

Protecting our waterways – research of novel methods for removal of nutrients from wastewaters

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Abstract

Disposal of nutrient rich wastewaters, both directly and indirectly, into rivers and lakes is common in New Zealand. These nutrients (nitrogen and phosphorus) are often limiting for the growth of algae and bacteria so their discharge can stimulate unsightly and potentially harmful algal and bacterial blooms. The consequences are now being realised in many parts of the country.

In this paper, a review of technologies for the removal of nitrogen and phosphorus from low volume domestic wastewaters is presented. For nitrogen removal from household systems, the installation of a novel biofilter system is discussed. The biofilter system facilitates the necessary nitrification and denitrification reactions by ensuring the presence of both aerobic and anoxic zones. In this work, the key factors limiting process performance are discussed, namely the availability of oxygen for nitrification and carbon for denitrification. For phosphorus removal from domestic wastewaters the use of rock filter media is proposed. Rock filters are a low-cost and low-maintenance technology, and they may be particularly applicable for low-flow wastewaters. Results from a field study conducted by the Centre for Environmental Technology and Engineering (Massey University) confirm that significant phosphorus removal can be achieved using these types of filters. However, their performance needs to be optimised in order to achieve a treated effluent with a suitably low phosphorus concentration.

Keywords

nutrients, nitrogen, phosphorus, onsite systems, rock filters

Introduction

Water pollution rising from the acceleration in population growth and expansion and intensification of agricultural practices has become a problem over the past few years (Harper, 1995). Discharge of nutrients (nitrogen and phosphorus) has been identified as a particular concern. Excess nutrient concentrations can lead to suffocation of aquatic life via rapid eutrophication and oxygen depletion. The consequences are now

being realised in many parts of the country. There is an urgent need to find effective and at the same time economically attractive solutions.

For large centralised wastewater treatment systems, biological nutrient removal and removal of phosphorus by chemical precipitation have attracted much attention. But the infrastructure and control systems involved make direct application of such technologies for low flow treatment systems inappropriate.

Decentralised locations have traditionally opted for simple onsite systems: septic tanks followed by land treatment (soakage fields). However, variability in performance of soakage fields (related to soil type and climatic conditions) has driven regulatory authorities to demand that onsite systems be improved to minimise nutrient (nitrogen) discharge to soils. This may be achieved by applying some of the effective processes utilised in centralised wastewater treatment plants. In this work, facilitation of biological nitrogen removal and physico-chemical phosphorus removal for decentralised systems are considered.

Nitrogen Removal

The typical concentration of nitrogen in domestic effluent is greater than 80 mgN/L (Burks and Minnis, 1994; Miller and Pratt, 2004 [unpublished data]). Much of this results from toilet wastes. Faeces consist of unabsorbed food material, which include particulate organic nitrogen, and urine includes urea [$\text{CO}(\text{NH}_2)_2$], which contributes to the concentration of both particulate and soluble nitrogen (Patterson, 2003). Kitchen wastes (from food preparation) and bathroom wash-water (contaminated with perspiration and some cleaning agents) also contribute to the nitrogen load (Patterson, 2003).

In this work, removal of nitrogen from domestic effluents by passive treatment systems is discussed. The passive system may be considered a 'sustainable technology' on two counts: (i) it does not require forced aeration, thus minimising energy input (Tyler, 2000), and (ii) it is primarily a biological degradation system so the pollutant is converted to stable products and not simply retained in the system. Such systems have been tested and employed. Most notable are recirculating sand filters, which have been shown to be capable of removing 50-70% of total influent nitrogen (USEPA, 2002). Other filter media have also been tested (foam, textile and even biodegradable media). Lombardo and Robertson (2003) showed that a passive biofilter (biodegradable) could be used to reduce total nitrogen concentrations to well below 10mg/L. However Loomis et al. (2001b) found similar biofilters to be less effective with effluent nitrogen concentrations ranging from near 30mg/L to 60mg/L. Loomis et al., (2001a,b) also tested recirculating sand and recirculating foam filters and found none performed consistently well (nitrogen effluents ranging from 10-80mgN/L). The result reported by Loomis et al. (2001a,b) results are not surprising considering the US EPA (2002) reports that generally such systems are yet to achieve an effluent with a suitably low nitrogen concentration. They conclude that more research is required in order to refine performance consistency and improve understanding of operational processes and mechanisms.

