

WASTEWATER DENITRIFICATION USING DENITRIFICATION BEDS

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ABSTRACT

With the increasing requirement for the removal of total nitrogen from wastewater discharges, especially within sensitive Lake catchments, GNS Science, Landcare Research and Taupo District Council set out to evaluate a new innovative, technology for wastewater denitrification.

The results of 3 years of full scale denitrification trials using a nitrified effluent from one of the Taupo SBR plants through a denitrification bed are presented and discussed. The process has shown effective removal of nitrate from the wastewater stream with minimal reduction in bed performance over time. This, and further work on dairy shed and glasshouse effluent, have shown that the denitrification beds can be a relatively robust way to ensure that very low levels of total nitrogen result in a wastewater discharge.

The system is attractive in its simplicity and that it is economically viable. Initial concerns associated with the media life appear to be misplaced, however the design for these systems does need to consider other parameters that may affect the discharge, such as loss of soluble carbon.

This paper presents and discusses the results from a municipal wastewater treatment plant at Kinloch, a dairy shed effluent treatment research project in Dargaville, and introduces a hothouse nutrient runoff treatment trial in Auckland, that show the successful performance of this emerging nitrogen reduction technology.

KEYWORDS

Eutrophication

Nitrogen

Nitrate

Denitrification

Denitrification Bed

1 INTRODUCTION / BACKGROUND

Nutrients are essential for plant growth; nitrogen and phosphorus are among the most important. However in excess, these nutrients can become harmful and even toxic to the receiving environment. In waterways, nitrogen and phosphorus are often responsible for excessive and nuisance plant and algae growth leading to eutrophication of receiving waters. Increasingly local body authorities around the world are tightening effluent consent parameters to limit the adverse affects of these pollutants on receiving waters. This is also true in New Zealand; the Resource Management Act (RMA) 1991 requires Regional Councils to develop policies and plans that provide for sustainable disposal of wastewaters.

Much of the excess nitrogen originates from nitrate leaching from intensive land use activities to groundwater, which then enters surface waters (PCE 2004). Another significant source of nitrogen contamination is discharge from wastewater treatment processes, which may incorporate ammonia removal using the nitrification process forming nitrate. As such nitrate has become recognized as one of the most common ground water contaminants in the world (Robertson *et al.*, 2001). The denitrification process; however, converts nitrate to nitrogen gas in the presence of a degradable form of carbon, removing the contaminant from a treated effluent stream.

Denitrification Beds are one method for on-site removal of nitrate. Denitrification beds are cost effective to install, low maintenance and capable of removing 99% of influent nitrate. Denitrification beds have been developed from the success of denitrification walls (Schipper and Vojvodic-Vukovic 2001, Schipper *et al.* 2005). A denitrification “wall” is constructed into the groundwater to intercept wastewater effluent plume (rich in nitrate). The wall slowly releases carbon to support the activity of denitrifying bacteria for biological treatment of nitrate. Results from previous trials have shown that denitrification walls could remove nitrate for at least 6 years (Robertson *et al.* 2000, Schipper *et al.* 2005).

GNS Science, University of Waikato, Landcare Research along with Taupo District Council (TDC) and AWT New Zealand has been working in partnership to further research the effectiveness of denitrification beds. Results from denitrification bed operation at Kinloch wastewater treatment plant (WWTP) and the prototype trial of dairy shed effluent treatment in Northland are presented. Reference to denitrification bed trials treating hydroponic hothouse discharge is also included.

2 DETAILS OF THE PROCESS

The following sub sections set out several details of how the process works.

2.1 PRINCIPLES OF DENITRIFICATION BEDS

Denitrification beds utilize the natural biological denitrification process that converts nitrate to nitrogen gas. Consequently, denitrification beds require nitrogen to be in the oxidized form (e.g., as nitrate). Typically this will require the pre-treatment of municipal wastewater to convert ammonia to nitrate (Equation 1).

A multitude of pre-treatment processes can be used for this purpose, such as: conventional activated sludge systems utilizing forced air injection, or fixed film processes such as trickling filters or packed bed reactors.

Simplified nitrification process:



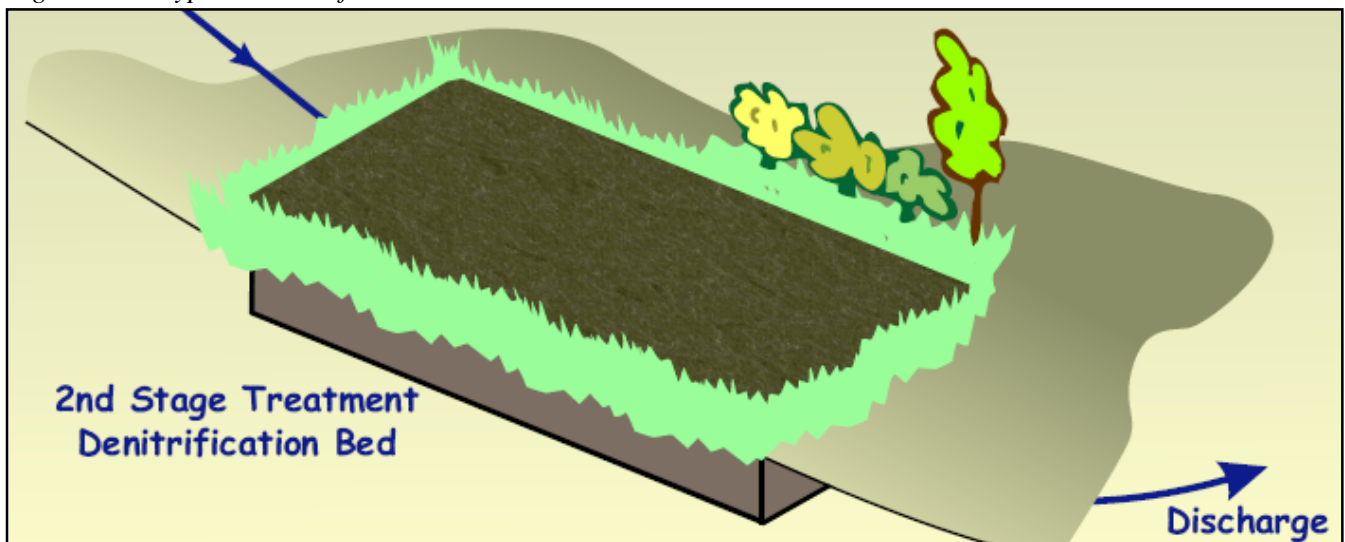
Often during the nitrification process the available forms of carbon in the effluent necessary for denitrification are depleted. Hence an additional carbon source is required for the denitrification process (Equation 2).

Simplified denitrification process:



A denitrification bed is essentially a large excavated lined pit infilled with a particulate organic carbon source. Nitrified effluent is piped into the upstream end of the bed, allowed to gravity flow through the carbon media and discharged from the bed via an outlet structure.

Figure 1.0 - Typical Denitrification Bed



2.2 DESIGN

The design of the denitrification beds rely on a number of factors

- **Bed dimensions and hydraulic performance** - The dimensions of a bed (LxWxD) for a particular application are dictated by the inlet and desired outlet nitrate concentrations. Hydraulic residence time (HRT) of effluent in the bed is also important to achieve design performance. HRT is controlled by water gradient and inputs rates within the bed. Research trials are currently being undertaken by GNS Science, University of Waikato and Landcare, TDC, and AWT to optimize bed design and hydraulic performance.
- **Inlet-outlet structures** - Design of the inlet and outlet structures are important to facilitate uniform flow through the bed and maximize effluent-media contact. The design of these structures must also allow for ease of maintenance.
- **Inlet nitrate concentration** – Denitrification beds have been shown to be capable of treating nitrate concentrations ranging from <5 mg/L to >350 mg/L. Some pre-treatment processes that incorporate a denitrification step require only “polishing” of the effluent (ie. removing only small levels of nitrate). Conventional domestic wastewater treatment systems incorporating nitrification require the treatment of 50-70mg/L of nitrate. Other applications where concentrations are even higher, such as dairy shed effluent, hot houses or industrial wastewater, treatment via denitrification beds is also possible.
- **Nitrate loading rate** – The volumetric requirement for media is also determined by the mass of input nitrate that can be applied to a set volume of media. This in turn is dependant on the type of media and the particle size and distribution.
- **Desired outlet concentration** – Denitrification beds can be designed to remove nitrate down to very low levels (<1mgN/L). However, the removal required from the denitrification beds is normally dictated by the resource consent conditions, often expressed as total nitrogen. Total nitrogen is the sum total of oxidized nitrogen (nitrate), ammonium and organic nitrogen. Hence if ammonium is removed or converted to nitrate in pre-treatment, the only way to lower the total nitrogen in the effluent is by lowering the nitrate.
- **Linier** – Denitrification beds are typically housed within an impermeable liner to prevent subsurface erosion and leaching of nitrate and carbon into the groundw ater, prior to treatment in the denitrification bed.
- **Carbon media** – The current denitrification bed design utilizes a woodchip mix as the carbon source. Research trials are currently being undertaken by GNS Science, University of Waikato and Landcare Research to identify optimum chip size and alternative carbon sources that may provide improved denitrification and hydraulic efficiencies and reduced bed construction costs.

