Shortcut nitrogen demonstration trial plant performance

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ABSTRACT

A 42,300GPD demonstration shortcut nitrogen removal plant, operated in anoxic/oxic mode with secondary clarification has operated since June 2017 at Melbourne Water's WTP. There have been four key periods (I - IV) exhibiting a high level of NOB out-selection, indicated by either NAR (= NO_2^-/NO_x) greater than 0.3 or NOB:AOB activity ratio (determined through *ex situ* SNR testing) less than 0.5. Period I observed effluent NAR average 0.77, higher than the baseline NAR of 0.01 to 0.17. Periods II, III and IV showed a low ratio of NOB:AOB activity rates, with measured ratios of 0.13 to 0.43, significantly lower than observed plant baseline of approximately 1.0 and the theoretical ratio of 0.78. The most efficient trial period is the sub-period IV(b) with an average 'COD efficiency' of 4.2kgCOD/kgTN removed compared with baseline ASP MLE process (9.40 kgCOD/kgTN) and Baseline 2 from the demonstration plant (without NOB out-selection) with 8.4 kgCOD/kgTN.

KEYWORDS

Short Cut Nutrient Removal, Secondary Treatment, Nitrite Shunt, Effluent TN

INTRODUCTION

A 42,300GPD (160kL/day) demonstration shortcut nitrogen removal plant, operated in anoxic/oxic (A/O) mode with secondary clarification has operated since June 2017 at Melbourne Water's Western Treatment Plant (WTP). WTP in Melbourne, Australia treats 140 MGD (530ML/d) sewage with a significant industrial load component. Melbourne Water is undertaking laboratory and demonstration-scale trials of short-cut nitrogen removal processes for implementation in an upcoming major secondary treatment capacity augmentation (Watson, 2016).

Carbon diversion for energy recovery is already practiced at the WTP with methane capture from the anaerobic lagoons. Therefore, the objective of this trial is to demonstrate shortcut nitrogen removal to meet low effluent total nitrogen (TN) standards (<10mgN/L) at reduced carbon availability (influent COD:TKN ratio of <7) without adding any supplemental chemicals at temperatures ranging from 17 -25 deg C.

A shortcut nitrogen demonstration plant was designed with extensive Biowin[TM] modelling (Regmi, 2016) and constructed comprising a primary sedimentation tank (used only when feed solids exceed design levels), bioreactor configured as A/O and secondary clarifiers. The plant operates with feed from a primary anaerobic lagoon (hydraulic residence time (HRT) 1.5–3 days). The primary anaerobic lagoon performance varies, providing a demonstration plant influent which displays a wide range of chemical oxygen demand (COD) and total suspended solids (TSS) quality. The plant was designed with nitrite-oxidising bacteria (NOB) out-selection selective pressures and control strategies identified in the WERF manual on

Mainstream Deammonification (WERF, 2015) including intermittent aeration, high DO (>1.5 mg/L), residual ammonia (>2.0 mgN/L) and low sludge age to promote ammonia-oxidising bacteria (AOB) activity and target out-selection of NOB which is essential for shortcut nitrogen removal.

KEY TRIAL OBJECTIVES FOR DEMONSTRATING MATERIAL CARBON SAVINGS FOR NITROGEN REMOVAL

The shortcut nitrogen demonstration plant has the following key objectives regarding assessment of carbon savings in TN reduction:

1) Test proof-of-process and stability of performance for shortcut nitrogen removal in the WTP conditions

2) Evaluate the impact of influent quality on plant performance and carbon savings

3) Determine ideal influent characteristics for the plant to achieve design effluent quality requirements

WTP BACKGROUND

WTP was first constructed in the 1890s and has been progressively augmented and upgraded over the years. The plant currently includes the following process steps:

- Primary covered anaerobic lagoons ("anaerobic pots")
- Biogas collected for energy generation, the plant is 80 to 100% energy self sufficient
- Aerated and facultative lagoons
- 2 No. modified ludzack-ettinger (MLE) activated sludge plants (ASPs), the 55E ASP, 25W ASP
- 1 No. Step-feed plant 160S NRP (recently commissioned)
- Class C and Class A (UV, chlorine) recycled water production

The site is an internationally significant (Ramsar) wetland, and manages sewage treatment and biodiversity requirements as well as a large agricultural operation. The site discharges treated wastewater, to Port Phillip Bay under an Environmental Protection Agency Victoria (EPAV) licence.

The oldest ASP on site, the 55E ASP, is due for renewal. In order to continue to meet required discharge load limits, the new plant is required to meet an effluent TN of <10mgN/L. Continued near energy neutral operation of the plant is desired to achieve the lowest whole-of-service cost for customers.

METHODS

The demonstration trial commenced in June 2017 and has been operating for 24 months (at the time of writing).

A process flow diagram (PFD) of the demonstration plant is provided in Figure 1. The demonstration plant was built at an existing trial site and connected into pre-existing common trial infrastructure (CTI). Key process elements of the demonstration plant include:

- Feed capacity of 42,300GPD (34,300 GPD to 45,400GPD) (160kL/day (130 to 172 kL/day))

- Primary sedimentation tank (PST),to remove excess solids if required – the feed pump station entrains additional solids compared with the expected full scale plant). Influent sampling point is downstream of the PST.

