DESIGN MODELS FOR THE REMOVAL OF BOD AND TOTAL NITROGEN IN REED BEDS

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Abstract

Attempts to model pollutant removal in subsurface flow wetlands (reed beds) have traditionally focused on first order plug flow kinetics using empirically derived reaction rate coefficients, temperature correction factors and background concentration levels. This paper describes an attempt to establish model parameters for the prediction of biochemical oxygen demand (BOD) and total nitrogen (TN) removal in reed beds based on Australian data. The parameters were established using data from 28 monitoring regimes conducted over the past eight years on 13 reed beds in north-eastern NSW. Volumetric reaction rate coefficients (k_{v20}) of 0.52 d^{-1} and 0.18 d^{-1} gave reliable predictions of BOD and TN removal respectively for reed beds greater than six months old treating combined domestic wastewater, greywater or laundry wastewater. A temperature correction factor (θ) of 0.95 was found to apply for BOD removal indicating a decrease in performance with increasing temperature. TN removal was found to be independent of temperature ($\theta = 1$) over the experimental range of 14.8^{o}C to 25^{o}C. Background concentrations (C^*) were found to be 5 mg/L and 1.5 mg/L for BOD and TN respectively. It is suggested that the exercise described in this paper could provide the starting point for the establishment of an Australian constructed wetland database leading to the further development and refinement of constructed wetland design models.

Keywords

BOD, design model, hydraulic residence time, reaction rate coefficient, reed bed, temperature, total nitrogen.

1 Introduction

Reed beds are being increasingly used in parts of Australia as secondary treatment devices for on-site wastewater management systems. A reed bed is a type of subsurface flow constructed wetland consisting of a sealed basin filled with a gravel substrate to a depth of about 0.6 metres and planted with emergent aquatic plants. The wastewater remains below the gravel surface as it moves from one end to the other through the root zone of the plants, and receives treatment through chemical, biological and physical interactions with microbes, the plants and the substrate. Whilst reed beds are capable of reducing the concentration of total suspended solids, phosphorus and faecal coliforms, they are generally used for their ability to significantly reduce biochemical oxygen demand (BOD) and total nitrogen (TN) concentrations. BOD is removed through the settling of organic solids, and the decomposition of colloidal and soluble organic matter through microbially mediated aerobic and anaerobic reactions (Reed *et al.* 1995). The main nitrogen removal processes are nitrification (of ammonium-N into nitrate) followed by denitrification (of nitrate-N into gaseous forms), and plant uptake (Kadlec and Knight, 1996).

The performance of a reed bed in removing these pollutants is affected by a range of factors, including the:

- length of time wastewater spends within the reed bed (hydraulic residence time- HRT);
- climate and season, as represented by temperature; and
- concentration of influent and type of wastewater being treated.

The removal of nitrogen in a reed bed generally occurs at a slower rate than for BOD. This is partly due to the fact that the oxygen transfer rates are slow in reed beds and nitrification (an oxygen requiring process) generally doesn't become fully operational until the BOD is reduced to below 20mg/L (Reed *et al.* 1995).

Since reed beds are not mass-produced, off-the-shelf treatment devices, there is a need for a reliable design approach that affords confidence in the prediction of BOD and TN removal performance. Based on monitoring experience, some NSW Councils utilise a rule-of-thumb approach to design, in which it is assumed that, for a reed bed receiving "typical" combined wastewater, a hydraulic residence time (HRT) of > 5 days will be capable of reducing BOD concentrations to less than 20 mg/L, and a HRT > 7 days will achieve a 50% reduction in TN. Whilst this approach is simple to use, it is of little value when designing a system to treat "atypical" wastewater, or to achieve a different set of treatment objectives. In such cases it is usual to assume that the pollutant passes, undispersed as a plug (plug flow) through the bed and that its concentration attenuates with time at a rate which is proportional to the first power of the concentration of the pollutant in question (first order differential equation) (Crites and Tchobanoglous, 1998).

