35	43.75	159	70	87.5	187	35	43.75
15	10/03/94	166	70	87.5	182	35	43.75	157	70	87.5	185	35	43.75
16	11/03/94	163	70	87.5	180	35	43.75	155	70	87.5	183	35	43.75
19	14/03/94	159	70	87.5	178	35	43.75	150	70	87.5	175	35	43.75
20	15/03/94	153	79	98.75	173	35	43.75	150	70	87.5	171	35	43.75
21	16/03/94	151	70	87.5	171	35	43.75	148	70	87.5	169	35	43.75
22	17/03/94	149	70	87.5	169	35	43.75	145	70	87.5	166	35	43.75
23	18/03/94	146	70	87.5	167	35	43.75	142	70	87.5	161	35	43.75
26	21/03/94	143	70	87.5	165	35	43.75	136	70	87.5	160	35	43.75
27	22/03/94	139	103	128.75	159	37	46.25	130	88	110	157	38	47.5
28	23/03/94	128	70	87.5	158	35	43.75	129	90	112.5	156	35	43.75
29	24/03/94	126	70	87.5	157	35	43.75	128	70	87.5	155	35	43.75
30	25/03/94	122	70	87.5	155	35	43.75	93	70	87.5	152	35	43.75

Average actual H	90	44	90	44



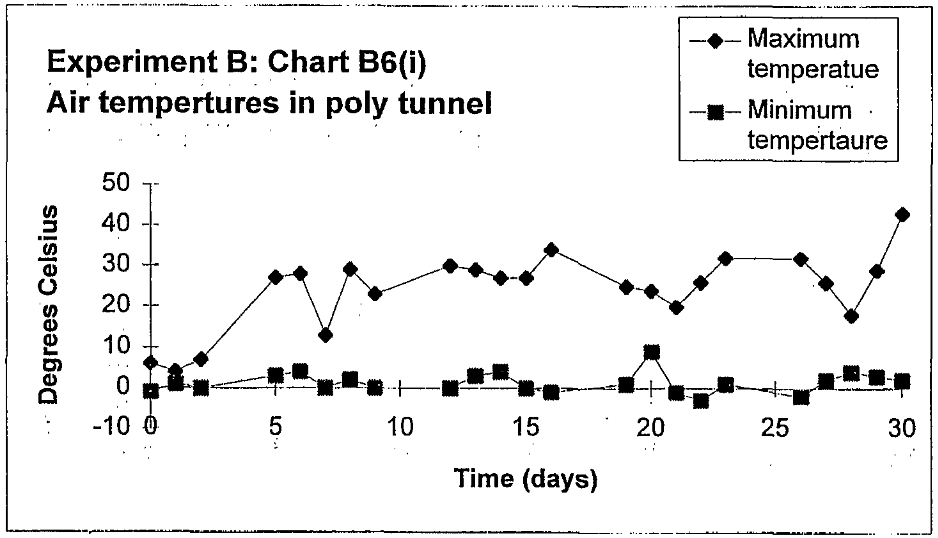
EXPERIMENT B: Chart B5
Leachate volume data

EXPERIMENT B Table B6: Air and soil temperature data

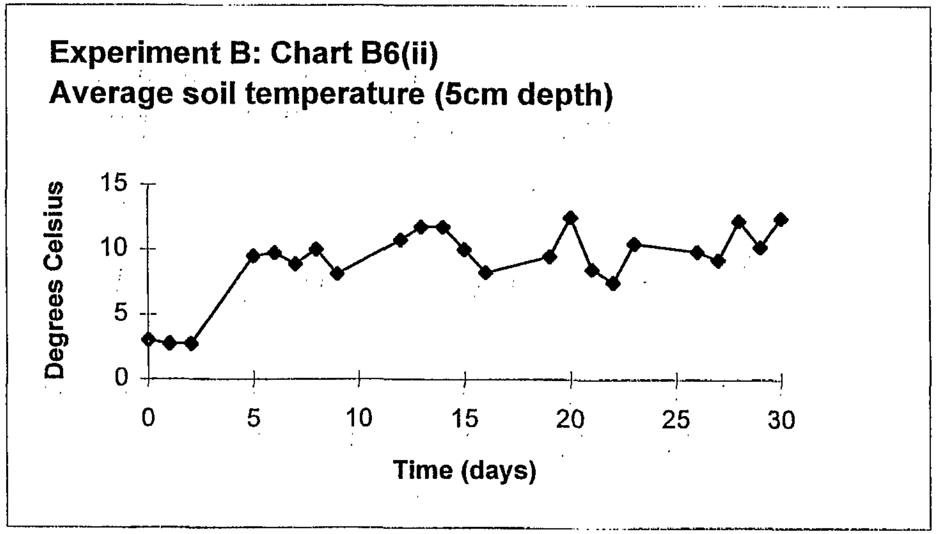
Dates: **23/02/94-25/03/94**

(Conducted in polytunnel)

		Air Temp. (°C)			Soil Temp. (°C)		
Day	Date	Max	Min	Ave.	10am	3pm	Ave.
0	23/02/94	6	-1	2.5	4	2	3
1	24/02/94	4	1	2.5	3	2.5	3
2	25/02/94	7	0	3.5	3	2.5	3
5	28/02/94	27	3	15	10.5	8.5	10
6	01/03/94	28	4	16	8.5	11	10
7	02/03/94	13	0	6.5	11.5	6.25	9
8	03/03/94	29	2	15.5	12	8	10
9	04/03/94	23	0	11.5	10	6.25	8
12	07/03/94	30	0	15	9	12.5	11
13	08/03/94	29	3	16	12	11.5	12
14	09/03/94	27	4	15.5	12	11.5	12
15	10/03/94	27	0	13.5	12	8	10
16	11/03/94	34	-1	16.5	9	7.5	8
19	14/03/94	25	1	13	10	9	10
20	15/03/94	24	9	16.5	13	12	13
21	16/03/94	20	-1	9.5	10	7	9
22	17/03/94	26	-3	11.5	9.5	5.5	8
23	18/03/94	32	1	16.5	12	9	11
26	21/03/94	32	-2	15	11.5	8.25	10
27	22/03/94	26	2	14	9.5	9	9
28	23/03/94	18	4	11	13	11.5	12
29	24/03/94	29	3	16	11	9.5	10
30	25/03/94	43	2	22.5	12.5		13
Average °C		24.30	1.35	12.83	9.93	8.13	9.13



Experiment B: Chart B6(i)
Air tempertures in poly tunnel



Experiment B: Chart B6(ii)
Average soil temperature (5cm depth)

EXPERIMENT C Table C1: pH, Chemical Oxygen Demand (COD), and Chloride (Cl^-) data

Dates: **26/04/94-09/05/94**

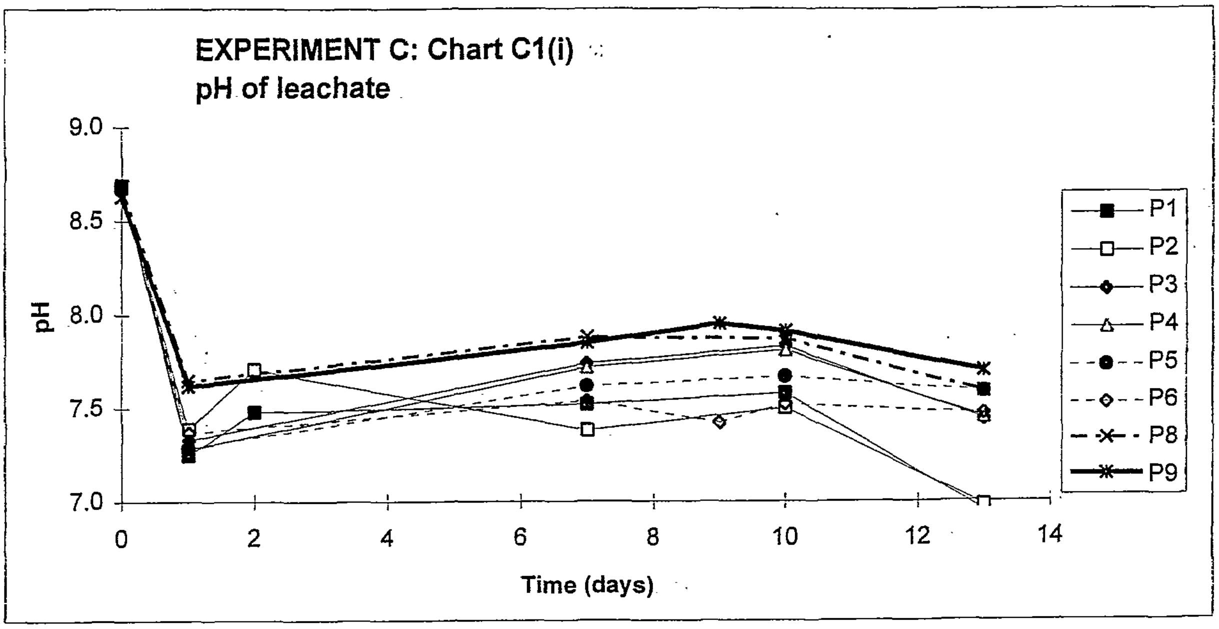
Plots 5,6 & 9 Hydraulic loading rate (H) = 450l/m^2/d Treatment plane surface area = 20m^2

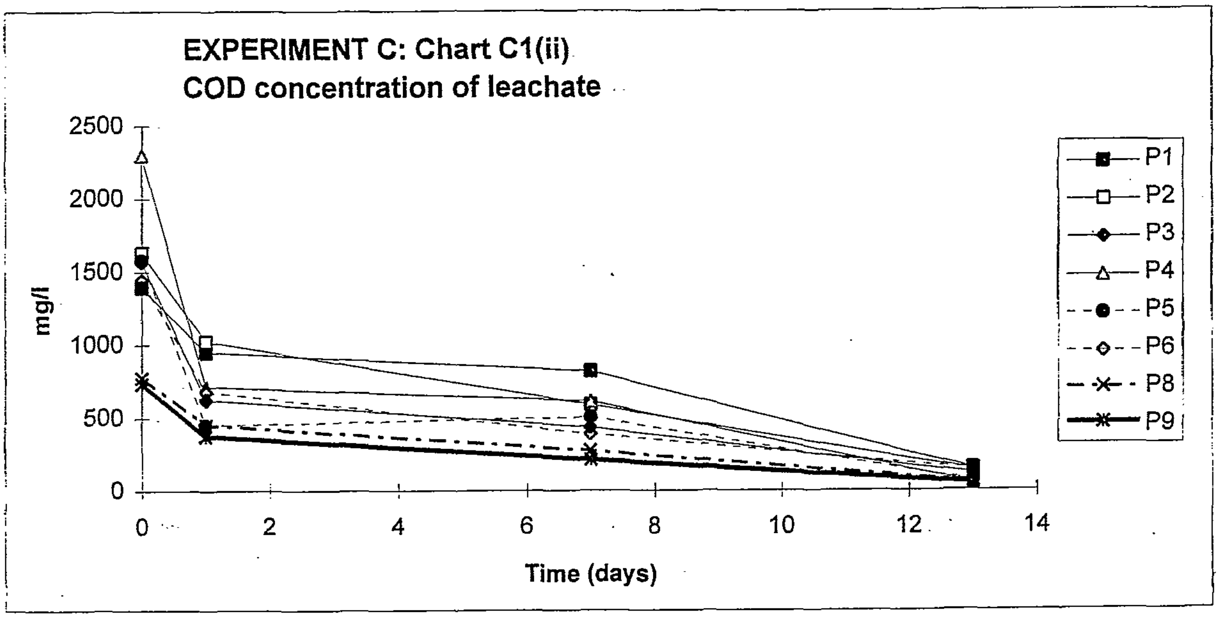
All other plots Hydraulic loading rate (H) = 900l/m^2/d Treatment plane surface area = 20m^2

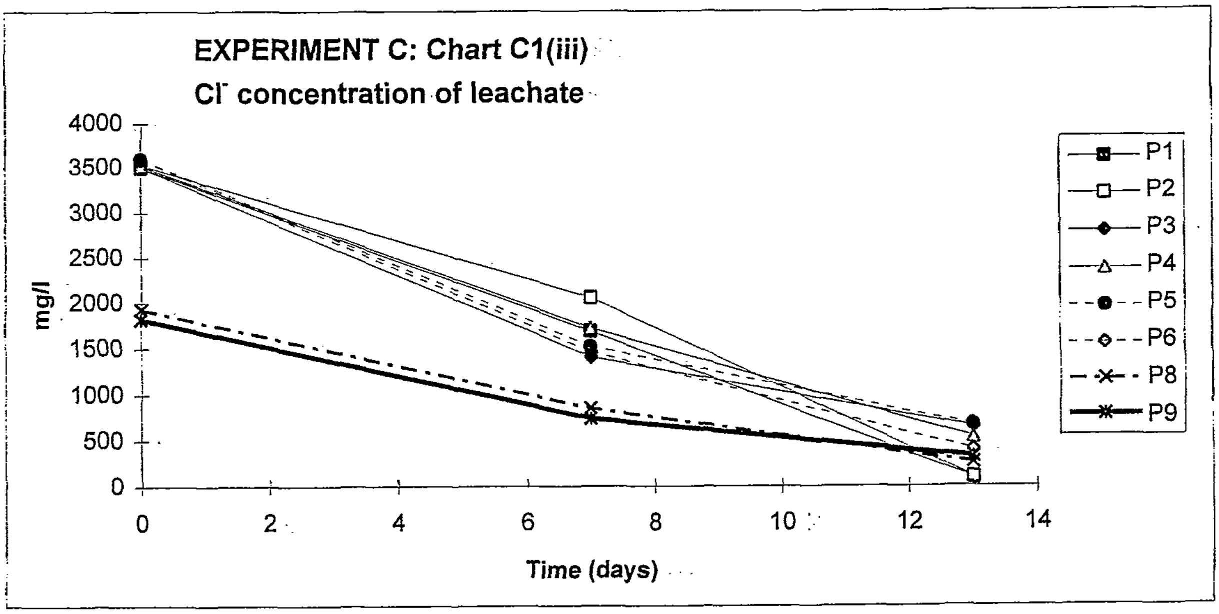
		pH data									
		P1	P2	P3	P4	P5	P6	P7	P8	P9	P10
0	26/04/94	8.69	8.69	8.68	8.69	8.68	8.66	8.67	8.68	8.63	
1	27/04/94	7.25	7.39	7.33	7.28	7.29	7.37	7.70	7.65	7.62	
2	28/04/94	7.48	7.71								8.64
3	29/04/94										
4	30/04/94										
5	01/05/94										
6	02/05/94										
7	03/05/94	7.52	7.38	7.74	7.72	7.62	7.54		7.88	7.85	
8	04/05/94										
9	05/05/94						7.42			7.95	
10	06/05/94	7.58	7.5	7.83	7.81	7.67	7.52		7.87	7.91	
11	07/05/94										
12	08/05/94										
13	09/05/94	6.95	6.98	7.44	7.45	7.59	7.47		7.59	7.7	

		COD data									
		P1	P2	P3	P4	P5	P6	P7	P8	P9	P10
0	26/04/94	1395	1630	1570	2300	1580	1445	860	775	735	
1	27/04/94	950	1025	625	715	450	680	390	455	375	
2	28/04/94										435
3	29/04/94										
4	30/04/94										
5	01/05/94										
6	02/05/94										
7	03/05/94	820	590	435	615	505	390		275	215	
8	04/05/94										
9	05/05/94										
10	06/05/94										
11	07/05/94										
12	08/05/94										
13	09/05/94	150	145	120	55	70	148		64	54	

		Cl^- data									
		P1	P2	P3	P4	P5	P6	P7	P8	P9	P10
0	26/04/94	3500	3530	3500	3520	3600	3590	1900	1930	1820	
1	27/04/94										
2	28/04/94										1140
3	29/04/94										
4	30/04/94										
5	01/05/94										
6	02/05/94										
7	03/05/94	1690	2060	1410	1725	1525	1465		855	740	
8	04/05/94										
9	05/05/94										
10	06/05/94										
11	07/05/94										
12	08/05/94										
13	09/05/94	90	100	650	535	670	400		260	325	


EXPERIMENT C: Chart C1(i)
pH of leachate


EXPERIMENT C: Chart C1(ii)
COD concentration of leachate


EXPERIMENT C: Chart C1(iii)
Cl⁻ concentration of leachate

EXPERIMENT C Table C2: NH_3-N, NO_2-N AND NO_3-N data

Dates: **26/04/94-09/05/94**

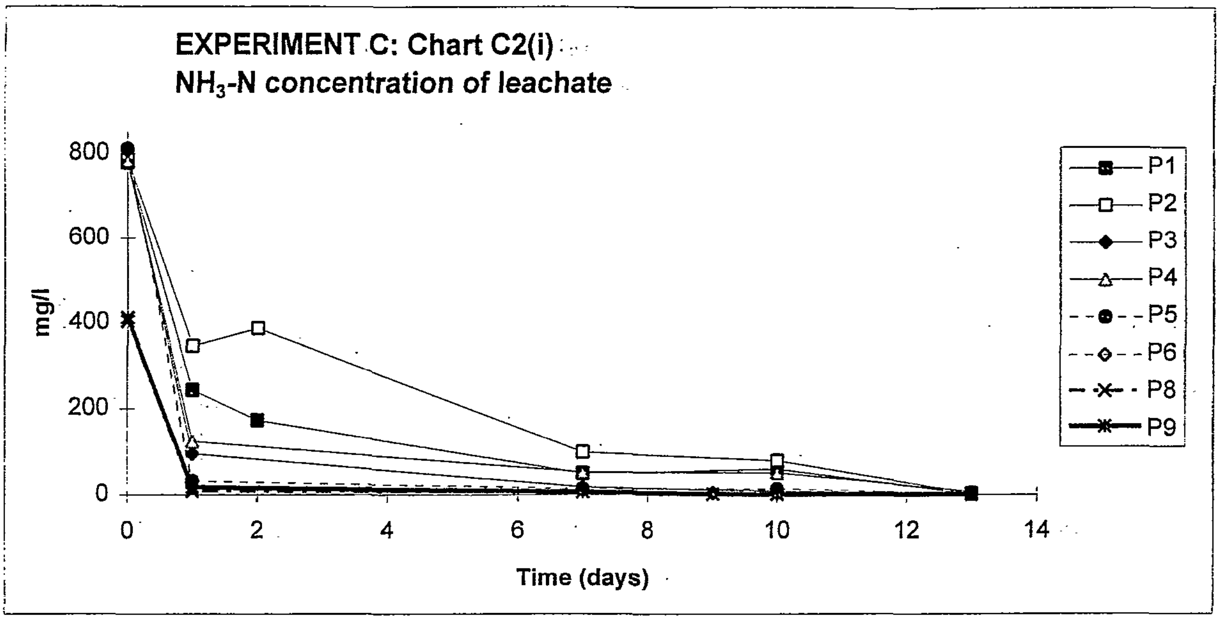
Plots 5,6 & 9 Hydraulic loading rate (H) = 450l/m^2/d Treatment plane surface area = 20m^2

All other plots Hydraulic loading rate (H) = 900l/m^2/d Treatment plane surface area = 20m^2

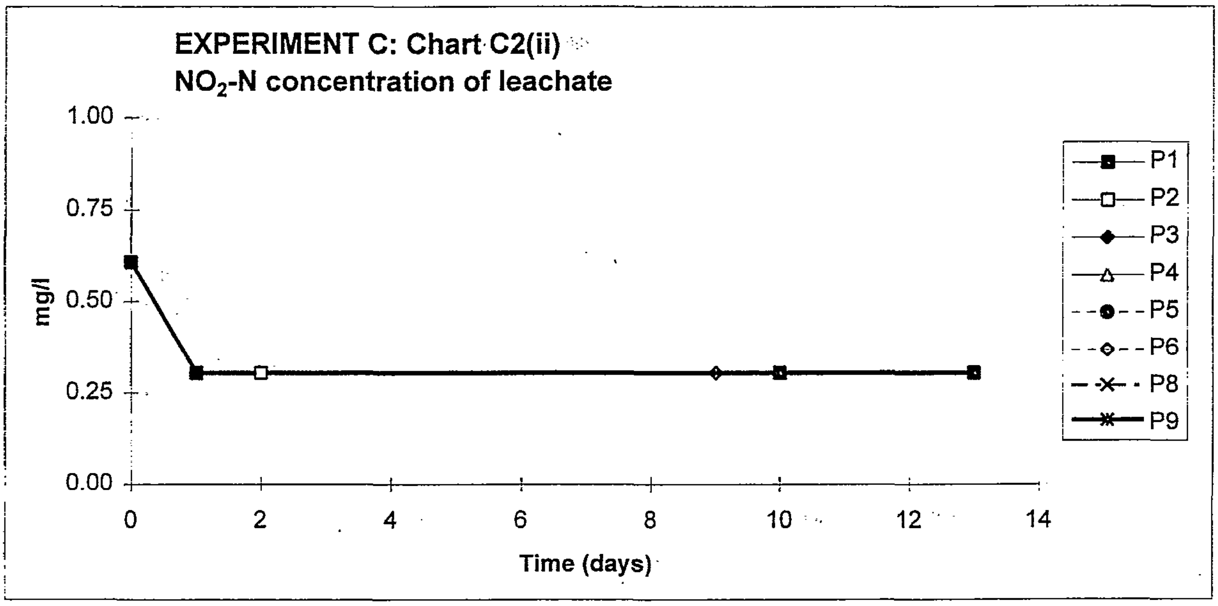
		NH_3-N									
		P1	P2	P3	P4	P5	P6	P7	P8	P9	P10
0	26/04/94	779	787	779	783	812	808	379	404	412	
1	27/04/94	243	346	95	124	31	18	10	8	17	
2	28/04/94	173	387								247
3	29/04/94										
4	30/04/94										
5	01/05/94										
6	02/05/94										
7	03/05/94	49	99	18	53	14	12		7	7	
8	04/05/94										
9	05/05/94						5			2	
10	06/05/94	59	79	9	51	13	5		3	2	
11	07/05/94										
12	08/05/94										
13	09/05/94	1	3	3	7	4	1		1	2	

		NO_2-N									
		P1	P2	P3	P4	P5	P6	P7	P8	P9	P10
0	26/04/94	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6	
1	27/04/94	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	
2	28/04/94	0.3	0.3								0.3
3	29/04/94										
4	30/04/94										
5	01/05/94										
6	02/05/94										
7	03/05/94										
8	04/05/94										
9	05/05/94						0.3				0.3
10	06/05/94	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3
11	07/05/94										
12	08/05/94										
13	09/05/94	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3

