Environmental RTDI Programme 2000–2006

An Investigation into the Performance of Subsoils and Stratified Sand Filters for the Treatment of Wastewater from On-site Systems

(2001-MS-15-M1)

Synthesis Report

Prepared for the Environmental Protection Agency

by

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Executive Summary

The safe disposal of on-site wastewater is essential for the protection of groundwater in Ireland and has come more into focus recently due to the publication of the EPA guidance manual *Treatment Systems for Single Houses*. This project reports the results from four separate field trials carried out on separate sites covering a range of different subsoil types, whereby two sites were discharging septic tank effluent into conventional percolation areas and the other two sites were discharging secondary treated effluent from a peat filter into similar percolation areas. Stratified sand filters were also constructed, one receiving septic tank effluent, the other receiving secondary treated effluent for comparison. The short duration of the research (the maximum amount of time that each site was monitored was 12 months) and the limited numbers of sites investigated mean that only tentative conclusions can be made about on-site wastewater treatment at this stage which will hopefully be corroborated by further research in the future.

The project showed that the 1.2 m of unsaturated subsoil receiving septic tank effluent (or 0.6 m for secondary treated effluent), as specified in the guidelines, provided good removal of both chemical and microbiological pollutants. The majority of degradation of septic tank effluent occurred in the first 300 mm below the percolation trenches and the quality of the percolating effluent after 1.0 m depth was found to be acceptable for discharge to groundwater. There was a much better removal of nitrogen in the subsoil from the septic tank effluent than from the secondary treated effluent which remained largely untouched in its nitrified form of nitrate. Phosphate removal on the sites seemed to depend mainly on the mineralogy of the subsoil.

The project also showed that the biomat development seemed to be a function of the organic load applied to the subsoil. The sites receiving secondary treated effluent (having a much lower load) did not develop any significant biomat over the duration of the project and resulted in a more concentrated plume of effluent loaded onto the front of the trenches. The biomat seemed to regulate the hydraulic capacity of the subsoil and no discernible difference could be made with regards to treatment performance between subsoils of different permeabilities.

The results from the two stratified sand filters showed that each treated their respective effluents to just as high quality as an equivalent percolation area. However, when the sand filter is used as a secondary filter (to treat the septic tank effluent) it should be designed for a hydraulic loading of no more than 30 l/m^2 per day whereas, when used as a polishing filter (to treat secondary effluent), it can be designed for a hydraulic loading up to 60 l/m^2 per day. Both filters also showed excellent removal of phosphorus which was attributed to the mineral content of the type of sand used in their construction.

Finally, the project showed that domestic water consumption was much lower than the 180 litres per capita per day (lcd) forecast and that a figure of 150 lcd would seem to be more reasonable for on-site treatment in Ireland.

1 Introduction

In Ireland, wastewater from over one-third of the population is treated by small-scale on-site systems where connection to a sewer is deemed to be unfeasible, usually in rural areas (DoELG *et al*., 1999). The most prevalent treatment application is the conventional septic tank system with over 350,000 systems currently installed in Ireland (EPA, 2000). Due to the ever-increasing pressure on the planning authorities to develop more rural sites, a rigorous site assessment procedure has been introduced according to guidelines from the Environmental Protection Agency (EPA, 2000). This procedure consists of a desk study followed by an on-site assessment which aims to determine the vulnerability of local groundwater resources. In situations where a septic tank installation is not suitable, some form of secondary treatment system such as a mechanically aerated system or filter system may be installed to improve the quality of the effluent before discharge to the subsoil, if ground conditions allow.

1.1 Background

Groundwater is an important resource in Ireland which is under increasing risk from human activities with contamination arising from both 'diffuse' (generally agricultural) and 'point sources', the latter being exemplified by farmyards (manure and silage storage) and septic tank systems (Daly, 1993). The main aquifers occur in fissured or fractured bedrock formations, overlain by superficial deposits (referred to as subsoils in Ireland) of variable thickness and permeability. In areas where the subsoil permeability is too low to allow sufficient soakage, there is a risk to surface watercourses from effluent ponding. Alternatively, groundwater is especially at risk in areas where bedrock is close to the surface, and/or where subsoils of high permeability underlie the site, and where the water table is close to the surface. The permeability governs the transmission rate of a fluid through the subsoil, and hence the period in which attenuation of contaminants can take place by physical, chemical and/or biological processes. With an estimated 200,000 wells and springs in use in Ireland (Wright, 1999) the prevention of groundwater contamination from on-site domestic sewage effluent is of critical importance as, once contaminated, the consequences are usually longer lasting than for surface water owing to longer residence times; moreover, groundwater remediation is usually expensive and often practically impossible.

The publication of the guidance manual *Treatment Systems for Single Houses* (EPA, 2000) is aimed at protecting groundwater resources from contamination by domestic wastewater effluent by defining acceptable site suitability criteria. Key to this approach is an intensive site assessment procedure. This assessment, comprised of a desk study followed by an on-site visual trial hole inspection and percolation test, determines both the vulnerability of local groundwater resources and also the assimilation capacity of the subsoil. It is recommended that the percolation rate obtained from the standard percolation test (the so-called T-value) for subsoils receiving septic tank wastewater effluent must fall within the specified range of 1–50. In addition, there should be a minimum unsaturated subsoil depth of 1.2 m below septic tank percolation fields before the site may be deemed suitable for on-site treatment of domestic wastewater. Where subsoil T-values fall outside the range 1–50, or the minimum unsaturated subsoil depth of 1.2 m does not exist, a second percolation test (the P-test) should be carried out from ground level. If the resulting P-value is in the range 1–50, then the guidance manual suggests the installation of some form of secondary treatment process, providing that there is 0.6 m of unsaturated subsoil for percolation of the secondary effluent (SE). These small-scale treatment systems provide secondary treatment aerobic degradation either by fixed film or suspended growth microbial processes. Another option promoted in the guidelines is the use of an intermittent stratified sand filter either as a secondary treatment unit or as a polishing filter in place of the percolation area.

This document represents the results of a 3-year research study funded by the EPA (under the Environmental Research Technological Development and Innovation (ERTDI) Programme as part of the National Development Plan 2000–2006) into the effectiveness of both septic tank and secondary treatment on-site wastewater systems on four sites in Ireland designed according to the *Treatment Systems for Single Houses* guidelines (EPA, 2000). The results of this study should enable the current EPA policy, as set out in the guidelines, to be evaluated and more confident engineering design parameters to be developed for the overall enhancement of groundwater protection in Ireland. This synthesis report is only able to provide a brief summary of the project. For more detailed information, the main report consisting of two documents, the Literature Review and MS-15 project report (EPA, 2004a,b), are available for download from the EPA website.

1.2 Project Aims and Objectives

The aim of the research project was to carry out a series of rigorous on-site trials in order to enhance the understanding of the processes involved and the performance of different subsoils in the wastewater treatment of typical domestic effluent from septic tanks and other small-scale secondary treatment applications. The project also studied the potential application of the stratified sand filter process for the treatment of such effluents.

Specifically, the trials were designed to assess the following parameters:

- the hydraulic and wastewater treatment performance of subsoils receiving septic tank effluent (STE): one trial on a subsoil with a T-value 1–20 and one trial on a subsoil with a T-value 30–50;
- the hydraulic and wastewater treatment performance of subsoils receiving secondary treated effluent: one trial on a subsoil with a T-value of less than 50 and one trial on a subsoil with a T-value greater than 50;
- the hydraulic and wastewater treatment performance of two stratified sand filters: one receiving effluent from a septic tank, the other receiving effluent from a typical secondary treatment process.

2 Site Selection

2.1 Site Selection Criteria

A number of essential criteria had to be satisfied during the site selection process in order for the four sites eventually selected to be deemed suitable. T-values of between 1 and 20, 30 and 50, and greater than 50 had to be identified, site location and trial hole inspections had to satisfy EPA (2000) guidelines, and there had to be a sufficient number of residents in each dwelling to ensure that at least four 20-m long percolation trenches could be used.

2.1.1 Desk study

A desk study was carried out for each site to obtain hydrogeological data relevant to assessing site suitability and to identify potential water resource targets at risk from the proposed installation of an on-site treatment system. Information on the subsoil type, bedrock type, aquifer category and vulnerability class was obtained as part of the Groundwater Protection Scheme (GWPS) framework which was used in conjunction with the Groundwater Protection Response Matrix for Single House Systems (DoELG, 1999).

2.1.2 On-site assessment

Trial hole

A trial hole was excavated to ensure that there was a sufficient depth of unsaturated subsoil below the invert of the percolation trench (set at a depth of 0.8 m from the surface) along its full length as shown in Fig. 2.1. For the purposes of this research project, it was decided to establish all four sites on 1.2 m unsaturated subsoil in order to make direct comparisons between effluent types and subsoil characteristics. The soil and subsoil characteristics were also examined in the trial hole as part of this integrated approach of on-site assessment and were described primarily on the basis of their material characteristics according to BS 5930, the British Standard Code of Practice for Site Investigations (BSI, 1981).

T-test

The T-test was used to ascertain the suitability of a subsoil to receive on-site wastewater effluent. It determines an average time for water to drop 25 mm in two pre-soaked, 300-mm square holes, 400 mm deep below the invert level of the percolation pipe, therefore giving an indication of the hydraulic assimilation capacity of the subsoil

Figure 2.1. Trial hole on Site 1.

surrounding the base of the percolation trench under saturated conditions.

2.2 Test Sites

A total of 74 sites were investigated over the course of the project in order to find the four sites that eventually satisfied the site selection criteria, i.e. 2 m unsaturated subsoil with a T-value of 1–52. This shows that only 5.41% of the sites would have been deemed suitable for the standard septic tank system with percolation trenches set at 0.8 m depths. The most common reason for site rejection was the presence of a high water table. In some of these cases, it may have been possible, according to the EPA guidelines, to raise the level of the percolation pipe to provide 1.2 m unsaturated subsoil beneath the base of the trench. However, these sites were not considered for the project since they would have involved raised mounds over the trenches which it was considered would not have been acceptable to the house owners.

The four suitable sites that were identified (two in County Kildare and two in County Wicklow) were all located in undeveloped areas and so it was possible to construct four new on-site treatment systems in undisturbed subsoil. The main features of the four trial sites are presented in Table 2.1.

2.2.1 *Site 1: The Curragh (T-value =15)*

Site 1 (27890 E, 21290 N) lies within a region of soil described as the Athy Complex (Conroy *et al.*, 1970). The parent material of these soils consists of calcareous, fluvioglacial coarse gravels and sands of Weichsel Age composed mainly of limestone with a small proportion of sandstone, schist, shale and conglomerate. On inspection of the trial hole, the subsoil below 0.8 m was classified as sandy CLAY (w/silt) interspersed with rounded cobbles (Fig. 2.1). Macropores, cracks and voids around some cobbles were also noticed. On initiation of the project, there were four adults resident at Site 1. However, this number fluctuated throughout the year with two females, an elderly lady and her carer, leaving in February to be replaced by two males. There is also a livery stable attached to the house in which three people were employed during the day.

2.2.2 *Site 2: Rochestown (T-value =29)*

Rochestown (28890 E, 20860 N) lies within a region of grey–brown podzolic soil described as the Elton Series which occurs most extensively in the northern and eastern portions of County Kildare (Conroy *et al.*, 1970) and is derived from predominantly limestone drift with a small admixture of shale and sandstone. The subsoil profile examined in the trial hole below the invert level of the distribution trench from 0.8 m down to 2.0 m was characterised as sandy CLAY (w/silt). However, the soil sample taken at 1.5 m had substantially lower fines content compared to the samples taken at 1.0 m and 2.0 m, indicative of a layer of greater permeability. The site contained a recently renovated cottage which had no form of on-site treatment system installed and the surface run-off and domestic effluent were discharged into a cess pit. For the duration of the project, there were five people resident at Site 2, a husband and wife, their daughter and two sons. The father ran a business from the premises and the mother worked away from home during the day.

2.2.3 *Site 3: Three Wells (T-value =33)*

Three Wells (31430 E, 18160 N) lies within a region of Lower Palaeozoic sandstone and shale till known as the Ribband Group and consists of mudstones, siltstones, quartzites and volcanic rocks (GSI, 2003). Site 3 was an elevated site on the side of a hill above the valley at 205 m AOD (Above Ordnance Datum). The subsoil profile for all three samples taken at depths of 1.0 m, 1.5 m and 2.0 m was characterised as gravelly–clayey SAND interspersed with striated cobbles. The site was a recently constructed three-bedroomed bungalow on which the septic tank treatment system had yet to be installed. There were four people resident on the site, a mother and her three children. The youngest child was cared for at home by his mother whilst the other two children were in school.

Table 2.1. Summary of the four trial sites.

	No. of occupants	T-value	Monitoring period	Effluent type	Stratified sand filter
Site 1	4	15	June 2002 – July 2003	Septic tank	No
Site 2	5	29	June 2002 – July 2003	Secondary	No
Site 3	4	33	July 2003 – March 2004	Septic tank	Yes
Site 4	4	52	July 2003 – March 2004	Secondary	Yes

2.2.4 Site 4: Killaveny *(T-value =52)*

Located approximately 10.5 km south-west of Site 3 in the same valley, the subsoil at Site 4 (30680 E, 17390 N) was also part of the Maulin Formation of the Ribband Group, described as a till with Lower Palaeozoic schists, sandstones, greywackes and shales dominant (GSI, 2003). The site was located near to the floor of the valley at an elevation of approximately 90 m AOD. The classification of the exposed material in the trial hole revealed the subsoil below the percolation area to be gravelly–clayey SAND interspersed with gravel and rounded cobbles. There was a reduction in the silt content with depth and an increase in the gravel content. While the results of the particle size analysis alone would generally suggest a high permeability subsoil, the high density of the matrix resulted in a T-value of 52. A planning condition in relation to an extension on the Killaveny site required the upgrading of the existing domestic wastewater treatment system. Four people were resident at Site 4, a mother, father and their two children who were both of school age. The mother was a housewife while the father worked locally and returned home for lunch most days. Another daughter was in college and often returned home at weekends.

3 Site Construction, Instrumentation and Sampling

3.1 Introduction

The effluent from each system on Sites 1 and 2 was split equally (via a distribution box) between four parallel percolation trenches (Fig. 3.1). On Sites 3 and 4, the effluent was split at the distribution box whereby half was sent to two parallel percolation trenches and the other half diverted to a stratified sand filter constructed at the site (Fig. 3.2). Diversion works were necessary at Sites 1, 2 and 4 to separate surface run-off from the domestic wastewater network and thus prevent the former entering the septic tank. The secondary treatment system installed on Sites 2 and 4 was a Puraflo® system produced by Bord na Móna. Puraflo® is a peat-based biofiltration system for the treatment of septic tank effluent which is pumped onto a fibrous peat media contained in moulded polyethylene modules. In this project, the treated effluent was collected in a sump from where it flowed by gravity to the percolation trenches.

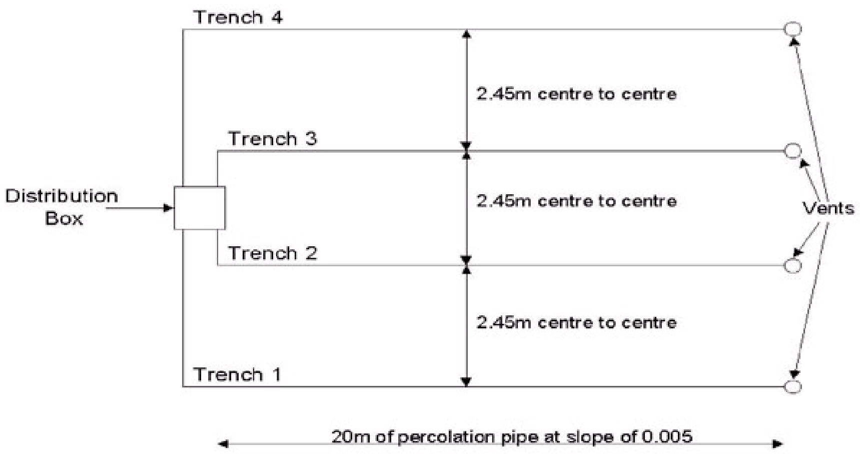

Figure 3.1. Plan of percolation area on Sites 1 and 2 (EPA, 2000).

