TREATMENT OF NITRIFIED WASTEWATER USING REED BEDS

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Abstract

Nutrient removal has become a recent focus of on-site wastewater management. Many of the secondary treatment systems employed to date achieve only limited nutrient removal, producing a nitrified effluent that is low in BOD. This paper describes a twelve month study examining nutrient removal in four reed beds receiving a nitrified wastewater (TN≈10 mg L^{-1}; TP≈ 0.5 mg L^{-1}). A hydraulic residence time of two days achieved an 80% load removal of TN and TP, producing outlet concentrations of < 0.5 mg L^{-1} (TN) and < 0.1 mg L^{-1} (TP). The reeds were found to play an integral role in nutrient removal. Despite the lack of influent BOD the reed beds generated enough organic carbon internally to fuel denitrification, with up to 41% of nitrogen removal being through this process. Due to the low influent concentrations, plant nutrient uptake rates were lower than those reported in other studies. However, incorporation of nutrients into biomass was the major removal pathway and accounted for 60% – 70% of N and P removal. Evapotranspiration losses from the reed beds ranged from 130 to 327 mm / month, with crop factors between 1.1 and 4.2. This had an effect of reducing the wastewater hydraulic load in all months except January in which there were 311 mm of rainfall. The study indicates that reed beds are a suitable technology for removing nutrients from the nitrified effluents produced by sand filters and AWTSs, thereby reducing the required effluent disposal area in LGAs which base disposal area on nutrient loadings.

Keywords

denitrification, evapotranpiration, nitrified wastewater, nitrogen, phosphorus, plant uptake, reed beds

1 Introduction

In recent years there has been a growing trend towards the use of treatment devices prior to disposal in on-site wastewater management systems. Our awareness of the role that on-site systems play in contributing to the nutrient pollution of waterways has increased, and so too has the focus on preventing such pollutants from leaving an on-site treatment/disposal system. In Australia aerated wastewater treatment systems (AWTS) have been the dominant technology in our approach to improving on-site treatment, while in the USA intermittently dosed sand filters have been popular. Both of these approaches can produce highly nitrified effluents (majority of NH_4^+ converted to NO_3^-) which are low in total suspended solids (TSS) and biochemical oxygen demand (BOD). In both cases there is little or no removal of nitrate (and hence TN removal efficiencies are low) because the predominantly aerobic conditions are not conducive to denitrification. This results in system designers having to rely heavily on plant uptake via irrigation of disposal areas to remove the remaining nutrients. However, irrigation areas that are sized based on nitrogen loading are often extremely large, expensive and unachievable on small blocks. Sand filter designers have been able to achieve higher TN removal by recirculating part of the nitrified sand filter effluent back into the influent where the presence of high BOD and anaerobic conditions facilitate denitrification. An alternative approach is to run nitrified effluents through a subsurface flow wetland (reed bed) (Russell *et*

al. 1994). The plants in a reed bed help to remove nutrients through up-take, while reducing hydraulic loads via evapotranspiration. The predominantly anaerobic conditions also facilitate denitrification, which is often the dominant nitrogen removal pathway. While reed beds are generally effective at removing nutrients (Reed *et al.*, 1995), nitrogen removal can be limited by insufficient organic carbon for denitrification (van Oostrom and Russell, 1994). Denitrification involves the reduction of nitrate to nitrogen gas by heterotrophic denitrifying bacteria (denitrifiers) under anaerobic conditions (Gersberg, Elkins and Goldman, 1983). The overall stoichiometric reaction for denitrification, with CH_3COOH representing organic carbon, is given in Equation 1:

$$5\ (CH_3COOH) + 8\ NO_3^- + 8\ H^+ \rightarrow 10\ CO_2 + 4\ N_2 + 14\ H_2O \qquad \text{(Eq. 1)}$$