2.3 FEATURES OF THE DENITRIFICATION BEDS

The advantages of denitrification beds over alternative nitrate removing treatment options are:

- Construction Cost - the beds are inexpensive to install when compared to other tertiary denitrification processes such as sand filtration.
- Low maintenance – the beds are very low maintenance with media replacement estimated to be in the vicinity of 5-10 years.
- Small footprint area – the footprint is small relative to other “natural” type systems for denitrification such as wetlands or ponds.
- Add on - a bed can be added onto an existing treatment system
- Removal rates - capable of > 99% removal of nitrate

Denitrification beds are typically used as the final stage in the treatment process. During the first few months of operation; however, the bed will release colour, BOD and organic nitrogen in the outflow and this can cause a deterioration in effluent quality and render the wastewater unsuitable for UV disinfection for example. However, trial results have shown that these parameters reduce to acceptable levels after several months of operation. Pre-leaching of the carbon media could be undertaken to minimize these effects if required.

High influent sulphate concentrations can also lead to H₂S production in the discharge effluent if nitrate limiting conditions in the bed occur. Appropriate bed sizing and the ability to alter the HRT will minimize this effect.

3 APPLICATIONS

Identified applications for denitrification beds include:

- Municipal wastewater
- Dairy shed effluent
- Hothouse discharge
- Industrial wastewaters
- Landfill leachate

3.1 MUNICIPAL WASTEWATER TREATMENT PLANTS

Kinloch WWTP (Taupo) utilizes a Sequencing Batch Reactor (SBR) treatment process. The effluent quality from the SBR is sometimes limited by the influent carbon fractions of the influent. Denitrification beds were installed to remove the residual nitrate of the SBR effluent.

Concentrations in inlet of the beds are typically in the order of 5-8 mg/L. Two carbon beds were installed at Kinloch in 2004. The dimensions of each are 50m length, by 4m width, and approximately 1.5 m deep. The denitrification beds at Kinloch have been in operation since January 2004 and have been effective with reducing nitrate and subsequently total nitrogen in effluent.

Motuteri WWTP (Taupo) utilizes a fixed film submerged aerated filter (SAF). The SAF plant has recently been installed to improve effluent quality; however, SAF process typically do not include a denitrification step. Hence, effluent nitrate concentrations are in the order of 30-40mg/L. A denitrification bed has been installed and commissioned, although have not yet commenced operation. The design outlet nitrate concentration from the denitrification bed is 0-2mg/L.

3.2 INDUSTRIAL WASTEWATER

There is also potential for industrial wastewater to be treated using denitrification beds provided there is a nitrification stage upstream.

Carbon beds may provide a viable denitrification alternative where there is a poor C:N ratio in the wastewater and where total nitrogen removal is required. This “supplemental” carbon is provided by the media downstream of a nitrifying process, e.g.,

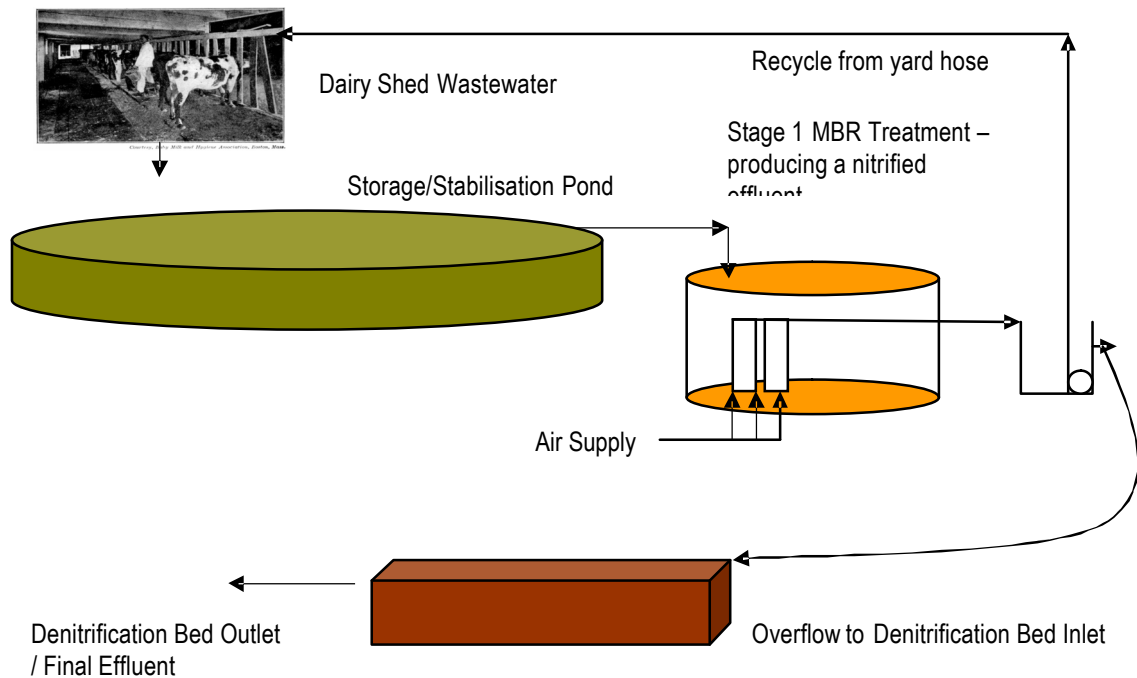
- Tanneries
- Fisheries
- Meat Processing industries
- Agricultural Industries