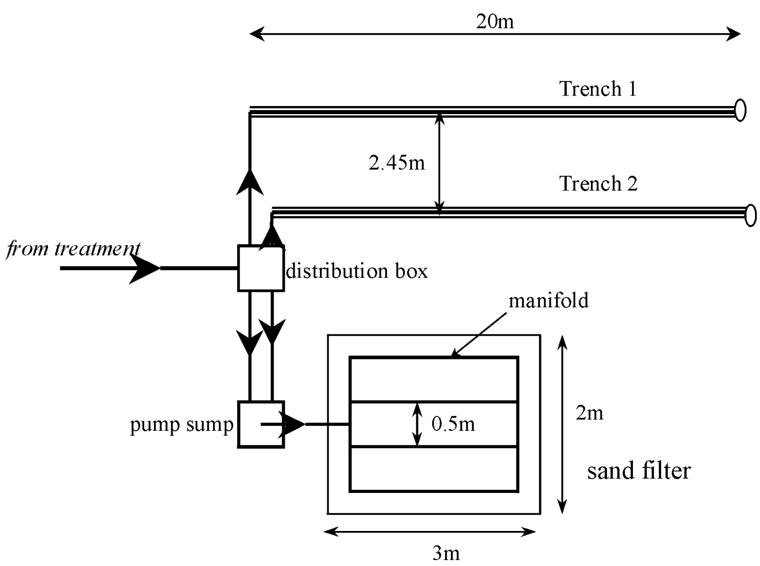

Figure 3.2. Plan of trenches and stratified sand filter on Sites 3 and 4.

3.2 Construction of Percolation Trenches

All sites required the construction of parallel percolation trenches of 20 m length, which were constructed strictly according to the recommendations specified by the EPA to promote even distribution of the effluent (EPA, 2000). The gravel was placed in the trench in two phases, an initial layer of 250 mm thickness as a distribution layer below the percolation pipe as shown in Fig. 3.3 and a subsequent 250 mm thick layer to protect the pipe. Prior to backfilling, a geotextile was placed over the second gravel layer to prevent fines being washed into the distribution gravel.

An equal loading rate on each trench was achieved within the distribution box. A short study indicated that the commercially available distribution boxes did not produce an even split over the four trenches and therefore a modification in the form of four V-notch weirs inserted into the inlet pipe was tested and optimised in the laboratory (see Fig. 3.4) before installation on all sites (Gill *et al.*, 2004). Regular inspection and cleaning were also carried out throughout the trial periods to ensure this even distribution.

Figure 3.3. Construction of percolation trench.

Figure 3.4. Distribution box with V-notch weir modifications in the laboratory.

3.3 Construction of Stratified Sand Filters

The stratified sand filters were designed to a hydraulic loading rate of 60 l/m^2 per day in accordance with the current EPA guidelines (EPA, 2000), which were based on an original design that had been tested in the USA (Nichols *et al.*, 1997). The plan area of each stratified sand filter (6 m^2), based on a design figure of half of the effluent from a four person house, was dimensioned to be 2 × 3 m to ensure compactness and promote even hydraulic distribution. In these trials, the effluent was allowed to percolate through the base of the sand filters into the subsoil at a depth of 1.05 m. The filters were constructed of alternate layers of sand and distribution gravel in as close accordance as possible to the original EPA guidelines although it was not possible to source the exact particle size characteristics from suppliers in Ireland. After a thorough search, the tightest specification to the guidelines (see Fig. 3.5) was eventually ordered from specialist water treatment filter sand suppliers in County Tyrone. This issue of availability of the raw material is important and should be considered in future design specifications. The effluent for the sand filter discharged by gravity into a concrete sump from where it was pumped into a pressurised manifold, as shown in Figs 3.6 and 3.7, which distributed it evenly over the surface area of the filter. The pump was operated by a float switch which could be adjusted to pump a known volume per cycle which also established the frequency of pumping events per day.

100 mm distribution gravel
200 mm COARSE SAND (0.5–1.0 mm); D_{10} = 0.55 mm
75 mm pea gravel (20–30 mm)
100 mm MEDIUM SAND (0.2–0.63 mm); D_{10} = 0.35 mm
75 mm pea gravel (20–30 mm)
200 mm FINE SAND (0.1–0.5 mm); D_{10} = 0.30 mm
250 mm pea gravel (20–30 mm)
50 mm medium sand (0.2–0.6 mm)

Figure 3.5. Schematic cross-section through stratified sand filter.

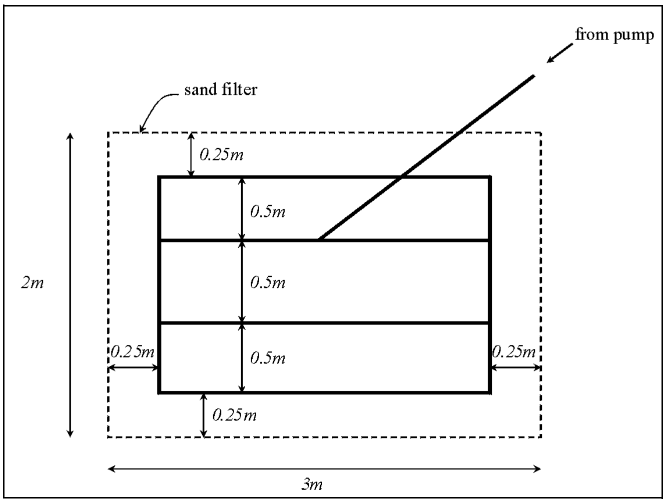

Figure 3.6. Dimensions of distribution manifold on top of sand filter (plan view).

Figure 3.7. Completed stratified sand filter on Site 4.

3.4 Instrumentation

3.4.1 Percolation area

Automatic samplers and flow monitors were installed downstream of the septic tanks and secondary treatment systems to obtain a profile of the effluent entering the percolation trenches (see Fig. 3.8). Nine suction lysimeters were installed along the length of the percolation trenches to obtain soil moisture samples for analysis for some of the characteristic constituents of domestic wastewater effluent. A vacuum is created within the lysimeter using a vacuum pump and moisture extracted from the soil matrix. The lysimeters were placed in groups of three at 10-m intervals, each trio consisting of different length lysimeters colour coordinated according to the depth below the trench invert, 0.3 m (red), 0.6 m (blue) and 1.0 m (black), as shown in Fig. 3.9.

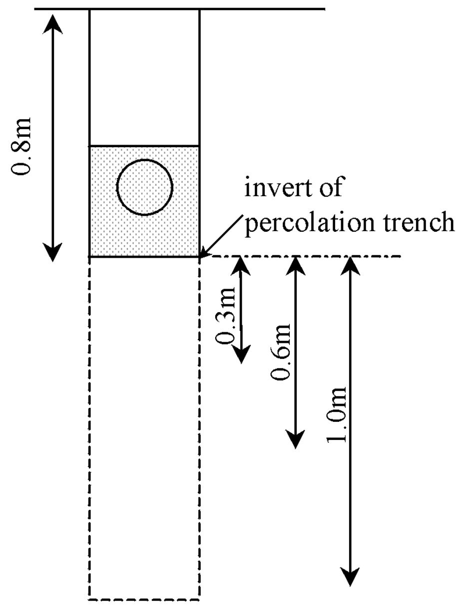

Figure 3.9. Cross-section and typical depths of instrumentation.

Tensiometers were also installed to monitor the soil moisture pressure below the percolation area and were installed in groups at the three different depths across the percolation area. The flow to the sites was measured by ultrasonic level detectors recording the change in effluent level within the sumps over 1-min time steps. Each site also had a tipping bucket rain gauge installed in the centre of the percolation areas.

3.4.2 Stratified sand filter instrumentation

Samples of effluent were taken within the stratified sand filter by means of gravity samplers which were positioned to intercept effluent coming from the three main sand layers, as indicated in Figs 3.10 and 3.11. Six suction lysimeters were also installed at the same red, blue and black depth profiles adjacent to each sand filter on the lower ground level sides of the sand filters in order to be down gradient of any slight groundwater direction. Finally, a piezometer was inserted into the middle of each sand filter in order to assess the depth of any effluent surcharge in the base of each sand filter.

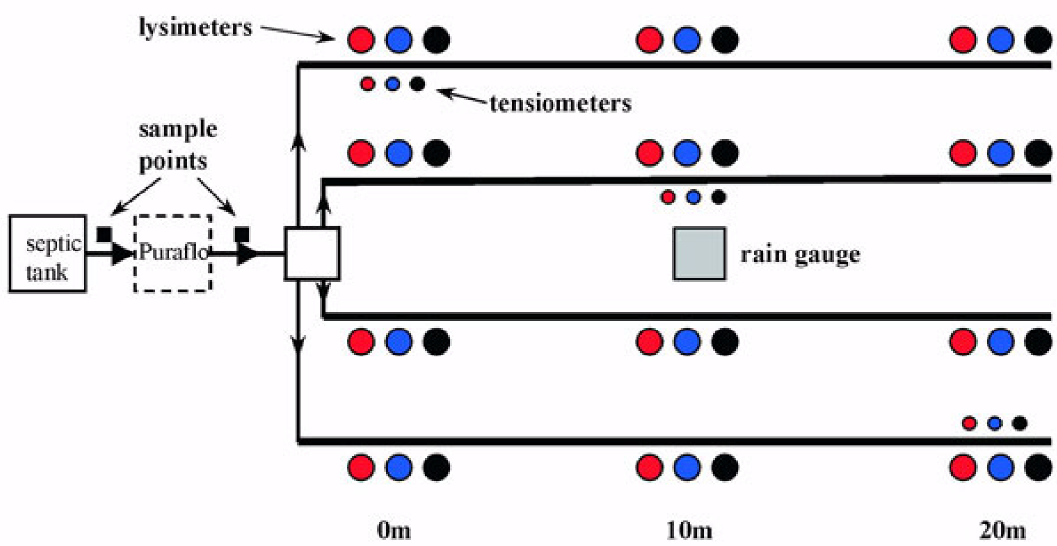

Figure 3.8. Schematic of instrumentation layout (Sites 1 and 2).

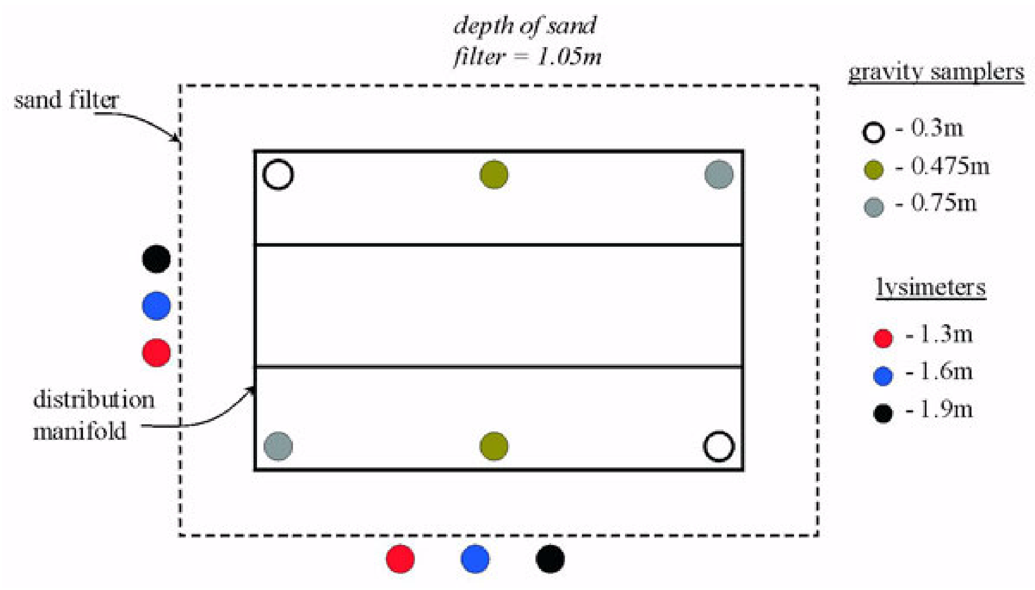

Figure 3.10. Plan view of filter indicating positions of sampling instrumentation (note: all depths expressed relative to ground level).

Figure 3.11. Installation of gravity samplers in sand filters.

3.5 Analysis Methodology

All septic tank, Puraflo®, soil moisture and sand filter samples were analysed for nitrate (NO_3-N), nitrite (NO_2-N), ammonium (NH_4-N), chemical oxygen demand (COD), *ortho*-phosphate (PO_4-P) and chloride (Cl) using a Merck Spectoquant Nova 60® spectrophotometer and associated reagent kits which are USEPA approved. During the sampling period, four duplicate sets of samples were also sent to CAL Ltd, an accredited laboratory in Dún Laoghaire, as a quality control measure. Several sets of bacteriological analyses were also carried out by CAL Ltd for indicator bacteria associated with faecal contamination during the project. All samples were analysed for total coliforms and *E. coli*, with analysis also carried out for enterococci, faecal streptococci and faecal coliforms on some occasions.

4 Analysis of Results Obtained from Site 1

4.1 Analysis of Flow Data

Installation of the septic tank and the percolation area was completed on 29 May 2002 and sampling began on 8 August, continuing through until 15 July 2003. The average flow on Site 1 was recorded as 418.8 l/day, which results in a consumption figure of 105 litres per capita per day (lcd). Although extensive separation works were carried out upstream of the septic tank during the installation period, it was discovered that a drain in the stable yard had been overlooked which received a small volume of surface run-off and hence the measured daily average domestic wastewater generation may slightly overestimate the real figure.

4.2 Results of Analysis of Septic Tank and Soil Moisture Samples

4.2.1 *Method of analysis*

As Cl does not take a significant part in any geochemical reactions (Marshall *et al.*, 1999), the results of the soil moisture sample analyses for Cl were used on all sites to identify differences in loading rates within the percolation area and thus determine the most representative method of reporting the attenuation of the percolating effluent. As is the case with the presentation of all the results of soil moisture samples, this method assumes homogeneous and isotropic subsoil properties and only takes account of matrix flow. The results of the laboratory analysis for Cl at the three sample positions along each trench, i.e. 0 m, 10 m and 20 m, were averaged over the depth plane on which they were recorded. This was then plotted over the research period to identify which of the following methods best represented the distribution of effluent within each percolation area:

1. **Planar Average**: this method involved the averaging, over the four trenches, of the concentrations of each parameter over the depth plane on which it was measured and comparing the difference between the 0.3 m, 0.6 m and 1.0 m depth planes.

2. **Depth Average**: the average concentration, over the four trenches, of each parameter within each plane was calculated at the three different sample distances along the length of the trenches and the corresponding differences in concentration between the planes compared.

When the average planar Cl concentrations at the three sample positions on the red plane were graphed, it showed that the planar average method was the more representative as little difference in the concentrations was observed between the three sample depths, as can be seen in Fig. 4.1. This was also confirmed by a tracer study carried out at the end of the trial period using a bromide solution.

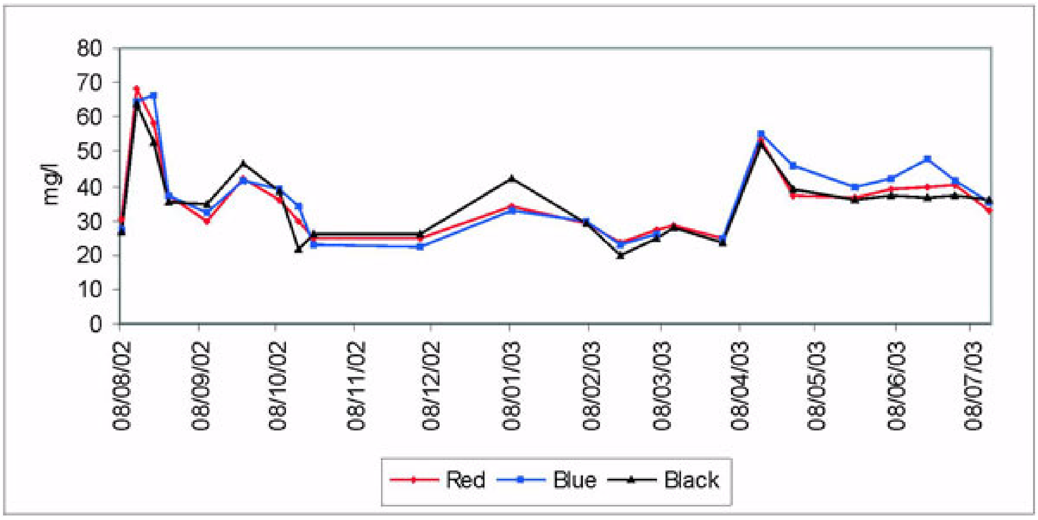

Figure 4.1. Planar average Cl concentrations.