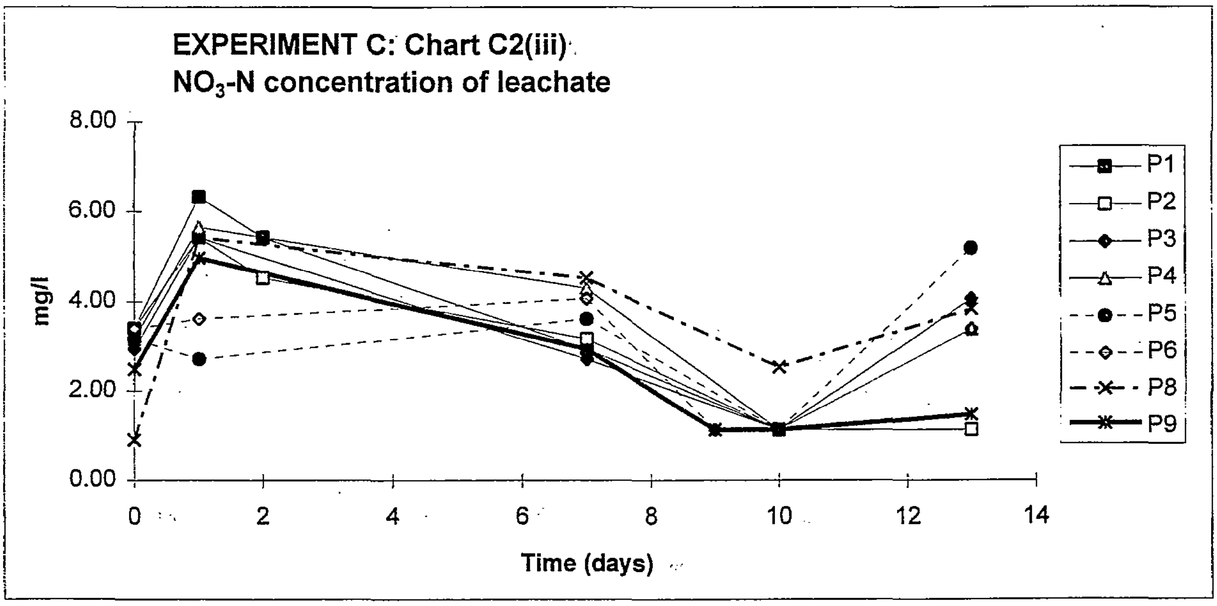
		NO_3-N									
		P1	P2	P3	P4	P5	P6	P7	P8	P9	P10
0	26/04/94	3.4	3.4	2.9	3.2	3.2	3.4	1.4	0.9	2.5	
1	27/04/94	6.3	5.4	5.4	5.7	2.7	3.6	4.5	5.4	5.0	
2	28/04/94	5.4	4.5								1.8
3	29/04/94										
4	30/04/94										
5	01/05/94										
6	02/05/94										
7	03/05/94	2.9	3.2	2.7	4.3	3.6	4.1		4.5	2.9	
8	04/05/94										
9	05/05/94						1.1			1.1	
10	06/05/94	1.1	1.1	1.1	1.1	1.1	1.1		2.5	1.1	
11	07/05/94										
12	08/05/94										
13	09/05/94	1.1	1.1	4.1	3.4	5.2	3.4		3.8	1.5	



EXPERIMENT C: Chart C2(i)
NH_3-N concentration of leachate



EXPERIMENT C: Chart C2(ii)
NO_2-N concentration of leachate



EXPERIMENT C: Chart C2(iii)
NO_3-N concentration of leachate

EXPERIMENT D Table D1: pH, Chemical Oxygen Demand (COD), and Chloride (Cl^-) data

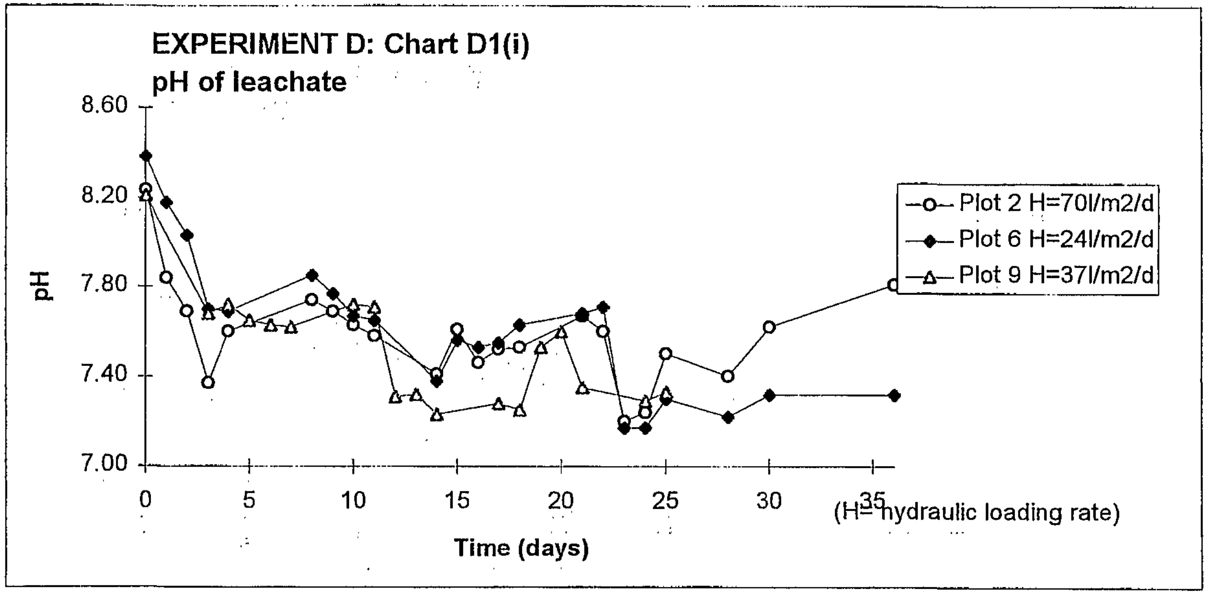
Dates: 23/05/94-28/06/94

Plot 2 (P2) Hydraulic loading rate (H)=70l/m^2/d *Treatment plane surface area=10m^2*

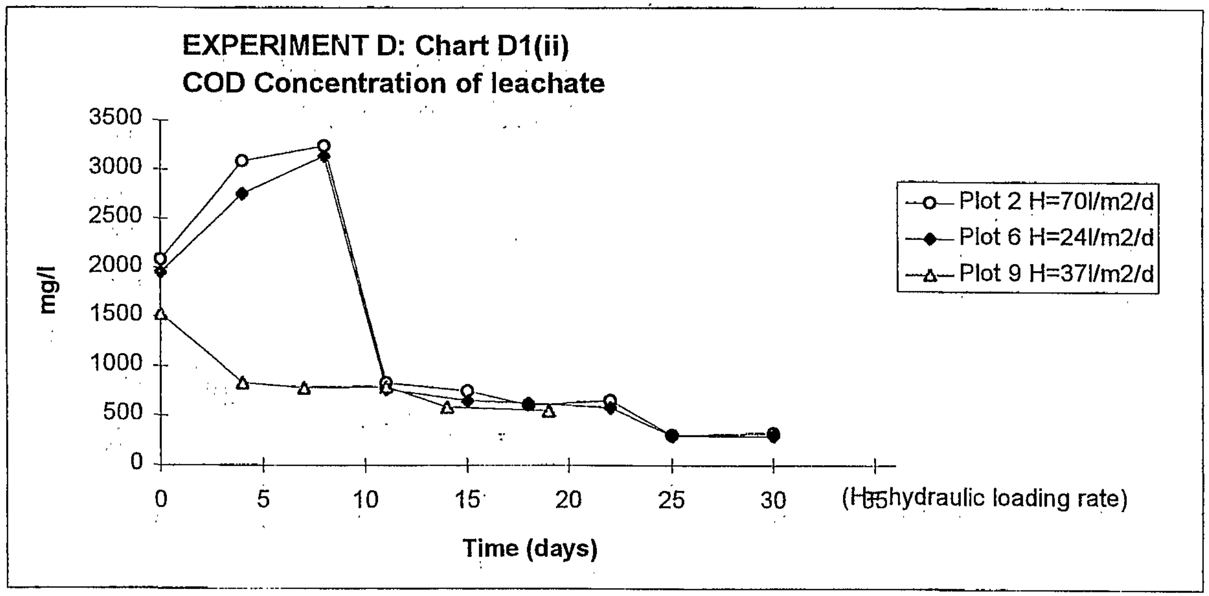
Plot 6 (P6) Hydraulic loading rate (H)=24l/m^2/d Treatment plane surface area=20m^2

Plot 9 (P9) Hydraulic loading rate (H)=37l/m^2/d Treatment plane surface area=20m^2

	(P9)		pH			COD conc. (mg/l)			Cl^- conc. (mg/l)			Leachate vol. (litres)			Cl^- total mass in leachate (kg)			Loading rate of Cl^- kg/m^2			Cl^- removal rate kg/m^2/d		
Day	Day	Date	P2	P6	P9	P2	P6	P9	P2	P6	P9	P2	P6	P9	P2	P6	P9	P2	P6	P9	P2	P6	P9
0		23/5/94	8.24	8.39		2085	1953		3415	3615		2370	2370		8.0936	8.5676		0.8094	0.4284		0.0940	0.0506	
1		24/5/94	7.84	8.18								2300	2300										
2		25/5/94	7.69	8.03								2200	2200										
3		26/5/94	7.37	7.7								2100	2175										
4		27/5/94	7.6	7.69		3080	2755					2000	2050										
8		31/5/94	7.74	7.85		3235	3135		795	770		1900	1925		1.5105	1.4823		0.1511	0.0741		-0.0986	0.0093	
9		1/6/94	7.69	7.77								1550	1900										
10		2/6/94	7.63	7.67								1450	1750										
11	0	3/6/94	7.58	7.65	8.21	830	765	1530			3565	1300	1600	2200			7.8430			0.3922			0.0300
14	3	6/6/94	7.41	7.38	7.68							1250	1600	2000									
15	4	7/6/94	7.61	7.56	7.72	745	650	830				1100	1400	1900									
16	5	8/6/94	7.46	7.53	7.65				2420	2460	2690	950	1300	1800	2.2990	3.1980	4.8420	0.2299	0.1599	0.2421	0.0198	0.0169	0.0139
17	6	9/6/94	7.52	7.55	7.63							850	1200	1750									
18	7	10/6/94	7.53	7.63	7.62	605	625	780				750	1150	1550									
21	10	13/6/94	7.67	7.68	7.72							625	1150	1550									
22	11	14/6/94	7.6	7.71	7.71	650	580	795				450	575	1300									
23	12	15/6/94	7.2	7.17	7.31				830	1855	2465	1100	450	1175	0.9130	0.8348	2.8964	0.0913	0.0417	0.1448	0.0094	-0.0027	0.0136
24	13	16/6/94	7.24	7.17	7.32							850	1100	1050									
25	14	17/6/94	7.5	7.3	7.23	305	295	585				650	975	950									
28	17	20/6/94	7.4	7.22	7.28							475	850	800									
29	18	21/6/94			7.25							300	675	550									
30	19	22/6/94	7.62	7.32	7.53	320	295	545	860	1805	2085	300	675	475	0.2580	1.2184	0.9904	0.0258	0.0609	0.0495	0.0043	0.0102	0.0083
31	20	23/6/94			7.6							150	675	950									
32	21	24/6/94			7.35							150	675	950									
35	24	27/6/94			7.29							150	675	950									
36	25	28/6/94	7.81	7.32	7.33				2080	2420	1895	150	675	950	0.3120	1.6335	1.8003	0.0312	0.0817	0.0900			



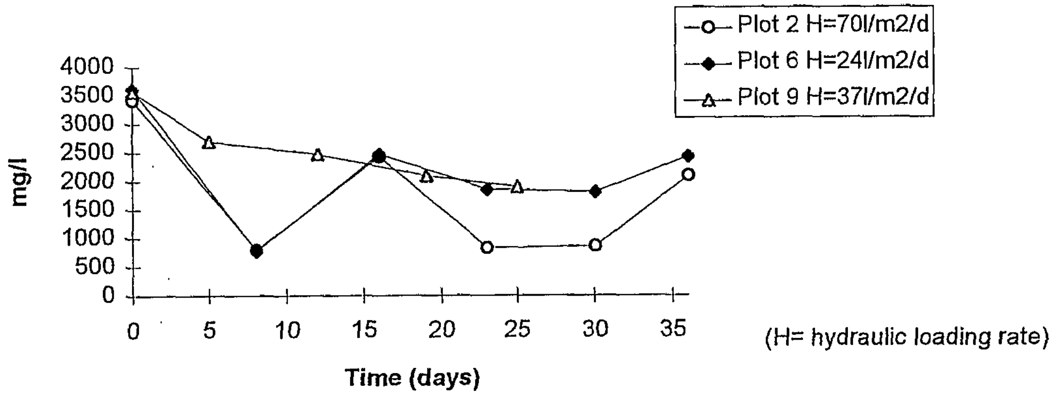
EXPERIMENT D: Chart D1(i)
pH of leachate



EXPERIMENT D: Chart D1(ii)
COD Concentration of leachate

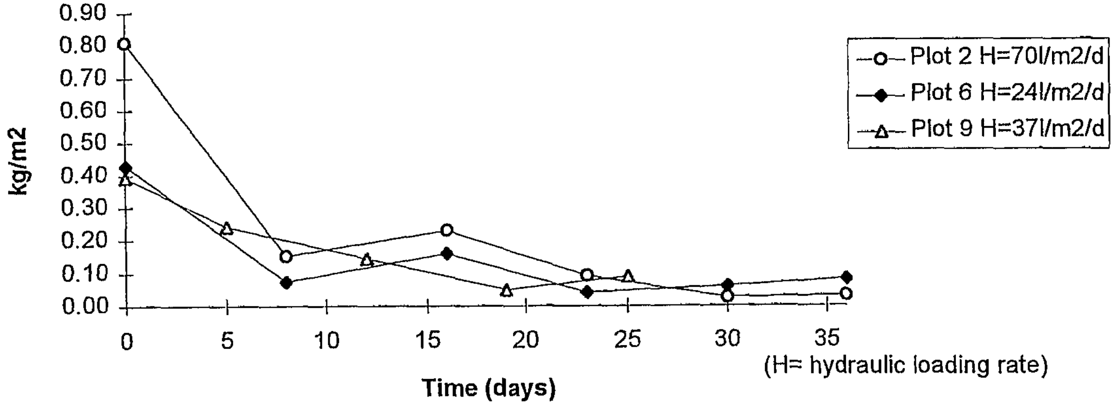
EXPERIMENT D: Chart D1(iii)

Cl^- Concentration of leachate



EXPERIMENT D: Chart D1(iv)

Mass of Cl^- in leachate per square metre of treatment area



EXPERIMENT D Table D2: Ammonia (NH_3) data

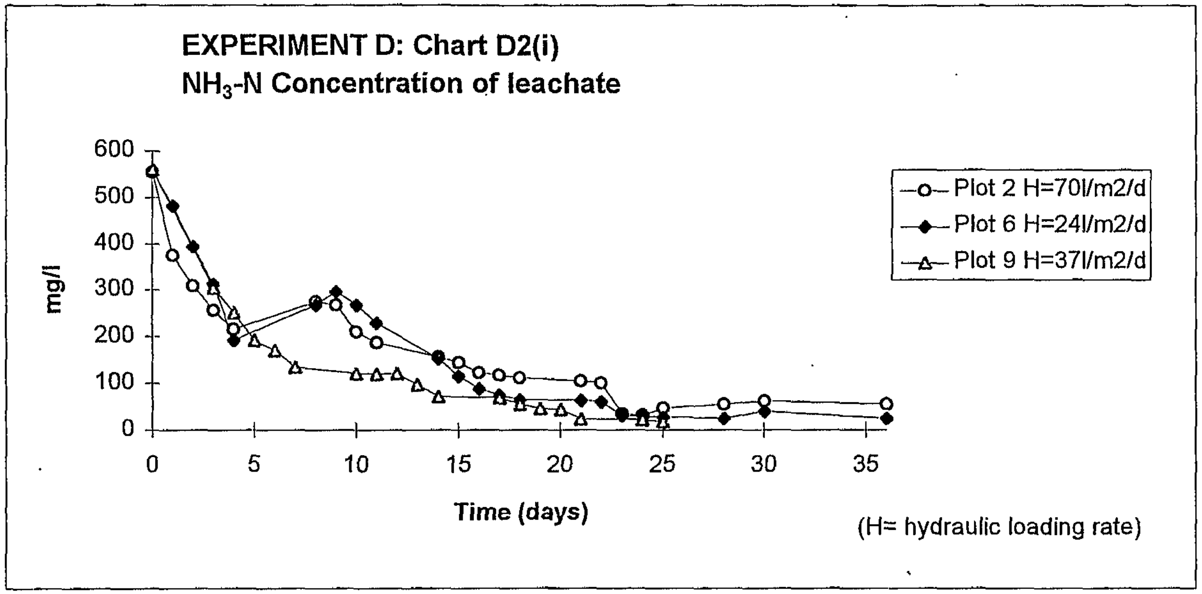
Dates: **23/05/94-28/06/94**

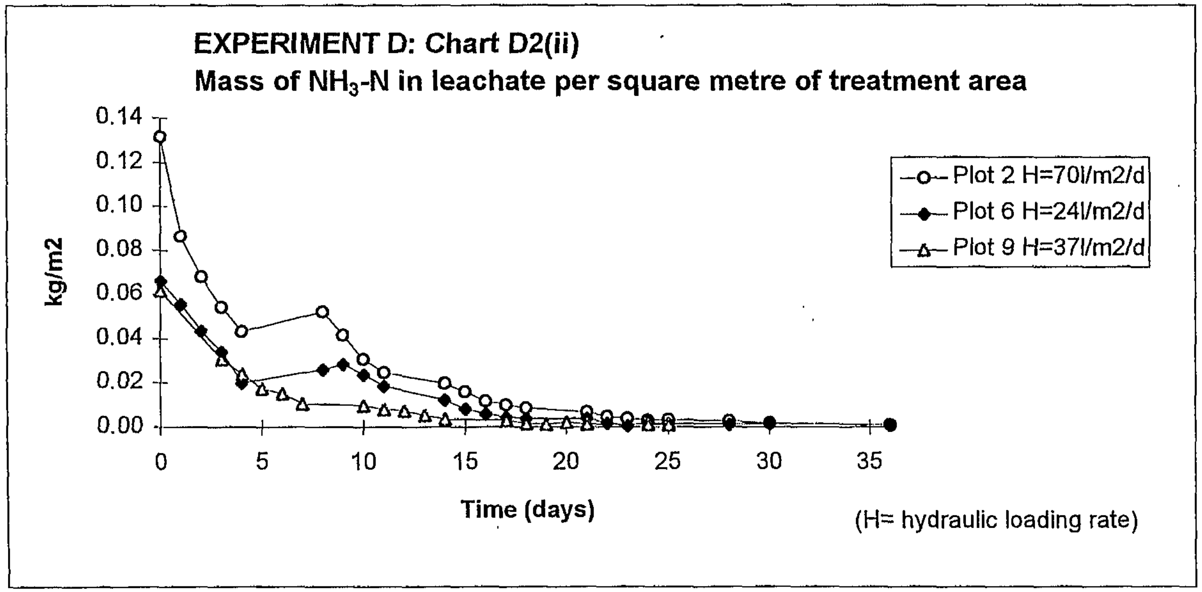
Plot 2 (P2) **Hydraulic loading rate (H)=70l/m^2/d** **Treatment plane surface area=10m^2**

Plot 6 (P6) **Hydraulic loading rate (H)=24l/m^2/d** **Treatment plane surface area=20m^2**

Plot 9 (P9) **Hydraulic loading rate (H)=37l/m^2/d** **Treatment plane surface area=20m^2**

	(P9)		NH_3 conc. (mg/l)			NH_3-N conc. (mg/l)			Leachate vol. (litres)			NH_3-N total mass in leachate (kg)			Loading rate of NH_3-N (kg/m^2)			NH_3-N removal rate (kg/m^2/d)		
Day	**Day**	**Date**	**P2**	**P6**	**P9**	**P2**	**P6**	**P9**	**P2**	**P6**	**P9**	**P2**	**P6**	**P9**	**P2**	**P6**	**P9**	**P2**	**P6**	**P9**
0		23/5/94	673	678		554	558		2370	2370		1.3133	1.3231		0.1313	0.0662		0.0451	0.0107	
1		24/5/94	455	585		375	482		2300	2300		0.8623	1.1087		0.0862	0.0554		0.0183	0.0121	
2		25/5/94	375	478		309	394		2200	2200		0.6798	0.8665		0.0680	0.0433		0.0140	0.0093	
3		26/5/94	312	380		257	313		2100	2175		0.5399	0.6810		0.0540	0.0341		0.0108	0.0143	
4		27/5/94	262	234		216	193		2000	2050		0.4318	0.3953		0.0432	0.0198		-0.0090	-0.0060	
8		31/5/94	333	325		274	268		1900	1925		0.5213	0.5155		0.0521	0.0258		-0.0106	-0.0024	
9		1/6/94	325	360		268	297		1550	1900		0.4151	0.5636		0.0415	0.0282		0.0110	0.0047	
10		2/6/94	255	325		210	268		1450	1750		0.3047	0.4687		0.0305	0.0234		0.0062	0.0051	
11	0	3/6/94	227	278	680	187	229	560	1300	1600	2200	0.2432	0.3665	1.2327	0.0243	0.0183	0.0616	0.0047	0.0061	0.0311
14	3	6/6/94	190	185	370	157	152	305	1250	1600	2000	0.1957	0.2439	0.6098	0.0196	0.0122	0.0305	0.0037	0.0041	0.0066
15	4	7/6/94	175	140	305	144	115	251	1100	1400	1900	0.1586	0.1615	0.4775	0.0159	0.0081	0.0239	0.0043	0.0024	0.0066
16	5	8/6/94	148	106	233	122	87	192	950	1300	1800	0.1159	0.1135	0.3456	0.0116	0.0057	0.0173	0.0017	0.0012	0.0024
17	6	9/6/94	141	90	207	116	74	171	850	1200	1750	0.0988	0.0890	0.2985	0.0099	0.0044	0.0149	0.0015	0.0008	0.0045
18	7	10/6/94	135	78	163	111	64	134	750	1150	1550	0.0834	0.0739	0.2082	0.0083	0.0037	0.0104	0.0018	0.0000	0.0010
21	10	13/6/94	127	77	147	105	63	121	625	1150	1550	0.0654	0.0730	0.1877	0.0065	0.0036	0.0094	0.0020	0.0019	0.0016
22	11	14/6/94	122	74	145	101	61	119	450	575	1300	0.0452	0.0351	0.1553	0.0045	0.0018	0.0078	0.0008	0.0011	0.0007
23	12	15/6/94	41	37	146	34	30	120	1100	450	1175	0.0372	0.0137	0.1414	0.0037	0.0007	0.0071	0.0010	-0.0009	0.0020
24	13	16/6/94	39	35	118	32	29	97	850	1100	1050	0.0273	0.0317	0.1021	0.0027	0.0016	0.0051	-0.0003	0.0003	0.0017
25	14	17/6/94	57	33	87	47	27	72	650	975	950	0.0305	0.0265	0.0681	0.0031	0.0013	0.0034	0.0004	0.0003	0.0006
28	17	20/6/94	67	30	84	55	25	69	475	850	800	0.0262	0.0210	0.0554	0.0026	0.0011	0.0028	0.0004	-0.0001	0.0013
29	18	21/6/94			66			54	300	675	550			0.0299			0.0015			0.0004
30	19	22/6/94	75	48	55	62	40	45	300	675	475	0.0185	0.0267	0.0215	0.0019	0.0013	0.0011	0.0002	0.0001	-0.0010
31	20	23/6/94			54			44	150	675	950			0.0423			0.0021			0.0010
32	21	24/6/94			29			24	150	675	950			0.0227			0.0011			0.0001
35	24	27/6/94			27			22	150	675	950			0.0211			0.0011			0.0002
36	25	28/6/94	66	30	21	54	25	17	150	675	950	0.0082	0.0167	0.0164	0.0008	0.0008	0.0008			


