NITROGEN REMOVAL FROM WASTEWATER TREATMENT LAGOONS

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ABSTRACT

In an attempt to gain a better understanding of ammonia and nitrogen removal processes in multi-pond wastewater treatment lagoons, an analysis was carried out of data obtained during regular monitoring of Lagoon 115E at the Western Treatment Plant in Melbourne. To do this, a contour plot approach was developed that enables the data to be displayed as a function of pond number and date. Superimposition of contour plots for different parameters enabled the dependence of ammonia and nitrogen removal rates on various lagoon characteristics to be readily assessed. The importance of nitrification as an ammonia removal mechanism was confirmed. Temperature, dissolved oxygen concentration and algal concentration all had a significant influence on whether or not sizeable nitrifier populations developed and persisted in lagoon waters. The analysis made it evident that a better understanding of microbial, chemical and physical processes in lagoons is needed before their nitrogen removal capabilities can be predicted with confidence. © 1999 IAWQ Published by Elsevier Science Ltd. All rights reserved

KEYWORDS

Ammonia; contour plot; correlations; lagoon; nitrogen; nitrification; pond; removal; sewage; wastewater.

INTRODUCTION

In Australia, as elsewhere, lagoon systems are used widely in wastewater treatment. Their effectiveness in removing BOD and suspended solids is well established. However, when it comes to nitrogen removal, their performance is much less predictable. This is especially true in temperate regions, where prolonged periods of good nitrogen removal in summer can be followed by much reduced levels of nitrogen removal in winter. Such is the case in lagoon systems at the Western Treatment Plant (WTP), at Werribee, near Melbourne.

The WTP handles around 55% of Melbourne’s sewage and is sited on 10850 ha of land adjoining the west shore of Port Phillip Bay. Sewage is treated by a combination of land filtration, grass filtration and lagoons. The effluents from these processes enter Port Phillip Bay via 4 separate outlets. Taken together, these effluent streams constitute one of the two largest inputs of nitrogen into the Bay (Murray, 1994). Nitrogen is believed to be the limiting nutrient as far as algal and bacterial growth in the Bay is concerned (Harris et al., 1996). Hence there is growing pressure on the WTP to reduce the nitrogen content of its effluents. For example, the amount of nitrogen the WTP is permitted to discharge to Port Phillip Bay is soon to be reduced from 4300 tonnes per year to 3500 tonnes per year.
There has been a longstanding awareness at the WTP of the need to improve the nitrogen removal capabilities of its treatment systems. Prospects for achieving better nitrogen removal in the land and grass filtration systems are poor. Consequently emphasis has been placed on improving the nitrogen removal performance of the lagoons.

Early work was aimed at establishing which nitrogen removal mechanisms were the most important and how their relative importance varied from pond to pond. (Most lagoon systems at the WTP consist of a sequence of around ten separate ponds, connected in series.) The studies of Hussainy (1979) and Morrison (1984) indicated that nitrification, with subsequent denitrification, was a major removal mechanism at the WTP. This was confirmed by the investigations of Constable (1988), who undertook a comprehensive study of the fate of nitrogen entering Lagoon 45W at the WTP. He estimated that 6% of the nitrogen removed in this lagoon was incorporated into lagoon sediments, 18 to 54% was lost through desorption (of ammonia from the lagoon surface to the atmosphere), and the balance was removed by coupled nitrification/denitrification.

Constable's (1988) work showed that the key to improving nitrogen removal at the WTP lay in finding ways to promote nitrification in the lagoons. Historically, the WTP lagoons have exhibited periodic episodes of strong nitrification in summer followed by an almost complete loss of nitrification in winter. During these episodes high concentrations (up to $10^7$ organisms/ml) of nitrifying bacteria occur in the water column of ponds in the latter half of the pond sequence (Morrison, 1984); achieving a high level of nitrification therefore appears linked to establishing and maintaining a large nitrifier population in these ponds.

Research since then has concentrated on trying to establish what combination of conditions leads to the development of a large nitrifier population in a pond's water column, and what changes bring about its subsequent disappearance. The most probable cause of a collapse in the nitrifier population is washout, which can be caused by an increase in the hydraulic load on the lagoon or by a fall in the nitrifier growth rate. This led to an attempt to develop a way of predicting the minimum hydraulic residence time a pond would require if nitrifier washout was to be avoided (Gross et al., 1994).