This equation indicates that at least 1.25 moles C is needed to reduce every mole of NO_3-N, or 1.07 g C to reduce 1 g N (Zhu and Sikora, 1995). The denitrifiers use this organic carbon (organic matter as measured by the BOD_5 test) as an energy source. Thus, there is a question of whether there will be sufficient organic carbon remaining in pretreated/nitrified wastewater for denitrification to occur. This highlights a major nitrogen removal paradox, in that for efficient nitrification to occur, the majority of BOD must first be removed. This is because carbon-consuming microbes tend to out-compete nitrifiers for available oxygen when BOD is present. Hence, by the time nitrification is complete, denitrification is often limited due to a lack of necessary organic carbon. In this context, reed beds have an advantage over other treatment devices in that they contain plants. The reeds can act as a self-perpetuating organic carbon source through the photosynthetic fixation of carbon dioxide (Brix, 1997). A secondary benefit of reed beds is their ability to reduce the hydraulic load going to a disposal area through evapotranspiration by the reeds.

This paper describes a study on the effect of reed beds on the nutrient content of simulated nursery irrigation runoff, a nitrified wastewater that is low in BOD. The composition of nursery runoff is similar to nitrified wastewater and poses the same set of challenges for treatment. The research has been conducted on four identical reed beds located on the northern coast of New South Wales. Specific objectives of the study were to:

- determine whether efficient nutrient removal can be achieved in reed beds receiving a highly nitrified wastewater low in BOD;
- conduct a nutrient budget to determine the main nitrogen and phosphorus removal pathways;
- determine the hydraulic residence time (and hence sizing) required to achieve a range of nutrient removal levels; and
- conduct a water budget with a view to determining the role that reed beds can play in reducing hydraulic loads on disposal areas.

2 Methods

2.1 Site Description

Four horizontal flow reed beds were constructed at the Tropical Fruit Research Station (NSW Agriculture) in Alstonville on the northern coast of New South Wales, in 1999. Figure 1 shows a plan view of the study facility. All four reed beds are identical in design, consisting of a fibreglass shell, 4 m long x 1 m wide, filled with 10 mm basaltic gravel to give a water depth of 0.5 m. A longitudinal section is shown in Figure 2. The beds were planted with rhizome cuttings of *Phragmites australis* (common reed) in April 1999. To promote reed growth and establishment, the reed beds were regularly topped-up with a soluble fertiliser until monitoring commenced five months later in September 1999.

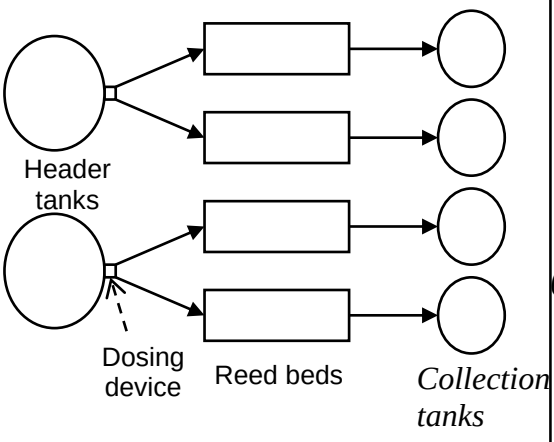

Figure 1. Plan View of Reed Bed System Arrangement.

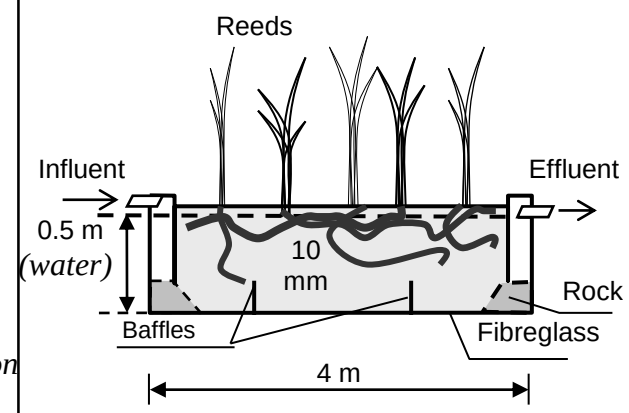

Figure 2. Simplified Longitudinal Section Through Reed Bed.