What is happening in these systems?

The passive systems referred to in this work rely on biological nitrogen removal, which is the conversion of ammonia-nitrogen to nitrogen gas. But it should be noted that in domestic effluents, nitrogen is not in ammonia form. Instead, much of the nitrogen is bound in organic form. As such, biological nitrogen removal must be preceded by the hydrolysis of particulate organic nitrogen to soluble organic nitrogen and ammonification of soluble organic nitrogen to ammonia (as described in the Activated Sludge Model No.1 presented by Henze et al., 1987). These processes are catalysed by heterotrophic bacteria in both aerobic and anaerobic environments. In onsite systems, the processes take place in an anaerobic septic tank.

The septic tank

Despite the fact that septic tanks are not directly responsible for much of the nitrogen removal (only N that is bound to settleable and floatable carbon material is removed), they still play an important role in N removal systems. In the tank, nitrogen is converted to a form which can be removed via the nitrogen cycle (see below), and carbon is fermented to more readily degradable forms (like volatile fatty acids), which are necessary for effective denitrification.

In a project conducted by the Centre of Technology and Engineering (Massey University), septic tanks have been confirmed as effective units for nitrogen and carbon conversion.

Table 1: Example of nitrogen conversion in a septic tank

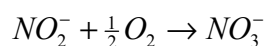
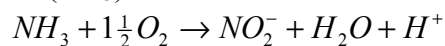
Tank Influent (mg N / L)			Tank Effluent (mg N / L)		
Total N	Ammonia N	% N as Ammonia	Total N	Ammonia N	% N as Ammonia
122	90	74%	87	73	84%

Table 2: Example of carbon conversion in a septic tank

Tank Influent			Tank Effluent (mg N / L)		
Total Organic Carbon	Acetic Acid	% C as Acetic Acid	Total Organic Carbon	Acetic Acid	% C as Acetic Acid
563 mg	227 mg	40%	375 mg	176 mg/L	47%
sCOD/L	COD/L		sCOD/L		

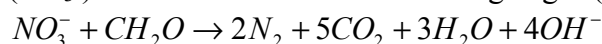
Biological nitrogen removal

Ammonia (NH₃) can be nitrified to nitrate (NO₃⁻):



Importantly, the process relies on the presence of sufficient oxygen.

Nitrate (NO₃⁻) can then be denitrified to nitrogen gas (N₂)



The denitrification process requires the presence of sufficient carbon.

It can be seen that the challenge is to provide a system with suitable aerobic and anoxic zones, and to ensure that sufficient carbon is present in the anoxic zone. In this project, biological nitrogen removal has been facilitated on a foam biofilter. The

objective is for the filter to act as a framework for biomass growth (resulting in a fixed film system). It is expected that the surface of the reactor is well oxygenated, thus allowing both aerobic carbon removal and nitrification. Below the surface, it is suspected that the oxygen concentration is depleted. Provided that some carbon remains, denitrification can take place in the sub-surface areas. See Figure 1 for a schematic of the system.

At this stage, the biofilter is still in ‘start-up’ phase. However, it is already apparent that significant nitrogen removal is being achieved (removal up to 63% TN and 86% $\text{NH}_3/\text{NH}_4^+$).

