Maximum growth and decay rates of autotrophic biomass to simulate nitrogen removal at 10°C with municipal activated sludge plants

J-M Choubert[1]*, A Marquot[2], A-E Stricker[3], S Gillot[1], Y Racault[2] and A Heduit[1]

[1] *CEMAGREF Hydrosystems and Bioprocesses Research Unit, Parc de Tourvoie – BP 44, 92163 Antony Cedex, FRANCE*
[2] *CEMAGREF Networks, Water Treatment and Quality Research Unit, 50 avenue de Verdun, 33612 Cestas, FRANCE*
[3] *Environment Canada, 867 Lakeshore Road – CP 5050, Burlington – Ontario L7R 4A6, CANADA*

Abstract

The present study aims at determining most likely values for the maximum growth rate ($\mu_{A,\max}$) and the endogenous decay rate (b_A) of nitrifiers for activated sludge processes treating municipal wastewater operated at low temperature (10°C).
The work used nitrification rate data measured on 10 full-scale plants and 2 pilot plants fed with domestic sewage. This set of data was combined with a modelling and a theoretical approach. The unified values ($\mu_{A,\max} = 0.45{\cdot}d^{-1}$ and $b_A = 0.13{\cdot}d^{-1}$) were obtained at 10°C for the kinetic parameters of the autotrophic biomass in the SRT range 10 to 50 d. In addition, the factors affecting the expected nitrification rate ($r_{v,\,nit}$) were established by a theoretical approach and confirmed by experimental results. For a given SRT, a linear relationship with the nitrogen volumetric loading rate was shown. The COD/TKN ratio of the influent on the nitrification rate was demonstrated. Finally, an operational tool for the verification of the nitrification rate in the design procedure of activated sludge processes is proposed.

Keywords: nitrification; kinetics; low temperature; autotrophic biomass, maximum growth rate; decay rate

Introduction

Activated sludge functioning with intermittent aeration is the main process used to remove nitrogen from municipal wastewaters in France. The size of the aeration tank is usually determined by the minimum sludge retention time (SRT) at 10°C. The nitrification rate is, however, useful to calculate the duration of oxygen presence required to nitrify a given amount of nitrogen and to reach an ammonia discharge objective. Reported values in the literature at 10°C range between 1.0 to 4.4 mg $N_{nit}{\cdot}gMLVSS^{-1}{\cdot}h^{-1}$ (Palis and Irvine, 1985; Oleszkiewicz and Berquist, 1988; McCartney and Oleszkiewicz, 1990; Burica et al., 1996) due to differences in the organic and the nitrogen loading rates or in the COD/TKN and COD/TSS ratios of the influents (Al-Sa'ed, 1988; Thiem and Alkhatib, 1988). For some time now it is recommended to use nitrification rate values expressed in $mgN_{nitrified}{\cdot}\ell^{-1}{\cdot}h^{-1}$ instead of mg $N_{nit}{\cdot}gMLVSS^{-1}{\cdot}h^{-1}$ that can be determined through modelling.

The Activated Sludge Model No. 1 (ASM_1 (Henze et al., 1987)) has been widely used for about 20 years to assess, predict or optimise the nitrification capacity of biological nutrient removal (BNR) wastewater treatment plants (WWTP). For given influent characteristics and with chosen parameter values for the heterotrophic and the nitrifying biomass, the ASM_1 model calculates the nitrification rates of the mixed liquor, and the nitrogen concentrations in the effluent. However, this tool still requires bioprocess experience and time to be used correctly for design purposes. In particular, the use of validated parameter values for the conditions of the simulations is necessary (e.g. similar sludge retention time (SRT) and/or loading rate). These values are particularly important when the processes are simulated at limiting conditions.

Recent studies have shown that too low a value has been used systematically for the endogenous decay rate of nitrifiers (see default values of $0.04{\cdot}d^{-1}$ at 20°C mentioned in Henze (1987)). This default value requires a specific value for the maximum autotrophic growth rate which depends on the applied SRT (Yuan et al., 1999; Dold, 2002; Lee and Oleszkiewicz, 2002). New values obtained from recent specific batch-test protocols under different sludges at 20°C were stable around $0.19{\cdot}d^{-1}$ (Fillos et al., 2000; Stensel et al., 2002; Dold et al., 2005; Marrs et al., 2004; Lopez et al., 2006). For a temperature of 10°C, very few b_A values can be found in the literature. Nevertheless, as these results come from several different laboratory experiments, the need to integrate these new parameter values has not been clearly demonstrated with on-site data.

The present study aims at determining most likely values for the maximum growth rate and the endogenous decay rate of nitrifiers at low temperature (10°C) for municipal activated sludge processes. The nitrification rate measurements in a pilot plant fed with domestic wastewater, and those from 10 full-scale BNR WWTPs are studied with both ASM_1 simulations and a theoretical approach. A practical design tool is then proposed to predict the maximum nitrification rate which can be expected at 10°C.

