NITROGEN REDUCTION IN SMALL COMMUNITY TREATMENT SYSTEMS

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Abstract

Many small communities have package sewage treatment plants and/or on-site sewage treatment facilities that are a source of contamination for ground and surface waters. Nitrogen, which typically is not removed in these conventional systems, is a major concern. A project funded through the Advanced Wastewater Treatment Technologies Scheme and the Department of Natural Resources and Mines was commenced to evaluate the capability of four sewage treatment technologies to reduce the amount of nitrogen being discharged in the effluent to the receiving environment. The four sewage treatment processes evaluated include a recirculating sand filter, bio-filter, slow sand filter and constructed subsurface wetland. Each treatment process was selected for its suitability to serve both small communities and single dwellings. The primary objective was to evaluate the capability of the treatment processes to reduce nitrogen, phosphorus, suspended solids and biochemical oxygen demand.

Each treatment process was sampled every two weeks and the samples analysed for ammonia-nitrogen, nitrate-nitrogen, total nitrogen, total phosphorus and alkalinity. Results of the sampling from March 2000 to 30 June 2001 have been evaluated. Preliminary analyses show that the recirculating sand filter is producing a high quality nitrified effluent. The bio-filter used in this study has not demonstrated potential for nitrogen removal. The percentage removal of total nitrogen through the wetland was disappointing even though a nitrified influent was being fed to the wetland. The slow sand filter with coarser grade sand has demonstrated capability to nitrify.

Keywords

bio-filter, nitrogen reduction, recirculating sand filter, slow sand filter, small community, subsurface flow wetland sewage treatment.

1. Introduction

The Queensland *Environmental Protection Act 1994* places a general environmental duty upon all persons to take all reasonable and practicable measures to prevent or minimise harm to the environment. Generally for small communities and on-site sewerage facilities, the effluent discharged from the facility must have no sustainable impacts on land, groundwater and surface waters. The *Environmental Protection (Policy) Water 1997* requires local governments to consider the cumulative impacts of on-site land application of effluent on the environment when assessing and approving development applications under the *Integrated Planning Act, 1997*. The policy further requires that the environmental values of Queensland waters be enhanced or protected.

Nutrient loading from these wastewater sources has been identified as one of the major water quality concerns in achieving sustainable discharge of effluent to the receiving environment. Nitrogen, which is typically not removed in conventional sewage treatment plants that serve small communities and single dwellings, is arguably the most important nutrient associated with these facilities.

2. Objective of Study

The main objective of this study was to demonstrate the capability of a recirculating sand filter, attached growth column with an anoxic reactor (bio-filter), slow sand filter and subsurface flow wetland to remove nitrogen through biological means. An additional objective was to assess the capability of the four treatment processes to reduce phosphorus, total suspended solids, biochemical oxygen demand and the microbiological quality of the effluent. This paper reports on the capability of each treatment process to effectively remove nitrogen.

3. Literature Review

Witmyer, *et al.*, (1991) reviewed a range of individual nitrogen removal systems as the first part of a two-phase project. The purpose of the project was to develop affordable on-site sewage treatment designs that would remove sufficient nitrogen to maintain concentrations in the groundwater below drinking water standards. Various physical and chemical methods such as ion exchange, reverse osmosis, chlorine oxidation, air stripping and electrodialysis have been used (Crites and Tchobanoglous, 1998) however these processes have high-energy costs and intensive operational control.

The biological removal of nitrogen through plant uptake, microbial assimilation or denitrification provides the best options for small communities and individual dwellings (Whitmyer, *et al.*, 1991). In most cases, available data regarding performance, maintenance and costs were found to be sparse and incomplete. The most promising systems that had performance and operational data were the various septic tank/recirculating sand filter designs.

Katers and Zanoni, (1998) in a laboratory scale system consisting of a septic tank followed by an attached growth column for nitrification and an anoxic reactor for denitrification achieved good reduction of nitrogen. The literature review revealed that there was no data available on field trials of a similar process.