- Bioreactor with a 25% anoxic fraction

- Waste activated sludge (WAS) pump station

- Duty/standby blowers

- Instrumentation (Influent TSS, Bioreactor dissolved oxygen (DO), pH, Ammonia, Nitrate and Nitrite)
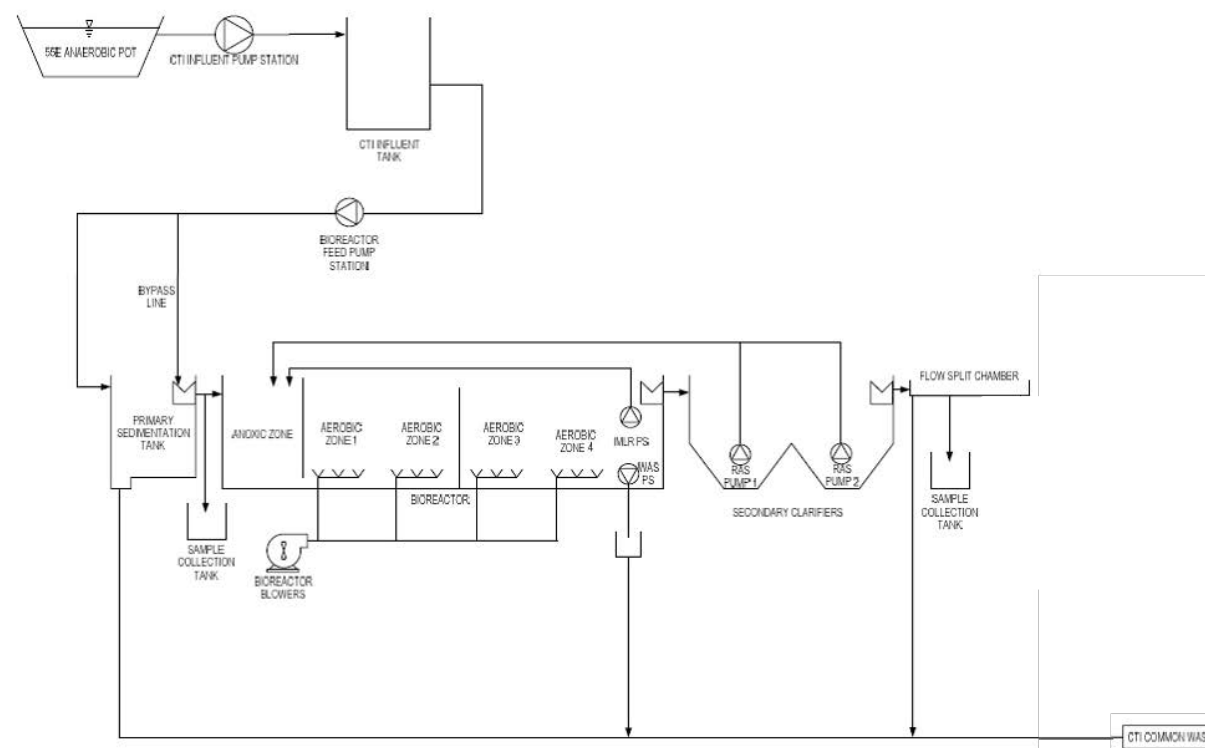

Figure 1: Demonstration Plant PFD

The demonstration plant has operated with intermittent aeration controlled based on measured ammonia, nitrite and nitrate.

Measuring NOB out-selection

The following two methods of measurement to estimate the apparent NOB out selection have been undertaken for the Demonstration Plant:

1) The measurement of the Nitrite Accumulation Ratio (NAR) of the effluent, determined as the effluent nitrite (NO_2)/NOx, which has been monitored since plant start up. It is used as a measure of the accumulation of nitrite compared with nitrate in the final effluent.

2) The measurement of *ex situ* Specific Nitrification Rate (SNR). This has been undertaken weekly since November 2017. SNR test procedure is outlined in Dold et al, 2015.

Quantitative polymerase chain reaction (qPCR) testing is planned to provide further understanding of the ammonia-oxidising bacteria (AOB) and NOB population changes over the trial period.

Measuring reductions in the carbon requirements for TN removal

COD Efficiency

A 'COD efficiency' parameter has been used to monitor the efficiency of the process, and allow assessment of the benefit of reduced carbon requirement for TN reduction when NOB out-selection is observed. The 'COD efficiency' is determined as the kgCOD removed per kgTN removed. A lower 'COD efficiency' result is an improvement in treatment performance, with less kg of COD required to remove a kg of nitrogen.

$$COD\ Efficiency = \frac{\text{kgCOD removed}}{\text{kg TN removed}} = \frac{\text{kgCODinfluent} - \text{kg sCOD effluent}}{\text{kgTKNinfluent} - \text{kgTNeffluent}}$$

Short periods of poor settleability were observed resulting in a small number of outlier effluent TN results, due to high effluent TSS concentrations. For those results with an effluent TSS >50mg/L, an organic N concentration of 3 mgN/L is adopted for analysis purposes and denoted as "TSS adjusted" values.