3.3 DAIRY SHED EFFLUENT

Dairy Shed Wastewater presents a significant pollutant load on New Zealand's rural environment if not adequately treated. (Heatley, 1995). Until recently, treatment techniques such as pond or barrier ditch systems were seen as adequate measures for the management of dairy shed wastewater. Wetlands have also sometimes been added to provide an additional treatment step. Land application of effluent can be successful in the recycling of nutrients where land form and hydrological conditions allow. In particular, land located in low lying areas with shallow water table, topography unsuitable for irrigator travel and run off, or porous soils with existing high nitrate groundwaters (e.g., areas of the Canterbury Plains). Also, land spraying involves a significant capital investment and incurs operational costs.

Trials using a prototype membrane bioreactor (MBR) system connected to a pond system have shown to be an effective means of treating dairy shed wastewater and in particular, oxidising the ammonium and organic nitrogen within the wastewater. This technology coupled with a down stream denitrification bed (Figure 2) can provide for in excess of 90% of total nitrogen removal from dairy shed wastewater shed wastewater. The primary objective of this research is the development of a sustainable low budget wastewater treatment plant that provides for an excess of 90% of total nitrogen from dairy shed wastewater.

Figure 2.0 –Plant Schematic for treatment of Dairy shed effluent



Results from this project are presented in Section 4.

3.4 HOTOUSE EFFLUENT

Denitrification beds are currently being used to remove nitrate from hydroponic hothouse discharge water in the Auckland area. Results to date show that the beds are capable of treating discharge waters with up to 350 mg/L $\text{NO}_3\text{-N}$.

4 RESULTS FROM ACTUAL INSTALLATIONS

4.1 MUNICIPAL WASTEWATER

The results of nitrate polishing from Kinloch WWTP effluent before and after the denitrification bed is shown in Figure 3.0 below. Influent concentrations fluctuated from 8mgN/L to 3mgN/L during a typical 3-month period which was reduced to generally less than 1 mgN/L. This represents on average a 5mgN/L reduction in nitrate and total nitrogen at the plant, a significant improvement in effluent quality.

This nitrogen removal is important as subsequent wastewater disposal is subsurface and onto Lake Taupo. Thus the carbon bed is a simple but effective way to minimize nutrient inputs from wastewater into the Lake

Figure 3.0 – Nitrate Removal Across the Denitrification Bed over a 3-month Period at Kinloch, Taupo.