During the project, it became apparent that the installation of certain lysimeters had not been successful and that samples taken at these points were not representative of matrix flow, but of preferential flow down the side of the lysimeters due to poor contact between the lysimeter and the subsoil. These sample points were therefore excluded from further chemical and biological analysis.

4.2.2 The effect of dilution on effluent attenuation

While the attenuation of the percolating effluent is mostly the result of physical, chemical and biological processes within the subsoil, the effects of dilution must also be considered. The rainfall available for dilution at the depth planes over the project duration, or effective rainfall, was calculated using rainfall figures obtained on site and evapotranspiration figures obtained from a meteorological station 3.5 km from Site 1. A model based on the FAO Penman-Monteith method (FAO, 1998) of potential evapotranspiration (PET) calculation was used to calculate actual evapotranspiration (AET). Where the soil moisture deficit (SMD) was greater than 40, the AET was considered to occur at a slower rate than PET and was therefore calculated using the Aslyng scale (Keane, 2001). Daily effective rainfall, or recharge, was then calculated by subtracting the daily AET and accumulated SMD figures from the daily rainfall measurement. Using this method it was found that, for a recorded rainfall of 852.8 mm for the period 1 August 2002 to 15 July 2003, the effective rainfall was 385.5 mm. PET was also calculated on all sites using the Hargreaves method which is applicable where only limited meteorological data are available (FAO, 1998). The Hargreaves effective rainfall value calculated for Site 1 was 372.5 mm proving very similar to the Penman-Monteith method.

The Cl concentrations were used as the basis for quantifying the contribution of effective rainfall to effluent dilution. The effect of dilution of the effluent by the rainfall, for example, can be seen from suppressed chloride concentrations during the period of sustained rainfall between November 2002 and March 2003 in Fig. 4.2. However, this reduction in Cl concentration is not entirely due to dilution as it also results from the effects of physical straining on the percolating effluent. This effect was quantified by examining the reduction in Cl concentration between the septic tank and the red depth plane over a period when the contribution of effective rainfall was zero, revealing an average reduction in Cl concentration of 27.1%. When the average Cl concentration for rainfall on Site 1 of 3.9 mg/l is taken into account, it was found that the effect of dilution was equivalent, on average, to the addition of 0.25 l/l (litres of effective rainfall per litre of effluent) (or 20.1% reduction in concentration) for the red depth plane, 0.32 l/l (or a 24.2% reduction in concentration) for the blue depth plane and 0.38 l/l (or 28.3% reduction in concentration) for the black depth plane.

When the average effective rainfall contribution for the red plane is calculated for the year it is found to be 38.22 m^3. By dividing this by the effective rainfall calculated by the Penman-Monteith method, it was possible to estimate that the zone of contribution of effective rainfall was 99.1 m^2.

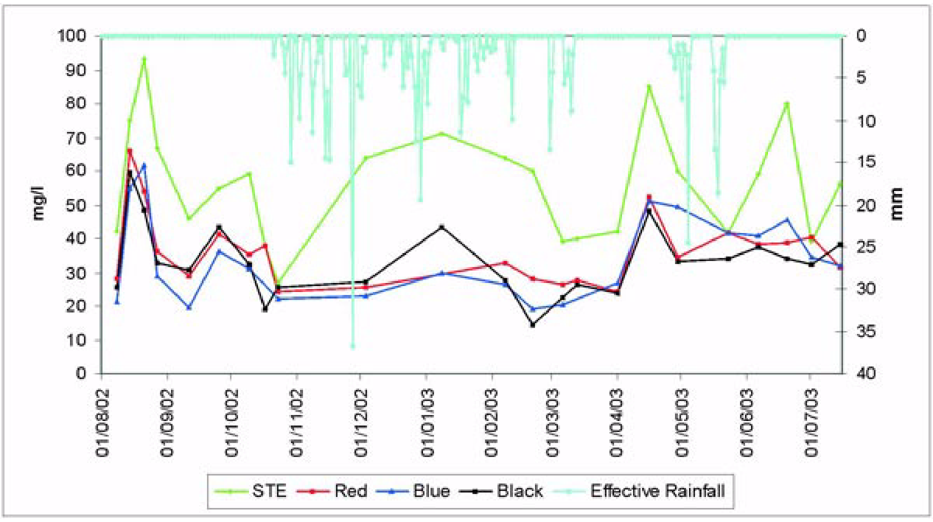

Figure 4.2. The effect of dilution by effective rainfall, calculated by the Penman-Monteith method, on Cl concentrations.

This equates to a zone of contribution of approximately 0.4 m on all sides of each trench taking the trench width of 0.45 m and an average trench length of 20 m. When the same calculations are carried out for the blue and black planes, it was found that the zone of contribution was slightly greater and appeared to extend in the region of 0.6–0.8 m on all sides of each percolation trench indicating the dispersion of the effluent plume below each percolation trench. Examination of the tensiometer readings at the sampling positions show that they follow the pattern of the more constantly percolating effluent than the sporadic contribution of effective rainfall. This corroborates the evidence of the dilution calculations and demonstrates that it is physical, chemical and biological processes rather than dilution that are the more prominent attenuation processes operating in the subsoil.

The STE had been distributed along the entire length of the percolation trenches, which would suggest that the organic load of the STE facilitated the formation of a biomat along the effluent subsoil interface, thereby promoting distribution along the base of the percolation trench. The presence of elevated Cl levels at the 10 m sample position throughout the project suggests that at the commencement of sampling, over 2 months after site commissioning, the biomat had already developed between the 0 m and 10 m sample positions. The presence of effluent was not recorded at the 20 m sample positions until a further 2 months although this did vary somewhat between trenches.

4.2.3 Results of chemical analysis

Table 4.1 summarises the results relating to the STE. The average organic concentrations in the STE (as indicated by the COD levels) were much lower than those measured on Sites 2, 3 and 4, which could be partly due to surface water infiltration and also the fact that due to the age of the house the toilet cisterns, baths, sinks, etc. were of much larger volume than in more contemporary houses on the other sites, thereby contributing to weaker effluent.

COD

The greatest reduction in effluent COD load and concentration in the percolation area occurred above the red depth plane (Table 4.2) and is attributed to aerobic processes within the distribution gravel in the percolation trenches, which are aerated along their full length by means of a ventilation pipe. The remaining reduction in COD concentration within the subsoil and incorporated biomat would result from a combination of further biological degradation, adsorption and physical straining.

Nitrogen

The greatest reduction in inorganic nitrogen loading was similarly recorded above the red depth plane (Table 4.3). The results suggest that the main nitrogen removal mechanism in the subsoil is nitrification followed by denitrification as can be seen in Fig. 4.3 where an increase in NO_3 concentrations in the subsoil from April 2003 corresponds with a period of minimal effective rainfall and also reduced hydraulic load from the house. The hydraulic load on the system throughout the year

Table 4.1. Summary of chemical analysis of STE on Site 1.

	Concentration (mg/l)					
	COD	**NO_3-N**	**NO_2-N**	**NH_4-N**	**PO_4-P**	**Cl**
Maximum	638.0	3.4	0.23	72.8	54.8	93.0
Minimum	188.0	0.0	0.08	20.3	5.2	27.0
Average	**383.4**	**0.7**	**0.16**	**53.0**	**14.2**	**56.6**

Table 4.2. Reduction in COD load attributed to the specific treatment steps.

	Concentration (mg/l)	Load (g/day)	Load Removal (g/day)
STE	383.4	160.6	–
Red depth plane (–0.3 m)	78.0	40.8	119.8
Blue depth plane (–0.6 m)	77.7	42.9	–2.1
Black depth plane (–1.0 m)	56.5	32.7	10.2

Table 4.3. Average concentration and loading rate of NO_3-N, NO_2-N, NH_4-N and total inorganic N measured in the STE and at the three depth planes.

	NO_3-N		NO_2-N		NH_4-N		Total N	
	Conc. (mg/l)	Load (g/day)	Conc. (mg/l)	Load (g/day)	Conc. (mg/l)	Load (g/day)	Conc. (mg/l)	Load (g/day)
STE	0.7	0.3	0.2	0.1	53.0	22.2	54.0	22.6
Red depth plane (–0.3 m)	4.1	2.1	0.2	0.1	9.9	6.5	14.5	8.8
Blue depth plane (–0.6 m)	6.8	3.8	0.3	0.2	5.1	2.8	12.0	6.6
Black depth plane (–1.0 m)	6.7	3.9	0.2	0.1	5.8	3.4	12.8	7.4

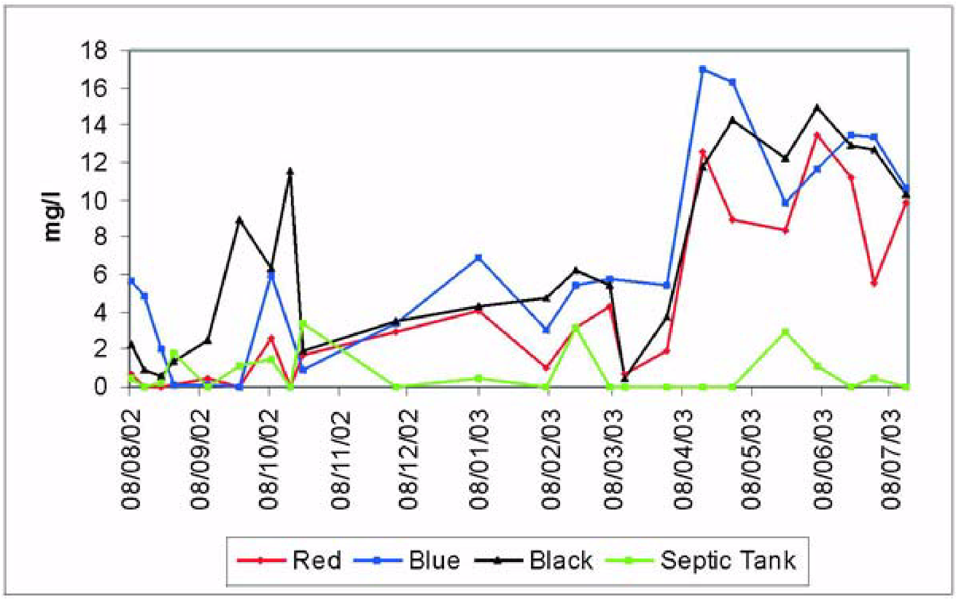

Figure 4.3. NO_3-N concentrations measured on Site 1.

probably promoted localised saturated conditions that facilitated denitrification of nitrified NH_4. However, the reduction in the hydraulic load from April 2003 would have reduced saturated conditions, thereby reducing the effect of denitrification resulting in the observed higher NO_3 concentrations in the percolating effluent. The intense biological activity in the biomat along the base of the trenches would also contribute to some of the reduction in inorganic nitrogen due to biological uptake for synthesis of nitrogen-containing cellular components.

Phosphorus

The *ortho*-PO_4 concentration of the STE varied throughout the year. The high clay content of the subsoil below the percolation area on Site 1 suggests that the removal of phosphate from the percolating effluent was controlled by soil adsorption. The large specific surface of clay particles, allied with the iron, aluminium and hydrous oxides coating the subsoil clay minerals and magnesium-hydroxy clusters on the weathered surfaces of ferromagnesium minerals provide excellent sorption sites. It can be seen from Table 4.4 that the greatest reduction in effluent *ortho*-PO_4 concentration and load occurred above the red depth plane during the project. It should also be noted there is still a significant *ortho*-PO_4 concentration at the black depth plane indicating a potential for groundwater pollution. It is important to note, for all the sites, that any given soil only has a limited capacity to fix phosphorus.

4.2.4 Results of bacteriological analysis

Table 4.5 presents the results of sample analysis for *E. coli* on four separate occasions over the research period. It should be noted that the minimum detection level of the bacterial concentrations was generally <10 cfu/100 ml due to the original sample undergoing a 1 in 10 dilution with distilled water before analysis.

Table 4.4. Reduction in *ortho*-PO_4-P attributed to the specific treatment steps.

	Concentration (mg/l)	Load	
		(g/day)	Removal (g/day)
STE	12.2	5.9	–
Red depth plane (–0.3 m)	2.2	1.2	4.7
Blue depth plane (–0.6 m)	1.2	0.7	0.5
Black depth plane (–1.0 m)	1.0	0.6	0.1

Table 4.5. Concentrations of *E. coli* measured on four separate occasions at Site 1.

	Number of samples	Number of samples with concentration (cfu/100 ml)			
		<10	10–100	101–1000	>1000
STE	4				4
Red depth plane (–0.3 m)	14	14			
Blue depth plane (–0.6 m)	9	7	1	1	
Black depth plane (–1.0 m)	11	9	1		1

The presence of *E. coli* on the black depth plane was confined to samples obtained from two specific sampling points early on. However, a reduction in bacterial concentration with time was evident with no *E. coli* found on the last two sampling days, 15 May 2003 and 28 August 2003. It is possible, therefore, that the initial high concentrations experienced may be due the presence of macropores that facilitated the initial movement of bacteria to the lysimeter porous cup but became blocked with time. If the results of bacteriological analysis for these two latter sample dates only are considered, it was found that almost complete removal of *E. coli* was achieved within the percolation area, apart from a single sample on the black plane on 28 August 2003 that detected 10 cfu/100 ml. It should be noted that a value of 10 cfu/100 ml actually equates to a single bacterium picked up in the sample analysis.

5 Analysis of Results Obtained from Site 2

5.1 Analysis of Flow Data

Installation of the septic tank and secondary treatment system was completed on 30 May 2002 and sampling began on 9 August and continued until 22 July 2003. The average flow measured over the research period was 281.7 l/day, which equates to 56.3 lcd. When the flow data are adjusted to take into account holiday periods, i.e. when the house was vacant, the daily average increases to 300.9 l/day equating to 60.2 lcd. No correlation between rainfall and septic tank effluent flow rate was found, which proved that the surface water separation works had been successful.

5.2 Results of the Analysis of Septic Tank and Secondary Effluent

Table 5.1 summarises the results relating to the STE, showing that the anaerobic environment of the septic tank facilitated the breakdown of organic nitrogen and phosphorus to their inorganic forms, NH_4-N and *ortho*-PO_4, respectively, which were the prevalent nutrient forms in the STE. The aerated environment of the secondary treatment system as seen in Table 5.2 promoted nitrification and the aerobic degradation of organic matter which, combined with the physical straining action of the bio-media, resulted in an effluent with a lower organic and higher nitrate concentration.

An overall and fairly consistent reduction in nitrogen loading was achieved by the secondary treatment over the research period as seen in Fig. 5.1. On average, there was a 51.6% reduction in inorganic-N loading across the secondary treatment system which was attributed predominantly to denitrification within the peat module, taking account of any subsequent mineralisation of organic nitrogen that might have occurred. The modifications to the design of the modules to enable the effluent to be gravity fed to the percolation trenches created slightly flooded conditions along the base of the module, thereby creating anoxic conditions in the base of the module, promoting denitrification.

The installation of a secondary treatment system on the site also greatly reduced the bacterial loading on the percolation area as highlighted by the results shown in Table 5.3. However, even when the removal efficiency of the secondary treatment system is taken into account, the high concentrations of bacteria in the SE still deem it unsuitable for discharge to groundwater prior to further treatment.

Table 5.1. Summary of chemical analysis of STE on Site 2.

	Concentration (mg/l)					
	COD	NO_3-N	NO_2-N	NH_4-N	PO_4-P	Cl
Maximum	1630.0	5.3	0.42	161.5	61.9	290.0
Minimum	484.0	0.0	0.00	98.8	19.3	74.1
Average	**791.6**	**1.4**	**0.28**	**131.0**	**32.3**	**117.8**

Table 5.2. Summary of the results of chemical analysis of SE on Site 2.