Material and methods

Methods for nitrification rate measurements

The maximum nitrification rate ($r_{V,\max\,nit}$, Eq. (1)) expressed in $mgN_{nitrified}{\cdot}\ell^{-1}{\cdot}h^{-1}$, is reached when the dissolved oxygen and the ammonia concentration are high enough compared to the half-saturation coefficients, and when no inhibition conditions are applied. It can be directly measured by a specific experiment in a

---

* To whom all correspondence should be addressed. Current affiliation: Cemagref ; 3 bis quai chauveau – CP 220 ; 69336 Lyon cedex France.
☎ +33 4 72 20 87 87; fax: +33 4 78 47 78 75;
e-mail: jean-marc.choubert@cemagref.fr

Received 29 January 2007; accepted in revised form 12 November 2007.

TABLE 1
Nomenclature of abbreviations and symbols

Abbreviations and symbols		Unit
b_A	Endogenous decay rate of nitrifiers	$\cdot d^{-1}$
$B_v(N)$	Nitrogen volumetric loading rate = daily applied nitrogen mass / volume of biological tanks (aerated + anoxic + anaerobic zones)	$mg\ N\cdot(\ell\cdot d)^{-1}$
$B_v(N_{nitrified})$	Nitrified volumetric loading rate	$mg\ N\cdot(\ell\cdot d)^{-1}$
DO	Dissolved oxygen concentration	$mg\ O_2\cdot\ell^{-1}$
f_{AT}	Fraction of the total sludge contained in biological tanks (intermittently aerated tank + anoxic + anaerobic zones)	%
F/M ratio	Food to micro-organism ratio	$kg\ BOD_5\cdot(kgMLVSS\cdot d)^{-1}$
$K_{O,\ A}$	Oxygen half-saturation coefficient for autotrophic biomass	$mg\ O_2\cdot\ell^{-1}$
$MX_{B,A}$	Mass of nitrifying bacteria	g COD
NPR	Nitrate production rate	$mg\ N_{nit}\cdot(\ell\cdot h)^{-1}$
NO_3-N	Nitrate concentration	$mg\ N\cdot\ell^{-1}$
$r_{v,\ max\ nit}$	Maximum nitrification rate	$mg\ N_{nit}\cdot(\ell\cdot h)^{-1}$
$r_{v,\ nit}$	Actual nitrification rate including oxygen and ammonia limitation	$mg\ N_{nit}.(\ell\cdot h)^{-1}$
SRT	Sludge retention time	days
$X_{B,A}$	Concentration of nitrifying bacteria	$g\ COD\cdot\ell^{-1}$
Y_A	Yield of nitrifying bacteria	$g\ COD_{produced}\cdot g\ N_{nitrified}^{-1}$
$\mu_{A,\ maxi}$	Maximum growth rate of nitrifiers	$\cdot d^{-1}$
φ_{Nnit}	Mass of nitrogen nitrified per day	$g\ N\cdot d^{-1}$
η_{BOD5}	Efficiency of BOD_5 removal	%
η_{TKN}	Efficiency of TKN removal	%

batch reactor, or estimated on-site by a mass balance on nitrogen species of daily flow proportional composite samples:

- ***Batch test reactor***

The maximum nitrification rate is measured on sludge under non-limiting conditions: initial $[NH_4\text{-}N]$ over 15 $mgN\cdot\ell^{-1}$, DO over 4 $mgO_2\cdot\ell^{-1}$. pH is monitored to be in the range 7 to 8 (see Fig. 1). In the mixed liquor, the nitrate concentration is measured every 10 min for 1 h. The slope of nitrate build-up (nitrate production rate: NPR) gives the maximum nitrification rate defined in Eq. (1):

$$r_{v,\max nit} = NPR = \frac{d[NO_3 - N]}{dt} = \frac{\mu_{A,\max}.X_{B,A}}{24.Y_A} \qquad (1)$$

- ***Nitrogen mass balance***

The maximum nitrification rate is estimated from the concentrations in TKN, NH_4-N, NO_3-N, COD of the influent and the effluent (daily flow proportional composite samples). These parameters were obtained from European (NF EN) or international (ISO) standardised analysis techniques: TKN (NF EN 256-63, mineralisation), NH_4-N and NO_3-N (ISO/TC147/2/NG/n 86, spectrophotometry), COD (NF T 90-101, mineralisation), TSS and MLTSS (NF EN 872, filtration).