The reed beds were dosed with a test solution that was manually made up each week using soluble nutrients. The target composition of the test solution is shown in Table 1. The test solution was mixed in two header tanks, with each tank supplying runoff to two reed beds (Figure 1). Timer activated pumps intermittently dosed test solution to each reed bed (six times per day). Water meters were used to record the volume of water entering the reed beds. The treated test solution from each reed bed was then held in a collection tank. The volume of reed bed outflow was recorded weekly via a level tube on the side of each collection tank.

Table 1. Target Concentration of Test Solution Ingredients.

Parameter	TN	TP	BOD	TSS	pH	Micro-nutrients / trace elements
Concentration	10 mg L^{-1} mainly nitrate	0.5 mg L^{-1} mainly phosphate	<5 mg L^{-1}	<5 mg L^{-1}	**7**	Various

2.2 Nutrient Monitoring

Monitoring of the reed beds involved the examination of water samples, and the estimation of the nutrient content of the reed biomass.

The reed beds were subjected to a range of different hydraulic residence times (HRTs) over the study period. Monitoring began on 7/9/1999 with a 5 day HRT for all four reed beds. The HRT was then decreased to 4 days on 5/1/2000. From this point onwards, two of the reed beds (Control Beds) were maintained at a 4 day HRT for the remainder of the study. The HRT of the other two reed beds (Treatment Beds) was decreased to 3 days on 1/4/2000, and subsequently to 2 days on 1/10/2000. Weekly water samples were collected from the inlet and outlet of each reed bed. During the 4 day and 3 day HRT periods halfway samples were also collected from a vertical length of 50 mm diameter perforated pipe running from the gravel surface to the bottom of each reed bed. These halfway samples were used to give an indication of treatment at half of the overall HRT. Thus, the HRTs examined were 5, 4, 3, 2, 1.5 days. Weekly samples were analysed for TN, NH_4^+, NO_2^-, NO_3^-, TP and Ortho-P using Flow Injection Analysis on a Lachat QuickChem 8000 Automated Ion Analyser. All methods were in accordance with those described in the Standard Methods for the Examination of Water and Wastewater (1995).

A one way analysis of variance (ANOVA) was conducted to determine if the percent load removal of TN and TP was affected by HRT. Where a significant difference was observed, the Tukey HSD test was used to ascertain between which HRTs the difference existed.

The uptake of nutrients into the reeds was determined on the two control beds by estimating the reed biomass and determining the nutrient content of that biomass. Reed biomass was split into above ground and below ground components. To estimate the mass of above ground biomass, all reed stems were harvested in June/July 2000 after approximately one year's growth by cutting them off at the gravel surface. Below ground biomass was estimated by coring into the gravel substrate with a 150 mm diameter steel pipe. The contents of the core were then excavated and sorted to separate the root/rhizome material from the gravel. Cores were taken from the inlet, halfway and outlet zones of each reed bed in September 2000 (one year after commencement of monitoring). All plant material was dried for 48 hours in a desiccator at 65° C and weighed. The dry weight from the below ground cores was scaled up to estimate the total below ground biomass for each reed bed. Subsamples of the dried material were ground and analysed for nitrogen and phosphorus. Nitrogen was analysed using an oxidative combustion method on a LECO instrument. Phosphorus content was determined by digesting the plant material using a semi-micro Kjeldahl digestion procedure, followed by spectrophotometric determination of the phosphorus content of the digests.

2.3 Water Budget

A water budget for the four reed beds was determined using the weekly inflow (water meters) and outflow (collection tanks) volumes, and rainfall data. Evapotranspiration (ET) losses from the four beds were calculated by the difference between the volumes going into (inflow + rain) and the volumes leaving the reed beds each week. Readings from an on-site class-A evaporation pan were used to determine crop factors for the reeds. The crop factor for a given period is the ET loss as a proportion of Class-A pan evaporation.

3 Results and Discussion

Water Quality Monitoring

The TN and TP inlet and outlet concentrations and percent load removals for the five HRTs studied are presented in Table 2.

Table 2. Means and standard errors of means (in parentheses) of inlet and outlet concentrations, and percentage load reductions for total nitrogen and total phosphorus at each HRT (*n* = sample no.).