	Concentration (mg/l)					
	COD	NO_3-N	NO_2-N	NH_4-N	PO_4-P	Cl
Maximum	316.0	60.5	13.6	45.2	85.6	185.0
Minimum	98.0	15.3	0.8	6.9	16.8	51.3
Average	**188.1**	**36.9**	**7.4**	**19.7**	**33.6**	**92.6**

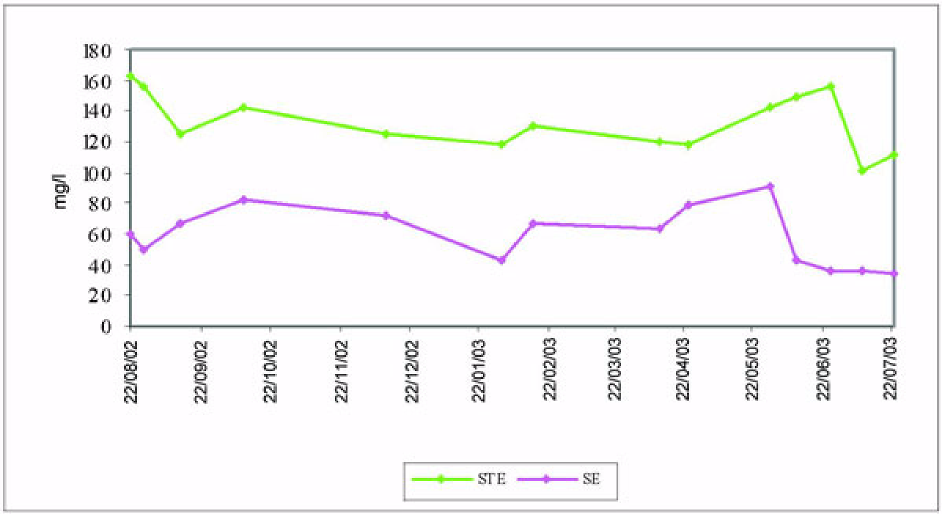

Figure 5.1. Reduction in total inorganic N concentration across the secondary treatment system.

Table 5.3. Example of the reduction in bacterial concentration of domestic wastewater effluent resulting from the installation of a Puraflo® system on Site 2.

Date	Bacteria	Effluent concentration (cfu/100 ml)		% Removal
		Septic tank	Puraflo® system	
15/05/2003	*E. coli*	397,260	4,320	98.91%
15/05/2003	Faecal coliforms	>486,840	17,200	>96.47%
28/08/2003	*E. coli*	1,416,600	5,040	99.99%
28/08/2003	Enterococci	238,200	600	99.99%
28/08/2003	Faecal coliforms	1,553,100	6,010	99.99%
28/08/2003	Total coliforms	>2,419,200	130,000	>94.62%

5.3 Results of the Analysis of Soil Moisture Samples

5.3.1 Method of analysis

During the research period, it was only possible to obtain four samples from the 1.0 m depth plane at the 0 m sample position. However, as a depth of only 0.6 m of unsaturated subsoil is required below the invert of the percolation trench on a site deemed suitable to receive SE (EPA, 2000), the absence of a complete set of samples from the lower plane was not of concern. The results of the analysis of soil moisture samples for Cl were used to determine which of the two methods outlined in Section 4.2.1, planar average or depth average, was the better method for representing the distribution of SE within the percolation area. When the average Cl concentrations measured for each of the sample positions were plotted, it was found that the concentration at the 0 m sample position, at all depths, was, on average, eight to nine times greater than the concentration measured at the other sample positions (Fig. 5.2). When the average Cl concentration for each depth plane at the 0 m sample position was compared, it was discovered that they were very similar indicating that the SE effluent was only reaching the 0 m sample position, a pattern that was maintained throughout the trial period.

Again, the findings of the chloride analyses were corroborated by the results of the bromide tracer study which showed that Br was recorded in all the lysimeters at the 0 m sample position but no tracer was sampled at any of the 10 m or 20 m sample positions.

5.3.2 The effect of dilution on effluent attenuation

As was the case for Site 1, the effective rainfall over the project duration was calculated using rainfall and other meteorological data. The measured rainfall for Site 2 from

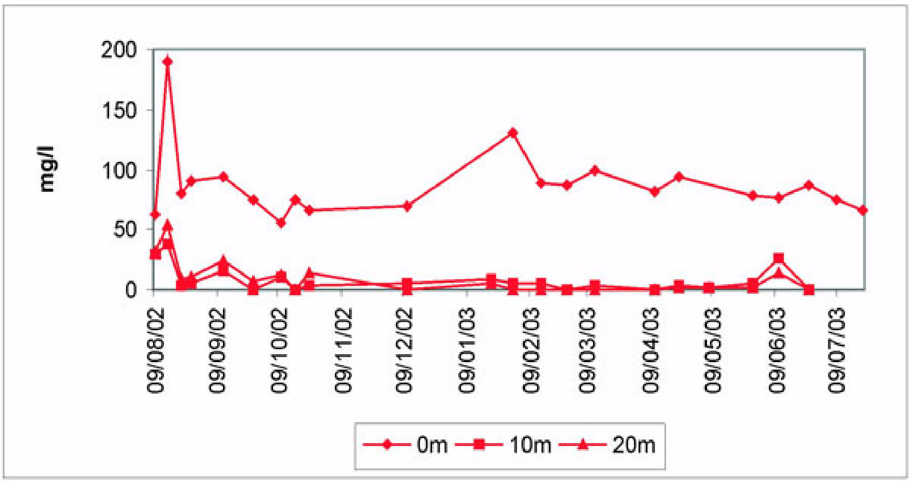

Figure 5.2. Cl concentration on the red depth plane at the three sample positions.

1 August 2002 to 22 July 2003 was 950.0 mm. Using the Penman-Monteith method it was calculated that the effective rainfall over this period was 419.3 mm whilst the Hargreaves method found that the effective rainfall was 407.9 mm. Again, the effect of dilution, i.e. the difference between Puraflo® and soil moisture Cl concentrations, was greatest during the period of sustained effective rainfall between November 2002 and March 2003.

The reduction in Cl concentration between the Puraflo® and both the red and blue depth planes was used to quantify this dilution effect and calculate the zone of contribution around each trench using an average rainfall Cl concentration of 4.8 mg/l. This assumes that the reduction in chloride concentrations due to the effects of physical straining, as seen in the subsoil for Site 1, had already been accounted for in the peat media of the secondary treatment unit and that any further reductions in chloride concentration in the subsoil were due to dilution. It was found that the effect of dilution was equivalent to, on average, the addition of 0.13 l/l (or 10.6% reduction in concentration) and 0.15 l/l (or 13.7% reduction in concentration) on the red and blue depth planes, respectively. Using the daily average flow of 281.7 l/day this equates to an average daily effective rainfall contribution of 36.6 l across the whole red plane and 42.3 l across the whole blue plane. Using the same method as outlined in Section 4.2.2, the average effective rainfall contribution for the red plane for the year was found to be 13.4 m^3, equating to a zone of contribution of effective rainfall of approximately 32.0 m^2. Therefore, taking the trench width of 0.45 m and an average trench length of 4 m this equates to a zone of contribution of approximately 0.5 m on all sides of each trench. When the same calculation was carried out for the blue plane, it was found that the zone of contribution was slightly greater at 36.8 m^2 due to the dispersion of the effluent plume below each percolation trench.

Examination of the soil moisture tension values at the 0 m and 20 m sample positions on Site 2 (Figs 5.3 and 5.4) again suggests that it is physical, chemical and biological processes rather than dilution that are the more prominent attenuation processes operating in the subsoil. The tensiometers at the 20 m sample position, where no effluent was recorded, react to the variation in effective rainfall over the sampling period, whereas the tensiometer readings at the 0 m position are more influenced by the percolating effluent, suggesting that the contribution of dilution to effluent attenuation is small.

5.3.3 Results of chemical analysis

COD

The reduction in COD concentration and load of the percolating SE with subsoil depth (Table 5.4) is small when compared to the reduction that takes place across the secondary treatment system. It appears that the reduced organic load of the SE failed to generate enough microbiological activity along the subsoil–effluent interface to promote significant biomat formation along the entire base and side-walls of the percolation trenches. This has had the effect of concentrating the effluent on less than half the percolation area, thereby reducing the effects of other attenuation processes such as dilution, dispersion and advection within the unsaturated subsoil.

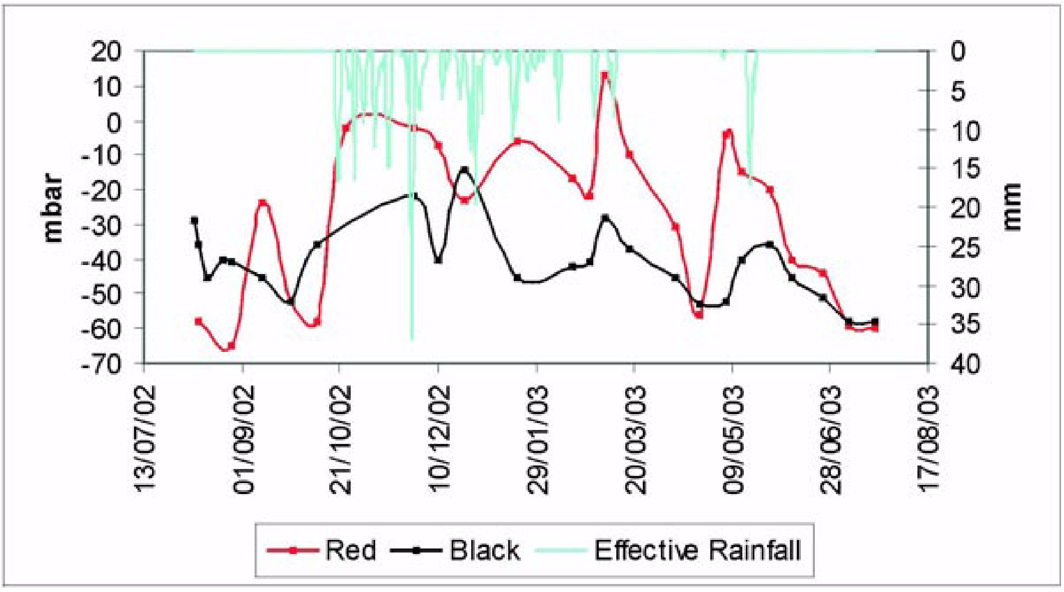

Figure 5.3. Soil moisture tension plotted against effective rainfall for the 20 m sample position on Site 2.

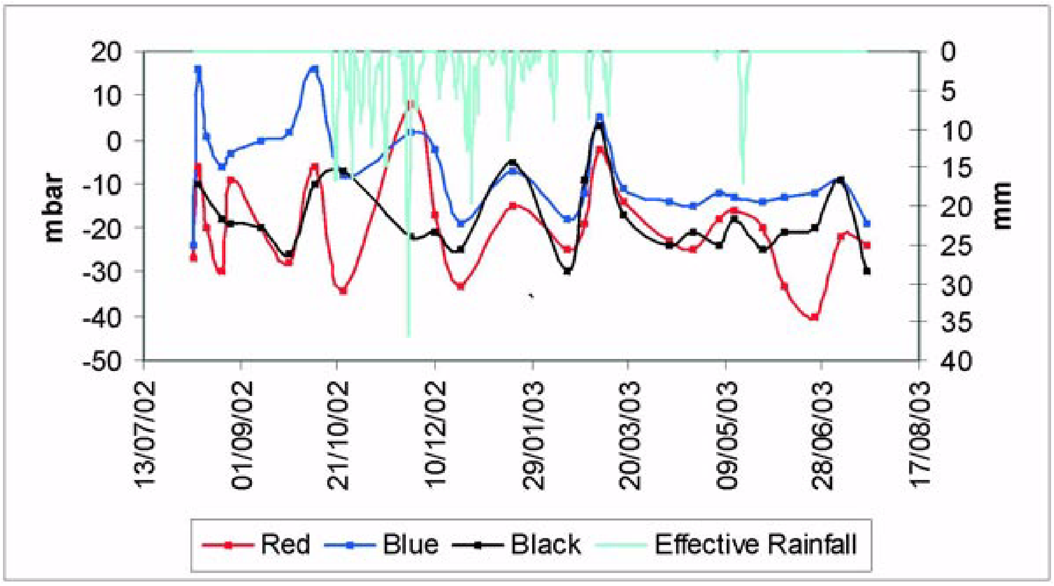

Figure 5.4. Soil moisture tension plotted against effective rainfall for the 0 m sample position on Site 2.

Table 5.4. Reduction in COD load attributed to the specific treatment steps.

Sample position	Concentration (mg/l)	Load	
		(g/day)	Removal (g/day)
STE	791.6	223.0	–
SE	188.1	53.0	167.5
Red depth plane (–0.3 m)	107.5	30.9	24.6
Blue depth plane (–0.6 m)	76.2	21.9	9.0

Nitrogen

The effluent from the secondary treatment underwent further slight nitrification within the subsoil as can be seen by Table 5.5. While near complete nitrification has occurred by the blue depth plane, there is little change in the total inorganic N concentration with depth throughout the research period.

The inhibition to biomat formation along the percolation trench base, resulting from the reduction in organic load attributed to secondary treatment, would result in a reduction in microbial activity, thereby reducing demand for inorganic nitrogen in the decomposition of organic matter. The absence of a biomat along the trench base would also have promoted unsaturated conditions which appeared to be prevalent in the subsoil directly below the percolation trenches. Where isolated incidents of saturation did occur, it is possible that the organic load was insufficient to promote some denitrification.

Phosphorus

Only a small decrease in *ortho*-PO_4 loading in the subsoil was observed above the blue depth plane with a noticeable increase in *ortho*-PO_4 fixation between the blue and black planes (Table 5.6). Particle size analysis of the subsoil sample taken at 1.0 m depth, or 0.2 m below the invert of the percolation pipe, shows a higher clay content than samples at 1.5 m and 2.0 m depth, suggesting a greater affinity for phosphate sorption. The ability of a soil to fix phosphorus is dependent, not only on its clay content, but also on the presence of Al, Fe, or Mn in acidic soils, either as dissolved ions, as oxides or as hydrous oxides, and the presence of Ca in alkaline soils. X-ray diffraction analysis of a sample taken from the sandy SILT (w/clay) layer shows that while it contains calcite, it is void of Al, Fe and Mn, oxides, hydrous oxides or dissolved ions and, therefore, in such a medium, fixation would be confined to the high pH range, generally occurring at a pH > 8. This can be seen on the few occasions where data are available from the black plane.

5.3.4 Results of bacteriological analysis

While the installation of the secondary treatment system greatly reduced the bacteriological load on the percolation area, the results of sample analysis for *E. coli* at the 0 m sample position (Table 5.7) show that there was still some evidence of enteric bacterial contamination with depth from a sample taken from the black plane, although nothing was found on the shallower red and blue planes. As the particle size analysis of the subsoil revealed it to have a high sand content, it is therefore possible that the associated grain size, and consequently pore size, facilitated the movement of bacteria through the subsoil. The reduced biomat development, the presence of which would improve filtration of the percolating effluent, would also have the effect of increasing the hydraulic load per unit area. However, again, it should be noted that a value of 10 cfu/100 ml equates to a single bacterium picked up in analysis.

Table 5.5. Average concentration and loading rate of NO_3-N, NO_2-N, NH_4-N and total inorganic N measured on the red and blue depth planes.

	NO_3-N		NO_2-N		NH_4-N		Total N	
	Conc. (mg/l)	Load (g/day)	Conc. (mg/l)	Load (g/day)	Conc. (mg/l)	Load (g/day)	Conc. (mg/l)	Load (g/day)
SE	37.1	10.5	7.4	2.1	20.5	5.8	64.0	18.0
Red depth plane (–0.3 m)	52.0	14.9	3.3	0.9	5.8	1.7	59.2	17.0
Blue depth plane (–0.6 m)	56.2	16.1	0.6	0.2	1.5	0.4	57.9	16.6

Table 5.6. Average *ortho*-PO_4-P concentration and loading rates measured on the four occasions where black depth plane samples were available.

