Constructed on-site sand filters as secondary and tertiary effluent treatment processes

L.W. Gill,[1] C. O'Súlleabháin, P.L. Veale, M. Murray
[1]Corresponding Author
[1]Trinity College Dublin, Dublin, Ireland.

Abstract

Full scale sand filters were constructed to treat effluent from two separate on-site wastewater treatment systems in Ireland; one a septic tank, the other a naturally-aerated peat filter. The respective effluents were pumped into intermittently dosed, stratified sand filters. Samples were taken at different layers within the sand filters as well as different depths in the subsoil beneath the filters which were tested at various hydraulic loading rates and analysed for chemical and bacteriological determinants. As a result of the trials, the recommendations for design hydraulic loading rates in Ireland were 30 L/m^2 day for filters receiving septic tank effluent and 60 L/m^2 day for filters receiving secondary treated effluent. A full scale trial was then set up to compare parallel tertiary treatment filters receiving on-site wastewater effluent; one constructed from indigenous sand media the other from a recycled glass media. On average the stratified glass filter performed similarly to the stratified sand filter for all of the monitored parameters. However, the overall mean nitrogen load removal from the glass filter proved to be higher compared to the sand filter, due to the higher level of organics reaching the bottom of the filter. Phosphorus removal throughout the 3 year trial was similar through both filters (which was surprising given the poor phosphorus adsorption properties of the glass) with no apparent reduction in removal efficiencies over time.

Keywords: sand filter; on-site wastewater treatment; recycled glass; nutrient removal.

Introduction

Ireland has over one third of its population using on-site wastewater treatment systems, mostly consisting of septic tanks discharging effluent into a subsoil percolation area. 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 in new Code of Practice by the Irish EPA (EPA, 2009) is the use of an intermittent stratified sand filter either as a secondary treatment unit or as a tertiary treatment / 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.

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). Studies have also 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 (Darby et al. 1996; Rodgers et al. 2006). 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. Two full scale stratified sand filters were constructed to treat effluent from two separate on-site wastewater treatment systems, one a septic tank, the other a naturally-aerated peat filter and studied in order to define suitable design criteria for Ireland.

Other full scale trials have also been set up to evaluate recycled glass in a single pass filter receiving on-site wastewater effluent in comparison to a filter constructed from indigenous sand media. At present almost all of Ireland's recovered glass is exported to the UK whilst specialist silica required for sand filters is often imported from overseas. The use of indigenous recycled glass as a filter media would thus reduce energy and transport costs addressing the concept of sustainability and complimenting the EU Waste Management Directives.

Methods

Site and filter construction

Site A A house with 4 PE discharging into a 4000 litre septic tank. The sand filter was designed on the basis of previous research in the US (Nichols *et al.*, 1997). It was constructed with a surface area of 3 m by 2 m, depth of 1.05 m and comprised of layers of sand, decreasing in particle size with depth from 1.0 to 0.1 mm diameter (see Fig. 1). The effluent was pumped onto the sand filter via a pressure distribution manifold from a pump sump with float switch. The distribution manifold was 38 mm diameter plastic pipe in a closed loop comprising four parallel laterals at 0.5 m spacing. The effluent was discharged via 3 mm diameter orifices set at 200 mm centres throughout the manifold which ensured an even distribution across the surface area of the filter. The subsoil beneath the filter into which the effluent percolated had a T-value of 33 (equivalent to a field saturated hydraulic conductivity (k_{fs}) of 0.13 m/day).

Site B A house with 4 PE discharging into a naturally-aerated peat filter (*Puraflo*®, Bord na Mona) installed downstream of a 4000 litre septic tank. The stratified sand filter was identical to the filter constructed at Site A. The subsoil beneath the filter had a T-value of 52 (k_{fs} of 0.08 m/day).