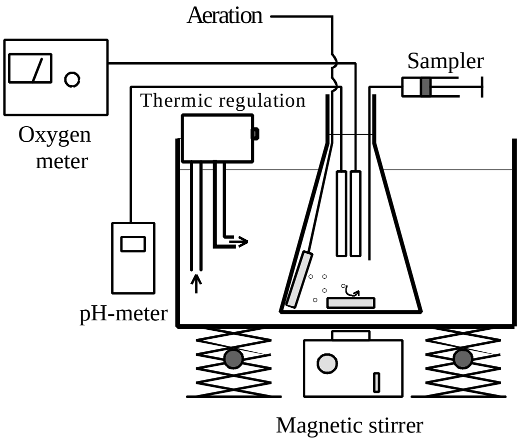

Figure 1
Diagram of the batch reactor

Considering that the assimilated nitrogen mass (φ_{Assim}) represents 5% of the removed BOD_5 mass (Henze et al., 1996), the amount of nitrogen nitrified ($\varphi_{Nitrified}$) during a 24 h period is obtained from the input TKN load (φ_{In}) and discharge (φ_{Out}). The actual nitrification rate is deduced dividing $\varphi_{Nitrified}$ by the aerobic time (Δt) and the volume of the aeration tank (V) as shown in Eq. (2):

$$r_{V,nit} = \frac{\varphi_{In} - \varphi_{Out} - \varphi_{Assim}}{\Delta t.V} \qquad (2)$$

When the ammonia concentration is above 5 mg $N\cdot\ell^{-1}$ in the effluent and DO is above 3 $mg\cdot\ell^{-1}$, the obtained value is close to the maximum rate (Choubert and Racault, 2000). For ammonia concentration below 5 mg $N\cdot\ell^{-1}$ in the effluent, the result obtained is approximately 1.5 times lower than the maximum rate (Oleszkiewicz and Berquist, 1988). The use of the Monod function and half-saturation constant (K_{NH} = 1 mg $N\cdot\ell^{-1}$) is necessary to obtain the maximum nitrification rate.

Nitrification rates database

Nitrification rate measurements have been performed on pilot plants and on full-scale WWTPs:

- ***Data from targeted pilot-plant experiment***

The pilot plant consisted of a 115 ℓ tank that was completely mixed and intermittently aerated (9 $cycles\cdot d^{-1}$). It was connected to a 45 ℓ clarifier with a scraper, and a sludge recycling loop. The devices were controlled by a timer switch and operated in a temperature-controlled room at 10°C. Domestic sewage was collected three times per week at a municipal WWTP and kept at 4°C. As it was sampled at 10:00 am which corresponds to the daily nitrogen peak load at the full-scale WWTP, the COD/TKN ratio of the influent was about 6.5. However, typical COD/TKN values for a daily influent composite sample are usually closer to 10.6 (Pons et al., 2004).

Two 6-month experiments were carried out with:

1st series: Three predefined organic loading rate stages from F/M = 0.09 to 0.14 kg BOD_5kg $MLVSS^{-1}\cdot d^{-1}$ applied for 6 weeks. The corresponding volumetric nitrogen loading rate (B_v(N)) was in the range 160 to 220 $mgN\cdot \ell^{-1}\cdot d^{-1}$ and the SRT from 15 to 10 d. To calibrate the ASM_1, two detailed sampling procedures were carried out in the aeration tank of the pilot plant to monitor the nitrogen concentrations every 10 min for three on/off aeration cycles over 8 h (Choubert et al., 2005);

2nd series: The plant was stabilised at an average organic loading rate of 0.07 kg BOD_5.kg$MLVSS^{-1}\cdot d^{-1}$ with a 20 d SRT. Different nitrogen volumetric loading rates were applied from 30 to 140 $mgN\cdot \ell^{-1}\cdot d^{-1}$. The nitrification rates were estimated with the nitrogen mass balance method.

- ***Data from full-scale WWTPs***

Ten French BNR WWTPs, designed to nitrify and denitrify sludge in the same tank with intermittent aeration, were investigated in winter (10 ± 2°C). They are: *Benfeld, Bavilliers, Cestas, Changis sur marne, Fontenay Tressigny, Hautot sur mer, Larchant, Meaux, Ménuires, Mouthe*. These WWTPs were operated at a volumetric nitrogen loading (B_v(N)) in the range 10 to 110 $mgN\cdot \ell^{-1}\cdot d^{-1}$, and SRT = 50 to 20 d, and they received municipal wastewaters (COD/TKN ratio of 10.5 ± 2.1), with a very low proportion of industrial effluent. For each plant, nitrification rates were obtained mainly from nitrogen mass balance.

Theoretical expression of nitrification rate

To determine the prevailing parameters of nitrification rates in an activated sludge process, a theoretical approach was followed. The relation obtained was used to examine the nitrification rates database.

