Nitrogen removal from domestic effluent using subsurface flow constructed wetlands: influence of depth, hydraulic residence time and pre-nitrification

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Abstract This paper describes two studies into the BOD and TN removal performance of horizontal subsurface flow wetlands (reed beds) in subtropical Australia. The aim of the first study was to determine the influence of HRT and vertical position on BOD and TN concentration and removal performance in a 0.5m deep reed bed (System 1) by taking samples from three levels (or layers) in the water column at five points along the length of the bed. The aim of the second study was to investigate the TN removal performance of a treatment train consisting of a vertical flow intermittently dosed sand filter preceding a reed bed (System 2). Both systems were dosed with primary settled municipal wastewater (BOD 194 mg L^{-1}; TN 49 mg L^{-1}). System 1 achieved a TN load removal of 58% under a HLR of 22 mm day^{-1} (HRT 10.5 days), producing effluent BOD concentrations consistently less than 8 mg L^{-1}. There was no significant difference in BOD attenuation rate between the three layers. While there were differences in both the nitrification and denitrification rates between the three layers, the TN concentration was found to decline steadily in all layers up to an HRT of 8.7 days. System 2 reduced TN influent load by 33%, less than half of which was removed by the reed bed. The lack of substantial TN removal within this reed bed was attributed to the low concentrations of BOD and consequent lack of dissolved organic carbon to drive the denitrification process.
Keywords Hydraulic residence time; nitrogen removal; reed bed

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Introduction

The traditional approach to on-site and decentralised domestic wastewater management in Australia has been to use a septic tank to remove some suspended solids and biochemical oxygen demand (BOD) prior to infiltrative disposal by subsurface land application, usually via a gravity flow leach field (absorption trench). Recent studies have indicated a high level of failure in these systems due to poor design, inappropriate location or lack of maintenance (Geary, 1992). A major failure mode of these systems has been the clogging of absorption trench surfaces by an impermeable film or "biomat" caused by excessive loadings of BOD and total suspended solids (TSS) leading to surface ponding of potentially pathogenic effluents. In more permeable soils, the leaching of nitrate into ground and surface waters is a common problem. Since the mid 1980s, it has become increasingly common in Australian on-site wastewater management practices for effluent to undergo secondary treatment prior to land application. In the last three years most Australian states have upgraded regulations relating to on-site domestic wastewater management, with many local government areas using TN loading as the determining factor in sizing a land application area. Thus, there has been increasing interest in low maintenance technologies capable of achieving the removal of TN as well as BOD and TSS.

The period since the mid 1990s has seen the gradual introduction of secondary treatment approaches based on constructed wetland technology in Australian on-site wastewater treatment systems. Monitoring of small subsurface flow wetlands (or reed beds) which have been built in recent years indicates that TSS and BOD load removals in excess of 90% and TN load removals of at least 50% are commonly being achieved (Davison *et al.*, 2001).

To date, most of the investigations into wetland treatment performance have been based on input-output monitoring of in-situ domestic systems. In order to look more deeply into the dynamics of wetlands and other natural treatment devices a research facility was constructed in Lismore on the moist sub-tropical east coast of Australia. The facility contains two reed beds and a vertical flow intermittently dosed single pass sand filter. The facility was completed in September 2000, and monitoring commenced in March 2001.

This paper describes two studies conducted at the facility during June–July 2001. The aim of the first study was to determine the effect of HRT and depth on the concentration of BOD and TN in a small reed bed system. The aim of the second study was to assess the effect of pre-nitrification (using the intermittently dosed single pass sand filter) on the TN removal capacity of a second, small reed bed system.

Methods

Experimental setup and sampling regime

The two reed bed systems are located at the research facility at the South Lismore Sewage Treatment Plant. System 1 is a single reed bed designed for intensive depth and length monitoring (Figure 1). System 2 consists of a hybrid treatment system incorporating a vertical flow intermittently dosed single pass sand filter preceding a reed bed (Figure 2). Both reed beds are identical in size and construction (5.5 m long × 1.6 m wide, with water depth 0.50 m), and are planted with *Phragmites australis* in a 10 mm diameter gravel substrate encased in a 0.75 mm plastic liner.