	Conc. (mg/l)	Loading (g/day)	pH
SE	33.6	9.5	6.42
Red depth plane (–0.3 m)	23.9	6.9	6.30
Blue depth plane (–0.6 m)	23.8	6.8	7.24
Black depth plane (–1.0 m)	6.9	2.2	8.15

Table 5.7. Concentrations of *E. coli* on sample planes on four separate occasions.

	Number of samples	Number of samples with concentration (cfu/100 ml)			
		<10	10–100	101–1000	>1000
SE	4				4
Red depth plane (-0.3 m)	5	5			
Blue depth plane (-0.6 m)	5	5			
Black depth plane (-1.0 m)	1		1		

6 Analysis of Results Obtained from Site 3

6.1 Analysis of Flow Data

The septic tank treatment system was commissioned on 9 July 2003 and sampling was carried out from 23 September 2003 until 18 March 2004. The average daily flow recorded on Site 3 was 329.2 l/day, which equates to a hydraulic load of 82.3 lcd. The dwelling had been newly built in June 2003 and although the surface run-off had been separated from the domestic wastewater there still appeared to be some enhancement of peak flows during rainfall events, meaning that the average domestic wastewater production may be overestimated slightly.

6.2 Results of Analysis of Septic Tank and Soil Moisture Samples

6.2.1 Method of analysis

When the average Cl concentrations at the three red sample positions were graphed (Fig. 6.1) it suggested that the depth average method (and not the planar average method) was the more representative as background-only Cl concentrations were measured at the other sample positions, suggesting that the effluent was distributed over less than the first 10 m of both percolation trenches. Isolated incidents of elevated Cl concentrations were picked up at 10 m, especially towards the end of the trial period or during periods of high STE flow, but in general it appears that biomat formation along the base of the percolation trench on Site 3 had not been as extensive as on Site 1.

The T-value of 33 on Site 3 is twice the T-value recorded on Site 1, but it is possible that it is not a true reflection of the overall percolation characteristics of the subsoil. The abundance of gravel and cobbles within the subsoil matrix lends itself to the possibility of the presence of preferential flowpaths. The presence of such preferential flowpaths over the first 10 m of percolation trench may have mitigated against distribution of the effluent along the base of the whole trench. It would also reduce the residence time of the effluent within the trench, thus impeding biomat formation. However, if such preferential flowpaths existed they were obviously not reflected at the discrete T-test hole locations nor intersected by any of the sampling lysimeters.

6.2.2 The effect of dilution on effluent attenuation

The quantification of effluent dilution within the subsoil and estimation of the zone of contribution proved problematic for Site 3 for a number of reasons. Due to the dense and gravelly nature of the subsoil on Site 3 it was not possible to install the lysimeters directly below the percolation trenches although they were installed as close as possible to the edge of the distribution gravel. As a result, the ceramic cups, especially those on the red depth plane, might not have been fully immersed in the effluent plume. With effluent dispersion, the deeper lysimeters

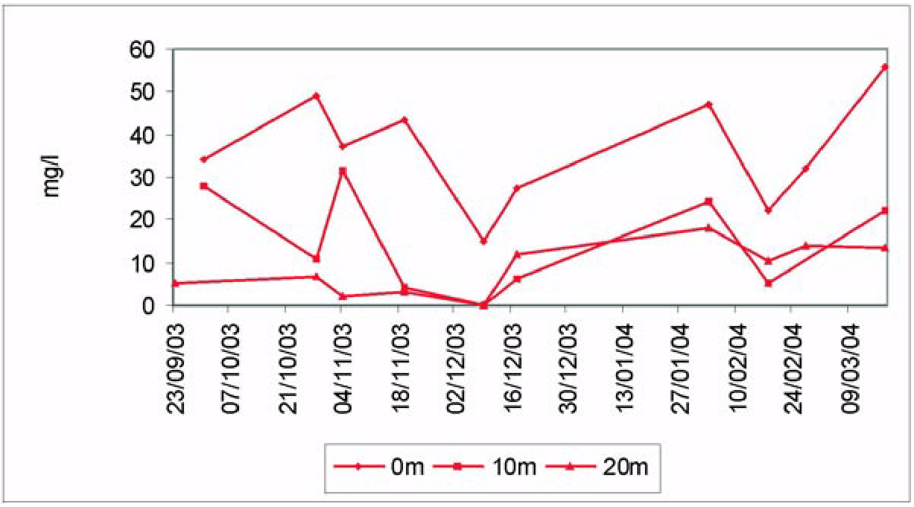

Figure 6.1. Average Cl concentrations on the red depth plane at the three sample positions.

would be more centrally located within the plume resulting in lower Cl concentrations at the shallower lysimeters. This is borne out by the soil moisture tension measurements which were also installed adjacent to, rather than in, the percolation trenches. The tensiometers at the 20 m sample position clearly responded to effective rainfall rather than the percolating effluent, whereas the tensiometers at the 0 m sample position, although following a similar pattern, showed a more muted response indicating that they were on the edge of the effluent plume. It is therefore possible, due to the narrow width of the effluent plume, that the effluent had spread further along the trenches but was not sampled.

The potential evapotranspiration was calculated using the Hargreaves method as only limited meteorological data were available. The rainfall at Site 3 for the period 1 September 2003 to 18 March 2004 was measured as 922.8 mm and the effective rainfall for this period was calculated as 697.3 mm. The dilution effect was greatest over the period of sustained effective rainfall between 19 November 2003 and 3 February 2004. As there was little effective rainfall outside this period, it was decided to let the difference in Cl concentration due to dilution between the septic tank and black depth plane samples obtained on these sample dates be equal to zero. These data were then used to approximate the effect of dilution on effluent attenuation and also the zone of contribution of effective rainfall.

As Cl concentrations measured on the black depth plane were, in general, greater than those measured on the other two depth planes (for reasons outlined above), it was decided to use the difference in Cl concentration between the filtered STE and the black depth plane to estimate the contribution of the effective rainfall to effluent dilution, and for the other two depth planes using a 2% difference between each depth plane (as found on Sites 1 and 2). This equated to an average dilution equivalent to the addition of 0.13 l/l (or 11.6% reduction in concentration) for the red depth plane, 0.16 l/l (or 14.1% reduction in concentration) for the blue depth plane and 0.20 l/l (or 16.6% reduction in concentration) for the black depth plane.

6.2.3 Results of chemical analysis (percolation area)

Table 6.1 summarises the results of the STE chemical analysis which shows relatively high organic effluent concentrations compared to the rest of the sites, although no particular reason was found for these elevated values.

COD

It is clear from Table 6.2 that the majority of COD is removed in the aerobic environment of the percolation gravel and possibly the top few centimetres of the subsoil rather than deep within the subsoil as was found in Site 1.

Nitrogen

Table 6.3 shows that the greatest reduction in nitrogen concentration occurred between the blue plane and the black plane.

Table 6.1. Summary of chemical analysis of STE on Site 3.

	Concentration (mg/l)					
	COD	**NH_4-N**	**NO_2-N**	**NO_3-N**	**PO_4-P**	**Cl**
Maximum	2703.0	71.1	0.7	4.3	16.7	135
Minimum	540.0	19.8	0.22	0.5	3.0	56
Average	**1307.8**	**41.7**	**0.45**	**2.0**	**7.4**	**88.4**

Table 6.2. Average reduction in COD on Site 3.

	Concentration (mg/l)	Load	
		(g/day)	**Removal (g/day)**
STE	1307.2	215.1	–
Red depth plane (–0.3 m)	128.5	23.9	191.2
Blue depth plane (–0.6 m)	102.7	19.6	4.3
Black depth plane (–1.0 m)	84.7	16.7	2.9

Table 6.3. Average NO_3-N, NO_2-N, NH_4-N and total inorganic N concentration measured on Site 3.

	NO_3-N		NO_2-N		NH_4-N		Total inorg. N		pH
	Conc. (mg/l)	Load (g/day)	Conc. (mg/l)	Load (g/day)	Conc. (mg/l)	Load (g/day)	Conc. (mg/l)	Load (g/day)	
STE	2.0	0.4	0.5	0.09	41.7	8.08	48.4	8.57	7.68
Red depth plane (–0.3 m)	22.0	3.6	0.3	0.05	5.1	0.9	30.1	4.55	6.80
Blue depth plane (–0.6 m)	20.9	3.4	0.7	0.12	7.2	1.2	31.3	4.72	6.78
Black depth plane (–1.0 m)	6.1	1.0	0.4	0.07	3.8	0.6	11.7	1.67	6.97

While nitrification was evident from the high concentration of NO_3 measured in soil moisture samples obtained from the red and blue depth planes, there was no parallel denitrification over the same subsoil thickness. It is possible that ,due to the location of these lysimeters within the fringe of the effluent plume, the hydraulic load was not sufficient to produce saturated conditions which would promote denitrification. An increase in soil moisture content with depth, as highlighted by the tensiometer readings, may indicate the creation of anoxic conditions thereby promoting denitrification between the blue and black depth planes. It is also possible that the saturated conditions experienced directly below the percolation trench promoted removal of NH_4 from the percolating effluent by cation exchange.

Phosphorus

It can be seen from Table 6.4 that the greatest reduction in effluent *ortho*-PO_4 concentration occurred above the red depth plane. The high clay content of the subsoil below the percolation area on Site 3, revealed by the particle size analysis, suggests that the removal of phosphate from the percolating effluent was controlled by soil adsorption. As discussed previously, the depth of subsoil active in PO_4 fixation would be expected to increase with time as the finite capacity of the subsoil gradually becomes saturated.

6.2.4 Results of bacteriological analysis (percolation area)

Assuming that the results obtained from the bacteriological analysis of these samples are representative of the sample position from which they were obtained, it can be seen from Table 6.5 that, allowing for the factor of safety introduced due to sample dilutions, there was complete removal of enteric bacteria by the blue depth plane.

6.3 Results of Analysis of Stratified Sand Filter

6.3.1 Hydraulic loading

The average hydraulic load on the sand filter during the year was 172 l/day equating to an average loading rate of 28.6 l/m^2 per day with a dosing frequency of 3.5 pumps per day. However, from 14 December 2003 to 21 January 2004 a high loading trial was carried out for 5 weeks whereby all the flow from the distribution box was directed onto the sand filter (i.e. none to the trenches). This was carried out to assess the filter's performance at higher loading rates which are closer to the original design value of 60 l/m^2 per day. During this period there was an increase in the average hydraulic loading rate to 57.2 l/m^2 per day which equated to 8.3 pumps per day. The piezometers in the sand filters revealed no significant head during the year at the lower loading rate of 28.9 l/m^2

Table 6.4. Average reduction in *ortho*-PO_4-P on Site 3.

	Concentration (mg/l)	Load	
		(g/day)	Removal (g/day)
STE	7.4	1.22	–
Red depth plane (–0.3 m)	0.4	0.07	1.15
Blue depth plane (–0.6 m)	0.2	0.04	0.03
Black depth plane (–1.0 m)	0.1	0.02	0.02

Table 6.5. Concentrations of enteric bacteria measured on Site 3.

	Number of Samples	Number of samples with concentration (cfu/100 ml)			
		<10	10–100	101–1000	>1000
STE	2				2
Red plane (–0.3 m)	2	1	1		
Blue plane (–0.6 m)	1	1			
Black plane (–1.0 m)	2	2			

per day but a continually rising head at the higher loading rate of 57 l/m^2 per day, increasing to 0.4 m above the base at the end of the trial after 5 weeks. This indicates that such a loading rate is probably too high for a filter receiving septic tank effluent discharging into a relatively low permeability subsoil with a T-value of 33.

6.3.2 *Results of chemical analysis (stratified sand filter)*

The load calculations for the stratified sand filters on Sites 3 and 4 have been calculated according to the average hydraulic loading rates for each period (the normal and high loading trials) augmented by the average rainfall values across each respective period.

COD

The results of the COD analyses are shown in Table 6.6 which presents the average values for both the normal and high hydraulic loading trial periods down through the sand filter layers and into the soil beneath.

Although the hydraulic loading rate during the high loading trial was approximately double that experienced during the rest of the year, the effluent concentration from the septic tank happened to be a lot weaker on average (coinciding with a period of greatest rainfall) which meant that the average COD load onto the filter was approximately the same during both periods. During the normal hydraulic loading period, the greatest COD removal was in the upper layers of the filter as expected. At shallow depths, there are high organic concentration gradients across the biofilm and also a plentiful supply of oxygen at the level closest to the surface. As the COD concentrations decreased with filter depth, there was a reduction in load removed, although a surprising drop in performance in the lowest fine sand layer which could be indicative of slightly anoxic conditions due to the extra

Table 6.6. Average COD concentrations and loads in sand filter and subsoil. Note: values in parentheses indicate values during high loading trial.

	COD conc. (mg/l)	COD load (g/day)	Load removed (g/day)
STE	**1432.2** **(660.0)**	**246.0** **(226.6)**	– –
Coarse sand (depth 0.3 m)	579.7 (500.0)	113.1 (197.4)	132.9 (29.2)
Medium sand (depth 0.475 m)	261.3 (276.0)	51.0 (109.0)	62.1 (88.4)
Fine sand (depth 0.75 m)	218.5 (276)	42.7 (109.0)	8.3 (0.0)
Subsoil (depth 1.3 m)	79.9 (70.0)	15.6 (27.5)	27.1 (82.0)
Subsoil (depth 1.6 m)	64.5 (53.0)	12.6 (20.9)	3.0 (6.6)
Subsoil (depth 1.9 m)	70.1 (52.9)	13.7 (20.9)	–1.1 (0.0)

hydraulic resistance through the finer sand. The COD concentrations measured below the filter in the subsoils at 1.3 m depth (i.e. 0.25 m below the sand filter) show that there had been further COD removal in the distribution gravel, base sand layer and top 250 mm of subsoil. At the two deeper sample depths, the COD removal was negligible.

At the higher hydraulic loading rate, the highest COD removal was in the medium layer of sand. This indicated that the effluent was percolating too quickly through the coarse layer of sand for an optimal removal at such a hydraulic loading rate. The effluent concentrations from the lowest fine layer of sand are the same as those from the middle level, which confirms the measurements from the piezometer that this level was flooded at this higher hydraulic loading rate. The COD concentrations below the filter in the subsoil at 1.3 m depth show that further removal of COD occurred in the distribution gravel, base sand layer and top 250 mm of subsoil, indicating unsaturated conditions once the effluent has passed through the resistance offered by the fine sand. Again, below the sand filter the COD removal in the subsoil was negligible down to 1.9 m depth. Hence, these results indicate that the maximum hydraulic loading rate for a stratified sand filter used as a secondary treatment process for septic tank effluent should be no greater than 30 l/m^2 per day if such a fine sand specification for the bottom layer is adopted.

Nitrogen

The results of the analyses for the nitrogen species are shown in Table 6.7. At the normal hydraulic loading rate, the filter was acting to nitrify the effluent with depth, the ammonia being converted into nitrate with a resultant pH drop. However, in the fine sand layer there was also denitrification occurring with a reduction of approximately half of the nitrogen load giving further evidence of partially saturated conditions as discussed previously. Nitrification continued as the effluent percolated from the fine sand into the distribution gravel, base sand layer and top 250 mm of subsoil. The nitrified effluent was also gradually denitrified with depth down to 1.9 m. At the higher hydraulic loading rate, there was little evidence of nitrification in the top two layers of sand but a significant reduction in the nitrogen load in the fine sand layer although no particular evidence of nitrification of the NH_4 before subsequent denitrification. Once the effluent has moved through the fine sand layer and infiltrated the subsoil, the NH_4 is further nitrified under unsaturated conditions and lower organic concentrations which is completed by the 1.6 m depth in the subsoil. The nitrified effluent is then denitrified in the subsoil down to the 1.9 m depth.

Phosphorus

The results of the analyses for *ortho*-PO_4 are shown in Table 6.8 which reveals that significant load removal

Table 6.7. Average nitrogen loads (g/day) in sand filter (Site 3). Note: values in parentheses indicate values during high loading trial.

