Secondary treatment by reed bed – eight years experience in north eastern New South Wales

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Abstract
Reed beds (subsurface flow constructed wetlands) have been employed as secondary treatment devices in on-site and decentralised wastewater management systems in the north east of the Australian state of New South Wales (NSW) for over a decade. Regular monitoring of beds since 1995 has led to the establishment of a database of performance data for removal of a number of pollutants. A total of 28 studies on reed beds treating a variety of commonly encountered wastewater streams yielded the following mean pollutant removal efficiencies: total suspended solids (TSS) 83%, biochemical oxygen demand (BOD) 81%, total nitrogen (TN) 57%, total phosphorus (TP) 35% and and faecal coliforms (FC) 1.9 logs. With combined wastewater, secondary treated quality can usually be expected after 5 days (approximately 4 m^2/EP) and a halving of TN after 7 days residence (approximately 5 m^2/EP). An annual crop factor relative to Class A Pan Evaporation of 2.6 was measured in a study on four reed beds planted with *Phragmites australis* in its second year. A study of six reed beds found six different species of earthworm present, mainly *Perionyx excavatus* (Indian Blue). A mesocosm experiment subsequently showed that the worms were translocating clogging material from the substrate interstices to the surface of the bed thereby indicating a possible method for prolonging reed bed life.

Keywords
earthworms, hydraulic performance, reed beds, substrate declogging, subsurface flow wetlands, treatment performance

INTRODUCTION

It is becoming increasingly common in Australia to include a secondary treatment device in the treatment train of on-site and decentralised wastewater management systems. Current options for secondary treatment include aerated wastewater treatment systems (AWTS), single pass sand filters, recirculating sand filters and reed beds (also known as subsurface flow wetlands). Compared to the other three technologies the reed bed has a number of advantages. It is relatively cheap to build, requires no power to operate and very little personal effort or money to maintain. In addition, a reed bed can become an aesthetically pleasing functional part of a garden. From the treatment perspective, the reed bed has been found to exhibit a superior nitrogen removal capacity than its competitors. On the other hand reed beds tend to require larger land areas than comparable AWTS or sand filter systems. In the last eight years approximately one hundred reed beds have been installed in on-site and decentralised wastewater treatment systems in the Lismore City and Byron Shire Council areas in the north eastern corner of the Australian state of New South Wales (NSW). The first of three aims of this paper is to summarise some of the lessons learned in relation to reed bed construction and operation.

The major life-limiting factor for reed beds is the tendency, over a number of years, for the substrate (in particular at the inlet end) to become clogged with solids. Consequently, the hydraulic conductivity of the substrate can be reduced to the point where water is forced to flow above surface with resulting reduction in treatment efficiency. While source control of TSS by means of a well designed, installed and maintained primary treatment device is the first line of defence against entrance zone substrate clogging, at least one natural mechanism for substrate declogging has been observed. Pratt (2002) studied several reed beds in northern NSW which had been colonized by earthworms. In one bed subjected to greywater loadings with a high solids content the inlet zone was found to be densely populated by small red worms. The surface of the gravel was covered to a depth of approximately 5 cm with a layer of rich humic material, while the substrate at depths greater than 10 cm below gravel surface (ie below the water level) was relatively clean. Even though the reed bed had been operating for six years at a relatively high hydraulic loading rate (HLR) of ~70mm/day (< 3 days residence) no surface flow was observed. These observations led to the hypothesis that the worms were grazing on solids deposited in the interstices of the substrate and excreting the material as castings on the surface. The second aim of this paper is to describe an experiment which tested this hypothesis.

The third aim of this paper is to summarise the findings of a number of studies conducted by the authors which have investigated hydraulic and treatment performance of reed beds operating on four types of commonly encountered wastewater and to present several methods for sizing reed beds.

METHODS

In the years since 1994 the principal and second authors of this paper have built, maintained, observed and monitored a number of reed beds and have been involved in the development of local government guidelines for their design and construction. The comments in this paper relating to reed bed structure are based on observations of the evolution of the various structural elements developed by the authors and other local reed bed designers and are reported more fully in Davison and Headley (in press).