System 1 was dosed with primary settled municipal wastewater at a Hydraulic Loading Rate (HLR) of 22 mm day^{-1}, giving a theoretical HRT of 10.5 days. Five sampling wells consisting of three 20 mm diameter PVC pipes constructed to enable water extraction from the upper, middle and lower layers of the water column were placed at equal intervals between the inlet and outlet devices. The wells corresponded to theoretical residence times of 1.7. 3.5, 5.2, 6.9 and 8.7 days if plug flow through the bed is assumed. An additional assumption made is that there was minimal mixing between layers of the reed bed.

The sand filter in System 2 was dosed six times per day with primary settled municipal wastewater, at a total daily HLR of 100 mm day^{-1}, resulting in a HLR to the reed bed of 67 mm day^{-1}, corresponding to a HRT of 3.7 days. Three sampling wells along the length of the bed (corresponding to theoretical HRTs of 0.9, 1.8 and 2.8 days) were used to extract samples from the mid layer of the water column.

Water samples were taken from the inlet and outlet of all treatment devices and from the sampling points in both reed beds of Systems 1 and 2. Samples were collected once per week for 8 weeks, between the 21st June and the 9th of August 2001 (Southern Hemisphere autumn/winter).

Wastewater quality

TN, ammonium nitrogen (NH_4-N), and oxidized nitrogen (NOx-N) concentrations for all water samples were determined using Flow Injection Analysis on a Lachat QuickChem 8000 Automated Ion Analyser (in accordance with the Standard Methods for the

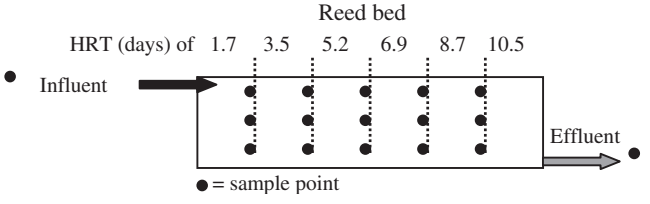

Figure 1 System 1 longitudinal view. Arrows represent wastewater flow

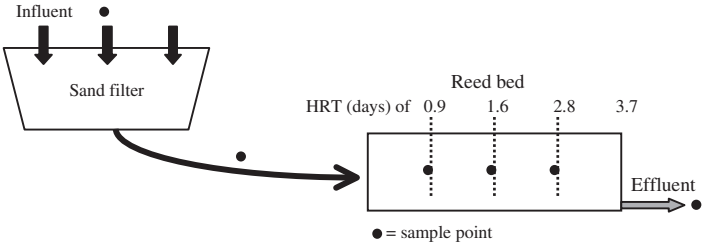

Figure 2 System 2 longitudinal view. Arrows represent wastewater flow

Examination of Water and Wastewater, 1995). Organic nitrogen (Org-N) and Total Kjeldahl Nitrogen (TKN) concentrations were determined using TN, NH_4-N, and NOx-N concentration results derived from laboratory analysis. Eq. (1) was used to determine the organic N concentration, while Equation 2 was used to determine TKN concentration.

$$\text{Org-N} = \text{TN} - (\text{NO}_X\text{-N} + \text{NH}_4\text{-N}) \quad (1)$$

$$\text{TKN} = \text{TN} - \text{NO}_X\text{-N} \quad (2)$$

A five day BOD analysis was performed on each sample, in accordance with the Standard Methods for the Examination of Water and Wastewater (1995). Redox Potential and pH readings were taken in the field at the time of wastewater collection, using a Hanna HI 8314 membrane pH meter.

