A Comparison of Stratified Sand Filters and Percolation Trenches for On-site Wastewater Treatment

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Abstract: Two separate on-site wastewater treatment systems were constructed at premises in eastern Ireland, one using a conventional septic tank, the other using a septic tank followed by a naturally-aerated peat filter. The respective effluents were then split at each site whereby half was directed into percolation trenches and the other half pumped into intermittently dosed, stratified sand filters for a year. Samples were taken at different depths in the subsoil beneath both the percolation trenches and sand filters and analysed for chemical and bacteriological determinants. Samples were also taken at different layers within the sand filters which were tested at various hydraulic loading rates. Although the sand filters require a much smaller surface area, the pollutants were attenuated to the same level in the subsoil when compared to the percolation trenches. As a result of the trials, the revised recommendations for design hydraulic loading rates were 30 L/m^2 day for filters receiving septic tank effluent and 60 L/m^2 day for filters receiving secondary treated effluent.

CE Database subject headings: Wastewater; Waste treatment; Septic tanks; Trickling filters; Unsaturated soils.

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Introduction

In Ireland, wastewater from over one third of the population is treated in small-scale independent systems (DoELG et al. 2004), the most common treatment application being the conventional septic tank system with percolation area. Groundwater resources provide over 25% of all water supplies (EPA 2005) and hence protection from contamination by on-site domestic wastewater effluent is crucial. Indeed, in many areas over 30% of private domestic and farm wells are polluted by microbiological contamination (Daly 2003). Due to the ever-increasing pressure on the planning authorities for development in more rural areas, a rigorous site assessment procedure is now being introduced according to guidelines from the Irish Environmental Protection Agency (EPA 2000). This is based upon a desk study followed by an on-site trial hole inspection and percolation test which aims to determine the vulnerability of local groundwater resources which are especially at risk in areas where the bedrock or water table is close to the surface or where subsoils of high permeability underlie the site. In situations where a septic tank installation is not suitable, some form of secondary treatment system can be installed such as mechanically-aerated systems or filter systems to improve the quality of the effluent before discharge to the subsoil. One of the options promoted 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. The immediate advantage of such a system is that it requires a much smaller plan area compared with the equivalent plot needed for a percolation field.

Field studies have been carried out into the fate of the pollutants within the subsoil beneath percolation areas (Reneau et al. 1989; Jenssen and Siegrist 1990) with many focussing particularly on the fate of pathogens (Nicosia et al. 2001; Schijven and Šimůnek 2002). The

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results, however, are difficult to extrapolate into an Irish context due to indeterminate percolation rates and different climatic conditions. Intermittent sand filters have been used effectively for wastewater treatment for individual premises up to larger scale (1700 p.e.) applications (Mottier et al. 2000). Various studies have shown that single stage intermittent sand filters, loaded organically and hydraulically at 5-20 gBOD/m^2 day and 40-100 L/m^2 day respectively, attain removal efficiencies of 90% COD, 95% BOD, 30% total nitrogen, 40% total phosphorous and 2-4 log removal of faecal coliforms (Sauer et al. 1976; Pell et al. 1990; Darby et al. 1996; Nichols et al. 1997; Widrig et al. 1998; Van Buuren et al. 1999). The effluent from sand filters can be of high quality with typical concentrations of 5 mg/L or less of BOD and SS, as well as nitrification of 80% or more of the applied ammonia (USEPA 1999). For example, more or less complete nitrification of septic tank effluent and four-log removal of faecal coliforms has been achieved using a stratified sand filter at hydraulic loading rates up to 60 L/m^2 day (Nichols et al. 1997). At higher loading rates denitrification can occur in anaerobic regions of the filter as a result of organic matter build-up promoting saturated conditions (Bahgat et al. 1999; Van Buuren et al. 1999). However, higher loading rates can have a negative influence on performance and increase filter cleaning frequency (USEPA 1985; Van Buuren et al. 1999). One study found that ponding occurred on sand filters if COD loads exceeded 47 g/m^2 day (Darby et al. 1996) and a maximum loading rate of 24 gBOD/m^2 day has been suggested (USEPA 1985). Higher loading rates up to 37 gBOD/m^2 day though have recently been demonstrated without clogging by the use of a hybrid system using a horizontal flow biofilm reactor above the filter (Rodgers et al. 2006).

The aerobic conditions in sand filters are maintained through the intermittent application of the effluent and oxygen consumption is balanced by the renewal of the air phase with atmospheric air by the means of convective and diffusive exchanges through the surface (Boller et al. 1993). The EPA (2000) recommends a hydraulic loading rate of 40–100 L/m^2

day and in general, studies have shown that slight improvements to treatment performance of filters can be gained by small-volume, short hydraulic flushes as opposed to more frequent, larger volume doses (Boller et al. 1993; Darby et al. 1996; Rodgers et al. 2006) which concurs with experience on other biofilm processes such as large-scale trickling filter applications. Dosing frequencies of between 4 and 24 times per day have been reported in the above studies and it would appear that a design value in the region of 12 doses per day gives an optimal treatment performance, although this is obviously also dependant on the overall hydraulic loading rate.

Several trials have also looked at recirculating sand filters (Gold et al. 1992; Nichols and Aboud 1995; Van Buuren et al. 1999; Christopherson et al. 2001; Healy et al. 2004) whereby a fraction of the effluent is pumped back to the join the influent normally at a recirculation ratio in the range of 3-5:1. This generally has the effect of increasing the hydraulic loading rate and dosing frequency but reducing the concentration of influent which can improve the mass transfer characteristics through the biofilm. It is also done to target nitrogen removal whereby the recirculated nitrified effluent can be passed through an anoxic zone (an upflow anaerobic process for example), to achieve denitrification before re-entering the filter (Urynowicz et al. 2007).

Phosphorous removal in sand filters is primarily due to the mineral content of the sand used and is controlled mainly by adsorption and mineral precipitation reactions. The adsorption capacity of a sand is regulated by the occurrence of natural minerals such as iron, calcium and aluminium but also affected by the chemical characteristics of the effluent (Redox potential and pH) within the filter. Although several studies have shown sorption of phosphate onto calcareous sands (Arias et al. 2001), non-calcareous sands have been shown to be effective at phosphate removal in certain cases, for example in an aluminium enriched sand (Robertson 2003).

The removal of microbiological organisms in sand filters has been measured in several studies (Van Buuren et al. 1999; Mottier et al. 2000) indicating a fall off in performance at higher loading rates (above 50 gCOD/m^2 day). However, the application of a 0.8m sand filter as a polishing filter for the disinfection of secondary treated effluent has been shown to be effective at hydraulic loading rates of 165–350 L/m^2 day giving 5.0-3.8 log removal of faecal coliforms respectively (Salgot et al. 1996). Several detailed studies have also looked at the removal of both virus and bacterial pathogens and indicators in laboratory sand columns. In general the removal of both bacteria and viruses has been shown to occur within the first 0.3 m depth of sand (Gross 1990; Hua et al. 2003) which has also been confirmed by a few in-situ trials carried out in the sandy subsoils (Nicosia et al. 2001) and dunes (Schijven et al. 1999) using dosed bacteriophages (viruses).