The amount of autotrophic biomass kept in an activated sludge system results from their specific net growth ($\Delta MX_{B,A}/MX_{B,A}$) during the duration "Δt". Equation (1) (Nowak et al., 1994) expresses the difference between the mass of bacteria produced by nitrification ($Y_A.\varphi_{Nnit}$) and the mass lost by decay ($b_A.\Delta t$) and by sludge wastage (Δt/SRT):

$$\frac{\Delta MX_{B,A}}{MX_{B,A}}(t) = \left[\frac{Y_A.\varphi_{Nnit}}{MX_{B,A}} - \left(b_A + \frac{1}{SRT}\right)\right].\Delta t \qquad (3)$$

For steady-state conditions ($\Delta MX_{B,A} = 0$), Eq. (3) gives the mass of nitrifiers ($MX_{B,A}$ [g COD]) contained in a WWTP shown in Eq. (4). Using the fraction (f_{AT}) of the total sludge contained in the biological reactors (intermittently aerated + anoxic + anaerobic zones + clarifier), and the volumetric nitrogen loading nitrified ($B_v(N_{nitrified})$), the mass of nitrifiers ($MX_{B,A}$) can be converted into their concentration ($X_{B,A}$ [mg $COD\cdot \ell^{-1}$]) in the biological reactor (Eq. (5)).

$$MX_{B,A} = \frac{Y_A}{b_A + \frac{1}{SRT}}.\varphi_{Nnit} \qquad (4)$$

$$X_{B,A} = f_{AT}.\frac{Y_A}{b_A + \frac{1}{SRT}}.B_v(N_{nitrified}) \qquad (5)$$

Considering η_{TKN} and η_{BOD5}, the efficiencies of TKN and BOD_5 removal, then the fraction of nitrogen available for nitrification (λ) is defined as Eq. (6):

$$\lambda = \frac{B_v(N_{nitrified})}{B_v(N)}$$

$$= \eta_{TKN} - 5\% . \eta_{BOD_5} . \frac{[COD]_{influent}}{[TKN]_{influent}} . \frac{[BOD_5]_{influent}}{[COD]_{influent}} \qquad (6)$$

From Eqs. (5) and (6) the maximum nitrification rate $r_{V,\ max\ nit}$ in $mgN_{nitrified}\cdot \ell^{-1}\cdot h^{-1}$ as a function of λ, f_{AT}, SRT, $\mu_{A,\ max}$, b_A, B_v(N) is expressed in Eq. (7):

$$r_{v,\ max\ nit} = \frac{\mu_{A,\ max}.X_{B,A}}{24.Y_A} = \lambda.\frac{f_{AT}}{24}.\frac{\mu_{A,\ max}}{b_A + \frac{1}{SRT}}.B_v(N) \qquad (7)$$

For a given SRT, Eq. (7) expresses a linear relationship between $r_{v,\ max\ nit}$ and B_v(N). It also demonstrates that SRT influences the value of $r_{v,\ max\ nit}$. Taking into account the oxygen limitation with a Monod type equation, the expression of the actual nitrification rate ($r_{v,\ nit}$) in the reactor becomes:

$$\boxed{r_{v,\ nit} = \frac{\mu_{A,\ maxi}.X_{B,A}}{24.Y_A}.\frac{DO}{DO + K_{O,A}} = \lambda.\frac{f_{AT}}{24}.\frac{\mu_{A,\ maxi}}{b_A + \frac{1}{SRT}}.\frac{DO}{DO + K_{O,A}}.B_v(N)} \qquad (8)$$

The operating conditions [SRT and B_v(N)] of the 10 WWTPs of the database were used to calculate the corresponding $r_{v,\ nit}$ with Eq. (8). The following values were considered: $K_{O,A}$ = 0.4 mg $O_2\cdot \ell^{-1}$ (Henze et al., 1987), DO = 3 mg $O_2\cdot \ell^{-1}$ (concentration when aeration is on), f_{AT} = 85 ± 10% estimated values with current values operating conditions like COD/BOD_5 = 2.5 ± 0.3, η_{TKN} = 97%, η_{BOD5} = 99%, COD/TKN ratio of the influent (λ = 0.76 ± 0.05 if COD/TKN = 10.5 ; λ = 0.85 ± 0.05 for COD/TKN = 6), 4 ± 1 g $MLSS\cdot \ell^{-1}$ for the sludge concentration in the aeration tank with 70 ± 5% for VSS fraction.

Results

The nitrification rate database has been analysed with both ASM_1 simulations and Eq. (8) (theoretical approach) to determine the more relevant value of maximum growth rate ($\mu_{A,\ max}$) and endogenous decay rate (b_A) of nitrifiers at 10°C. Figure 2 illustrates the calibration and on-site validation strategies.

ASM_1 has been calibrated on the data of the detailed sampling carried out during the 1st series of pilot-plant experiment. Most default parameter values proposed by Henze (1987) have been used. Only 2 parameters have been modified: the maxi-

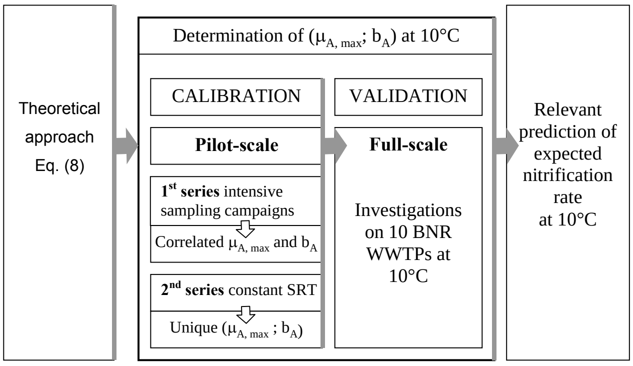

Figure 2
Applied strategy to determine $\mu_{A,\ max}$ and b_A at 10°C from both pilot- and full-scale data