EXPERIMENT D: Chart D2(i)
NH_3-N Concentration of leachate


EXPERIMENT D: Chart D2(ii)
Mass of NH_3-N in leachate per square metre of treatment area

EXPERIMENT D Table D3: Nitrite (NO_2) data

Dates: **23/05/94-28/06/94**

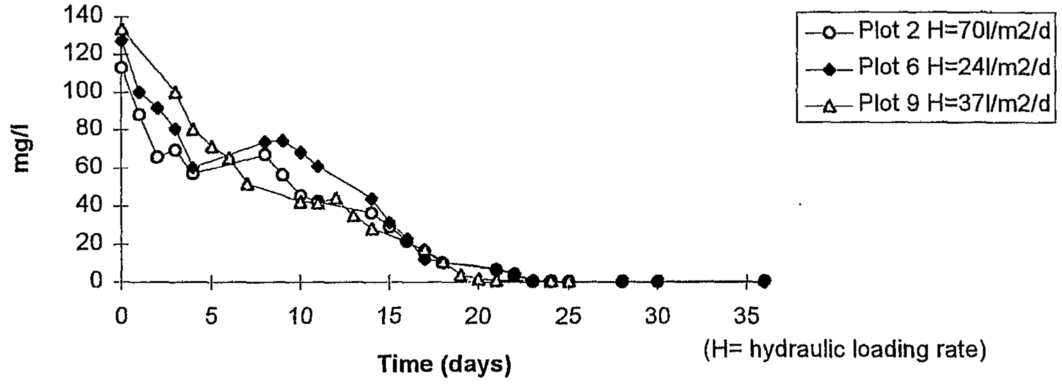
Plot 2 (P2) **Hydraulic loading rate (H)=70l/m^2/d** **Treatment plane surface area=10m^2**

Plot 6 (P6) **Hydraulic loading rate (H)=24l/m^2/d** **Treatment plane surface area=20m^2**

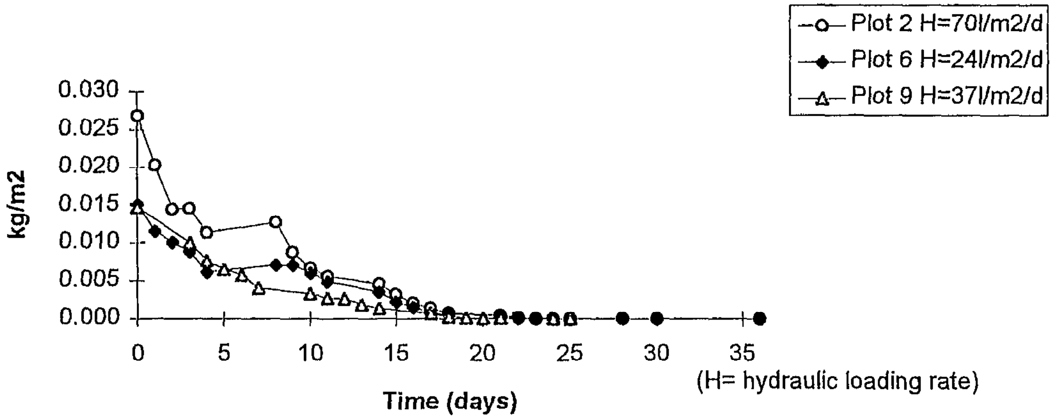
Plot 9 (P9) **Hydraulic loading rate (H)=37l/m^2/d** **Treatment plane surface area=20m^2**

	(P9)		NO_2 conc. (mg/l)			NO_2-N conc. (mg/l)			Leachate vol. (litres)			NO_2-N total mass in leachate (kg)			Loading rate of NO_2-N (kg/m^2)			NO_2-N removal rate (kg/m^2/d)		
Day	Day	Date	P2	P6	P9	P2	P6	P9	P2	P6	P9	P2	P6	P9	P2	P6	P9	P2	P6	P9
0		23/5/94	373	420		113	128		2370	2370		0.2684	0.3026		0.0268	0.0151		0.0066	0.0036	
1		24/5/94	290	330		88	100		2300	2300		0.2028	0.2307		0.0203	0.0115		0.0058	0.0014	
2		25/5/94	216	302		66	92		2200	2200		0.1445	0.2020		0.0144	0.0101		-0.0001	0.0013	
3		26/5/94	228	266		69	81		2100	2175		0.1456	0.1759		0.0146	0.0088		0.0032	0.0026	
4		27/5/94	187	198		57	60		2000	2050		0.1137	0.1234		0.0114	0.0062		-0.0013	-0.0009	
8		31/5/94	220	242		67	74		1900	1925		0.1271	0.1416		0.0127	0.0071		0.0040	0.0000	
9		1/6/94	185	245		56	74		1550	1900		0.0872	0.1415		0.0087	0.0071		0.0021	0.0011	
10		2/6/94	150	225		46	68		1450	1750		0.0661	0.1197		0.0066	0.0060		0.0011	0.0011	
11	0	3/6/94	140	200	440	43	61	134	1300	1600	2200	0.0553	0.0973	0.2943	0.0055	0.0049	0.0147	0.0010	0.0013	0.0047
14	3	6/6/94	120	145	330	36	44	100	1250	1600	2000	0.0456	0.0705	0.2006	0.0046	0.0035	0.0100	0.0014	0.0013	0.0024
15	4	7/6/94	95	103	265	29	31	81	1100	1400	1900	0.0318	0.0438	0.1531	0.0032	0.0022	0.0077	0.0011	0.0007	0.0012
16	5	8/6/94	71	75	235	22	23	71	950	1300	1800	0.0205	0.0296	0.1286	0.0021	0.0015	0.0064	0.0007	0.0008	0.0007
17	6	9/6/94	53	40	215	16	12	65	850	1200	1750	0.0137	0.0146	0.1144	0.0014	0.0007	0.0057	0.0006	0.0001	0.0017
18	7	10/6/94	33	35	171	10	11	52	750	1150	1550	0.0075	0.0122	0.0806	0.0008	0.0006	0.0040	0.0004	0.0002	0.0007
21	10	13/6/94	21	23	140	6	7	43	625	1150	1550	0.0040	0.0080	0.0660	0.0004	0.0004	0.0033	0.0002	0.0003	0.0006
22	11	14/6/94	12	14	137	4	4	42	450	575	1300	0.0016	0.0024	0.0541	0.0002	0.0001	0.0027	0.0001	0.0001	0.0001
23	12	15/6/94	1	3.2	146	0	1	44	1100	450	1175	0.0003	0.0004	0.0522	0.0000	0.0000	0.0026	0.0000	0.0000	0.0008
24	13	16/6/94	1.6	1	115	0	0	35	850	1100	1050	0.0004	0.0003	0.0367	0.0000	0.0000	0.0018	0.0000	0.0000	0.0005
25	14	17/6/94	1	1	93	0	0	28	650	975	950	0.0002	0.0003	0.0269	0.0000	0.0000	0.0013	0.0000	0.0000	0.0007
28	17	20/6/94	1	1.4	56	0	0	17	475	850	800	0.0001	0.0004	0.0136	0.0000	0.0000	0.0007	0.0000	0.0000	0.0004
29	18	21/6/94			35			11	300	675	550			0.0059			0.0003			0.0002
30	19	22/6/94	1	1	12.7	0	0	4	300	675	475	0.0001	0.0002	0.0018	0.0000	0.0000	0.0001	0.0000	0.0000	0.0000
31	20	23/6/94			5.9			2	150	675	950			0.0017			0.0001			0.0000
32	21	24/6/94			3.2			1	150	675	950			0.0009			0.0000			0.0000
35	24	27/6/94			2.5			1	150	675	950			0.0007			0.0000			0.0000
36	25	28/6/94	2.5	1.2	2.1	1	0	1	150	675	950	0.0001	0.0002	0.0006	0.0000	0.0000	0.0000			

EXPERIMENT D: Chart D3(i)
NO_2-N Concentration of leachate



EXPERIMENT D: Chart D3(ii)
Mass of NO_2-N in leachate per square metre of treatment area



EXPERIMENT D Table D4: Nitrate (NO_3) data

Dates: **23/05/94-28/06/94**

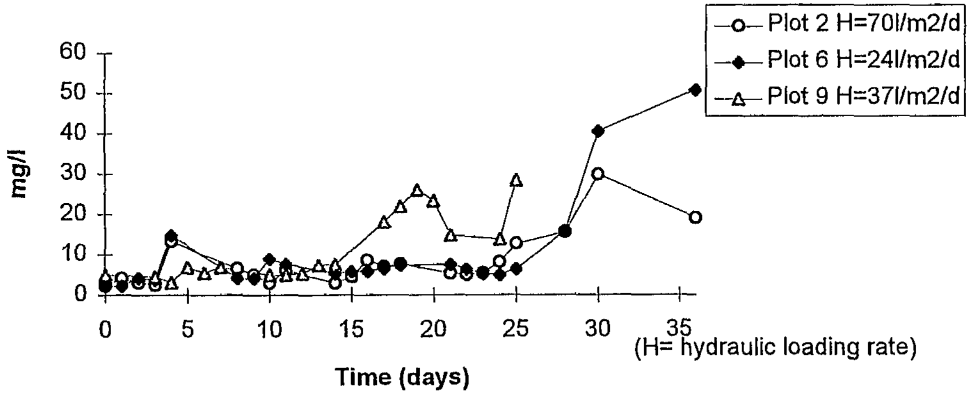
Plot 2 (P2) **Hydraulic loading rate (H)=70l/m^2/d** **Treatment plane surface area=10m^2**

Plot 6 (P6) **Hydraulic loading rate (H)=24l/m^2/d** **Treatment plane surface area=20m^2**

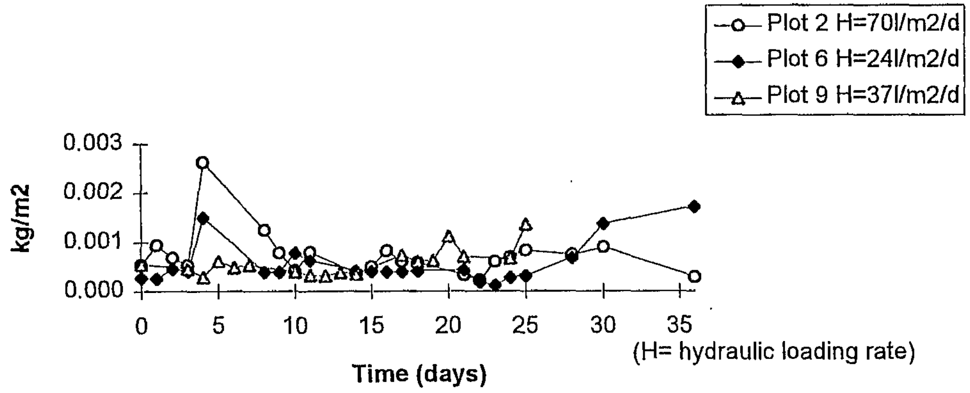
Plot 9 (P9) **Hydraulic loading rate (H)=37l/m^2/d** **Treatment plane surface area=20m^2**

	(P9)		NO_3 conc. (mg/l)			NO_3-N conc. (mg/l)			Leachate vol. (litres)			NO_3-N total mass in leachate (kg)			Loading rate of NO_3-N (kg/m^2)			NO_3-N removal rate (kg/m^2/d)		
Day	**Day**	**Date**	**P2**	**P6**	**P9**	**P2**	**P6**	**P9**	**P2**	**P6**	**P9**	**P2**	**P6**	**P9**	**P2**	**P6**	**P9**	**P2**	**P6**	**P9**
0		23/5/94	10	10		2	2		2370	2370		0.0053	0.0053		0.0005	0.0003		-0.0004	0.0000	
1		24/5/94	18	10		4	2		2300	2300		0.0094	0.0052		0.0009	0.0003		0.0003	-0.0002	
2		25/5/94	13.6	18.2		3	4		2200	2200		0.0068	0.0090		0.0007	0.0005		0.0002	0.0000	
3		26/5/94	10.8	16.4		2	4		2100	2175		0.0051	0.0081		0.0005	0.0004		-0.0021	-0.0011	
4		27/5/94	58	65		13	15		2000	2050		0.0262	0.0301		0.0026	0.0015		0.0014	0.0011	
8		31/5/94	29	18		7	4		1900	1925		0.0125	0.0078		0.0012	0.0004		0.0005	0.0000	
9		1/6/94	22	18		5	4		1550	1900		0.0077	0.0077		0.0008	0.0004		0.0004	-0.0004	
10		2/6/94	12.5	39		3	9		1450	1750		0.0041	0.0154		0.0004	0.0008		-0.0004	0.0002	
11	0	3/6/94	27	34	22	6	8	5	1300	1600	2200	0.0079	0.0123	0.0109	0.0008	0.0006	0.0005	0.0004	0.0002	0.0001
14	3	6/6/94	12.6	23	20	3	5	5	1250	1600	2000	0.0036	0.0083	0.0090	0.0004	0.0004	0.0005	-0.0001	0.0000	0.0002
15	4	7/6/94	20	25	13.3	5	6	3	1100	1400	1900	0.0050	0.0079	0.0057	0.0005	0.0004	0.0003	-0.0003	0.0000	-0.0003
16	5	8/6/94	38	26	30	9	6	7	950	1300	1800	0.0082	0.0076	0.0122	0.0008	0.0004	0.0006	0.0002	0.0000	0.0001
17	6	9/6/94	31	29	24	7	7	5	850	1200	1750	0.0060	0.0079	0.0095	0.0006	0.0004	0.0005	0.0000	0.0000	-0.0001
18	7	10/6/94	34	32	30	8	7	7	750	1150	1550	0.0058	0.0083	0.0105	0.0006	0.0004	0.0005	0.0003	0.0000	0.0001
21	10	13/6/94	23	33	22	5	7	5	625	1150	1550	0.0032	0.0086	0.0077	0.0003	0.0004	0.0004	0.0001	0.0002	0.0001
22	11	14/6/94	22	28	22	5	6	5	450	575	1300	0.0022	0.0036	0.0065	0.0002	0.0002	0.0003	-0.0004	0.0001	0.0000
23	12	15/6/94	24	23	23	5	5	5	1100	450	1175	0.0060	0.0023	0.0061	0.0006	0.0001	0.0003	-0.0001	-0.0002	-0.0001
24	13	16/6/94	36	22	32	8	5	7	850	1100	1050	0.0069	0.0055	0.0076	0.0007	0.0003	0.0004	-0.0001	0.0000	0.0000
25	14	17/6/94	56	28	33	13	6	7	650	975	950	0.0082	0.0062	0.0071	0.0008	0.0003	0.0004	0.0001	-0.0004	-0.0004
28	17	20/6/94	69	70	80	16	16	18	475	850	800	0.0074	0.0134	0.0145	0.0007	0.0007	0.0007	-0.0001	0.0003	0.0001
29	18	21/6/94			97			22	300	675	550			0.0121			0.0006			0.0000
30	19	22/6/94	132	180	115	30	41	26	300	675	475	0.0089	0.0275	0.0123	0.0009	0.0014	0.0006	0.0001	-0.0001	-0.0005
31	20	23/6/94			103			23	150	675	950			0.0221			0.0011			0.0004
32	21	24/6/94			65			15	150	675	950			0.0140			0.0007			0.0000
35	24	27/6/94			61			14	150	675	950			0.0131			0.0007			-0.0007
36	25	28/6/94	84	225	126	19	51	28	150	675	950	0.0028	0.0343	0.0271	0.0003	0.0017	0.0014			

EXPERIMENT D: Chart D4(i)
NO_3-N Concentration of leachate



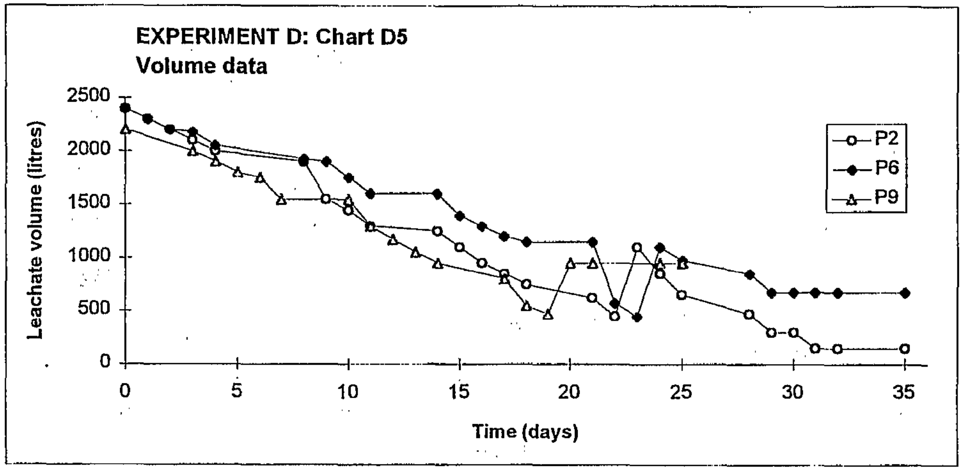
EXPERIMENT D: Chart D4(ii)
Mass of NO_3-N in leachate per square metre of treatment area



EXPERIMENT D Table D5: Leachate volume and Hydraulic loading rate (H) data

Dates:	23/05/94-28/06/94	
Plot 2 (P2)	Hydraulic loading rate (H)=70l/m²/d	Treatment plane surface area=10m²
Plot 6 (P6)	Hydraulic loading rate (H)=24l/m²/d	Treatment plane surface area=20m²
Plot 9 (P9)	Hydraulic loading rate (H)=37l/m²/d	Treatment plane surface area=20m²
Units:	Volume (litres), Hydraulic loading rate (litres/m²/day) Shaded cells denote the addition of borehole water	

	(P9)		P2			P6			P9		
Day	Day	Date	Total	Reception	H	Total	Reception	H	Total	Reception	H
0		23/5/94	2400	0	75	2400	0	20			
1		24/5/94	2300	750	75	2300	400	20			
2		25/5/94	2200	750	75	2200	400	23.75			
3		26/5/94	2100	750	85	2175	475	32.5			
4		27/5/94	2000	850	100	2050	650	22.5			
8		31/5/94	1900	1000	55	1925	450	25			
9		1/6/94	1550	550	85	1900	500	22.5			
10		2/6/94	1450	850	85	1750	450	30			
11	0	3/6/94	1300	850	85	1600	600	35	2200	0	38.75
14	3	6/6/94	1250	850	80	1600	700	27.5	2000	775	46.25
15	4	7/6/94	1100	800	95	1400	550	32.5	1900	925	38.75
16	5	8/6/94	950	950	85	1300	650	30	1800	775	42.5
17	6	9/6/94	850	850	80	1200	600	30	1750	850	41.25
18	7	10/6/94	750	800	67.5	1150	600	25	1550	825	41.25
21	10	13/6/94	625	675	47.5	1150	500	6.25	1550	825	31.25
22	11	14/6/94	450	475	32.5	575	125	23.75	1300	625	38.75
23	12	15/6/94	1100	1125	62.5	450	475	12.5	1175	775	38.75
24	13	16/6/94	850	625	70	1100	1100	20	1050	775	41.25
25	14	17/6/94	650	700	55	975	400	18.75	950	825	37.5
28	17	20/6/94	475	550	35	850	375	21.25	800	750	32.5
29	18	21/6/94	300	350	35	675	425	21.25	550	650	28.75
30	19	22/6/94	300	350		675	425		475	575	23.75
31	20	23/6/94	150			675			950	1100	
32	21	24/6/94	150			675			950		
35	24	27/6/94	150			675			950		
36	25	28/6/94	150			675			950		
Average actual H					70			24			37



EXPERIMENT D **Table D6: Evapotranspiration (ET), Rainfall (RF) and Temperature data.**

Dates:	**23/05/94-28/06/94**
Plot 2 (P2)	**Hydraulic loading rate (H)=70l/m^2/d**
Plot 6 (P6)	**Hydraulic loading rate (H)=24l/m^2/d**
Plot 9 (P9)	**Hydraulic loading rate (H)=37l/m^2/d**
Units	Both ET and RF are measured in mm, air temperature in Degrees Centigrade Shaded cells denotes no irrigation, i.e. weekends.

