Simultaneous Organic Matter Removal and Nitrification in a Biofilm-Enhanced Highly Loaded Aerated Lagoon

Bernard Patry[1,2], Paul Lessard[2], Peter A. Vanrolleghem[1,2]

[1]model*EAU* – Université Laval; [2] CentrEau – Université Laval

ABSTRACT

A full-scale biofilm-enhanced aerated lagoon using a fixed submerged media was monitored over one year to quantify its simultaneous organic matter removal and nitrification performance. The system was operating at a high organic loading rate averaging 5.8 $gCBOD_5/m^2$ of media per day (23.9 $gCBOD_5/m^3$ of lagoon per day) and temperatures ranging from 1.6°C to 20.8°C. The system showed an extended seasonal nitrification period compared to a typical suspended growth system of the same dimensions. An extension of complete nitrification with approximately 1 month was observed in the fall despite the decrease of operating temperature down to 4°C. During this maximum nitrification period, substantial total nitrogen removal was measured (30%), effluent un-ionized ammonia percent was reduced, and a temporary loss of nitrification related to the high presence of solids was experienced. During wintertime, a low nitrate production was still present, suggesting year-long retention of nitrifying bacteria in the biofilm.

Keywords: Aerated Lagoon, Biofilm, Fixed Media, Nitrification, Cold Temperature

INTRODUCTION

Aerated lagoon technology is widely used for wastewater treatment in small communities of the United States and Canada. Current design for this type of technology is not done in view of achieving nitrification, even if their design comes with long retention times (hydraulic and solids). However, since they are extensive systems importantly influenced by seasonal variations of temperature (from 0 to 20°C plus in some cases), partial or complete seasonal nitrification is likely to occur (Houweling et al., 2008). When temperature is high enough, the growth rate of autotrophic nitrifying bacteria becomes higher than the rate of biomass wastage and nitrification is enabled. The latter conditions are obviously observed during the summer period whose duration differs widely depending on the location (elevation and latitude) of the treatment facility. Seasonal nitrification in aerated lagoon systems is reported to be inconsistent compared to typical activated sludge operating at a similar solids retention time (SRT) (Rich, 1999). These aspects make it hard for the aerated lagoon process to be in line with the current regulation context. Indeed, current concerns about effluent toxicity impacting the receiving water biodiversity translates in tighter limits for un-ionised ammonia (Wastewater Systems Effluent Regulations, 2012). Ammonia, in its un-ionized form, is toxic to aquatic organisms (Emerson et al., 1975).

Research and industrial development have been trying to overcome the limits of the aerated lagoon system regarding nitrification. Model-based, pilot-scale and full-scale experiments have been carried out to study the potential of lagoon process modifications and complementary technologies. The tested solutions include tertiary treatment with biofilm-based processes such as moving bed biofilm reactors (MBBR) (Hoang et al., 2014; Young et al., 2016) and underground

aerated clean stone beds (Mattson et al., 2018). Monitoring of pilot and full-scale tertiary systems showed good nitrification performance at very low temperature (1°C and lower). This translates in a year-long nitrification potential. However, these systems imply additional reaction volume which results in a potentially restrictive increase in the footprint of the facility. Enhancement of the original lagoon with bioaugmentation or increased dissolved oxygen (DO) (Houweling et al., 2008) have also been evaluated. As demonstrated in model simulations, these solutions were found to significantly increase the duration of the nitrification period.

The use of a support material directly in the lagoon for biofilm growth has also been identified as a promising solution (Choi et al., 2008; Wang et al., 2012; Boutet et al., 2018). Its interest resides in the simplicity of its implementation using no added operation nor reactive volume. However, in contrast with the tertiary treatment solutions, using the same reactor volume means dealing with simultaneous organic matter removal and nitrification. Few data are available in the literature to validate this approach at full-scale and specifically considering the effect of a high load (compared to design load). This scenario is currently of interest since a growing number of aging aerated lagoon systems are or will soon be facing an overloaded situation. For example, in the province of Québec (Canada), in 2013, 29% of the lagoon systems were hydraulically overloaded and 19% were facing an organic overload (Québec, 2015).