RESULTS AND DISCUSSION

Influent quality

A summary of the Demonstration Plant influent quality (downstream of the PST) (June 2017 to April 2019) is provided in Table 2. Due to the variable performance of the operation of the Anaerobic Pot (which provides feed to the Demonstration Plant) the plant is required to treat a variable influent COD. Figure 2 provides an indication of the feed quality variation observed, which is considered typical of the Anaerobic Pot Effluent.

Table 1: Demonstration Plant Influent quality

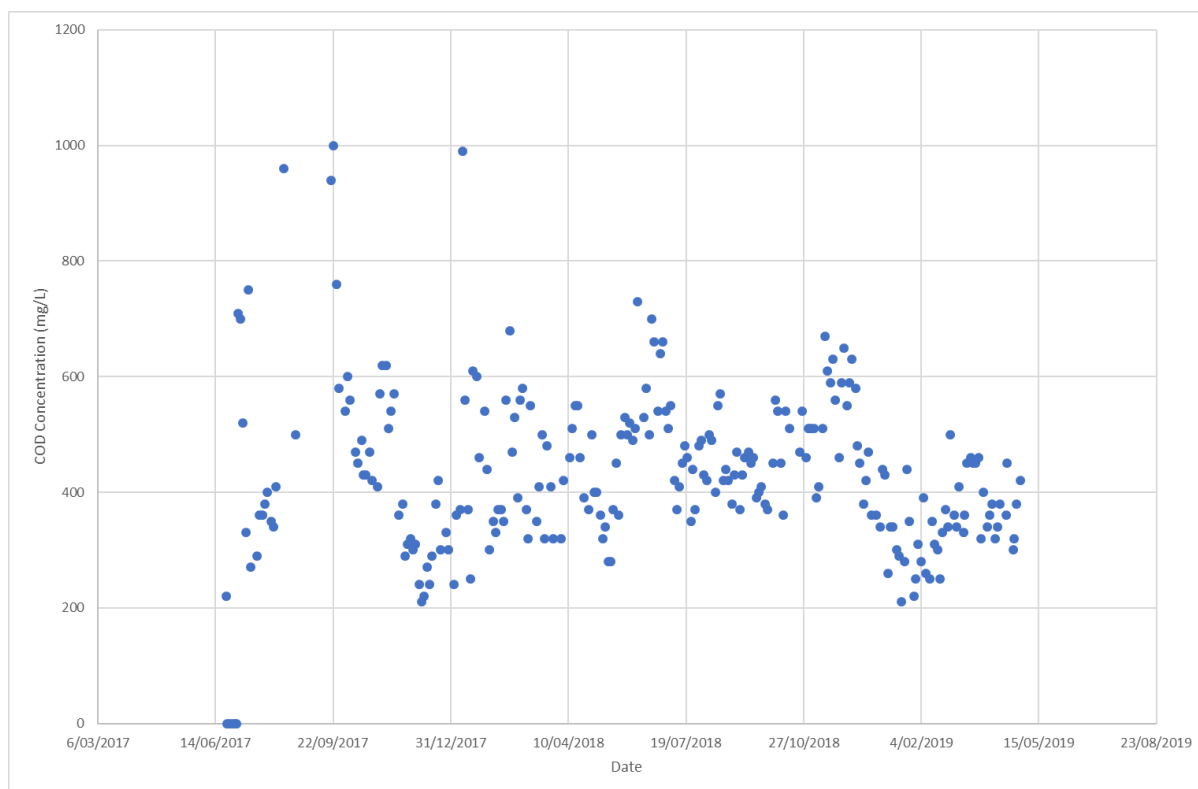|	COD	sCOD	TKN	NH$_4^+$	COD:TKN	Total P	TSS	Alkalinity
	mg/L	mg/L	mg/L	mgN/L	-	mg/L	mg/L	mg$_{CaCO3}$/L
10%ile	300	93	59	43	4.6	8.3	71	310
Median	420	170	68	59	6.3	9.7	120	370
90%ile	590	260	77	65	8.9	16.0	219	410