The potential for constructed wetlands to remove nitrogen has been the subject of several investigations (Gersburg *et al.*, 1984; Ogden, 1994; Green, 1994; and Johns *et al.*, 1998). Subsurface flow wetlands have demonstrated an ability to denitrify the available nitrate-nitrogen, however the limitation on nitrogen removal is the preceding nitrification step (Crites and Tchobanoglous, 1998).

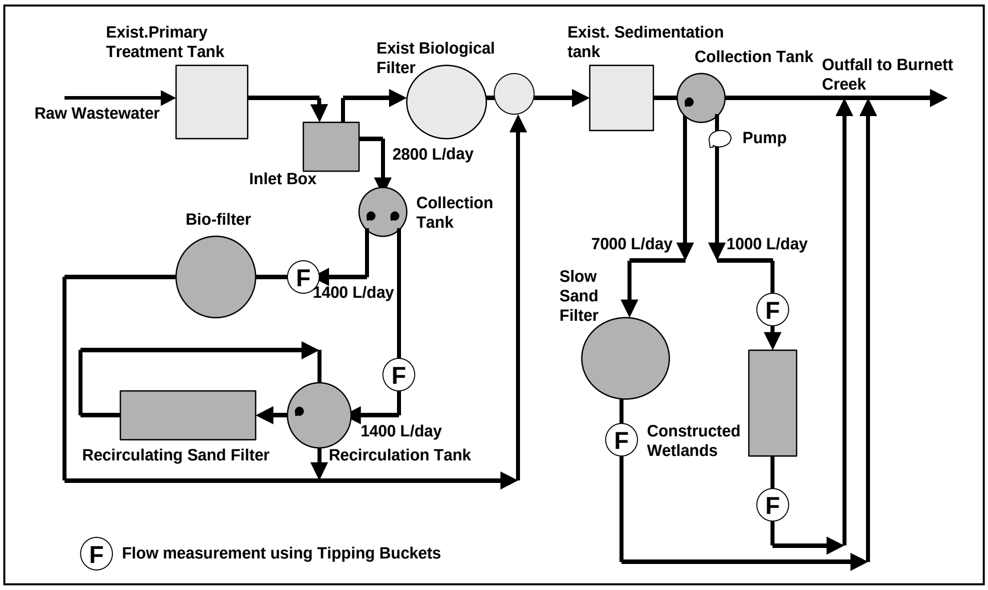
Slow-sand filtration has been investigated in recent years as an advanced wastewater treatment process at laboratory and pilot plant scales. Studies by Ellis, (1987) and Al-adham, (1989) reported good removal of biochemical oxygen demand, total suspended solids, turbidity and coliform bacteria. Ellis, (1987) reported significant occurrence of denitrification in the filter bed but no nitrification was observed during the filtration process. The findings of Farooq *et al.*, (1994) concluded that concentrations of nitrate essentially remained the same or decreased in the filtrate for coarse sand indicating that some denitrification takes place in the filter bed.

4. Test Facility and Treatment Processes

The test facility was established at the Maroon Dam Complex located 120 km south west of Brisbane. An existing sewage treatment plant serves an Outdoor Education Centre and several dwellings that accommodate SunWater maintenance staff. There was ample space for construction of the test facility at the site, a sufficient source of primary treated effluent was available and a means for final effluent disposal.

The test facility was established to evaluate four-wastewater treatment process streams shown schematically in Figure 1. Wastewater from the existing primary treatment tank was diverted to a collection tank that served as a source for the recirculating sand filter and the bio-filter. Secondary treated effluent is diverted to a collection tank that served as a source for the slow sand filter and the subsurface flow wetland. The recirculating sand filter and biofilter are each designed to treat 1400 L/day, the slow sand filter 7000 L/day and the wetland 1000 L/day. Effluent flow to each process was measured using tipping buckets.

