Nitrification in biofilters under variable load and low temperature

J.-P. Canler*, J.-M. Perret*, F. Lengrand* and A. Iwema**

* Cemagref, 3 bis, quai Chauveau, CP 220, 69 336 Lyon Cedex 09, France

** Agence de l'Eau Rhône Méditerranée Corse, 2-4, Allée de Lodz, 69 363 Lyon Cedex 07, France

Abstract The evolution of European legislation has led to the rehabilitation of many wastewater treatment plants, sometimes through the installation of a biological complementary treatment stage. Among these sites, some plants in mountain areas are considering a biofiltration process. The design of such plants, especially for winter, appears to be tricky because of the very low influent temperature, the high performance requested for ammonia removal and the important and short term variations of the influent loads. The monitoring of a site during two consecutive winters has allowed us to study some aspects of the treatment. The major results are:

- a maximal nitrification capacity of about 0.59 kg of formed $N\text{-}NO_3^-.m^{-3}$ of material.d^{-1} with an influent temperature around 7°C at the plant inlet
- a nitrifying biomass growth rate, expressed as nitrifying capacity increase, of 0.03 kg of $N\text{-}NO_3^-.m^{-3}$ of material.d^{-2}
- quick and short terms load variations require a specific operation of the filters prior to the load increase, in order to grow enough active biomass to be able to treat the peak load immediately.

Keywords Biofilter; low temperature; nitrification; variable load

Water Science and Technology **Vol 47 No 11 pp 129–136**

Introduction

The evolution of the European legislation about urban wastewater treatment implies such a high effluent quality for cities of more than 2000 PE that a biological wastewater treatment process is necessary. In case the receiving water is sensitive to ammonia, this secondary treatment will also have a nitrification and, in some case, a denitrification step.

Its implementation is not easy for wastewater treatment plants located in mountain areas with important tourist activity (very high and quick load variations, low temperature of wastewater, infiltration inflow). Therefore the following questions are arising:

- Concerning the performance, does the effluent quality have to be guaranteed all year round, even during the winter peak period (often a few weeks only), or is a lower treatment quality temporarily acceptable?
- Concerning the technology, which nitrifying biological process can be compatible with high load variations and low temperatures? In addition, which load increase factor is acceptable to maintain a constant effluent quality?

Cemagref, with the technical collaboration of the Agence Rhône Méditerranée Corse (regional waterboard), has started to study a process which seems to deal especially well with this problem: biofiltration. This study assesses the nitrifying capacity at low temperature and defines a method for the plant operation, which aims at providing a sufficient nitrification capacity to the plant to deal with the sudden load increase.

Materials and methods

The study has been carried out on site and covers two winter periods. Long term monitoring provided data about influent temperature, pollutant loads and true performance of the plant in such conditions.

The main problem of biological treatment plants subjected to highly variable load is the low nitrifying capacity as the peak season is getting closer. Because of the modular aspect of the biofiltration process, different cell preparation modes for high load increase have been studied: seeding effect of nitrifying sludge from washwater, effect of external ammonia supply in order to obtain maximal nitrification capacity, effect of cell feed rotation.

The treatment plant

The wastewater treatment plant is fed by a combined sewer collecting domestic effluent only, from villages having a very high tourist activity. The main plant design data are shown in Table 1. The effluent quality objectives are: BOD_5: 25 $mg.L^{-1}$, TKN: 12 $mg.L^{-1}$.

According to these data, a biofiltration process (Biostyr©, by the OTV company) has been chosen, with the following setup: a pre-treatment step, a primary treatment stage (chemically enhanced settling), followed by a biological treatment step consisting of 8 identical biofiltration cells. Their main process parameters are shown in Table 2.

With a $N\text{-}NH_4^+$/TKN ratio of about 70% in the raw wastewater, and an effluent concentration of 8 $mg.L^{-1}$ TKN (as specified by the manufacturer), this design implies a nitrification capacity of 0.58 kg $N\text{-}NO_3^-.m^{-3}$ of material.d^{-1} at 8°C.