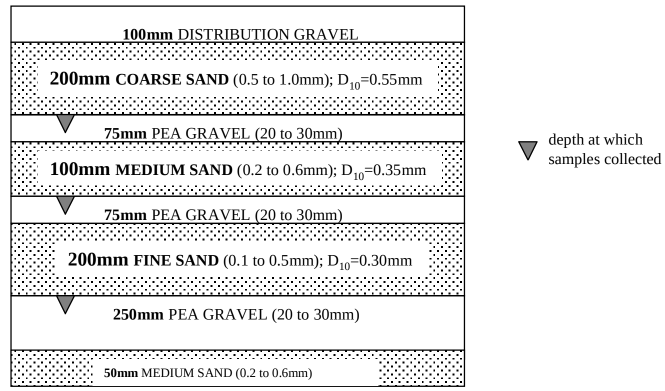

Fig. 1. Cross section through stratified sand filter

Site C The study site consisted of a package secondary treatment unit (BioCycle™) treating effluent from a single house containing a family of 5 (2 adults and 3 children) which also operated as Bed & Breakfast service with an allowance for up to 6 additional guests. The effluent from the BioCycle™ was pumped to two unvegetated stratified sand and glass filters in parallel acting as tertiary treatment polishing units as shown on Fig. 2. Both the sand and glass filters were designed as per the EPA Code of Practice (EPA, 2009) on the basis of a design hydraulic loading rate of 60 L/m^2.d with the resulting total area of the two tertiary treatment filters of 15 m^2, divided into two tanks 3.0 m x 2.5 m in plan. The effective depth for treatment in the filter tanks was 0.9 m which was stratified into layers from the top down as follows: 100 mm gravel, 200 mm media (granite sand/glass), 75 mm gravel, 100 mm limestone, 75 mm gravel, 300 mm media (granite sand/glass) and 50 mm gravel. The gravel layers (28 mm single grade pea gravel) separated the different layers of media in the tank and ensured an even distribution of the influent throughout. The effluent was discharged to the tanks via a pressurised 32 mm diameter manifold, consisting of 9 arms in parallel, with a series of 3 mm holes, 300 mm apart to ensure even distribution over the entire surface area of the filter.

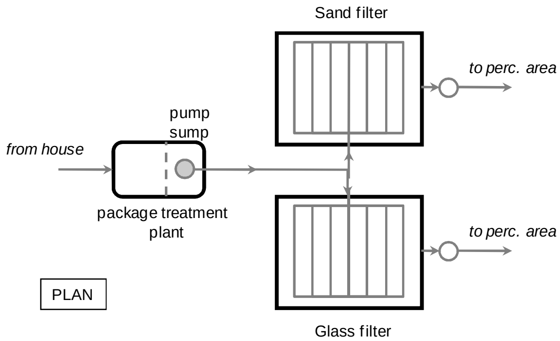

Fig. 2. Schematic plan of stratified sand and glass filters.

The particle sieve analyses are summarised for the media used in each of the filters in Table 1. This highlights the higher uniformity coefficients for the granite and limestone sands sourced locally for Site C compared to the specialist sand shipped in for the filters constructed at Sites A and B. The layer of limestone sand on Site C was incorporated into both filters specifically to target the removal of phosphorus.

Table 1. Particle size distribution for filter media

	D_{10} (mm)	D_{60} (mm)	D_{60}/D_{10}
Coarse (Sites A&B)	0.55	0.68	1.24
Medium (Sites A&B)	0.35	0.52	1.48
Fine (Sites A&B)	0.30	0.41	1.38
Glass (Site C)	0.23	0.53	2.30
Limestone (Site C)	0.58	0.95	1.64
Granite (Site C)	0.15	0.58	3.87

Sampling and analysis

Gravity cups were installed within the sand filters (three per level) to capture effluent en route down through the sand (or glass) matrix so that the treatment performance with respect to each media layer could also be determined. Ultrasonic level sensors (Siemens Milltronics) and data loggers were installed within the pump sump chambers to monitor the hydraulic loading and the dosing frequency on each filter. Suction lysimeters (Soilmoisture Equipment Corp.) were installed at Sites A and B to collect samples of percolating effluent in the subsoil beneath the filters. Rainfall, wind speed, temperature, solar intensity and relative humidity were also monitored at each site using a weather station (Campbell Scientific).

All filters were operated in a standard unsaturated single-pass mode (i.e. with no recycle). The overall treatment efficiency of the filters in parallel was compared at different organic and hydraulic loading rates. Sampling was carried out on a biweekly basis on both tanks influent and effluent and throughout their respective depths during the trial periods. All samples were analysed for pH, conductivity and temperature on site and then chemical and microbiological parameter analysis in the laboratory. Chemical oxygen demand (COD), ammonium (NH_4-N), nitrite (NO_2-N), nitrate (NO_3-N), Total nitrogen and ortho-phosphate (PO_4-P) were analysed using the Spectroquant Nova 60® spectrophotometer and associated reagent kits whilst total coliforms and *E. coli* were quantified using the Colilert® method.