Figure 2: Influent COD concentration variation

NOB Out-selection

During the plant operation to date there have been four key periods (I to IV) that exhibited apparent out-selection of NOB, shown by the mustard periods labelled Period I to IV in Figure 3 and detailed in Table 3. A high level of out-selection of NOB was indicated by either a NAR (= NO_2^-/NO_x) greater than 0.3 or an NOB:AOB activity ratio (as determined through *ex situ* SNR testing) less than 0.5. To validate the *ex situ* tests, when the conditions have been suitable (high bioreactor ammonia and nitrite), *in situ* tests have also been carried out by changing to continuous aeration and tracking bioreactor nitrogen. To date, these *in situ* tests have demonstrated very similar relative activities providing a strong level of assurance that the *ex situ* tests are representative. Blue periods in Figure 3 labelled Baseline 1 and Baseline 2 indicate two periods of operation without NOB out-selection.
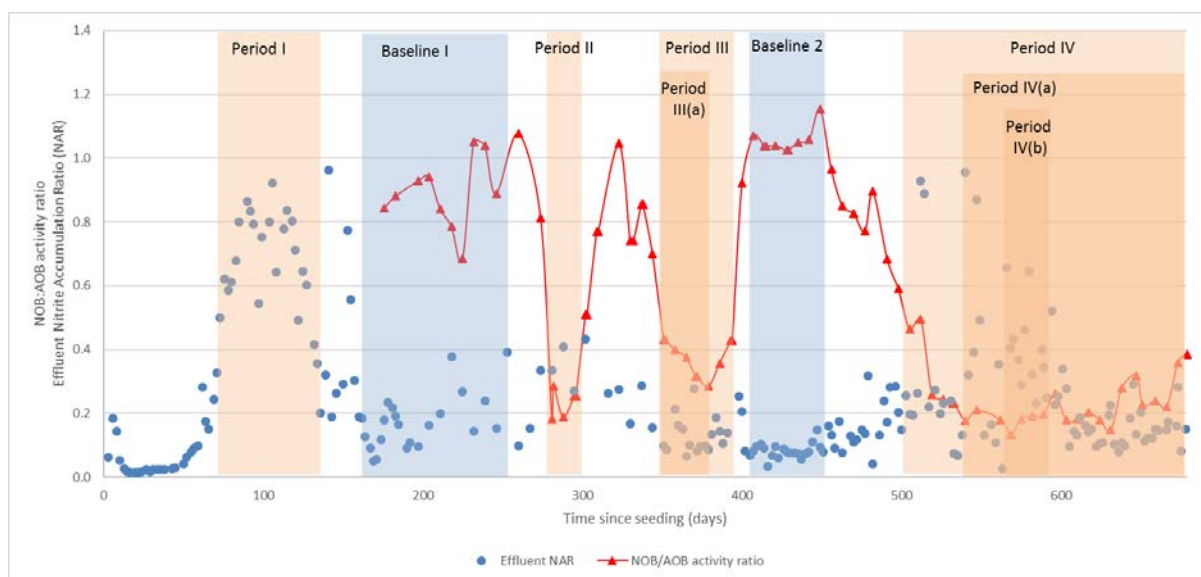

Figure 3: NOB Out-selection as indicated by NAR, ratio of specific nitrification rates (NOB:AOB activity ratio)

NOB out-selection was initially achieved intermittently over the first 500 days of plant operation. Over this period a number of operational upsets were experienced, predominately due to issues with the feed system, pipe blockages, issues with instruments (on-going), power outages, and control fine tuning. A greater understanding of the operational conditions required for NOB out-selection at the WTP has also been gained over the trial operation. More stable operations since Day 500, typical of expected operation of the plant at full scale, have allowed for success in obtaining sustained NOB out-selection.

Period I observed an effluent NAR average 0.77, higher than the baseline NAR of 0.01 to 0.17, indicating a high level of out-selection of NOB. No SNR test results were available before Day 176 and so interpretation of Period I is solely based on NAR. Periods II, III and IV showed a low ratio of NOB:AOB activity rates, with measured NOB:AOB activity rate of 0.13 to 0.43, significantly lower than the observed plant baseline of approximately 1.0 and the theoretical ratio of 0.78 [assuming NO3 production rate /NOx production rate (during SNR test) = growth rate of NOB (0.7 d^{-1})/growth rate of AOB (0.9 d^{-1})] (Dold et. al, 2015).

The two extended periods without significant NOB out-selection are of interest from the Demonstration Plant operating period as they provide baseline data for comparison of the

improvement in treatment performance. The two baseline periods selected for analysis are Baseline 1 (Days 164–253) and Baseline 2 (Days 407 to 449), over these periods a material level of NOB out-selection was not achieved, as observed by the low effluent NAR (average 0.21 ± 0.10), and NOB:AOB ratio (0.91 ± 0.10). WTP 25W ASP Baseline results are also available from a 180 ML/d conventional MLE activated sludge plant (ASP) at the WTP which operates in conditions promoting simultaneous nitrification denitrification (SND) (Vellacott *et al.*, 2017) due to low and irregular DO (approximately 1.3 mg/L), with average effluent NAR of 0.01 and NOB:AOB activity ratio of 0.98.

NOB out-selection has been achieved over a range of influent qualities (COD:TKN of 3.1 to 11.4) and bioreactor temperatures (17.4 to 23.9ºC).

Table 2: Baseline and Period of NOB Out-selection, NAR and NOB:AOB activity ratio

	NAR	NOB:AOB activity ratio
WTP 25W ASP Baseline	0.01±0.02	0.98
Baseline 1	0.19±0.07	1.05±0.02
Baseline 2	0.08±0.02	1.06
Period I	0.77	Results not available
Period II	0.36	0.31
Period III	0.13	0.37
Period IV	0.26	0.24

Improvement in nitrogen removal during periods of NOB Out-selection

Table 4 provides a summary of the feed quality (COD:TKN), bioreactor operating conditions (temperature, NOB:AOB activity ratio), effluent quality (TN), and performance (%TN removal, 'COD efficiency' and efficiency of the use of available carbon), over the two baseline conditions and four periods of NOB out-selection.

The intermittent aeration, A/O process observed a higher efficiency TN reduction than the baseline ASP MLE process when operating without apparent NOB out-selection with the baseline ASP result of 9.40 kgCOD/kgTN compared against Baseline 2 from the demonstration plant with 8.4 kgCOD/kgTN . Baseline 1 with a 'COD efficiency' of 11.3 kgCOD/kgTN removed was observed at the lowest influent COD:TKN ratio of the three baseline periods (a COD:TKN ratio of 6.2).