The hypothesis that earthworms may be cleaning the interstitial spaces in reed bed media was tested using a controlled laboratory-based experiment involving seven mesocosms (Figure 1). These were 40cm x 20cm x 4cm and constructed from waterproofed timber and clear Perspex to create a 'slice' of reed bed where worm behaviour and the movement of solids could be easily observed. The length of each container was divided vertically into nine sections so that the movement of soil could be accurately recorded. A scale was created on one side of the mesocosms to easily record water level and locations of specific worms. Clogging material (sludge) from the surface of a reed bed was collected and oven dried at 100 degrees C. Six hundred grams of this material was placed at the base of each mesocosm. Three kilograms of clean, dry reed bed media (10 mm gravel) was then weighed and placed over the sludge. Effluent from the same reed bed was used to saturate all mesocosms to a depth of approximately 20cm. Thirty six worms of the species *Perionyx excavatus*, *Metaphire posthuma* and *Amynthas spp.* were added to six of the mesocosms, with the seventh acting as a control (no worms). The mesocosms were kept in a dark, cool place and were monitored regularly (every few

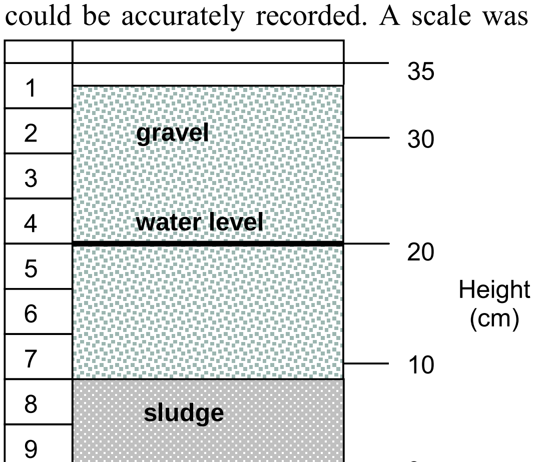

Figure 1. Design of mesocosm showing layers of gravel and sludge, water level and the nine sections used in monitoring.

days, at night if possible to minimise disturbance) and photographed (once a week). Because initial photographs did not satisfactorily show the position of sludge within the mesocosms, a template was made to represent sludge movement. A sheet of clear plastic was taped to the Perspex of the mesocosm and position of sludge was traced onto the plastic. This image was then traced onto paper and reduced using a photocopier. This process was carried out in week 6 of the experiment and again at the conclusion of the experimental period (a template of the control mesocosm was also made to compare soil movement). In order to get an approximate idea of how long it took worms to move solids to the surface, one mesocosm (no. 6) was monitored every 6 hours after worms were introduced until solids were observed in the surface layers. Effluent was added to each mesocosm as required (to keep the water level at around 20 cm). The duration of the experiment, which is fully described in Pratt (2002), was nine weeks, after which time a worm census and dry matter budget of the sludge were conducted.

The findings relating to treatment and hydraulic performance are based on 28 monitoring regimes conducted over the past eight years on 13 reed beds (eg Davison et al. 2001; Davison et al. 2002; Headley and Davison 1999). The hydraulic performance data comes from a water balance study described in Headley (in preparation).

RESULTS AND DISCUSSION

Structural features

A reed bed typically consists of a *substrate* (usually gravel) confined within an impermeable *skin* supporting *macrophytes* such as reeds or rushes (Fgure 2). Water enters via an *inlet structure* and flows horizontally over a period of days to the *outlet structure.* Treatment occurs within the bed as a result of a number of physical, chemical and biological processes that occur during the water's passage through the bed. A standpipe or swivel control in the outlet box can be used to adjust the water level.