Measurements and analysis

Refrigerated samplers, flowmeters and other sensors (pH ; temperature,…) have been installed on site. All analytical parameters have been measured according to standard methods, and all necessary precautions have been taken during sample storage (acidification, filtration, 4°C).

Results

Characteristics of raw wastewater

Influent temperature. Influent temperature is lower than 8°C between the end of November and mid-February. Below this temperature, the requested treatment performances cannot be guaranteed. During this period, the wastewater temperature varies as a function of air and/or precipitation temperature.

The comparison of both measured temperatures (plant influent and biofilter effluent) shows an increase of 1.5°C. This increase depends on the retention time in the process and on the heating effect of the air which is injected in different stages of the process.

Nitrogen load to be treated

The evolution of the ammonia input during the 1999/2000 winter allows us to quantify the load increase versus time (Figure 1).

Table 1 Main plant design data

Parameters	Unit	Peak season	Off season
Design capacity	P.E.	45,000	/
Design daily dry weather flow	$m^3.d^{-1}$	9,000	2,250
BOD_5	$kg.d^{-1}$	2,250	563
TKN	$kg.d^{-1}$	540	135

Table 2 Main process parameters

Peak hydraulic loading	3.8	$m.h^{-1}$	(4.4 with 1 cell in wash)
BOD_5 volumetric loading	1.32	$kg.m^{-3}.d^{-1}$	
TKN volumetric loading	0.75	$kg.m^{-3}.d^{-1}$	

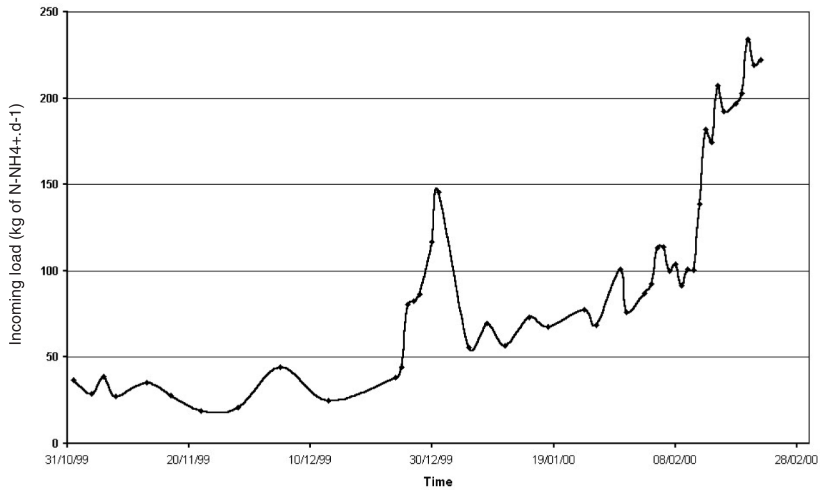

Figure 1 Time evolution of incoming N-NH_4^+ load

We can observe that the nitrogen load varies between 40 kg of N-NH_4^+.d^{-1} (off season) and 240 kg.d^{-1} during the tourist season (school holidays). The load increase factor is thus equal to 6 within 2 months. The highest increases can be seen during Christmas and February school holidays, and appear to be a little less than double the load within 24 hours (factor 1.85) (Figure 2).

The seeding state of the cell by nitrifying biomass is approximated by the quantity of formed nitrates by m^3 of material and by filtration cycles of 24 consecutive hours (Table 3).

First, low TKN volumetric loadings are limiting the autotrophic biomass and thus the formed nitrates volumetric loadings. Then, when the nitrogen volumetric loading increases, the quantity of formed nitrates increases also, but slowly compared to the important evolution of the applied loads. This slower evolution can be explained by the relatively low growth rate of the autotrophic biomass at such temperatures. The observed nitrifying capacity might then not have been maximal because the volumetric load rate isn't long enough.

