Estimation of nitrification capacity of rock media trickling filters in external nitrification BNR

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Abstract

In the external nitrification (EN) biological nutrient removal (BNR) activated sludge (AS) system, the nitrification process is removed from the BNR activated sludge system and performed 'externally' on an integrated nitrifying trickling filter (NTF). As such, optimum design and operation of the NTF is essential for reliable performance of the ENBNRAS system. Although information on the design and operation of NTFs is available in the literature, this experience is not directly applicable to the NTF in the ENBNRAS system. To address this deficiency, a full-scale ENBNRAS prototype was implemented at the Daspoort Wastewater Treatment Works (DWWTW) in Tshwane, South Africa. In this investigation an average apparent nitrification capacity of approximately 1.25 to 1.29 gN per m^2 of media surface area per day [gN/($ms^2 \cdot d$)] ammonia removal was determined for 2 existing rock media TFs retrofitted as NTFs in the prototype ENBNRAS system (nominal surface area of 45 ms^2/m^3 for the rock media). This nitrification capacity corresponded to a removal efficiency of about 14 mgN/ℓ (96%), or 149 kgN/d, of the influent ammonia load applied to the NTFs (average influent flow rate of 10 Mℓ/d). General concordance was found with corresponding nitrate and nitrite production and alkalinity usage measurements, which substantiated the observed removal performance. This paper details determination of the nitrification capacity of the 2 rock media NTFs used in the prototype ENBNRAS system.

Keywords: full-scale, activated sludge, BNR, nitrification, nitrifying trickling filter

Introduction

In the external nitrification (EN) biological nutrient removal (BNR) activated sludge (AS) system, the nitrification process is removed from the BNR activated sludge system and performed 'externally' on an integrated nitrifying trickling filter (NTF) system (Hu et al., 2000; 2003). As such, optimum design and operation of the NTF system is essential for reliable performance of the ENBNRAS system. Although information on the design and operation of NTFs is well established in the literature (Boller and Gujer, 1986; Lutz et al., 1990; Parker et al., 1989; 1995), this experience is limited to tertiary treatment applications. That is, as an upgrade of conventional wastewater treatment (e.g. activated sludge, aerated lagoon) systems to nitrify the treated effluents to meet ammonia discharge requirements (Lutz et al., 1990). Additionally, NTF design for tertiary treatment typically recommends plastic media, flooding capability for predator control, forced ventilation, continuous dosing and a well clarified secondary treated effluent as influent (Parker et al., 1989;1995). However, ENBNRAS implementation typically is intended as an upgrade or extension of existing facilities, in which case the NTF specifications are pre-existing (e.g. rock media, natural ventilation). Further, NTF performance as an integral unit process within ENBNRAS systems, particularly in combination with an upstream internal settling tank (IST), is lacking. Where such information has been developed, it has been within the area of research investigating the potential for anoxic P-uptake during denitrification (e.g. Wanner et al., 1992; Bortone et al., 1996; Kuba et al., 1996). The main advantage of anoxic P-uptake is purportedly in using the same substrate for both BEPR and denitrification (but comes at a cost to BEPR, Hu et al., 2000). However, by focusing principally on anoxic P-uptake, this body of experience provides little and often inappropriate information regarding the performance dynamics of the attached growth NTF, the IST and the optimum operating and design guidelines for the integrated IST-NTF unit process in full-scale ENBNRAS implementation – all of which are essential for accurate characterisation and overall optimisation of the ENBNRAS system. Particularly lacking is appropriate estimation of the nitrification capacity of the NTFs in the ENBNRAS configuration, which is necessary for optimal specification of the NTFs, related flow streams and process loading rates. To remedy this deficiency, in collaboration between the City of Tshwane and University of Cape Town, a full-scale prototype ENBNRAS system was implemented at the Daspoort Wastewater Treatment Works (DWWTW) in Tshwane, South Africa, in 2003 (Muller et al., 2004). This paper describes determination of the nitrification capacity of the rock media NTFs used in this implementation.

Overview of ENBNR implementation at Daspoort WWTW

Detailed descriptions of the design and implementation of the prototype ENBNRAS system at Daspoort WWTW (DWWTW) are contained in Muller et al. (2004). In brief, DWWTW is located in downtown Pretoria and draws influent wastewater from a main collector sewer at an approximately constant rate. The raw wastewater undergoes screening, grit removal and primary sedimentation in Dortmund-type primary settling tanks (PSTs). The main treatment facilities available for the ENBNRAS implementation are listed in Table 1.

The general design approach was to integrate the trickling filters (TFs) of Modules 5-6 with the BNRAS system in Module 9 in the ENBNRAS configuration (Hu et al., 2000). Modules

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TABLE 1
Summary of the main secondary treatment facilities at Daspoort WWTW

Module	Location in plant	Type of unit process (Number)	Constructed, upgraded	Cap. (Mℓ/d)
1 – 4	Eastern Works	Single bed rock media trickling filters (16)	1913 – 1920	9
5 – 6	Eastern Works	Dual bed rock media trickling filters (4)	1945, 1995	9
9 – 11	Western Works	3-Stage Bardenpho activated sludge (3)	1975, 1988	40