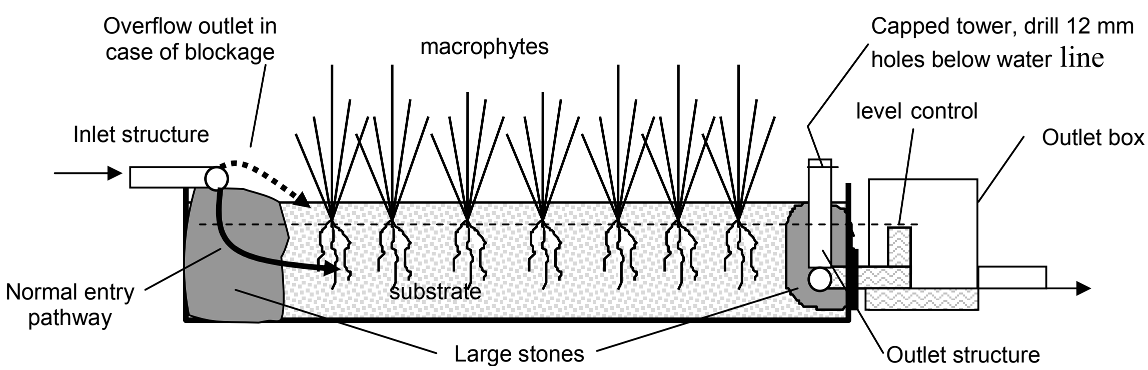

Figure 2. Elevation and plan views of typical horizontal subsurface flow wetland showing major components

The substrate surface provides the site for growth of the microbial biofilms which mediate many of the pollutant removing chemical reactions. Choice of substrate size is governed by the tradeoffs between maximisation of specific surface area (favoured by small particles) and the need to avoid clogging of interstices (favoured by large particles). In most cases gravel (10-20mm) is chosen. Larger stones (eg rail ballast 60-80 mm) are placed in the first metre of the bed (inlet zone) where clogging is most likely to occur, and sometimes adjacent to the outlet structure. The roots of most macrophytes have been observed to grow poorly in stones > about 40 mm, presumably because the roots find it difficult to push through.

Materials that have been used for reed bed skin or containment in north eastern NSW include fabricated reinforced concrete slabs, ferro-cement, stainless steel, polyethylene and concrete cattle troughs, fibreglass troughs, sealed concrete blocks laid on concrete slab, and flexible liner membranes. The use of a liner membrane in a prepared hole is the cheapest approach for all but the smallest applications When using a liner care should be taken to ensure that it is laid onto consolidated surfaces, as voids behind the liner can provide penetration sites for macrophyte rhizomes. *Pharagmites australis* (common reed) has a particularly aggressive rhizome and, while this is an advantage from the treatment perspective, it has caused membranes to be pierced. The practice of using a geo-textile protector both below and above the liner to lessen the chance of root penetration and to protect it against damage by sharp particles is recommended. A plastic tank manufacturer in northern NSW has developed a 3m x 2m x 0.68m deep polyethylene tub specifically for use as reed bed containment. These are proving popular for use in single dwelling units. A typical family home would requiree three or four tubs to accommodate the needs of four or five people.

Most reed beds built on the NSW north coast had until recently been planted with *Phragmites australis*. The aggressive nature of its rhizome system and a tendency to senescence (and hence a rather ragged appearance) in the winter months have prompted a search for other species. Macrophytes that have been used with success in this region are *Schoenoplectus validus* (river club rush), *Typha orientalis* (bull rush), Bolboschoenus fluviatilis (marsh clubrush) and *Baumea articulata* (jointed twigrush).

In choosing a design for the inlet structure there are tradeoffs to be made between capacity to spread the influent evenly across the inlet end of the bed (critical for the establishment of hydraulic efficiency) and ability to resist clogging of openings in the spreader pipe (usually ~12 mm diameter in the bottom of a 100mm UPVC pipe). It has been found that primary treated greywater is particularly prone to causing slime buildup in the plumbing upstream of the inlet structure. Sloughed slime can block openings and an alternative overflow pathway should be designed as shown in Figure 2. An outlet structure design that minimises the possibility of intrusion by macrophyte roots incorporates a series of 150 mm diameter, capped, vertical towers spaced evenly across the width of the bed (Figure 2). Effluent enters the towers from the bed via 15-25 mm diameter holes surrounded by stones > 50 mm diameter. Hand access to the towers is available should clogging of the holes occur. A swivel pipe or a series of variable length stand pipes in the outlet box can be used to vary the water level in the bed. In this way the wetland can be flooded to help with control of terrestrial weeds during macrophyte establishment. Periodic water level lowering can encourage downward root penetration, promoting oxygenation of the lower level of the bed and thereby enhancing treatment at that level. Drying of the upper layers of the bed will also enhance breakdown of carbon and nitrogen trapped in substrate interstices and its return to the atmosphere.