Equation 1 is the first order plug flow model resulting from the solution to this differential equation. It describes the exponential decline of pollutant concentration from its inlet value to a background concentration (C*) generated by the return of decomposing litter, root and biofilm material to the effluent. The reed bed is sized on the basis of the length of time predicted by this first order plug flow model to achieve the desired pollutant concentration.

$$C = (C_{in} - C^*) \exp(-k_v t) + C^* \qquad \text{Eq 1}$$

Where C = pollutant concentration, mg L^{-1} after t days (d) of residence in the reed bed
C_{in} = influent pollutant concentration, mg L^{-1}
C^* = background pollutant concentration mg L^{-1}
k_v = first-order volumetric reaction rate coefficient, d^{-1}

If C is taken to be the outlet concentration, then t becomes the HRT of the reed bed. The unknown parameter in the model is the reaction rate coefficient, k_v. Since BOD and TN are lumped or aggregate parameters (i.e. they can be comprised of a range of possible particulate, colloidal, soluble, organic, inorganic, oxidised and/or reduced constituents) it is possible that the reaction rate coefficient may vary depending on the type of wastewater being treated (e.g. combined, greywater, school wastewater, or laundry effluent). Reed *et al*. (1995) suggests that TN removal performance in reed beds may display an adaptation period during start-up as plants and microbes establish. In a similar way, Headley and Davison (1999) reported that a newly commissioned reed bed treating school wastewater took six months to approach the level of BOD removal achieved in a similar eight-year old system. It is also commonly believed that temperature has an effect on the rate of nitrogen removal (Crites and Tchobanoglous, 1998), although there is considerable uncertainty about whether the same is true for BOD (Kadlec and Reddy, 2001). The implications of temperature dependence are that treatment performance may display variation with season and climate (i.e. location).

The effect of temperature on k_v is generally accounted for through a modified Arrhenius temperature dependence, as summarised by equation 2:

$$k_v = k_v20\ \theta^{(T-20)} \qquad \text{Eq. 2}$$

where k_v20 = first-order volumetric reaction rate coefficient at 20° C, d^{-1}
θ = temperature correction factor
T = water temperature, °C

In effect, the temperature correction factor is a "fudge-factor" that causes the rate of reaction predicted by the model to either increase ($\theta>1$) or decrease ($\theta<1$) with temperature.

While the first order, plug flow modelling approach has been found to be reasonably accurate in predicting treatment performance overseas, there has been a lack of model calibration and verification under Australian conditions. Consequently, there is a need to derive locally relevant reaction rate coefficients (k_v) and determine whether temperature has a significant effect on the treatment performance of reed beds under Australian climatic conditions. A plethora of studies have been conducted in north-eastern New South Wales (NSW), dating back to the Honours study of Glenn Marshall completed in 1995, examining the treatment performance of a number of different reed bed treatment systems. These studies cover a range of different wastewater types (combined, grey, school and laundry effluents), HRTs, operating temperatures and design/construction techniques, and may therefore provide the starting point for deriving Australian based modelling parameters for BOD and TN removal.

The aim of this paper is to derive design models for BOD and TN removal in reed beds based on eight years of monitoring data from northeastern NSW. The objectives of the paper are to:

- summarise existing treatment performance data for BOD and TN;
- derive reaction rate coefficients and consequently design models for BOD and TN removal;
- determine if temperature, system age or effluent type have any apparent effect on reed bed treatment performance; and
- assess the accuracy of the derived design models at predicting performance.

2 Methods

The data from a number of published and unpublished studies into the treatment performance of reed beds conducted through the School of Environmental Science and Management at Southern Cross University were collated and used as the basis for modelling BOD and TN removal. All of the studies were conducted under the supervision of one of the authors of this paper (Davison). Details of the different studies are summarised in Table 1. In total, data from 10 different researchers, covering 28 different monitoring programs (sub-studies) of 13 different reed bed systems are included in the data set. This includes some monitoring of the same systems by different researchers at different points in time, and repeated studies on the same systems by some authors (e.g. to compare the effect of HRT or season).

All the studies included inlet and outlet BOD (measured by 5-day BOD test) and TN concentration data from the relevant reed beds, analysed in accordance with APHA (1995) in the Environmental Analysis Laboratory at Southern Cross University. Some studies contained data from fractional sample points located along the length of the reed beds. Data from these sample points were used to determine treatment performance at a HRT proportional to the fractional distance between the inlet and outlet. For example, a sample point located halfway along a reed bed with a HRT of 10 days would be assumed to represent a HRT of 5 days.