Figure 1: Schematic of Test Facility at Maroon Dam showing the four treatment process streams



4.1 Recirculating Sand filter

The recirculating sand filter is an open top sand filter with a sand media depth of 600 mm. A layer of graded gravel (about 300 mm) is provided under the sand for support to the media and to surround the underdrain system. Washed durable sand with an effective size 2.6 mm and uniformity coefficient 1.7 is used as the filter medium. A portion of the mixture (primary treated effluent and sand filtrate) is dosed by submersible pump through a distribution system that applies it evenly over the sand filter. A splitter valve manufactured in the USA by Orenco Systems Incorporated and purchased for this project from Watertec Wastewater Systems is used to divide the flow to the set recirculation ratio.

Pump flow rates were initially set to provide a 4:1 recycle ratio. During the course of monitoring the recycle ratio has varied from 4:1 up to 8:1.

4.2 Bio-filter

The bio-filter process is based on the laboratory scale testing of a modified septic tank by Katers and Zanoni, (1998). The attached growth column is 1.2 m high and is packed with an open-structured 40 mm diameter pipe media with a surface area of 314 m^2/m^3. The attached growth column sits on top of the main tank that consists of 2 compartments, an inlet compartment and a main reaction compartment with a baffle near the outlet. Effluent from the collection tank is pumped into the inlet compartment where it is pumped to the attached growth column and then returned to the anoxic reactor. A quiescent zone exists behind the baffle before discharge of the effluent. The biomass in the anoxic chamber is mixed using a submersible pump.

4.3 Slow Sand Filtration

The slow sand filter is contained within a 1400 mm diameter fibreglass tank. The filter was designed with a maximum of 20 hours retention of effluent for the filtration system. For the first 12 months of operation the filter media sand had an effective size of 0.25 mm and a depth of 1000 mm. To increase the length of filter runs the media was replaced with sand having an effective size of 0.45-0.55 mm and a depth of 1300 mm.

The sand media is placed over three layers of graded sand and gravel that form the underdrain system. Directly beneath the sand media is a 75 mm thick layer of coarse sand with an effective size of 1.5-3 mm. Under the coarse sand is a 75 mm thick layer of 3-6 mm gravel and a 150 mm layer of 6-12 mm gravel. A flow control system has been installed so as to ensure 100 mm submergence of the filter media under all conditions.

4.4 Constructed subsurface flow wetland

The constructed subsurface flow wetland designed for a flow of 1000 L/day is a shallow rectangular trench with base dimensions of length 10.5 m and width 2.5 m. The overall depth is 450 mm that allows for 17.5 m^3 of gravel medium. Coarse gravel, size 30-60 mm was placed at the inlet and outlet zone and the bed media was made up of gravel with a nominal size 5-20 mm. Before placing the gravel medium the excavated trench was lined with Canvacon liner 5000 to retain the effluent in the wetland. A geotextile (Geofabric Bidem A34) was placed on top of the liner to prevent the gravel from puncturing the liner. The wetland was planted with a mixture of *Phragmites* and *Schoenoplectus*.

5. Sampling

Composite 24 hour samples using a Sigma automatic sampler were collected from the recirculating sand filter and biofilter one week and samples from the slow sand filter and wetland were collected on alternate weeks. These samples were analysed for ammonia-nitrogen, nitrate-nitrogen, total nitrogen, total phosphorus and alkalinity as $CaCO_3$. At three-monthly intervals the samples were analysed for biochemical oxygen demand and total suspended solids. Temperature, pH, dissolved oxygen and turbidity were measured on-site at weekly intervals.

6. Results and Discussion

The four-treatment processes commenced operation in October 1999. Monitoring the performance of each process commenced in March 2000 that allowed a period of four months for each process to stabilise and rectify any operational problems. General maintenance on all treatment processes was undertaken at weekly intervals. A feature of each treatment process has been the low level of maintenance required.