Earthworms as substrate declogging agents

As noted in the introduction, the presence of earthworms was first observed in a heavily loaded bed treating greywater from a domestic source. Three species of worm were identified in that bed. Five additional reed beds were investigated and all were found to contain varying numbers of earthworms. Table 1 summarises some of the features of the worms which were found. By far the most common species was *Perionyx excavatus* (Indian Blue) which was found in four of the beds. This small red worm is one of three species commonly used in commercial vermicomposting operations and is classified as an epigeic feeder. In terrestrial situations epigeic worms ingest mainly surface organic material and very little mineral soil. The only non epigeic feeder found during this investigation was the anecic feeder (ingests some mineral soil material), *Pontoscolex corenthrurus.* The large garden worm *Metaphire posthuma* was found in three of the four beds occupied by *P. excavatus*. In the three beds co-occupied by these two species it was generally found that *P. excavatus* was more abundant towards the inlet end of the bed.

Table 1. Details of earthworm species identified in six reed beds (after Pratt 2002).

Species	common name	ecotype	colour	length (mm)	Frequency of occurrence
Perionyx excavatus	Indian Blue	epigeic	can appear red when young adults begin to phosphoresce deep blue/purple on exposure to light	30 - 180	4
Esenia fetida	Tiger Worm	epigeic	rusty colour with a distinct yellow band on each segment	60 - 120	1
Metaphire posthuma		epigeic	brown in colour, phosphoresce blue in sunlight	45 - 270	3
Amynthas morrisi		epigeic	grey/ brown in colour	50 - 250	1
Amynthas rodericensis		epigeic	grey/ brown in colour	50 - 250	1
Pontoscolex corenthrurus		anecic	dark brown with tinge of yellow	60 - 120	1

The hypothesis that the worms were translocating interstitial organic clogging material to the surface was tested by constructing mesocosms and observing interactions between worms and clogging material. Intensive observation of Mesocosm 6 immediately after addition of the worms revealed that a number of worms had migrated to below the water level within 6 hours. Within 18 hours small amounts of sludge could be observed above the water level. By week two, sludge had been transported vertically to the top layers of gravel in all mesocosms. The smaller composting worms such as *Perionyx excavatus* were observed in the bottom layers of the mesocosms below the water level within the sludge layer while the larger worms (*Metaphire posthuma*) were observed just above water level. The relative niches occupied by the two worm species was fairly constant throughout the study period. At week 5 a distinctive band of sludge approximately 3-4cm thick was observed just above the water level in all mesocosms (being more pronounced in some than others). At the same time worms were noticed congregating around this zone of sludge accumulation. This trend continued in all mesocosms until the conclusion of the experiment in week 9. In week 8 the water level in Mesocosm 6 was increased to a depth of approximately 30cm (from the top of section 5 to the top of section 3 – Figure 1). As a result the band of sludge at section 5 was seen to disperse and begin to reform at the new water level within the final week of the study. No movement of sludge was observed in the control (no worms) mesocosm. Over the nine week study the average worm survival rate was 94%. Of the 600 g (dry weight) of sludge added to the mesocosms an average of 267 g was lost.

Over nine weeks, observations of the mesocosms confirmed the hypothesis that worms are responsible for cleaning the substrate and depositing organic matter on or near to the surface. A management outcome of this finding could be the inoculation of reed beds with earthworms to clean the substrate and prolong their useful life.

Hydraulic performance

Headley (in preparation) performed a two year study on four pilot scale (4m x 1m) reed beds planted with *Phragmites australis.* Accurate water balances enabled monthly evapotranspiration (ET) rates to be determined. Figure 3 shows a plot of the monthly averages of daily ET from the four beds commencing in September 1999, four months after the reeds were planted. ET rates ranged from 3.2 mm/day to 15.1 mm/day over the two year period of the study. The effects of seasonality and maturity are apparent with summer ET rates being higher than the cooler months and the second year showing a higher average rate (10.6 mm/day) than the first (7.0 mm/day) due to greater leaf area present. Annual crop factors relative to class A Pan Evaporation varied from 1.9 in the first year to 2.6 in the second with a maximum monthly crop factor of 4.5 occurring in April and May of the second year when the standing leaf crop was at its maximum. A similar water balance performed on small reed beds (5m x 2m), also planted with *Phragmites australis,* in the same area of northern NSW (Davison and Headley in press) came to similar conclusions with respect to ET quantity, seasonality and maturity effects. It is probable that the high ET rates recorded in these small beds are partly a result of edge effects and that larger beds would record lower evaporative performance. Nevertheless these beds are of similar dimensions to those typically used in on-site applications