The KAMAK™ technology, developed by Bionest (Shawinigan, Québec, Canada), is an example of upgrade technology using an inert self-supported submerged media directly in the aerated lagoon. Its design is based on the results of a pilot-scale study (Boutet et al., 2018) that showed the potential for simultaneous removal of ammonia and organic matter under high organic loading rates (>5 $gCBOD_5/m^2 \cdot d$) and cold temperatures (<1°C). It includes two aerated biofilm reactor zones (RX1 and RX2) as well as three minimally aerated (CL1) or unaerated zones (CL2 and CL3) for sedimentation and accumulation of solids (Figure 1). Each zone is separated by a watertight membrane. RX1 is designed for organic matter removal and partial nitrification while RX2 is designed for oxidation of residual organics and ammonia.

The main objective of the present study is to quantify the simultaneous organic matter removal and nitrification performance and evaluate the viability of a full-scale highly loaded aerated lagoon enhanced with a fixed submerged biofilm support media. The underlying objectives of this research are to increase process understanding and identify bottlenecks related to biofilm-enhanced aerated lagoon design, focusing on nitrification.

METHODOLOGY

Experimental Site and Studied System

The case study is a full-scale KAMAK™ installation in the aerated lagoon of Grandes-Piles, a small municipality (360 PE) of the province of Québec, Canada. The system is installed in the first third of the existing lagoon to simulate an overload situation (Figure 1c). The total volume of the studied KAMAK™ is 520 m^3. The aerated reactor zones RX1 and RX2 have respective volumes of 34.5 m^3 and 37.5 m^3. The available surface areas for biofilm growth are respectively 1418 m^2 (10 columns, 32% fill) and 709 m^2 (5 columns, 15% fill). The volumetric surface area within an individual column is 130 m^2/m^3. A start-up period including a nitrification period preceded the measuring campaign conducted for this study to allow complete colonization of the

media. The reactors are separated from the sedimentation zones CL1, CL2 and CL3 by ballasted high-density polyethylene membranes. Holes of 60 cm by 60 cm in the membranes allow water to flow through the system as described on the flow diagram presented in Figure 1e. For odor control, CL1 is minimally aerated (approximately 100 l/min) with a Premier Tech (Rivière-du-Loup, Québec, Canada) Atara^{TM} static aerator from the original lagoon. CL2 and CL3 are unaerated. The volume of each CL is 149.5 m³. The hydraulic behaviour of the system was characterized by performing a multi-point tracer test with Rhodamine WT (Patry, 2019).

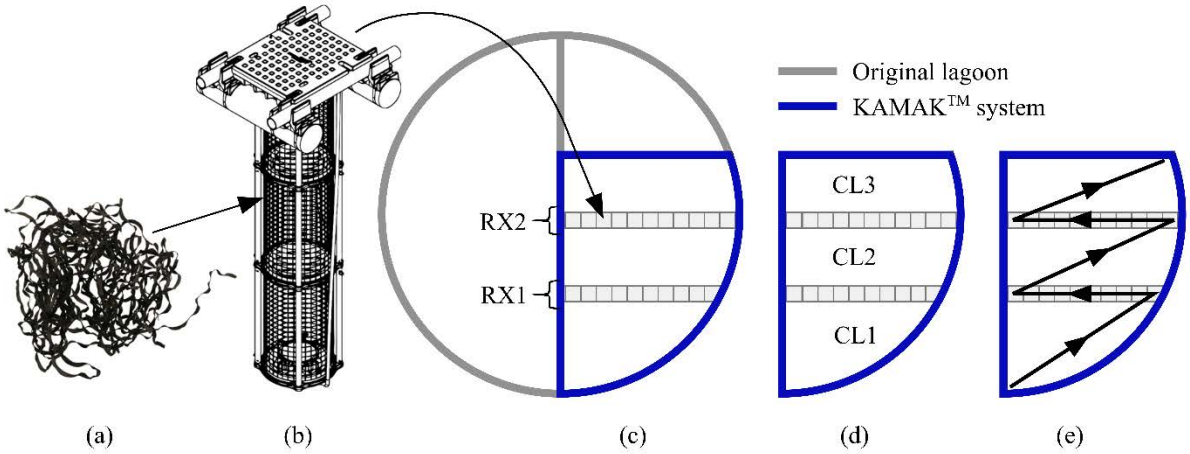

Figure 1: KAMAK^{TM} system with (a) the BIONEST® bacterial support, (b) the floating columns, (c) the biofilm reactor zones RX1 and RX2, (d) the sedimentation and accumulation zones CL1, CL2 and CL3 and (e) the flow diagram