9, 10 and 11 are three parallel BNRAS systems each comprising a series of 9 x 750 m^3 compartments, for a total process volume of 6 750 m^3 per module. Modules 5 and 6 each comprise a pair of dual bed rock media (specific surface area of 45 m_s^2/m^3)* TFs of 21.6 m diameter x 3.7 m height, with 1 284 m^3 of media per TF (Table 2). [**To distinguish between a ‘m^2’ of cross-sectional (or ‘plan’) area, e.g. as usually used to quantify applied hydraulic loadings, and a ‘m^2’ of media specific surface area, e.g. in expressing substrate loading or removal rates, a subscript ‘s’ is used to define ‘ms^2’ for the latter; i.e. for reference to the media specific surface area (A_{ms}).*] In the prototype ENBNR system, the 9 AS compartments of Module 9 were modified as follows (Fig. 1): Compartment 1 partitioned into pre-anoxic and anaerobic (1/3 and 2/3 respectively) zones, Compartments 2 to 3 anaerobic, Compartments 4 to 6 primary anoxic and Compartments 7 to 9 aerobic, with Compartment 7 to be switched to primary anoxic later on in the operation. For the required internal settling tanks (ISTs) between the anaerobic and anoxic reactors, 4 of the 6 Dortmund PSTs serving Modules 9 to 11 were modified for use as ISTs while the remaining 2 were retained for primary settling, to provide a common settled sewage to parallel Modules 9 to 11. A summary of the selected design criteria for ENBNR implementation at Daspoort is listed in Table 2. A process diagram of the implemented system is in Fig. 2, which shows newly installed pumps (P1 to P7) and existing a-recycle (P8) and RAS (P9) pumps in the system.

The ENBNRAS prototype system was started-up on 18th August 2003. Operational implementation generally followed a conservative 3-Phased strategy, summarised in Table 2. Numerous process disruptions occurred during start-up, which required various operational interventions to safeguard overall plant performance. Additionally, several operational modifications were implemented to effect the necessary process conditions of the start-up strategy, including utilisation of only the Module 5 TFs (in parallel), 3 x ISTs and 1 x secondary settling tank (SST). Furthermore, dedicated operational routines and procedures were implemented to develop more detailed process information on the system. The increased monitoring highlighted:

- Ineffective isolation of the anaerobic (AN) reactor
- Accurate flow balancing and pump capacities for optimum process loadings
- The flexibility to balance NTF ammonia loading and wetting rate requirements, as particular problems negatively impacting full optimisation of NTF performance. These issues and related NTF performances are described below.

Operational factors affecting NTF performance

For a comprehensive description of the main operating conditions and full-scale performance of the ENBNR activated sludge system, see Muller et al. (2005; 2006). The aspects specific to operation and performance of the NTFs, and, hence, determination of the maximum nitrification capacity in the Daspoort ENBNR system, are presented here.

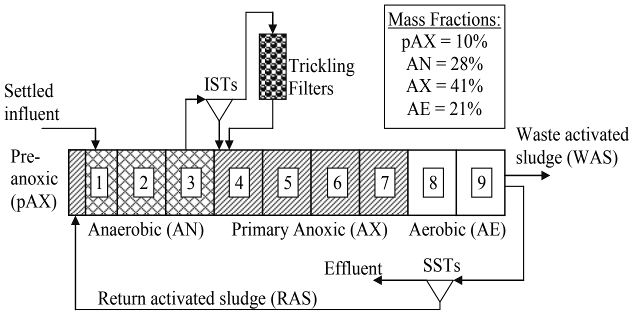
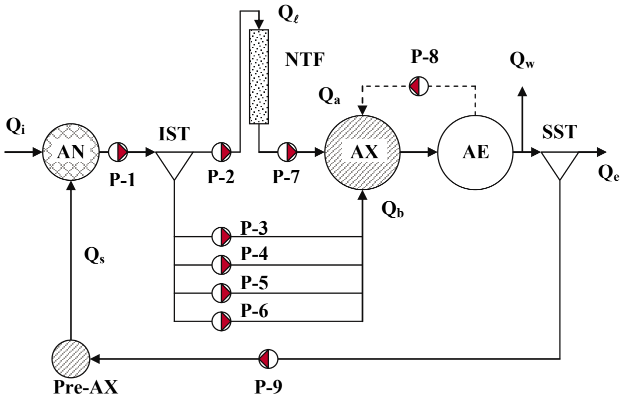


Figure 1
Design configuration of the prototype ENBNR activated sludge system at Daspoort Wastewater Treatment Works, shown with Compartment 7 anoxic



Note: The ◐ symbol denotes a pump.

where:
AN = Anaerobic zone; AX = Anoxic zone;
AE = Aerobic zone; pAX = Pre-anoxic zone
NTF = Nitrifying trickling filter; IST = Internal settling tank;
SST = secondary settling tank; Q = Flowrate;
P = pump, with numbered reference
& Subscripts*:*
i = influent; e = effluent; s = RAS recycle and w = WAS flow ratios respectively
a = internal AE to AX mixed-liquor recycle *(dashed line indicates a temporary condition)*
l = IST ‘liquid’ overflow to NTF; b = IST sludge underflow ‘bypass’ to main AX

Figure 2
Process flow diagram of the prototype external nitrification (EN) BNRAS system implemented at Daspoort Wastewater Treatment Works (Muller et al., 2004)

Ineffective isolation of the anaerobic reactor

Effective isolation of the anaerobic (AN) zone is a fundamental requirement for EN, without which an excessive amount of influent free and saline ammonia (FSA) will bypass the mixed-liquor (ML) withdrawal point in the AN zone (for transfer to the ISTs, see Fig. 1). Hence, this FSA will bypass the NTFs and need to be nitrified in the AS system (as in a conventional BNRAS

TABLE 2
Design criteria (basis: January 2000 – April 2002) selected for full-scale implementation of external nitrification BNRAS at Daspoort WWTW *(*Assumed value)*