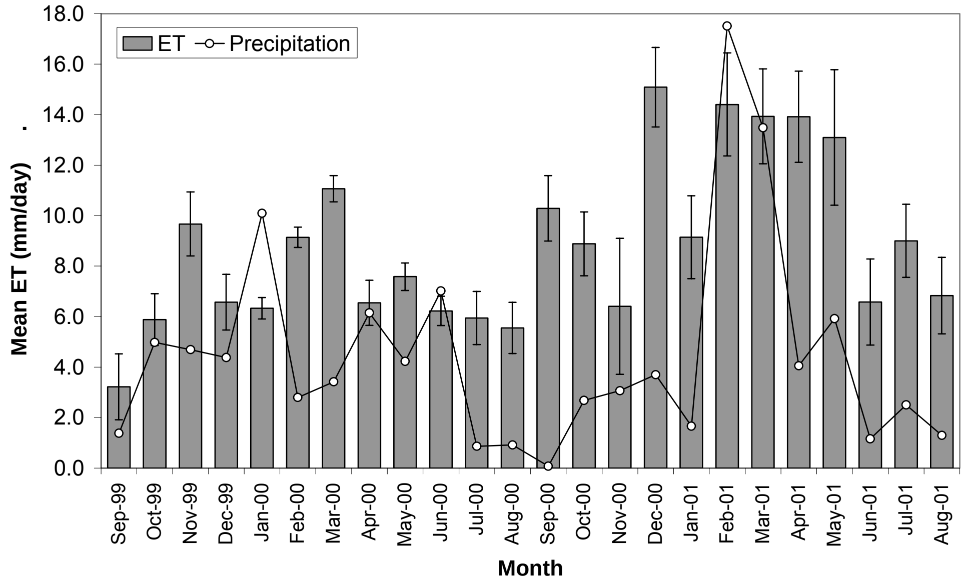

Figure 3. Mean monthly evapotranspiration (ET) and precipitation rates (mm/day) for the four reed beds. Error bars represent +/- one standard error of the mean.

Treatment performance

Table 3 contains a summary of reed bed treatment performance, as measured by percent reduction in concentration, obtained from 32 studies, on four different types of wastewater, conducted since 1995. Overall, the data indicate that the reed beds are effective at removing BOD (mean 81%), TSS (mean 83%) and TN (mean 57%). In general removal of TP has been found to be a temporary because the main removal processes for this nutrient are adsorption and precipitation onto a finite number of sites on the substrate. Overall mean reduction in FC was 1.9 logs. It can be seen from the differences in minimum and maximum reduction for all studies that performance for all five parameters varies considerably from study to study. In many cases this variation is caused by differences in hydraulic residence time (HRT). The decline in concentration of some pollutants as a function of HRT can be approximated using the first order model presented in Equations 1 and 2.

$$\frac{C_o - C^*}{C_i - C^*} = \exp(-k_v HRT) \qquad \text{(Eq. 1)}$$

where Co = pollutant concentration at reed bed outlet (mg/L)
Ci = pollutant concentration at reed bed inlet (mg/L)
C* = background concentration due to return of pollutant (mg/L)

k_v = volumetric rate constant (d^{-1}) which varies with temperature according to Equation 2.

$$k_v = k_{v20}\theta^{(T-20)} \qquad \text{(Eq. 2)}$$

where k_{v20} = value of volumetric rate constant at 20°C
θ = temperature correction factor
T = water temperature (°C)

Table 3. Treatment performance summary (as measured by percent reduction) from 32 studies on reed beds treating four types of wastewater. (HRT = mean hydraulic residence time).