The initial relationship developed by Gross was based on published material about the influence of pH, temperature, dissolved oxygen level and ammonia concentration on nitrifier growth rate. However, experimental work on a series of four pilot-scale ponds showed that this relationship was not particularly successful in practice. An unexpected result of Gross' work was the discovery that the predictive success of the relationship improved substantially when a factor involving the algal concentration in the ponds was included. Quite why this should be the case remains uncertain.

Given these uncertainties, a logical next step was to analyse routine monitoring data accumulated by the WTP to see if any further insights into lagoon operation could be gained. This was not a trivial task as the amount of data amassed over the many years the WTP has been in operation is enormous. To keep the workload manageable it was decided to limit the scope of the investigation to the data for a single lagoon. That selected was Lagoon 115E, the first of the new generation of lagoons currently being developed at the WTP. The rest of this paper describes the approach used in analysing these data, and the results obtained.

**LAGOON CHARACTERISTICS**

Lagoon 115E is situated in the north-east corner of the WTP site and was commissioned in 1986. It originally comprised eleven ponds, with the first nine being in series and the last two in parallel. Then in 1993 it was reconfigured, with ponds 10 and 11 being combined into a single pond. It receives an average hydraulic load of 55 ML/day and the average dry weather flow (ADWF) is 18300 ML per year. The lagoon surface area is 199.6 ha and the average liquid retention time in the system is 80 days. (More information on this lagoon's characteristics can be found in Hurse and Connor (1997) and Hurse (1996)).

Conditions in Lagoon 115E have been monitored regularly since it was commissioned. The procedure followed is to collect grab samples of water from the ponds for subsequent analysis in the WTP laboratories. Initially samples were taken from every pond but more recently only every second pond has been sampled. The sampling frequency has varied, generally being between one and three weeks. The following
characteristics of the samples are measured: pH, temperature, and the concentrations of: BOD$_5$, BOD$_3$ (nitrification suppressed), chlorophyll 'a', dissolved oxygen, H$_2$S, ammonia, nitrite, nitrate, organic nitrogen, TOC, total P and suspended solids. For all characteristics but pH, BOD$_3$ (nitrification suppressed), H$_2$S and total P, there is a virtually continuous data set extending back to the lagoon's inception.

These measurements show that average total nitrogen levels in Lagoon 115E's influent and final effluent are 53 mg/l and 22 mg/l respectively. This corresponds to an overall nitrogen removal rate of 60%, equivalent to 600 tonnes per year. The removal rate is not constant over the year, peaking at 73% in summer and falling to a low of 47% in winter. This reflects the seasonal dependence of the various nitrogen removal processes, particularly coupled nitrification/denitrification.

**DATA ANALYSIS**

With 10 years worth of data to be analysed, it was clear that the only practical approach was to use a computer based technique. Before this could be done, results recorded as 'not detected' (ND) or in the form of inequalities (i.e. as 'less than' or 'greater than' a specified value) had to be converted to a number. The approach adopted was to treat an ND as equivalent to a zero, while the two inequalities were treated as equivalent to 'equals'. The effect of these approximations is believed to be small, not only because only 5.1% of the entries were affected, but also because the computer analysis techniques developed were set up to detect anomalous values, which were then checked against the original records.

As indicated earlier, the reason for analysing the monitoring data for Lagoon 115E was to learn more about factors affecting nitrification. However, the wastewater characteristics measured in the lagoon monitoring program do not provide a direct measure of how much nitrification has occurred in a given pond or sequence of ponds. One related parameter that can be determined from the available data is the extent of ammonia removal occurring across ponds. At first sight this parameter appears of limited use as it includes not only ammonia losses due to nitrification but also losses due to desorption. However, physical considerations suggest that, under otherwise similar conditions, losses due to desorption will remain reasonably constant. Therefore any marked short-term increase or decrease in ammonia removal rate can only be attributed to the establishment or disappearance of active water column nitrifier populations. In addition, any pond showing consistently high ammonia removal rates can safely be assumed to be actively nitrifying.

As no two ponds are equivalent, the loss of ammonia across a pond is an inappropriate parameter for use in a generalised analysis. More appropriate is an ammonia removal rate normalised with respect to some lagoon characteristic or property. For reasons explained in more detail in Hurse and Connor (1997), the normalising parameter selected was the flowrate through the pond under consideration. The resulting 'flow-normalised ammonia removal rate', with units of (mg/s)/(l/s), was the key nitrification related parameter used throughout the subsequent analysis.