Settled Sewage Influent Characteristics	Symbol	Value	Unit
Influent flow rate	Q_i	10	Mℓ/d
COD concentration	S_{ti}	320	mgCOD/ℓ
Unbiodegradable particulate (and soluble) fraction	f_{up} (f_{us})	0.04* (0.10*)	COD/COD
TKN concentration (ammonia concentration)	N_{ti} (N_{ai})	35.8 (19.5)	mgN/ℓ
Nitrifying Trickling Filters (Dual bed, Rock-media Type)			
Number available (per Module)		4 (2)	
Nominal volume per TF (net volume of media per TF, V_{ms})[1]		1928 (1284)[1]	m^3
Rated media specific surface area (A_{ms})		45	m_s^2/m^3
Total (net) media surface area per TF (per Module)[1]		57780 (115560)[1]	m_s^2
Nominal nitrification capacity *(⇒ max allowable N loading)*		1*	$gN/(m_s^2 \cdot d)$
Activated Sludge System:			
Sludge age	R_s	11	d
MLSS concentration	X_t	2.5	gTSS/ℓ
MLVSS/MLSS ratio	f_i	0.85	VSS/TSS
Dilute sludge volume index	DSVI	140	mℓ/g
RAS recycle ratio (s)	s	0.5	s:1 w.r.t. Q_i
System aeration capacity (Compartments 8 + 9)		2 x 45	kW
Start-up criteria Phase I: Qi = 5 Mℓ/d; s = 0.5:1; R_s = 15 d; a-recycle = yes; Basin 7 = AE			
Start-up criteria Phase II: Qi = 10 Mℓ/d; s = 0.5:1; R_s = 10 d; a-recycle = no; Basin 7 = AX			
Start-up criteria Phase III: Qi = 10 Mℓ/d; s = 0.5:1; R_s = 10 d; a-recycle = no; Basin 7 = AX			

Note: [1] Each TF has a centre well ≈ 4.6m in diameter ⇒ the net media cross-sectional area (A_{cs}) of each TF = 347 m^2;
∴ the net media volume = 1 284 m^3 and net media surface area = 45*1 284 = 57 780 m_s^2 per TF.

system). Apparent dilution of the influent FSA had been consistently observed in the AN reactor due to back-flow from the main anoxic (AX) reactor (and indirectly from the aerobic reactor due to the a-recycle) to the AN reactor, mainly through a pre-existing overflow scum-slot connecting Compartmℓents 3 and 4 of Module 9 (see Fig. 1). This resulted in improper loading of the NTFs via the clarified supernatant from the ISTs, which was confirmed by flow balances and comparison of series-samples of FSA along the process stream through the AN reactors. Substantially increased influent flow conditions (from 5.5 to 8.5 Mℓ/d), removal of the a-recycle and structural modifications were subsequently implemented in April to May 2004 to inhibit back-mixing of AX ML from entering the AN reactor. The influent flow was increased further to the design target of 10 Mℓ/d (on 26/7/04), which acted as an additional hydraulic barrier. Follow-up series-sampling confirmed effective isolation of the AN reactor, with FSA concentrations in the IST overflow of about 22 mgN/ℓ (27/7 to 19/10/04) on average. It should be noted however, that this issue is site-specific to the DWWTW system and is unlikely to be encountered in general application of the ENBNR system at other sites.

Flexibility to optimally balance NTF ammonia load with wetting rate

An essential requirement for optimum nitrification performance in the NTFs is correct balancing of the applied ammonia load and media wetting rate (Parker et al., 1989; 1995). In particular, if the ammonia loading is too low then the nitrify growth will be reduced, which will result in uneven distribution of the nitrifiers in the media bed and unreliable nitrification performance. Alternatively, a too high ammonia load may result in exceeding the nitrification capacity of the NTF, giving rise to high ammonia in the NTF effluent. Furthermore, with a too-low media wetting rate, hydraulic short-circuiting will occur in the media bed resulting in the formation of dry-spots and 'patchy' biofilm development, which will promote the proliferation of biofilm predators ('grazers') and unreliable nitrification performance, respectively, to the detriment and potential loss of nitrification in the NTF. In contrast, a too high wetting rate may flood the void spaces in the media bed resulting in 'ponding' of the excess water on the surface of the NTF (a common occurrence with rock media TFs, e.g. Biddle and Wheatley, 1992), which will restrict efficient aeration and oxygen transfer through the media, also detrimental to optimum nitrification performance.

Accordingly, the focus of NTF operation had been initially on maximising the influent loading conditions applied to the NTFs, principally through maximisation of the FSA concentration and flow rate applied to the NTFs. In particular, the number of NTFs in operation was maintained at 2 (only Module 5) despite progressively increasing the settled influent wastewater load to the ENBNR system, i.e. from 5 to 8.5 to 10 Mℓ/d between April to October 2004 (see above). As a result of these loading increases, the average nitrification performance from April to October exhibited maximum ammonia removal rates (subject to inhibition by unintentional biodegradable COD loads due to IST failures) of approximately 0.98 to 1.25 $gN/(m_s^2 \cdot d)$ (~68-83%), which was comparable to optimum performance by purpose-designed plastic media tertiary treatment NTFs (approximately 0.85-1.5 $gN/(m_s^2 \cdot d)$ on average, see Boller and Gujer, 1986; Lutz et al., 1990; Parker et al., 1989; 1995). However, despite this high removal, a maximum 'plateau' did not become evident (Fig. 3, 2004) during this operation (despite relatively consistent influent FSA levels), which indicated relative instability in the performance of the NTFs. Furthermore, the corresponding removal efficiency of ~68-83% meant that ~17-32% of the applied FSA

TABLE 3
Summary of average nitrification performances by the rock media NTFs of Module 5 from April to June and July to October 2004