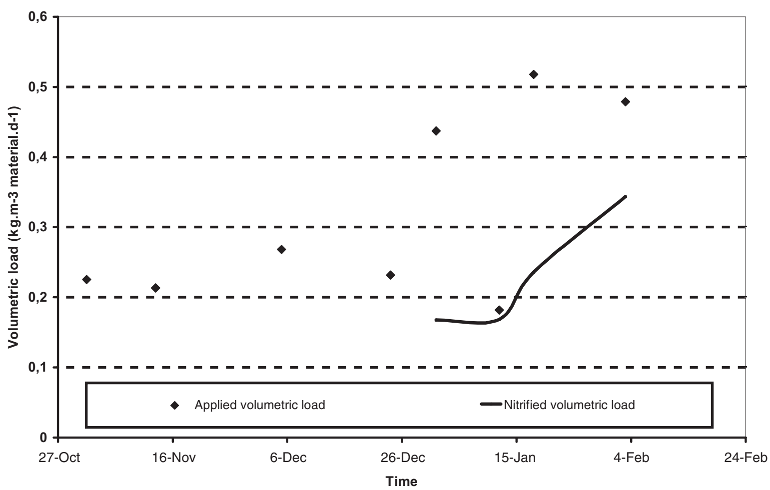

Figure 2 Increase of the applied and nitrified volumetric loads on the plant before Feb. 4th

Table 3 Quantity of nitrates formed

	Project targets	Measured values
kg of TKN.m^{-3} of material.d^{-1}	0.75	from 0.25 to more than 0.8
kg of N-NO_3^- formed.m^{-3} material.d^{-1}	0.58	0.18 to 0.34

Nitrifying capacity

Maximal nitrifying capacity. The monitoring of cells fed with high loadings during a long period and without limiting factors (oxygen, pH, HCO_3) led to the maximal nitrification capacity of the system at the given temperature (Figure 3).

We observed a maximal nitrification capacity of 0.59 kg formed N-NO_3^-.m^{-3} material.d^{-1} at a temperature of 6.5°C for the influent, and 8°C in the biofilters. This capacity can be called "maximal", as there are a few mg.L^{-1} residual nitrogen in the effluent. Reaching low concentration at the outlet would lead to a partial utilization of the reactor volume, meaning that the nitrification capacity is lower than the maximal potential (low concentration of the influent: effect on the kinetics and the distribution: plug-flow).

Increase rate of the nitrification capacity. The increase rate of the nitrification capacity, expressed in kg of formed nitrate by m^3 of material during a 24-hour filtration cycle and by day, has been studied during the two winter seasons. Very different values, from 0.01 to 0.05 kg of formed N-NO_3^-.m^{-3} of material.d^{-2} have been measured. These differences are strictly bound to the history of the monitored filter, to its initial seeding level, and to the parameters influencing nitrification, particularly the soluble or total COD loading.

For a volumetric loading of 2.6 kg $COD_{soluble}$.m^{-3} of material.d^{-1}, at stabilized rate and in absence of other factors penalizing the nitrification, a nitrifying capacity increase rate of 0.03 kg of formed N-NO_3^-.m^{-3} d^{-2} can be taken at 8°C in the cell. This value corresponds to a growth rate of about 8 to 10% per day of the autotrophic biomass already present inside the filter.

This biomass growth rate is too low to deal with a doubling of the load, if not more, within 24 hours. Therefore, in order to meet the quality requirements of the treated water during a quick load increase, it is necessary to start additional filtration cells which are already ready for nitrogen treatment. This means that these filters have to be prepared well before the load peak period.

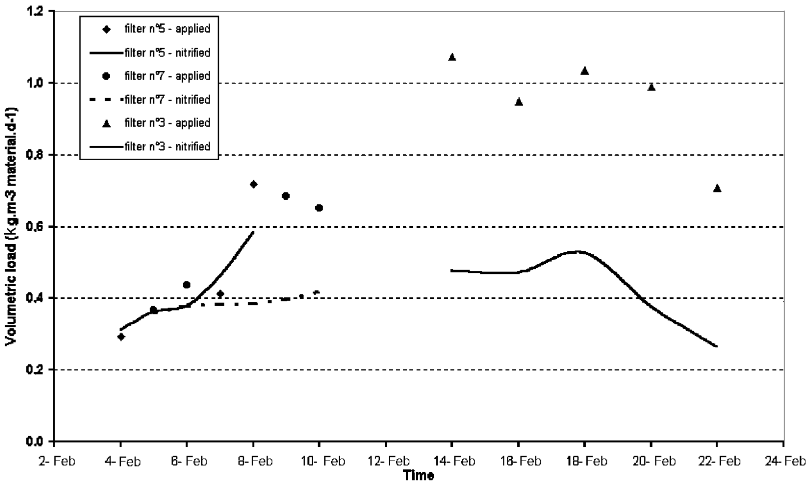

Figure 3 Evolution of the applied and nitrified volumetric loads on three different cells after Feb. 4th

Preparation of the biofiltration cells

Different preparation modes of the biofilter cells aiming at growing enough autotrophic biomass have been tested.