Results and discussion

System 1 – reed bed intensive sampling

Table 1 contains redox potential readings obtained from each sample along the length of System 1. Redox potentials were positive throughout the reed bed, with all values increasing with HRT, with readings in the upper sampling layer consistently (but not significantly – $p = 0.4$) higher than those in the middle and lower layers throughout the sampling period. After an HRT of 5.2 days, mean redox potentials in all layers had exceeded 100 mV. According to Kadlec and Knight (1996), nitrate reduction occurs within this zone via the micobial process of denitrification.

Organic matter – BOD. Table 1 displays BOD removal characteristics and mean BOD concentration at all sample points within System 1. Figure 3 displays BOD concentration along the length of the reed bed at the three sample layers. BOD removal occurred rapidly within the reed bed, with an 80% concentration decrease (154 mg L^{-1}) occurring within the first 1.7 days. Removal occurred at somewhat slower rates thereafter, with secondary treatment (<20 mg L^{-1} according to the Australian and New Zealand Standard, 2000) achieved between 3.5 and 5.2 days. ANOVA showed that BOD concentration between sampling layers did not differ significantly ($p = 0.4$), indicating that BOD removal was occurring at similar rates throughout the depth profile.

Nitrogen removal. Table 1 contains nitrogen removal characteristics as well as mean nitrogen species concentrations at all sample points within System 1. Figure 4 shows graphically the decline in TKN concentration with HRT in all three layers.

NH_4^+ volatilization within treatment wetlands can provide a removal pathway for nitrogen, however the reaction is pH dependent. Reddy and Patrick (1984) state that NH_4^+ losses within flooded soils and sediments via volatilization are insignificant at a pH below 7.5, with significant losses not occurring at a pH below 8.0. As outlined in Table 1, the pH within System 1 ranged between 6.8 and 7.0, below the pH where substantial NH_4^+

Table 1 Water quality parameters and overall removal characteristics within the reed bed of System 1. All values displayed as concentrations (mg L^{-1}) unless otherwise stated (n = 8)

	Sample layer	*(Inf.)* 0	*Hydraulic Residence Time (days)* 1.7	3.5	5.2	6.9	8.7	*(Eff.)* 10.5	*Removal rate* ($g\ m^{-2}day^{-1}$)	*Load removal* (%)
BOD	Upper	193.6	39.4	16.0	12.0	8.07	5.98	–	–	–
	Middle	–	36.7	27.4	16.3	10.1	5.64	–	–	–
	Lower	–	43.4	24.8	15.8	11.8	7.19	6.6	4.13	97
Org-N	Upper	8.0	5.35	5.39	2.26	3.64	1.88	–	–	–
	Middle	–	4.63	4.11	1.73	2.08	2.66	–	–	–
	Lower	–	4.96	4.87	2.38	3.26	2.45	2.22	0.13	74
NH_4-N	Upper	38.5	34.7	26.5	24.4	19.4	13.8	–	–	–
	Middle	–	37.1	33.8	28.7	24.0	16.5	–	–	–
	Lower	–	36.8	33.6	29.5	23.9	19.4	15.8	0.51	60
TKN	Upper	46.5	40.1	31.9	26.7	23.0	15.7	–	–	–
	Middle	–	41.7	37.9	30.5	26.1	19.2	–	–	–
	Lower	–	41.8	38.5	31.9	27.1	21.9	18.0	0.63	81
NOx-N	Upper	0.54	1.57	3.93	5.61	7.61	2.50	–	–	–
	Middle	–	0.10	0.66	1.51	1.99	0.94	–	–	–
	Lower	–	0.06	0.28	0.17	1.49	0.91	4.83	*	*
TN	Upper	47.0	41.7	35.8	32.3	30.6	18.2	–	–	–
	Middle	–	41.8	38.5	32.0	28.1	20.1	–	–	–
	Lower	–	41.8	38.8	32.0	28.6	22.8	23.0	0.61	58
Redox	Upper	–	28	71	144	225	255	–	–	–
Potential	Middle	–	18	33	113	201	246	–	–	–
(mV)	Lower	–	15	44	93	164	179	–	–	–
pH	Upper	6.8	6.9	6.8	6.9	6.7	6.7	6.9	–	–
	Middle	–	6.9	6.9	6.9	6.9	6.8	–	–	–
	Lower	–	6.8	7.0	6.9	6.9	6.8	–	–	–

