Nutrient reduction evaluation of sewage effluent treatment options for small communities

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Abstract Small communities that are sewered by either package sewage treatment plants or on-site sewerage facilities are finding that the ground and surface waters are being contaminated. Nitrogen, which typically is not removed in these conventional systems, is a major concern. This project evaluated 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, biofilter, slow sand filter and constructed subsurface flow wetland. These processes were evaluated for their capability to reduce nitrogen, phosphorus, BOD₅ and TSS. The primary objective of the project was to evaluate the capability of these treatment processes to reduce nitrogen using biological processes nitrification and denitrification. This paper reports on the performance of these processes to reduce nitrogen. The study demonstrated that the biofilter was capable of removing from a primary treated influent 40% of the total nitrogen. For the same quality influent the recirculating sand filter was capable of removing 35% of the total nitrogen. Secondary treated effluent was fed to the slow sand filter and the subsurface flow wetland. There was a 52% reduction in total nitrogen through the wetland however there was virtually no reduction in total nitrogen through the slow sand filter.

Keywords Biofilter; denitrification; nitrification; nitrogen reduction; recirculating sand filter; slow sand filter; sewage treatment; subsurface flow wetland

Introduction
Existing sewage treatment plants serving small communities and single dwellings discharge a large volume of effluent to the receiving environment. The quality of this effluent is extremely variable and could arguably be regarded as a major source of contaminants in both surface and ground water. Since many of these small community sewage treatment plants were constructed using technology appropriate at the time, today’s effluent quality requirements are more stringent than considered attainable by the technology currently in use.

What remedies have been developed to improve the effluent quality? There are several treatment processes that can be considered for new and/or upgrading small community treatment plants. Appropriate treatment technologies include stabilisation ponds or lagoons, slow sand filters, recirculating sand filters, intermittent sand filters and constructed wetlands. These processes may be regarded as affordable to build, reliable in treatment performance and can be maintained by locally available labour.

The performance of the above treatment technologies is well documented in relation to biochemical oxygen demand (BOD₅) and total suspended solids (TSS) reduction, however performance in reduction of nitrogen and phosphorus is sparse and incomplete (Whitmyer et al., 1991). Contamination of surface and ground water from these nutrients has been identified as one of the major water quality concerns in achieving sustainable discharge of effluent.

Funding was obtained through the Advanced Wastewater Treatment Technologies (AWTT) program to trial four sewage treatment processes, namely a biofilter, recirculating sand filter (RSF), slow sand filter (SSF) and subsurface flow constructed wetland...
SFCW) for their capability to reduce nitrogen, phosphorus, BOD₅ and TSS. The primary objective of the project was to evaluate the capability of these treatment processes to reduce nitrogen using the biological processes, nitrification and denitrification. This paper reports on the performance of these treatment processes to reduce nitrogen from primary and secondary treated wastewater. The complete report on the project is available at the following website www.dlgp.qld.gov.au/local_govt/grants_subsidies/

The biological reduction of nitrogen through plant uptake, microbial assimilation or denitrification provides the best option for small communities and individual dwellings (Whitmyer et al., 1991). The activated sludge process is considered by almost all international text authors to be the most difficult to operate and maintain of all the wastewater treatment concepts (Kreissl, 1996). There is also considerable information in the literature on the performance of activated sludge systems. Therefore, it was decided that an activated sludge system would not be included.

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 a 59% reduction in total nitrogen. The potential for constructed wetlands to remove nitrogen has been the subject of several investigations (Gersburg et al., 1984; Ogden, 1994; Green, 1994; Johns et al., 1998 and Davison et al., 2002). Subsurface flow wetlands have demonstrated an ability to denitrify the available nitrate-nitrogen, however the limitation on nitrogen removal is the preceding nitrification step (Crities and Tchobanoglous, 1998).