Seeding by sludge coming from nitrifying cells. The nitrifying capacity of several cells which had been stopped for more than 100 days (without feed nor aeration) has been measured during start-up. It yields the results in Table 4.

Already after the first 24-hour filtration cycle, a high nitrification yield of about 0.3 kg of formed $N\text{-}NO_3^-.m^{-3}$ of material.d^{-1} is observed. The results show that a part of the previous seeding can be re-utilized, but then the growth rate of the biomass is very low.

The monitoring of a filter which had been seeded beforehand with washwater from nitrifying biofilters did not yield any significant results. These results are questionable because the tests have not been repeated, because of the low concentration of the washwater injected in the filtration beds during the pre-feeding, and because of the low $N\text{-}NH_4^+$ loading during some phases of the monitoring.

Artificial addition of ammonia. If the nitrogen load is too low before the peak season to allow a sufficient nitrifying biomass, it can be enhanced by the addition of an artificial nitrogen source. This procedure has been studied on one cell. The scope of the injected quantities is an increase of the nitrifying capacity of 0.03 kg $N\text{-}NO_3^-$ formed $.m^{-3}.d^{-1}$, in order to prevent a too high ammonia concentration in the effluent (Table 5).

The results show a lower increase rate for the second year of the monitoring. The reasons are mainly a higher carbonaceous loading, mostly as particles, and a limited oxygenation.

Applying a high load on cells by rotation. The last biofilter preparation procedure is the so-called "rotation" technique. It is the most interesting method and it has been studied more closely.

The principle is to use the nitrogen of the wastewater in order to grow a sufficient nitrifying biomass before the peak period. To that purpose, each cell is fed by rotation before the peak period, with a volumetric loading close to the design value through the stoppage of some other cells. It has been decided to feed each cell during one day, and to adapt the stoppage time according to the total number of filters involved in this rotation.

The success of the cell rotation procedure depends on the ability of the non-fed cells to keep their biomass during the waking time.

The capability of keeping the nitrifying biomass has been tested by monitoring the evolution of the nitrification capacity. The assessment criterion was the duration to recover the initial nitrification level as measured before the filter stoppage, versus the duration of the

Table 4 Nitrifying capacity of several cells stopped for >100 d

	24-hour filtration cycles			Temperature
	1st cycle	2nd cycle	3rd and 4th cycle	
kg of formed $N\text{-}NO_3^-.m^{-3}$ of material.d^{-1}	≃ 0.1	≃ 0.3	≃ 0.3	≃ 7°C

Table 5 Enhancement of nitrogen load

	Applied loadings		Temperature	Increase rate of the nitrification capacity
Year	kg total $COD.m^{-3}.d^{-1}$	kg soluble $COD.m^{-3}.d^{-1}$	°C	kg $N\text{-}NO_3.m^{-3}.d^{-2}$
2000	3.85	2.64	8	0.03
2001	5.00	2.4	8	0.02

imposed non-feeding periods. To do so, some cells were stopped during variable periods, with 2 minutes aeration every 2 hours during the waking periods, and then were restarted. The results are shown in Table 6.

These results were measured on well seeded filters (stable performance). They show that a 3-day stopping period is a good compromise to maintain the biomass in activity, because it allows us to go back to the initial nitrification performance after 10 hours feeding.

Three different aeration procedures during waking state have also been tested: 3 minutes aeration every 2 hours, continuous aeration, no aeration. The rotation sequence was 1 day feeding followed by 3 days stoppage. Yields measurements have been carried out every other 24-hour filtration cycle during two months. Due to a substrate limitation at the beginning of the monitoring ($N\text{-}NH_4^+$ effluent concentration negligible) and to a non stable phase during the load increase, the results are based only on the end of the monitoring period (Table 7).