HRT	TN			TP		
(days)	**IN** (mg L^{-1})	**OUT** (mg L^{-1})	**% red.**	**IN** (mg L^{-1})	**OUT** (mg L^{-1})	**% red.**
5	**3.68**	**0.405**	**86.8**	**0.487**	**0.025**	**94.4**
(*n* = 64)	(0.244)	(0.023)	(0.720)	(0.022)	(0.003)	(0.565)
4	**7.21**	**0.386**	**87.6**	**0.520**	**0.064**	**86.8**
(*n* = 88)	(0.400)	(0.042)	(1.73)	(0.017)	(0.014)	(2.44)
3	**11.37**	**1.69**	**87.2**	**0.629**	**0.012**	**97.9**
(*n* = 22)	(0.293)	(0.533)	(3.75)	(0.021)	(0.002)	(0.255)
2	**7.21**	**1.56**	**80.0**	**0.507**	**0.097**	**77.4**
(*n* = 97)	(0.393)	(0.235)	(1.84)	(0.017)	(0.012)	(2.62)
1.5	**10.47**	**4.85**	**57.8**	**0.574**	**0.018**	**96.6**
(*n* = 27)	(0.483)	(0.624)	(5.09)	(0.031)	(0.003)	(0.535)

TN load removals of 87% were achieved at HRTs of 5,4 and 3 days (Figure 3), indicating that nitrogen removal was not limited by the low BOD (< 5 mg L^{-1}) of the influent.

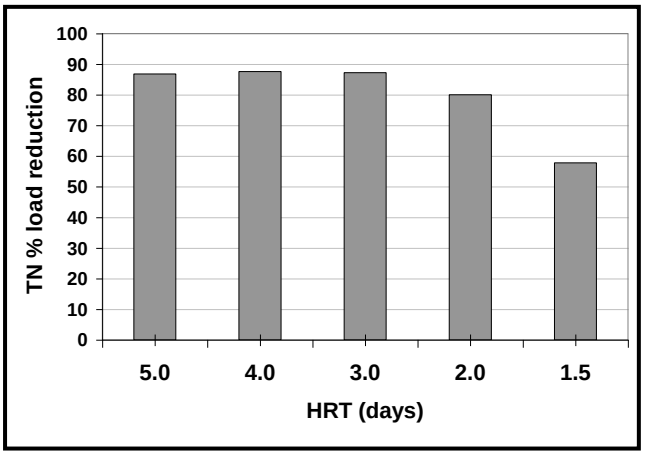

Figure 3. Mean TN % Load Reduction per HRT Treatment

At an HRT of 1.5 days, only 57.8% of the TN load entering the reed beds was removed. The ANOVA found that TN removal was affected by HRT ($P < 0.001$), with the 1.5 day HRT being significantly less efficient than all other HRTs. This suggests that there is little additional benefit in having HRTs of greater than 2 days with respect to TN removal from a nitrified effluent. At HRTs of 5 and 4 days outlet TN concentrations were generally less than 0.5 mg L^{-1}. HRTs of 3 and 2 days generally achieved outlet TN concentrations of less than 2 mg L^{-1}, while outlet concentrations were generally over 4 mg L^{-1} for the HRT of 1.5 days. Figures 4 and 5 show the different nitrogen species that make up the TN in the inlet and outlet water for each HRT. The majority of nitrogen entering the reed beds was in the form of nitrate. The 5 and 4 day HRTs achieved virtually complete removal of nitrate, with the only remaining nitrogen being organic nitrogen (mean 0.37 mg L^{-1}). The poorer nitrogen removal at shorter HRTs was due to incomplete removal of nitrate.