A three-year project investigating four separate sites (Gill et al. 2005a) was funded by the Irish EPA to test out the new guidelines (EPA 2000) which had been developed. The project included an ongoing field study at two sites, 7 km apart, located in County Wicklow in eastern Ireland in order to assess the effectiveness of such stratified sand filters under prevailing conditions. Two separate sites were constructed, one receiving effluent from a septic tank, the other receiving effluent from a secondary treatment peat biofilter, following which the effluent was split evenly between a stratified sand filter and two, gravity fed, 20 m long percolation trenches.

Materials and Methods

Site Selection and Construction

The site selection was carried out in strict accordance with the EPA recommendations (EPA 2000). In general, a minimum unsaturated subsoil depth of 1.2 m below septic tank percolation fields is required (or a minimum 0.6 m unsaturated subsoil for secondary treated effluent) before the site may be deemed suitable for on-site treatment of domestic wastewater effluent. In addition a falling head percolation test (Mulqueen and Rodgers 2001), known as the T-test, must fall within the specified range of 1 to 50 (minutes per 25 mm of water level fall). In this study both sites had relatively slow draining subsoils which were characterized according to BS5930 (BSI 1981) as gravelly-clayey sands. Site A had a 4000 litre septic tank installed with a T-value of 33 and Site B had a naturally-aerated peat filter (*Puraflo*®, Bord na Mona) installed downstream of a 4000 litre septic tank and subsoil of a T-value of 52.

Both sites had identical percolation areas constructed to the recommended EPA specifications consisting of 110 mm diameter, perforated PVC pipe bedded in 300 mm of gravel in a 450 mm wide trench at a slope of 1:200. The effluent was split using a modified distribution box (Gill et al. 2005b) so that half the effluent went onto the trenches and the other half pumped onto a stratified sand filter (see Fig. 1). The sand filter was designed and constructed in accordance with the EPA recommendations using the design loading rate of 60 L/m^2 day. Based on the design wastewater production rate of 180 litres per head per day, the surface area of each filter was 3 m by 2 m. The constructed filters were 1.05 m deep and comprised of layers of sand, decreasing in particle size with depth from 1.0 to 0.1 mm diameter (see Fig. 2). The effluent was pumped onto the sand filter from a pump sump with float switch which was monitored by an ultrasonic level probe (*The Probe*, Siemens Milltronics) in order to determine the flow and also the dosing frequency.

Suction lysimeters (Soilmoisture Equipment Corporation) were installed on each site to collect samples of percolating effluent in the subsoil. They were installed at the beginning (0 m), middle (10 m) and end (20 m) of each trench to nominal depths of 0.3 m, 0.6 m and 1.0 m below the invert of the percolation trenches respectively (as shown in Figure 1a), which represent depths of 1.1 m, 1.4 m and 1.8 m depth below the ground surface. Six suction lysimeters were also installed beneath each sand filter, two sets on either down-slope side of the filter at the same depths. Within the sand filters, gravity cups were installed (two per level) to capture effluent en route down through the sand matrix. A piezometer was also installed in each sand filter to monitor the depth of effluent at the base. Each site also had six tensiometers (Soil Measurement Systems) installed to obtain a profile of soil moisture tension across the percolation area, and a weather station to gain rainfall and evapotranspiration data to calculate the diluting effect of net recharge in both the subsoil sand filters throughout the year.

Composite samplers (*xian 1000*, Bühler Montec), which sampled the septic tank and secondary effluent every hour over a 24 hour period, were installed on both sites. Both sites started to receive effluent in June 2003. On the 22 December 2003 the effluent going into the trenches was blocked, hence doubling the loading rate on the filters for a period of five weeks.

Sampling and Analysis

The day before sampling all suction lysimeters were put under a suction of 50.7 kPa (50 cbar) and the gravity samplers in the sand filters were emptied. All samples were collected 24 hours later and taken directly to the laboratory for analysis. Diurnal samples were also collected from the automatic samplers. All samples were analysed for chemical parameters using the

Spectroquant Nova 60$^{®}$ spectrophotometer and associated reagent kits (USEPA approved) for chemical oxygen demand (COD), ammonium (NH_4-N), nitrite (NO_2-N), nitrate (NO_3-N), ortho-phosphate (PO_4-P) and chloride (Cl). Samples were also sent periodically to an accredited external laboratory and analysed for enteric bacterial indicators: total coliforms and *E. coli*.

Results and Discussion

Comparison of Trenches and Sand Filter

Chloride was used as a crude tracer for the preliminary data analysis from both sites since it does not take a significant part in any geochemical reactions (Marshall et al. 1999). Hence, chloride concentrations at the three sample positions along each trench (0 m, 10 m and 20 m) were averaged between the two trenches at the same depth. This enabled the identification of the appropriate sample points which were receiving the percolating effluent (assuming isotropic and homogeneous soil properties) and, in consequence, allowed a reasonable estimate to be made of the extent of any biomat development. This analysis was also corroborated by graphs of tensiometer measurements against effective rainfall on both sites which clearly show the more continuous effect of wetting by the effluent compared to the more seasonal wetting effect of the rainfall. For example, Fig. 3(a) shows the results from instrumentation on Site B the start of the trenches (0 m) where effluent was known to be percolating which can be compared to Fig. 3(b) at the end of the trenches (20 m) which received no effluent during the project. It should be noted that the sites were still in their first year of operation and so were in the early stages of biomat development. Trials on previous sites had demonstrated that the reduced organic loading in secondary treated effluent had inhibited the formation of a biomat, thereby preventing distribution of the effluent along the full length of the trenches (O'Súlleabháin 2005).

Loading rates at the different depths were calculated on a daily basis according to a mass balance of effluent flow plus any rainfall recharge. The rainfall available for dilution at the depth planes over the project duration, or effective rainfall, was calculated using rainfall figures and evapotranspiration figures obtained from the weather station data measured at each site based on the Penman-Monteith method (FAO 1998). The potential evapotranspiration (PE) calculation was used to calculate actual evapotranspiration (AE). Where the soil moisture deficit (SMD) was greater than 40 mm the AE was considered to occur at a slower rate than PE and was calculated using the Aslyng scale. Daily effective rainfall (recharge) was then calculated by subtracting the daily AE and accumulated SMD figures from the daily rainfall measurement.