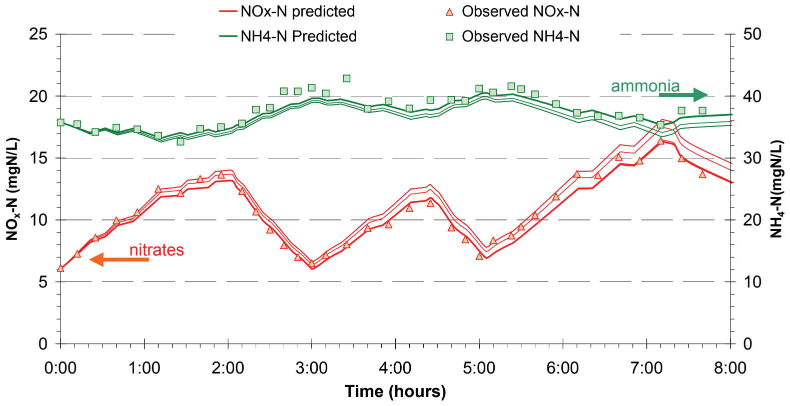

Figure 3
Pilot plant, 1st series, with high NH_4-N

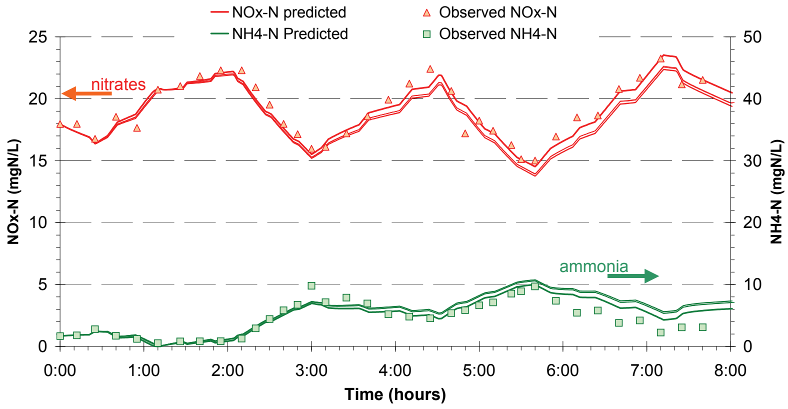

Figure 4
Pilot plant, 1st series, with low NH_4-N

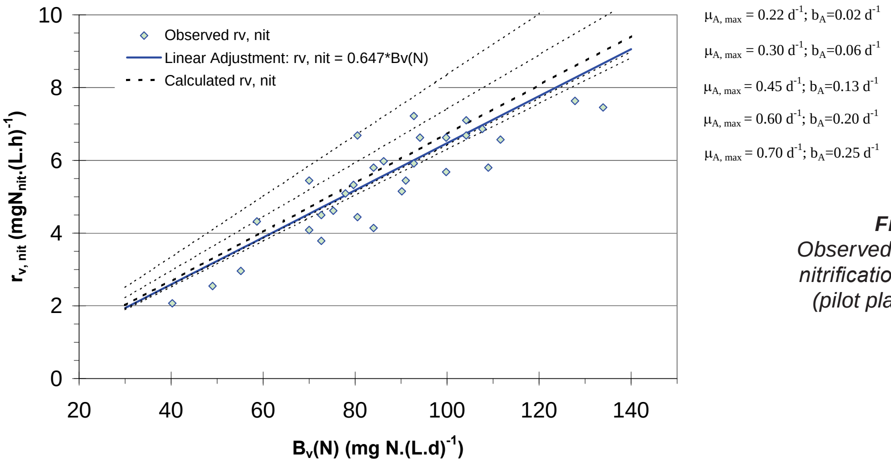

Figure 5
Observed and calculated nitrification rates at 10°C (pilot plant, 2nd series)

mum autotrophic growth rate ($\mu_{A,\ max}$) and the decay rate (b_A) of the autotrophic bacteria. With high ammonia concentration in the effluent (Fig. 3) and with low ammonia concentration (Fig. 4), the fit between observed and simulated concentrations could be obtained for several pairs ($\mu_{A,\ max}$; b_A) = (0.22 ; 0.02) or (0.30 ; 0.06) or (0.45 ; 0.13) or (0.60 ; 0.20) or (0.7 ; 0.25) (simulated ammonia and nitrates curves are represented for each pair). The following continuous linear relationship has been adjusted on these five pairs: "b_A [d^{-1}] = 0.47*$\mu_{A,max}$ - 0.08" (r^2 = 1).