	NH_4-N	NO_2-N	NO_3-N	Total N	pH
STE	8.08 (9.77)	0.09 (0.06)	0.40 (0.38)	8.53 (9.33)	7.8 (7.2)
Coarse sand (depth 0.3 m)	5.38 (11.90)	0.08 (0.10)	0.85 (0.83)	6.29 (12.82)	7.8 (7.3)
Medium sand (depth 0.475 m)	2.85 (10.00)	0.10 (0.05)	2.87 (0.18)	5.76 (10.22)	7.7 (7.5)
Fine sand (depth 0.75 m)	1.44 (7.49)	0.07 (0.04)	2.38 (0.29)	3.87 (7.82)	7.3 (7.3)
Subsoil (depth 1.3 m)	0.31 (4.19)	0.02 (0.19)	2.81 (3.48)	3.13 (7.85)	7.1 (6.7)
Subsoil (depth 1.6 m)	0.27 (0.08)	0.01 (0.05)	1.92 (3.63)	2.19 (3.76)	6.7 (6.6)
Subsoil (depth 1.9 m)	0.37 (0.06)	0.01 (0.14)	1.36 (2.11)	1.74 (2.31)	6.99 (6.50)

Table 6.8. Average *ortho*-PO_4-P concentrations, loads and removal in sand filter and subsoil. Note: figures in parentheses indicate values during high loading trial.

	Ortho-PO_4 conc. (mg/l)	*Ortho*-PO_4 load (g/day)	Load removed (g/day)
STE	9.15 (2.96)	1.57 (1.02)	– –
Coarse sand (depth 0.3 m)	4.56 (3.02)	0.89 (1.09)	0.68 (–0.07)
Medium sand (depth 0.475 m)	1.83 (0.24)	0.36 (0.09)	0.53 (1.00)
Fine sand (depth 0.75 m)	1.48 (0.27)	0.29 (0.11)	0.07 (–0.02)
Subsoil (depth 1.3 m)	0.28 (0.01)	0.05 (0.00)	0.24 (0.11)
Subsoil (depth 1.6 m)	0.06 (0.01)	0.01 (0.00)	0.04 (0.00)
Subsoil (depth 1.9 m)	0.06 (0.01)	0.01 (0.00)	0.00 (0.00)

occurred in both the coarse and medium sand layers under the normal hydraulic loading regime. This was explained after X-ray diffraction analysis of the three types of sand used in the filters revealed the existence of goethite in both the coarse and medium sands but not in the fine sand. Goethite is ferric oxide (Fe_2O_3) which will act as an adsorption site for the soluble phosphate to form a ferric phosphate precipitate. The final removal of *ortho*-PO_4 by the 1.3 m depth in the subsoil could be attributed to the thin layer of 50 mm of medium sand bedding on the base of the filter, although results from the percolation trenches indicate that the mineralogy of the subsoil is also conducive to phosphate adsorption on this site.

During the high loading trial, *ortho*-PO_4 concentrations from the septic tank were significantly lower than the average values for the rest of the year. At these low concentrations and at double the hydraulic loading rate, the main phosphate removal takes place in the medium sand layer. No removal was observed in the coarse sand (as had been measured at the slower rate with higher concentrations) since the effluent presumably moved too quickly through the sand for adsorption to occur at the lower concentrations. Again, all the remaining phosphate is removed by the 1.3 m depth in the subsoil. It should be recognised that the capacity for phosphate removal is specific to the type of sand used for the construction of the filter and is finite.

6.3.3 Results of bacteriological analysis (stratified sand filter)

The general performance of the sand filter with respect to bacterial removal can be gauged by examining the total coliform concentration through the stratified sand filter (Fig. 6.2) which revealed a far better removal efficiency at the lower hydraulic loading rate than at the higher rate, whereby the bacteria are removed at approximately twice the rate with an inactivation kinetic $k = –8.7$ at 29 l/m^2 per day compared to $k = –4.6$ at 57 l/m^2 per day.

This is confirmed by the analyses of *E. coli* sampled in the filter and in the subsoil beneath (Table 6.9) which shows viable concentration throughout the subsoil at the higher loading rate even though the initial septic tank effluent concentration was an order of magnitude less during that period.

No viable *E. coli* were sampled beneath the sand filter at the lower loading rates. Hence, this breakthrough of enteric bacteria again confirmed that the design hydraulic loading rate for stratified sand filters used as a secondary treatment process should be no greater than 30 l/m^2 per day.

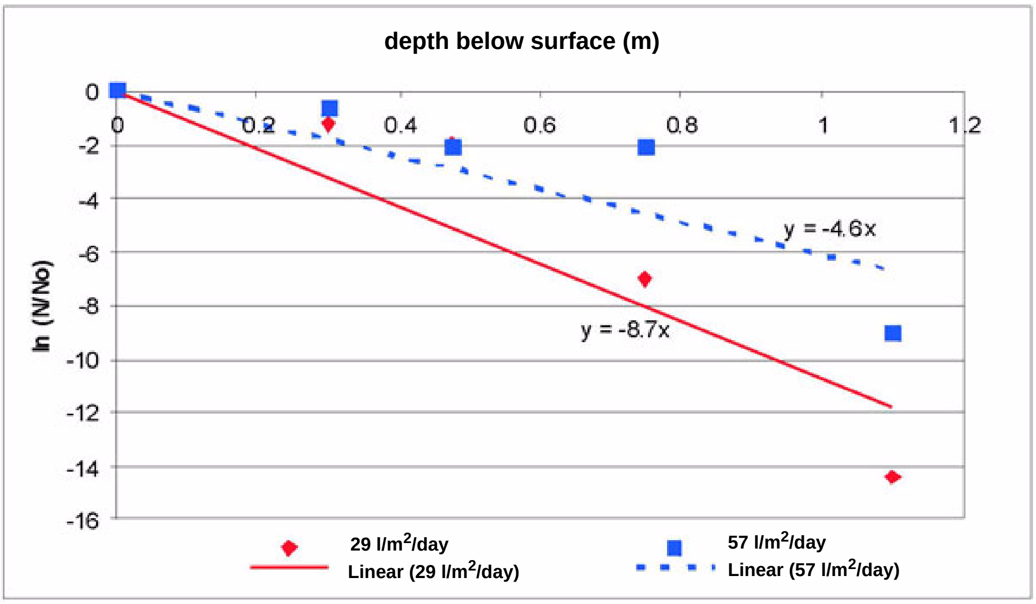

Figure 6.2. Removal of total coliforms with depth through the sand filter (Site 3). N, number of bacteria; N_0, original number from septic tank.

Table 6.9. *E. coli* concentrations in sand filter and subsoil (Site 3). Note: figures in parentheses indicate values during high loading trial.

	Number of samples	Number of samples with concentration (cfu/100 ml)				
		<10	10–100	101–1000	1001–10,000	>10,000
STE	2 (1)				(1)	2
Coarse sand (depth 0.3 m)	2 (1)		(1)			2
Medium sand (depth 0.475 m)	2 (1)		(1)		1	1
Fine sand (depth 0.75 m)	2 (1)		1 (1)	2		
Subsoil (depth 1.3 m)	2 (1)	1	(1)			
Subsoil (depth 1.6 m)	2 (1)	1	(1)			
Subsoil (depth 1.9 m)	2 (1)	1	(1)			

6.4 Comparison of Percolation Area and Stratified Sand Filter

A comparison of the loading levels at the three different subsoil depth planes beneath the percolation trenches and the stratified sand filter (at an average loading rate of 29 l/m^2 per day) is presented in Table 6.10. The effluent beneath the stratified sand filter has been treated to a slightly higher quality by the 1.3 m depth plane, which is not surprising since it has passed through a 1.05 m sand filter compared to 0.3 m of subsoil beneath the percolation pipes. However, by the time the effluent has reached 1.9 m in the subsoil (black plane), the performance of both systems is similar with loading rates for all parameters reduced to similar levels.

Table 6.10. Comparison of average loading rates in the subsoil at the different depth planes beneath the percolation area and beneath the stratified sand filter (in italics) on Site 3.

	Loading Rate (g/day)					
	COD	**NO_3-N**	**NO_2-N**	**NH_4-N**	**Total N**	**PO_4-P**
STE	215.3	0.40	0.09	8.08	8.57	1.57
Red depth plane (1.1–1.3 m)	21.2	3.6	0.05	0.9	4.55	0.07
	15.6	*2.8*	*0.02*	*0.31*	*3.14*	*0.05*
Blue depth plane (1.4–1.6 m)	16.9	3.4	0.12	1.2	4.72	0.03
	12.6	*1.9*	*0.01*	*0.27*	*2.20*	*0.01*
Black depth plane (1.8–1.9 m)	13.9	1.0	0.07	0.6	1.67	0.02
	13.7	*1.4*	*0.01*	*0.37*	*1.74*	*0.01*

7 Analysis of Results Obtained from Site 4

7.1 Analysis of Flow Data

The septic tank treatment system and secondary treatment system were commissioned on 15 July 2003 and sampling began on 23 September and continued until 18 March 2004. The average daily hydraulic load measured over the project period was 492.1 litres, equating to 123.0 lcd. This included a small contribution by surface run-off from a small section of roof at the front of the house and therefore again overestimates the average daily domestic wastewater generation on site.

7.2 Results of the Analysis of Septic Tank and Secondary Effluent

As can be seen from the results of the analysis of the STE and SE from Site 4 (Tables 7.1 and 7.2), the treatment by the aerated peat and associated bio-media of the Puraflo® module reduced the organic concentration of the SE compared to the STE but still had a high concentration of nutrients. The NH_4 had undergone nitrification and, as discussed in Section 5.2, the modifications to the standard Puraflo® unit created an average 25% reduction in the overall inorganic nitrogen concentration between the STE and SE.

A similarly high bacterial removal efficiency associated with the installation of a Puraflo® system in Site 2 was achieved although again the concentrations of enteric bacteria highlighted the requirement of SE to undergo further treatment prior to discharge to groundwater.

7.3 Results of the Analysis of Soil Moisture Samples

7.3.1 Method of analysis

Examination of the results of soil moisture samples for Cl revealed that, of the two methods outlined in Section 5.3.1, the depth average method was more representative of the behaviour of the SE in and below the percolation trenches (Fig. 7.1). This would suggest that, as appeared to be the case on Site 2, the reduction in STE organic load brought about by the installation of a secondary treatment system inhibited the formation of a biomat along the base of the percolation trenches thus confining effluent loading to less than the first 10 m of both trenches.

7.3.2 The effect of dilution on effluent attenuation

It was not possible to install the sampling equipment directly below the percolation trenches due to the dense nature of the subsoil on Site 4 and so, for the purpose of the quantification of effluent dilution by effective rainfall, Cl concentrations were compared between the Puraflo® and the black depth plane only, as was the case at Site 3. As for Site 2, it was assumed that the reduction in chloride

Table 7.1. Summary of the results of chemical analysis of STE on Site 4.

	Concentration (mg/l)				
	COD	NH_4-N	Total N	PO_4-P	Cl
Maximum	1393.0	83.0	85.2	13.9	116
Minimum	446.0	27.8	29.13	3.8	33.3
Average	**812.6**	**56.6**	**57.85**	**7.9**	**68.8**

Table 7.2. Summary of the results of chemical analysis of SE on Site 4.

	Concentration (mg/l)				
	COD	NO_3-N	Total N	PO_4-P	Cl
Maximum	370.0	63.4	66.3	11.8	85.0
Minimum	68.0	23.6	31.8	5.1	20.1
Average	**215.8**	**42.0**	**48.7**	**8.1**	**55.4**

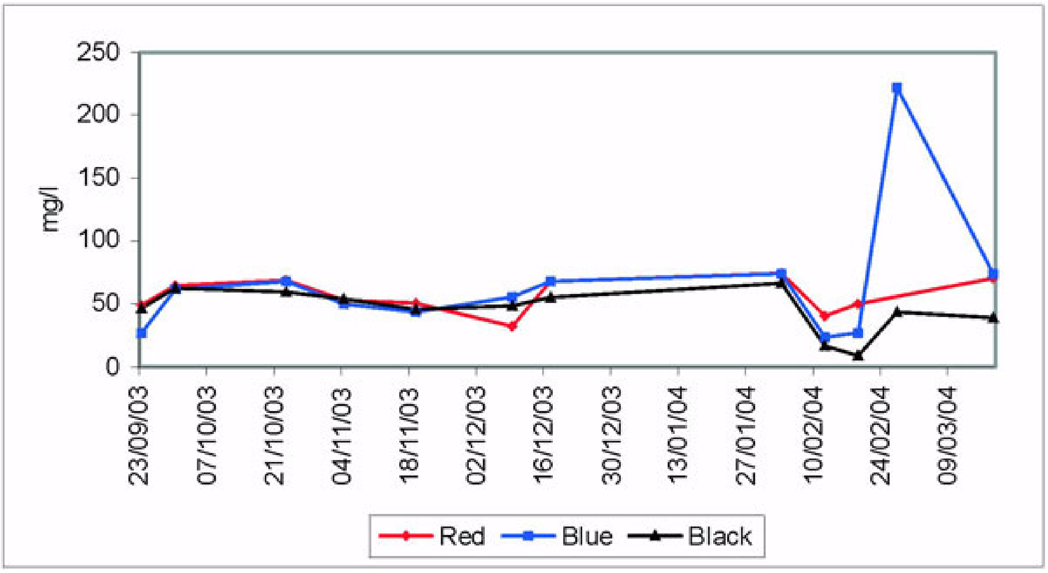

Figure 7.1. Cl concentration measured on the three depth planes at the 0 m sample position on Site 4.

concentrations due to physical straining had already been accounted for in the peat media of the secondary treatment unit. The effective rainfall calculated using the Hargreaves method was 414.9 mm between 1 September 2003 and 18 March 2004 for a measured rainfall of 640.4 mm. These data were then used to approximate the effect of dilution on effluent attenuation and also the zone of contribution of effective rainfall as described in Section 6.2.2.

The effect of dilution was equivalent to, on average, 0.11 l/l of effluent, or a 7.7% reduction in concentration by the black depth plane. This equates to an effective rainfall contribution of 27.3 l/day or 10.0 m^3/year giving a zone of contribution of effective rainfall of approximately 14.3 m^2. The effect of dilution on the red and blue and black depth planes then equated to an approximate zone of contribution of 10.9 m^2, 17.5 m^2 and 24.1 m^2, respectively. Assuming an approximate length of trench over which the effluent was distributed as 5 m with the trench width of 0.45 m, this equates to a zone of contribution of approximately 0.3 m, 0.5 m and 0.7 m on all sides of each trench for the red, blue and black depth planes, respectively.

It appears from Fig. 7.2 that the tensiometers installed at the 20 m sample position, where no effluent was recorded, react to the variation in effective rainfall over the sampling period while the tensiometers installed at the 0 m sample position (Fig. 7.3) appear to react independently of the effective rainfall, confirming that it is the percolating effluent that influences the change in soil moisture tension, and that it is the physical, chemical and biological processes, rather than dilution, which are the more prominent effluent attenuation processes, as calculated by the chemical analysis.

7.3.3 Results of chemical analysis (percolation area)

COD

The reduction in COD concentration of the domestic wastewater effluent with subsoil depth is small when compared to the reduction that takes place across the Puraflo® unit (Table 7.3). This reduction in organic load has had the effect of concentrating the effluent over less than half the percolation area by inhibiting the formation of a biomat along the subsoil–effluent interface. The similarity between the COD results obtained from Sites 2 and 4, especially given the very different nature of the subsoils, again suggests that the majority of COD reduction within the percolation area occurs above the red depth plane or within the distribution gravel.

Nitrogen

There was a small reduction in the total inorganic nitrogen concentration with subsoil depth (Table 7.4). The reduction in NH_4 concentration with depth was not reflected by a corresponding increase in NO_3 concentration. In fact, it can be seen that there was a decrease in NO_3 concentration with depth reflected by an increase in pH. This reduction in both NO_3 and NH_4 may

Table 7.3. Reduction in COD concentration on Site 4.