	Module 5 NTF Loading and Performance		
Parameter	**Jul – Oct 2004**	**Apr – Jun 2004**	**Units**
Applied influent flowrate, Q_{P2}	9.12	9.55	Mℓ/d
Influent FSA concentration, $N_{ai,NTF}$	18.3	17.2	mgN/ℓ
Effluent FSA concentration, $N_{ae,NTF}$	5.85	2.37	mgN/ℓ
FSA removed, $\Delta N_{a,nitrified}$	12.45	14.8	mgN/ℓ
FSA mass loading rate[1]	167	164	kgN/d
Mass FSA Nitrified (as a percentage)	113.5 (68.0)	144.3 (86.2)	kgN/d (%)
Number of NTFs in operation	2	2	Quantity
Hydraulic loading rate[1] *(per NTF)*	13.1 *(13.1)*	13.8 *(13.8)*	$m^3/m^2\,d$
Surface specific loading rate[1] *(per NTF)*	1.44 *(0.72)*	1.42 *(0.71)*	$gN/(m_s^2{\cdot}d)$
Surface specific nitrification rate[1] *(per NTF)*	0.98 *(0.49)*	1.25 *(0.63)*	$gN/(m_s^2{\cdot}d)$

Note: [1] Based on a *net* cross-sectional area (A_{cs}) of 347 m^2 per NTF and a nominal media specific surface area (A_{ms}) of 45 m_s^2/m^3 for the rock media. This gives a net volume of 1 284 m^3 media in each NTF, for a total A_{ms} ($A_{ms,t}$) of 115 560 m_s^2 for the 2 NTFs (Table 2).

load was in excess of the NTFs' nitrification capacity and had to be nitrified in the AS system, adding to the influent bypass load already entering the system via the AN-AX scum-slot. Clearly, the NTFs' nitrification capacity would need to be fully optimised to minimise the ammonia load discharged back to the AS system with the NTF effluent, and thus reduce dependence on the AS system for supplemental nitrification. Therefore, it became necessary to consider optimisation of the NTF ammonia loading and wetting rate requirements independently of each other, and, thus, to optimise overall EN capacity in the NTFs. Hence, the process flexibility for operating the Module 5 trickling filters in series instead of in parallel was investigated and implemented in December 2004.

Implementation of pump capacity upgrades and increased NTF loading rates

Following the review of ENBNR operation in the first year (October 2003 to October 2004), essential recommendations to optimise the system flow balance and NTF loading rates for the design influent condition of 10 Mℓ/d were implemented in December 2004. Specifically, the flow capacities of pumps P1, P2 and P7 were upgraded and the two Module 5 NTFs ('5-East, 5E' and '5-West, 5W' respectively) operated in series, with 5E and 5W configured as primary and secondary NTFs respectively. In this way the design hydraulic load of 15 Mℓ/d (with RAS ratio 0.5:1) applied to the AN reactor was balanced by the system pumping configuration shown in Fig. 2. Additionally, with series configuration of the Module 5 NTFs, the wetting and ammonia loading rates were doubled on 5E (i.e. as primary NTF it received the full P2 discharge flow, ~11 Mℓ/d), while 5W (as secondary NTF it received the effluent from 5E as influent) received double the wetting rate (same flow as the full P2 discharge) but with reduced ammonia loading. A review of the new system configuration in March 2005 indicated no bypass of mixed-liquor through the AN-AX scum-slot and nearly continuous rotation of the NTFs' distributor arms (i.e. maximum dosing frequency) with no ponding – i.e. the increased wetting rate was successfully achieved (Muller et al., 2005). Further, observations of predator prevalence in the NTFs indicated only small snails (i.e. no adults) and very little flies and worms present, in contrast to the previous parallel operation when predators were significant. Several operational problems did occur during this time, however, most notably the successive failure of ISTs 4 and 6 between 10 and 14 February 2005. These failures caused a sudden reduction in the available IST settling surface area (by half), which, together with eventual start-up of the repaired ISTs, resulted in significant ML solids (active biomass) in the IST effluent and subsequent loading on the NTFs, with detrimental impacts on reliable nitrification; highlighting the sensitivity of the NTFs to IST failure in the ENBNR system.

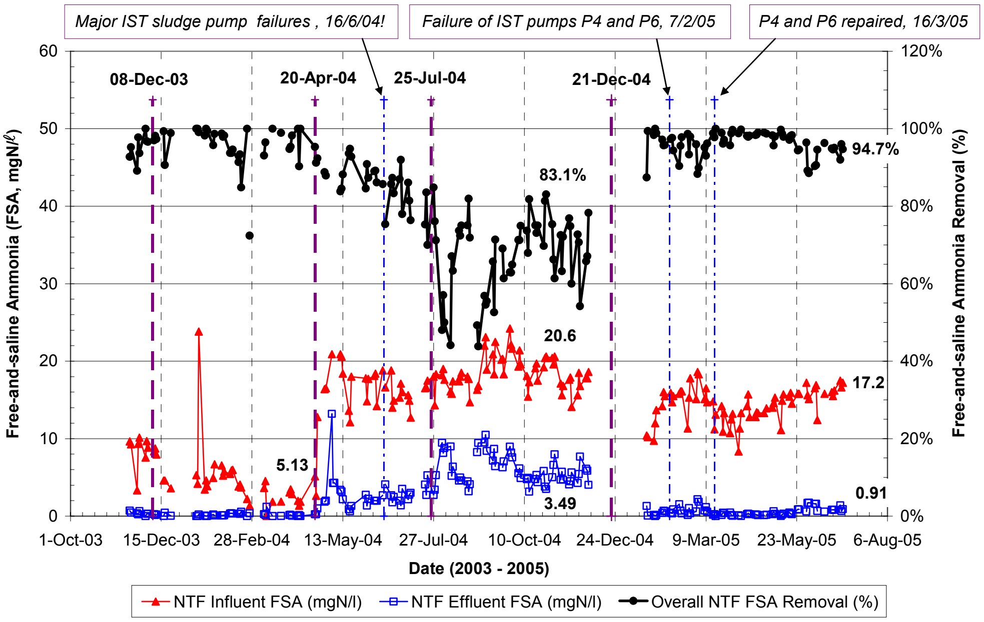
Maximum nitrification efficiency in the rock media NTFs