Periods I and III(a) operated with higher influent COD:TKN ratios than Periods II and IV(a). It is noted that in Period I, whilst a lower % TN removal and poorer 'COD efficiency' was observed, provided effluent with a higher NAR suitable as feed to an Anammox moving bed bioreactor (MBBR). At higher influent COD:TKN ratios it is noted that the 'COD efficiency' carbon usage includes additional COD that would be removed via oxidation in the bioreactor, and therefore comparison of the 'COD efficiency' is most representative when assessing periods of similar influent COD:TKN quality.

Periods III(a), operated at the lowest temperature of the periods where NOB out-selection was observed. During this period effluent TN was below the target of 10mgN/L (8.3mgN/L) and an average TN removal of 87% was observed, with a 92% efficiency of the carbon available, and low effluent NAR. This period observed a high feed COD:TKN (10.3), limiting the 'COD efficiency' achieved, with an average 11.3 kgCOD/kgTN removed.

Period IV(a) provided a sustained period of NOB out-selection at lower feed COD:TKN ratio and is shown in greater detail in Figure 5. Over Period IV(b) a significant reduction in the carbon requirements for TN removal was demonstrated, with an average 'COD efficiency' of 4.2kgCOD/kgTN removed. Compared with Baseline 1, Period IV(b) observes a 50% reduction in required COD, and compared with Baseline 2 a 33% reduction.

As shown in Figure 4, when a high degree of NOB out-selection is observed (as indicated by a NOB:AOB activity ratio <0.3) the 'COD efficiency' is limited by the feed COD:TKN ratio, with the two trends closely matched.

The most efficient period of the trial is the sub-period IV(b) (Day 565 – 590) with an average 'COD efficiency' of 4.2kgCOD/kgTN removed. The most efficient N removal was observed with a 'COD efficiency' of 3.1kgCOD/kgTN removed, however due to the feed quality typically being higher than this, sustained operation at this most efficient rate was not observed.

Allowing for a fraction of unbiodegradable COD (potentially a COD:BOD ratio of 2, with some oxidation of biological carbon), an NOB out-selection of 83%, the carbon utilization for denitritation is approaching, or potentially lower than the stoichiometric carbon requirement of 1.71gCOD per g $NO_2 \rightarrow N_2$ gas. A lower than the stoichiometric carbon requirement could indicate that some nitrogen removal may be occurring via Anammox.