Day	(P9) Day	Date	RF (mm)	ET (mm)	Minimum temp. (°C)	Maximum temp. (°C)	Average temp. (°C)
0		23/5/94	0.2	1.5	8.7	15.2	12.0
1		24/5/94	1.3	1.4	8.6	13.9	11.3
2		25/5/94	4.1	1.4	7.5	12.3	9.9
3		26/5/94	0.2	1.1	8.7	11.0	9.9
4		27/5/94	0.3	2.0	3.8	12.5	8.2
5		28/5/94	0.0	1.4	5.5	13.4	9.5
6		29/5/94	0.1	2.6	-0.5	15.5	7.5
7		30/5/94	0.0	3.0	-0.6	17.0	8.3
8		31/5/94	0.0	3.4	6.0	20.5	13.3
9		1/6/94	0.0	3.0	3.4	24.6	14.0
10		2/6/94	0.0	1.4	10.3	19.0	14.7
11	0	3/6/94	1.1	2.3	10.5	16.7	13.6
12	1	4/6/94	2.0	1.5	7.5	13.2	10.4
13	2	5/6/94	0.5	2.7	3.2	17.0	10.1
14	3	6/6/94	0.0	1.4	10.2	21.2	15.7
15	4	7/6/94	0.3	3.0	11.4	20.7	16.1
16	5	8/6/94	0.2	2.7	11.5	16.7	14.1
17	6	9/6/94	1.1	1.4	4.6	14.0	9.3
18	7	10/6/94	0.0	2.0	9.1	16.0	12.6
19	8	11/6/94	0.0	3.7	5.2	18.7	12.0
20	9	12/6/94	0.0	3.0	6.2	20.1	13.2
21	10	13/6/94	0.0	3.7	5.6	22.3	14.0
22	11	14/6/94	0.0	4.1	9.8	24.3	17.1
23	12	15/6/94	0.0	4.2	6.1	22.6	14.4
24	13	16/6/94	0.0	3.6	9.3	22.0	15.7
25	14	17/6/94	0.0	2.6	6.7	24.0	15.4
26	15	18/6/94	0.0	1.8	11.2	20.5	15.9
27	16	19/6/94	0.0	2.7	12.0	20.6	16.3
28	17	20/6/94	1.1	1.3	13.0	18.7	15.9
29	18	21/6/94	0.6	0.3	11.5	18.7	15.1
30	19	22/6/94	0.0	4.0	13.0	21.0	17.0
31	20	23/6/94	0.0	3.9	5.4	22.7	14.1
32	21	24/6/94	12.1	3.7	10.7	25.7	18.2
33	22	25/6/94	0.0	2.4	14.5	22.1	18.3
34	23	26/6/94	0.0	2.5	11.2	21.0	16.1
35	24	27/6/94	0.0	3.6	11.6	24.3	18.0
36	25	28/6/94	3.9	3.2	9.2	27.2	18.2

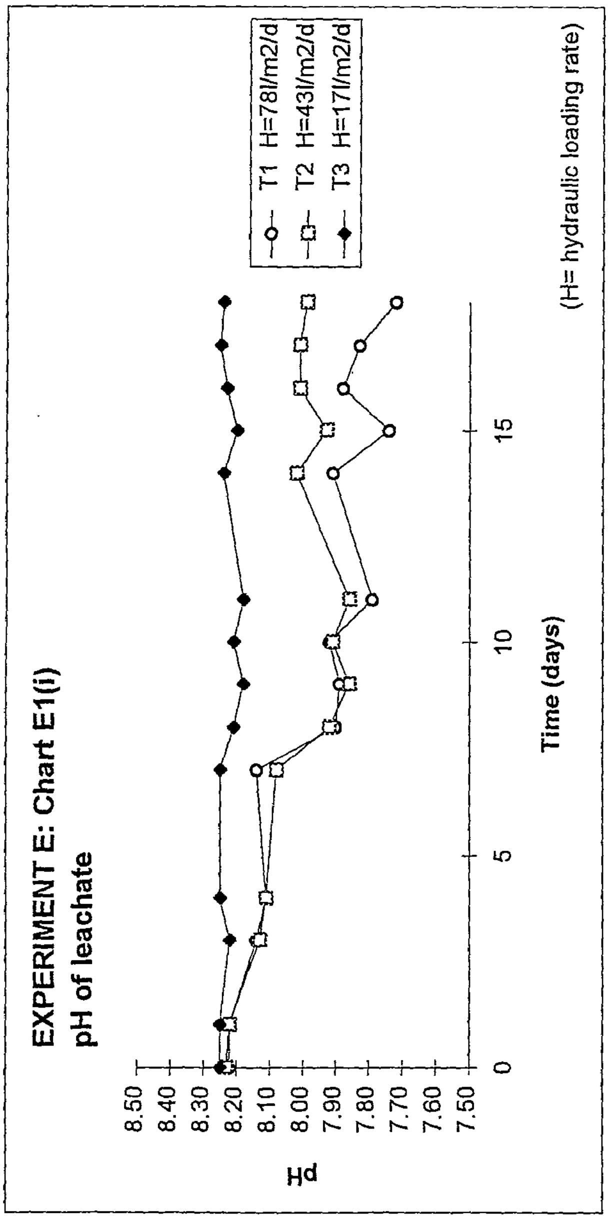
	RF (mm)	ET (mm)
Total mm (P2&P6)	29.7	93.5
Total mm (P9)	23.5	71.3

	Minimum temp. (°C)	Maximum temp. (°C)	Average temp. (°C)
Average °C (P2 & P6)	8.2	19.1	13.6
Average °C (P9)	9.2	20.5	14.9

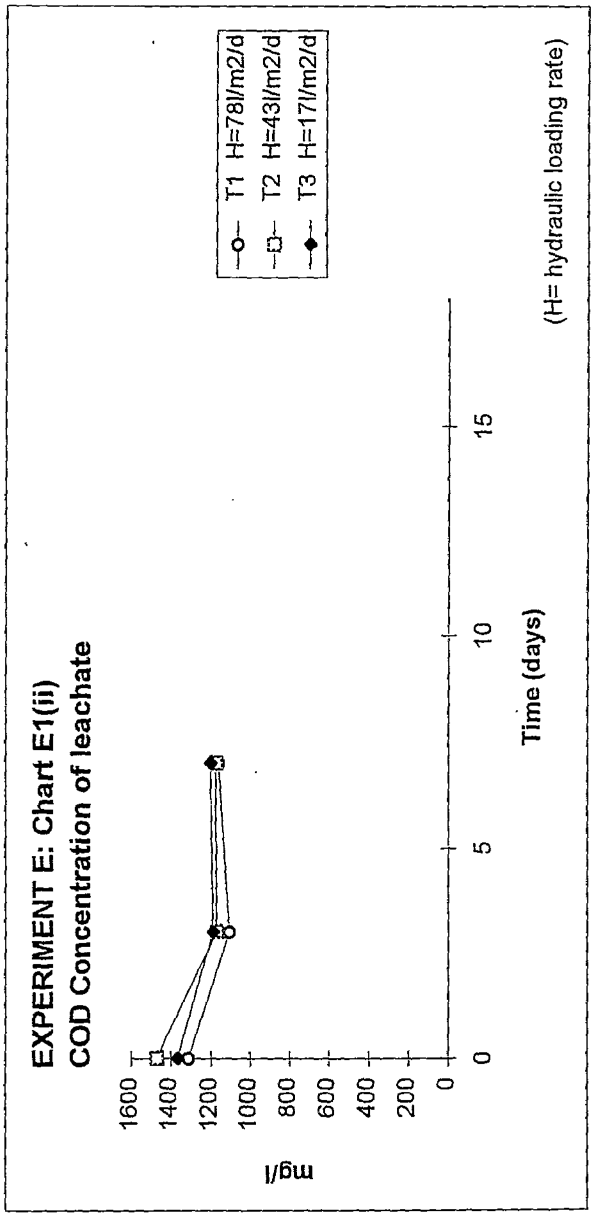
EXPERIMENT E Table E1: pH, Chemical Oxygen Demand (COD), and Chloride (Cl^-) data

Dates: 13/06/94-01/07/94
Trough 1 (T1) Hydraulic loading rate (H)=78l/m^2/d Treatment plane surface area=0.8m^2
Trough 2 (T2) Hydraulic loading rate (H)=43l/m^2/d Treatment plane surface area=0.8m^2
Trough 3 (T3) Hydraulic loading rate (H)=17l/m^2/d Treatment plane surface area=0.8m^2

		pH			COD conc. (mg/l)			Cl^- conc. (mg/l)			Leachate volume (l)			Cl^- total mass in leachate (kg)			Loading rate of Cl^- kg/m^2			Cl^- removal rate kg/m^2/d		
Day	**Date**	**T1**	**T2**	**T3**	**T1**	**T2**	**T3**	**T1**	**T2**	**T3**	**T1**	**T2**	**T3**	**T1**	**T2**	**T3**	**T1**	**T2**	**T3**	**T1**	**T2**	**T3**
0	13/6/94	8.22	8.23	8.25	1310	1470	1365	3510	3705	3630	210	210	215	0.7371	0.7781	0.7805	0.9214	0.9726	0.9756	0.0188	0.0283	0.0205
1	14/6/94	8.22	8.22	8.25							205	203	215									
2	15/6/94										197	199	205									
3	16/6/94	8.14	8.13	8.22	1105	1170	1190				193	188	196									
4	17/6/94	8.11	8.11	8.25							196	185	193									
7	20/6/94	8.14	8.08	8.25	1160	1175	1200	3510	3480	3580	180	178	186	0.6318	0.6194	0.6659	0.7898	0.7743	0.8324	-0.0010	-0.0024	0.0843
8	21/6/94	7.9	7.92	8.21							172	170	181									
9	22/6/94	7.89	7.86	8.18							171	170	179									
10	23/6/94	7.92	7.91	8.21							166	165	175									
11	24/6/94	7.79	7.86	8.18							164	162	171									
14	27/6/94	7.91	8.02	8.24				3750	3745	1090	170	169	178	0.6375	0.6329	0.1940	0.7969	0.7911	0.2425			
15	28/6/94	7.74	7.93	8.2							164	163	168									
16	29/6/94	7.88	8.01	8.23							158	160	166									
17	30/6/94	7.83	8.01	8.25							154	156	163									
18	1/7/94	7.72	7.99	8.24							149	153	158									



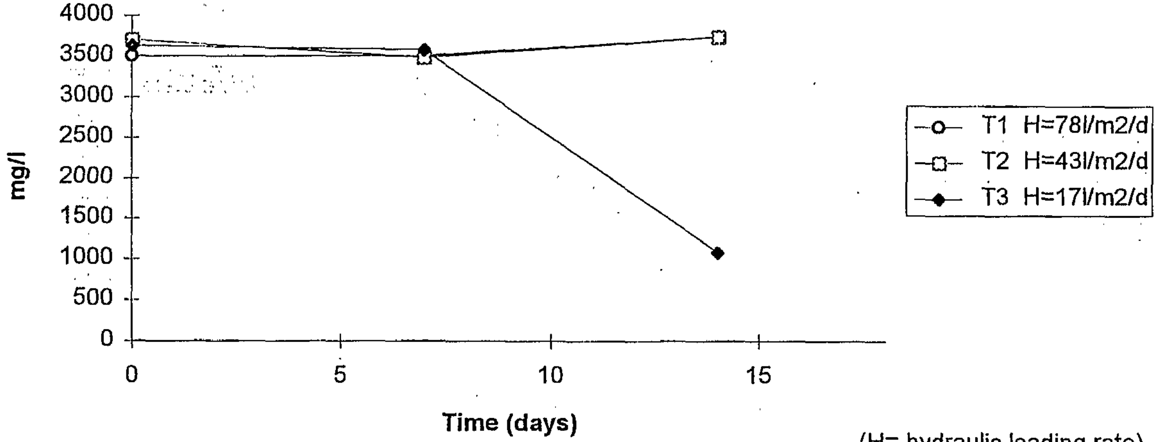
EXPERIMENT E: Chart E1(i)
pH of leachate



EXPERIMENT E: Chart E1(ii)
COD Concentration of leachate

EXPERIMENT E: Chart E1(iii)

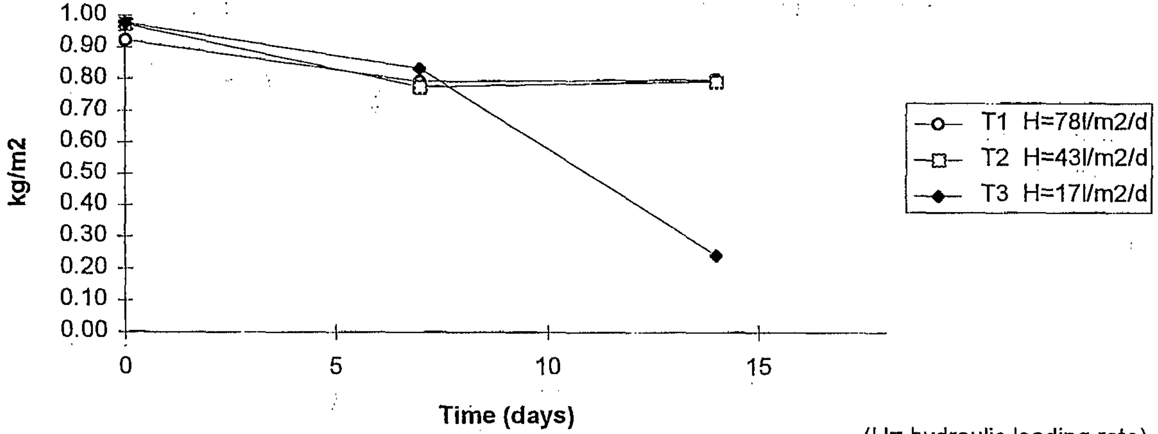
Cl⁻ Concentration of leachate



(H= hydraulic loading rate)

EXPERIMENT E: Chart E1(iv)

Mass of Cl⁻ in leachate per square metre of treatment area



(H= hydraulic loading rate)

EXPERIMENT E   Table E2: Ammonia (NH_3) data

Dates: 13/06/94-01/07/94

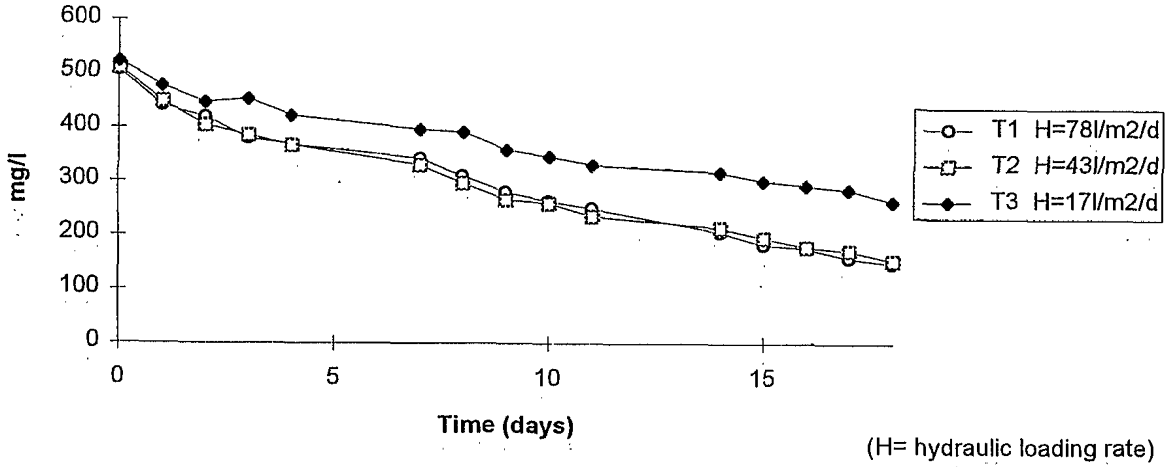
Trough 1 (T1) Hydraulic loading rate (H)=78l/m^2/d   Treatment plane surface area=0.8m^2

Trough 2 (T2) Hydraulic loading rate (H)=43l/m^2/d   Treatment plane surface area=0.8m^2

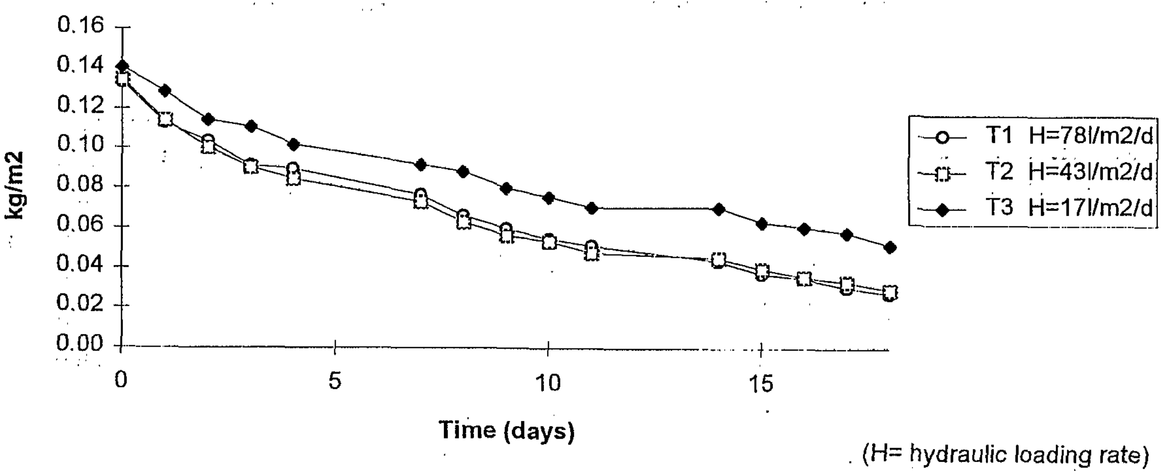
Trough 3 (T3) Hydraulic loading rate (H)=17l/m^2/d   Treatment plane surface area=0.8m^2

		NH_3 conc. (mg/l)			NH_3-N conc. (mg/l)			Leachate volume (l)			NH_3-N total mass in leachate (kg)			Loading rate of NH_3-N (kg/m^2)			NH_3-N removal rate (kg/m^2/d)		
Day	Date	T1	T2	T3	T1	T2	T3	T1	T2	T3	T1	T2	T3	T1	T2	T3	T1	T2	T3
0	13/6/94	615	620	635	507	511	523	210	210	215	0.1064	0.1073	0.1125	0.1330	0.1341	0.1406	-0.0201	0.0202	0.0122
1	14/6/94	535	545	580	441	449	478	205	203	215	0.0904	0.0912	0.1028	0.1130	0.1140	0.1284	0.0095	0.0135	0.0140
2	15/6/94	510	490	542	420	404	447	197	199	205	0.0828	0.0803	0.0916	0.1035	0.1004	0.1144	0.0120	0.0100	0.0036
3	16/6/94	460	467	549	379	385	452	193	188	196	0.0732	0.0723	0.0887	0.0914	0.0904	0.1108	0.0014	0.0056	0.0089
4	17/6/94	446	445	513	368	367	423	196	185	193	0.0720	0.0678	0.0816	0.0900	0.0848	0.1020	0.0133	0.0115	0.0098
7	20/6/94	414	400	481	341	330	396	180	178	186	0.0614	0.0587	0.0737	0.0768	0.0733	0.0921	0.0103	0.0103	0.0036
8	21/6/94	375	360	475	309	297	391	172	170	181	0.0531	0.0504	0.0708	0.0664	0.0630	0.0886	0.0066	0.0067	0.0084
9	22/6/94	340	322	435	280	265	358	171	170	179	0.0479	0.0451	0.0642	0.0599	0.0564	0.0802	0.0052	0.0028	0.0045
10	23/6/94	320	315	420	264	260	346	166	165	175	0.0438	0.0428	0.0606	0.0547	0.0535	0.0757	0.0035	0.0058	0.0049
11	24/6/94	303	286	402	250	236	331	164	162	171	0.0409	0.0382	0.0566	0.0512	0.0477	0.0708	0.0074	0.0025	0.0000
14	27/6/94	250	260	386	206	214	318	170	169	178	0.0350	0.0362	0.0566	0.0438	0.0453	0.0708	0.0064	0.0055	0.0074
15	28/6/94	221	237	366	182	195	302	164	163	168	0.0299	0.0318	0.0507	0.0373	0.0398	0.0633	0.0023	0.0040	0.0025
16	29/6/94	215	217	356	177	179	293	158	160	166	0.0280	0.0286	0.0487	0.0350	0.0358	0.0609	0.0045	0.0023	0.0026
17	30/6/94	192	208	347	158	171	286	154	156	163	0.0244	0.0267	0.0466	0.0305	0.0334	0.0583	0.0031	0.0041	0.0063
18	1/7/94	178	186	319	147	153	263	149	153	158	0.0219	0.0234	0.0415	0.0273	0.0293	0.0519			

EXPERIMENT E: Chart E2(i)
NH_3-N Concentration of leachate



EXPERIMENT E: Chart E2(ii)
Mass of NH_3-N in leachate per square metre of treatment area



EXPERIMENT E Table E3: Nitrite (NO_2) data

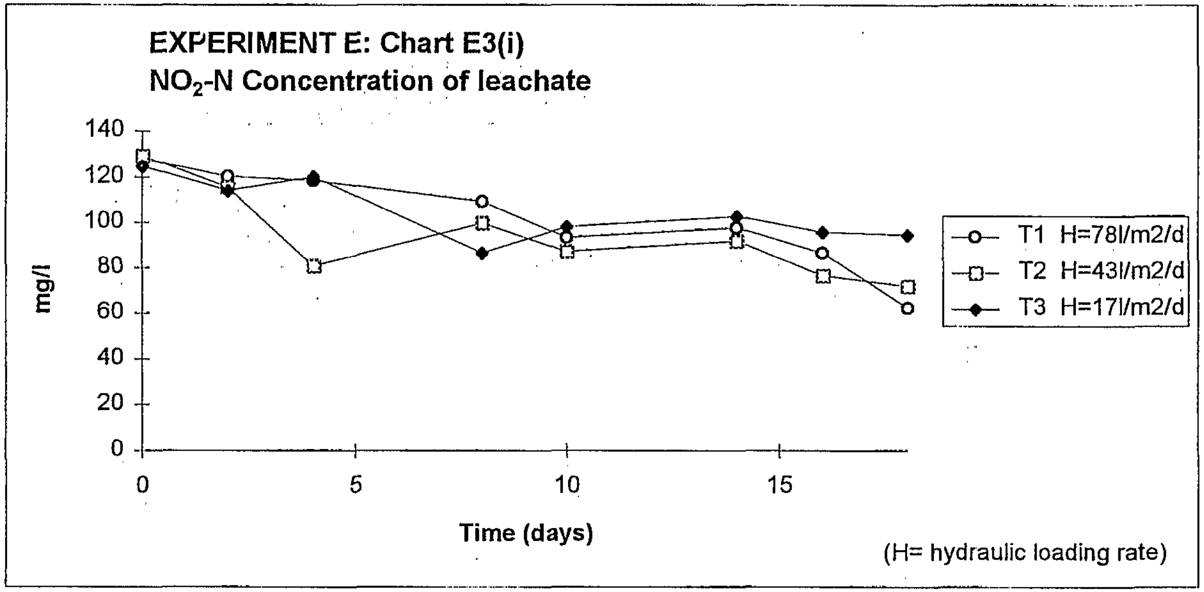
Dates: **13/06/94-01/07/94**

Trough 1 (T1) **Hydraulic loading rate (H)=78l/m^2/d** **Treatment plane surface area=0.8m^2**

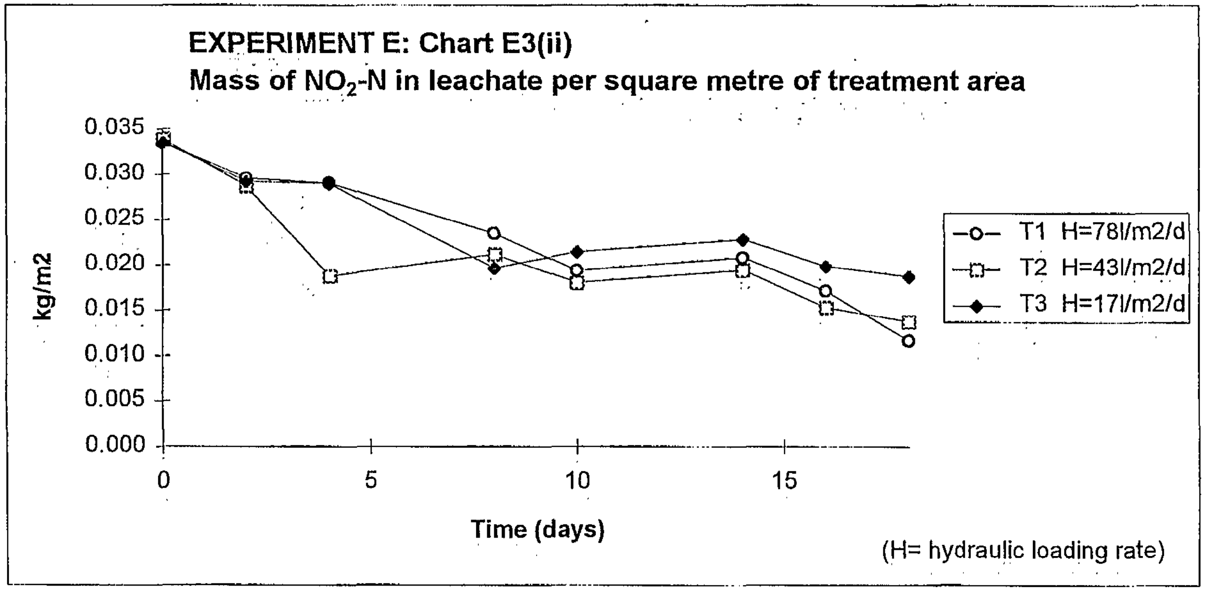
Trough 2 (T2) **Hydraulic loading rate (H)=43l/m^2/d** **Treatment plane surface area=0.8m^2**