For each study (or sub-study), the mean BOD and TN concentration was determined for each sample point (inlet, outlet and fractional). In all cases, a minimum of five samples was used to calculate the mean concentrations. The data from reed beds with sufficiently long HRTs were examined to determine the background concentration (C*) for each pollutant. The technique outlined in Tchobanoglous *et al.* (2003) was used to determine the first order rate coefficients for BOD and TN by way of integration. This involved plotting -ln(C-C*)/(Cin-C*) against HRT. The reaction rate coefficient is then the slope of the line-of-best-fit through this plot.

Table 1. Summary of studies and the relevant reed bed systems from which data were used to compile the data set for the modelling exercise.

Author	System No.	Year	Wastewater type	Reed bed age (years)	Mean HRT (days)[a]	Mean Temp. (°C)[b]
Marshall	1	1995	grey	1	5.5	14.7
	2	1995	laundry	0.1	3.7	14.5
	3	1995	grey	0.5	6.4	16
Headley	4	1997	school	0.3	12.1	17.3
				0.5	12.1	20.1
				0.7	12.1	24.9
	5	1997	school	8	12.1	16
					12.1	17.5
					12.1	24.3
Murray	2	1998	grey + laundry	3	4.5	17.2
Edmonds	2	1999	grey + dairy products	4	4.5	15.6
	6	1999	grey	0.75	6.9	20.8
				1.0	4.7	16.5
				1.2	6.1	14.8
Locke	4	2000	school	3.3	10.4	17.8
	7	2000	school	0.5	9.3	19.7
Craven	8	2000	combined	1	7.8	17.7
		2001		1.5	7.8	23.7
	9	2000	grey	0.5	4.2	17.7
		2001		1.0	4.2	23.7
Bayley	10	2001	combined	0.7	5.95	22.57
				1	10.5	16
	11	2001	combined	0.7	11.1	22.57
Hazell	10	2002	combined	1.5	11	24.3
	11	2002	combined	1.5	11	24.3
Winmill	12	2002	laundry	0.5	6.6	16.9
Herity	12	2003	laundry	1.0	8	25
	13	2003	combined	0.5	5.8	24.6

[a] Mean HRT represents the nominal HRT calculated based on estimated water holding capacity of the reed beds and the measured or estimated hydraulic loading rates.

[b] Mean temperature is the water temperature, unless unavailable, in which case the mean of the maximum and minimum air temperatures for the study period from the nearest weather station is reported.

Temperature correction factors were determined using equation 3. Data were selected for this purpose from systems that were monitored at different temperatures, but without substantial variation in other factors, such as inlet concentration or system age.

$$\frac{k_v 2}{k_v 1} = \theta^{(T2-T1)} \qquad \text{Eq. 3}$$

where k_v1 = reaction rate coefficient at temperature *T1*, d^{-1}
k_v2 = reaction rate coefficient at temperature *T2*, d^{-1}
T = temperature, °C

To determine if there was any effect of system age on BOD and TN removal, reaction rate coefficients were determined for each system using equation 1 and plotted against age. A correlation analysis was also conducted.

Equation 1 was then used with the derived model parameters (C^*, k_v, and θ) to predict the BOD and TN concentration from the original data set. These predicted concentrations were then checked against the actual concentrations in order to assess the reliability of the model.

3 Results and Discussion

Background concentrations of 5.0 mg/L and 1.5 mg/L were identified for BOD and TN respectively. The data indicated that a HRT of greater than 12 days would be necessary to achieve the background concentration for TN. BOD and TN reaction rate coefficients (k_{v20}) were determined from the slope of the lines of best fit in figure 1 (BOD) and figure 2 (TN). A highly significant correlation was found between "HRT" and "-ln (C-C*/Cin-C*)" in all cases. It can be seen that the reaction rate coefficients varied depending on the type of wastewater being treated.

The BOD lines of best fit for combined (black and grey) wastewater and greywater were very similar, and therefore yielded similar reaction rate coefficients of close to 0.52 d^{-1}. However, the attenuation of BOD in laundry and school wastewater occurred at a considerably slower rate, yielding reaction rate coefficients of approximately 0.35 d^{-1} and 0.16 d^{-1} respectively.