In order to determine how the flow-normalised ammonia removal rate (hereafter referred to simply as the ammonia removal rate) was related to conditions in the lagoon, a visual means of comparing variations in the ammonia removal rate with corresponding variations in lagoon characteristics was required. After considering a number of possibilities, a contour plot approach was adopted. Development of this approach entailed finding ways to accurately fit a surface to a data set within which values were often missing or non-uniformly distributed. Version 5.03 (1995) of the proprietary graphics package 'Surfer', produced by Golden Software, proved capable of handling the required interpolations and producing a surface that followed closely the original data; for more than 95% of the data points there was less than a 5% difference between the original value and that read from the fitted surface (Hurse, 1996).

A segment of a contour plot produced using the 'Surfer' software package is shown in Figure 1. The x-axis on this plot shows the number of the pond to which a data point refers; the date on which the relevant sample was taken is given on the y axis. (For convenience, the date is represented as the number of days elapsed since the lagoon was commissioned.) Shaded regions show in which ponds, and over what periods of time, a particular parameter has values greater than or less than a specified value. For example, in Figure 1 the regions of forward shading show where and when in 1987 the ammonia removal rate exceeded 10 (mg/s)/(l/s) while the backward shaded areas designate regions where the total oxidised nitrogen (nitrite plus
nitrate) concentration is greater than 6 mg/l. This ability to superimpose information about different parameters shows the usefulness of the contour plot approach in assessing how closely particular parameters are related. In this case, a glance is sufficient to show that regions where oxidised nitrogen levels are high usually overlap or follow regions where ammonia removal rates are high.

![Contour plot showing regions where the ammonia removal rate was greater than 10 (mg/s)/(l/s) (forward shading) and the total oxidised nitrogen concentration was greater than 6 mg/l (backward shading).](image)

To establish how ammonia removal rate was dependent on the range of lagoon parameters covered by the available data, use was made of the superimposition technique illustrated above. Three different contour plots for ammonia removal rate were generated, depicting regions where the ammonia removal rates were greater than 5, 10 and 15 (mg/s)/(l/s) respectively. Each of these plots was superimposed in turn on between three and five plots for each parameter that might influence nitrification rate. In constructing these plots, values were chosen that spanned the usual range of values for the parameter in question; for example, in the case of dissolved oxygen, plots were prepared delineating regions where concentrations were greater than 1, 3 and 5 mg/l respectively. The superimposed contour plots were then systematically examined to establish the extent to which shaded regions overlapped or failed to overlap, and whether any consistent patterns were evident. Attention was concentrated on certain well-defined episodes (such as those marked 1 to 4 in Fig. 1) where there appeared to have been a period of sustained high nitrification rates.

**RESULTS AND DISCUSSION**

**Temperature**

The data set contained entries for pond temperature ranging from 4 to 27°C; however the normal range is from around 8 to 23 °C. Temperature is known to influence the nitrification process considerably and there
is general agreement that nitrification rate increases as the temperature rises from 5 to 30°C (Shammas, 1986; Halling-Sørensen and Jørgensen, 1993). This information is in accord with observations at the WTP, where nitrification tends to occur only when pond temperatures are at the upper end of their annual range.

The contour plot analyses supported the above observations and suggested that, for the flowrates normally experienced in Lagoon 115E, 16°C is a key temperature. When pond temperatures fell below this figure, occurrences of ammonia removal rates greater than 5 (mg/s)/(l/s) were uncommon and usually attributable to other changes. Instances where removal rates exceeded 10 (mg/s)/(l/s) generally overlapped or were preceded by regions where temperatures were greater than 20°C.

The influence of the rate of temperature change was also explored. In general there was no obvious link between rate of temperature change and major changes in ammonia removal rate. However, in a few cases a period of declining temperature was associated with the end of a high removal rate period or a period of rising temperatures immediately preceded the onset of a spell of high ammonia removal rates.

Dissolved oxygen

Many previous researchers have stated that there is a threshold dissolved oxygen (DO) concentration of around 1 to 2 mg/l below which nitrification is seriously retarded. This accords with Constable's (1988) finding that ammonia removal rates at the WTP were greatly slowed when the DO fell below 2 mg/l. The contour plot analyses confirmed these findings, showing that the ammonia removal rate rarely exceeded 5 (mg/s)/(l/s) unless the dissolved oxygen concentration was above 1 mg/l. In addition, the higher the dissolved oxygen concentration used in constructing the DO contour, the greater was the degree of overlap between the resulting high DO regions and regions of high ammonia removal rate. This suggests that the higher the dissolved oxygen level, the greater is the ammonia removal rate the pond can support. Nevertheless, a high DO level alone does not guarantee a high ammonia removal rate.

pH

Little of value could be learnt from analyses of pond pH data. In part this was because regular monitoring of pH only began several years after the lagoon was commissioned. More importantly, the pH values in the data set are those measured at the time pond waters are sampled, which usually occurs at around 9 to 9.30 in the morning. It has been shown that measurements made at this time are generally close to the mean diurnal pH value (Gross et al., 1994). However, the pH of pond waters can follow a quite pronounced diurnal cycle, especially when algal concentrations are high. The impact of pH variations on bacterial communities is likely to be greatest when pH values are at their most extreme, yet past monitoring practices provide no information on the amplitude of these variations.