With $\mu_{A,\ max}$ = 0.22·d^{-1} and b_A = 0.02·d^{-1}, Eq. (8) provides relevant calculated nitrification rate (7.5 mgN_{nit}·ℓ$^{-1}$·h^{-1} vs. 7.3 mgN_{nit}·ℓ$^{-1}$·h^{-1} at B_v(N) = 130 mgN·ℓ$^{-1}$·d^{-1} and SRT = 17 d) (1st series). Nevertheless, for higher SRT, the calculated value is overestimated by 250% due to the too low b_A value (4.7 mgN·ℓ$^{-1}$·h^{-1} at B_v(N) = 30 mgN·ℓ$^{-1}$·d^{-1} and SRT = 42 d) (Dold, 2002).

To obtain the most likely pair for ($\mu_{A,\ max}$; b_A), the results of the 2nd series were studied (SRT = 20 d). The calculated values (Eq. (8)) obtained with the 5 previous pairs ($\mu_{A,\ max}$; b_A) were compared to the linear relation ($r_{v,\ nit}$ = 0.647 * B_v(N), r^2 = 0.77) obtained with adjustments on observed nitrification rates. Figure 5 represents the calculated and the observed nitrification rates (with the corresponding linear adjustment) as a function of B_v(N) in the range 30 to 140 mgN·ℓ$^{-1}$·d^{-1} for the given SRT = 20 d.

The simultaneous increase in $\mu_{A,\ max}$ and b_A reduces the difference between the observed and the calculated nitrification rates: the pairs ($\mu_{A,\ max}$; b_A) = (0.22·d^{-1}; 0.02·d^{-1}) and (0.30 d^{-1}; 0.06·d^{-1}) overestimate nitrification rate by 25 and 15% respectively. For ($\mu_{A,\ max}$ = 0.45·d^{-1}; b_A = 0.13·d^{-1}), the difference with the linear adjustment is approximately 3%. Above those values [for pairs (0.60·d^{-1}; 0.20 ·d^{-1}) or (0.7·d^{-1}; 0.25·d^{-1})], the calculated

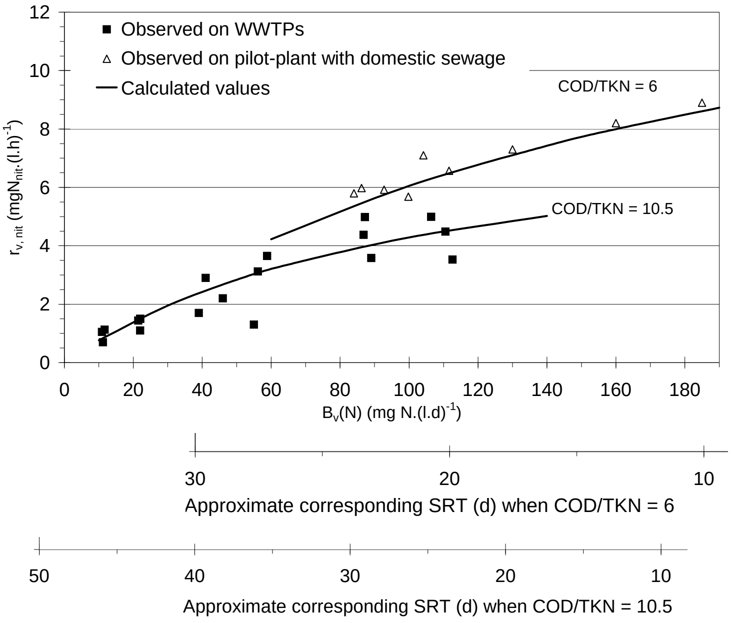

Figure 6
Observed and calculated nitrification rates as a function of the nitrogen volumetric loading rate and the influent COD/TKN ratio (for each B_v(N) corresponds to a particular SRT)

nitrification rates are lower than those of the observed value, and the difference does not significantly decrease.

The values ($\mu_{A,\,max}$ = 0.45·d^{-1} ; b_A = 0.13·d^{-1}) obtained from the continuous flow reactors are in agreement with the ones proposed from batch tests at 20°C corrected with temperature coefficients, 1.072 for $\mu_{A,max}$ and 1.029 for b_A (Stensel et al., 2002). They are slightly lower than the ones proposed by Orhon (2000) obtained for tannery wastewaters.

Considering the batch test values ($\mu_{A,\,max}$ = 0.93·d^{-1}; b_A = 0.17·d^{-1}) from (Jones et al., 2002; Dold et al., 2002), the expected batch test values at 10°C would be: $\mu_{A,max}$(10°C) = 0.93 * 1.072^{-10} = 0.464·d^{-1} and b_A(10°C) = 0.17 * 1.029^{-10} = 0.128·d^{-1}.