wastewater type		HRT days	BOD %reduction	TSS %reduction	TN %reduction	TP %reduction	FC log reduction
Combined	Mean	8.9	92.5	88.7	60.2	25.0	2.5
Greywater	Mean	5.2	83.8	81.5	62.0	46.8	1.8
Laundry	Mean	6.1	61.2	82.7	62.4	31.9	0.8
School	Mean	11.5	74.9	79.3	38.1	33.7	1.7
All studies	Mean	8.3	81.3	82.9	56.5	34.9	1.9
	Min	3.7	34.7	55.9	8.1	-21.7	0.4
	Max	17	96.6	97.9	93.8	76.6	3.3
	n	32	28	23	24	26	27

Headley and Davison (2003) used data on BOD and TN decline obtained from the studies mentioned above to estimate values for the model parameters $k_{v20,}$ C* and θ for these two pollutants. These values are presented in Table 4. The model parameters result in an accurate prediction of the BOD removal from combined wastewater and greywater but give an under-estimate of the BOD concentration (i.e. over-predict performance) in the laundry and school wastewaters. The TN model parameters achieve a reasonably accurate prediction of the TN concentration in combined, grey and laundry wastewaters, but considerably over-estimate performance for the school wastewater.

Table 4. Suggested 1st order model parameters for TN and BOD removal from gravel based horizontal flow wetlands with a wetted depth between 0.4 m and 0.6 m.

Pollutant	Volumetric rate constant, k_{v20} (d^{-1})	Background conc., C* (mg/L)	Temperature correction factor, θ
BOD	0.52	5.0	0.953
TN	0.18	1.5	1.00

Sizing reed beds

The reed bed's strength is its capacity to remove BOD and TN from effluents. Therefore a reed bed's size is usually based on the need to achieve a certain treatment objectives in one or both of these pollutants. For non standard effluents or situations, Equations 1 and 2 can be used to determine the HRT required to achieve a given effluent concentration from an influent of known concentration. For relatively standard effluents such as domestic greywater or combined wastewater, where influent concentrations can be predicted with some confidence, it is possible to use rules of thumb based on either the required HRT or surface area of the reed bed. Table 5 lists a set of rules of thumb that has been adopted by Lismore City Council (2003) for this purpose.

Table 5: Rule of thumb surface area requirements (m^2/EP) for reed beds with wetted depth of 0.5m using 10mm or 20mm gravel substrate adopted by Lismore City Council (2003).

Treatment objective	Secondary (BOD<20 mg/L)	20% TN removal	30% TN removal	40% TN removal	50% TN removal	60% TN removal
Greywater	3	2	3	4	5	6
Combined wastewater	4	2	3	4	5	6

CONCLUSIONS

Reed beds have been found to be effective, low maintenance secondary treatment devices in a number of Council areas in northern NSW with BOD and TN removal rates in excess of 90% and 50% respectively being regularly achieved. While reed beds are effective at removing TSS, overloading with solids can cause substrate clogging and lead to hydraulic failure. Therefore they should only be used in conjunction with a well maintained primary treatment device fitted with an outlet filter. Nonetheless a natural mechanism for cleaning clogged substrates does exist. A mesocosm experiment showed that worms of the species *Perionyx excavatus* and *Metaphire posthuma*, among others, were translocating clogging material from the substrate interstices to the surface of the bed thereby indicating a possible method for prolonging reed bed life. A study of six reed beds found a total of six colonizing earthworm species. While 2 logs FC attenuation can be expected after 5 days residence in a reed bed it is rare to achieve concentrations < 1,000 cfu/100mL. TP removal will occur at high rates initially, but taper off as adsorption and precipitation sites fill up. Reed bed designers have adopted a number of approaches to the structural elements which comprise a reed bed and there has been some experimentation with macrophyte species used. With combined wastewater, secondary treated quality (BOD<20mg/L) can usually be expected after 5 days and a halving of TN loading after 7 days residence. One Council has adopted a set of rules of thumb which relates reed bed surface area to a number of water quality outcomes for a reed bed of standard depth and substrate (Tabe 5). For non standard effluents sizing can be based on first order models for BOD and TN removal. An annual crop factor relative to Class A Pan Evaporation of 2.6 was measured with *Phragmites australis* in its second year.

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