The aeration of the biofilm reactors is made using coarse bubble diffusers (perforated PVC pipes) at the base of the columns containing the support material. Dissolved oxygen (DO) concentration, maintained to be non-limiting in the reactors, varied from 6 to 13 g/m³ during the one-year monitored period, from January 26th, 2017 to January 26th, 2018. Manual DO measurements were performed weekly in the reactors using a YSI (Yellow Springs, Ohio) ProODO portable probe. Biofilm thickness control in the reactors is achieved by significantly changing the level of aeration (by a factor 4) in each column every 4 hours for 8 minutes to increase the shear stress on the biofilm.

The system is fed with raw municipal wastewater at an average flowrate of 84.3 m³/d. During the monitored period, alkalinity was measured using a Hach (Loveland, Colorado) manual titrator (method 8203) and adjusted adding sodium bicarbonate as needed to ensure that nitrification wasn't limited. Effluent alkalinity varied from 39 to 162 g $CaCO_3$/m³ during the monitored period.

Water Quality Monitoring

RSM30 monitoring stations from Primodal (Hamilton, Ontario, Canada) were installed at the influent and the effluent of the system. The stations included a total of 11 sensors measuring 10 different variables (Table 1). A procedure for cleaning, validating and calibrating the sensors was followed every week to ensure the validity of the collected data. An off-line univariate data

quality assessment and filtering procedure (Alferes & Vanrolleghem, 2016) consisting in detecting outliers, reducing noise and detecting sensor faults was applied to improve online data quality for better process performance analysis. Analyses were also performed on grab samples for the effluent and intermediate points (input and output of each zone) and composite (time proportional) samples for the influent to complete the data sets. 5-day carbonaceous biological oxygen demand ($CBOD_5$), Total nitrogen (TN), ammonia and nitrate concentrations were measured on samples taken weekly. Nitrites were measured prior to the monitored period discussed in this paper and they were found to be negligible in the nitrogen mass balance. $CBOD_5$ measurements were performed using standard methods. Hach methods 10208, 10205, 10206 and 10207 were respectively used for TN, ammonia, nitrates and nitrites measurements.

Table 1: Sensors included in the water quality monitoring stations

Sensor	Supplier	Measured variables	Influent	Effluent
spectro::lyser	s::can[a]	COD[c], filtered COD, TSS[d], NO_3-N	x	x
ammo::lyser	s::can[a]	pH, temperature, NH_4-N, K	x	x
Solitax turbidimeter	Hach[b]	TSS	x	x
pHD	Hach[b]	pH, temperature	x	x
Inductive conductivity	Hach[b]	Conductivity, temperature	x	x
LDO	Hach[b]	DO[e], temperature		x

[a]Vienna, Austria; [b]Loveland, Colorado; [c]Chemical oxygen demand; [d]Total suspended solids; [e]Dissolved oxygen

Biofilm Monitoring

Biofilm characteristics in RX1 and RX2 were measured weekly from July 11th to August 14th, 2017. Colonized media samples were taken at two different depths (1/6 and 1/2 of the total depth) from one column in each reactor to perform biofilm thickness and dry density measurements. The procedure was based on the methodology described by Horn and Hempel (1997). Samples were first drained for 30 minutes, then weighed before being dried at 105°C and weighed again. To estimate biofilm volume and thickness, wet biofilm density was assumed to be equal to 1000 kg/m³. The weight of media was subtracted from the total weight of the colonized media to get the biofilm mass (wet and dry) after complete cleaning of the material using a Fisher Scientific (Hampton, New Hampshire) CPXH ultrasonic bath.

Biofilm detachment dynamics was also monitored indirectly by continuously measuring the total suspended solids (TSS) concentration in RX1 and RX2 (next to the last column of each reactor) with a Hach Solitax turbidimeter. The sensor maintenance and data filtration procedures used for influent and effluent water quality monitoring were also used to ensure the quality of the time series collected in the reactors.

Modelling

A model simulation was performed to compare the performance of the studied system with a typical suspended growth process and thus assess its viability. The software WEST (2017) by DHI (Hørsholm, Denmark) was used to build the model and run the dynamic simulations.