Greywater, combined wastewater and laundry wastewater all yielded somewhat similar TN reaction rate coefficients of 0.208, 0.188 and 0.149 d^{-1} respectively. Therefore, a rate coefficient of 0.18 d^{-1} may be suitable for describing the reduction of TN in these three types of wastewater. However, the reaction rate coefficient for school wastewater was substantially lower at 0.047 d^{-1}. The low reaction rate coefficients for school wastewater are primarily due to the very high BOD and TN concentrations that are characteristic of this type of effluent. When compared to the other three wastewater types, school wastewater would be mainly composed of toilet (black) water, with a potentially greater proportion of nitrogen-rich urine being present than in a typical domestic situation (Headley & Davison, 1999).

No significant relationship existed between temperature and reaction rate constants for both BOD and TN when the entire data set was used. However, for several reed beds, data were available from more than one temperature, and temperature correction factors could be determined for individual beds. While no trend existed for TN, BOD temperature correction factors were consistently less than one, with a mean of 0.953. Although many authors make the assumption that BOD reaction rates should increase with temperature (e.g. Crites and Tchobanoglous, 1998; Reed *et al.*, 1995), Kadlec and Reddy (2001) reported a mean temperature correction factor of 0.983 based on data from 23 constructed wetland systems. It appears that, although the decomposition activity of microbes may increase with temperature, the overall effect on BOD removal may be masked or even over-ridden by factors such as the seasonal growth pattern of plants. It is important to realise that the data used in this study were collected from a relatively limited temperature range (14.8°C to 25°C). Thus, the temperature correction factors determined here for BOD and TN of 0.953 and 1.0 need to be verified for systems at temperatures outside this range, particularly at lower temperatures.