*negative removal rate

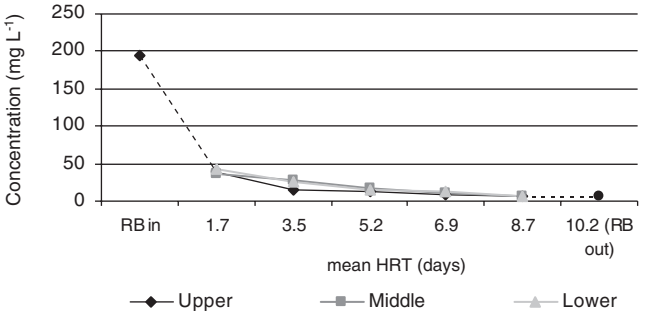

Figure 3 BOD concentration versus HRT at upper, middle and lower water layers

volatilization occurs. Although NH_4^+ can be removed from wastewater via a cation exchange adsorption reaction with organic sediments and substrate within a wetland system, Kadlec and Knight (1996) point out that removal via this pathway occurs only during the early stage of a wetland's life when adsorption sites are available. At the time of sampling, both reed beds under investigation were approximately 1 year old. Thus, TN removal via NH_4^+ adsorption was considered negligible. Therefore, nitrification can be assumed to be the main NH_4^+ removal pathway.

Because volatilization and adsorption were most likely negligible contributors to the decline in TKN concentration with HRT, the slope of the TKN curves in Figure 4 can be used as an indicator of the rate of nitrification in System 1. Figure 4 shows that the nitrification rate was highest in the upper layer between 1.7 and 3.5 days when TKN concentration was declining at a rate of 4.8 mg L^{-1} day^{-1}. This compares with the much lower nitrification

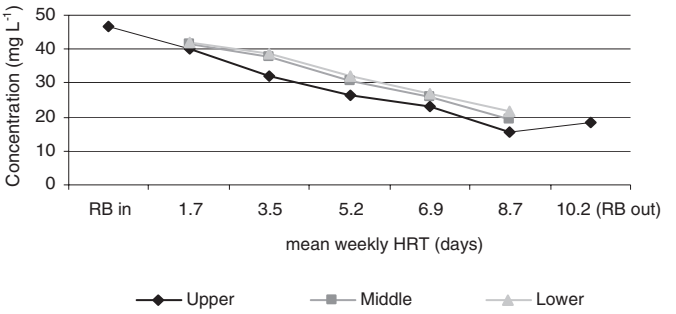

Figure 4 TKN concentration versus HRT at upper, middle and lower layers

rate of 2.3 mg L^{-1} day^{-1} in the two lower layers at this HRT. In the interval from 3.5 to 8.7 days nitrification in the upper layer dropped to 3.2 mg L^{-1} day^{-1} while in the middle and lower layers it increased to 3.7 and 3.6 mg L^{-1} day^{-1} respectively.

The nitrification of TKN contributed to increased concentrations of NOx-N as displayed in Figure 5 which shows that, up to 6.9 days, NOx-N increased with HRT in all three layers, before decreasing. According to Kadlec and Knight (1996) the main NOx-N removal pathways available in wetlands are plant uptake and denitrification. Kadlec *et al.* (2000) state that yearly nitrogen plant uptake rates within reed beds generally range between 1,000 and 2,500 kg ha^{-1} $year^{-1}$ (or 0.27 and 0.67 g m^{-2} day^{-1}). Table 1 shows that the overall TN removal rate in the reed bed was 0.61 g m^{-2} day^{-1} indicating that both pathways were possibly playing a significant role in NOx-N removal. However, during the winter study period, plant growth, and hence nitrogen uptake, would be slow. Thus, in the period to 6.9 days the combined effect of these two removal processes is outpaced by the nitrification of TKN, causing a build up of NOx-N. This effect is most marked in the upper layer where the NOx-N concentration peaks at 7.6 mg L^{-1} as opposed to only 1.99 and 1.49 mg/L in the middle and lower layers respectively. This difference could be a result of (a); more efficient plant uptake in the middle and lower layers or (b); more efficient denitrification in the middle and lower layers or (c); the increased rate of nitrification in the upper layer between 1.7 and 3.5 days, noted above.