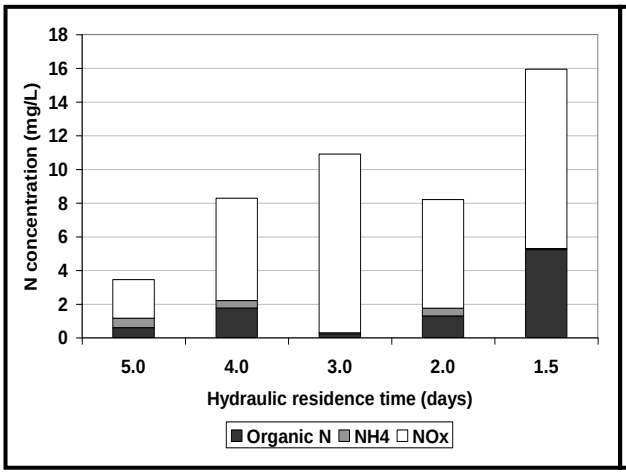

Figure 4. Mean Inlet Total Nitrogen Concentration showing species breakdown

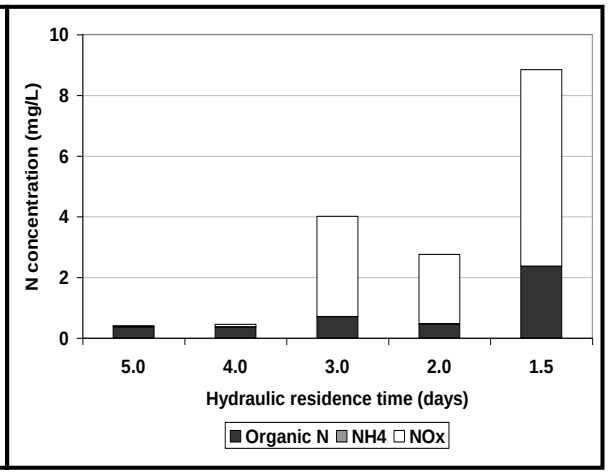

Figure 5. Mean Outlet Total Nitrogen Concentration showing species breakdown

Removal of TP was generally high (77% to 98%), although more variable than TN removal (Figure 6). While the ANOVA found significant differences in TP load removal between HRTs, Figure 6 indicates that TP load removal was independent of HRT. TP removal at 2 day HRT was significantly different to 5, 3 and 1.5 day HRTs, and the 3 day HRT was different to the 4 day HRT. This lack of response to HRT, accompanied with the fact that TP removal was generally high (> 77%) suggests that, under the range of HRTs examined here, other factors may have had a stronger influence over the observed treatment than the HRT.

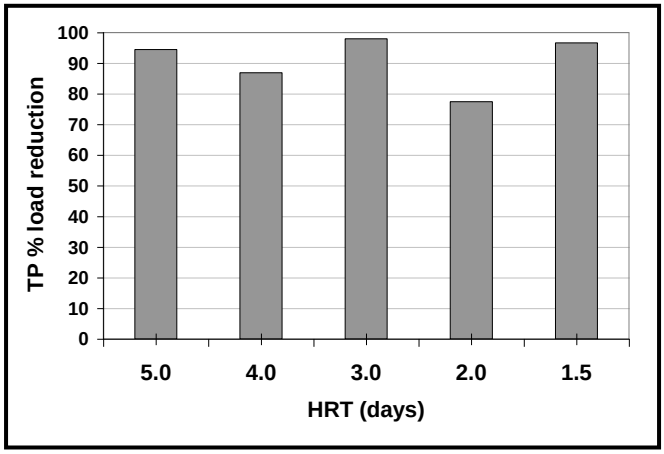

Figure 6. Mean TP % Load Reduction per HRT Treatment

Figures 7 and 8 show the different phosphorus species in the inlet and outlet water. The majority of phosphorus entering the reed beds was orthophosphate. The outlet TP was composed mainly of organic P, the majority of which would have been generated from within the reed beds through the growth and decay of plants and microorganisms. Very low outlet TP concentrations of less than 0.1 mg L^{-1} were consistently achieved at all HRTs, although levels of around 1 mg L^{-1} (higher than the inlets) were observed infrequently. These sporadic outlet TP spikes were generally in the form of organic P from internally generated sources. The mechanisms behind these releases are unclear. In any case, an HRT as short as 1.5 days is capable of achieving very low outlet concentrations (< 0.02 mg L^{-1}).