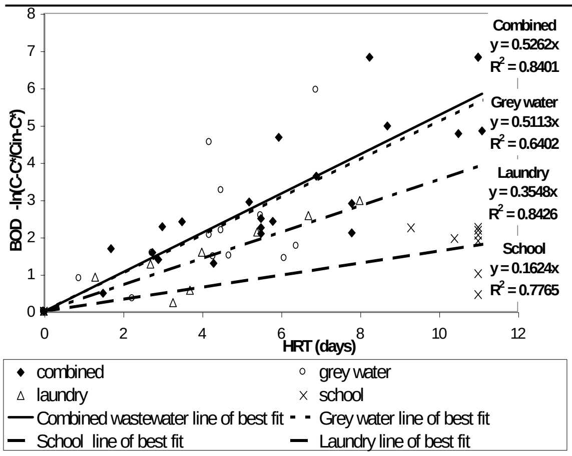

Figure 1. Plot of –ln (C-C*/Cin-C*) versus HRT for BOD (slope of the lines of

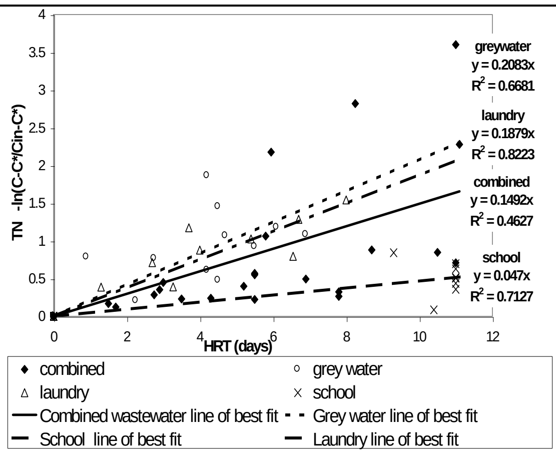

Figure 2. Plot of –ln (C-C*/Cin-C*) versus HRT for TN (slope of the lines of

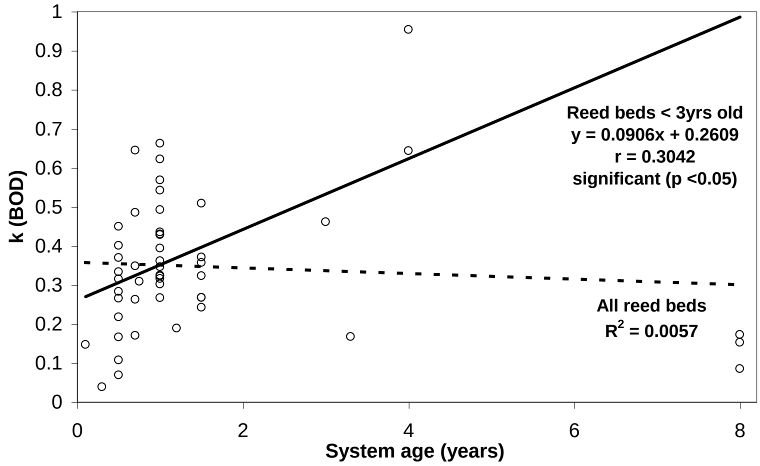

Figure 3. BOD reaction rate coefficients versus reed bed age

Correlation analysis found no significant relationship between the TN reaction rate coefficients for each study (or sub-study) and reed bed age. The same was true for BOD overall. However, if the data were confined to reed beds less than three years old, a significant positive relationship was found ($r = 0.3042$, $p < 0.05$) (Figure 3). This indicates that reed beds undergo an adaptation period in terms of BOD removal, with performance improving during the first three years of operation.

The first order design model parameters derived in this study are summarised in Table 2. Using these parameters, BOD and TN concentrations were predicted using the inlet concentrations and HRTs from the different sub-studies. Figures 4 and 5 are plots of the predicted versus actual concentrations for BOD and TN respectively.

Table 2. Recommended first-order model parameters for BOD and TN removal combined domestic wastewater, greywater or laundry wastewater in beds > six months old

Pollutant	Background conc. (*C**) mg/L	Temp. correction factor (θ)	Reaction rate coefficient (k_{v20}) d^{-1}
BOD	5	0.953	0.52
TN	1.5	1.0	0.18

The model parameters result in an accurate prediction of the BOD removal from combined wastewater and greywater ($r=0.89$, $P < 0.001$), as indicated by the closeness of the line of best fit to the 1:1 line (predicted = actual) in Figure 4. However, the model parameters tend to give an under-estimate of the BOD concentration (i.e. over-predict performance) in laundry and school wastewaters. The model also over-predicts the performance when the BOD concentration in either greywater or combined wastewater is greater than 250 mg/L (these data were excluded from the line-of-best-fit in Figure 4). This supports the notion that a lower reaction rate coefficient should be used for atypical wastewaters that are relatively high in BOD, such as school wastewater. The model parameters may, however, be suitable for laundry wastewater, as a much more accurate prediction was achieved when the data from a laundry reed bed that was less than six months old were not included.

The TN model parameters achieve a reasonable prediction of the TN concentration in combined grey and laundry wastewaters. When the data for combined wastewater and greywater were grouped, the correlation between predicted and actual concentrations was highly significant ($r = 0.73$, $p < 0.001$) while laundry waste-water resulted in a significant correlation ($r = 0.742$, $p < 0.05$).

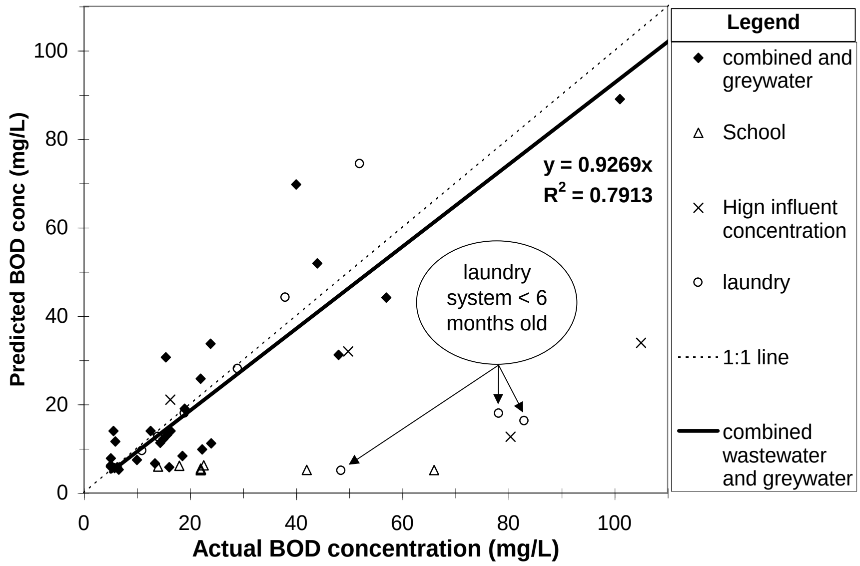

Figure 4. Actual BOD concentrations versus concentrations predicted using the derived model parameters