Trough 3 (T3) **Hydraulic loading rate (H)=17l/m^2/d** **Treatment plane surface area=0.8m^2**

		NO_2 conc. (mg/l)			NO_2-N conc. (mg/l)			Leachate volume (l)			NO_2-N total mass in leachate (kg)			Loading rate of NO_2-N (kg/m^2)			NO_2-N removal rate (kg/m^2/d)		
Day	**Date**	**T1**	**T2**	**T3**	**T1**	**T2**	**T3**	**T1**	**T2**	**T3**	**T1**	**T2**	**T3**	**T1**	**T2**	**T3**	**T1**	**T2**	**T3**
0	13/6/94	420	425	410	128	129	125	210	210	215	0.0268	0.0271	0.0268	0.0335	0.0339	0.0335	-0.0020	0.0026	0.0021
1	14/6/94							205	203	215									
2	15/6/94	395	380	375	120	116	114	197	199	205	0.0237	0.0230	0.0234	0.0296	0.0287	0.0292	0.0003	0.0050	0.0001
3	16/6/94							193	188	196									
4	17/6/94	390	266	395	119	81	120	196	185	193	0.0232	0.0150	0.0232	0.0290	0.0187	0.0290	0.0014	-0.0006	0.0023
7	20/6/94							180	178	186									
8	21/6/94	359	328	285	109	100	87	172	170	181	0.0188	0.0170	0.0157	0.0235	0.0212	0.0196	0.0020	0.0016	-0.0009
9	22/6/94							171	170	179									
10	23/6/94	307	287	323	93	87	98	166	165	175	0.0155	0.0144	0.0172	0.0194	0.0180	0.0215	-0.0004	-0.0003	-0.0003
11	24/6/94							164	162	171									
14	27/6/94	322	302	338	98	92	103	170	169	178	0.0166	0.0155	0.0183	0.0208	0.0194	0.0229	0.0018	0.0020	0.0015
15	28/6/94							164	163	168									
16	29/6/94	285	252	315	87	77	96	158	160	166	0.0137	0.0123	0.0159	0.0171	0.0153	0.0199	0.0027	0.0008	0.0006
17	30/6/94							154	156	163									
18	1/7/94	206	237	312	63	72	95	149	153	158	0.0093	0.0110	0.0150	0.0117	0.0138	0.0187			



EXPERIMENT E: Chart E3(i)
NO_2-N Concentration of leachate



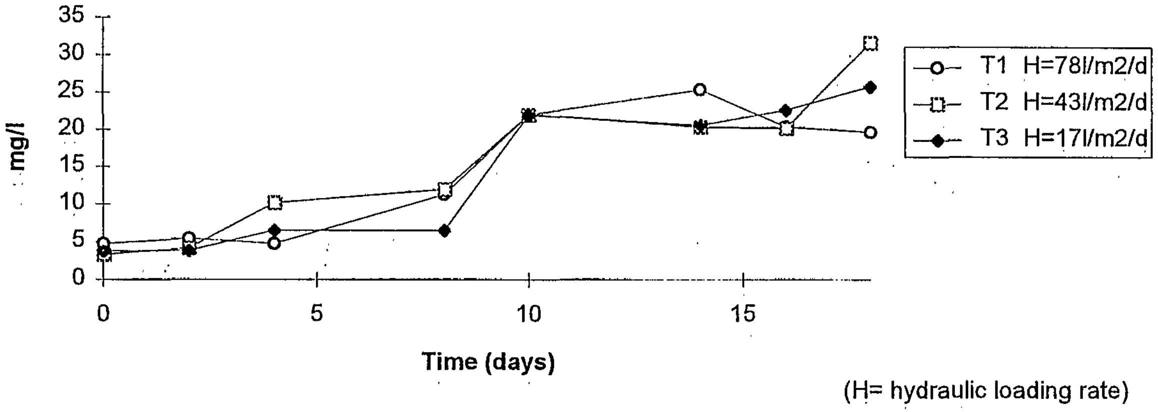
EXPERIMENT E: Chart E3(ii)
Mass of NO_2-N in leachate per square metre of treatment area

EXPERIMENT E Table E4: Nitrate (NO_3) data

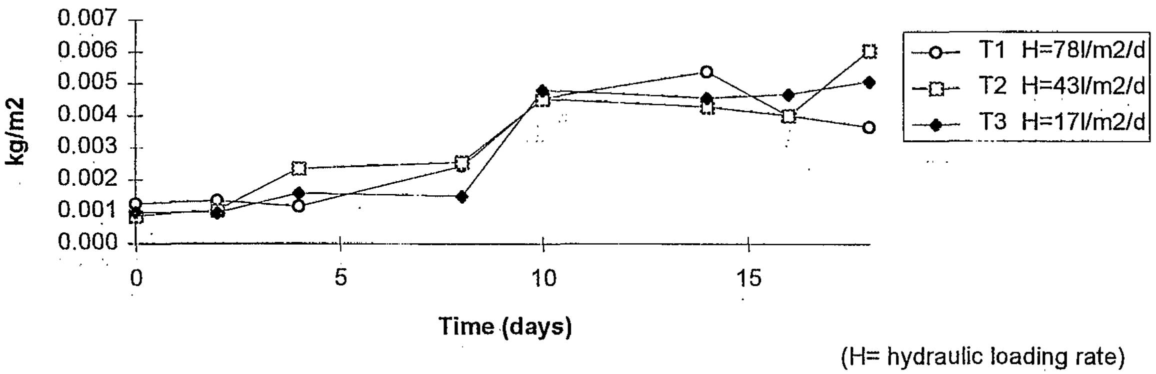
Dates:	13/06/94-01/07/94	
Trough 1 (T1)	Hydraulic loading rate (H)=78l/m^2/d	Treatment plane surface area=0.8m^2
Trough 2 (T2)	Hydraulic loading rate (H)=43l/m^2/d	Treatment plane surface area=0.8m^2
Trough 3 (T3)	Hydraulic loading rate (H)=17l/m^2/d	Treatment plane surface area=0.8m^2

		NO_3 conc. (mg/l)			NO_3-N conc. (mg/l)			Leachate volume (l)			NO_3-N total mass in leachate (kg)			Loading rate of NO_3-N (kg/m^2)			NO_3-N removal rate (kg/m^2/d)		
Day	Date	T1	T2	T3	T1	T2	T3	T1	T2	T3	T1	T2	T3	T1	T2	T3	T1	T2	T3
0	13/6/94	21	15	16	5	3	4	210	210	215	0.0010	0.0007	0.0008	0.0012	0.0009	0.0010	0.0000	-0.0001	0.0000
1	14/6/94							205	203	215									
2	15/6/94	24	19	17	5	4	4	197	199	205	0.0011	0.0008	0.0008	0.0013	0.0010	0.0010	0.0001	-0.0007	-0.0003
3	16/6/94							193	188	196									
4	17/6/94	21	45	29	5	10	7	196	185	193	0.0009	0.0019	0.0013	0.0012	0.0024	0.0016	-0.0003	0.0000	0.0000
7	20/6/94							180	178	186									
8	21/6/94	50	53	29	11	12	7	172	170	181	0.0019	0.0020	0.0012	0.0024	0.0025	0.0015	-0.0011	-0.0010	-0.0017
9	22/6/94							171	170	179									
10	23/6/94	97	97	97	22	22	22	166	165	175	0.0036	0.0036	0.0038	0.0045	0.0045	0.0048	-0.0002	0.0001	0.0001
11	24/6/94							164	162	171									
14	27/6/94	112	90	91	25	20	21	170	169	178	0.0043	0.0034	0.0037	0.0054	0.0043	0.0046	0.0007	0.0001	-0.0001
15	28/6/94							164	163	168									
16	29/6/94	90	89	100	20	20	23	158	160	166	0.0032	0.0032	0.0038	0.0040	0.0040	0.0047	0.0002	-0.0010	-0.0002
17	30/6/94							154	156	163									
18	1/7/94	87	140	114	20	32	26	149	153	158	0.0029	0.0048	0.0041	0.0037	0.0061	0.0051			

EXPERIMENT E: Chart E4(i)
NO_3-N Concentration of leachate



EXPERIMENT E: Chart E4(ii)
Mass of NO_3-N in leachate per square metre of treatment area



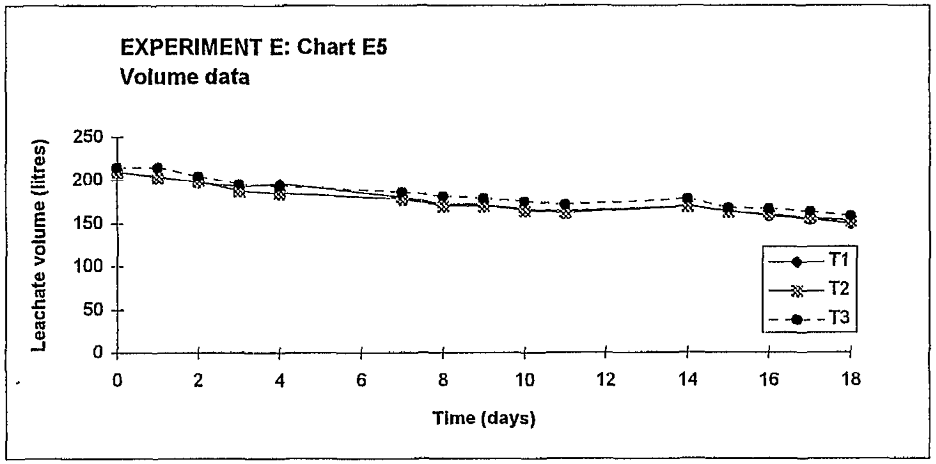
EXPERIMENT E

Table E5: Leachate volume and Hydraulic loading rate (H) data

Dates:	13/06/94-01/07/94	
Trough 1 (T1)	Hydraulic loading rate (H)=78l/m^2/d	Treatment plane surface area=0.8m^2
Trough 2 (T2)	Hydraulic loading rate (H)=43l/m^2/d	Treatment plane surface area=0.8m^2
Trough 3 (T3)	Hydraulic loading rate (H)=17l/m^2/d	Treatment plane surface area=0.8m^2
Units:	Volume (litres), Hydraulic loading rate (litres/m^2/day)	
	Shaded cells denote the addition of borehole water	

		T1			T2			T3		
Day	Date	Total	Delivered	H	Total	Delivered	H	Total	Delivered	H
0	13/6/94	210	60	75	210	37	46.25	215	5	6.25
1	14/6/94	205	58	72.5	203	26	32.5	215	22	27.5
2	15/6/94	197	64	80	199	89	111.25	205	19	23.75
3	16/6/94	193	70	87.5	188	37	46.25	196	12	15
4	17/6/94	196	67	83.75	185	37	46.25	193	17	21.25
7	20/6/94	180	66	82.5	178	30	37.5	186	12	15
8	21/6/94	172	55	68.75	170	30	37.5	181	12	15
9	22/6/94	171	56	70	170	25	31.25	179	9	11.25
10	23/6/94	166	59	73.75	165	20	25	175	12	15
11	24/6/94	164	57	71.25	162	18	22.5	171	5	6.25
14	27/6/94	170	62	77.5	169	31	38.75	178	15	18.75
15	28/6/94	164	64	80	163	29	36.25	168	14	17.5
16	29/6/94	158	59	73.75	160	37	46.25	166	14	17.5
17	30/6/94	154	75	93.75	156	37	46.25	163	17	21.25
18	1/7/94	149		0	153	119		158		

Average actual H	77.86	43.13	16.52



EXPERIMENT E: Chart E5
Volume data

EXPERIMENT E

Table E6: Evapotranspiration (ET), Rainfall (RF) and Temperature data.

Dates:	**13/06/94-01/07/94**	
Trough 1 (T1)	**Hydraulic loading rate (H)=78l/m^2/d**	**Treatment plane surface area=0.8m^2**
Trough 2 (T2)	**Hydraulic loading rate (H)=43l/m^2/d**	**Treatment plane surface area=0.8m^2**
Trough 3 (T3)	**Hydraulic loading rate (H)=17l/m^2/d**	**Treatment plane surface area=0.8m^2**
Units	Both ET and RF are measured in mm, air temperature in Degrees Centigrade	
	Shaded cells denotes no leachate irrigation, i.e. weekends.	

Day	Date	RF (mm)	ET (mm)	Minimum temp. (°C)	Maximum temp. (°C)	Average temp. (°C)
0	13/6/94	0	3.7	5.6	22.3	14.0
1	14/6/94	0	4.1	9.8	24.3	17.1
2	15/6/94	0	4.2	6.1	22.6	14.4
3	16/6/94	0	3.6	9.3	22	15.7
4	17/6/94	0	2.6	6.7	24	15.4
5	18/6/94	0	1.8	11.2	20.5	15.9
6	19/6/94	0	2.7	12	20.6	16.3
7	20/6/94	1.1	1.3	13	18.7	15.9
8	21/6/94	0.6	0.3	11.5	18.7	15.1
9	22/6/94	0	4	13	21	17.0
10	23/6/94	0	3.9	5.4	22.7	14.1
11	24/6/94	12.1	3.7	10.7	25.7	18.2
12	25/6/94	0	2.4	14.5	22.1	18.3
13	26/6/94	0	2.5	11.2	21	16.1
14	27/6/94	0	3.6	11.6	24.3	18.0
15	28/6/94	3.9	3.2	9.2	27.2	18.2
16	29/6/94	0	4.2	13.4	20.7	17.1
17	30/6/94	0	4.3	6.3	23	14.7
18	1/7/94	0	3.4	6.3	24.3	15.3

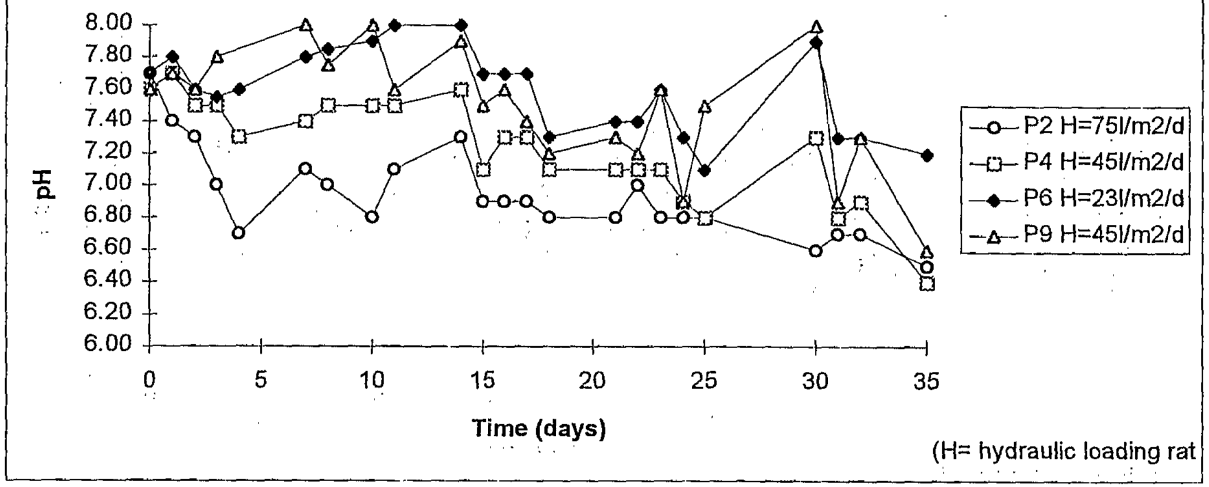
Total mm	17.7	59.5			
Average °C			9.8	22.4	16.1

EXPERIMENT F Table F1: pH, Chemical Oxygen Demand (COD), and Chloride (Cl^-) data

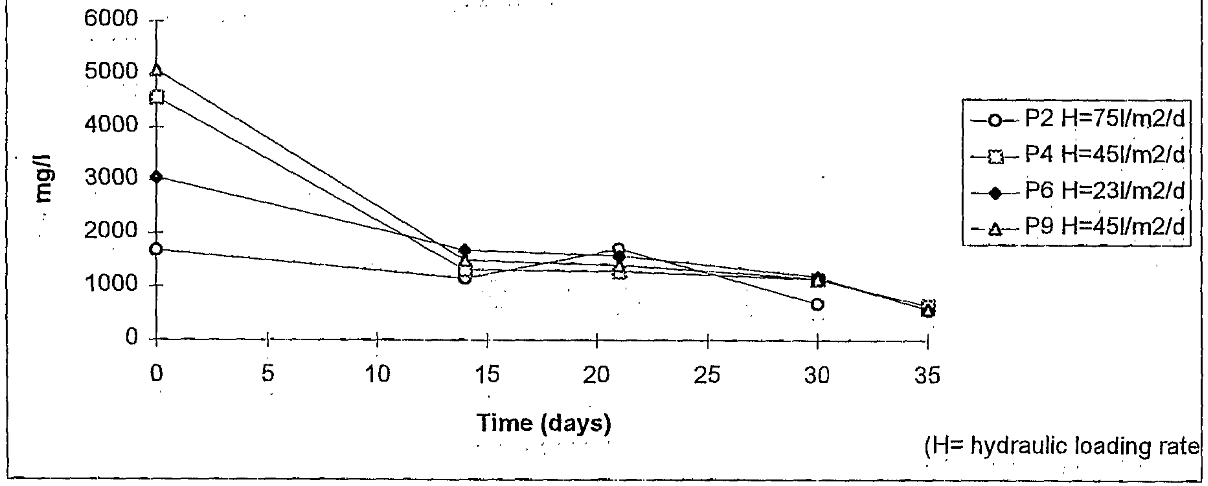
Dates:	01/08/94-05/09/94	
Plot 2 (P2)	Hydraulic loading rate (H)=75l/m^2/d	Treatment plane surface area=10m^2
Plot 4 (P4)	Hydraulic loading rate (H)=45l/m^2/d	Treatment plane surface area=10m^2
Plot 6 (P6)	Hydraulic loading rate (H)=23/m^2/d	Treatment plane surface area=10m^2
Plot 9 (P9)	Hydraulic loading rate (H)=45l/m^2/d	Treatment plane surface area=10m^3

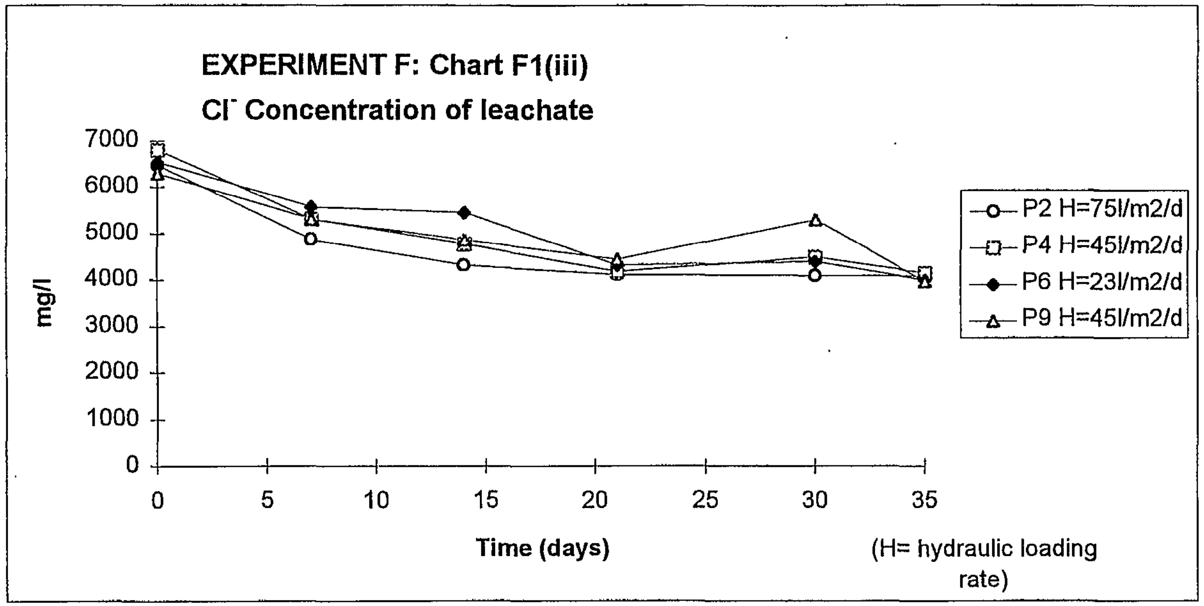
		pH					COD conc. (mg/l)					Cl^- conc. (mg/l)					Leachate volume (l)				Cl^- total mass in leachate (kg)				Loading rate of Cl^- kg/m^2				Cl^- removal rate kg/m^2/d			
Day	Date	P2	P4	P6	P9	Ctrl	P2	P4	P6	P9	Ctrl	P2	P4	P6	P9	Ctrl	P2	P4	P6	P9	P2	P4	P6	P9	P2	P4	P6	P9	P2	P4	P6	P9
0	1/8/94	7.70	7.6	7.70	7.6	7.7	1680	4560	3048	5064	9304	6480	6800	6550	6300	6400	2350	2400	2350	2300	15.2280	16.3200	15.3925	14.4900	1.5228	1.6320	1.5393	1.4490	0.1025	0.0690	0.0485	0.0622
1	2/8/94	7.4	7.7	7.8	7.7												2000	2200	2200	2000												
2	3/8/94	7.3	7.5	7.6	7.6												1880	2200	2150	1900												
3	4/8/94	7	7.5	7.55	7.8												1870	2220	2200	1900												
4	5/8/94	6.7	7.3	7.6													1800	2220	2200	1905												
7	8/8/94	7.1	7.4	7.8	8	7.9						4880	5320	5580	5320	5990	1650	2160	2150	1905	8.0520	11.4912	11.9970	10.1346	0.8052	1.1491	1.1997	1.0135	0.0354	0.0242	0.0115	0.0264
8	9/8/94	7	7.5	7.85	7.75												1500	2100	2080	1780												
10	11/8/94	6.8	7.5	7.9	8												1440	2070	2060	1780												
11	12/8/94	7.1	7.5	8	7.6												1400	2100	2100	1705												
14	15/8/94	7.3	7.6	8	7.9	8.2	1150	1310	1680	1490	2340	4320	4780	5460	4860	5920	1290	2050	2050	1705	5.5728	9.7990	11.1930	8.2863	0.5573	0.9799	1.1193	0.8286	0.0796	0.1400	0.1599	0.1184
15	16/8/94	6.9	7.1	7.7	7.5												1120	2000	2000	1550												
16	17/8/94	6.9	7.3	7.7	7.6												1005	1940	1950	1550												
17	18/8/94	6.9	7.3	7.7	7.4												950	1850	1920	1450												
18	19/8/94	6.8	7.1	7.3	7.2												880	1830	1900	1450												
21	22/8/94	6.8	7.1	7.4	7.3	7.9	1700	1275	1580	1390	2940	4110	4190	4320	4450	4340	725	1800	1900	1410	2.9798	7.5420	8.2080	6.2745	0.2980	0.7542	0.8208	0.6275	0.0426	0.1077	0.1173	0.0896
22	23/8/94	7	7.1	7.4	7.2												700	1730	1830	1295												
23	24/8/94	6.8	7.1	7.6	7.6												600	1680	1820	1295												
24	25/8/94	6.8	6.9	7.3	6.9												540	1620	1800	1215												
25	26/8/94	6.8	6.8	7.1	7.5												480	1580	1750	1215												
30	31/8/94	6.6	7.3	7.9	8	7.9	680	1130	1180	1150	1720	4100	4500	4400	5300	5200	400	1540	1700	1135	1.6400	6.9300	7.4800	6.0155	0.1640	0.6930	0.7480	0.6016	0.0071	0.0183	0.0133	0.0354
31	1/9/94	6.7	6.8	7.3	6.9												310	1420	1640	995												
32	2/9/94	6.7	6.9	7.3	7.3												355	1480	1710	995												
35	5/9/94	6.5	6.4	7.2	6.6	8.0		650	570	590	660	4080	4150	4010	3970	2800	315	1450	1700	1070	1.2852	6.0175	6.8170	4.2479	0.1285	0.6018	0.6817	0.4248				