Site A – Septic Tank Effluent

The flow from the septic tank to the percolation area was by gravity and so constantly variable but the average total flow from the dwelling (one adult and three children) was 329 L/day discharged at an average flow rate of 3.7 L/min. The mean chloride concentration from the septic tank was 76 mg/L (inter-quartile range 58 to 92 mg/L). The analysis of the chloride concentrations on Site A (see Fig. 4) reveals that the high concentrations, indicative of the septic tank effluent, are found only at the 0 m sampling points at all three depths, indicating that the development of the biomat had not yet reached 10 m along each trench.

Hence, the average loading rates measured at each depth at the 0 m sample points only are considered and compared with the same depths in the subsoil below the stratified sand filter (see Table 1). It is clear from these results that most of the effluent attenuation beneath both the trenches and the sand filter had occurred between the septic tank and the 1.1 m depth plane, with little change in the pollutant loading rates at greater depths. The loading rates for most of the parameters at this depth seem to be broadly similar for both systems.

The septic tank effluent that had been nitrified passing through the filter (as discussed later) can be seen to undergo denitrification below the sand filter between the 1.1 m and 1.4 m depth. This is evidenced by the resultant rise in pH and has probably been promoted by saturated anoxic conditions in the subsoil due to the localised high hydraulic loading rate beneath the sand filter. This same loss of nitrogen from the trench effluent starts to occur at the deeper level between 1.4 m and 1.8 m. Bacteriological analyses carried out during the trials revealed concentrations of *E. coli.* in the septic tank effluent to be 3 x 10^5 cfu/100 mL. However, all samples taken beneath the trenches or beneath the sand filter were found to be below the limit of detection (<2 cfu/100 mL) for *E. coli.* meaning that the removal had been achieved within the first 0.3 m of subsoil beneath the trenches or within the sand filter.

Site B – Secondary Treated Effluent

The flow was pumped periodically to the peat filter and then discharged by gravity to the percolation area. The average total flow from the dwelling (2 adults and 3 children) over the monitoring period was 492 L/day discharged at an average flow rate of 4.3 L/min. The mean chloride concentration from the peat filter was 59 mg/L (inter-quartile range 42 to 72 mg/L). Analysis of chloride levels at Site B (Fig. 5) shows significantly lower concentrations at the 10 m and 20 m sample positions (apart from a single peak in late October). This again suggests that the biomat has not developed far along the trench, as expected for the secondary treated effluent, and hence the 0 m sampling points have been taken to be the most representative in order to assess the pollutant attenuation.

The results for the average pollutant loadings on Site 2 are presented in Table 2. These loads reveal that the levels in the subsoil beneath the sand filter are slightly lower than beneath the trenches. The exception is the ortho-phosphate load which is significantly lower at this point beneath the sand filter compared to the trenches, although the loads do reduce with depth in the subsoil beneath the trenches which is discussed later. Interestingly, compared to the septic tank effluent in Site A, there does not appear to be the same level of denitrification occurring in the subsoil, as shown in Fig. 6, which could be due to relatively lower organic concentrations (the heterotrophic denitrifying bacteria are facultative anaerobes and need carbon in addition to using nitrate as an electron acceptor in anoxic conditions) and a faster percolating, more aerated effluent. Slight evidence of denitrification can be seen beneath the sand filter, again probably due to anoxic saturated conditions due to the higher hydraulic loading rate. The bacteriological analyses revealed a large 3-4 log removal of enteric bacteria across the peat filter with average *E. coli* concentrations of only 60 cfu/100 mL in the secondary treated effluent. All samples taken at all depths beneath the trenches or beneath the sand filter were below the limit of detection of <2 cfu/100 mL.

Sand Filter Comparison

The performance of the stratified sand filters was analysed by sampling within the filter beneath each layer of sand. The filters were subjected to a normal hydraulic loading until the end of December 2003 at which point the effluent to the trenches in both sites was blocked to promote an increased loading onto the sand filters for a five-week period, as follows.

Site A - normal loading rate = 28.6 L/m^2 day (dosing 3.5 times per day)
- high loading trial = 57.2 L/m^2 day (dosing 8.3 times per day)

Site B - normal loading rate = 41.0 L/m^2 day (dosing 7.3 times per day)
- high loading trial = 97.9 L/m^2 day (dosing 18.8 times per day)

At Site A the piezometers in the sand filters revealed no significant head at the lower hydraulic loading rate of 28.6 L/m^2 day but a continually rising head at the higher loading rate of 57.2 L/m^2 day, increasing to 0.7 m above the base after five weeks. This indicates that such a loading rate was too high for a filter receiving septic tank effluent with such a fine sand layer at the base and discharging into subsoil with a T-value of 33. At Site B, even though the subsoil has a slower percolation T-value of 52, no head level above the base was measured during either loading period indicating a much reduced biomat development due to the low organic loading compared with Site A. The organic loading rate during normal operation was 41.1 gCOD/ m^2 day which is close to suggested maximum (Darby et al. 1996) value of 47 gCOD/ m^2 day. Surprisingly the organic loading rate the during the high load trials was only 37.7 gCOD/ m^2 day due to suppressed COD concentrations during that period for some unknown reason. This would indicate that the combination of hydraulic load and biofilm build up due to the organic load during the normal filter operation was close to the limit since the filter started to back up under higher hydraulic but lower organic loading rates.

Analyses of nitrogen species are presented for the sand filters on both sites (Tables 3 and 4 and Figure 6). On Site A, at the lower hydraulic loading rate of 28.6 L/m^2 day, significant nitrification has occurred within the filter with subsequent denitrification suggested in the finer sand lower down. However, at the higher loading rate (approaching the EPA design value of 60 L/m^2 day) nitrification was not complete by the base of the filter with much of the nitrogen still in an ammoniacal form.

At Site B, the septic tank effluent was nitrified in the peat filter before being dosed onto the sand filter with the associated pH drop (due to the alkalinity requirement for the process). No particular evidence of denitrification can be seen in the sand filter presumably due to the combination of unsaturated, aerated conditions in the filter with low organic loads and a shortage of carbon, thus inhibiting the denitrifying bacteria. This pattern is similar at the higher loading levels although there was evidence of denitrification again in the lower fine sand layer arising from localised saturation at this higher hydraulic loading rate. An interesting comparison with the Site A sand filter (Figure 6), reveals that a much larger drop in total nitrogen occurs in the upper sand layer receiving the high organic load than in the corresponding layer dosed with secondary treated effluent. The organic loading rate during normal operation was 8.8 gCOD/ m^2 day and 10.4 gCOD/ m^2 day during the high load trials. The load removal was however was worse at the higher hydraulic loading rate, which to some extent contradicts the evidence in the literature stating a general improvement in performance at higher dosing frequencies.