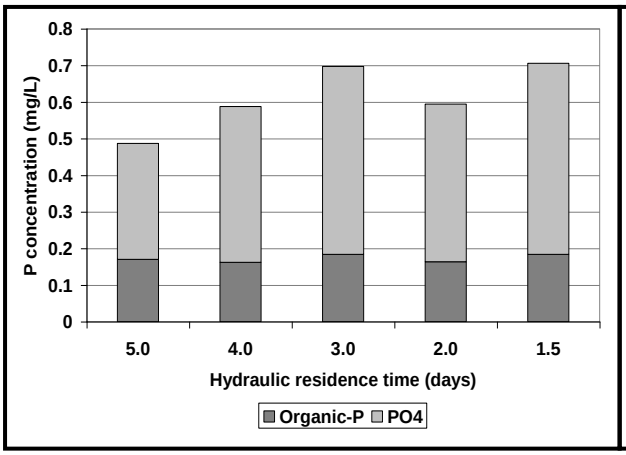

Figure 7. Mean inlet total phosphorus concentration showing species breakdown

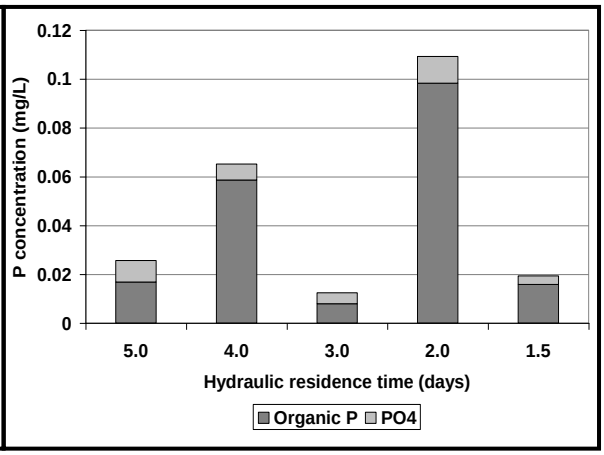

Figure 8. Mean outlet total phosphorus concentration showing species breakdown

The low outlet concentrations of TN and TP achieved by the reed beds have important implications for the design and sizing of disposal areas in those LGAs where nutrient loadings are considered (e.g. Lismore City Council, 1999).

3.2 Reed biomass monitoring

During the first year of growth, the mean above ground biomass growth rate was 2.6 kg/m^2/yr (dry weight). Below ground biomass accumulated at a rate of 2.7 kg/m^2/yr (dry weight). Table 3 shows the mean removal rates of nitrogen and phosphorus via incorporation into above ground and below ground reed components and other removal processes (denitrification and phosphorus fixation). The amount of nitrogen lost through denitrification and phosphorus through fixation onto the gravel are derived by subtraction of plant uptake from the total measured nutrient removal.

Table 3. Nitrogen and Phosphorus Removal Pathways in Control Beds.
Above ground removal: Sep-99 to Jul-00.
Below ground removal: Sep-99 to Sep-00.
Non-plant removal calculated by subtraction.

	Nitrogen				**Phosphorus**			
	Plants			**Other**	**Plants**			**Other**
	Above Ground	**Below ground**	**Total**	**Denitri-fication**	**Above ground**	**Below ground**	**Total**	**Gravel fixation**
Removal g	119	130	**249**	173	9.9	10.7	**20.6**	8.8
Removal Rate g/m^2/day	0.11	0.10	**0.21**	0.14	0.008	0.009	**0.017**	0.007
% of Total Removal	29.5%	29.5%	**59%**	41%	38%	31%	**70%**	30%

Due to the low influent nutrient concentration, plant uptake rates were lower than those reported in other studies looking at higher nutrient loads (Burgoon *et al.* 1991). Above ground and below ground reed components accumulated nutrients at very similar rates. Plant uptake accounted for 59% of overall nitrogen removal and 70% of phosphorus removal. While this is higher than figures commonly cited in the literature (see Reed *et al.*, 1995; Davies and Cottingham, 1993), other authors have observed similar uptake rates to the current study for a number of macrophyte species (Breen, 1992). This disparity in the literature is probably a function of the range of effluents, plant species and conditions that reed beds have been subjected to in the various studies. Despite the low BOD of the influent, denitrification was responsible for approximately 41% of nitrogen removal. This suggests that the reeds provide an additional benefit (aside from direct uptake) of supplying organic carbon to fuel denitrification.