Discussion

To validate at full-scale plant level the values of $\mu_{A,\,max}$ and b_A obtained from the pilot-plant experiments, the theoretical nitrification rates (Eq. (8)) were compared to the values observed on full-scale plants (database). All operating conditions of nitrogen loading rate [Bv(N)] and sludge retention time [SRT] were considered. The results are presented in Fig. 6 as a function of the volumetric nitrogen loading rate (B_v(N)) and the corresponding SRT for a usual domestic influent (i.e. COD/TKN ratio = 10.5) and for a nitrogen-enriched influent (COD/TKN ratio = 6 obtained for the influent used with pilot-plants sampled at 10:00 am which corresponds to the specific daily nitrogen peak load at full-scale WWTP).

Three main conclusions can be drawn from the results presented in Fig. 6:

- At 10°C and for two different COD/TKN ratios, the values ($\mu_{A,\,max}$ = 0.45·d^{-1}; b_A = 0.13·d^{-1}) for autotrophic biomass characteristics reconcile the observed and the calculated nitrification rates for B_v(N) from 10 to 180 mgN·ℓ$^{-1}$·d^{-1} and SRT from 50 to 10 d. With these values, Eq. (8) becomes a relevant verification tool for the design of activated sludge plants operated under low loading rates and with intermittent aeration. The domain of validity is wide and corresponds to the current operating conditions of the activated sludge process for which nitrogen removal is expected.
- The COD/TKN ratio of the influent has a major effect on the value of the maximal nitrification rate. When COD/TKN = 6 (pilot experimental study), $r_{v,\,nit}$ reaches 9 mgN$_{nit}$· ·ℓ$^{-1}$·h^{-1} whereas when COD/TKN = 10.5 (common value for daily composite sample) $r_{v,\,nit}$ is 4 mgN$_{nit}$·ℓ$^{-1}$·h^{-1}. Converted in mg N$_{nit}$·gMLVSS^{-1}·h^{-1} (2.8 and 1.3 mg N$_{nit}$·gMLVSS^{-1}·h^{-1} respectively), the rates observed in this study are in accordance with the literature data reported at 10°C (Palis and Irvine, 1985; McCartney and Oleszkiewicz, 1990): 1 and 4 mg N$_{nit}$·gMLVSS^{-1}.h^{-1} with COD/TKN of 12 and 2 respectively.
- Compared to the linear increase shown in Fig. 5 which has been recorded with a fixed SRT, the actual increase in the maximum nitrification rate is not proportional to the volumetric loading rate when the SRT decreases (Fig. 6). There is an attenuation resulting from the decrease of the mass of nitrifiers when the carbon and the nitrogen loading rates are simultaneously increased (SRT decreases when Bv(N) increases);
- The expected nitrification rate is 1.5 mgN$_{nit}$·ℓ$^{-1}$·h^{-1} for B_v(N) below 20 mgN·ℓ $^{-1}$·d^{-1}. For B_v(N) in the range 20 to 50 mgN·ℓ $^{-1}$·d^{-1}, $r_{v,\,nit}$ increases from 2 to 4 mgN$_{nit}$·ℓ$^{-1}$·h^{-1} for both COD/TKN value of the influent. Above 50 mgN·ℓ$^{-1}$·d^{-1}, the expected nitrification rate depends on the COD/TKN value of the influent.

Conclusions

The parameters prevailing on nitrification capacity of activated sludge plants have been investigated at 10°C from full-scale measurements and long-term pilot-scale experiments.

This study has confirmed that a large number of combinations can be used for the autotrophic biomass parameters ($\mu_{A,\,max}$; b_A) to simulate the concentration of the nitrogen species in an aeration tank. But, only one provides a correct fit with nitrification rate for a wide domain of validity of SRT and nitrogen loading rate conditions. The unique pair at 10°C is ($\mu_{A,\,max}$ = 0.45·d^{-1}; b_A = 0.13·d^{-1}). These values obtained on continuous reactors confirm those reported in the literature with batch-test procedures.

The maximum nitrification rate is demonstrated to be proportional to the nitrogen volumetric loading rate when the SRT is constant. The operating conditions such as the COD/TKN ratio of the influent and the sludge retention time are also shown to determine the value of the maximum nitrification rate. With a typical domestic influent (COD/TKN = 10.5), the $r_{v,\,nit}$ at 10°C increases from 1 to 5 $mgN_{nit}\cdot\ell^{-1}\cdot h^{-1}$ when $B_v(N)$ increases from 10 to 140, whereas for nitrogen-enriched influent (COD/TKN = 6), $r_{v,\,nit}$ reaches 9 $mgN_{nit}\cdot\ell^{-1}\cdot h^{-1}$.

Acknowledgements

This research was financially supported by the French Agriculture Ministry (FNDAE fund). The authors would like to thank the technical Cemagref staff for investigating the 10 WWTPs. A. Marquot is now at WTSim in Pessac City (FRANCE).

References

AL-SA'ED R (1988) Investigations on nitrification of ammonia rich wastewater in activated sludge systems. *Water Supply* **6** 235-242.

BURICA O, STRAZAR M and MAHNE I (1996) Nitrogen removal from wastewater in a pilot plant operated in the recirculation anoxic-oxic activated sludge mode. *Water Sci. Technol.* **33** (12) 255-258.