Chlorophyll 'a' (algal concentration)

The contour plot analyses support the observations of Gross et al. (1994) that ammonia removal rates are closely correlated with algal concentration (as determined by chlorophyll 'a' measurements). The greater the ammonia removal rate, the greater the chlorophyll 'a' concentration tended to be, and the degree of correlation was highest at high removal rates. For example, in regions where removal rates were above 15 (mg/s)/(l/s), chlorophyll 'a' concentrations were almost always above 200 µg/l, and where removal rates exceeded 10 (mg/s)/(l/s), chlorophyll 'a' levels were almost always above 100 µg/l. Removal rates above 5 (mg/s)/(l/s) also tended to coincide with periods when chlorophyll 'a' concentrations exceeded 50 µg/l. However, whilst high removal rates were associated with high chlorophyll 'a' concentrations, the converse was not true - a high chlorophyll 'a' concentration did not guarantee a high ammonia removal rate.

The reason why waters with high algal concentrations tend to nitrify more effectively is still unresolved. One possible explanation is based on the fact that at high algal concentrations turbidity levels increase. There is evidence that nitrifying bacteria are inhibited by light (Abeliovitch and Vonshak, 1993; Hodgson and Papasliaris, 1995) and the impact of such inhibition would presumably diminish substantially in turbid waters. The validity of this hypothesis remains to be confirmed, however.
Biochemical Oxygen Demand

There is a broad consensus among researchers and practitioners that when the BOD$_5$ is high, nitrification rates will be low. Where a wastewater contains both ammonia and substantial amounts of readily oxidisable organic matter, one would expect competition for oxygen between the nitrifiers and the heterotrophic bacteria that degrade the organics. The heterotrophs have higher maximum specific growth rates and lower saturation constants than the nitrifiers (Halling-Sørensen and Jørgensen, 1993), and thus would be predicted to both outgrow and outcompete them.

The contour plot analyses generally supported the above picture, with higher ammonia removal rates occurring only infrequently in regions where the BOD$_5$ was high. However, there was no consistent trend of decreasing ammonia removal rate with increasing BOD$_5$. In part this is attributable to the fact that the BOD$_5$ test measures contributions to oxygen demand of a variety of compounds. These include both dissolved and suspended materials, the amounts, nature and relative proportions of which change along the pond chain. It also includes both a carbonaceous and a nitrogenous component, the last of which may or may not manifest itself within the 5-day test period.

However, these uncertainties about what the BOD$_5$ test is actually measuring are still inadequate to explain what occurred in two particular episodes when ammonia removal rates were high. In these two episodes, there was not a decrease but an increase in ammonia removal rate as the BOD$_5$ levels increased. In both episodes, chlorophyll 'a' concentrations (and hence algal concentrations) were also very high. It was at first postulated that the high mass of algae present might be causing the high observed BOD$_5$ values yet not be interfering with the activities of the nitrifiers. To test this hypothesis, measured chlorophyll 'a' and BOD$_5$ data for ponds at the end of the pond chain were used to derive a factor relating the algal contribution to the BOD$_5$ to the chlorophyll 'a' concentration. Details of the method used are given in Hurse (1996).

The estimated value of the above factor was 0.011 mg BOD$_5$/µg chlorophyll 'a', though the scatter of the data made it clear that this figure must be treated as only a rough estimate. By using this factor, the algal contribution to the BOD$_5$ in the two episodes referred to above was determined and then subtracted from the measured BOD$_5$ to produce an estimate of the non-algal BOD$_5$ concentration. Far from explaining the anomalies noted above, this approach only compounded the problem. This was because increases in ammonia removal rate during the two episodes in question correlated even more strongly with increases in non-algal BOD$_5$ than with the uncorrected BOD$_5$ values. For example, removal rates greater than 15 (mg/s)/(l/s) always coincided with non-algal BOD$_5$ levels greater than 20 mg/l while removal rates above 10 (mg/s)/(l/s) were not observed once the non-algal BOD$_5$ level fell below 10 mg/l.