A question remains whether this high level of plant uptake will be maintained through subsequent growing seasons. During the first year of growth, the plant compartment of the reed bed is rapidly expanding and has a relatively large potential for uptake of nutrients as roots, rhizomes and stems grow to fill up the reed bed. However, there is an upper limit to the amount of below ground biomass that can be contained within a reed bed. Once this limit has been reached, after two or three growing seasons, the growth of new roots/rhizomes will decrease substantially and so too will the incorporation of nutrients into below ground components. Above ground biomass on the other hand, undergoes a seasonal cycle of growth followed by winter senescence, and has the potential to be harvested. The uptake of nutrients into this component has the potential to be sustained in the long term providing an annual harvesting regime is practiced. Uptake into above ground biomass should actually increase from that of the first year as reed coverage becomes more complete.

Water Budget

The data from the weekly water budget monitoring has been summed together into monthly figures and averaged across the four reed beds, as shown in Table 4. Evapotranspiration (ET) losses from the reed beds varied between 130 and 327 mm/month. The effluent volume from the reed beds was less than the influent volume in all months except January 2000 when there was 311 mm of rainfall. Thus, reed beds are capable of reducing the hydraulic load on a disposal area in all but the wettest months. The mean crop factor for the year was 2.0, which ranged from 1.1 (December 1999) to 4.2 (June 2000). This indicates that for many months of the year the reeds actively pump (transpire) water into the atmosphere at a rate exceeding evaporation alone. The higher crop factors (March through to June) correspond with the times when the standing crop would have been greatest.

Table 4. **Mean Monthly Water Budget Figures**

Summarised from the four reed beds during the first year of monitoring.
Note: crop factor in "Total" column is actually the mean.

Month	Sep 99	Oct 99	Nov 99	Dec 99	Jan 00	Feb 00	Mar 00	Apr 00	May 00	Jun 00	Jul 00	Aug 00	**Total**
In mm	1211	1190	1327	1363	1650	1350	1663	2080	1695	1769	2086	1768	**19152**
Out mm	1144	1131	1197	1321	1806	1144	1491	1995	1598	1733	1883	1623	**18066**
Rain mm	63	133	131	161	311	52	155	135	124	222	26	19	**1532**
ET mm	130	192	261	203	155	258	327	220	221	258	229	164	**2618**
A pan mm	99	124	131	184	130	131	101	110	70	62	91	89	**1322**
Crop Factor	1.3	1.5	2.0	1.1	1.2	2.0	3.2	2.0	3.2	4.2	2.5	1.8	***2.0***

4 Conclusions

Nitrogen and phosphorus removal from the nitrified wastewater was generally high. A HRT of 2 days achieved 80% load removal of TN, with little benefit coming from a longer HRT. TP load removal showed a weaker dependence on HRT, with over 96% removal being achieved with a HRT of 1.5 days. This study showed that reed beds are capable of achieving outlet concentrations of < 0.5 mg L^{-1} (TN) and < 0.1 mg L^{-1} (TP). Despite the lack of influent BOD, over 40% of the nitrogen removal was a result of denitrification, indicating that the reeds provided an internal source of organic carbon to fuel this process. Storage in plant biomass was the main nutrient removal process during the first year of operation, accounting for 60% of TN removal and 70% of TP removal. It is anticipated that, while removal via below ground biomass accumulation (30% of TN and TP removal) will decline during subsequent years, the significance of incorporation into above ground biomass should increase (> 30%), and represents a sustainable removal pathway provided that reed stems are harvested each year. In those LGAs where disposal areas are based on nutrient, as well as hydraulic, loadings the nutrient removal capacity of the reed bed will lead to smaller disposal area sizes. Water loss via ET varied from 130 mm/month to 327 mm/month, with higher rates generally being achieved during warmer months and in the second half of the growing season when the standing crop of reeds was greatest. The reed beds reduced the wastewater hydraulic load in all months except January when 311 mm of rain fell. Crop factors, with regard to Class A pan evaporation, ranged from 1.1 to 4.2, highlighting the role of reeds in actively pumping water into the atmosphere.

Acknowledgements

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