CHOUBERT JM and RACAULT Y (2000) Assessment of the evolution of nitrification capacity in activated sludge process. *Proc. 1st World Water Congress of the International Water Association (IWA)* (ISBN: 2-9515416-0-0). 3-7 Jul 2000, Paris (France). 1-4.

CHOUBERT JM, RACAULT Y, GRASMICK A, BECK C AND HEDUIT A (2005) Nitrogen removal from urban wastewater by activated sludge process operated over the conventional carbon loading rate limit at low temperature. *Water SA* **31** (4) 503-510.

DOLD PL (2002) Importance of decay rate in assessing nitrification kinetics. *Proc. Weftec 2002, 76th Annual Conference & Exhibition.* 11-15 Oct 2003, Los Angeles, California (USA). 1-21.

DOLD PL, JONES RM and BYE CM (2005) Importance and measurement of decay rate when assessing nitrification kinetics. *Water Sci. Technol.* **52** (10-11) 469-477.

FILLOS J, KATEHIS D, RAMALINGAM K, CARRIO LA and GOPALAKRISHNAN K (2000) Determination of nitrifier growth rates in NYC water pollution control plants. *Proc. Weftec 2000, 73th Annual Conference & Exhibition.* Date? Anaheim, California (USA).pp 1-17.

HENZE M, GRADY CPL, GUJER W, MARAIS GVR and MATSUO T (1987) *Activated Sludge Model N°1, IAWQ Scientific and Technical report.* N°1, IAWPRC, London. ISSN: 1010-707X 1-33.

HENZE M, HARREMOËS P, LA COUR JANSEN J AND ARVIN A (1996) *Wastewater Treatment. Biological and Chemical Processes.* Springer Verlag, Berlin (Germany). 383 pp.

JONES RM, BYE CM and DOLD PL (2004) Nitrification parameter measurement for plant design-experience and experimental issues with new method. *Proc. 4th IWA World Water Congress and Exhibition.* Dates? Marrakech (Morocco). 1-8.

LEE Y and OLESZKIEWICZ JA (2002) Evaluation of maximum growth and decay rates of autotrophs under different physical and environmental conditions. *Proc. Weftec 2002, 76th Annual Conference & Exhibition.* date? Los Angeles, California (USA). 1-16.

MARRS D, NEWMAN J, SEN S, BOSWELL N, LUBARSKY M and MELCER H (2004) Field application of WERF low F/M protocol to measure nitrifier growth and endogenous decay. *Proc. Weftec 2004.* date? New Orleans, Louisiana (USA). 1-28.

McCARTNEY DM and OLESZKIEWICZ JA (1990) Carbon and nutrient removal in a sequencing batch reactor at low temperatures. *Environ. Technol.* **11** 99-112.

LOPEZ C, PONS MN and MORGENROTH E (2006) Endogenous processes during long-term starvation in activated sludge performing enhanced biological phosphorus removal. *Water Res.* **40** (8) 1519-1530.

NOWAK O, SCHWEIGHOFER P and SVARDAL K (1994) Nitrification inhibition – A method for the estimation of actual maximum autotrophic growth rates in activated sludge systems. *Water Sci. Technol.* **30** (6) 9-19.

OLESZKIEWICZ JA and BERQUIST SA (1988) Low temperature nitrogen removal in sequencing batch reactors. *Water Res.* **22** (9) 1163-1171.

ORHON O, GENCELI EA and SÖZEN S (2000) Experimental evaluation of the nitrification kinetics for tannery wastewaters. *Water SA* **26** (1) 43-50.

PALIS JC and IRVINE RL (1985) Nitrogen removal in a low-loaded single tank sequencing batch reactor. *JWPCF* **57** (1) 82-86.

PONS MN, SPANJERS H, BAETENS D, NOWAK O, GILLOT S, NOUWEN J and SCHUTTINGA N (2004) Wastewater characteristics in Europe - A survey. European Manager Management [online]. Official Publication of the *European Water Association (EWA)* **4** 1-10.

STENSEL HD, KE DL, DOLD PL, JONES R, BYE C and MELCER H (2002) Methods for measuring nitrifier maximum specific growth rate: crucial for plant capacity rating. *Proc. Weftec 2002, 76th Annual Conference & Exhibition.* 11-15 Oct 2003, Los Angeles, California (USA) 1-25.

THIEM LT and ALKHATIB EA (1988) *In situ* adaptation of activated sludge by shock loading to enhance treatment of high ammonia content petrochemical wastewater. *JWPCF* **60** (7) 1245-1252.

YUAN Z, BOGAERT H, DEVISSCHER M, VANROLLEGHEM P, VAN LOOSDRECHT MCM and VERSTRAETE W (1999) On-line estimation of the maximum specific growth rate of nitrifiers in activated sludge systems. *Biotechnol. Bioeng.* **65** (3) 265-273.