A detailed performance analysis of the Daspoort ENBNR prototype system is contained in Muller et al. (2006b). This Section presents the performance trends in nitrification efficiency and determination of the nitrification capacity of the 2 (retrofitted) rock media NTFs of Module 5 in the ENBNR configuration.

Initial optimisation of NTF performance (April to October 2004)

The initial nitrification performance exhibited by the rock media NTFs is illustrated graphically in Fig. 3 (April to October 2004) and analyzed in Table 3. In this analysis, process parameters were evaluated within the data set 95% confidence interval, with values lying outside this interval (≈mean ± 1.96*sample standard deviation) rejected as outliers. The abbreviations AVG, SSD and N refer to average, sample standard deviation and number of data, respectively.

The ammonia removal trend for 2003 to 2004 in Fig. 3 shows that although a high ammonia removal efficiency (~95%) was attained in the period prior to the April flow increases (i.e. before 21/4/04), the influent ammonia concentration at that time was very low, around 6 mgN/ℓ. Together with an average discharge rate of 6.77 Mℓ/d measured for P2 (see Fig. 2) at the time, this gave very low mass removal rates for NTF operation from January to March 2004; about 0.33 $gN/(m_s^2{\cdot}d)$ on an


Major IST sludge pump failures , 16/6/04!

Failure of IST pumps P4 and P6, 7/2/05

P4 and P6 repaired, 16/3/05

Figure 3

Ammonia removal trend from November 2003 to August 2005, showing the six-month (January to June 2005) period following series operation on 22 December 2004

average apparent[#] media specific surface area basis (corresponding hydraulic loading rate ~9.76 $m^3/m^2 \cdot d$). [# *Refers to a nitrification rate based on the difference between influent and effluent ammonia concentrations over the entire height of the NTF tower, as opposed to that derived from nitrification profiles taken at intervals down the tower height. That is, in the 'apparent' rate estimation, the ammonia concentration in the effluent may already have been achieved higher up in the media bed, yet the volume of media surface assigned to that nitrification, i.e. used in the calculation, is for the entire tower volume*]. With the increased settled influent flow rate implemented on 21/4/04 (from ~5 to 8.5 Mℓ/d), the influent ammonia concentration applied to the NTFs increased correspondingly, to approximately 16 mgN/ℓ. In response, the trend in nitrification efficiency exhibited a slight decline, presumably due to a low inventory of nitrifiers initially present, from about 95 to 85% over April to June 2004.

The performance analyses in Table 3 indicate that an average of approximately 68% of the influent FSA to Module 5 was nitrified between July and October 2004, for operation at an average applied ammonia loading rate (ALR) of 1.44 $gN/(m_s^2 \cdot d)$ and an average applied hydraulic loading rate (HLR) of 13.1 $m^3/(m^2 \cdot d)$. This removal performance translates into 113.5 kgN/d for the average influent flow-rate of approximately 9.1 Mℓ/d, which gives an average apparent surface specific ammonia removal rate of about 0.98 $gN/(m_s^2 \cdot d)$ for the 2 rock media NTFs. By comparison, this performance was noticeably lower (~22%) than that previously observed from April to June (Table 3), even though the applied loading to the NTFs remained relatively consistent (ALR ~1.4 $gN/(m_s^2 \cdot d)$, HLR ~14 $m^3/(m^2 \cdot d)$). In particular, the average apparent surface specific nitrification rate had decreased from about 1.25 $gN/(m_s^2 \cdot d)$ in April-June to 0.98 $gN/(m_s^2 \cdot d)$ in July-October. However, despite being noticeably lower than before, the apparent nitrification performance in July-October was practically equal to the nitrification capacity of 1 $gN/(m_s^2 \cdot d)$ assumed in the original design evaluation (Table 2), and within the range of optimum performances observed with plastic media NTFs in tertiary treatment (0.85-1.5 $gN/(m_s^2 \cdot d)$, see above). That is, the improved nitrification performance exhibited by the NTFs from April to October 2004 (≈0.98-1.25 $gN/(m_s^2 \cdot d)$) validated the increased ALR achieved on the NTFs with the operational modifications implemented in April and July.

Maximised (external) nitrification performance (January to June 2005)

The effect of series operation of the Module 5 NTFs and the upgraded P1-P2-P7 pump capacities (implemented on 22 December 2004) on maximum nitrification performance by the NTFs, is assessed for the 6-month operating period from January to June 2005 in Fig. 3 and Tables 4 to 5 below. In Fig. 3, the ammonia removal trend indicates a significant improvement in the period from January to June 2005 (as compared to July to October 2004) due to the increased hydraulic and FSA loading rates applied to the NTFs with the series configuration. In particular, the FSA removal efficiency varied between 85 to 100% throughout the 6-month period and, despite deterioration due to successive IST failures in February to March 2005, was generally >94%. The results in Tables 4 and 5 indicate that an average of approximately 14 mgN/ℓ of the influent FSA to Module 5 was nitrified between January-June 2005. This translates into a nitrification efficiency of roughly 96% or, equivalently, about 149 kgN/d for the average influent flow of approximately 10.6 Mℓ/d discharged to Module 5. Overall, this gives an average apparent surface specific nitrification rate of about 1.29 $gN/(m_s^2 \cdot d)$ for the 2 rock media NTFs, which compares well with the average optimum performances attained by plastic media NTFs in tertiary treatment applications (i.e. 0.85-1.5 $gN/(m_s^2 \cdot d)$).