6.1 Influent characteristics

The average characteristics of the influent to the recirculating sand filter, bio-filter, slow sand filter and wetland are presented in Table 1. Large solids such as rags, paper and plastic materials are removed from the influent to the recirculating sand filter and bio-filter in an existing primary treatment tank. The influent to the slow sand filter and wetland is a mixture of effluent from the existing biological filter and effluent from the recirculating sand filter and bio-filter. It can be seen from Table 1 that the ammonia-nitrogen entering the recirculating sand filter and biofilter is converted to nitrate (i.e. nitrified). It would also appear from these results that nitrification is being achieved in the existing biological filter.

Table 1
Influent Characteristics for Period March 2000 to June 2001

Parameter	Recirculating Sand Filter and Bio-filter influent	Slow Sand Filter and Wetland Influent
	Average mg/L	Average mg/L
Ammonia-nitrogen (as N)	50.6	9.3
Nitrate-nitrogen (as N)	0.253	36.1
Nitrogen, Organic (Calc)	8.9	4.1
Phosphorus, filterable, reactive (as P)	7.7	7.5
Nitrogen, Total (as N)	59.8	49.5
Phosphorus, Total (as P)	8.8	8.0
Alkalinity	337	55.2
Biochemical Oxygen Demand (BOD)	96	16

6.2 Recirculating sand filter

During the four-month process stabilisation period the orifices in the distribution pipe required regular cleaning. The residual pressure head at the orifices was about 50 to 100 mm resulting in poor distribution of effluent over the media. Monitoring of the influent and effluent to the filter commenced in March 2000 and the results showed good nitrification was being achieved even though the effluent distribution was not regarded as being satisfactory. In October 2000 it was decided to replace the submersible pump in the recirculating tank and the delivery pipe to the distribution pipework was replaced with a 25 mm dia. PVC pipe. These modifications increased the residual head on the orifices to approximately 2.0 m. Since the completion of these modifications there have been no problems with blockages of the orifices.

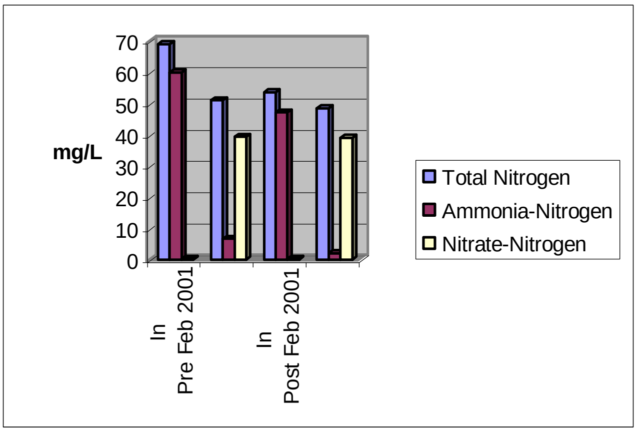


Figure 1 - Influent and Effluent Total Nitrogen, Ammonia-Nitrogen and Nitrate Nitrogen Concentrations

Figure 1 shows the average total nitrogen ammonia-nitrogen and nitrate-nitrogen concentration of the influent and effluent to the recirculating sand filter from March 2000 to June 2001. Over this period good nitrification has been achieved with an average 90% reduction in ammonia-nitrogen.

Prior to February 2001 the concentration of nitrate-nitrogen increased on average from 0.3 mg/L in the influent to 39.3 mg/L in the effluent (Figure 1), which coincided with a 26% reduction in total nitrogen. These findings indicate that denitrification was not being achieved through the filter. In February 2001 it was decided to modify the outlet of the recirculating sand filter so as to maintain a submerged collection pipe in the bottom of the filter. It was hoped that this modification would create anaerobic conditions around the collection pipe thereby improving the conditions for denitrification. Figure 1 shows the average nitrate-nitrogen concentration in the effluent did not change following this modification. The results indicate that no improvement in denitrification has been achieved through the modification.