The concentrations of ortho-phosphate passing through both filters have been noticeably reduced as seen in the subsoil results (Tables 3 and 4). A plot of the process efficiency of both filters with depth (Fig. 7) reveals an almost total removal of phosphate (k= 1.16) for hydraulic loadings in the range of 24-57 L/m^2 day. However, at the higher loading rate of 97.9 L/m^2 day the removal efficiency is markedly reduced indicating that the residence time in the filters is not sufficient for the adsorption removal process to take place effectively. This indicates that, in terms of phosphorous removal using this sand specification, a design hydraulic loading rate of 60 L/m^2 day appears to be a reasonable value for incorporation into the national guidelines. Samples of the three different sands used in the sand filters were analysed using X-ray diffraction analysis (Phillips PW1720) to reveal the respective mineral composition. Apart from the expected predominance of quartz, goethite (Fe_2O_3) was also found in the coarse and medium sands but not in the fine sand sample. Hence, the iron oxide will be acting as a site for cation exchange with the soluble phosphate. This is validated by the results which show that the largest removals were found in the medium sand layer (see Fig. 8) which was only 100 mm thick but contained the highest levels of goethite.

Finally, analysis of *E. coli* removal through the sand filters and into the subsoil below at the different loading rates for the septic tank effluent (Fig. 9), reveals a correlation between overall removal and hydraulic loading rate: removal coefficient k = –8.7 at 28.6 L/m^2 day and k = –4.6 at 57.2 L/m^2 day. Complete removal has occurred at the lower loading rate whilst there are still viable concentrations of *E. coli* discharging to the subsoil at the higher rate. In general, the main removal of bacteria occurred in the top few centimetres of the sand as reported in other studies (Hua et al. 2003). Interestingly, no such correlation for *E. coli* against hydraulic loading rate was found for Site B, with all samples below the limit of detection by the base of the sand filter irrespective of loading rate.

Conclusions

A detailed study on two sites receiving different quality effluent revealed that both treatment systems greatly reduced the chemical and biological loading rates of domestic wastewater effluent, reducing the potential for groundwater pollution. In both cases the majority of both chemical and biological treatment had occurred before the 1.1 m depth within the subsoil. The introduction of stratified sand filters discharging directly to the subsoil appears to achieve the same overall level of treatment on both sites as the standard percolation trenches which require a much larger area of land. However, the results indicate that for septic tank effluent the recommended hydraulic loading rate on relatively slowly draining subsoils should not exceed 30 L/m^2 day both due to ponding problems in the base of the filter and also to ensure the effective removal of enteric bacteria. This is low compared to other studied systems but gives a comparable organic loading rate at the top end of the spectrum due to the relatively concentrated septic tank effluents found in Ireland. Ortho-phosphate removal in the filters is related to the mineral composition of the sand used. In these trials a maximum loading rate of 60 L/m^2 day appeared to be the optimum for phosphate removal. However, it should be acknowledged that the removal efficiency would reduce over time as the potential adsorption sites become full.

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Table 1. Average loading rates at Site A under trenches (at 0 m sampling position) and under sand filter. *Note: 329 L/day split evenly between trenches and sand filter.*

Parameter	Loading Rate (g/day)						
	Septic tank effluent	1.1 m depth[*]		1.4 m depth[*]		1.8 m depth[*]	
		Beneath Trench	*Beneath Sand Filter*	Beneath Trench	*Beneath Sand Filter*	Beneath Trench	*Beneath Sand Filter*
COD	**246.3**	23.9	*15.6*	19.6	*12.6*	16.7	*13.7*
NH_4-N	**8.1**	0.9	*0.31*	1.2	*0.27*	0.6	*0.37*
NO_2-N	**0.09**	0.05	*0.02*	0.12	*0.01*	0.07	*0.01*
NO_3-N	**0.4**	3.6	*2.81*	3.4	*1.92*	1.0	*1.36*
Total N	**8.6**	4.6	*3.13*	4.7	*2.19*	1.7	*1.74*
Ortho-P	**1.57**	0.07	*0.05*	0.04	*0.01*	0.02	*0.01*
pH	**7.68**	6.80	*7.10*	6.78	*6.71*	6.97	*6.99*

±

Table 2. Average loading rates at Site B under trenches (at 0 m sampling position) and under sand filter. *Note: 492 L/day split evenly between trenches and sand filter.*

Parameter	Loading Rate (g/day)						
	Secondary treated effluent	1.1 m depth*		1.4 m depth*		1.8 m depth*	
		Beneath Trench	*Beneath Sand Filter*	Beneath Trench	*Beneath Sand Filter*	Beneath Trench	*Beneath Sand Filter*
COD	**53.1**	28.0	*24.1*	22.0	*19.0*	22.0	*16.4*
NH_4-N	**1.64**	0.94	*0.59*	0.74	*0.65*	0.52	*0.54*
NO_2-N	**0.06**	0.10	*0.02*	0.08	*0.02*	0.03	*0.01*
NO_3-N	**10.4**	12.9	*10.85*	12.7	*9.60*	12.1	*8.51*
Total N	**13.1**	13.7	*11.45*	13.2	*10.27*	12.5	*9.06*
Ortho-P	**2.13**	1.71	*0.06*	1.32	*0.01*	0.20	*0.03*
pH	**6.39**	6.04	*6.68*	6.17	*6.63*	6.58	*6.86*

* depth below ground level

Table 3. Average nitrogen and ortho-PO_4 loads (g/day) in sand filter (Site A).

Note: figures in brackets indicate values during high loading trial.

Effluent sample	**NH_4-N**	**NO_2-N**	**NO_3-N**	***Total N***	**Ortho-P**	**pH**
Septic tank	8.08 (9.77)	0.09 (0.06)	0.40 (0.38)	*8.57* *(9.33)*	1.57 (1.02)	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)*	0.89 (1.09)	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)*	0.36 (0.09)	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)*	0.29 (0.11)	7.3 (7.3)

Table 4. Average nitrogen ortho-PO_4 loads (g/day) in sand filter (Site B).

Note: figures in brackets indicate values during high loading trial.

Effluent sample	NH_4-N	NO_2-N	NO_3-N	*Total N*	Ortho-P	pH
Septic tank	11.95 (35.46)	0.09 (0.40)	0.79 (5.02)	*12.83* *(40.88)*	2.24 (4.29)	7.3 (7.1)
Peat filter	1.64 (6.83)	0.06 (0.08)	11.42 (18.39)	*13.12* *(25.29)*	2.07 (3.69)	6.4 (6.1)
Coarse sand **(depth 0.3m)**	0.84 (2.81)	0.10 (0.24)	11.76 (23.52)	*12.57* *(26.57)*	1.90 (3.64)	6.7 (6.3)
Medium sand **(depth 0.475 m)**	0.66 (3.89)	0.05 (0.20)	10.68 (21.86)	*11.53* *(25.95)*	1.15 (3.44)	6.9 (6.5)
Fine sand **(depth 0.75 m)**	0.75 (1.01)	0.04 (0.12)	10.94 (21.54)	*11.65* *(22.67)*	1.17 (3.07)	6.8 (6.8)

Fig. 1. Site layout: **(a)** Cross-section and depths of instrumentation **(b)** Plan view of trenches and stratified sand filter *(not to scale).*

Fig. 2. Schematic cross-section through stratified sand filter.