TABLE 4a
NTF influent characteristics for the period 19 January to 30 June 2005

Symbol	Units	AVG	SSD	N	Data Period/Ref.
pH	-	6.89	0.141	65	19/01/05 – 30/06/05
T	°C	22.4	2.33	66	19/01/05 – 30/06/05
COD	mgCOD/ℓ	88.6	40.2	64	19/01/05 – 30/06/05
TSS	mgTSS/ℓ	31.7	32.2	65	19/01/05 – 30/06/05
TKN	mgN/ℓ	19.1	3.6	64	19/01/05 – 30/06/05
Alkalinity	mg/ℓ as $CaCO_3$	205.5	11.8	63	19/01/05 – 30/06/05
FSA	mgN/ℓ	14.6	2.0	65	19/01/05 – 30/06/05

TABLE 4b
NTF 5 East and West effluent concentrations for 19 January to 30 June 2005

Parameter	**Units**	**NTF 5 East (Lead)**			**NTF 5 West (Follow)**		
		AVG	**SSD**	**N**	**AVG**	**SSD**	**N**
pH	-	7.28	0.127	63	7.22	0.138	64
T	°C	22.1	2.5	66	21.85	2.64	66
COD	mgCOD/ℓ	93.9	43.4	63	52.67	17.9	63
TSS	mgTSS/ℓ	39.3	25.2	63	16.7	9.1	61
TKN	mgN/ℓ	10.4	3.67	62	3.66	1.5	64
Alkalinity	mg/ℓ as $CaCO_3$	135.9	13.0	59	98.4	8.8	60
NO_3	mgN/ℓ	9.1	1.55	55	15.43	2.0	58
NO_2	mgN/ℓ	0.34	0.12	55	0.18	0.174	57
FSA	mgN/ℓ	5.73	1.86	62	0.58	0.515	66
Module 9 Effluent	**Units**				**AVG**	**SSD**	**N**
NO_3^-	mgN/ℓ	-	-	-	4.18	1.25	40
NO_2^-	mgN/ℓ	-	-	-	1.35	1.42	40
FSA	mgN/ℓ	-	-	-	0.25	0.36	41

TABLE 5
Average loadings and performance parameters for series operation of the Module 5 NTFs from January to June 2005

	Loading and Performance Parameters for Module 5 in Series		
Parameter	**NTF 5-East (Lead)**	**NTF 5-West (Follow)**	**Units**
Applied influent flow rate (≡ Q_{p2})	10.64	(10.64)	Mℓ/d
Applied hydraulic loading rate[1]	30.66	(30.66)	$m^3/m^2\cdot d$
Influent FSA concentration, $N_{ai,NTF}$	14.6	(5.73)[2]	mgN/ℓ
Effluent FSA concentration, $N_{ae,NTF}$	5.73	0.58[3]	mgN/ℓ
FSA removed, $\Delta N_{a,nitrified}$	8.87	5.15	mgN/ℓ
Total influent FSA loading rate[1]	*14.6*10.64 = 155.3*		*kgN/d*
⇒ overall mass loading rate	*1.34*		*$gN/(m_s^2\cdot d)$*
Total (combined) FSA removed	*8.87+5.15 = 14.02*		*mgN/ℓ*
Overall FSA removal rate (as a %)	*10.64*14.02 = 149.17*	*(96%)*	*kgN/d*
Mass FSA nitrified (as a % of total removal)	94.38 (63.3)	54.80 (36.7)	kgN/d (%)
FSA mass loading rate	155.3	60.97	kgN/d
Surface specific loading rate[1]	2.69	1.06	$gN/(m_s^2\cdot d)$
Surface specific nitrification rate[1]	1.63	0.95	$gN/(m_s^2\cdot d)$

Note: [1] Based on a *net* cross-sectional area (A_{cs}) of 347 m^2 per NTF and a nominal media specific surface area (A_{ms}) of 45 m_s^2/m^3 for the rock media. This gives a net volume of 1284 m^3 media in each NTF, for a total A_{ms} ($A_{ms,t}$) of 115 560 m_s^2 for the 2 NTFs (Table 2).

[2] In series operation, the influent to 5W is the same as the effluent from 5E.

[3] In series operation, the effluent from 5W is the ultimate effluent from the NTF (EN) system discharged to the AS process.

The validity of this nitrification performance (Table 5) by the rock media NTFs is supported by the nearly constant trend in ammonia removal efficiency over the 6-month period (January-June 2005, Fig. 3), and the relatively little variation indicated by the small standard deviations in the sample data (Table 4). Accordingly, the January to June nitrification performance of 1.29 $gN/(m_s^2\cdot d)$ indicates a reliable maximum rate, and therefore characterises the nitrification capacity of the Module 5 NTFs.