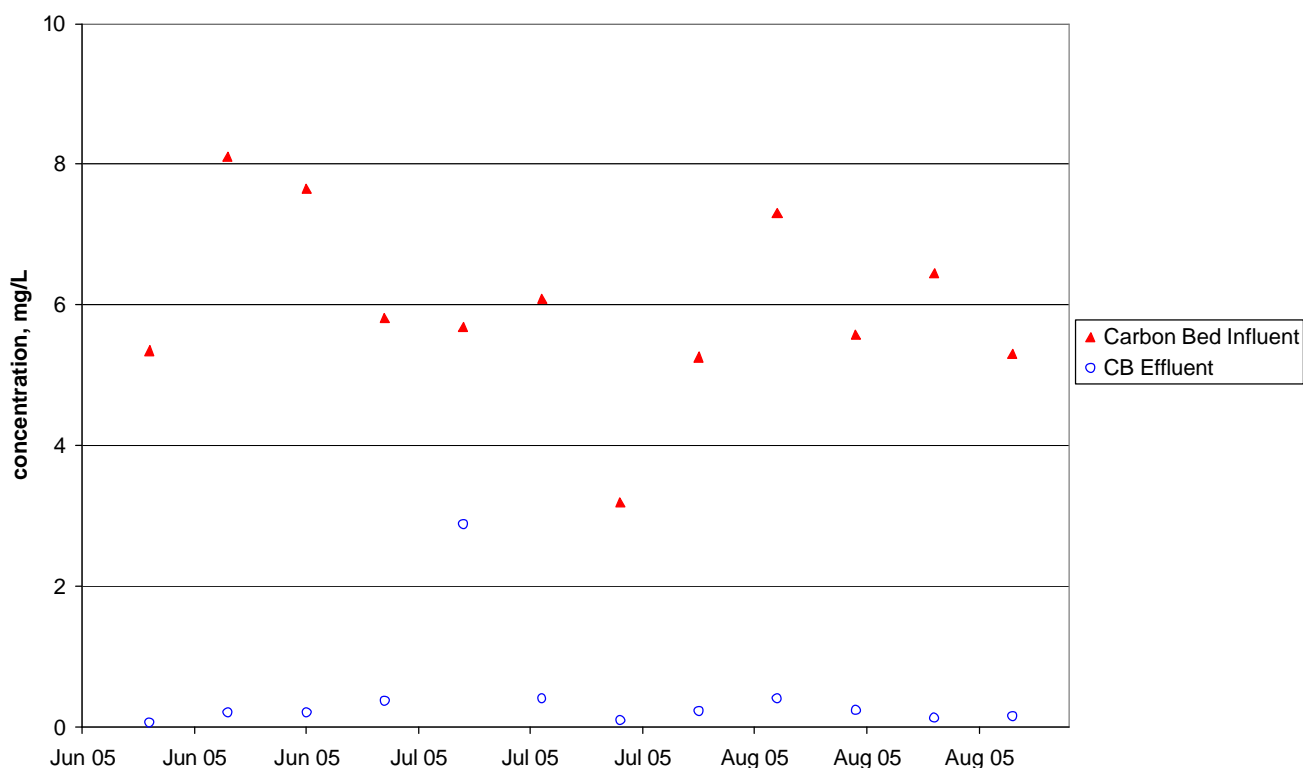


Figure 4.0 - Average Inlet and Outlet Nitrogen Fractions Across the Denitrification Bed Kinloch, Taupo.