Materials and method

Test facility

The test facility was established at the Maroon Dam Complex located 120 km south west of Brisbane, Queensland. An existing sewage treatment plant serves an Outdoor Education Centre and several dwellings that accommodate SunWater maintenance staff. The daily flow from the education centre and dwellings ranges between 4000 and 16,000 L/day. The existing sewage treatment plant provides primary treatment and secondary treatment by biological filtration and sedimentation with discharge of the treated effluent to Burnett Creek.

The test facility shown schematically in Figure 1 was established to evaluate four wastewater treatment process streams. Wastewater from the existing primary treatment...
tank was diverted to a collection tank that served as a source of primary treated influent to a biofilter and recirculating sand filter. Secondary treated effluent is diverted to a collection tank that served as a source for a slow sand filter and subsurface flow wetland. A description of the four process streams follows.

Process stream 1 – biofilter
The biofilter consists of an attached growth reactor that sits above an anoxic reactor. The attached growth reactor was 1.2 m in height and 900 mm in diameter with a volume of 0.76 m³. The attached growth reactor was packed with an open structured 40 mm diameter corrugated plastic pipe with a surface area of 314 m²/m³. A circular tank, 1.79 m diameter and 1.84 m in height was used for the anoxic reactor. Two baffles were added to the tank to create three compartments, i.e. an inlet compartment with a submersible pump, the anoxic reactor dedicated for denitrification and an outlet compartment. A constant hydraulic loading of 1400 L/day was applied to the biofilter. Mixing within the anoxic reactor was not included at the outset of the testing program. However, mixing was incorporated along with recirculation at the midway point of testing.

Process stream 2 – recirculating sand filter
The RSF was a 7.0 m × 1.0 m 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 has been used as the filter medium. A portion of the mixture (primary treated effluent and sand filter filtrate) is dosed by submersible pump through a distribution system that applies the wastewater evenly over the sand filter. The recirculation ratio was set at 4 to 1 based on forward flow. The dosing interval was set by a timer and was 3 min every 30 min. A constant hydraulic loading of 1400 L/day was applied to the RSF.

Process stream 3 – slow sand filter
Influent for the SSF and SFCW is taken from the existing effluent discharge pipeline. The influent has been secondary treated using biological filtration and settled in a settling tank. The effluent from RSF and the biofilter is combined with the effluent from the biological filter.

A 1400 mm diameter fiber glass tank was used as the container for the SSF. The SSF was designed for a flow of 7000 L/day with a maximum of 20 hours effluent retention for the filtration system. The filter media was 1,000 mm deep sand with an effective size 0.3–0.5 mm. Directly beneath the sand media was a 75 mm thick layer of coarse sand with a nominal size of 1.5–3 mm. Under the coarse sand were 75 mm thick layer of 3–6 mm gravel and 150 mm thick layer of 6–12 mm gravel. The 50 mm diameter underdrain was placed within the 150 mm layer of gravel. A flow control system was installed to ensure 100 mm submergence of the filter media under all conditions. After four months operation, a horizontal-flow roughing filter was installed between the collection tank and the slow sand filter to remove suspended solids and subsequently extend filter runs beyond seven days.

Process stream 4 – subsurface flow constructed wetland
Process stream 4 uses a SFCW to provide further treatment of the wastewater. A SFCW was selected because of the land area requirements and avoidance of mosquito problems. The SFCW was designed for a flow of 1000 L/day. It is a shallow rectangular trench with base dimensions of length 10.5 m and width 2.5 m. The overall depth of gravel media is
450 mm that allows for 17.5 m³ gravel medium. A 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. The nominal hydraulic residence time is calculated as 5.8 days assuming a porosity of 0.4 and a design flow of 1000 m³/day.

Before placing the gravel medium the excavated trench was lined with Canvacon Liner 5000 to retain the effluent in the wetland. A geotextile (Geofabric Bidim A34) was placed on top of the liner to prevent the gravel in the bed from puncturing the liner. The wetland was planted with a mixture of Phragmites and Schoenoplectus. These aquatic plants were selected because the roots would extend to the liner thus providing oxygen to the root zone.