An alternative explanation for the above observations is that the presence of high concentrations of algae promotes nitrification to a far greater extent than the activity of heterotrophic BOD$_5$-degrading bacteria retards it. This would be consistent with earlier observations that algal concentration exercises a marked influence on nitrogen removal rates (Gross et al., 1994). How this influence is exercised is as yet uncertain, but one possible explanation is discussed in the previous section.

One component of the overall BOD$_5$ that might be expected to correlate closely with nitrification rate, and hence ammonia removal rate, is the nitrogenous oxygen demand (NOD), i.e. the difference between the overall BOD$_5$ value and the nitrification-suppressed BOD$_5$ value. The latter parameter was measured less often than most other parameters, and then only for ponds 7 to 11, so the data base for NOD was somewhat limited. Nevertheless, on the contour plots there was good to very good overlap between regions of high NOD and regions where the ammonia removal rates were high. A high NOD was not an infallible predictor of a high ammonia removal rate, however, as there were a few instances where high NODs coincided with low removal rates.

Total suspended solids

No clearcut pattern emerged from the contour plot analyses of the total suspended solids (TSS) data. This was a little surprising, given the demonstrated link between algal concentrations and ammonia removal rates and the possible connection between increases in removal rate and increases in turbidity. Part of the
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problem may well be that the nature of the suspended solids changes along the course of the lagoon system. At the start, the solids are typical of those entering the sewer system whereas at the end of the pond chain they are largely algal in nature. Using known chlorophyll ‘a’ data and assuming that any suspended solids in the final ponds were composed predominantly of algal matter, it was estimated that every µg of chlorophyll ‘a’ was roughly equivalent to 0.042 mg/l of TSS. This factor was used to split measured TSS values into algal and non-algal fractions. Contour plot analyses based on the algal fraction in effect confirmed the previously established link between algal concentration and ammonia removal rate. In the case of the non-algal fraction, nothing clearcut emerged and it would appear that much still needs to be learnt about the characteristics of suspended solids in lagoon systems and how they alter along the pond chain.

Nitrogen-related parameters

Ammonia concentration. For this parameter the contour plots largely confirmed what should be intuitively obvious. For example, low ammonia concentrations were to be found immediately downstream of regions where ammonia removal rates were high. In addition, high ammonia removal rates were not observed in ponds where the influent ammonia concentration was already very low.

Total oxidised nitrogen (TON). This term was used to refer to the sum of the nitrite (NO\text{$_2^-$}) and nitrate (NO\text{$_3^-$}) concentrations. Since the only plausible source of TON is nitrification, comparison of TON levels with ammonia removal rates should provide an important means of confirming earlier assumptions about the role played by nitrification in ammonia removal. Contour plot analyses showed that, for a number of episodes exhibiting high ammonia removal rates, regions for which the ammonia removal rate exceeded 10 (mg/s)/(l/s) overlapped closely with regions where there was a TON of more than 6 mg/l. In certain other episodes, the extent of coincidence between high removal rates and high TON levels was less well marked. Denitrification of some of the TON provides a ready explanation for this, however, and the conclusion that nitrification plays a major role in ammonia removal is not compromised.

Total nitrogen. Contour plots with superimposed total nitrogen and ammonia removal rates often showed the total nitrogen removal rate peaking downstream of the ammonia removal rate peak. In these cases it is inferred that the mechanism of nitrogen loss is denitrification since if desorption were the dominant loss mechanism, the two removal rate peaks should coincide. These observations provide further confirmation of the important role played by coupled nitrification/denitrification in nitrogen removal from the WTP lagoons.

CONCLUSIONS

The contour plot approach described above provides a valuable means of visually displaying the large amounts of monitoring data accumulated on the lagoon systems at the WTP. It also enables the nature and extent of interrelationships between various measured and derived parameters to be evaluated, at least on a qualitative basis. However, it also makes evident the complexity of the interrelationships between microbial, chemical and physical processes in lagoon systems.

The analyses conducted using the contour plot approach confirmed the importance of coupled nitrification/denitrification as a nitrogen removal process in Lagoon 11SE. Parameters confirmed as having a significant to substantial influence on nitrification and hence nitrogen removal included temperature, algal concentration and dissolved oxygen level. The usefulness of NOD and TON as a means of determining when ponds are actively nitrifying was also shown. No conclusions could be drawn about the role played by pH and TSS as past monitoring practices did not record all relevant information.

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