To explore this possibility and help identify the underlying reason for the high efficiency an Anammox activity test was undertaken on the bioreactor MLSS. However, the test did not indicate any significant Anammox activity as there was no significant reduction in ammonia under anoxic conditions.
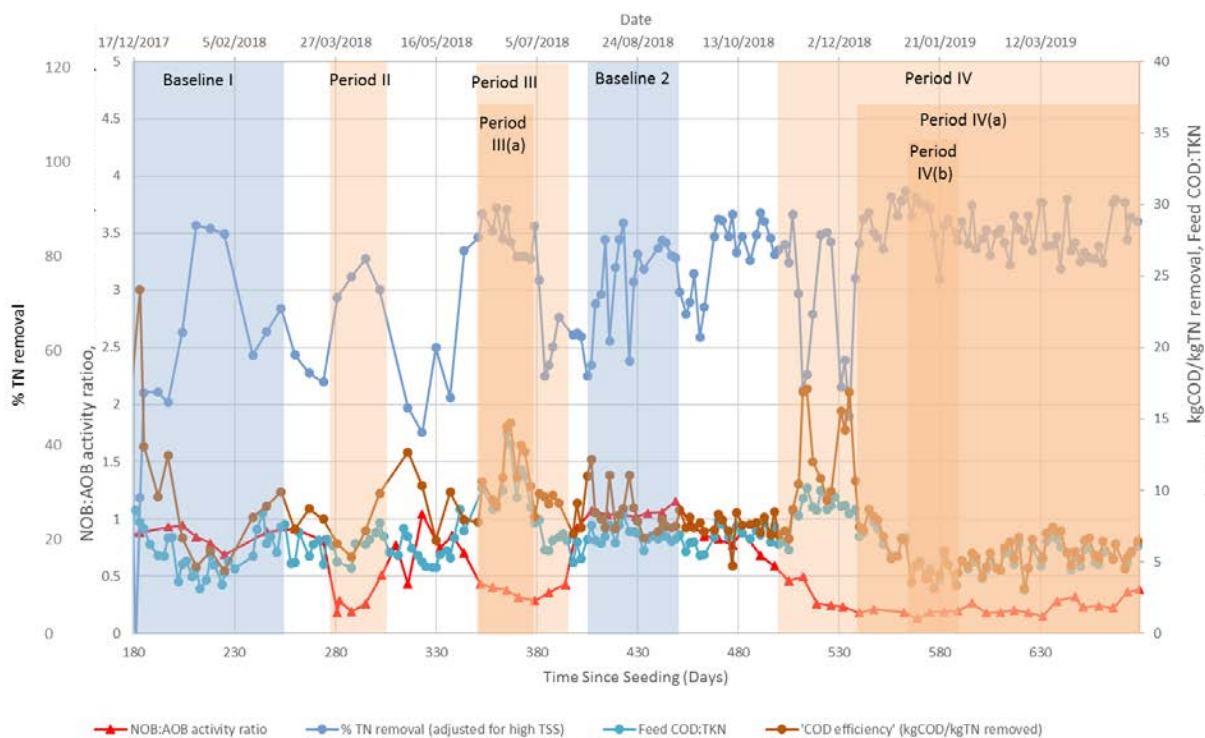
Figure 4: NOB Out-selection as indicated by Nitrite accumulation ratio, ratio of specific nitrification rates (NOB:AOB activity ratio)
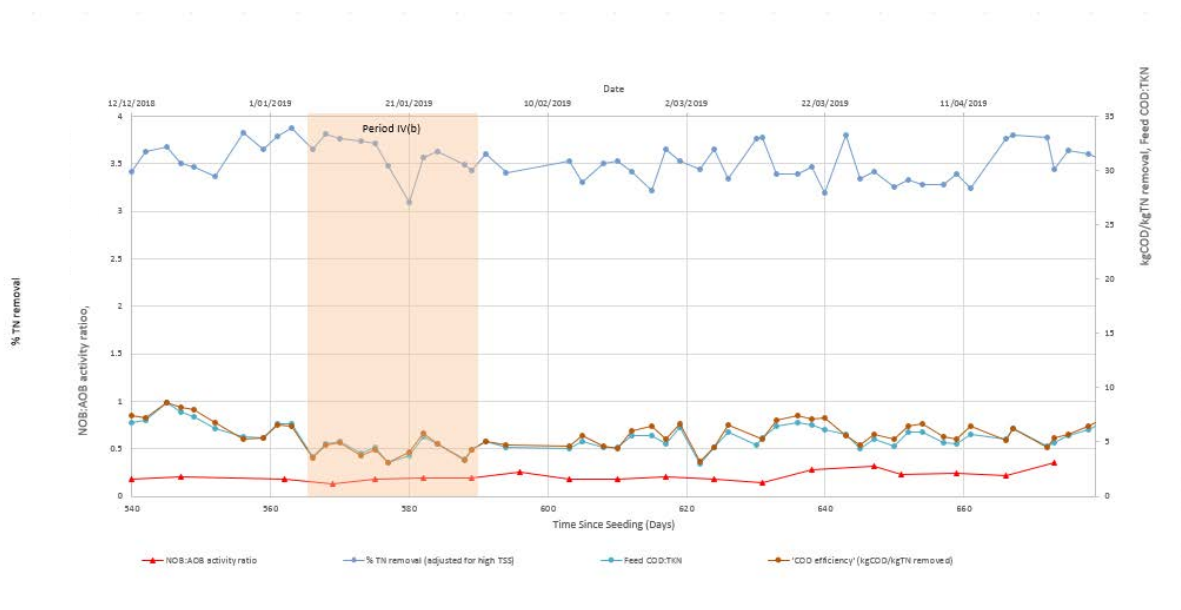

Figure 5: Feed COD:TKN ratio, 'COD efficiency' and NOB:AOB ratio (%TN removal) (Period IV(b))

Table 3: Demonstration plant conditions and conditions for periods of NOB out-selection and baseline data for comparison (averages)

Period	Days	Temp	Feed COD:TKN	TN removal efficiency	Effluent TN	'COD efficiency' COD per N removed	NAR	NOB:AOB Activity Ratio	Efficiency of use of available COD
	-	°C	-	%		kg/kg	-	-	%
Baseline 25W ASP	-	21.4	6.6		30.2	9.4	0.01	0.98	70%
Baseline 1	164 - 253	22.5	6.2	60	25.9	11.3	0.17	0.89	68%
Baseline 2	407 - 449	17.7	6.9	78	14.1[1]	8.4	0.08	1.05	84%
Period I	83-120	18.9	8.3[2]	77	18.1[1]	10.4±[2]	0.77	-	83%
Period II	278-305	21.7	6.3	77	15.9	7.1±	0.36	0.31±	83%
Period III (a)	352-379	18.9	10.3	87	7.6	11.3±	0.13	0.35±	92%
Period IV (a)	540-679	19.6	5.3	88	8.0	5.6±	0.26	0.22	96%
Period IV (b)	565-590	23.9	4.3	89	7.4	4.2	0.41	0.17	100%

[1] TSS adjusted

[2] Influent COD measurement may have been compromised over this period.

Comparison with other relevant trials

The 'COD efficiency' achieved in Period IV(a), and in particular Period IV(b) provides a 40% to 60% reduction in the carbon requirements compared with operation of the plant without NOB out-selection (Baseline 1), and compared with the published results for the Changi, Strass and HRSD short-cut nitrogen plants.