The data collected in this study do not permit analysis of nutrient removal by plant uptake; therefore no comment can be made on this factor. With respect to the possibility of differences in the denitrification rate between layers, Table 1 shows that the redox potential in all layers is within the range for effective denitrification. Also Figure 3 shows that BOD – and hence dissolved organic carbon (DOC) – concentrations vary little between layers. Therefore it is unlikely that there is any significant difference in denitrification rate between layers. It is probable then that the higher peak in NOx-N concentration in the upper layer is a result of the early increased rate of nitrification between 1.7 and 3.5 days.

At 6.9 days (Figure 5) NOx-N concentrations decreased within all layers. Reference to Figure 5 shows that nitrification of TKN was still proceeding at this HRT, therefore it is likely that an increase in NOx-N removal rate occurred at this point. This theory is supported by the fact that reed growth in the final quarter was more vigorous than in the initial three quarters of the bed. This increased growth (approximately corresponding to 6.9 days) could have had a five-fold effect on NOx-N removal. Firstly, a dense stand of reeds will improve nutrient removal through plant uptake. Secondly, there is some evidence that macrophytes may secrete root exudates rich in organic carbon (Brix 1997). Thirdly, the abundance of plant roots, particularly in the upper layer, would provide an organic carbon source as dead roots break down and decay. Fourthly, a healthy root system would also facilitate the establishment of a rich and productive community of microorganisms, such as the attached

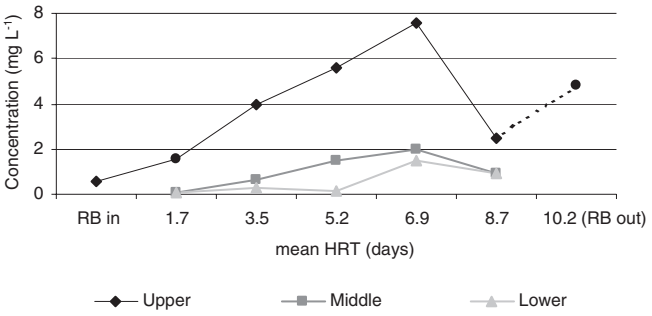

Figure 5 NOx-N concentration versus HRT at upper, middle and lower layers

growth denitrifiers. Finally, the above-ground biomass of *Phragmites australis* may supply organic carbon to the system through the breakdown and decay of dead leaf and stem material on the surface of the reed bed, eventually leaching through into the water column. The effect of the last four factors would be to increase the concentration of dissolved organic carbon, particularly in the upper layer, and enhance NOx-N removal via denitrification. This view is supported by Gersberg *et al.* (1983) and Headley *et al.* (2001) who both suggest that reed beds can internally produce organic carbon to fuel the denitrification process.

The above theory would have been supported by the detection of elevated BOD concentrations (reflecting increased DOC) towards the end of the bed. Although this was not the case it is possible that organic inputs from the above sources would probably be slight compared to the resolution of the BOD test. Furthermore, in the situation where a carbon limitation exists there becomes a denitrification related demand for organic carbon. Subsequently, any inputs of organic carbon would be rapidly consumed by denitrifying bacteria before being detected in the water samples collected.