The ASM1 model (Henze et al., 2006) including the effect of temperature was used to describe the biokinetics. A completely mixed tank was used to describe the hydraulics in the lagoon. To assume complete mixing is a common simplification when modelling the hydraulics of aerated lagoons (Ouldali et al., 1989; Houweling et al., 2005). The ASM1 default kinetic and stoichiometric parameters found in WEST 2017 for municipal wastewater treatment were all used for the simulations. An influent file based on the measured influent composition and the fractionation described in Vanrolleghem et al. (2003), Roeleveld and van Loosdrecht (2002) and Henze et al. (2006) was built and fed to the model. A volume equal to the total volume of the studied system (520 m^3) was used. The observed effluent temperature (Figure 2a) variation was also fed to the model. The initial conditions were computed running a 50-day steady state simulation with the influent composition averaged over the two first weeks. DO was maintained above 6 g/m^3 in the reactor during the simulations. Sedimentation was not included in the model.

RESULTS AND DISCUSSION

System Hydraulic Behaviour

The response curves obtained from the tracer test showed that back-mixing flows are significant between the 5 zones of the system (Patry, 2019). This behaviour makes the analysis of results at intermediate points confusing, especially for soluble components. Only the effluent concentrations affected by the whole system are thus analysed to assess its treatment performance. For the same reason, effluent temperature is considered as an acceptable estimate of the operating temperature for the whole process.

Influent Composition and Loading Rates

The average influent composition over the one-year monitored period is presented in Table 2. The observed composition is typical for municipal wastewater. Because of the reduced reactor volume, the organic loading rates are high compared to typical aerated lagoon design criteria (10.6 $gCBOD_5/m^3 \cdot d$ for a 3-cell system targeting an effluent $CBOD_5$ of 30 g/m^3 with an influent $CBOD_5$ of 170 g/m^3 and a design temperature of 2°C) (USEPA, 2011). Since organic matter removal and nitrification are simultaneously occurring in the studied system, competition between heterotrophic biomass and autotrophic biomass for dissolved oxygen (DO) is significant. Biodegradable organic matter loading rates over 5 $gCBOD_5/m^2 \cdot d$ were reported as resulting in no nitrification in MBBR systems (Hem et al., 1994; Rusten et al., 1995). However, the pilot study used as a basis for the design of the KAMAK™ system (Boutet et al., 2018) showed that important nitrification was possible at higher loading rates (>7 $gCBOD_5/m^2 \cdot d$).

Nitrification and Nitrogen Fractionation

The online data presented on Figure 2a show the seasonal variation of water temperature at the effluent of the studied system. Recorded temperature varied from 1.6°C to 20.8°C over the monitored year. Effluent ammonia and nitrate concentrations are presented on Figure 2b. The correlation between temperature and nitrification is clear. Nitrate production began early May 2017 when temperature reached 9°C. Maximum nitrification was observed from mid-June to the beginning of December covering the warmer period of the year, but also during the return to winter temperatures down to 4°C. Nitrification loss was observed during the month of December

with a return to minimal nitrate concentrations around mid-January 2018. During the maximum nitrification period, the organic loading rate was on average 6.2 $gCBOD_5/m^2 \cdot d$. This result is in accordance with the conclusions of Boutet et al. (2018) who observed important nitrification at high organic loading rate with the same biofilm support media. An average ammonia concentration of 2.9 g/m^3 was measured at the effluent of the system during the maximum nitrification period despite a nitrification loss episode (Figure 2b) observed from the end of July to the end of August (discussed below). This type of episode is of course undesirable.

Table 2: Average daily influent composition and loading rates for the one-year monitored period

Variable	Influent concentration[a] (g/m^3)	Average volumetric loading rate (g/m^3 of lagoon·d)	Average surface loading rate (g/m^2 of support·d)
COD[b]	388 (121)	64.0	15.7
fCOD[b]	128 (40)	20.4	5.0
$CBOD_5$[c]	168 (41)	23.9	5.8
TSS[b]	167 (70)	28.5	7.0
NH_4-N[b]	25 (10)	3.7	0.9
TN[c]	38 (6)	5.5	1.4

[a]Average (standard deviation); [b]Online sensor data; [c]Time proportional composite samples