Fig. 3. Site B: soil moisture tension plotted against effective rainfall for: **(a)** the 0 m sample position and **(b)** the 20 m sample position.

Fig. 4. Chloride concentrations at all sampling positions along percolation trench length (Site A). *Note: three sampling depths per sampling position.*

Fig. 5. Chloride concentrations at all sampling positions along percolation trench length (Site B). *Note: three sampling depths per sampling position.*

Fig. 6. Comparison of total nitrogen removal down through the filter and underlying subsoil to the subsoil beneath the trenches on: **(a)** receiving septic tank effluent and **(b)** secondary treated effluent.

Fig. 7. Graph of loading rate versus removal for ortho-phosphate for both stratified sand filters (Sites A and B) during both the high and low hydraulic loading trials.

Fig. 8. Comparison of ortho-phosphate removal down through the filter and underlying subsoil to the subsoil beneath the trenches on: **(a)** receiving septic tank effluent and **(b)** secondary treated effluent.

Fig. 9. Removal of *E. coli* with depth through the sand filter and subsoil (Site A).

N= number *E. coli*, N_0= Original number from septic tank.

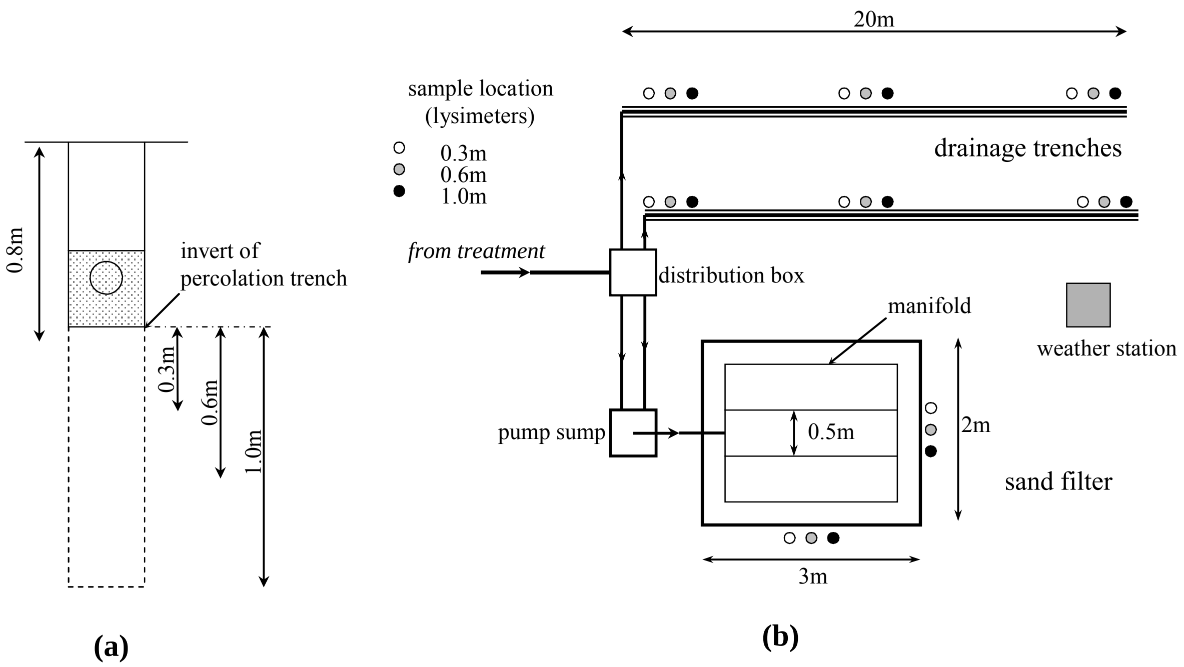


Fig. 1. Site layout: **(a)** Cross-section and depths of instrumentation **(b)** Plan view of trenches and stratified sand filter *(not to scale).*

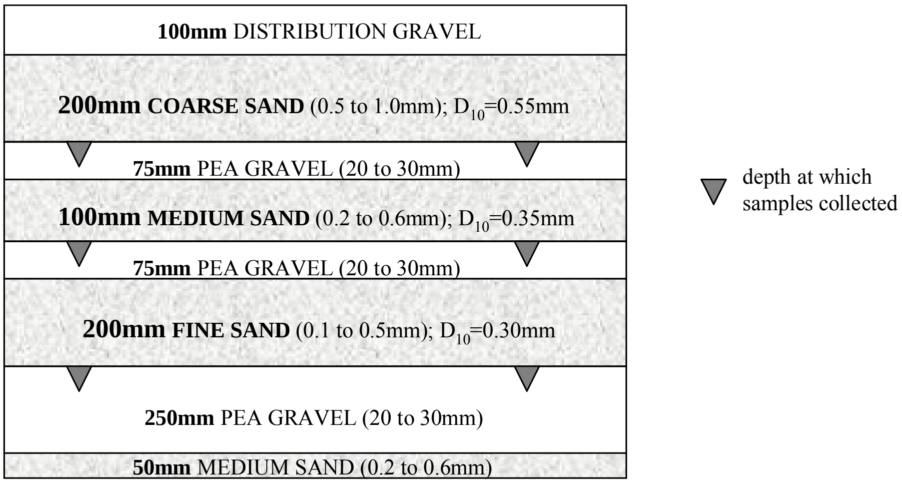


Fig. 2. Schematic cross-section through stratified sand filter.