EXPERIMENT F: Chart F1(i)
pH of leachate



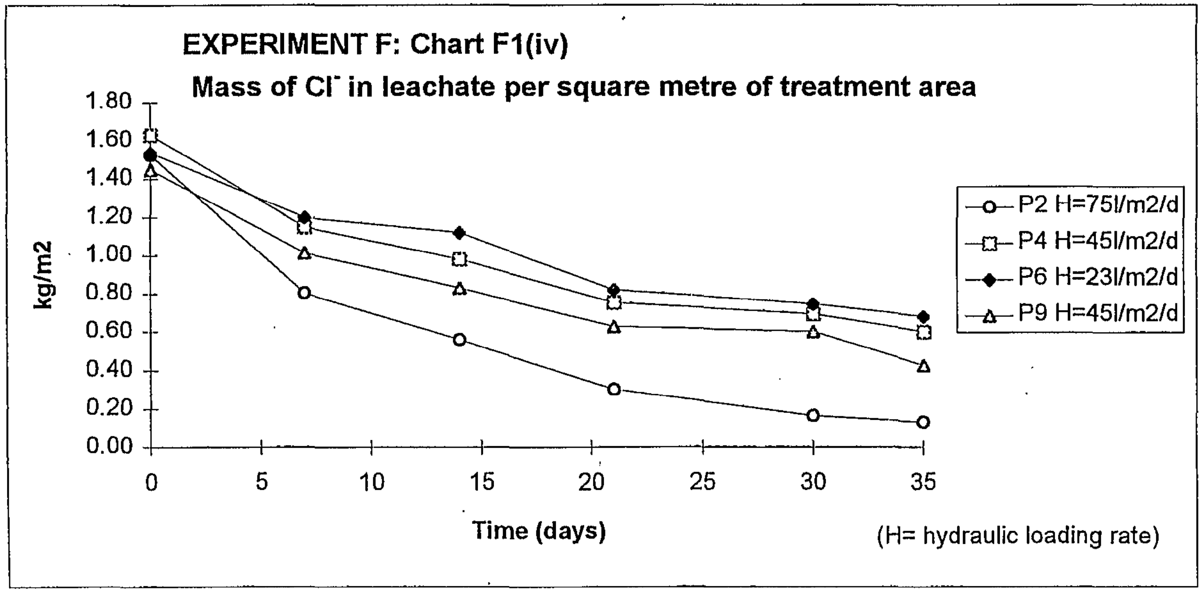
EXPERIMENT F: Chart F1(ii)
COD Concentration of leachate





EXPERIMENT F: Chart F1(iii)

Cl⁻ Concentration of leachate



EXPERIMENT F: Chart F1(iv)

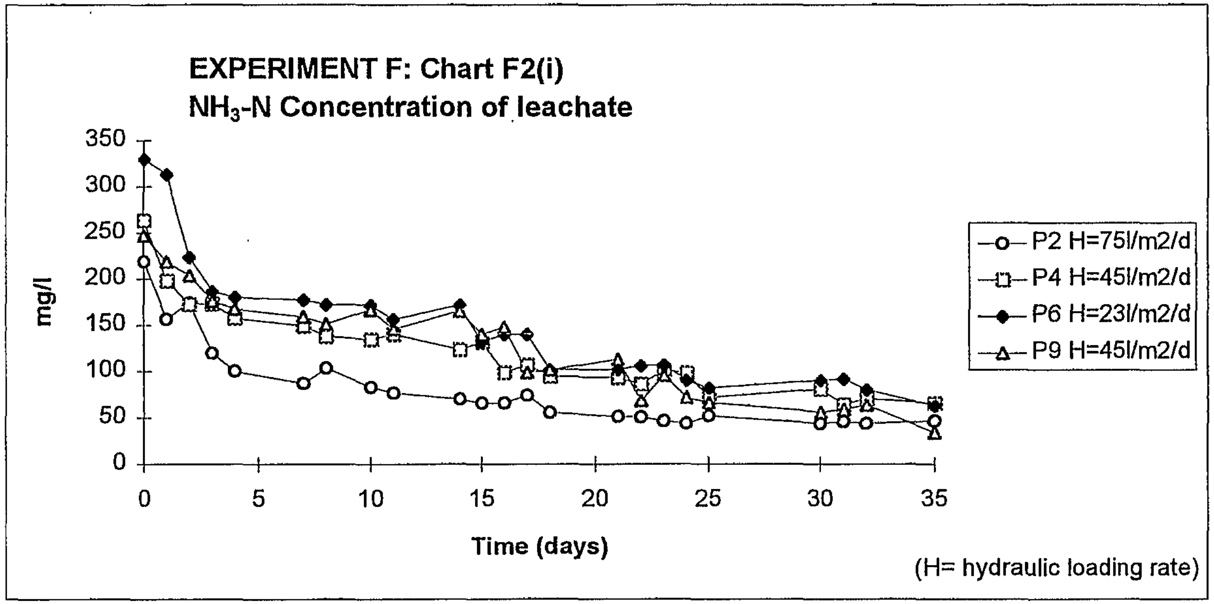
Mass of Cl⁻ in leachate per square metre of treatment area

EXPERIMENT F Table F2: Ammonia (NH_3) data

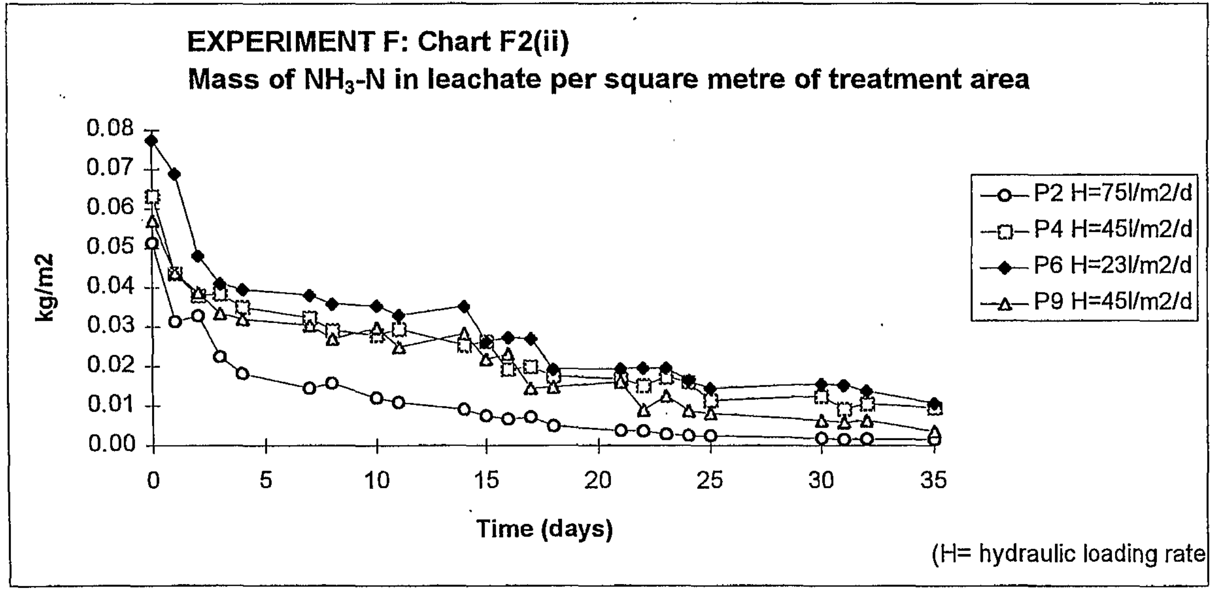
Dates: 01/08/94-05/09/94
Plot 2 (P2) Hydraulic loading rate (H)=75l/m^2/d Treatment plane surface area=10m^2
Plot 4 (P4) Hydraulic loading rate (H)=45l/m^2/d Treatment plane surface area=10m^2
Plot 6 (P6) Hydraulic loading rate (H)=23/m^2/d Treatment plane surface area=10m^2
Plot 9 (P9) Hydraulic loading rate (H)=45l/m^2/d Treatment plane surface area=10m^3

		NH_3 conc. (mg/l)					NH_3-N conc. (mg/l)					Leachate volume (l)			
Day	Date	P2	P4	P6	P9	Ctrl	P2	P4	P6	P9	Ctrl	P2	P4	P6	P9
0	1/8/94	265	320	400	300	260	218	264	330	247	214	2350	2400	2350	2300
1	2/8/94	190	240	380	265		157	198	313	218		2000	2200	2200	2000
2	3/8/94	211	209	271	247		174	172	223	204		1880	2200	2150	1900
3	4/8/94	145	210	226	213		119	173	186	176		1870	2220	2200	1900
4	5/8/94	122	191	218			101	157	180	167		1800	2220	2200	1905
7	8/8/94	106	181	215	193	244	87	149	177	159	201	1650	2160	2150	1905
8	9/8/94	126	168	209	184		104	138	172	152		1500	2100	2080	1780
10	11/8/94	101	164	208	202		83	135	171	166		1440	2070	2060	1780
11	12/8/94	93	170	190	177		77	140	157	146		1400	2100	2100	1705
14	15/8/94	85	150	208	201	311	70	124	171	166	256	1290	2050	2050	1705
15	16/8/94	80	160	160	170		66	132	132	140		1120	2000	2000	1550
16	17/8/94	80	120	170	180		66	99	140	148		1005	1940	1950	1550
17	18/8/94	90	130	170	120		74	107	140	99		950	1850	1920	1450
18	19/8/94	67	115	123	123		55	95	101	101		880	1830	1900	1450
21	22/8/94	62	113	124	138	241	51	93	102	114	199	725	1800	1900	1410
22	23/8/94	61	105	129	83		50	87	106	68		700	1730	1830	1295
23	24/8/94	56	123	130	117		46	101	107	96		600	1680	1820	1295
24	25/8/94	53	120	110	87		44	99	91	72		540	1620	1800	1215
25	26/8/94	63	87	100	81		52	72	82	67		480	1580	1750	1215
30	31/8/94	53	98	110	68	300	44	81	91	56	247	400	1540	1700	1135
31	1/9/94	55	78	112	71		45	64	92	59		310	1420	1640	995
32	2/9/94	53	86	97	77		44	71	80	63		355	1480	1710	995
35	5/9/94	56	80	76	41	290	46	66	63	34	239	315	1450	1700	1070

		NH_3-N total mass in leachate (kg)				Loading rate of NH_3-N (kg/m^2)				NH_3-N removal rate (kg/m^2/d)			
Day	Date	P2	P4	P6	P9	P2	P4	P6	P9	P2	P4	P6	P9
0	1/8/94	0.5131	0.6328	0.7746	0.5686	0.0513	0.0633	0.0775	0.0569	0.0200	0.0198	0.0086	0.0132
1	2/8/94	0.3131	0.4351	0.6889	0.4367	0.0313	0.0435	0.0689	0.0437	-0.0014	0.0056	0.0209	0.0050
2	3/8/94	0.3269	0.3789	0.4801	0.3867	0.0327	0.0379	0.0480	0.0387	0.0103	-0.0005	0.0070	0.0053
3	4/8/94	0.2234	0.3841	0.4097	0.3335	0.0223	0.0384	0.0410	0.0333	0.0042	0.0035	0.0015	0.0031
4	5/8/94	0.1810	0.3494	0.3952	0.3187	0.0181	0.0349	0.0395	0.0319	0.0037	0.0027	0.0014	0.0049
7	8/8/94	0.1441	0.3222	0.3809	0.3030	0.0144	0.0322	0.0381	0.0303	-0.0012	0.0031	0.0023	0.0033
8	9/8/94	0.1557	0.2907	0.3582	0.2699	0.0156	0.0291	0.0358	0.0270	0.0036	0.0011	0.0005	-0.0026
10	11/8/94	0.1198	0.2797	0.3531	0.2963	0.0120	0.0280	0.0353	0.0296	0.0013	-0.0014	0.0024	0.0048
11	12/8/94	0.1073	0.2942	0.3288	0.2487	0.0107	0.0294	0.0329	0.0249	0.0017	0.0041	-0.0023	-0.0034
14	15/8/94	0.0904	0.2534	0.3514	0.2824	0.0090	0.0253	0.0351	0.0282	0.0017	-0.0010	0.0088	0.0065
15	16/8/94	0.0738	0.2637	0.2637	0.2171	0.0074	0.0264	0.0264	0.0217	0.0008	0.0072	-0.0009	-0.0013
16	17/8/94	0.0662	0.1918	0.2732	0.2299	0.0066	0.0192	0.0273	0.0230	-0.0004	-0.0006	0.0004	0.0087
17	18/8/94	0.0705	0.1982	0.2690	0.1434	0.0070	0.0198	0.0269	0.0143	0.0022	0.0025	0.0076	-0.0004
18	19/8/94	0.0486	0.1734	0.1926	0.1470	0.0049	0.0173	0.0193	0.0147	0.0012	0.0006	-0.0002	-0.0013
21	22/8/94	0.0370	0.1676	0.1941	0.1603	0.0037	0.0168	0.0194	0.0160	0.0002	0.0018	0.0000	0.0072
22	23/8/94	0.0352	0.1497	0.1945	0.0886	0.0035	0.0150	0.0195	0.0089	0.0007	-0.0021	0.0000	-0.0036
23	24/8/94	0.0277	0.1703	0.1950	0.1248	0.0028	0.0170	0.0195	0.0125	0.0004	0.0010	0.0032	0.0038
24	25/8/94	0.0236	0.1602	0.1632	0.0871	0.0024	0.0160	0.0163	0.0087	-0.0001	0.0047	0.0019	0.0006
25	26/8/94	0.0249	0.1133	0.1442	0.0811	0.0025	0.0113	0.0144	0.0081	0.0007	-0.0011	-0.0010	0.0017
30	31/8/94	0.0175	0.1244	0.1541	0.0636	0.0017	0.0124	0.0154	0.0064	0.0003	0.0033	0.0003	0.0005
31	1/9/94	0.0140	0.0913	0.1514	0.0582	0.0014	0.0091	0.0151	0.0058	-0.0001	-0.0014	0.0015	-0.0005
32	2/9/94	0.0155	0.1049	0.1367	0.0631	0.0016	0.0105	0.0137	0.0063	0.0001	0.0009	0.0030	0.0027
35	5/9/94	0.0145	0.0956	0.1065	0.0361	0.0015	0.0096	0.0106	0.0036				


EXPERIMENT F: Chart F2(i)
NH_3-N Concentration of leachate

(H= hydraulic loading rate)


EXPERIMENT F: Chart F2(ii)
Mass of NH_3-N in leachate per square metre of treatment area

(H= hydraulic loading rate

EXPERIMENT F Table F3: Nitrite (NO_2) data

Dates: **01/08/94-05/09/94**

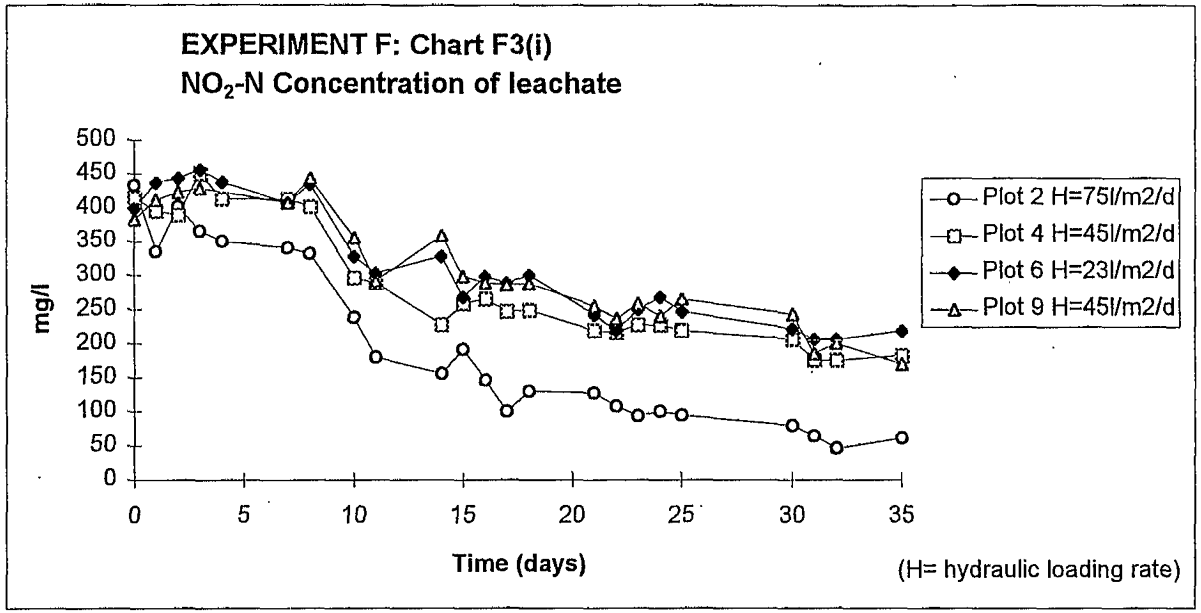
Plot 2 (P2) Hydraulic loading rate (H)=75l/m^2/d Treatment plane surface area=10m^2

Plot 4 (P4) Hydraulic loading rate (H)=45l/m^2/d Treatment plane surface area=10m^2

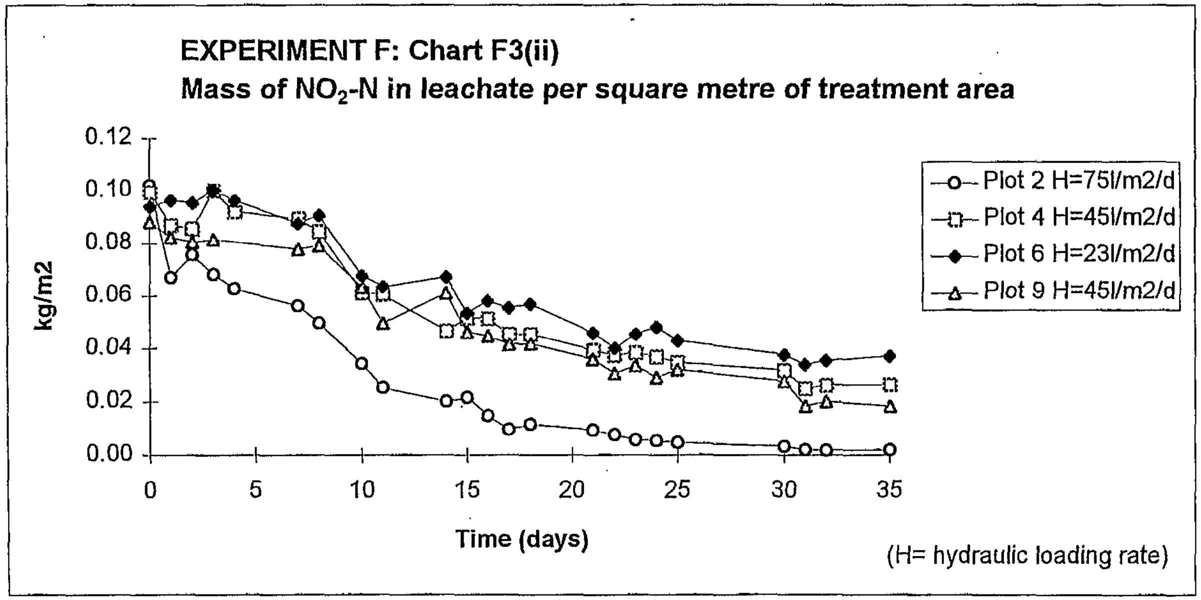
Plot 6 (P6) Hydraulic loading rate (H)=23/m^2/d Treatment plane surface area=10m^2

Plot 9 (P9) Hydraulic loading rate (H)=45l/m^2/d Treatment plane surface area=10m^3