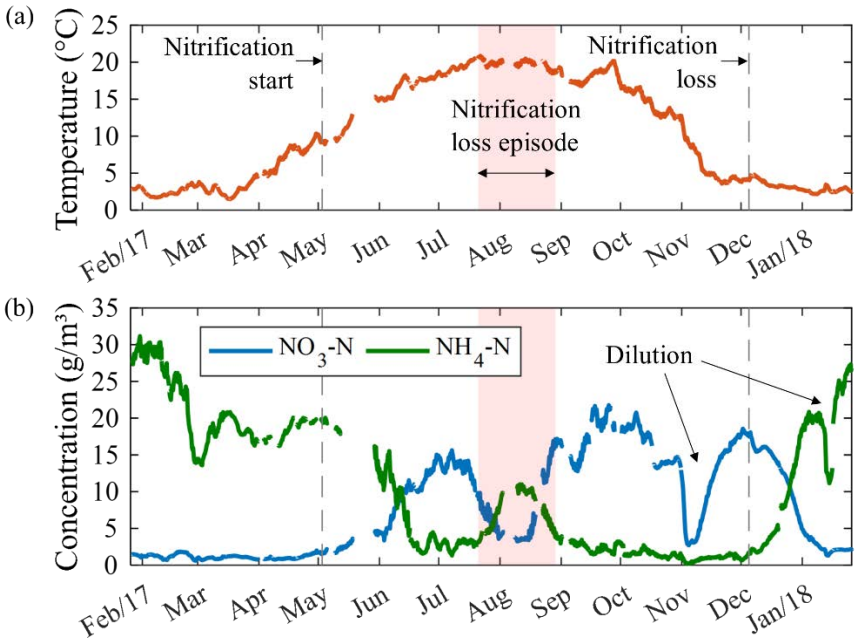

Figure 2: Effluent (a) temperature, (b) ammonia and nitrates over the one-year monitored period

The available data concerning the biofilm reactors have been analysed to try understanding the cause of the observed nitrification loss episode. Figure 3 shows the biofilm detachment dynamics

in the first reactor. Similar results were obtained in RX2. The turbidimeter signal shows the impact of the intense biofilm thickness control aeration cycles on the TSS concentration in the reactor. The latter is considered an index of biofilm detachment. Figure 3a shows the dynamics before the nitrification loss episode while Figure 3b shows the dynamics during the episode. Biofilm thickness (L) and dry density (ρ) during the respective periods are also given. Two important findings emerge from the data presented on Figure 3. First, unlike biofilm density which had similar variations in both periods, the range of biofilm thickness was different before and during the nitrification loss episode. Larger, but also thinner biofilm was observed during the episode. Before, the thickness range was narrower. The second interesting observation is that detachment was significantly increased during the episode. This is shown by the higher TSS peaks (that doubled) and the higher total particulate matter loss (the integral of the concentration peaks).

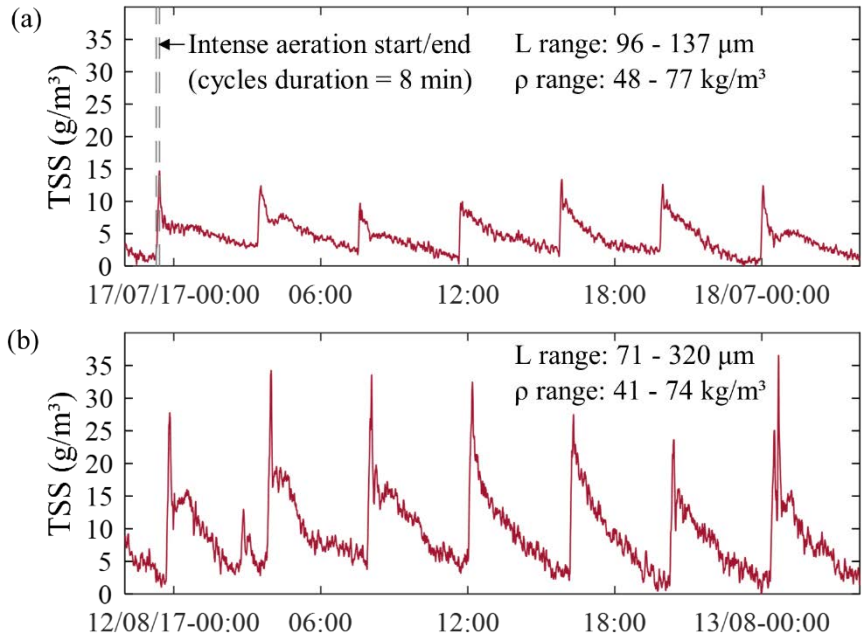

Figure 3: Biofilm detachment dynamics and biofilm characteristics in RX1 (a) before and (b) during the nitrification loss episode