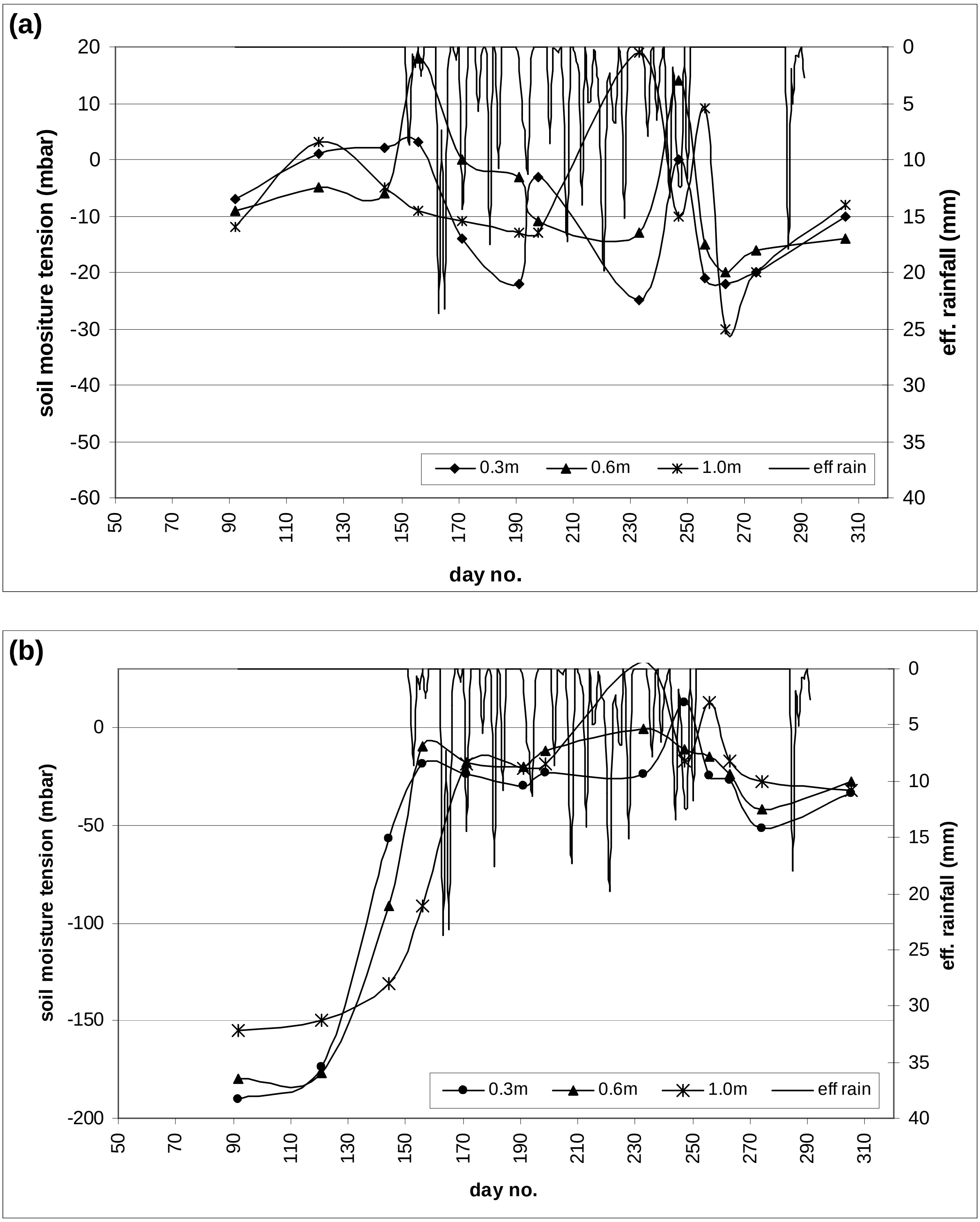


Fig. 3. Site B: soil moisture tension plotted against effective rainfall for: **(a)** the 0 m sample position and **(b)** the 20 m sample position.

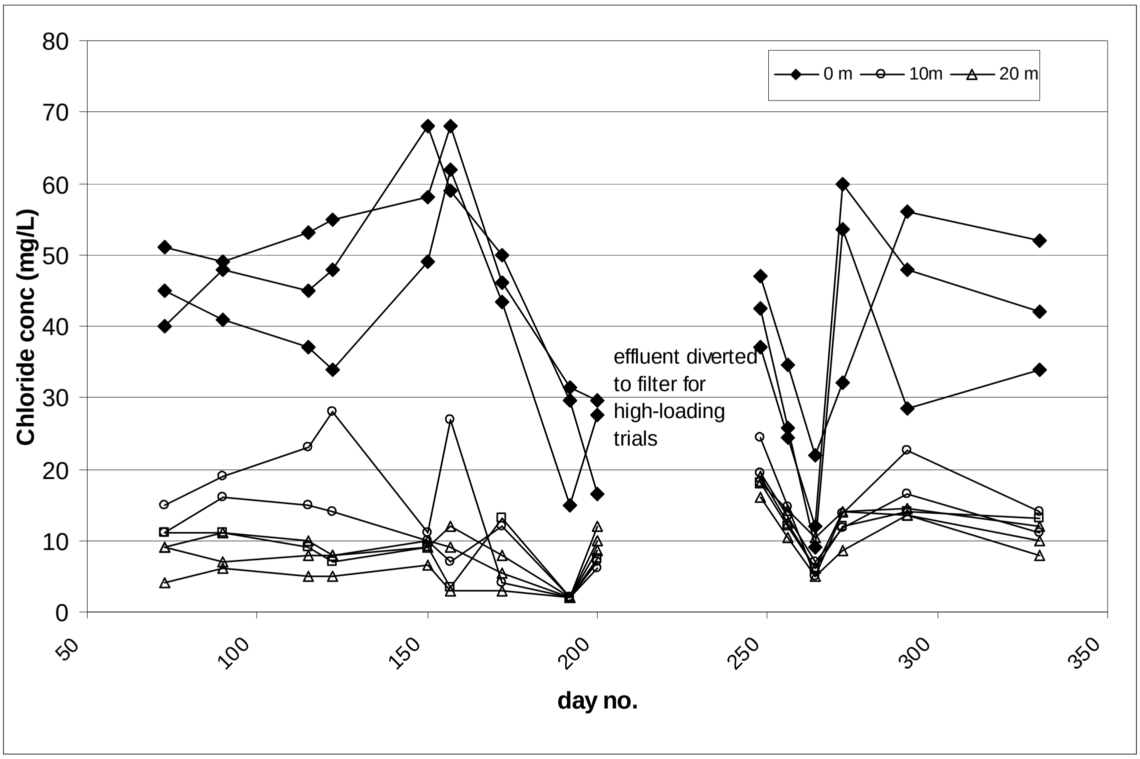


Fig. 4. Chloride concentrations at all sampling positions along percolation trench length (Site A). *Note: three sampling depths per sampling position.*