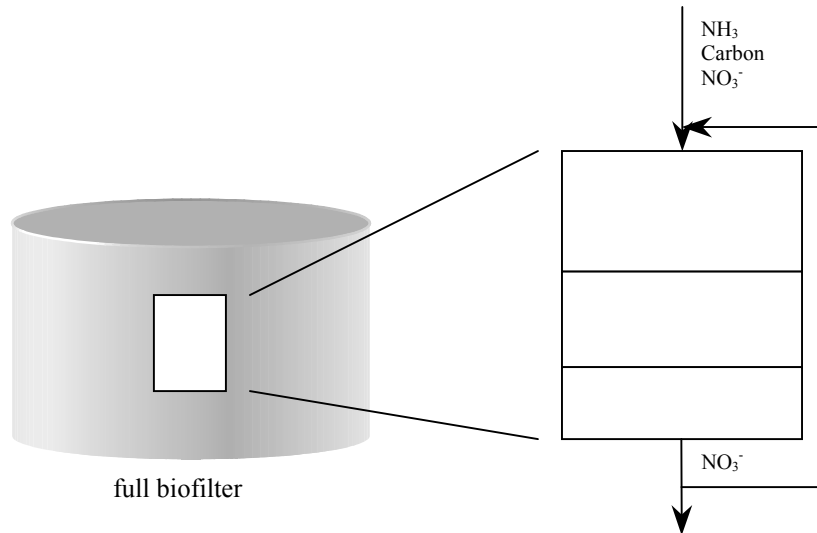


Figure 1: Nitrogen conversion in a biofilter

The objective of the research is to investigate the limiting factors. Typically, flow through onsite systems are carbon limited. The ratio of carbon to nitrogen in influent should exceed 5:1 (US EPA, 2002). Carbon limitation prevents complete denitrification taking place. This would be evidenced with the presence of significant levels of nitrate in the effluent. To overcome this problem, recirculation is often employed (as shown in Figure 1). In this way, available carbon can be used for denitrification at the surface of the filter (provided oxygen free zones are present, which is invariably the case in fixed film systems).

In the system studied by Massey University, elevated levels of nitrate in the effluent were not observed. This suggests that the system is not carbon limited. Instead, it is suspected that the system may be oxygen limited. Mass transfer limitation of oxygen in biofilms has been shown by many authors (eg. Siegrist et al., 1987), leading to oxygen depletion at distances significantly less than the full film thickness. [This phenomenon may allow denitrification to occur at the filter surface, as proposed above]. Furthermore, the concentration of oxygen in the bulk phase will decrease as the wastewater passes deep into the filter. The drop in dissolved oxygen is caused by heterotrophic activity on carbon. For this reason, it has been reported that filters should not be loaded above 6-12 $\text{gBOD}/\text{m}^3/\text{day}$ (US EPA, 2002). However, it is suspected that the loading rate may be significantly increased if aeration can be optimised.

Phosphorus Removal

Phosphorus is commonly found in the form of inorganic phosphates and originates from human urinary excretions, agricultural run-off and from household detergents. For centralised systems, enhanced biological phosphorus removal (EBPR) or phosphorus removal by precipitation is normally employed. However, neither technology is appropriate for decentralised systems:

- EBPR is a complex and sensitive technology, requiring enrichment of a particular biomass population. Operation of EBPR involves cycling the active biomass through anaerobic and aerobic zones. Controlling the process is difficult.
- Phosphorus precipitation is relatively straightforward, but the cost of chemical addition and the problem associated with waste sludge production makes this technology unfavourable for decentralised systems.

At this stage, decentralised systems generally do not facilitate phosphorus removal.

In this work, the removal of phosphorus from domestic wastewaters by physico-chemical means in rock filters is discussed. Like the biofilters discussed previously, the rock filters are a 'passive' form of treatment as little energy input is required. Yet ironically, the filters are referred to as 'active' filters as reactions take place on the filter surface.

'Active' filters have emerged as a promising solution for P removal from effluents around the world (Kadlec et al., 2000; Shilton et al., 2004). It is suspected that the mechanisms for P removal in these systems are adsorption and/or precipitation and complexation with Fe, Al or Ca rich substrate (Richardson, 1985). As such, the selection of filter material is a crucial factor in design. Over the past 10 years various materials have been tested for their ability to retain phosphorus (an extensive review is presented in Drizo et al. (2002)). It has been found that electric arc furnace slag (EAF slag) has one of the highest P retention capabilities. Also, it is noted that iron and steel slags have been earmarked for regulation under various waste classifications (US Geological Survey, 1997). So their use in a wastewater treatment process could defer the problems that will be associated with their disposal.

What is happening on the filter?

Immobilisation of phosphorus occurs through substratum adsorption, chemical precipitation, bacterial action and algae uptake (summarised by Drizo et al. (1999)). Of these, adsorption (chemical and physical) may play the greatest role, so it is important to select media with the highest P adsorption capacities. The material should also have a high surface area, and be permeable to allow maximum wastewater contact.