The observed heterogeneity in the biofilm thickness during the nitrification loss episode is in line with the known relationships between biofilm thickness and detachment. A rapid growth of the biofilm (resulting from attachment or biomass production) leads to the development of a thicker biofilm, as observed on some samples taken during the episode. This rapid growth is associated with increased detachment (Wanner et al., 2006), which was also observed during the episode. When the detachment mode is sloughing, which is likely to occur in presence of thick biofilm (Morgenroth, 2003), large pieces of biofilm detach resulting in lower average thickness for some samples. The cause of the nitrification loss during the high biofilm detachment period can thus be the reduced retention time of the slow-growing nitrifying autotrophs due to increased biomass sloughing. It can of course also be the limitation of DO penetration by diffusion due to excessive biofilm thickness. Concerning this second explanation, previous studies (Särner & Marklund, 1985; Figueroa & Silverstein, 1992) have indeed highlighted the negative influence of particulate

matter on nitrification and more generally, on dissolved component removal in biofilms. The presence of particulate matter can, on the one hand, inhibit nitrification by physically interfering with oxygen transfer (diffusion). On the other hand, in presence of a high concentration of biodegradable particulate matter in the biofilm, inhibition can be caused by heterotrophs outcompeting nitrifying autotrophs for DO utilisation.

Based on complementary data collected to monitor the accumulation and digestion of solids in the KAMAK™ system (Patry et al., 2018), the high presence of solids in the biofilm reactors during the nitrification loss episode is attributable to the large amount of accumulated particulate matter in the CLs at the end of winter. During winter, little degradation takes place due to low temperature. Following the increase of temperature, peak sludge digestion and gas production leading to solids resuspension was observed during the loss period. Given the advective transport of the resuspended solids to the RXs, an increase in the attachment of solids to the biofilm follows. The observed resuspension also leads to DO consumption in the bulk and thus lower DO in the bulk, further limiting DO penetration in the biofilm.

A return to normal behaviour (maximum nitrification) was observed from mid-August to the beginning of September along with the decline of sediment activity and the consequent drop of the concentration of solids in the RXs. Model simulations integrating all the processes included in the system would help confirm these mechanisms and the major cause of nitrification loss.

Average influent and effluent nitrogen fractionations are presented in Figure 4. Figure 4a shows the fractionation when nitrification was at its lowest (mid-January to early May) while Figure 4b shows fractionation during the maximum nitrification period (mid-June to early December) omitting the nitrification loss episode. The influent fractionation for both periods is typical for municipal wastewater (Rieger et al., 2012). During the cold temperature period, no significant TN removal is observed. However, a non-negligible production of nitrates is measured, suggesting that autotrophs are retained in the biofilm during winter and remain slightly active. This finding is in line with the results of the pilot-scale study presented by Boutet et al. (2018) which showed significant nitrification at cold temperatures (<1°C) with the BIONEST® biofilm support media. During the maximum nitrification period, an average TN removal of 30% is observed. Denitrification within the biofilm or in the un-aerated CLs is thus operating.

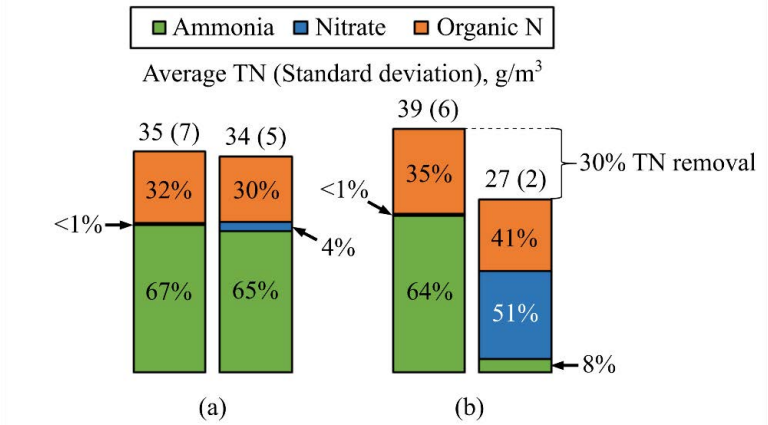

Figure 4: Average nitrogen fractionation for the influent and the effluent (a) during the cold period and (b) the warm period (omitting the nitrification loss episode)