The results have been obtained in a short period of time and haven't been repeated, so the final conclusion has to be drawn with care. The intermittent aeration procedure can be considered as a satisfying technical and economical compromise, as aeration represents an important part of the treatment cost.

Discussion and synthesis

Nitrification capacity at low temperature

On a well seeded filter and at 8°C in the biological reactor (6.5°C at plant inlet), the maximal measured performances were 0.55 to 0.59 kg of formed nitrates per m^3 of material and per day. These values are high and have been obtained with a quite important ammonia residual concentration in the effluent (TKN: 12 $mg.L^{-1}$ being the required effluent quality level), a low soluble COD volumetric loading of 2.64 $kg.m^{-3}$ of material.d^{-1} (= 3.8 kg total COD per $m^{-3}.d^{-1}$), and in absence of limiting factors (O_2, HCO_3, pH). For the design, a maximal nitrification of 0.55 kg of formed $N\text{-}NO_3^-.m^{-3}$ of material. d^{-1} should be used.

Impact of the load variation factor on the design

The preparation of the biofilters for the maximal load is based on the rotation of the feeding prior to the peak season, in order to apply a load close to the design value on each active cell.

The ratio between the number of cells installed in order to treat the design load and the number of cells being used off season should be close to the load variation factor between low and high season, in order to grow an important biomass able to treat a maximum load between these two periods. The loads used in the design project have to be as close as possible to the reality. In fact, underestimating the off season load would lead to an

Table 6 Results for cells stopped during variable periods

Stopping duration	Initial volumetric nitrification capacity (kg of formed $N\text{-}NO_3^-.m^{-3}.d^{-1}$)	Feeding period after which the nitrification level was recovered
1 day	0.51	Immediately
3 days	0.39	After 10 hours
5 days	0.60	After 24 hours
7 days	0.58	After 40 hours

Table 7 Yield measurements

	3 min aeration/2 hours	Continuous aeration	No aeration
kg of formed $N\text{-}NO_3^-.m^{-3}$ of material.d^{-1}	0.29	0.33	0.30
Ratio/continuous aeration mode	88%	100%	91%

under-loading and so to an under-seeding of the cells. For the high season, a too important safety coefficient or an over-estimation of the village development would increase the load variation factor, and induce a too important number of filters, which means difficulties to maintain the autotrophic biomass. In addition, in these mountain area villages, the coefficient of organic load variation is seldom correlated with the evolution of the hydraulic load, as the sewerage network is usually a combined system. The strong dilution of wastewater out of the peak season will make it difficult to apply a high nitrogen volumetric loading, as the hydraulic loading would be the limiting factor. Therefore, this has to be taken into account during the design phase.

Managing the load increase

For plants with variable load, maintaining a nitrification capacity means that the biomass should grow at the same rate as the load. At 8°C, the autotrophic biomass growth rate, as verified during this study, is about 8 to 10% biomass increase per day. This allows a daily load increase of the same ratio, for the same level of treated water quality. The load increase factor is variable from one site to another, but often quicker than the growth rate of the biomass. This leads to a non-compliant effluent quality due to the increase of the ammonia discharge. For the studied plant, the maximal increase coefficient between two following days is 1.8. The mere biomass increase through normal growth is not sufficient to ensure the treatment of the additional load.

The solution which consists in accepting a lower effluent quality during the pollution peak, with improvement with time, because of the slow growth of the autotrophic biomass at such temperatures, is not acceptable. The response time is too long compared to the short timing of the pollution peak in these villages. The best solution is to use one of the advantages of the biofiltration process, which is its modular aspect: the cells can be operated in feeding rotation, so that the maximum of the autotrophic biomass is maintained. With such a rotation, the continuous presence of autotrophic biomass at a sufficient level can be obtained thanks to the application of a constantly high volumetric loading (close to design value) to each cell.