**Sampling methods**

Composite 24-hour samples using a Sigma automatic sampler were collected from the primary treated wastewater collection tank (collection tank 1), the outlet of the biofilter and the outlet of the RSF at fortnightly intervals. On alternate weeks, samples were collected from the secondary treated effluent collection tank (collection tank 2), the outlet of the roughing filter, the outlet of the SSF and the outlet of the SFCW. The sample collection bottle was packed in ice during the 24-hour sampling period.

At three monthly intervals samples were taken from the same sample points and analysed for BOD₅, and total suspended solids. From October 2001 to the end of the monitoring period sugar was added to the primary treated wastewater collection tank for reasons explained later in the paper. During this period samples were collected weekly for BOD₅ and total suspended solids analysis.

The sample collection bottles were removed from the automatic samplers and 250 mL unused, reverse osmosis water washed plastic bottles were filled and capped for total nitrogen, total phosphorus and alkalinity as CaCO₃ analysis. 100 mL unused, reverse osmosis water washed plastic bottles were used for filtered samples for ammonia-nitrogen, oxides of nitrogen and phosphate analysis. The samples were filtered using white cellulose acetate membrane filters, pore size 0.45 μm. All samples were packed in ice and transported to the laboratory on the same day as collection. Temperature, pH, dissolved oxygen and turbidity were measured on-site at weekly intervals.

**Results and discussion**

The mean percent reduction of total nitrogen loading by each process stream is summarised in Table 1 for the full sampling period. From Table 1 it can be seen that during the first 11 months of operation the RSF performed better than the biofilter in relation to total nitrogen removal. By reference to Figure 2 there was very little nitrification evident in the biofilter during this period. The biofilter was then modified to allow recirculation and the pump running times adjusted to achieve a recirculation ratio of 1:1. There was an overall improvement in total nitrogen reduction going from 10.5% before recirculation to 20.6% after recirculation was installed.

Sugar was added to collection tank 1 to increase the available carbon in the influent to the biofilter and the RSF. One kilogram of sugar mixed with two litres of water was added to the contents of collection tank 1 three times per week over a six-month period so as to maintain an influent BOD₅ concentration of approximately 150 mg/L compared with a mean of 95 mg/L prior to the addition of sugar. The higher organic content resulted in a definite improvement with total nitrogen reduction averaging 51% and on two sampling occasions total nitrogen reduction was in excess of 80%. These results reflect the laboratory results achieved by Katers and Zanoni (1998) who achieved a 59% reduction in total nitrogen.
By reference to Figure 3 excellent nitrification was being achieved through the RSF with the outlet in its initial position. It is also evident from Figure 3 that denitrification was only partially achieved in the lower portions of the RSF. The limited denitrification may have been due to a poor anoxic environment within the lower portions of the filter media and insufficient organic carbon being available as an energy source for the heterotrophic bacteria. After 12 months operation the outlet of the RSF was modified to maintain a submerged collection pipe. The depth of submergence was 300 mm. The aim of this modification was to create anoxic conditions around the collection pipe, thereby establishing more appropriate conditions for denitrification. From Figure 3 it is evident that there has been little change in the effluent ammonia and nitrate nitrogen thus indicating that the modification did not achieve the aim of establishing more appropriate conditions for denitrification. This leads to the conclusion that there was insufficient organic carbon as an energy source for the bacteria.

Table 1 Summary of mean percent total nitrogen reduction through each treatment process