System 2 – sand filter and reed bed hybrid treatment system

Table 2 and Table 3 display BOD and nitrogen species concentrations and removal charac-

Table 2 BOD and nitrogen species concentrations within System 2. All values in mg L^{-1}

	BOD	TKN	NOx-N	TN	pH	Redox potential (mV)
Sand filter influent	186	48.1	0.0	48	6.8	–
Sand filter effluent	3.8	12.2	28	41	6.1	–
Reed bed influent	3.8	12.2	28	41	6.1	–
Reed bed – 0.9 HRT	2.5	9.9	28	38	6.4	208
Reed bed – 1.8 HRT	1.8	11.0	29	40	6.4	206
Reed bed – 2.8 HRT	2.1	10.0	29	39	6.4	201
Reed bed effluent	2.8	10.4	25	36	6.3	–

Table 3 BOD and nitrogen species removal characteristics of System 2

	BOD	TKN	NOx-N	TN
Sand filter load reduction (%)	98	78	*	17
Sand filter removal rate (g m^{-2} day^{-1})	16	3.3	*	0.75
Reed bed load reduction (%)	33	18	16	15
Reed bed removal rate (g m^{-2} day^{-1})	0.077	0.18	0.28	0.39
System load reduction (%)	98	81	*	33
System removal rate (g m^{-2} day^{-1})	6.8	1.4	*	0.60

* negative removal rate

teristics in System 2. Sand filter effluent (becoming reed bed influent) was characterised by a very low BOD concentration and a high NOx-N concentration. The mean load reduction of TN within the reed bed following the sand filter in System 2 averaged only 15% under the HRT of 3.7 days. This, combined with the TN removal achieved in the sand filter, gave an overall system TN load removal of approximately 33%.

As shown in Table 2, despite the added complexity of System 2 compared to System 1, very little TN was removed. Given that the redox potential throughout the reed bed in System 2 was consistently within the denitrification range of between +100 and +300 mV (Table 2) (Kadlec and Knight, 1996), the lack of substantial denitrification occurring within the reed bed was probably the result of a limited supply of carbon (as reflected by the low BOD concentrations). Given that 16% of the TN load entering the reed bed was removed throughout the sampling period, plant uptake and/or some degree of denitrification within the reed bed must have occurred. The internal supply of carbon through the death and decay of biomass communities within the reed bed could have possibly provided the carbon necessary for the limited denitrification that occurred.

Conclusions

System 1 achieved an average BOD load removal of 97%, reducing average concentrations from 194 mg/L to 6.6 mg L^{-1}, with secondary treatment achieved in less than 5 days. Sampling within the upper, middle and lower layers in the reed bed showed that the BOD removal rate was independent of depth. System 1 achieved a TN load removal efficiency of 58%. TKN concentrations declined steadily with increased HRT in all layers, with removal rates highest in the upper layer during the first 3.5 days of residence due to a higher nitrification rate in that layer. NOx-N concentrations increased steadily with increased HRT in all layers, peaking at 6.9 days. Subsequent decline in NOx-N concentration was attributed to a combination of increased plant uptake and denitrification caused by passage through an area of particularly vigorous reed growth at the tail end of the bed. Total nitrogen concentration declined steadily within all layers up to 8.7 days before leveling off in the final 1.7 days. The relatively good pollutant removal in the bottom layer suggests that beds considerably deeper than the 0.5 m used in this trial may be worth experimenting with. System 2, consisting of a pre-nitrifying intermittently dosed sand filter feeding a horizontal flow reed bed, removed 33% of the average total nitrogen load. The sand filter effectively nitrified 78% of the TKN influent load and, in removing 98% of the BOD loading, reduced BOD to concentrations consistently below 5 mg L^{-1}. TN load removal efficiency of the reed bed was only 15%, at a rate of 0.39 g m^{-2} day^{-1} (36% lower than the 0.61 g m^{-2} day^{-1} of the reed bed in System 1). The low TN removal within the reed bed can be attributed to the lack of carbon within the system to fuel denitrification.

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