Adsorption isotherms

The phosphate adsorption capacity of the different media (sand and recycled glass) was compared before it was added to the filters by the determination of the Freundlich and Langmuir isotherms. Adsorption isotherms were determined by preparing solutions of potassium ortho-phosphate and potassium nitrate to give concentrations of 320, 160, 80, 40, 20, 10, 5 and 2.5 mgP/L. 5g of each sand / glass sample were put into 125ml Nalprene bottles followed by 100 ml of the respective solution. The samples were then sealed and fixed to a slowly rotating wheel which kept the sample and solution continually mixed for a period of 20 hours. The concentration of the solution was then analysed for ortho-phosphate before and afterwards to calculate the percentage adsorbed.

Results

Sites A and B. 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 for the first 10 months at which point the effluent which was being diverted to parallel percolation trenches in both sites was blocked to promote an increased loading onto the sand filters, 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 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, discharging into subsoil with a T-value of 33. The organic loading rate during the normal hydraulic loading period was 41.1 gCOD/ m^2 day. At Site B, even though the subsoil had a slower percolation T-value of 52, no head level above the base was measured during either loading period indicating much reduced biofilm development due to lower organic loading compared with Site A. The organic loading rate during normal operation at Site B was 8.8 gCOD/ m^2 day

Analyses of nitrogen species are presented for the sand filters on both sites (Fig. 3). 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. 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 was similar at the higher loading levels although there was evidence of denitrification again in the lower fine sand layer arising from localized saturation at this higher hydraulic loading rate. Figure 3(a) reveals a much larger drop in total nitrogen occurred in the upper sand layer receiving the high organic load than in the corresponding layer dosed with secondary treated effluent.

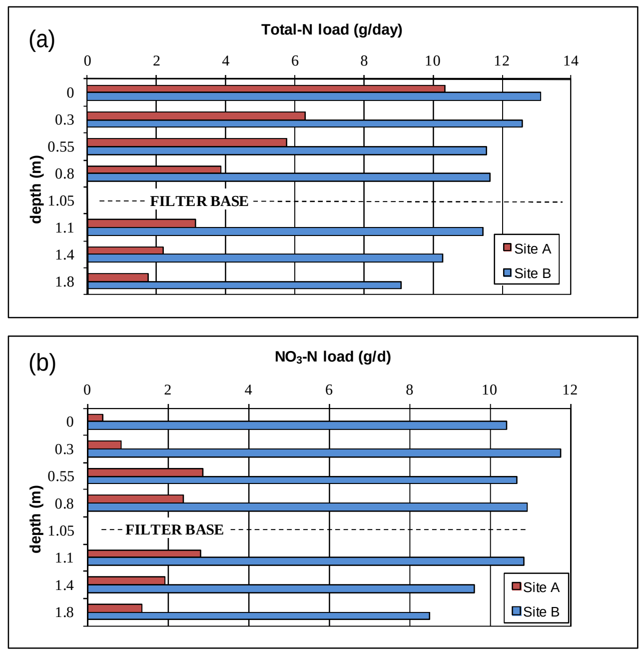

Fig. 3. Comparison of (a) total nitrogen and (b) nitrate removal down through the filters and underlying subsoil.

The concentrations of ortho-phosphate passing through both filters were noticeably reduced as seen in Fig. 4. A plot of the process efficiency of both filters with depth revealed an almost total removal of phosphate giving a correlation coefficient between phosphorous loading and removal (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 appeared to fall away indicating that the residence time in the filters may not have been sufficient for the adsorption removal process to take place effectively. This indicates that, in terms of phosphorous removal using this sand specification, an upper design hydraulic loading rate of 60 L/m^2 day should be applied. 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 would have acted 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. 4) which was only 100 mm thick but contained the highest levels of goethite. The results from the Langmuir adsorption isotherm experiments on the medium sand yielded estimates that the phosphate adsorption capacity of the sand filter under a typical on-site ortho-phosphate load of 3.5 g/day would be expected to last over 370 days. This was confirmed on both filters where the performance of the filters with respect to phosphate removal showed no noticeable decrease up to the end of the fieldwork after about 340 days of operation. This does have obvious implications, however, for the long-term performance of phosphate removal in such sand filters.