<table>
<thead>
<tr>
<th>Process stream no.</th>
<th>Treatment process</th>
<th>Sampling period</th>
<th>Treatment process modification</th>
<th>Mean TN reduction %</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Biofilter</td>
<td>15/12/99 to 25/10/2000</td>
<td>Initial configuration</td>
<td>10.5</td>
</tr>
<tr>
<td>1</td>
<td>Biofilter</td>
<td>25/10/20 to 17/10/01</td>
<td>Recirculation of effluent steam to packed tower and mixing in anoxic chamber</td>
<td>20.6</td>
</tr>
<tr>
<td>1</td>
<td>Biofilter</td>
<td>17/10/01 to 24/4/02</td>
<td>Sugar added to collection tank</td>
<td>51.3</td>
</tr>
<tr>
<td>2</td>
<td>R.S.F.</td>
<td>15/12/99 to 6/2/01</td>
<td>Initial Configuration</td>
<td>25.4</td>
</tr>
<tr>
<td>2</td>
<td>R.S.F.</td>
<td>6/2/01 to 17/10/01</td>
<td>Outlet modified to maintain flooded underdrain</td>
<td>8.7</td>
</tr>
<tr>
<td>2</td>
<td>R.S.F.</td>
<td>17/10/01 to 24/4/02</td>
<td>Sugar added to collection tank and outlet reverted to initial configuration</td>
<td>34.6</td>
</tr>
<tr>
<td>3</td>
<td>S.S.F.</td>
<td>15/12/99 to 6/2/01</td>
<td>Initial configuration including roughing filter</td>
<td>17.6</td>
</tr>
<tr>
<td>3</td>
<td>S.S.F.</td>
<td>6/2/01 to 19/9/01</td>
<td>Sand and support media replaced and aeration distribution installed at top of filter</td>
<td>14.3</td>
</tr>
<tr>
<td>4</td>
<td>Wetland</td>
<td>15/12/99 to 7/8/01</td>
<td>Initial configuration</td>
<td>36.7</td>
</tr>
<tr>
<td>4</td>
<td>Wetland</td>
<td>8/8/01 to 24/4/02</td>
<td>Outlet manifold lowered to change flow pattern</td>
<td>49.7</td>
</tr>
</tbody>
</table>

By reference to Figure 3 excellent nitrification was being achieved through the RSF with the outlet in its initial position. It is also evident from Figure 3 that denitrification was only partially achieved in the lower portions of the RSF. The limited denitrification may have been due to a poor anoxic environment within the lower portions of the filter media and insufficient organic carbon being available as an energy source for the heterotrophic bacteria. After 12 months operation the outlet of the RSF was modified to maintain a submerged collection pipe. The depth of submergence was 300 mm. The aim of this modification was to create anoxic conditions around the collection pipe, thereby establishing more appropriate conditions for denitrification. From Figure 3 it is evident that there has been little change in the effluent ammonia and nitrate nitrogen thus indicating that the modification did not achieve the aim of establishing more appropriate conditions for denitrification. This leads to the conclusion that there was insufficient organic carbon as an energy source for the bacteria.
With the addition of sugar to the influent and the outlet returned to its initial configuration there was definite improvement in the total nitrogen reduction through the RSF. As noted previously the sugar increased the BOD₅ of the influent, however by reference to Figures 4 and 5 there is no relationship between the percent reduction of total nitrogen and the increased BOD₅ of the influent. This is further supported by there being no correlation coefficient $R^2 = 0.02$ (biofilter) and $R^2 = 0$ (RSF) shown in Figures 4 and 5.

The temperature of the influent and effluent to the biofilter were recorded each week during the sampling period at the top and bottom of the anoxic reactor. There was no statistical difference between the temperature at the top and bottom of the anoxic reactor. A plot of percent reduction of total nitrogen against the temperature of the biomass in the anoxic reactor, Figure 6, suggests that there is a better reduction of nitrogen at higher temperatures. However, the correlation coefficient, $r^2 = 0.33$ falls short of the value of 0.497 required for statistical significance. Similarly there is no correlation $r^2 = 0.23$ with the percent reduction of total nitrogen and the temperature of the influent to the RSF. In general, the biomass temperature was above 15 °C as noted in the literature review therefore the results for the biofilter confirm that temperature effects can be neglected in design.

**Subsurface flow constructed wetland**

The mean percent reduction of total nitrogen through the SFCW ranged from 37–50% for both outlet configurations. The nominal hydraulic retention time through the SFCW was 5.8 days and this was not varied during the study. The influent to the SFCW is
characterised by a low ammonia concentration (mean 7.5 mg/L) and a mean nitrate concentration of 33.0 mg/L. The nitrification step has been achieved in the existing biological filter plant, the biofilter and the RSF process streams. Subsurface flow wetlands have the ability to denitrify the available nitrate-nitrogen. The limitation on nitrogen reduction is the nitrification step. The subsurface flow regime is nearly anaerobic apart from the top 50 to 100 mm. Experience has shown that the limiting condition for nitrification is the availability of oxygen. The availability of oxygen is related to the extent of root penetration and efficiency of oxygen transfer to those roots in a subsurface flow wetland.