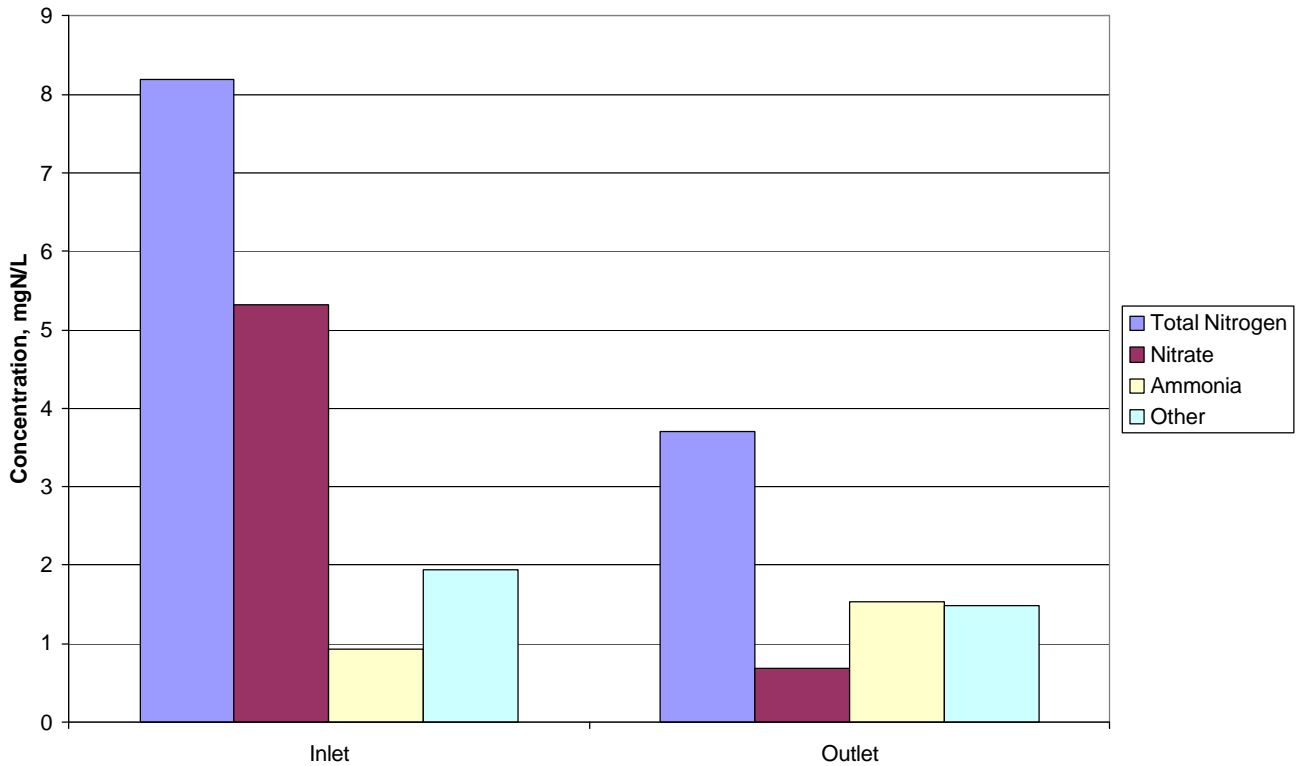


Figure 4.0 shows the different nitrogen fractions over the 2 year trial period in both the inlet and outlet of the denitrification bed. The total nitrogen column shows the sum of the nitrogen fractions adjacent to it, namely nitrate, ammonia and other forms of nitrogen. As discussed there was a significant reduction in average nitrate concentrations, corresponding to a decrease in over 50% of the total nitrogen. There was a small increase in ammonium from the bed in the order of 0.5 mg/L. This can likely due to degradation of organic nitrogen in the denitrification bed media or conversion of nitrate to ammonium instead of nitrogen gas. The sum ammonium and other nitrogen fraction (TKN) remained consistent. This supports, research to date that denitrification beds are only effective if the influent contains nitrogen in the form of nitrate. This has implications for the pre-treatment process, especially in municipal treatment plants to produce a fully nitrified effluent. It should be noted that there is also typically a 2-3mg/L non-degradable fraction of organic nitrogen in municipal wastewater.

Figure 5.0 below shows the results of weekly BOD₅ outlet samples from denitrification bed since the beginning of the trial. A trendline has been fitted to show that there is a gradual decrease in BOD₅ from the denitrification bed. This is consistent with other trial investigations by GNS, Landcare Research and University of Waikato support a decline over time in the amount of carbon released from the bed.

4.2 DAIRY SHED EFFLUENT

Table 1.0 below presents effluent quality from a dairy shed pond system that would normally be irrigated and thus represents the input parameters to the research trial plant.

Table 1.0 – Typical Dairy Shed Pond Effluent Concentrations

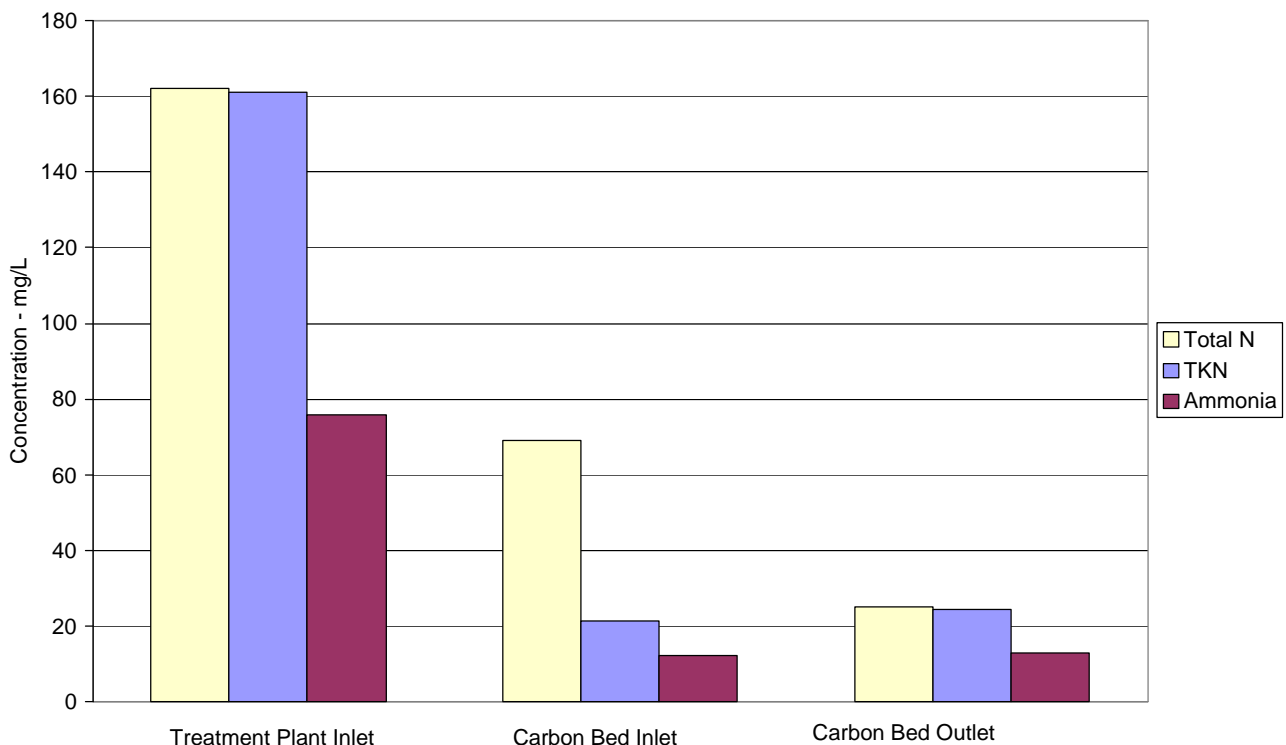
Parameter	Unit	Average	90%ile
COD	mg/L	1775	2520
SS	mg/L	3254	11027
TKN	mg/L	161	206
NH ₃ -N	mg/L	76	124
TP	mg/L	33	45

The data shows that the system needs to be capable of reviewing high concentrations of nitrogen and suspended solids. All of the nitrogen into the system from the pond is in the form of TKN made up from ammonia and/or organic nitrogen.