		NO_2 conc. (mg/l)					NO_2-N conc. (mg/l)					Leachate volume (l)				NO_2-N total mass in leachate (kg)				Loading rate of NO_2-N (kg/m^2)				NO_2-N removal rate (kg/m^2/d)			
Day	Date	P2	P4	P6	P9	Ctrl	P2	P4	P6	P9	Ctrl	P2	P4	P6	P9	P2	P4	P6	P9	P2	P4	P6	P9	P2	P4	P6	P9
0	1/8/94	1426	1364	1312	1258	1476	434	415	399	382	449	2350	2400	2350	2300	1.0187	0.9952	0.9373	0.8796	0.1019	0.0995	0.0937	0.0880	0.0349	0.0127	-0.0024	0.0058
1	2/8/94	1102	1298	1438	1352		335	395	437	411		2000	2200	2200	2000	0.6700	0.8681	0.9617	0.8220	0.0670	0.0868	0.0962	0.0822	-0.0084	0.0012	0.0007	0.0019
2	3/8/94	1320	1280	1460	1390		401	389	444	423		1880	2200	2150	1900	0.7544	0.8561	0.9543	0.8029	0.0754	0.0856	0.0954	0.0803	0.0072	-0.0143	-0.0049	-0.0012
3	4/8/94	1200	1480	1500	1410		365	450	456	429		1870	2220	2200	1900	0.6822	0.9988	1.0032	0.8144	0.0682	0.0999	0.1003	0.0814	0.0053	0.0081	0.0040	0.0019
4	5/8/94	1150	1360	1440			350	413	438			1800	2220	2200	1905	0.6293	0.9178	0.9631		0.0629	0.0918	0.0963		0.0067	0.0025	0.0087	
7	8/8/94	1120	1360	1340	1340	1570	340	413	407	407	477	1650	2160	2150	1905	0.5618	0.8930	0.8758	0.7760	0.0562	0.0893	0.0876	0.0776	0.0065	0.0050	-0.0028	-0.0014
8	9/8/94	1090	1320	1430	1460		331	401	435	444		1500	2100	2080	1780	0.4970	0.8427	0.9042	0.7900	0.0497	0.0843	0.0904	0.0790	0.0155	0.0230	0.0228	0.0157
10	11/8/94	782	974	1080	1170		238	296	328	356		1440	2070	2060	1780	0.3423	0.6129	0.6763	0.6331	0.0342	0.0613	0.0676	0.0633	0.0091	0.0006	0.0040	0.0137
11	12/8/94	590	950	996	958		179	289	303	291		1400	2100	2100	1705	0.2511	0.6065	0.6358	0.4966	0.0251	0.0606	0.0636	0.0497	0.0050	0.0139	-0.0037	-0.0115
14	15/8/94	512	750	1080	1180	1460	156	228	328	359	444	1290	2050	2050	1705	0.2008	0.4674	0.6731	0.6116	0.0201	0.0467	0.0673	0.0612	-0.0014	-0.0049	0.0138	0.0150
15	16/8/94	630	850	880	980		192	258	268	298		1120	2000	2000	1550	0.2145	0.5168	0.5350	0.4618	0.0215	0.0517	0.0535	0.0462	0.0068	0.0004	-0.0046	0.0014
16	17/8/94	480	870	980	950		146	264	298	289		1005	1940	1950	1550	0.1466	0.5131	0.5809	0.4476	0.0147	0.0513	0.0581	0.0448	0.0051	0.0058	0.0026	0.0033
17	18/8/94	330	810	950	940		100	246	289	286		950	1850	1920	1450	0.0953	0.4555	0.5545	0.4144	0.0095	0.0456	0.0554	0.0414	-0.0019	0.0000	-0.0016	-0.0003
18	19/8/94	428	818	988	947		130	249	300	288		880	1830	1900	1450	0.1145	0.4551	0.5707	0.4174	0.0114	0.0455	0.0571	0.0417	0.0022	0.0061	0.0111	0.0059
21	22/8/94	418	721	795	836	1090	127	219	242	254	331	725	1800	1900	1410	0.0921	0.3945	0.4592	0.3583	0.0092	0.0395	0.0459	0.0358	0.0017	0.0021	0.0058	0.0053
22	23/8/94	354	710	721	776		108	216	219	236		700	1730	1830	1295	0.0753	0.3734	0.4011	0.3055	0.0075	0.0373	0.0401	0.0305	0.0019	-0.0010	-0.0054	-0.0028
23	24/8/94	307	750	822	848		93	228	250	258		600	1680	1820	1295	0.0560	0.3830	0.4548	0.3338	0.0056	0.0383	0.0455	0.0334	0.0002	0.0014	-0.0027	0.0042
24	25/8/94	330	750	880	790		100	228	268	240		540	1620	1800	1215	0.0542	0.3694	0.4815	0.2918	0.0054	0.0369	0.0482	0.0292	0.0009	0.0024	0.0051	-0.0030
25	26/8/94	310	720	810	870		94	219	246	264		480	1580	1750	1215	0.0452	0.3458	0.4309	0.3213	0.0045	0.0346	0.0431	0.0321	0.0014	0.0027	0.0054	0.0045
30	31/8/94	260	680	730	800	1290	79	207	222	243	392	400	1540	1700	1135	0.0316	0.3183	0.3773	0.2760	0.0032	0.0318	0.0377	0.0276	0.0012	0.0068	0.0038	0.0092
31	1/9/94	210	580	680	610		64	176	207	185		310	1420	1640	995	0.0198	0.2504	0.3390	0.1845	0.0020	0.0250	0.0339	0.0185	0.0004	-0.0011	-0.0014	-0.0015
32	2/9/94	150	580	680	660		46	176	207	201		355	1480	1710	995	0.0162	0.2610	0.3535	0.1996	0.0016	0.0261	0.0353	0.0200	-0.0003	-0.0004	-0.0019	0.0017
35	5/9/94	200	600	720	560	1280	61	182	219	170	389	315	1450	1700	1070	0.0192	0.2645	0.3721	0.1822	0.0019	0.0264	0.0372	0.0182				


EXPERIMENT F: Chart F3(i)
NO_2-N Concentration of leachate

(H= hydraulic loading rate)


EXPERIMENT F: Chart F3(ii)
Mass of NO_2-N in leachate per square metre of treatment area

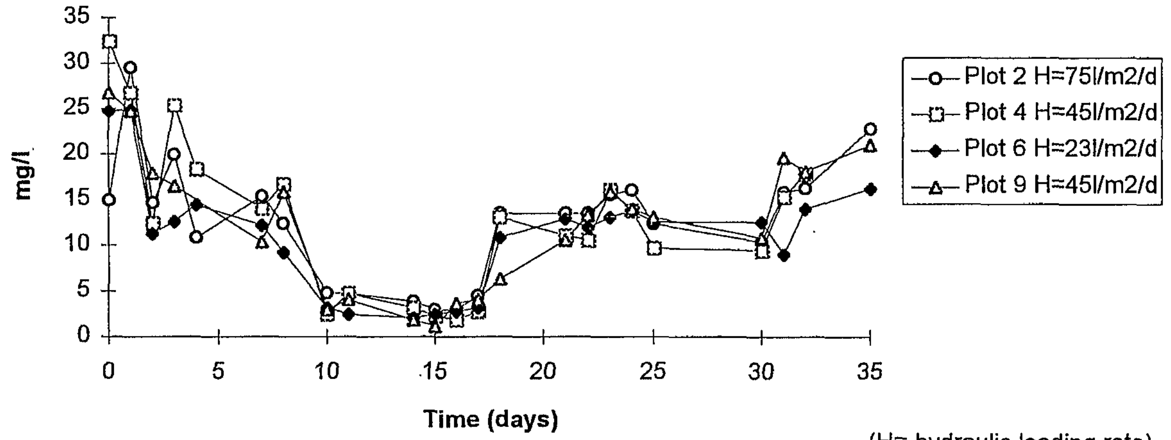
(H= hydraulic loading rate)

EXPERIMENT F Table F4: Nitrate (NO_3) data

Dates: 01/08/94-05/09/94
Plot 2 (P2) Hydraulic loading rate (H)=75l/m^2/d Treatment plane surface area=10m^2
Plot 4 (P4) Hydraulic loading rate (H)=45l/m^2/d Treatment plane surface area=10m^2
Plot 6 (P6) Hydraulic loading rate (H)=23/m^2/d Treatment plane surface area=10m^2
Plot 9 (P9) Hydraulic loading rate (H)=45l/m^2/d Treatment plane surface area=10m^3

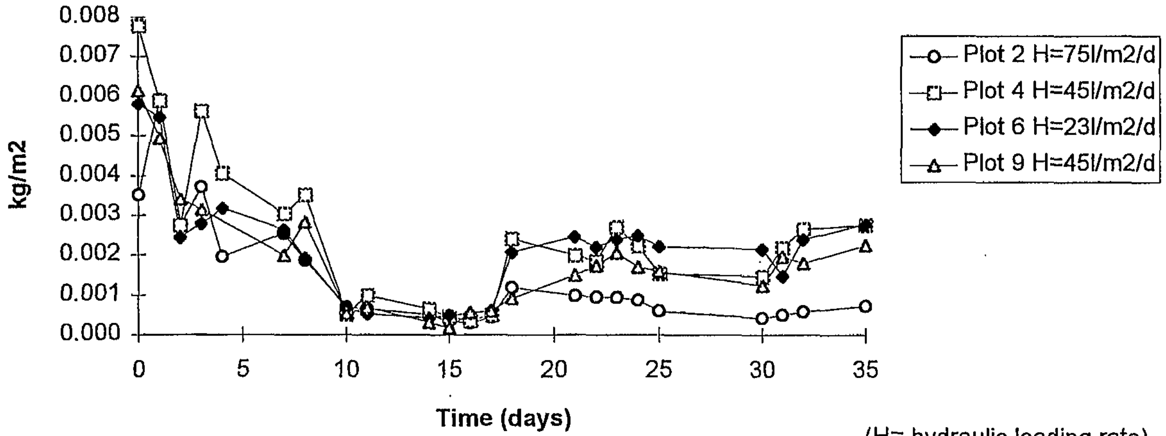
		NO_3 conc. (mg/l)					NO_3-N conc. (mg/l)					Leachate volume (l)				NO_3-N total mass in leachate (kg)				Loading rate of NO_3-N (kg/m^2)				NO_3-N removal rate (kg/m^2/d)			
Day	**Date**	**P2**	**P4**	**P6**	**P9**	**Ctrl**	**P2**	**P4**	**P6**	**P9**	**Ctrl**	**P2**	**P4**	**P6**	**P9**	**P2**	**P4**	**P6**	**P9**	**P2**	**P4**	**P6**	**P9**	**P2**	**P4**	**P6**	**P9**
0	1/8/94	66	143	109	118	98	15	32	25	27	22	2350	2400	2350	2300	0.0351	0.0778	0.0580	0.0614	0.0035	0.0078	0.0058	0.0061	-0.0024	0.0019	0.0003	0.0012
1	2/8/94	131	118	110	109		30	27	25	25		2000	2200	2200	2000	0.0591	0.0588	0.0546	0.0494	0.0059	0.0059	0.0055	0.0049	0.0032	0.0031	0.0030	0.0015
2	3/8/94	65	55	50	79		15	12	11	18		1880	2200	2150	1900	0.0276	0.0273	0.0243	0.0339	0.0028	0.0027	0.0024	0.0034	-0.0010	-0.0029	-0.0004	0.0003
3	4/8/94	88	112	56	73		20	25	13	16		1870	2220	2200	1900	0.0372	0.0562	0.0278	0.0313	0.0037	0.0056	0.0028	0.0031	0.0018	0.0016	-0.0004	0.0004
4	5/8/94	48	81	64			11	18	14			1800	2220	2200	1905	0.0195	0.0406	0.0318		0.0020	0.0041	0.0032		-0.0006	0.0010	0.0006	
7	8/8/94	68	62	54	46	77	15	14	12	10	17	1650	2160	2150	1905	0.0254	0.0303	0.0262	0.0198	0.0025	0.0030	0.0026	0.0020	0.0007	-0.0005	0.0007	-0.0008
8	9/8/94	55	74	41	70		12	17	9	16		1500	2100	2080	1780	0.0186	0.0351	0.0193	0.0282	0.0019	0.0035	0.0019	0.0028	0.0012	0.0030	0.0013	0.0023
10	11/8/94	21	11	14	13		5	2	3	3		1440	2070	2060	1780	0.0068	0.0051	0.0065	0.0052	0.0007	0.0005	0.0007	0.0005	0.0000	-0.0005	0.0001	-0.0002
11	12/8/94	21	21	11	18		5	5	2	4		1400	2100	2100	1705	0.0066	0.0100	0.0052	0.0069	0.0007	0.0010	0.0005	0.0007	0.0002	0.0003	0.0001	0.0004
14	15/8/94	17	14	9	8	11	4	3	2	2	2	1290	2050	2050	1705	0.0050	0.0065	0.0042	0.0031	0.0005	0.0006	0.0004	0.0003	0.0002	0.0002	-0.0001	0.0001
15	16/8/94	13	10	11	5		3	2	2	1		1120	2000	2000	1550	0.0033	0.0045	0.0050	0.0018	0.0003	0.0005	0.0005	0.0002	0.0000	0.0001	0.0000	-0.0004
16	17/8/94	13	8	12	16		3	2	3	4		1005	1940	1950	1550	0.0030	0.0035	0.0053	0.0056	0.0003	0.0004	0.0005	0.0006	-0.0001	-0.0002	-0.0001	0.0000
17	18/8/94	20	12	14	18		5	3	3	4		950	1850	1920	1450	0.0043	0.0050	0.0061	0.0059	0.0004	0.0005	0.0006	0.0006	-0.0008	-0.0019	-0.0015	-0.0003
18	19/8/94	60	58	48	28		14	13	11	6		880	1830	1900	1450	0.0119	0.0240	0.0206	0.0092	0.0012	0.0024	0.0021	0.0009	0.0002	0.0004	-0.0004	-0.0006
21	22/8/94	60	49	57	47	51	14	11	13	11	12	725	1800	1900	1410	0.0098	0.0199	0.0245	0.0150	0.0010	0.0020	0.0024	0.0015	0.0000	0.0002	0.0003	-0.0002
22	23/8/94	60	47	53	59		14	11	12	13		700	1730	1830	1295	0.0095	0.0184	0.0219	0.0173	0.0009	0.0018	0.0022	0.0017	0.0000	-0.0009	-0.0002	-0.0003
23	24/8/94	69	71	58	70		16	16	13	16		600	1680	1820	1295	0.0094	0.0270	0.0239	0.0205	0.0009	0.0027	0.0024	0.0020	0.0001	0.0005	-0.0001	0.0003
24	25/8/94	71	61	61	62		16	14	14	14		540	1620	1800	1215	0.0087	0.0223	0.0248	0.0170	0.0009	0.0022	0.0025	0.0017	0.0003	0.0007	0.0003	0.0001
25	26/8/94	55	43	56	58		12	10	13	13		480	1580	1750	1215	0.0060	0.0154	0.0221	0.0159	0.0006	0.0015	0.0022	0.0016	0.0002	0.0001	0.0001	0.0004
30	31/8/94	46	42	56	48	51	10	9	13	11	12	400	1540	1700	1135	0.0042	0.0146	0.0215	0.0123	0.0004	0.0015	0.0022	0.0012	-0.0001	-0.0007	0.0007	-0.0007
31	1/9/94	70	68	40	87		16	15	9	20		310	1420	1640	995	0.0049	0.0218	0.0148	0.0196	0.0005	0.0022	0.0015	0.0020	-0.0001	-0.0005	-0.0009	0.0002
32	2/9/94	72	79	62	80		16	18	14	18		355	1480	1710	995	0.0058	0.0264	0.0240	0.0180	0.0006	0.0026	0.0024	0.0018	-0.0001	-0.0001	-0.0004	-0.0005
35	5/9/94	101	84	72	93	61	23	19	16	21	14	315	1450	1700	1070	0.0072	0.0276	0.0277	0.0225	0.0007	0.0028	0.0028	0.0023				

EXPERIMENT F: Chart F4(i)
NO_3-N Concentration of leachate



(H= hydraulic loading rate)

EXPERIMENT F: Chart F4(ii)
Mass of NO_3-N in leachate per square metre of treatment area



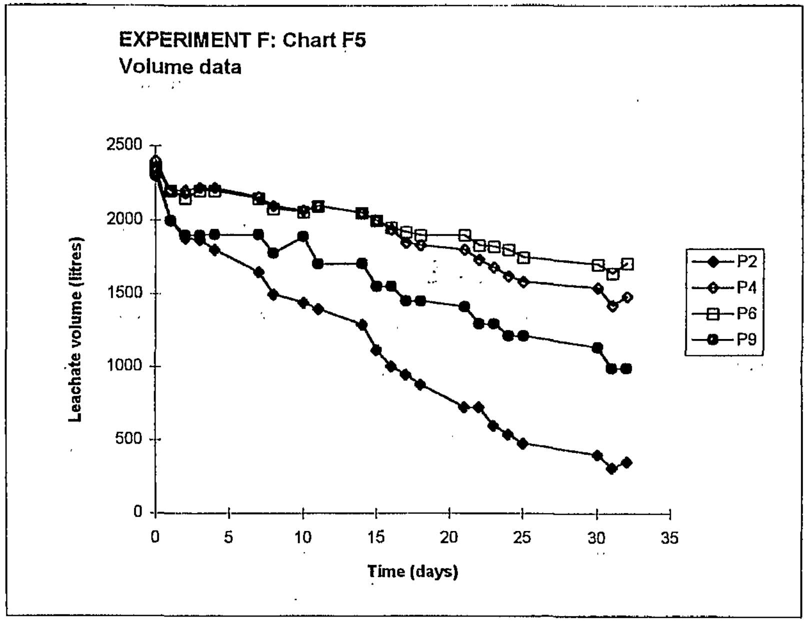
(H= hydraulic loading rate)

EXPERIMENT F

Table F5: Leachate volume and Hydraulic loading rate (H) data.

Dates:	01/08/94-05/09/94	
Plot 2 (P2)	Hydraulic loading rate (H)=75l/m^2/d	Treatment plane surface area=10m^2
Plot 4 (P4)	Hydraulic loading rate (H)=45l/m^2/d	Treatment plane surface area=10m^2
Plot 6 (P6)	Hydraulic loading rate (H)=23/m^2/d	Treatment plane surface area=10m^2
Plot 9 (P9)	Hydraulic loading rate (H)=45l/m^2/d	Treatment plane surface area=10m^3

		P2			P4			P6			P9		
Date	Day	Total	Vol applied	H	Total	Vol applied	H	Total	Vol applied	H	Total	Vol applied	H
1/8/94	0	2350	875	87.5	2400	500	50	2350	225	22.5	2300	475	47.5
2/8/94	1	2000	880	88	2200	440	44	2200	220	22	2000	440	44
3/8/94	2	1880	870	87	2200	440	44	2150	255	25.5	1900		
4/8/94	3	1870	880	88	2220	440	44	2200	240	24	1900	440	44
5/8/94	4	1800	860	86	2220	440	44	2200	220	22	1905		
8/8/94	7	1650	880	88	2160	440	44	2150	220	22	1905	460	46
9/8/94	8	1500	880	88	2100	440	44	2080	200	20	1780		
11/8/94	10	1440	880	88	2070	460	46	2060	320	32	1890	510	51
12/8/94	11	1400	880	88	2100	440	44	2100	220	22	1705		
15/8/94	14	1290	950	95	2050	440	44	2050	220	22	1705	440	44
16/8/94	15	1120	880	88	2000	440	44	2000	240	24	1550		
17/8/94	16	1005	880	88	1940	440	44	1950	220	22	1550	450	45
18/8/94	17	950	880	88	1850	440	44	1920	220	22	1450		
19/8/94	18	880	880	88	1830	440	44	1900	220	22	1450	440	44
22/8/94	21	725	725	72.5	1800	525	52.5	1900	220	22	1410	440	44
23/8/94	22	725	725	72.5	1730	440	44	1830	220	22	1295		
24/8/94	23	600	600	60	1680	490	49	1820	310	31	1295	470	47
25/8/94	24	540	540	54	1620	440	44	1800	240	24	1215		
26/8/94	25	480	480	48	1580	440	44	1750	220	22	1215	440	44
31/8/94	30	400	400	40	1540	440	44	1700	220	22	1135	440	44
1/9/94	31	310	310	31	1420	440	44	1640	270	27	995		
2/9/94	32	355	355	35.5	1480	440	44	1710	220	22	995	440	44



EXPERIMENT F

Table F6: Evapotranspiration (ET), Rainfall (RF) and Temperature data.

Dates:	**01/08/94-05/09/94**	
Plot 2 (P2)	**Hydraulic loading rate (H)=75l/m^2/d**	**Treatment plane surface area=10m^2**
Plot 4 (P4)	**Hydraulic loading rate (H)=45l/m^2/d**	**Treatment plane surface area=10m^2**
Plot 6 (P6)	**Hydraulic loading rate (H)=23/m^2/d**	**Treatment plane surface area=10m^2**
Plot 9 (P9)	**Hydraulic loading rate (H)=45l/m^2/d**	**Treatment plane surface area=10m^3**
Units:	Both ET and RF are measured in mm, air temperature in Degrees Centigrade	
	Shaded cells denotes no leachate irrigation, i.e. weekends.	

Day	Date	RF (mm)	ET (mm)	Minimum temp. (°C)	Maximum temp. (°C)	Average temp. (°C)
0	1/8/94	0	2.9	12.4	23.7	18.1
1	2/8/94	0.5	2.3	11.4	23.5	17.5
2	3/8/94	11.2	2.8	16.0	29.4	22.7
3	4/8/94	0.6	2.1	16.7	23.3	20.0
4	5/8/94	0	3.9	16.0	26.3	21.2
5	6/8/94	0	2	13.1	23.9	18.5
6	7/8/94	0	3.1	14.2	23.7	19.0
7	8/8/94	0	3	12.6	22.0	17.3
8	9/8/94	2.5	2.2	10.1	23.0	16.6
9	10/8/94	8.7	1.3	13.0	18.0	15.5
10	11/8/94	1.8	1.5	13.7	18.0	15.9
11	12/8/94	0	2.4	12.0	19.4	15.7
12	13/8/94	0	3.1	9.0	19.5	14.3
13	14/8/94	0	3.5	6.0	20.9	13.5
14	15/8/94	0	3.4	4.0	23.0	13.5
15	16/8/94	2.1	0.9	6.5	23.0	14.8
16	17/8/94	1.3	1.8	10.9	17.8	14.4
17	18/8/94	0.7	2.1	9.1	21.0	15.1
18	19/8/94	0	2.4	13.2	22.9	18.1

Total mm	29.4	46.7			
Average °C			11.6	22.2	16.9

10. APPENDIX 2 - OPERATIONAL LEACHATE TREATMENT PLANES

10.1 BROGBOROUGH LANDFILL SITE

10.1.1 Site Background

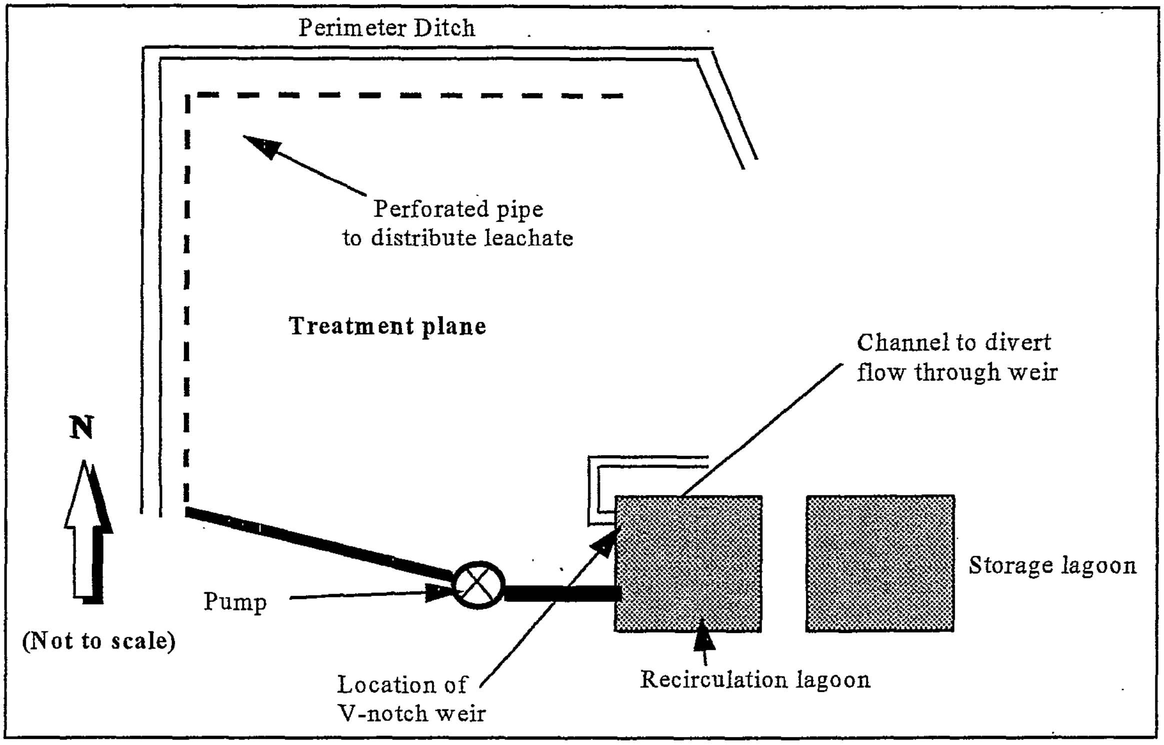
Brogborough Landfill Site is located in the Marston Vale approximately 2 miles from Junction 13 of the M1 motorway. Clay extraction for the brick making industry had left a void of 35 million cubic metres. The site was first used as a landfill site by London Brick Landfill Ltd in January 1983. Shanks & McEwan (Southern) Ltd. took over the site in 1986. The site covers an area of 182 hectares. Under current conditions the site has 5-6 years before completion. Waste from London, Hertfordshire, Bedfordshire, North Buckinghamshire and Northampton arrives by road, in up to 700 vehicles per day and 2.5 million tonnes of waste per annum. The waste is mainly commercial, industrial (including hazardous non-special wastes), and household. Restoration is well underway on completed areas of the site.