	Concentration (mg/l)	Load	
		(g/day)	Removal (g/day)
STE	812.6	200.0	–
SE	215.8	53.1	146.9
Red depth plane (–0.3 m)	109.3	28.0	25.1
Blue depth plane (–0.6 m)	89.5	22.0	6.0
Black depth plane (–1.0 m)	89.7	22.0	0.0

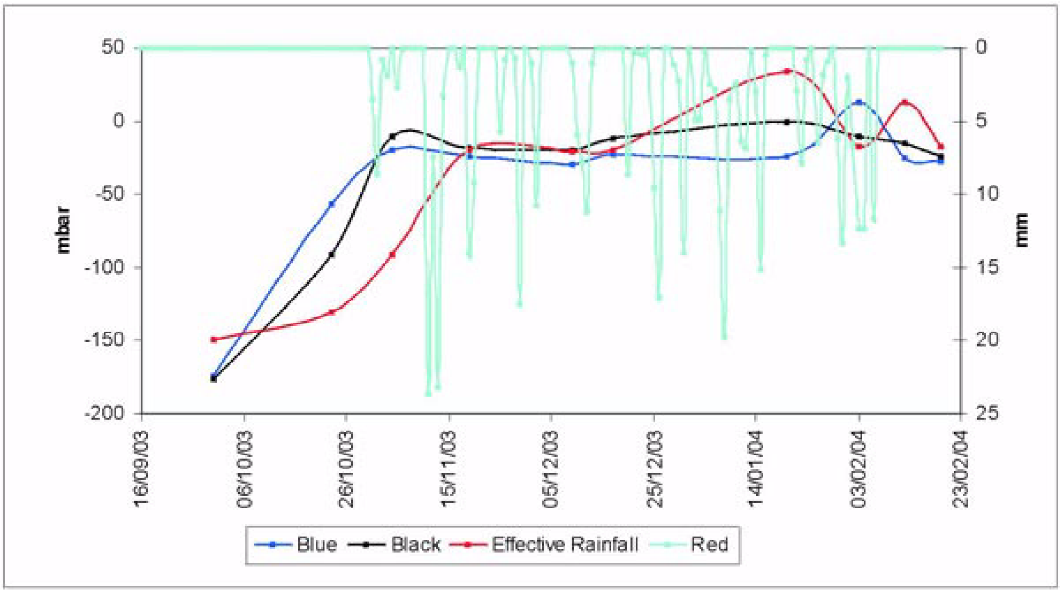

Figure 7.2. Soil moisture tension plotted against effective rainfall for the 20 m sample position on Site 4.

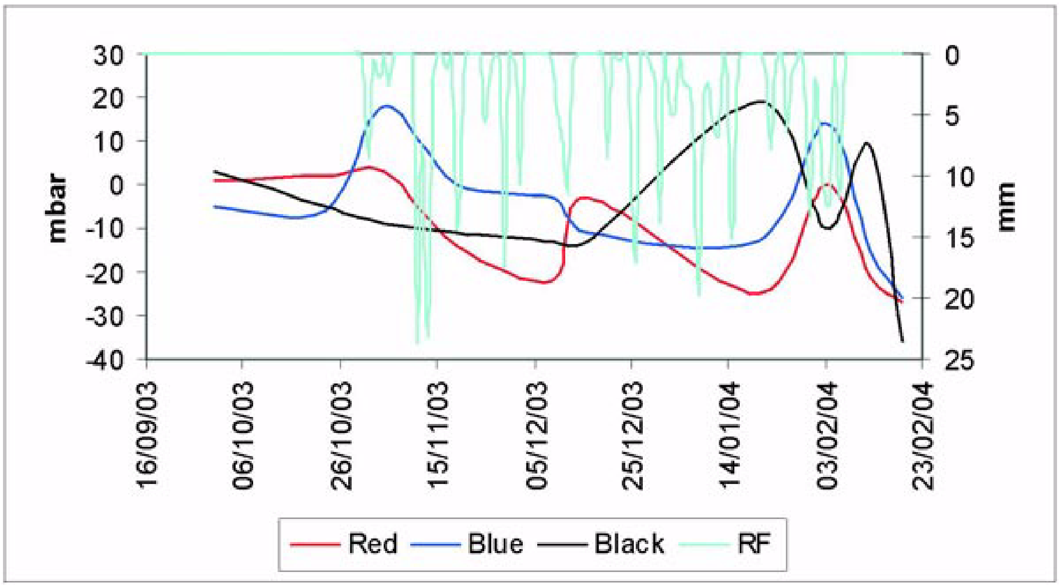

Figure 7.3. Soil moisture tension plotted against effective rainfall for the 0 m sample position on Site 4.

Table 7.4. Average concentration of NO_3-N, NO_2-N, NH_4-N and Total inorganic N measured on the three depth planes.

	NO_3-N		NO_2-N		NH_4-N		Total inorg. N		pH
	Conc. (mg/l)	Load (g/day)	Conc. (mg/l)	Load g/day)	Conc. (mg/l)	Load (g/day)	Conc. (mg/l)	Load (g/day)	
SE	42.0	10.3	0.2	0.06	6.5	1.6	48.7	12.0	6.4
Red depth plane (–0.3 m)	50.6	12.9	0.4	0.10	3.8	1.0	53.7	13.7	6.0
Blue depth plane (–0.6 m)	48.5	12.7	0.3	0.08	3.0	0.8	50.5	13.2	6.2
Black depth plane (–1.0 m)	45.6	12.1	0.1	0.03	2.1	0.6	46.9	12.5	6.6

be an indication of simultaneous nitrification and denitrification or possible evidence of the anaerobic oxidation of ammonia, the so-called Anammox pathway.

Phosphorus

As can be seen in Table 7.5, the greatest reduction in *ortho*-PO_4 concentration occurred between the blue and black depth planes, even though the particle size analysis of the subsoil samples taken at 1.0 m, 1.5 m and 2.0 m below ground level resulted in a uniform classification of the subsoil. The low clay and high sand content of the subsoil would suggest a reduced capacity for phosphate fixation and it can be seen that there is only a small reduction in concentration between the SE and the blue depth plane. As the pH of the soil moisture samples was acidic, this suggested that the ability of the soil to fix PO_4 depended not only on the clay content but also on the presence of Al, Fe and/or Mn as dissolved ions, oxides or hydrous ions.

7.3.4 Results of bacteriological analysis (percolation area)

It can be seen from Table 7.6 that there was complete removal of enteric bacteria by the black depth plane. Analysis of the first sample, which was obtained on 2 December 2004, showed the presence of enteric bacteria in the red and black depth planes at the 10 m sample position and in the blue and black depth planes at the 20 m sample position. However, as the chemical analysis highlighted the absence of SE at these locations it suggests a non-anthropogenic source, which serves to highlight the sensitivity and relative insignificance of the low microbiological results of *circa* 10 cfu/100 ml.

Table 7.5. Reduction in *ortho*-PO_4-P concentration on Site 4.

	Concentration	Load	
	(mg/l)	(g/day)	Removal (g/day)
SE	8.1	2.0	–
Red depth plane (–0.3 m)	6.8	1.7	0.3
Blue depth plane (–0.6 m)	4.8	1.3	0.4
Black depth plane (–1.0 m)	0.6	0.2	1.1

Table 7.6. Concentration of *E. coli* measured at the 0 m sample position on Site 4.

	Number of samples	Number of samples with concentration (cfu/100 ml)			
		<10	10–100	101–1000	>1000
SE	2		1	1	
Red depth plane (–0.3 m)	2	2			
Blue depth plane (–0.6 m)	2	2			
Black depth plane (–1.0 m)	1	1			

7.4 Results of Analysis of Stratified Sand Filter

7.4.1 *Hydraulic loading*

The average hydraulic load on the sand filter during the year was 246 l/day equating to an average loading rate of 41.0 l/m^2 per day with a dosing frequency of 7.3 pumps per day. A high loading trial was carried out from 14 December 2003 to 21 January 2004 during which time there was an increase in the average hydraulic loading rate to 97.9 l/m^2 per day which equated to 18.8 pumps per day. The piezometers in the sand filters revealed no significant head during the year at either loading rate. Since the subsoil has a higher T-value than Site 3, this absence of flooding in the bottom of the filter is indicative of reduced biofilm development in the fine sand layer due to the low organic load of the SE.

7.4.2 *Results of chemical analysis (stratified sand filter)*

COD

The results of the COD analyses are shown in Table 7.7 which gives the average values for both the normal and high hydraulic loading trial periods down through the sand filter layers and into the soil beneath.

The results show that there is little organic removal using the filter as a polishing filter at either the normal loading rate or the high loading rate. The slight increase in COD levels at the higher loading rate in the filter in the coarse and medium layers could be due to the increased hydraulic loading creating high shear stress on the biofilm and removing some of the thickness that had accumulated during the lower loaded period. There is a significant COD removal between the bottom of the filter and the 1.3 m depth in the subsoil by which point the organic concentration was down to low levels comparable to those measured on Site 3.

Nitrogen

The results of the analyses for the nitrogen species are shown in Table 7.8. At an average hydraulic loading rate of 41 l/m^2 per day, there does not seem to have been a large change in the nitrogen compounds in the filter apart from some small nitrification of any remaining ammonia in the secondary effluent in the first coarse sand level.

There was evidence of some denitrification in the subsoil (and no further nitrification) which could indicate slightly saturated conditions in this slowly percolating soil. At the higher hydraulic loading rate of 98 l/m^2 per day, there appeared to be some loss of nitrogen in the fine sand layer but no change in the nitrate loading which would either suggest nitrification in the top of the layer with subsequent denitrification in a saturated lower section due to such a high hydraulic load or possibly the direct conversion of ammonia to nitrogen by the Anammox pathway. Within the subsoil, there is no strong evidence of further reductions in nitrogen load at the higher hydraulic loading rate.

Table 7.7. Average COD concentrations and loads in sand filter and subsoil. Note: values in parentheses indicate values during high loading trial.

	COD conc. (mg/l)	COD load (g/day)	Load removed (g/day)
SE	215.8 (106.0)	53.1 (62.3)	– –
Coarse sand (depth 0.3 m)	239.3 (175.0)	63.2 (107.6)	–10.1 (–45.3)
Medium sand (depth 0.475 m)	208.9 (181.0)	55.2 (111.3)	8.0 (–3.7)
Fine sand (depth 0.75 m)	183.9 (143.8)	48.5 (88.4)	6.7 (22.9)
Subsoil (depth 1.3 m)	91.1 (45.0)	24.1 (27.7)	24.4 (60.7)
Subsoil (depth 1.6 m)	71.9 (31.0)	19.0 (19.1)	5.1 (8.6)
Subsoil (depth 1.9 m)	62.2 (36.0)	16.4 (22.1)	2.6 (–3.0)

Table 7.8. Average nitrogen loads (g/day) in sand filter (Site 4). Note: values in parentheses indicate values during high loading trial.

	NH_4-N	NO_2-N	NO_3-N	Total N	pH
SE	1.64 (6.83)	0.06 (0.08)	10.34 (18.39)	12.04 (25.29)	6.39 (6.09)
Coarse sand (depth 0.3 m)	0.84 (2.81)	0.10 (0.24)	11.76 (23.52)	12.57 (26.57)	6.71 (6.28)
Medium sand (depth 0.475 m)	0.66 (3.89)	0.05 (0.20)	10.68 (21.86)	11.53 (25.95)	6.92 (6.54)
Fine sand (depth 0.75 m)	0.75 (1.01)	0.04 (0.12)	10.94 (21.54)	11.65 (22.67)	6.81 (6.81)
Subsoil (depth 1.3 m)	0.59 (0.01)	0.02 (0.05)	10.85 (23.55)	11.45 (23.61)	6.68 (6.72)
Subsoil (depth 1.6 m)	0.65 (0.21)	0.02 (0.02)	9.60 (25.8)	10.27 (25.81)	6.63 (6.67)
Subsoil (depth 1.9 m)	0.54 (0.01)	0.01 (0.02)	8.51 (26.32)	9.06 (23.65)	6.86 (6.35)

Phosphorus

Table 7.9 shows the results of the analyses for *ortho*-PO_4 which reveal that significant load removal occurs in the medium sand layer and to a lesser extent in the coarse sand layer under an average hydraulic loading regime of 41 l/m^2 per day, presumably associated with the presence of goethite, as discussed previously. However, at the higher hydraulic loading rate of 98 l/m^2 per day, there is a much reduced removal of phosphate in the medium sand layer although there is some removal in the fine sand layer. The final removal of *ortho*-PO_4 by the 1.3 m depth in the subsoil is most likely attributable to the thin layer of 50 mm of medium sand bedding on the base of the filter, rather than to the mineralogy of the subsoil since the percolation area results (Table 7.5) indicate that there is little phosphate adsorption in the subsoil at this depth. As observed in Site 3, there is little phosphate adsorption in the coarse sand layer at the higher hydraulic loading rates even though this sand has been shown to contain some goethite.

7.4.3 Results of bacteriological analysis (stratified sand filter)

It is not possible to reveal any difference in performance for the removal of total coliforms through the stratified sand filter between the two loading rates since the average total coliforms concentration in the secondary treated effluent was only 5000 cfu/ml. Analysis of *E. coli*

Table 7.9. Average *ortho*-PO_4-P concentrations, loads and removal in sand filter and subsoil. Note: values in parentheses indicate values during high loading trial.

	Ortho-PO_4 conc. (mg/l)	*Ortho*-PO_4 load (g/day)	Load removed (g/day)
SE	8.42 (6.29)	2.07 (3.69)	– –
Coarse sand (depth 0.3 m)	7.18 (5.91)	1.90 (3.64)	0.17 (–0.05)
Medium sand (depth 0.475 m)	4.37 (5.60)	1.15 (3.44)	0.75 (0.20)
Fine sand (depth 0.75 m)	4.45 (5.00)	1.17 (3.07)	–0.02 (0.33)
Subsoil (depth 1.3 m)	0.22 (0.01)	0.06 (0.01)	1.11 (3.06)
Subsoil (depth 1.6 m)	0.03 (0.01)	0.01 (0.01)	0.05 (0.00)
Subsoil (depth 1.9 m)	0.12 (0.01)	0.03 (0.01)	–0.02 (0.00)

sampled in the filter and in the subsoil beneath (Table 7.10) shows that viable concentrations were found throughout the depth of the sand filter at both loading rates and that the filter only affected a 1 log reduction in the enteric bacteria from the typically low concentrations in the secondary effluent. However, no viable *E. coli* concentrations were sampled beneath the sand filter at either loading rate.

7.5 Comparison of Percolation Area and Stratified Sand Filter

In the percolation area, it was found that the greatest reduction in COD concentrations occurred between the SE and the red depth plane while the greatest reduction in *ortho*-phosphate concentrations occurred between the blue and black depth planes. When the difference in loading rates between the SE and the black depth plane was compared, it was found that, while there had been complete removal of enteric bacteria and a reduction of COD to almost background levels, the effluent still contained a substantial nutrient load (Table 7.11).

The sand filter was used as a polishing filter on this site and only had a moderate enhancement on the secondary effluent when compared to the standard percolation trenches, although it should be remembered that it requires a significantly smaller footprint. The nitrogen loads down through the subsoil are still high, although there is a moderate 30% reduction in the overall load when compared to the trenches at a depth of 1.9 m. The main advantage of using the sand filter appears to be the phosphate removal in the filter associated with the mineral composition of the sand. This removal was shown to be efficient at an average hydraulic loading rate of 41 l/m^2 per day but dropped away sharply at a higher loading rate of 98 l/m^2 per day. Hence, it is recommended that the existing design figure of 60 l/m^2 per day is maintained for the stratified sand filter used as a *polishing treatment process*.

Table 7.10. *E. coli* concentrations in sand filter and subsoil (Site 4). Note: figures in parentheses indicate values during high loading trial.

	Number of samples	Number of samples with concentration (cfu/100 ml)			
		<10	10–100	101–1000	>1000
SE	2 (1)		1 (1)	1	
Coarse sand (depth 0.3 m)	2 (1)		1 (1)	1	
Medium sand (depth 0.475 m)	2 (1)		2 (1)		
Fine sand (depth 0.75 m)	2 (1)		2 (1)		
Subsoil (depth 1.3 m)	2 (1)	2 (1)			
Subsoil (depth 1.6 m)	2 (1)	2 (1)			
Subsoil (depth 1.9 m)	2 (1)	2 (1)			

Table 7.11. Comparison of average loading rates in the subsoil at the different depth planes beneath the percolation area and beneath the stratified sand filter (in italics) on Site 4.