The significant improvement in the 'COD efficiency' in this trial is likely the product of drawing influent from an anaerobic lagoon, which typically removes 50-70% of the raw influent COD and the significant out-selection of NOB. The lower influent COD:TKN means that there is less excess COD, i.e. COD above the requirement for nitrogen removal. The outcome is that the true potential COD efficiency can be observed, with results to date showing that an influent COD:TKN as low as approximately 3 still was not limiting for nitrogen removal when significant NOB out-selection is achieved. The demonstration plant's most efficient period of operation, Period IV(b), achieved an average 'COD efficiency' of 4.2kgCOD/kgTN removed over a period of 25 days with an average NOB:AOB activity ratio of 0.17.
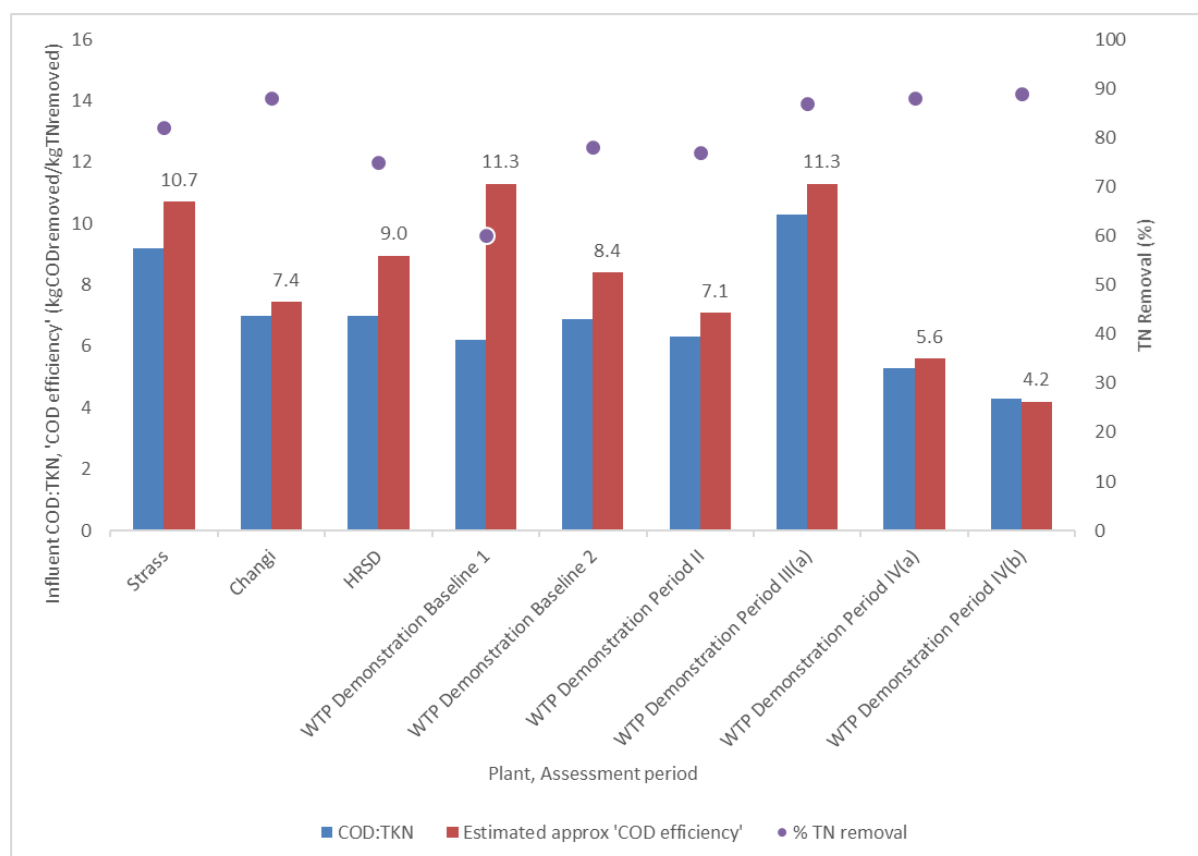

Figure 6: Influent COD:TKN, 'COD efficiency', TN removal (%) for the WTP demonstration plant and comparison shortcut nitrogen removal plants (data from Strass, Changi and HRSD was adapted from Cao et al. 2017))

Effluent TN <10mgN/L achieved

The Demonstration Plant target effluent quality of average <10mgN/L has been achieved over the Period IV(a) with an average influent COD:TKN ratio of 5.3. Effluent TN and the observed NOB:AOB activity rate ratio over the Period IV(a) is trended in Figure 7.
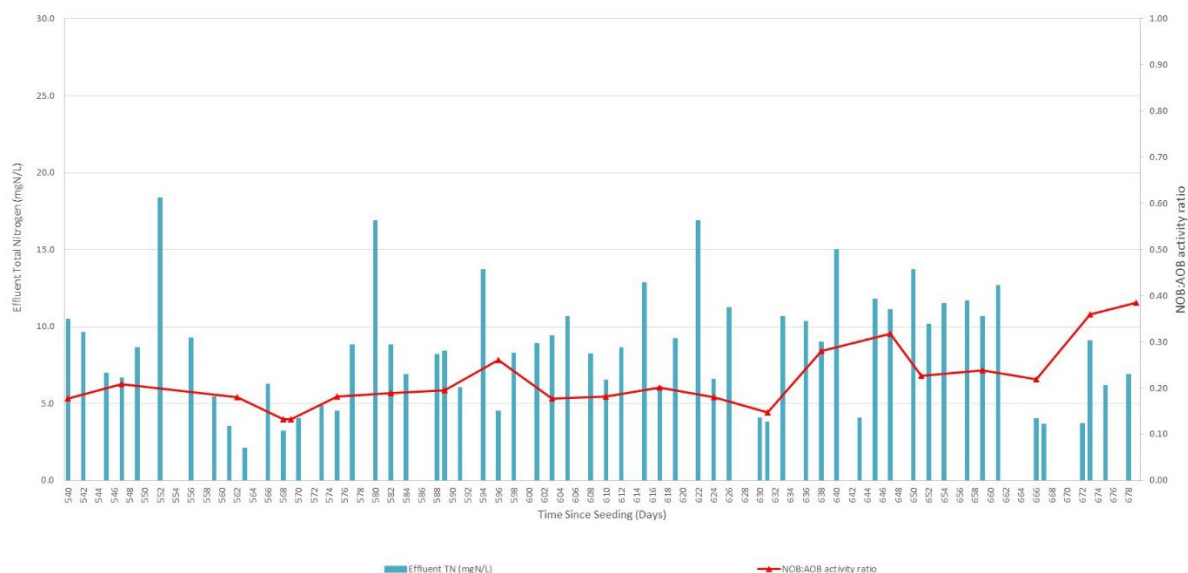