Comparing the media specific nitrification rate of 1.29 $gN/(m_s^2\cdot d)$ for January-June 2005 when the two NTFs were operated in series (Table 5) with the values of 0.98to 1.25 $gN/(m_s^2\cdot d)$ for April to October 2004 when the two NTFs were operated in parallel (Table 3), clearly series operation significantly enhanced NTF performance (overall FSA loading rates generally similar, 1.3 ≈ 1.4 $gN/(m_s^2\cdot d)$ respectively). Further, visual inspections indicated that substantially fewer predatory organisms were present with series than with parallel operation, and that the flow distribution across the media was significantly improved. These changes can be ascribed directly to the increased wetting rates with series operation controlling predator proliferation and improving flow distribution, and are in agreement with observations in the literature, as noted above. Thus, changing the NTF operating mode from parallel to series operation provides the means to increase media wetting rates without changing the *overall* ammonia loading rate treated (Table 5, but ammonia loading rates to the *individual* NTFs are changed as noted above), resulting in significantly improved performance.

The assessment of maximised nitrification performance by the rock media NTFs from January to June 2005 is substantiated by the almost constant difference between the influent and effluent FSA trend lines in Fig. 3. In particular, as shown in Fig. 4, this relationship is especially evident in the relatively parallel trajectories of the influent and effluent FSA trends for NTF 5E (the lead NTF). In this plot, the 5E effluent FSA concentration trend generally matches the variation in the 5E influent FSA with an almost constant difference of 8 to 10 mgN/ℓ, which is particularly noticeable in the period after 12 April when the effluent values exhibit consistent increase with the increase in influent FSA.

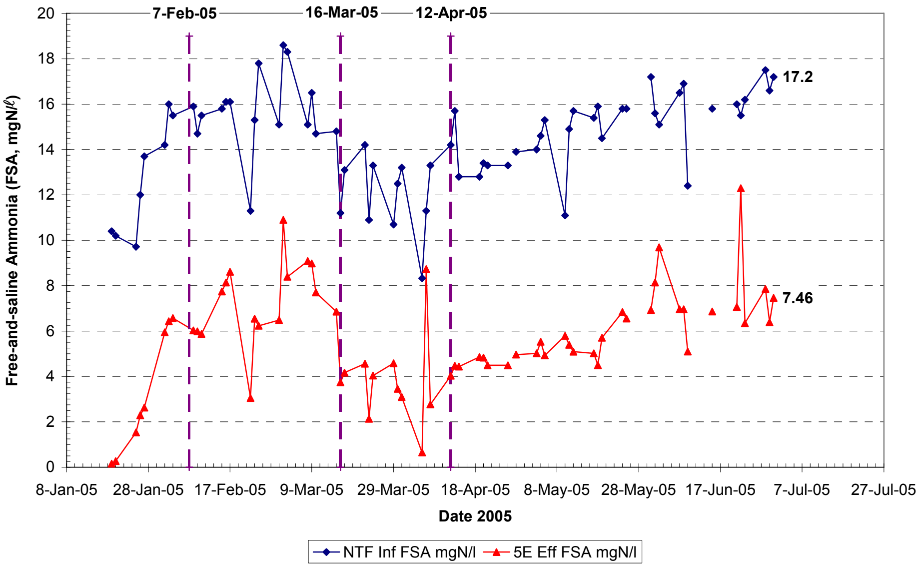


Figure 4

Evidence of maximised ammonia removal performance by the Module 5 NTFs during January to June 2005, indicated by near parallel trajectories of influent and effluent FSA trend lines in NTF 5-East (the lead NTF)

Therefore, on this basis, an average apparent nitrification capacity of approximately 1.25 to 1.29 ($\approx$1.27) gN/(m_s^2·d) can be assessed for the 2 rock media NTFs of Module 5, which is comparable to optimum performances by tertiary treatment NTFs (0.85to 1.5 gN/(m_s^2·d)), and close to the nominal value of 1 gN/(m_s^2·d) assumed in the preliminary design evaluation (Table 2). It should be noted, however, that the applied HLR associated with the maximised performance of the series operated NTFs (Table 5) is significantly lower than the 72-96 m^3/m^2·d recommended by Boller and Gujer (1986) for plastic media NTFs in tertiary treatment, and much less than the optimum $\approx$120 m^3/m^2·d used in studies with ‘biofilm controlled’ (BC)NTFs by Parker et al. (1989, 1995). Yet, despite this inconsistency, the maximum nitrification rate of $\approx$1.27 gN/(m_s^2·d) achieved with the rock media NTFs at Daspoort is comparable with the average optimal performances of 0.85 to 1.5 gN/(m_s^2·d) achieved in these applications. Conversely, however, the ALRs of 1.1 and 2.7 gN/(m_s^2·d) applied to the secondary and primary NTFs respectively during the (maximised) performance are consistent with applied ALRs of 1.24 to 2.45 gN/(m_s^2·d) associated with maximum performances by tertiary treatment NTFs (e.g. Duddles et al., 1974; Parker et al., 1995; 1997). Accordingly, this discrepancy of inconsistent HLR but consistent ALR conditions for optimised NTF performance in ENBNR vs. tertiary treatment applications emphasises that direct extrapolation of NTF experience in tertiary treatment to design and operation of the NTF (typically conventionally designed TFs retrofitted to serve as NTFs) in the ENBNR system should be approached with due care.