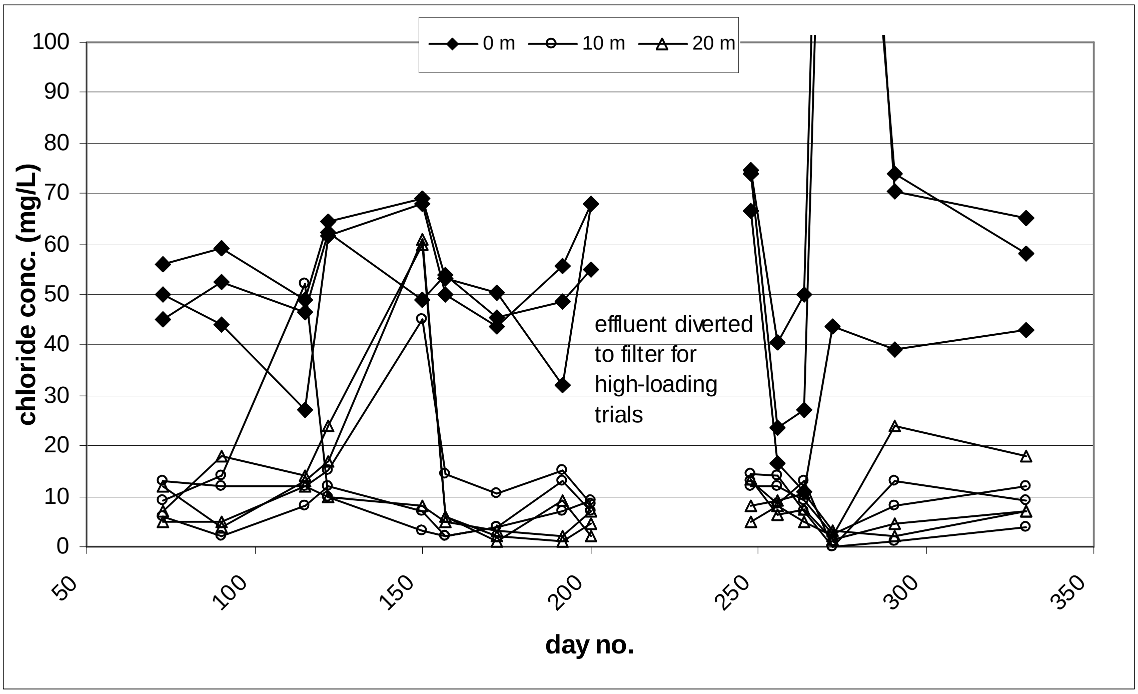


Fig. 5. Chloride concentrations at all sampling positions along percolation trench length (Site B). *Note: three sampling depths per sampling position.*

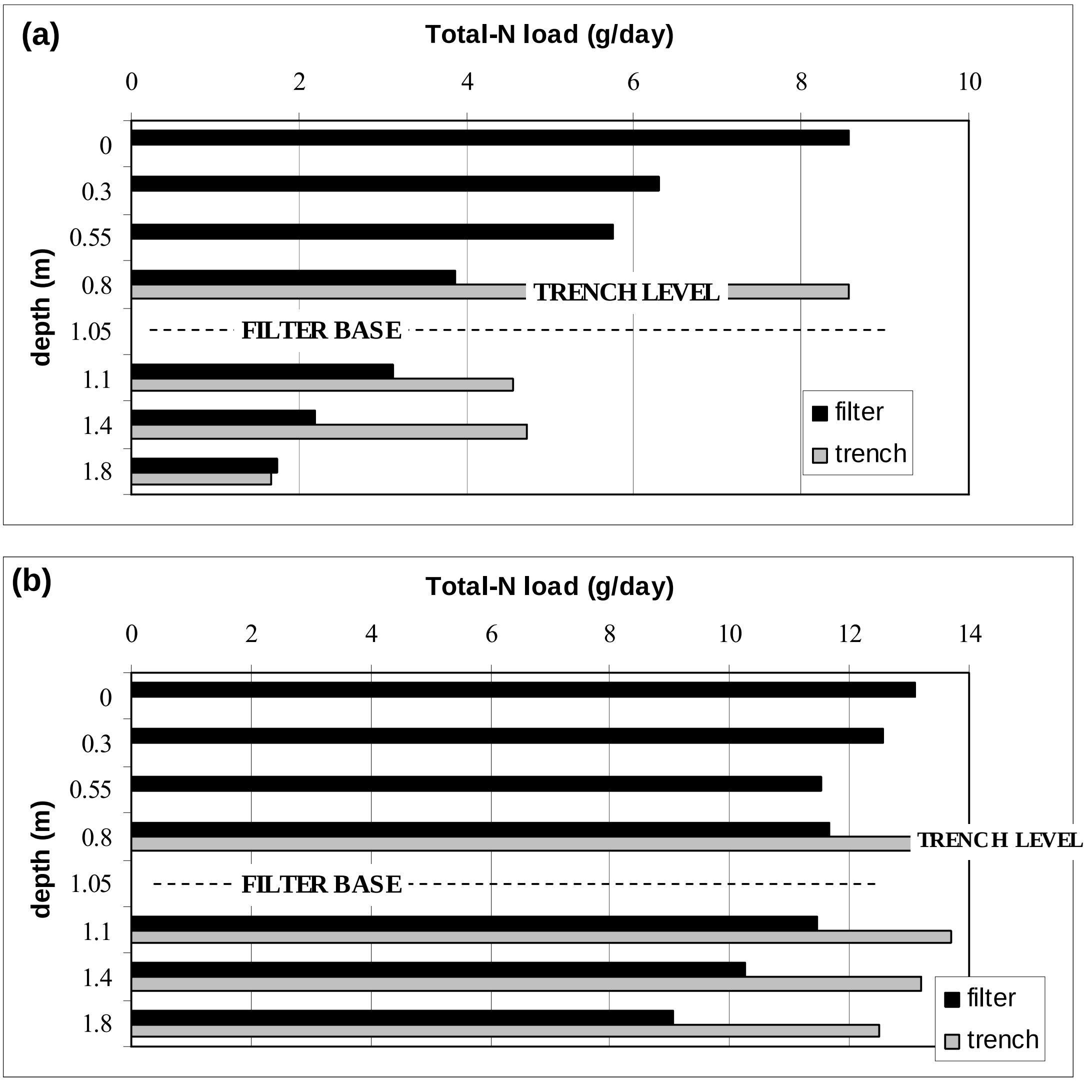
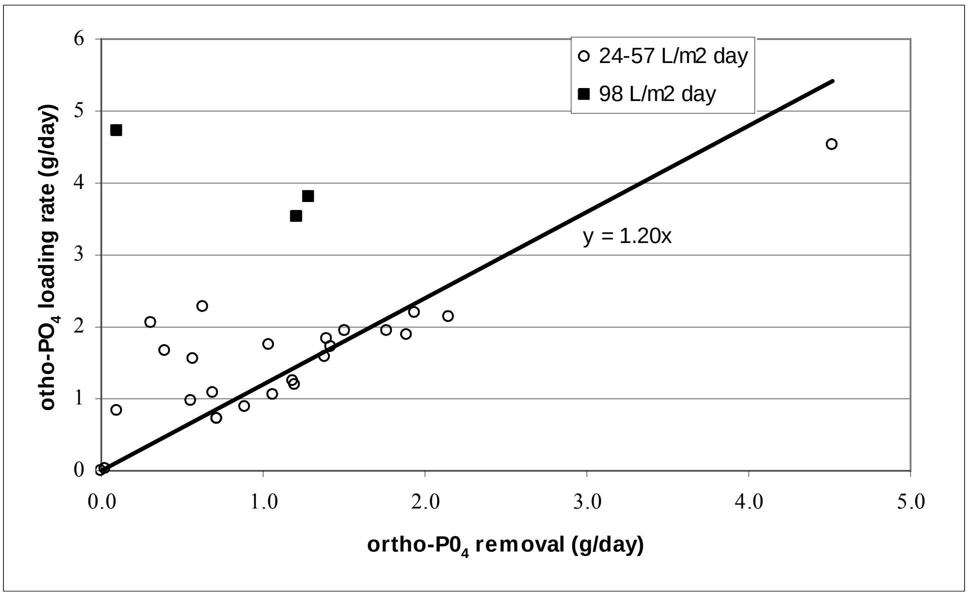


Fig. 6. Comparison of total nitrogen removal down through the filter and underlying subsoil to the subsoil beneath the trenches on: **(a)** receiving septic tank effluent and **(b)** secondary treated effluent.