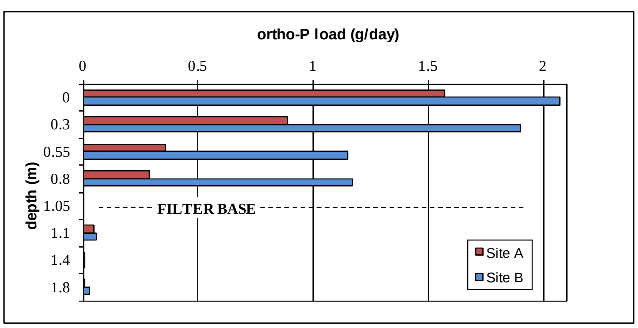

Fig. 4. Average PO_4-P loads as a function of depth through the two stratified filters.and underlying subsoil.

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. 5), revealed 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 occurred at the lower loading rate whilst there were 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 centimeters of the sand as reported in other studies. 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.

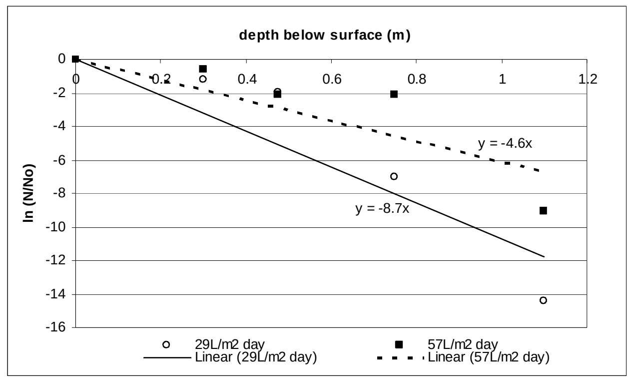

Fig. 5. Removal of *E. coli* with depth through the sand filter and subsoil (Site A).

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

Site C. The average hydraulic loading rate on the filters across the trial period was 567 L/d (38 L/m^2.d) but with relatively high variations throughout the trial due to the nature of the Bed and Breakfast trade whereby the population of the house regularly fluctuated between 5 to 9 people on a daily basis. The filters were dosed on average 8 times per day throughout the trial.

The average influent COD loadings from the wastewater treatment unit across the trial were 108±59 g/day (144±58 mg/L). The overall removal efficiency (assessed from the final effluent quality from each filter) showed that the sand and recycled glass filter media performed equally well on average over the course of the study, returning average COD removal rates of 75 % and 73% between the sand and glass respectively. The average effluent loads from the sand and glass filters were 28±21 g/d (34±24 mg/L) and 27±21 g/d (36±30 mg/L). Comparisons between the sand and glass throughout the tank depth showed that 52% of COD removal occurred within the first 300 mm filter layer in the sand filter compared to 30% across the glass. In the remaining 100 mm limestone layer and 200 mm sand/glass filter the sand and glass showed further removal rates of 22% and 44% respectively. This shows that the sand media was more efficient than the glass under the higher effluent COD conditions in the first 300 mm filtrate layer. However, this difference in COD removal between the two filters became muted with depth as the COD concentrations of the percolating effluent reduce with depth and the kinetics should become more externally controlled through the biolfilm and move from half to first order.

The phosphorus adsorption capacity of the crushed glass, granite sand and limestone sand established by the adsorption isotherms indicated that the glass has very little adsorption capacity or affinity for phosphate. The comparison of the sand samples showed that the limestone sand has a high affinity for phosphate compared to the granite sand. The average P loading onto the filters from the BioCycle™ secondary treatment unit was measured at 6.4±4.3 g/d (11.0±4.1 mg/L). On average the sand and glass filters removed 51% and 40% PO_4-P respectively. The average effluent loads from the sand and glass filter were 3.4±3.5 g/d (5.6±4.0 mg/L) and 3.8±3.5 g/d (6.5±4.5 mg/L). The relative removals of PO_4-P in the sand filter across the top, limestone and bottom layers were 38%, 52% and 10% respectively in comparison to the glass filter at 40%, 55% and 5% respectively. The 40% removal across the top layer of glass is somewhat surprising in the context of the isotherm results but is thought to be associated with the maximum biomat activity in this area of the filter due to the highest organic loading. Approximately 54% of the PO_4-P removal occurred in the limestone layers which was not as impressive as had been hoped for in the design of the filters. The final effluent concentrations from both filters exceeded a level that would be acceptable, for example for surface water discharge. The trend for the removal efficiency of PO_4-P over time for both filters was only slightly negative (see Fig. 6), with no significant reduction in removal efficiency apparent over time, which might be evidence that the filters (and in particular the limestone layer in each filter) was becoming saturated over this relatively short period. Calculations using the results of the Freundlich isotherm and mean loadings of P on the filter suggest that the glass filter should have become saturated after approximately 15 months for example.