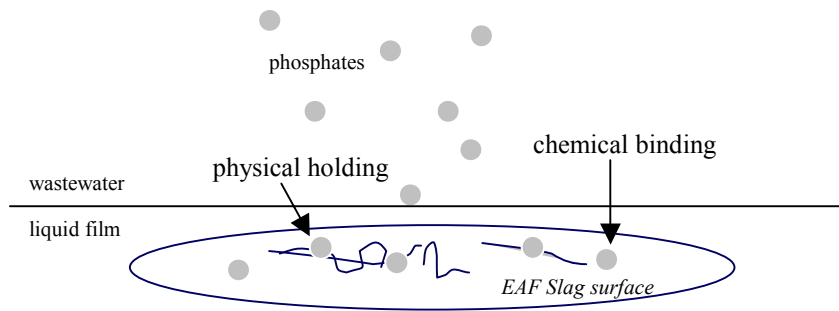


Figure 2: Phosphate adsorption on EAF slag

Chemical precipitation also likely contributes to phosphorus removal. The metal precipitates formed could remain bound on the filter or wash through with the effluent. The fate of these precipitates is currently being studied at Massey University.

Integrating rock filters with existing low cost systems

The concept of sustained phosphorus removal by adsorption and/or precipitation and complexation with filter media originated as an inherent property of constructed wetlands. But now, the identification of EAF slag as an effective media offers opportunity for rock filters to be installed as a polishing step at existing low cost technologies like the onsite technologies described earlier or larger pond/lagoon treatment systems (see Figure 3).

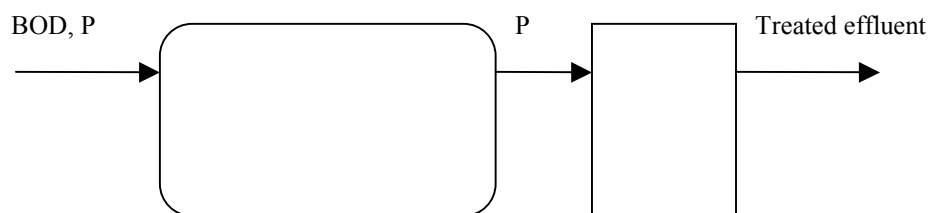


Figure 3: Configuration of a treatment system that incorporates a rock filter

P removal as a function of hydraulic residence time (HRT)

Rock filters have been installed as per Figure 3 for final removal of BOD and suspended solids. The design recommendation for these filters is to have a residence time of about 160hrs (Mara, 2004). The Centre for Environmental Technology and Engineering (Massey University) has shown that given the same design criteria, at least 50% P removal could be obtained if EAF steel slag was used as the filter media (Figure 4).

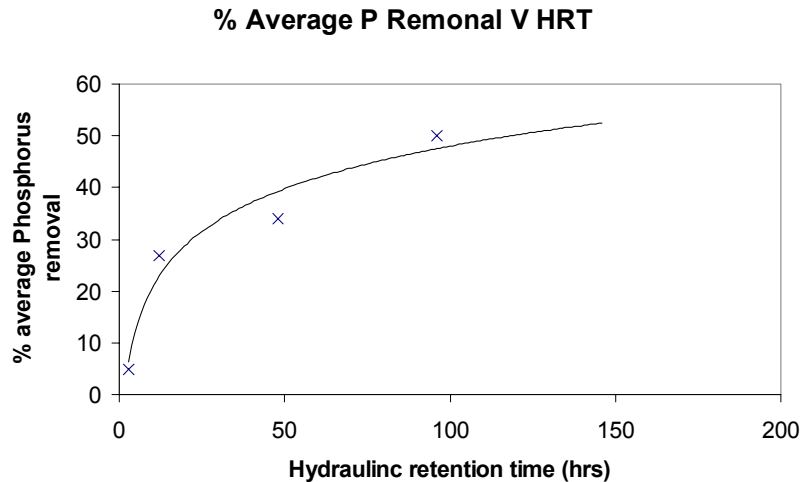


Figure 4: P removal as a function of hydraulic residence time

The challenge is to improve filter performance to >80% phosphorus removal. In order to achieve this, a greater understanding of the influence of operational parameters (pH and flow dynamics) and biological phenomena (growth on active sites) on the mechanisms of adsorption, precipitation and complexation is required.

Conclusion

Authorities have recognised the effects of untreated nutrients in the water system and now, in many countries, have imposed stringent criteria on their release. In New Zealand, a number of regional councils now demand low levels of nitrogen in discharge waters. And there is an expectation that the release of phosphorus will also soon be restricted. For small, decentralised wastewater treatment systems (including onsite and pond systems), this means an upgrade in treatment technology is required.

- For nitrogen, it appears possible to apply biological nitrogen removal to onsite systems;
- For phosphorus, specific filter media have been shown to be capable of removing significant quantities of P.

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