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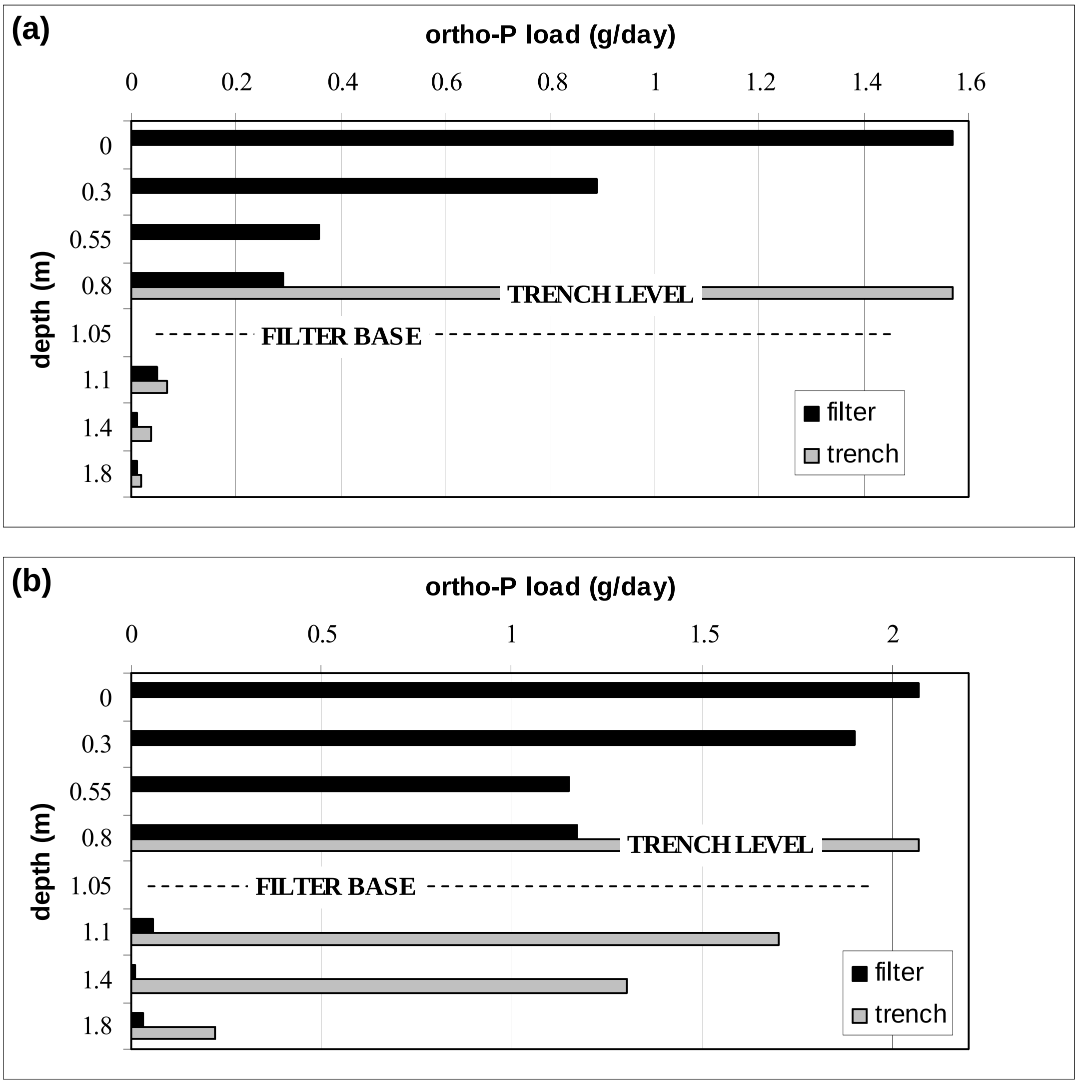

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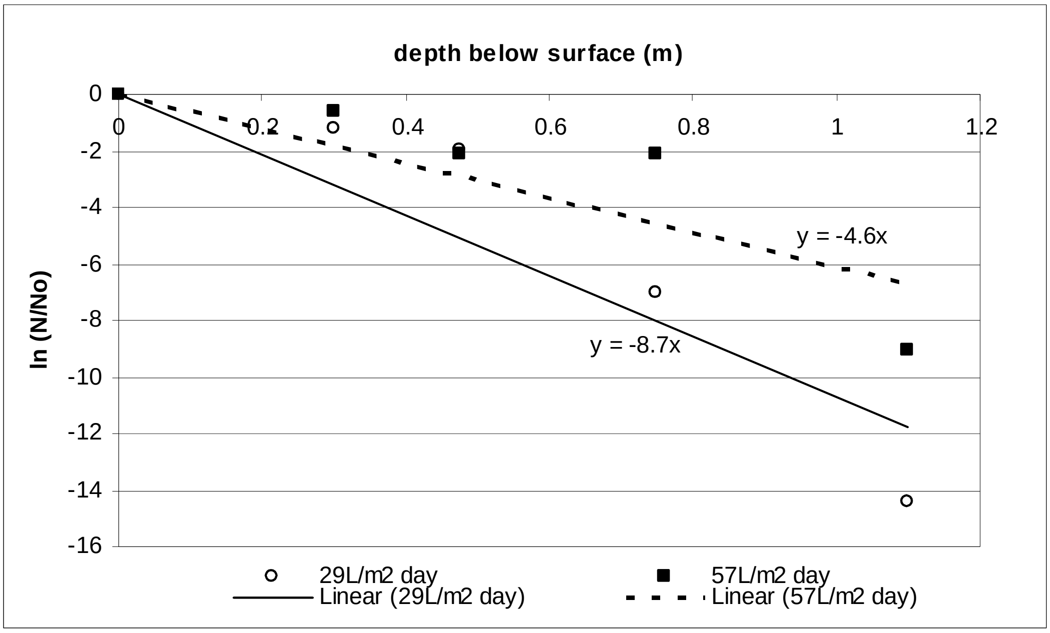

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