Related external nitrification system performances

Nitrate and nitrite production trends in (ultimate) NTF effluent

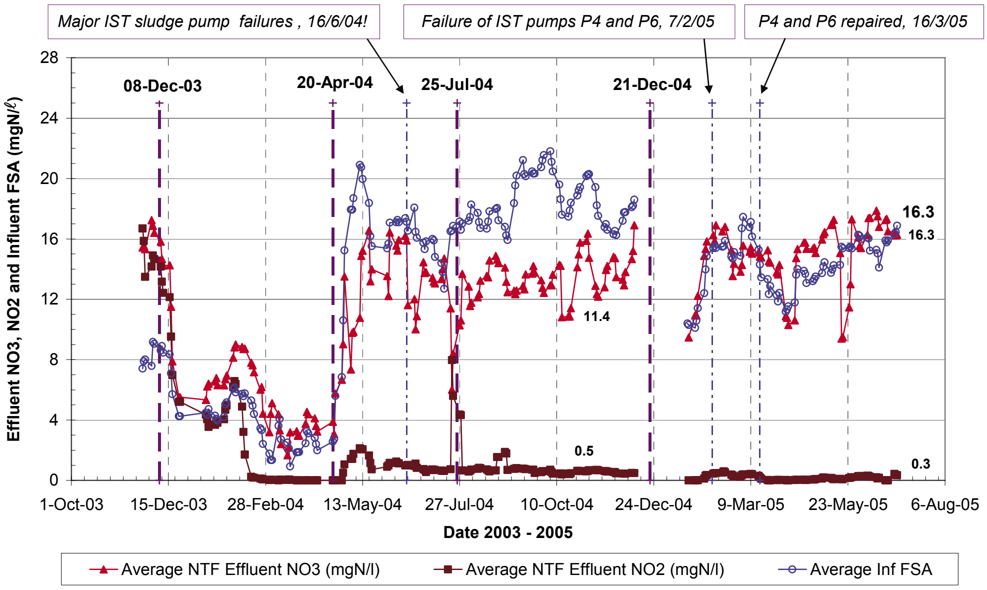
For comparison, the NO_3^- and NO_2^- concentration trends in the effluent from Module 5 are presented together with the NTF influent FSA in Fig. 5. As expected, for the period of maximised nitrification performance (January to June 2005), the trend in effluent NO_3^- closely matches the corresponding influent FSA supporting the near 100% nitrification efficiency observed in Fig. 3 (corresponding NO_2^- levels were negligible throughout). On average, about 15.6 mgN/ℓ NO_3^-+NO_2^- (‘NO_x’) was formed between January to June, which is about 166 kgN/d for the average influent flow of 10.6 Mℓ/d (Tables 4 to 5). This is a difference of ~11% with respect to the average 149.2 kgN/d FSA removal estimated for the period, which indicates a reasonable N balance for the observed ammonia removal.

Average observed alkalinity utilisation

Additionally, the corresponding average alkalinity utilisation was approximately 107.1 mg/ℓ as $CaCO_3$ (Table 4). Accepting that 7.1 mg/ℓ as $CaCO_3$ alkalinity is utilised per mgN/ℓ FSA nitrified (WRC, 1984), this is equivalent to a theoretical nitrification performance of approximately 15.1 mgN/ℓ (or 160.5 kgN/d) for the Module 5 NTFs. By comparison, this is only about 8% more than the average observed ammonia removal of 14 mgN/ℓ and about 3% less than the average observed NO_x production of 15.6 mgN/ℓ. Therefore, together with the 11% difference between the average observed NO_x production and FSA nitrified, the comparison of average observed nitrification with alkalinity usage indicates a good balance for the process data of January to June 2005, which substantiates the maximum rate of 1.25-1.29 ($\approx$1.27) gN/(m_s^2·d) estimated for the 2 rock media NTFs.

Effect of influent COD loading on nitrification efficiency

The average NTF influent COD and TSS concentrations during maximised nitrification performance (January to June 2005) are shown in Table 4. Overall, the difference between average influent and effluent COD values appear contradictory when examining periods of lowered (July to October 2004, Table 3) and optimal (January to June 2005, Table 5) nitrification performances. In particular, the average nitrification efficiency of 68% in July to October corresponded with NTF influent and effluent COD values of 98.7 and 94.8 mgCOD/ℓ respectively, indicating no apparent COD utilisation and hence suggestive of no apparent competitive heterotrophic activity in the NTFs that



Major IST sludge pump failures, 16/6/04!

Failure of IST pumps P4 and P6, 7/2/05

P4 and P6 repaired, 16/3/05

Figure 5

NO_3^- and NO_2^- concentration trends in the effluent from Module 5

would undermine the nitrifiers' efficiency (it was subsequently concluded that the lowered nitrification was mainly due to ineffective media wetting and consequent predator proliferation, Section 3). In contrast, the maximum nitrification efficiency in January-June, achieved with increased wetting and loading rates on the NTFs (hence suppressed predators and improved biofilm control, Parker et al., 1989), corresponded to an apparent COD utilisation of 35.9 mgCOD/ℓ (~40%) in the NTFs (Table 4), yet near complete removal (96%) of the influent ammonia was achieved. Thus, it would appear that the NTFs sustained some measure of heterotrophic activity (COD utilisation) while achieving near complete ammonia removal, and reduced efficiency although heterotrophic activity was negligible.

Conclusion

In conclusion, the ammonia removal performance in the rock media NTFs of the prototype ENBNR system indicated successful enhancement of nitrification efficiency following increased wetting rates applied to the NTFs (with additionally increased FSA loading applied to the lead NTF), by changing from parallel to series operation of the NTFs. This performance corresponded to a maximum removal efficiency of 14 mgN/ℓ (96%) of the applied influent FSA, or 149 kgN/d for the applied influent flow of 10 Mℓ/d, and translates into a media-specific nitrification capacity of approximately 1.29 $gN/(m_s^2 \cdot d)$ (compared to 0.98-1.25 $gN/(m_s^2 \cdot d)$ in parallel operation). This maximum rate compared well with corresponding $NO_3^- + NO_2^-$ production and alkalinity usage measurements, which substantiated the observed performance. Hence, an overall ammonia removal capacity of 1.25-1.29 (≈1.27) $gN/(m_s^2 \cdot d)$ was assessed for the 2 rock media NTFs of the ENBNR prototype system at Daspoort WWTW.

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