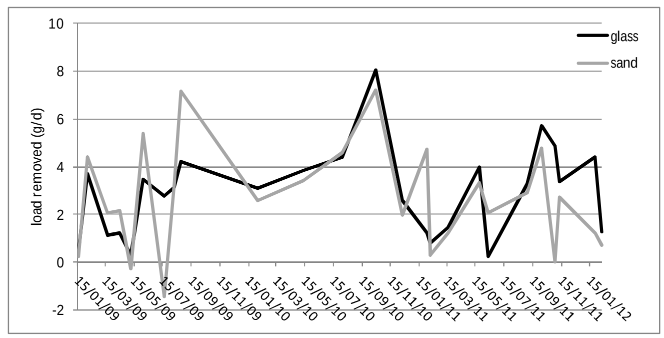

Fig. 6. PO_4-P load removal over time through the stratified sand and glass filters.

Fig. 7 displays an overview of the average nitrogenous loads as total nitrogen (TN), organic nitrogen (Org-N), ammonium (NH_4-N), nitrite (NO_2-N) and nitrate (NO_3-N) as a function of tank depth.

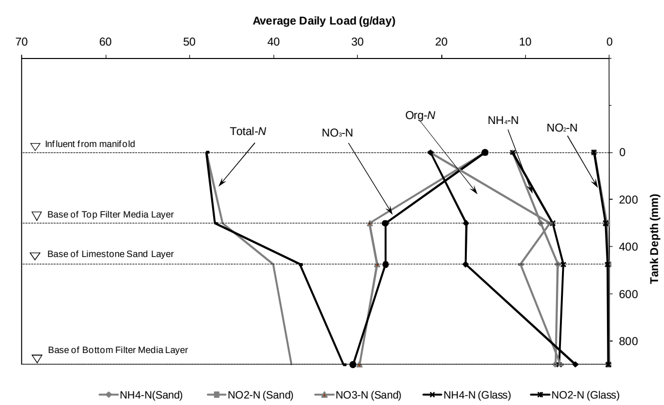

Fig. 7. Nitrogen loadings as a function of depth through the sand and glass media filters.

Nitrogen removal can be seen to have occurred throughout the tank depth with daily average total nitrogen (TN) removal rates across the sand and glass units of 16% (average effluent discharge of 35.1±26.2 g/d, 49.3±21.8 mg/L) and 28% (average effluent discharge of 29.5±19.1 g/d, 43.0±16.7 mg/L) reduction respectively from average TN loading onto the filters of 48.1±26.5 g/d, 54.6±18.3 mg/L. The higher TN removal in the glass filter is interesting and can be explained by higher organic loads percolating down to the limestone glass layer and lower glass layer as discussed earlier (i.e. 52% of COD removal occurred within the first 300 mm filter layer in the sand filter compared to only 30% COD removal across the first glass layer). These higher organic concentrations in the lower layers of the filter provided food for the heterotrophic denitrifying bacteria in the layers where there were also high nitrate concentrations with much of the nitrification occurring in the upper layer in both filters, as can be seen in Fig. 7. In this zone the Org-N was also being reduced through mineralisation and converted to NH_4-N which offsets somewhat the decrease in NH_4-N loads as a result of the nitrification process.