Trial Results

Figure 6.0 below presents nitrogen reduction across the entire treatment system and also identifies removal across the denitrification bed process.

Figure 6.0 - Average Total Nitrogen, TKN and ammonia removal from dairy shed effluent. Averages represent data collected during an 18 month trial period comprising about 40 samplings.

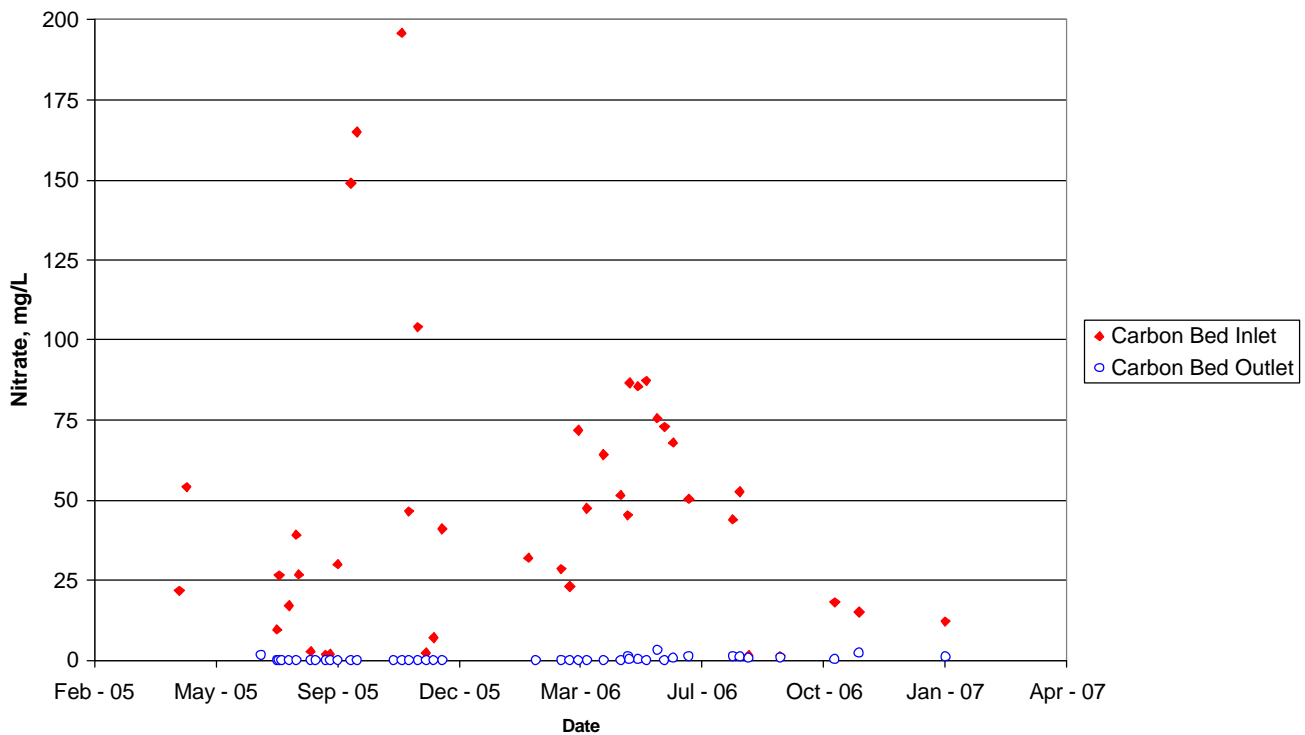


Nitrogen in the treatment plant inlet (outlet from the pond) was predominately TKN with a significant portion being in the form of ammonium. The nitrogen input to the denitrification bed was predominately nitrate due to

nitrification in the membrane bioreactor. The denitrification bed was particularly effective at removing this nitrate; however, the bed had little effect on the remaining TKN or ammonium. This lack of removal was likely because the denitrification bed operates under anoxic conditions and therefore provides limited ability for nitrification. A slight increase in TKN across the carbon bed was likely due to release of organic nitrogen from the wood media.