6.2 Biofilter

Figure 2 shows that the decrease in total nitrogen concentration in the biofilter is approximately 15%. The field trial of this process has not proved as efficient in nitrogen removal as demonstrated in the bench scale tests where results indicated more than 50% of the total nitrogen could be removed (Katers and Zanoni, 1998). At initial start-up recirculation of effluent through the packed tower was not included, as the bench scale study did not include recirculation. After several months operation the packed tower was slightly modified to improve air circulation through the media with the hope of improving nitrification. There was little improvement in nitrogen removal.

The U.S.EPA. (1993) recommends that a recirculation ratio of 1:1 is appropriate to achieve nitrification. In October 2000, 2/100 mm dia holes were drilled in the wall between the reactor tank and the inlet compartment and the pump running times adjusted to achieve a recirculation ratio of 1:1. With recirculation in operation there was an improvement in the build-up of micro-organisms on the media in the packed tower but only a slight improvement in total nitrogen reduction. However it was considered that further reduction might be achieved by installing a mixer in the anoxic compartment. The submersible pump that was taken out of the recirculating tank of the recirculating sand filter was installed in the anoxic compartment.

Mixing in the anoxic compartment marginally improved the total nitrogen reduction but it must be acknowledged that this process has not performed up to expectations. At the time of preparing this paper further investigation is continuing into the reasons for the poor nitrogen reduction of this process.

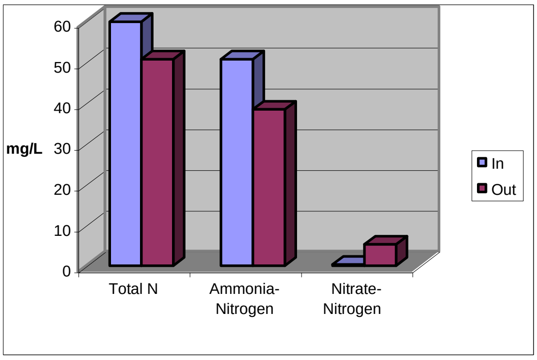


Figure 2 – Bio-filter Influent and Effluent Total Nitrogen, Ammonia-Nitrogen & Nitrate-Nitrogen Concentrations

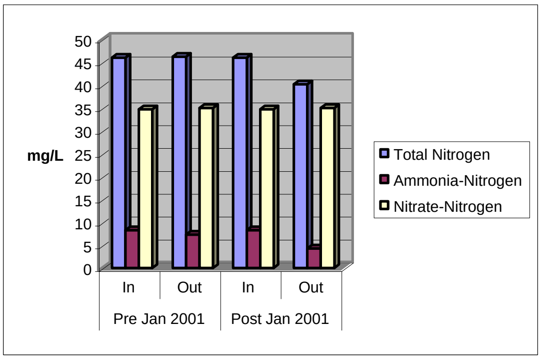


Figure 3 – Slow Sand Filter Influent & Effluent Total Nitrogen, Ammonia-Nitrogen and Nitrate-Nitrogen Concentrations

6.3 Slow Sand Filtration

Following initial start-up, the slow sand filter required removal of the layer of material deposited on top of the filter bed (Schumtzdecke) after 7-14 days operation at a filtration rate of 0.2 $m^3/m^2/hr$. Adjustment of the filtration rate to 0.14 $m^3/m^2/hr$ did not improve the filter operation. In May 2000 a horizontal flow roughing filter, 5.0m long by 0.5 m wide by 1.0 m deep of graded gravel was installed in front of the slow sand filter. The roughing filter contains 2.5 m of 12 to 20 mm aggregate, 1.25 m of 6 to 12 mm aggregate and 1.5 m of 3 to 6 mm aggregate with a filtration rate of 0.5 $m^3/m^2/hr$. The filtration rate to the slow sand filter was adjusted back to 0.2 $m^3/m^2/hr$ and the operation of the filter extended to a maximum of 28 days. The addition of the roughing filter has made no difference to the nitrogen reduction performance of the slow sand filter.