	Loading rate (g/day)					
	COD	NO_3-N	NO_2-N	NH_4-N	Total N	PO_4-P
SE	53.1	10.34	0.06	1.64	12.09	2.07
Red depth plane (1.1–1.3 m)	27.1	12.53	0.99	0.94	13.57	1.70
	24.1	*10.85*	*0.02*	*0.59*	*11.53*	*0.06*
Blue depth plane (1.4–1.6 m)	22.2	12.01	0.07	0.74	12.82	1.20
	19.0	*9.60*	*0.02*	*0.65*	*10.27*	*0.01*
Black depth plane (1.8–1.9 m)	24.7	11.29	0.02	0.52	12.90	0.22
	16.4	*8.51*	*0.01*	*0.54*	*9.06*	*0.03*

8 Discussion and Comparisons

The trials on the four sites yielded interesting results, particularly in terms of the differences between the percolation areas receiving septic tank effluent compared to secondary treated effluent. The project has also revealed other issues worthy of consideration with respect to the existing EPA policy as set out in the current guidelines (EPA, 2000). It should be noted that the trials were only carried out for a maximum period of 12 months and that further development of the biomat (and thus percolation characteristics) on all sites may have occurred over a longer period.

8.1 On-Site Wastewater Production

The average wastewater production on the sites ranged from 56 to 123 lcd. This indicates that the EPA guideline figure of 180 lcd appears to overestimate the per capita domestic wastewater production. All sites had new on-site systems installed that were closely scrutinised during construction for the research project and so the figures are likely to represent all wastewater production without any leakage upstream of the percolation areas. It should also be noted that there were suspicions that there may have been small contributions of surface water to the wastewater network on Sites 1, 3 and 4, which would have slightly enhanced the flow rate figures. This does not mean to say that the length of trenches specified in the EPA manual should necessarily be changed however, since this project indicates that the hydraulic resistance of the biomat seems to exert the main influence in the extent of distribution of the effluent across the percolation area.

8.2 Comparison of On-site Treatment Systems

The results from the project demonstrate a clear difference between the fate of septic tank effluent on Sites 1 and 3 discharged into the subsoil and the fate of the secondary treated effluent on Sites 2 and 4 from the peat filter. Sites 1 and 3 revealed that the vast majority of COD removal occurred above the red depth plane , in the percolation gravel and top 300 mm of subsoil. Equally, there was a significant drop in the nitrogen load in this zone on both sites due to nitrification of the ammonia in the effluent and then subsequent denitrification in localised saturated pockets. As the effluent percolated down through the subsoil to the black plane on both sites a slight improvement in the quality of the effluent was noticed but the main removal had already occurred in the first 300 mm of subsoil. The high bacteriological load in the septic tank effluent was also predominantly eliminated by the red plane although there were incidences of low concentrations of viable *E. coli* (10 cfu/100 ml) sampled at isolated points at depth in the subsoil on both sites.

The installation of the secondary treatment systems in the form of a Puraflo® peat filter on Sites 2 and 4 greatly reduced the bacterial and organic load onto the percolation area. The peat filter also acted to nitrify most of the ammonia in the septic tank effluent to nitrate at both sites. A similar pattern on both sites was observed with respect to the fate of the pollutants in the percolation area, whereby the effluent was only picked up at the 0 m sampling points on all trenches. This was evidence of the muted development of the biomat along the trench due to the relatively low organic substrate levels compared to the sites receiving septic tank effluent. This lack of biomat development has the effect of promoting a more intense plume moving down through the subsoil than if the effluent had been distributed over a wider area. This can be seen from the nitrogen loads on Sites 2 and 4 which remain high (in nitrate form) all the way down through the subsoil with no significant evidence of denitrification since there is very little organic matter left in the secondary treated effluent. The overall nutrient load on the groundwater is therefore potentially higher from the more treated effluent than from the septic tank effluent which has a more balanced recipe of pollutants for natural attenuation in the subsoil (see Table 8.1). It also should be remembered that the results on Sites 2 and 4 probably represent a best-case scenario in terms of nitrogen loads since the specific design of the Puraflo® system for this project had promoted some unintentional nitrogen removal from the effluent (due to the saturation in the base of the modules) of up to 50% before entering the subsoil which would not necessarily be the case with other package plants. With regard to bacterial removal, however, no enteric bacteria were found in the subsoil at 0.6 m depth, the secondary treatment step removing significant quantities, although other incidences of *E. coli* were found on both sites at the lower black depth plane. There were also measured

Table 8.1. Comparison of average total nitrogen loading rates in the subsoil beneath the percolation areas on all sites. Note: the measured load rates on Sites 3 and 4 have been multiplied by two to give the comparative equivalent loads to Sites 1 and 2 where the effluent had been distributed across four trenches.

	Site 1 (STE)	Site 3 (STE)	Site 2 (SE)	Site 4 (SE)
	Total N load (g/day)	Total N load (g/day)	Total N load (g/day)	Total N load (g/day)
Effluent (STE/SE)	22.6	17.1	18.0	24.2
Red depth plane (–0.3 m)	8.8	9.1	17.0	27.1
Blue depth plane (–0.6 m)	6.6	9.4	16.6	25.6
Black depth plane (–1.0 m)	7.4	3.3	–	25.8

incidences of enteric bacteria at both the 10 m and 20 m sampling points on Site 4 where the effluent was known not to have reached.

The results from the sites have shown that, under the subsoil conditions tested, the septic tank system with a carefully constructed percolation area provided a comparable, if not better, attenuation of the chemical pollutants in on-site domestic wastewater effluent compared to the secondary treatment system with percolation area. The evidence from this research indicates that the septic tank effluent had achieved an equivalent quality to the secondary treated effluent after percolating through 0.6 m depth of unsaturated subsoil. However, the secondary treatment system does seem to ensure a slightly higher removal of enteric bacteria in the subsoil compared to the septic tank effluent where more frequent isolated incidences of low concentrations of indicator bacteria were found. It must be stated, though, that the levels of enteric bacteria found in the subsoil on all sites were very low and, as demonstrated on Sites 2 and 4, such levels could be attributed to non-anthropogenic sources or possibly to sampling and analytical errors. However, due to the relatively low number of samples analysed over the course of the project, more extensive study on the microbiological quality of the effluents would be required before definitive conclusions can be made.

8.3 Comparison of Subsoils

The on-site effluent from the four sites was discharged into different subsoils, all with an unsaturated depth greater than 2 m, classified according to the percolation test T-values, as follows:

Site 1: T-value 15 (septic tank effluent)

Site 2: T-value 29 (secondary effluent)

Site 3: T-value 33 (septic tank effluent)

Site 4: T-value 52 (secondary effluent).

It might have been expected, therefore, that Site 1, with the fastest percolating subsoil, would have demonstrated the slowest development of lateral distribution of the effluent across the percolation area. However, the opposite result has been obtained whereby Site 1 was the only site where effluent was shown to be distributed along the whole length of the trenches across the entire percolation area. On Sites 2 and 4, this can potentially be explained by the much reduced biomat formation due to low organic loads in the secondary treated effluent, suggesting that the development of the biomat (a function of both the effluent and subsoil characteristics) has the biggest influence on percolation and distribution over the area. Site 3, however, with highly concentrated organic effluent and a T-value of 33 would have been expected to behave similarly to Site 1, whereas the effluent was only reliably picked up at the 0 m sampling points on the trenches, although there were incidences of effluent reaching the 10 m mark towards the end of the trial period, particularly after higher flow events. The apparent lack of biomat formation on Site 3 could be attributed to a number of factors: the trial period being shorter which included the loss of 5 weeks effluent during the high loading trial on the stratified sand filter, the possibility of preferential flowpaths due to the presence of gravel and cobbles within the subsoil matrix, and the lysimeters being installed slightly outside the effluent plume. It could also be evidence of non-isotropic subsoil conditions on the site compared to the results gained from the site investigation.

There is no evidence that a T-value of 52 creates any particular problem for the secondary treated effluent in terms of ponding. Indeed, more slowly percolating subsoil should act to distribute the effluent more widely along the trenches and increase residence times, although this could not be observed from the limited sampling positions along the trenches on Site 4.

Finally, one main difference between the subsoils that could be observed was that *ortho*-phosphate removal was seen to be dependent on subsoil characteristics which varied between the different subsoil layers on each site. For example, the high clay content in Sites 1 and 3 proved to be excellent for phosphate adsorption whereas little phosphate removal on Sites 2 and 4 occurred until the effluent reached the black depth plane at which depth there was a change in the subsoil characteristics. Another reason for this, however, could be that the adsorption of phosphate was suppressed due to the more acidic nature of the secondary treated effluent arising from the nitrification of the effluent in the treatment plant and lack of recovery of pH, with subsequent denitrification in the subsoil, as was observed in Sites 1 and 3.

8.4 Comparison of Stratified Sand Filters

The two stratified sand filters performed slightly better than the equivalent parallel percolation areas on both sites. The main advantage of the stratified sand filter compared with the standard percolation area was that it enables a smaller footprint to be used; however, it also requires pumping with associated maintenance.

The stratified sand filter has been used as a successful secondary treatment process on Site 3 but its design hydraulic load should be reduced to 30 l/m^2 per day to prevent hydraulic surcharge created by the fine sand layer and also the breaking through of bacteria. Indeed, the specification of the fine sand layer should be examined in more detail as it does not appear to be achieving very much apart from limiting the hydraulic capacity of the filter. The organic loading of the filter was 41 g COD/m^2 per day which is comparable to many of the sand filters considered in the Literature Review (EPA, 2004a). This confirms that a hydraulic loading rate of 30 l/m^2 per day would appear to be a reasonable design figure for Irish conditions.

The sand filter was used as a polishing filter on Site 4 and only achieved a moderate enhancement to the quality of the secondary effluent when compared to the standard percolation trenches. The main advantage was in phosphate removal which was shown to be efficient at an average hydraulic loading rate of 41 l/m^2 per day but dropped away sharply at a higher loading rate of 98 l/m^2 per day. Hence, it is recommended that the existing design figure of 60 l/m^2 per day is maintained for use of the stratified sand filter as a polishing treatment process. It should be noted that the *ortho*-phosphate removal in both the sand filters was attributed to the presence of goethite in both the coarse and medium sand layers. The mineral composition of sand will differ according to its source and so such phosphate removal in sand filters may not always occur. The adsorption capacity of the sand is also finite and will reduce with time.

8.5 Construction of On-site Systems

The construction of four separate percolation areas and two stratified sand filters for the project provided an interesting exposure to the existing practice of on-site system installation amongst practitioners in Ireland and also the practicality of using the EPA guidelines (EPA, 2000). It seems to be common practice for builders to divert at least some storm water drains into the septic tank, presumably because this saves on the expense and time involved in laying extra pipework. Although this did not seem to significantly affect the hydraulic loading rates on the sites chosen for this project, which were under the constant scrutiny of a research team, the practice would probably be much more acute in the normal situation where builders are effectively unsupervised.

A major weakness in the implementation of the guidelines is the question of how to achieve an even effluent distribution between percolation trenches. Trials carried out both on site and in the laboratory proved that the current distribution box designs available in Ireland fail to distribute evenly between four trenches at the range of hydraulic loads experienced from on-site wastewater disposal, even if they are installed with care and are exactly level. Again, on-site experience demonstrated that the correct distribution of effluent did not appear to be an issue that was of particular concern during the installation of on-site systems and yet should be considered fundamental to the whole principle of on-site wastewater treatment and disposal.

9 Conclusions and Recommendations

9.1 Conclusions

For the range of subsoil characteristics tested, the septic tank and percolation system provided a comparable treatment performance with respect to groundwater protection to the packaged secondary treatment system without the need for ongoing maintenance or energy consumption. At the sites investigated, there did not appear to be any advantage in specifying 1.2 m depth of unsaturated subsoil for septic tank effluent but only 0.6 m depth for secondary effluent. The evidence from this research indicates that the septic tank effluent has achieved an equivalent quality to the secondary treated effluent after percolating through 0.6 m depth of unsaturated subsoil. The extra 0.6 m of unsaturated subsoil required for septic tank effluent can thus be considered to act as a safety buffer, particularly in terms of microbiological pollutants, for example on sites with high permeability subsoil (low T-values).

The majority of the treatment of the septic tank effluent took place in the distribution gravel and the first 300 mm of subsoil where there was also a reduction in the total nitrogen load. The 1.2 m of unsaturated subsoil did not fully remove all enteric bacteria from the septic tank effluent. Isolated incidences of low concentrations of *E. coli* were found in the subsoil on both septic tank sites.

Secondary treated effluent discharged onto a percolation area did not appear to develop a significant biomat and hence the effluent was concentrated over a relatively small area. Secondary treated effluent did not receive significant treatment in the subsoil (with the exception of phosphate which is dependent on the mineral characteristics of the subsoil) and resulted in higher nitrogen loads moving down to the groundwater when compared to the septic tank effluent percolation system. However, the secondary treatment systems significantly reduced the on-site wastewater bacterial loads to levels where only one incidence of enteric bacteria was found in the subsoils across both sites.

No discernible differences in treatment performance could be found between the sites according to their different percolation characteristics (T-values in the range 18–52). The actual distribution of effluent and percolation characteristics seemed to depend more on the development of the biomat which is a function of the organic load in the effluent.

The stratified sand filters performed slightly better compared to the percolation areas on both sites receiving septic tank and secondary treated effluent, respectively. They fared particularly well with regards to phosphate removal which was demonstrated to be due to the particular mineral composition of the sand used in the filters. A stratified sand filter used as a secondary treatment process should be designed to receive a hydraulic loading rate of not more than 30 l/m^2 per day to prevent ponding in the base and breaking through of bacteria. A stratified sand filter used as a polishing filter should be designed to receive a hydraulic loading rate of 60 l/m^2 per day to optimise phosphate removal.

The current distribution boxes available in Ireland do not distribute the effluent effectively. Emphasis should be placed on even distribution between trenches in the guidance manual and the development of a functional design. The installation of on-site systems also needs to be regulated since there is currently no guarantee that, after a thorough site investigation, the systems specified in the guidelines will actually be installed below ground surface due to poor work practices in the industry.

The wastewater generation in the four sites was much lower than the EPA guidance value of 180 lcd: a value of 100 lcd would seem to be closer to the reality for individual family houses.

9.2 Recommendations for Future Research

This research project has only looked at the sites for a maximum period of 12 months. Hence, longer term trials are needed to assess the effect of the development of the biomat over a period of years on sites receiving septic tank and secondary effluent. Such research should also consider the existence of preferential flowpaths and whether they become blocked with time, especially with septic tank effluent. There should also be further trials targeting sites with high permeability subsoils (T-values in the range 1–5) which have not been considered here and appear to be of high concern to the planning authorities. These trials should particularly focus on the fate of bacteria and viruses. Equally, further trials should be carried out on sites for secondary effluent discharging into subsoils with T-values greater than 75 to assess whether the reduced permeability promotes more extensive lateral distribution of the effluent.

In terms of the engineering aspects of the project, urgent consideration needs to be given to the development of an effective distribution box for on-site systems, as discussed previously. There should also be research into methods of distributing secondary treated effluent wider over the percolation area and also the means of introducing a simple denitrification retrofit for such package treatment plants.

The project has evaluated only one design of stratified sand filter which has raised several other areas for further research. The effect of different sand sizes on the performance of the stratified sand filter needs to be more thoroughly investigated and also whether stratification makes any significant difference to treatment performance compared to a monogrammed filter. Such research should also be carried out using sands which are widely available in Ireland to make the findings more relevant to the practical installation of these systems. Other research projects could look at the effect of ventilation pipes down into sand filter to improve aeration at depth and thereby potentially increase the design loading rates. The design of a balanced distribution manifold for filters which prevents blockages also needs to be looked into. Finally, research should be carried out into the concept of using a sacrificial layer of sand, particularly in areas of nutrient sensitivity whereby an adsorptive layer of sand can be replaced by fresh sand periodically when its capacity has been reached. This would also involve the analysis of sand types available in Ireland with regard to their phosphate removal efficiency.

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