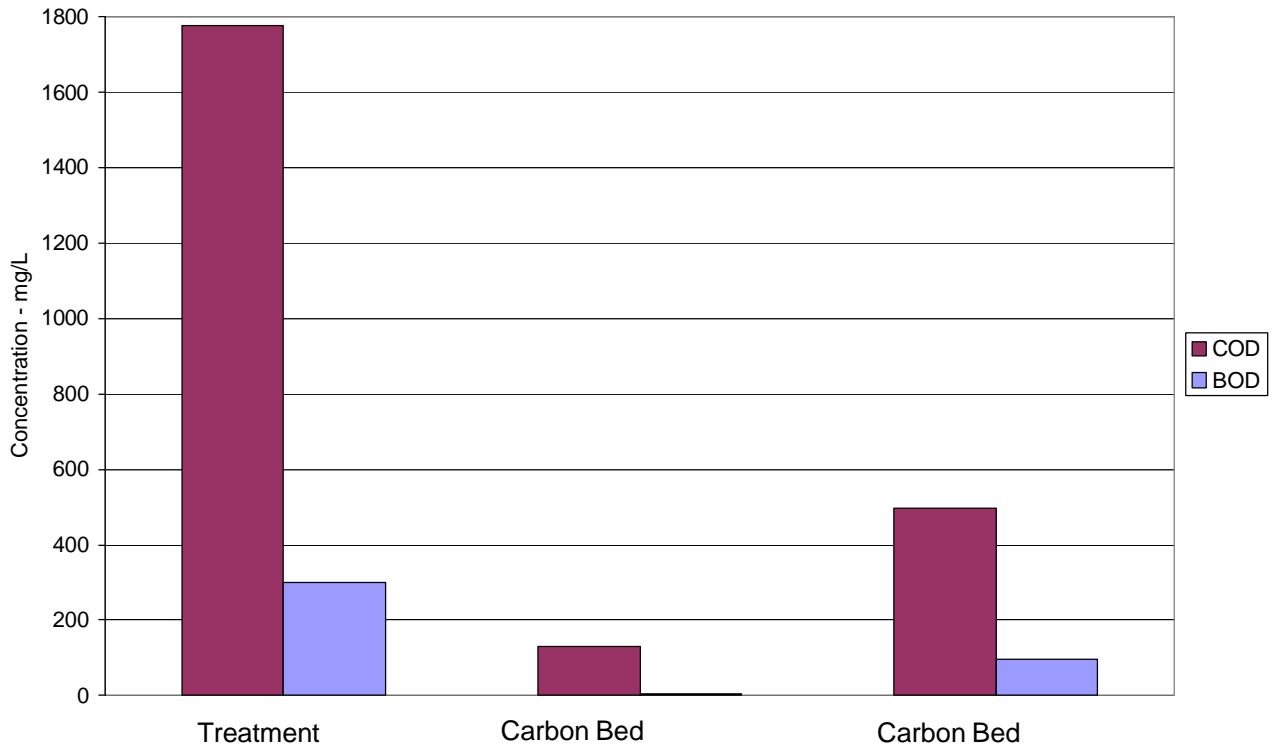
Figure 7.0 shows the individual data points for inlet and outlet concentrations. The bed removed approximately 99% of nitrate during the 18 month trial period.

Figure 7.0 - Inlet and Outlet Nitrate Concentrations of the denitrification beds treating dairy shed effluent.



The outlet nitrate concentration remains relatively constant between 0-5mg/L even with significant variation in the influent nitrate concentrations to the denitrification bed (5-195mgN/L). The average COD and BOD values across the prototype trial for the 18 month period are presented in figure 8.0. These results show removal of organic matter across the MBR system; however, carbon increased in the outlet of the denitrification bed. While the bed provides carbon for denitrification, the loss of soluble carbon also added both colour organic load to the final discharge. This loss of carbon maybe problematic depending on the receiving environment and the resource consent requirements. However, results from the other trial beds has shown that the excess in carbon breakthrough is usually short lived and that in the longer term increases in BOD across the beds are not excessive.

Figure 8.0 - Average COD and BOD removal over 18 months (~40 data points)



Overall, the dairy shed trial showed that this denitrification bed was effective at removing nitrate and played an important role with the removal of total nitrogen. The process shows a slight increase in colour and organic load added to the wastewater across the bed. Given the current state of a number of dairy shed discharges this was considered to have minimal environmental effects when compared to a direct discharge from a pond system.

5 CONCLUSIONS

Results of existing denitrification bed trials in New Zealand offer positive outlook for the effective nitrate removal from a wide range of effluents. These beds are relatively cheap to construct, with low maintenance requirements, and experience overseas indicates that the lifespan of the carbon media is in excess of 7-8 years.

In the municipal and dairy shed applications investigated, nitrate removal was about 95-99% even with widely varying influent nitrate concentrations. This reduction in nitrate corresponded to a significant reduction in total nitrogen concentrations when coupled to an upstream nitrification process. Investigations into agricultural applications are underway, and other industrial applications may also prove to benefit from the denitrification beds.

Future Research Work

GNS Science, University of Waikato and Landcare Research, in conjunction with Taupo District Council and AWT are currently undertaking trials to optimise nitrate removal in denitrification beds, determine bed longevity, and minimise adverse effects, such as carbon leakage. This work is being undertaken at the Taupo Pollution Control Plan (PCP) with a purpose built fixed film nitrification process followed by a number of trial beds.

ACKNOWLEDGEMENTS

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