In January 2001 it was decided to determine if operation of the filter could be extended beyond the 14-28 days without sacrificing the quality of the filtrate. This was hoped to be accomplished by increasing the effective size of the sand to 0.45-0.55 mm and depth of the sand to 1300 mm. The filtration rate was adjusted to 0.16 $m^3/m^2/hr$. The filter has operated for 143 days without any clogging.

From Figure 3 it can be seen that the influent concentrations of ammonia-nitrogen to the slow sand filter averaged 8.3 mg/L whereas the filtrate concentrations of ammonia-nitrogen averaged of 7.3 mg/L before January 2001 and averaged of 4.3 mg/L after January 2001. The influent nitrate-nitrogen concentrations averaged 34.7 mg/L whereas the filtrate nitrate-nitrogen concentrations averaged 35.0 mg/l before January 2001 and remained the same after January 2001.

These findings indicate that nitrification did not take place with the fine grade sand however some nitrification did occur with the coarser grade sand and the increased sand depth. The improvement in nitrification after January 2001 may have occurred through the changes to the distribution pipework, which would have enhanced the influent dissolved oxygen content. The results indicate that denitrification did not occur through the media. These findings differ from those of Ellis (1987) and Farooq (1994). The limited results for suspended solids removal indicate that the change in effective size and increased depth of the media made no appreciable difference to the quality of the filtrate but did significantly improved the duration of filter run.

6.4 Subsurface flow wetland

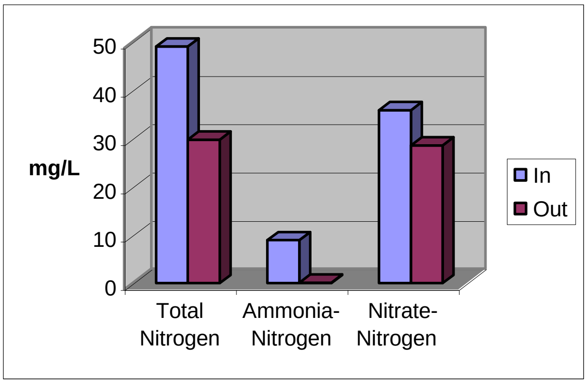


Figure 4 – Wetland Influent & Effluent Total Nitrogen, Ammonia-Nitrogen, and Nitrate Nitrogen Concentrations

The average ammonia-nitrogen concentration of the influent to the wetland is 8.9 mg/L and the average nitrate-nitrogen concentration is 35.8 mg/L. The average ammonia-nitrogen concentration in the effluent from the wetland is 0.1 mg/L, which demonstrates that nitrification is occurring. The low ammonia-nitrogen concentrations in the influent indicate that nitrification has been achieved during treatment prior to the wetland.

The average nitrate-nitrogen concentration in the effluent collected at the outlet of the wetland is 28.5 mg/L, showing that a 20% reduction in nitrate-nitrogen has been achieved through the wetland. Some denitrification has occurred in the wetland, but is most likely limited by the amount of biodegradable organic carbon in the influent. The average total nitrogen concentration in the influent is 48.8 mg/L and the effluent concentration is 29.7 mg/L, producing a 39% reduction in total nitrogen reduction through the wetland.

7. Conclusions

The following conclusions about the capability of the four treatment processes to remove nitrogen through biological means may be drawn.

- The recirculating sand filter is capable of producing a high quality nitrified effluent. Using flooded underdrains or following the filter with an anaerobic filter provided there is an adequate carbon source available might achieve further nitrogen removal.
- The biofilter used in this study has not demonstrated potential for nitrogen removal. Further investigations are being carried out to determine the possible reasons for the process not achieving the expected results.
- The slow sand filter with coarser grade sand has demonstrated capability for nitrification. However, no evidence of denitrification was found.

- The percentage removal of total nitrogen through the subsurface flow wetland was disappointing even though a nitrified influent was being fed to the wetland. The performance of the wetland might be linked to the available biodegradable organic carbon in the wetland.
- The recirculating sand filter and subsurface flow wetland findings suggest that further investigation be undertaken to determine if improvements with nitrogen reduction can be achieved.

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