E. coli removal in both the sand and glass was approximately the same at 3 log removal with more than 2 log removal being achieved within the first 0.2 m layer in both filter media at 99.6% and 99.0% respectively (Fig. 8). A further average 1 log removal occurred down through the remaining layers of both filters. It should be noted however, that there were still concentrations of *E. coli* of the magnitude 10^3 MPN/100ml in the final effluent from both filters which would not be suitable for direct discharge to groundwater. When assessing the removal rate as a function of hydraulic loading, there was no evidence of reduction in *E. coli* removal rates with increased loading conditions, as might have been expected. The overall removal coefficient k for the sand and glass filters (from a plot of $\ln(N/N_0)$ versus filter depth) was -7.2 and -7.6 respectively, at the average hydraulic loading rate of 38 L/m^2.d throughout the trial period.

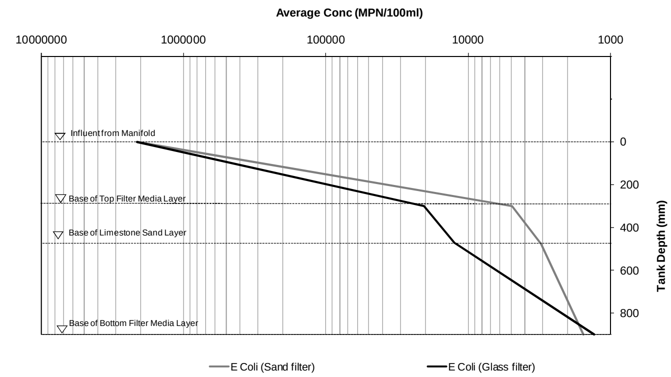

Fig. 8. *E. coli* removal as a function of tank depth.

Conclusions

The detailed study on the two stratified sand filters receiving different quality effluent revealed that both treatment systems greatly reduced the chemical and biological loading rates of domestic wastewater effluent discharging directly to the subsoil below, reducing the potential for groundwater pollution. 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 loading rate has been adopted in the EPA Code of Practice (EPA, 2009). Ortho-phosphate removal in the filters is related to the mineral composition of the sand used and these trials showed that 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 fill.

The comparison between the tertiary treatment stratified glass and sand filters showed that, on average they performed similarly for all of the monitored parameters. However, within the filters there were some differences in process kinetics between the two systems which led to some interesting results with respect to nitrogen removal. Although the overall organic matter removal through the two filters was very similar, there was a much slower breakdown of organics through the top layer of the recycled glass filter than the sand filter which provided a carbon source for higher levels of denitrification in the lower parts of the filter where the nitrate concentrations were more optimal. Hence, the overall mean nitrogen load removal from the glass filter proved to be 18.6 g/d compared to the only 13.0 g/d through the sand filter.

Phosphorus removal was higher through the sand filter than the recycled glass filter, 51% and 40% respectively, which was to be expected due to the poor phosphorus adsorption properties of the glass. The limestone layer in both filters only accounted for approximately half of the P removed which was disappointing as laboratory studies had shown it to have excellent phosphorus adsorption properties. There was no strong evidence that the limestone layer was starting to approach saturation. Finally, on average 3 log removal of enteric microorganisms through both filters using the indicator bacteria *E. coli* was shown which, although reasonable compared to other tertiary treatment systems, still left significant numbers of bacteria in the effluent which would not be suitable for direct discharge into groundwater. These trials show that the use of recycled glass as a filter media as replacement for sand could be promoted due to its similar performance which would complement sustainability concepts.

References

Boller M., Schwager A., Eugster J., Mottier V. (1993). Dynamic behaviour of intermittent buried filters. *Water Science & Technology*, 28(10), 99–107.

Darby J.G., Tchobanoglous G., Nor M.A. (1996). Shallow intermittent sand filtration: performance evaluation. *Small Flows Journal*, 2, 3-14.

EPA (2009). *Code of Practice: Wastewater Treatment and Disposal Systems Serving Single Houses*. Environmental Protection Agency, Ireland.

Nichols D.J., Wolf D.C., Gross M.A., Rutledge E.M. (1997). Renovation of septic effluent in a stratified sand filter. *Site Characterisation and Design of On-site Septic Systems, American Soc. for Testing & Materials STP 1324.* 11-22.

Rodgers M., Healy M.G., Predergast J. (2006). Novel hybrid filter for the treatment of septic tank effluent. *J. Environ. Eng.*, 132(7), 764–768.

Acknowledgments

Acknowledgement is given to the Environmental Protection Agency for the funding for the trials on Sites A and B as well as start-up funding for the filters on Site C.