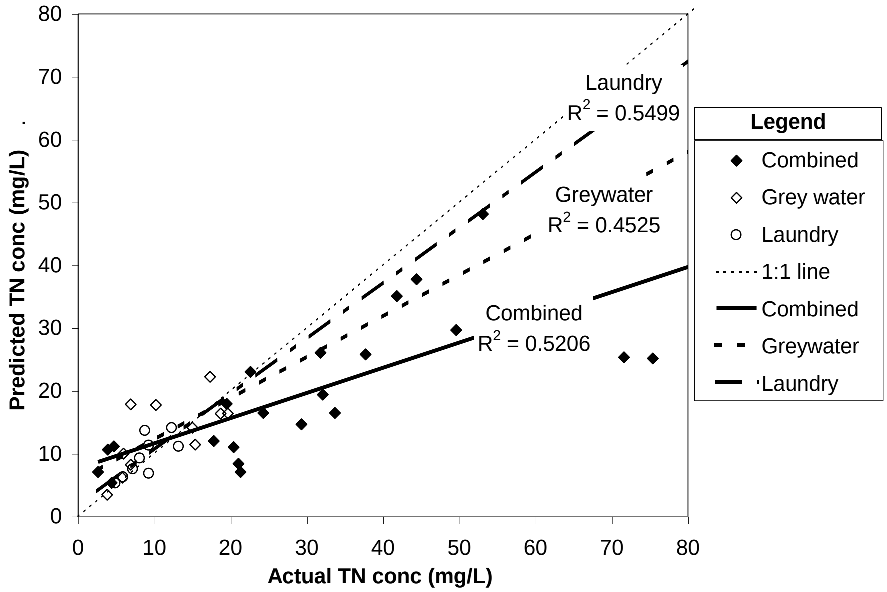

Figure 5. Actual TN concentrations versus those predicted using the derived model parameters

The model over-estimates performance at higher concentrations, and under-estimates performance at lower concentrations as shown by the lines of best fit. This tendency is greatest for combined waste-water, followed by greywater, while the laundry predictions are relatively close to the 1:1 line (predicted = actual). Such a design model would generally be used to determine the HRT required to achieve concentrations at the lower end of the scale, resulting in a conservative design estimate. On the basis of the available data, the model parameters resulted in a poor prediction of the TN concentration for the reed beds treating school wastewater, with predicted concentrations being dramatically lower than the actual concentrations (data not shown). This indicates that a lower reaction rate coefficient may be needed to design a reed bed to remove TN from school wastewater, which would result in longer HRTs for such systems. This would be mainly due to the relatively high concentration of reduced forms of nitrogen (urea and ammonium-N) in school wastewater.

One strategy to deal with this situation may be to precede the reed bed with an oxidising treatment device, such as a vertical flow wetland or sand filter, which are much more efficient at oxidising the reduced nitrogen into nitrate.

4 Conclusions

Using the data from 28 different monitoring regimes of 13 reed beds in north-eastern NSW, first-order plug-flow design model parameters were derived to enable the prediction of BOD and TN removal in reed bed treatment systems. The rate of BOD and TN reduction, and therefore the reaction rate coefficient, varied depending on the type of wastewater being treated. Volumetric reaction rate coefficients (k_{v20}) of 0.52 d^{-1} and 0.18 d^{-1} gave reliable predictions of BOD and TN removal respectively for combined wastewater, greywater and laundry wastewater, providing reed beds were greater than six months old. Lower rate coefficients need to be used for reed beds treating school wastewater. An adaptation trend was apparent for BOD removal, with performance improving steadily during the first three years. BOD removal performance decreased as temperature increased, resulting in a temperature correction factor (θ) of 0.953. Contrary to other authors, no significant relationship was found between TN removal and temperature. Thus, a TN temperature correction factor of 1.0 is recommended. However, it should be noted that the data used in this study were collected at a relatively narrow temperature range of 14.8-25°C, and that temperature correction factors should be determined for climates that experience a greater variation in water temperature (particularly at colder temperatures). Background concentrations (C^*) for BOD and TN were found to be 5 and 1.5 mg/L respectively. Overall, the model parameters derived in this study provide a reliable basis for determining the HRT required to achieve a desired effluent BOD and TN concentration for reed beds treating combined wastewater, greywater and laundry effluent, for most wastewaters between 15 and 25°C.

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