Figure 7: Period IV(a) Effluent Total Nitrogen and NOB:AOB activity rate ratio

Potential Preference for Nitrite Reduction over Nitrate Reduction

During Periods II, III(a) and IV(a) (and to a lesser extent sub-period IV(b)) when SNR tests indicated that NOB had been out-selected to a significant degree, NAR remained low (0.13–0.43) compared to Period I (NAR 0.77+/-0.1). It was hypothesised that a sufficient influent COD:TKN ratio during this period was providing a reasonable degree of denitrification; however, nitrite was being consumed preferentially over nitrate allowing for efficient denitritation. Initial batch testing has indicated that nitrate denitrification is occurring at approximately 66% of the rate of nitrite denitrification, leading to a lower NAR than expected based on NOB:AOB specific nitrification rate tests. This is in line with reported values of 65–85% (Jimenez *et al.*, 2014) and 61% (Turk, 1987).

Biological Phosphorus removal (BioP) observed during periods of sustained NOB out-selection

The EPA discharge licence does not require WTP to achieve total phosphorus (TP) reduction in the treatment process, and therefore the Demonstration Plant was not designed to achieve BioP. Influent and effluent TP has been monitored over the trial period and periods of BioP have been observed concurrent with NOB out-selection.

Figure 8 trends influent TP, Effluent TP, Effluent NOx and Influent COD:TKN over Period IV. Over this period the average NOB:AOB activity ratio observed was 0.24, and intermittent BioP was observed. BioP was observed to occur when influent COD:TKN was above 6.
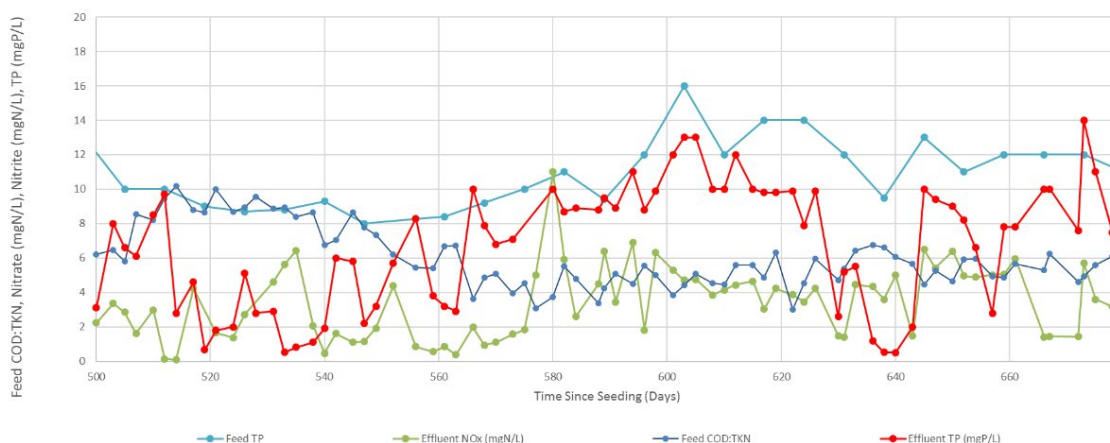
Figure 8: Influent TP, Effluent TP, Effluent NOx, Influent COD:TKN (Period IV: Day 500 to Day 679)

CONCLUSIONS

With global interest in the application of short-cut nitrogen processes in wastewater treatment for improved effluent quality at reduced operating costs, these demonstration trial results provide significant findings from the trial on the carbon efficiency achieved when operating a plant with a material level of NOB out-selection. Over the first 24 months of demonstration plant operation, the trial has observed:

- NOB out-selection (NOB: AOB ratio < 0.5) was maintained at low influent COD:TKN and low temperatures

- Intermittent aeration control was effective for NOB out-selection

- COD requirements for N removal was very low compared to other efficient biological nutrient removal (BNR) systems

- Intermittently aerated A/O process was able to achieve target effluent TN goal of < 10 mg/L at influent C/N ratio of <6

- BioP was observed at influent COD:TKN ratios above 6 with NOB:AOB activity ratio average of 0.24

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