The results show that maintaining the biomass during the feed stoppage period depends on the number of the cells involved in the rotation. The stoppage should not exceed three days, as longer waking durations lead to a decrease of the nitrification capacity. This way, the nitrification capacity can be maintained for plants where the load variation ratio is not greater than 4 (one feeding day followed by three stoppage days).

In case the load variation factor would be greater than 4, the following recommendations can be made according to the present state of knowledge and data:

For example, 4 cells are continuously seeded by rotation during off season. When the load to be treated is greater than 3 cells, another un-seeded cell will be progressively introduced into the rotation. In this case, the effluent quality will slightly deteriorate because of the lack of seeding. The last fed cell will be considered as seeded (same level as a so-called "nitrifying" cell) after 6 to 8 filtration cycles of 24 hours, with waking periods lower than 3 days between each filtration cycle.

This cell will then be integrated in the rotation cycle without penalizing the effluent quality. If the system needs an important number of "non-seeded" cells versus the seeded cells, the effluent quality level will be met only if the design took this into account. These recommendations are based on the following data:

- Seeding target: 0.55 kg of formed $N\text{-}NO_3^-.m^{-3}$ of material.d^{-1}
- Seeding level at start up: 0.3 kg of formed $N\text{-}NO_3^-.m^{-3}$ of material.d^{-1}
- Average daily increase rate: 0.03 kg $N\text{-}NO_3^-.m^{-3}$ of material.d^{-2}

Other seeding techniques (artificial addition of ammonia, seeding with sludge from nitrifying cells) have been studied, but the results are poor and/or imply high operating or economical constraints. They can be used only for plants subjected to very stringent effluent quality requirements during the winter pollution peaks, and when the load increase ratio between off and high season is greater than 4, with a very high increase from one day to another.

Acknowledgements

The authors wish to thank CGE (local company), OTV (builder) and the Syndicat intercommunal de la Vallée de l'Ubaye (village community).

References

Borregaard, V.R. (1997). Experience in nutrient removal in a fixed-film system at full-scale wastewater treatment plant *Wat. Sci. Tech.*, **36**(1), 129–137.

Canler, J.-P. (1994). L'épuration par biofiltration Documentation technique FNDAE, hors série no 8, 1994 – 61 p.

Canler, J.-P., Durand, C. and Perret, J.-M. (1996). Efficacité des biofiltres vis-à-vis de l'azote. In *Traitement de l'azote – Cas des eaux résiduaires urbaines et des lisiers. Actes du colloque, Lyon, 25 octobre 1996.* CEMAGREF éditions, p. 39–52.

Choi, E., Na Y.-H. and Lee C.-G. (1999). Nitrogen removal by BAF from weak sewage at low temperature *in* "IAWQ Conference on Biofilm Systems – Program and Proceedings. October 17–20, 1999. New York." IAWQ – session 5a.

Fdz-Polanco, F., Villaverde, S. and Garcia, P.A. (1994). Temperature effect on nitrifying bacteria activity in biofilters: activation and free ammonia inhibition *Wat. Sci. Tech.*, **30**(11), 121–130.

Fdz-Polanco, F., Villaverde, S. and Garcia, P.A. (1996). Nitrite accumulation in submerged biofilters – combined effects *Wat. Sci. Tech.*, **34**(3/4), 371–378.

Gilmore, K.R. *et al.* (1999).Influence of organic and ammonia loading on nitrifier activity and nitrification performance for a two-stage biological aerated filter system *Wat. Sci. Tech.*, **39**(7), 227–234.

Mann, A., Mendoza-Espinosa, L. and Stephenson, T.A. (1998). Comparison of Floating and Sunken Media Biological Aerated Filters for Nitrification *J. Chem. Technol. Biotechnol.*, **72**, 273–279.

Paffoni, C. *et al.* (1990). Aerated biofilters for nitrification and effluent polishing *Wat. Sci. Tech.*, **22**(7/8), 181–189.

Pujol, R., Lemmel, H. and Gousailles, M. (1998). A keypoint of nitrification in an upflow biofiltration reactor *Wat. Sci. Tech.*, **38**(3), 43–49.

Stensel, H.D. *et al.* (1988). Biological aerated filter evaluation *Journal of Environmental Engineering*, **114**(3), 655–671.