10.1.2 Leachate treatment plane characteristics

Leachate is estimated to be accumulating at a rate of 200 m^3/d within the waste. Some of this is extracted by pumping from wells stored in a lagoon of approximately 3000m^3 capacity to await treatment using the treatment plane. From here, it is transferred in batches as required to a recirculation lagoon which is the reservoir from which leachate is withdrawn and returned to following application onto the treatment plane. Fig. 10.1.1 shows the layout of the treatment area.

The treatment plane, constructed in 1985 on an area of waste clay material (callow), covers an area of approximately 4 hectares. It was laid with a shallow gradient draining down to the recirculation lagoon and is now covered with natural vegetation. Leachate was originally applied by pumping it into a channel along the upper perimeter of the plane. Unfortunately, this proved incapable of providing uniform discharge along its length and was replaced by slotted pipes placed around the treatment area. A major shortcoming for experimental purposes was created by differential settlement across the plane. This induced channelling, ponding and the creation of dry areas. As a result it was not possible to accurately determine the effective operational area of the plane, although it was estimated to be no more than 1 Ha out of the total of 4 Ha.

Fig.10.1.1 Brogborough treatment plane layout



10.1.3 Soil properties

The treatment plane is situated on clay from the Jurassic Oxford Clay Series. The callow clay is generally massive with root penetration limited to a few centimetres. Large lenticular crystals of selenite (a variety of gypsum) are widespread. Reasons for this are discussed in the following section. Physical and chemical tests have been carried out at Silsoe College. The findings are listed in Table 10.1.1.

Table 10.1.1 Soil properties of the Brogborough treatment plane

Property	Value
Average bulk density	1.39 g/cm^3
pH	7.2
Hydraulic conductivity	4×10^{-9} to 1×10^{-9}
Sodium adsorption ratio	343.9
Exchangeable sodium percentage	83.5%
Organic matter content	4.28%

* *Gypsum in soils*

The solubility of gypsum in soils is a function of the presence of other salts in the system. Its solubility increases in the presence of chlorides, particularly sodium and magnesium chlorides (present in the leachate). Compared with other chloride and sulphate salts in soil gypsum is least soluble. Twinned crystals are found when the gypsum content is very high. When iron sulphides are oxidised they release sulphuric acid which alters calcium carbonate to gypsum.

$$FeS_2 + 2O_2 \text{--->} FeSO_4$$

$$2FeSO_4 + 3H_2O + O_2 \text{--->} Fe_2O_3,H_2O + 2H_2SO_4$$

$$2H_2O + H_2SO_4 + CaCO_3 \text{--->} CaSO_42H_2O + H_2CO_3$$

A soil solution saturated with Ca^{2+} results in the fixation of trace elements, specifically Mn, Zn and Cu. Therefore we might expect to observe high concentrations of such elements in the treatment plane soil.

Several soil samples were taken from various locations on the treatment plane. These were analysed for trace metals. Results are summarised in Table 10.1.2. The last row of the table shows the trigger concentrations (mg/kg air dried soil) identified by ICRCL (1987) as the threshold of these contaminants for parks, playing fields and open spaces. The treatment plane site may therefore be regarded as uncontaminated with respect to the trace metals sampled.

Table 10.1.2 Trace metal analyses for treatment plane soil at Brogborough

Sample	Cr (ppm)	Cd (ppm)	Pb (ppm)	Zn (ppm)	Cu (ppm)	Ni (ppm)	Kjeldahl nitrogen
S029201	23	1.4	22	44	13	34	970
S029202	24	1.7	17	53	17	34	810
S029203	26	2.0	21	54	20	36	1020
S029204	25	1.6	26	45	15	36	1150
S029205	20	1.5	25	53	19	36	310
S029206	28	1.4	19	53	16	39	1200
S029207	34	1.7	25	66	28	38	820
S029208	21	1.7	19	68	16	37	1070
S029209	26	1.3	22	52	16	39	960
ICRCL	1000	15	2000	300	130	70	

10.1.4 Vegetation

In the past, large amounts of PVA glue waste and lesser amounts of sewage sludge have been applied to the treatment plane, but apart from this natural vegetation has been allowed to establish without interference. Table 10.1.3 lists the most common species present in the spring of 1992. The vegetative cover is very well established over most of the treatment plane. Partly as a result of this there is little evidence of soil erosion, except at the lower end of the plane where the returning flows of run-off congregate into a channel immediately before returning to the lagoon.

Table 10.1.3 Plant species found on the Brogborough treatment plane

Species	**Common name**
Agrostis stolonifera	Creeping bent
Alopecurus geniculatus	Marsh/Floating fox tail
Atriplex patula	Common orache
Ayropyron repens	Couch/Twitch
Ballota nigra	Black horehound
Bromus mollis	Soft Brome/Lop grass
Calamagrostis epigejos	Wood small reed
Cardus tenuiflorus	Slender headed thistle
Chrysanthemum leucanthemum	Ox-eye/Dog daisy
Dactylis glomerata	Cocksfoot
Daucus carota	Wild carrot
Dipsacus fullonum	Fullers' teasel
Epilobium hirsutum	Great willow herb
Festuca arundinacea	Tall fescue
Festuca pratensis	Meadow fescue
Galium uliginosum	Fen bedstraw
Geranium dissectum	Cut-leaved Cranesbill
Holcus lanatus	Yorkshire fog
Juncus acutus	Sharp rush
Juncus inflexus	Hard rush
Picris echioides	Bristley Ox-tongue
Plantago lanceolata	Ribwort
Ranunculus repens	Creeping Buttercup
Reseda luteola	Dyers' rocket / weld
Rosa canina	Dog rose
Rubus sp.	Blackberry
Rumex hydrolapathum	Water dock
Scrophularia nodosa	Figwort
Senecio jacobaea	Ragwort
Solanum dulcamara	Bittersweet/Woody nightshade
Sonchus oleraceus	Milk/Sow thistle
Tussilago farfara	Coltsfoot
Typha latifolia	Great reedmace/bullrush
Urtica dioica	Stinging nettle

10.1.5 Leachate Treatment data

In order to obtain a complete picture of leachate treatment at Brogborough several pieces of information are required:

- Leachate analyses - pH, Biochemical Oxygen Demand (BOD), Chemical Oxygen Demand (COD), Chloride (Cl^-), Sodium (Na^+), Ammonia (NH_3), Nitrate (NO_3^-) and Nitrite (NO_2^-).

- Volumetric data - daily volume in recirculation lagoon, pumping rate & irrigation schedule, additions to and discharges from the recirculation lagoon.
- Climatic data - rainfall and evapotranspiration, air temperature.

All chemical analyses were carried out at Shanks & McEwans' Central Laboratory. Other analysis was performed at Silsoe College. The volumetric data proved difficult to collect for a number of reasons. A V-notch weir at the entrance to the recirculation lagoon proved to be an unreliable method of measuring flow into the lagoon. The channel leading to the weir was badly eroded in periods of high rainfall and the whole area surrounding the lagoon was unstable. A sight board was erected in the lagoon itself to allow the site staff to take a daily depth reading. Daily readings were not always possible, however, due to staff shortages. In times of high rainfall the treatment plane area became practically inaccessible, so no readings or samples were taken. For much of the time the volumetric data was extremely patchy and this led to difficulties with interpretation.

Climatic data for the site was not available so data from nearby Woburn was used.

10.1.6 Results

During 1992 raw leachate and leachate from the recirculation lagoon was analysed for up to 12 determinands. Unfortunately, no reliable volumetric data is available for this year so we are unable to draw any firm conclusions about treatment efficiency. Towards the end of 1992, high rainfall meant that the lagoons became inaccessible. Therefore sampling was resumed in early 1993 when conditions improved. During 1993 a more limited analysis suite was employed and further attempts were made to obtain volumetric and climatic data. Chemical data for the raw and recirculation lagoons for 1992 and 1993 are presented in Table 10.1.4 and 10.1.5 resepctively. Due to the lack of volumetric data and uncertainty about the area of the treatment plane in contact with the leachate it is impossible to calculate an accurate hydraulic loading rate. The estimated average hourly pumping rate is 30m^3 and irrigation usually continues for 24 hours per day Based on an estimated treatment plane area actually receiving leachate of 10000m^2, the estimated hydraulic loading rate is 72 l/m^2/d. During one week of monitoring, when a larger pump was in use, the estimated hydraulic loading rate was 200 l/m^2/d.

Table 10.1.4 Brogborough raw and recirculation lagoon leachate analyses 1992

	Raw Lagoon							Recirculation Lagoon						
Date	pH	COD	BOD	Cl^-	NH_3-N	NO_2-N	NO_3-N	pH	COD	BOD	Cl^-	NH_3-N	NO_2-N	NO_3-N
16/3	7.8	3800	610	2100	1236	0	279	8.5	180	8	190	27	0	6
27/4	5.4	11000	4500	320	16	0	4	8.4	280	11	290	0	0	0
5/5	7.4	6600	2200	2000	989	0	223	7.7	500	110	470	2	0	0
11/5	7.5	3200	2000	1800	824	0	186	7.7	420	81	460	4	0	1
19/5	7.3	6200	5800	1800	148	0	34	7.9	430	49	490	0	0	0
27/5	7.6	8200	3000	2000	989	0	223	7.7	420	70	500	1	0	0
1/6	7.2	3800	<200	690	264	0	60	8.9	260	14	390		0	
9/6	7.7	3900	910	2000	989	0	223	8.1	240	16	320	0	0	0
16/6	8.3	2400	290	1200	272	0	61	7.5	220	5	370		0	
24/6	7.8	2300	660	1400	313	0	71	7.4	310	33	510	5		1
29/6	8.1	3400	300	1600	371	0	84	7.8	1700	50	990	181		41
6/7		2700	400	1200	412	0	93		1500	110	980	91		20
13/7		6800	450	1300	420		95		1400	50	990	157		35
20/7		2600	540	1400	379		86		1900	130	1000	91		20
27/7		3200	400	1300	363		82		1100	50	870	124		28
3/8		3400	310	1500	173		39		1300	50	900	33		7
10/8		2800	430	1000	148		34	7.9	1400	40	770	124		28
17/8		2200	220	1300	321		73		790	79	680	63		14
24/8		1900	260	1200	222		50		800	20	670	57		13
1/9		2300	290	1300	297		67		1100	8.5	780	69		16
7/9		2600	300	1000	313		71		1100	50	790	91		20
21/9		1900	730	870	297		67		1000	200	880	132		30
29/9		2200	100	450	132		30		320	<0.5	390	35		8
8/10		390	47	360	15		3		360	30	480	2		0
14/10		730	70	400	54		12		610	18	450	15		3
3/11		2200	1100	350	63		14		200	4	280	3		1

Table 10.1.5 Brogborough raw and recirculation lagoon leachate analyses 1993

	Raw Lagoon					Recirculation Lagoon				
Date	pH	COD	Cl^-	NH_3-N	NO_3-N	pH	COD	Cl^-	NH_3-N	NO_3-N
13/7	8.26	860	990	297	10	8.11	270	420	1	5
19/7	8.14	934	860	247	3	7.96	250	340	1	16
26/7	8.12	1800	1055	391	0	8.09	287	460	1	2
2/8	8.13	1200	1230	396	13	8.31	740	430	89	3
9/8	8.11	1200	1240	474	9	7.76	435	505	33	3
16/8	8.3	1620	1050	445	11	7.99	330	560	1	2
23/8	8.29	1200	1280	371	2	8.05	710	780	91	9
1/9	8.56	1400	1470	371	7	8.36	1670	340	461	8
6/9	7.48	2270	1560	428	1	7.7	1040	970	19	16
13/9	7.63	3800	2030	1549	1	7.65	460	775	1	4
21/9	7.62	3690	2100	1557	0	7.76	370	730	2	1
28/9	8.22	2920	1960	1030	0	8.02	380	720	2	0
7/10	8.49	2011	1500	585	2	8.31	222	505	1	0
25/10	8.03	1750	1450	511	0	7.87	170	390	1	0
4/11	8.16	2020	1555	577	5	7.81	175	400	1	0
23/11	7.95	2300	1650	750	4	7.47	310	390	25	5
29/11	8.07	2400	1570	816	0	7.77	210	390	20	2
6/12	7.93	2140	1410	742	10	7.86	190	430	3	5
13/12	7.95	3050	1480	824	0	7.82	150	330	1	4

10.1.7 Comment on the Brogborough treatment data

It was intended that the Brogborough data would be compared to the data from the Silsoe College experiments. Unfortunately, the operation of the Brogborough lagoons and treatment plane made such comparison difficult. The system for making leachate additions to lagoons is managed by operational staff on an *ad hoc* basis. This made it very difficult to identify when leachate transfers occurred, what volumes and concentrations were involved and as such reasons why leachate concentrations may have changed. The difficulties associated with interpreting the available data coupled with serious flooding of the treatment plane and lagoon system in the Autumn/Winter of 1993 prompted the decision to abandon the data collection exercise at Brogborough and to seek an alternative site from which to gather information.

Despite the limitations of the treatment plane monitoring exercise, some patterns of leachate quality fluctuation in the raw and recirculation lagoons can be identified.

Raw lagoon quality fluctuated considerably in 1992 but less so in 1993. These fluctuations may be explained by inputs to the raw lagoon from different sources: leachate from different parts of the site, condensate from the gas wells (high organic acid content but low NH_3-N content) and possibly ingress of surface water. Subsequent to the 1992 findings, condensate was recirculated into the fill and this may explain the stability of the 1993 data.

The recirculation lagoon data demonstrate fluctuations commensurate with successful batch treatment. However, as it is impossible to delineate the times at which batch treatment began and finished, if additions were made to the lagoon "mid-way" through a batch, and confusion associated with condensate additions, conclusions regarding treatment efficiency remain tentative. Despite these problems of interpretation, it is apparent from the NH_3-N data that the treatment plane system is capable of achieving considerable quality improvements. For example, during the 2 week periods 2/8/93 - 16/8/93 and 1/9/93 - 13/9/93, NH_3-N concentrations fell from 89 mg/l to 1 mg/l and from 491 mg/l to 1 mg/l respectively.

The Brogborough leachate is different to the leachate used on the Silsoe College trials in terms of its NO_2-N content. The Brogborough leachate contains no NO_2-N whereas the Calvert leachate contained significant quantities thus no comparison can be made for NO_2-N removal. During the monitoring period, NO_3-N concentrations in the raw lagoon fell from up to 270 mg/l to 10 mg/l or less. During 1992 when NO_3-N concentrations in the raw lagoon were highest, NO_3-N concentrations in the recirculation lagoon were low. This finding supports the Silsoe College experience that removal of NH_3-N does not lead to significant production of NO_3-N and suggests that in this case, NO_3-N removal (perhaps through plant uptake or denitrification) is occurring.

10.1.8 Costings for the Brogborough treatment plane

Estimated costs associated with the construction and running of the Brogborough treatment plane are set out below:

Table 10.1.6 Costings for the Brogborough treatment plane

Construction costs	**£**
Lagoon construction	5670
Ditch construction	2550
Fencing	1150
Access road	1350
Flow meters	1000
Pumps and pipes	8250
Miscellaneous	1200
Sub total	**21170**
Running costs (annual)	
Equipment maintenance	1500
Labour (5 hr / week)	2500
Sampling	4500
Fuel (140 l/d)	6370
Management	720
Sub total	**15500**

10.2 CALVERT LANDFILL SITE

10.2.1 Site Background

The Calvert landfill site occupies an area of more than 120 hectares and, like the Brogborough site, utilises voids left by the brick making industry. Landfilling operations began in 1980. The waste is transported mainly by rail from other counties and by road from Bucks. Almost 70% is domestic waste. By the start of 1994 some 7.5 million m^3 had already been filled and filling continues at a rate of 0.5 million m^3 per year.

10.2.2 Leachate treatment

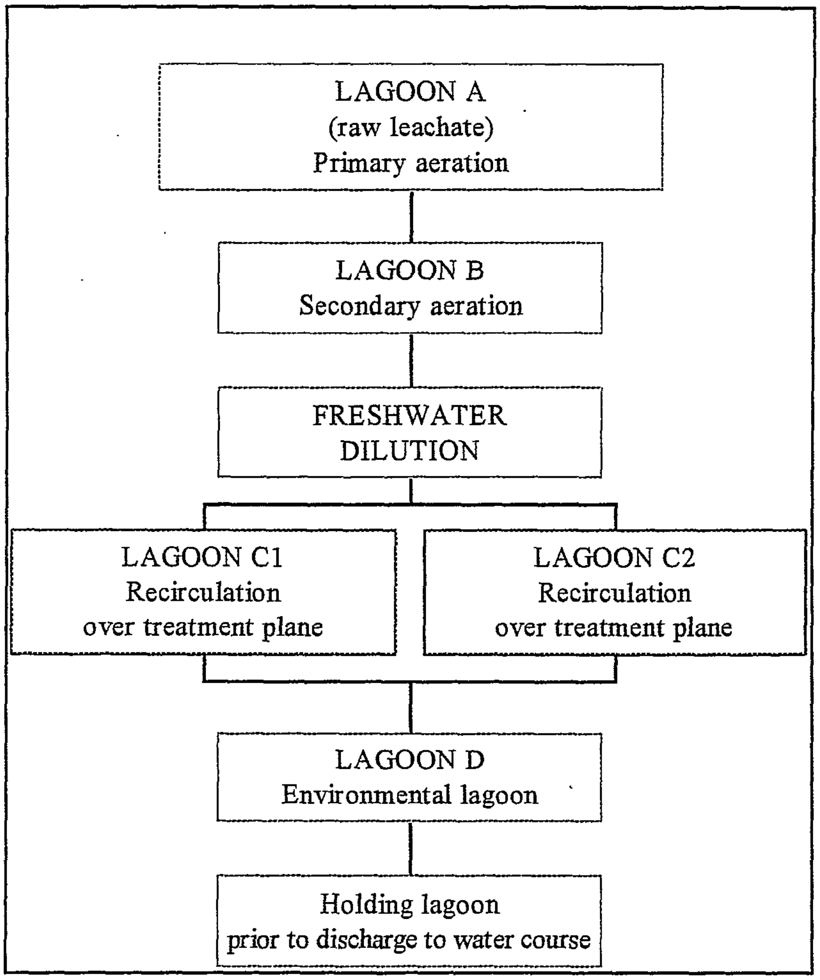
Typical chemical values for raw Calvert leachate are given in Table 10.2.1

Table 10.2.1 Raw leachate quality at Calvert

pH	6.9 - 8.42
Chemical Oxygen Demand	1780 - 5000 mg/l
Biochemical Oxygen Demand	85 - 770 mg/l
Chloride	1720 - 6020 mg/l
Ammoniacal-N	600 - 2000 mg/l

The leachate undergoes a multi-stage treatment process prior to discharge. The leachate is actively abstracted from the filled area by automatically operated pumps sited in the gas collection wells. The leachate is batched into a series of approxomately 1000m^3 capacity aeration lagoons where it is aerated until it reaches <20 mg/l BOD and <100 mg/l NH_3-N. for around ten days. At the second treatment stage small batches (approx.300m^3) of the aerated leachate are transferred to another lagoon where they are diluted at a ratio of 9:1 (water/leachate) using collected rainwater. Thirdly, the leachate is circulated over the treatment plane for approximately two weeks. Finally, to encourage the settlement of suspended solids, the leachate is moved to the 'Environmental' lagoon. The leachate is polished as it passes through an area of reeds and then into a holding lagoon, stocked with fish, where it flows over a weir into the Claydon Brook. On average the site discharges treated leachate once a month, depending on climatic conditions. At present the Calvert Landfill Site extracts and treats 6900m^3 of raw leachate per year. The treatment sequence is outlined in Fig. 10.2.1.

Fig. 10.2.1 The treatment process at Calvert



10.2.3 Treatment plane characteristics

The treatment planes consists of waste clay material (callow), unsuitable for brick making, which was excavated from elsewhere on the site and stored in this area. When landfilling operations began the callow stockpiles were roughly contoured to form a treatment plane of 3.7 ha area and with a range of shallow and relatively steep slopes (approximately 10-30%). A mixture of grass seed was sown at this stage but there has been no other management of the vegetative cover since. As a result a wide range of species thrive on the treatment plane, much like the situation at Brogborough. No work has been carried out on soil properties at the Calvert site.

10.2.4 Leachate treatment data

Table10.2.2 follows a batch of leachate through the treatment sequence at Calvert.

Table 10.2.2 Leachate quality within the Calvert treatment system

Leachate status	pH	NH_3	Cl-
Raw	8.42	650	3700
Post-aeration	8.69	200	1700
Post-dilution	8.13	8	220

NB. Batch recirculated for three weeks prior to transfer to environmental lagoon. No information available on quality after leaving treatment plane.

10.2.5 Comment

The investigation at Calvert did not provide the information desired on treatment plane efficiency. This is because the principal treatment process at the Calvert landfill site is aeration. The majority of the BOD and NH_3-N is removed by this process. Subsequent to aeration, the leachate is diluted. Dilution of landfill leachate is often required to meet chloride discharge consent conditions. Pre-treatment plane dilution is conducted at Calvert in order to protect the treatment plane grass from the effects of high salinity. Thus, NH_3-N concentrations are already low prior to application onto the treatment plane. There is considerable expenditure associated with pumping leachate onto the treatment plane. The same 'treatment effect' could be achieved by a slightly higher dilution or by a slightly longer period of aeration. There seems to be little justification for the current sequence of treatment steps.

The broader issue of dilution should be raised. As previously stated, dilution is nearly always be required at some stage in the leachate treatment process to bring chloride concentrations down to acceptable levels. However, should dilution be before or after the treatment plane? Pre-treatment plane dilution is not desirable in terms of the efficiency of ammonia removal as the Silsoe research has demonstrated that the treatment plane is relatively inefficient at low NH_3-N concentrations. In addition, pre-treatment plane dilution means that much money is spent in pumping freshwater around rather than leachate. The only justification for some degree of pre-treatment plane dilution is to ensure that treatment plane vegetation is not adversely affected by salinity. However, even this reason has been questioned by the Silsoe College research. Further research into grass health under conditions of intermittently applied full-strength leachate is recommended.