Figure 7 compares ammonia-N, nitrate-N and total nitrogen in the influent and effluent for the SFCW during the sampling period. The data shows efficient nitrification with a complete reduction of the remaining ammonia through the SFCW. This result indicates good root growth with the \textit{Phragmites} and there was an efficient transfer of oxygen for nitrification.

The reduction of nitrate via biological denitrification requires anoxic conditions, which are almost assured in a SFCW. The average nitrate-N in the influent to the wetland before the outlet was modified was 35 mg/L (Figure 7) and the average in the effluent was 28 mg/L representing a 20% reduction in nitrate-N. The flow pattern through the wetland was altered by lowering the outlet manifold from 50 mm to 400 mm below the top of the gravel. After the outlet was modified the effluent nitrate-N dropped to 15 mg/L. The reduction of total nitrogen through the wetland was similar to the nitrate-N. The average total-N in the effluent after the outlet was lowered was 18.5 mg/L as demonstrated in Figure 7. The altered flow pattern through the wetland brought about a significant change in the performance of the wetland and is probably more representative of the anoxic conditions present in a SFCW.
Slow sand filter

By comparison with the SFCW the SSF performed rather poorly in total nitrogen reduction from a well-nitrified secondary treated effluent. Based on the laboratory experiments by Ellis (1997) it was expected that the nitrified influent would denitrify in the anoxic conditions created in the lower portion of the filter media. The influent nitrate concentrations ranged from 55 to 21 mg/L whereas the effluent nitrate concentrations ranged from 48 to 15 mg/L in the case of fine sand and 46 to 22 mg/L in the case of coarse sand. These results demonstrate that denitrification has not occurred as expected and the replacement of the fine-grained filter media with a coarse-grained filter media did not improve the denitrification process. The mean percent total nitrogen reduction with the fine-grained filter media was 17.6% and it dropped slightly to 14.3% reduction with the coarse-grained filter media. The lack of an organic carbon source is probably the most significant factor contributing to the poor denitrification.

Conclusions

The study demonstrated that the biofilter is capable of consistently removing 40% of the total nitrogen from primary treated wastewater. There was a definite improvement in percent reduction of total nitrogen after the sugar addition and was more pronounced in the biofilter than the RSF. This is most likely due to the denitrifying bacteria being able to more efficiently use the carbon for energy in the conversion of nitrate to nitrogen gas. Whilst the additional carbon did have the effect of improving denitrification in the RSF there is still uncertainty on the anoxic environment in the lower portion of the sand filter. A more appropriate configuration might be to recirculate the nitrified effluent through the primary treatment chamber where an anaerobic environment is available for denitrification. Another option that is often shown in the literature is to recirculate the nitrified effluent through an anaerobic upflow filter.

Results from the monitoring program demonstrate that the SFCW is capable of reducing the ammonia concentration too less than 1.0 mg/L. Complete denitrification did not occur even with the more representative sampling after lowering the outlet manifold. The conclusion drawn from the monitoring is that the plant litter and natural organic detritus did not provide a sufficient supplementary carbon source in this particular wetland. The results however, do support the findings of Davison et al. (2002) and Leonard (2000) that 60% total nitrogen reduction is achievable. Because of the complexities of nitrogen

Figure 7 SFCW, ammonia-N, nitrate-N and total nitrogen in influent and effluent

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reduction it is difficult to isolate one particular parameter that would simply increase nitrogen reduction through the wetland.

In order to make any significant impact on denitrification in a slow sand filter an external organic carbon source is necessary. It is concluded from this study that the slow sand filter is not a suitable process for nitrogen reduction for a small community.

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