Viability of the Biofilm-Enhanced Lagoon

A model simulation was performed to compare the KAMAK™ performance with a suspended growth process of the same dimensions. The simulation results are shown and compared to the measured data on Figure 5. The results clearly show that the biofilm helps retaining the autotrophic biomass when temperature is dropping during fall. An extension of the nitrification period with approximately 1 month is possible thanks to the biofilm system. The data from fall-winter 2014-2015 are also shown on the Figure. These data were collected at the original lagoon prior to the upgrade with biofilm, at the same point as the KAMAK™ effluent point. They show poor nitrification in the original system with high ammonia concentrations even early fall when the operating temperature is still high. The differences between these results and the model results can be explained by the differences in oxygen transfer efficiency and hydraulics that were not characterized at the original lagoon and thus not included in the model. Aeration was probably insufficient to maintain 6 g/m³ of DO the bulk and to keep the biomass suspended. The model was built to represent ideal suspended growth conditions.

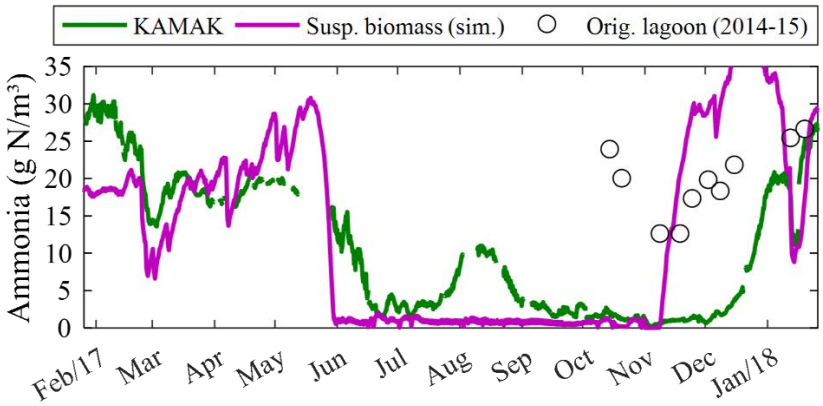

Figure 5: Comparison of the KAMAK™ nitrification performance with simulated performance for a suspended biomass system and the measured performance of the original lagoon without biofilm enhancement

The results for the spring season show that the KAMAK™ system starts nitrifying approximately at the same time as the suspended growth system. However, maximum nitrification comes nearly 15 days earlier for the suspended growth system suggesting a difference between the autotrophs growth kinetics of the studied system and the modelled one. This difference is probably related to diffusion limitation in the biofilm system. A difference in the transition rate is also observed between the model and the measurements during the nitrification loss in winter. It is, however, less obvious for this period. These observations concerning autotrophic biomass retention at cold temperatures and growth in the biofilm reinforce the interest for proper modelling of the KAMAK™ system to better understand its nitrification dynamics.

Reducing effluent toxicity is a major objective of promoting nitrification in a system such as an aerated lagoon. Knowing that total ammonia nitrogen (TAN) toxicity is related to the fraction present as un-ionized ammonia (NH_3), it is interesting to look at its evolution over time in the

system. This fraction is strongly dependent on water temperature and pH (Emerson et al., 1975). The percent NH_3 relative to TAN was computed using the equations presented in Emerson et al. (1975). The results are presented over the one-year monitored period in Figure 6b. The difference between the two presented curves shows the difference of NH_3 percent explained by pH effects. Indeed, the temperature variation (online data) was the same for both curves, but the online pH measurements (Figure 6a) were only used for the blue curve. The other curve was obtained using a constant pH equal to the average pH measured when nitrification was minimal. The curves show that the benefits of adding biofilm to the lagoon for consistent seasonal nitrification are not only related to the reduction of the TAN effluent concentration during summer. They are also related to the significant NH_3 percent decrease during the warmer months because of the acidifying effect of nitrification. A pH drop of approximately 0.6, on average, was observed during the summer in the KAMAK™ system. As shown by the dark gray curve, this period is critical for TAN toxicity.

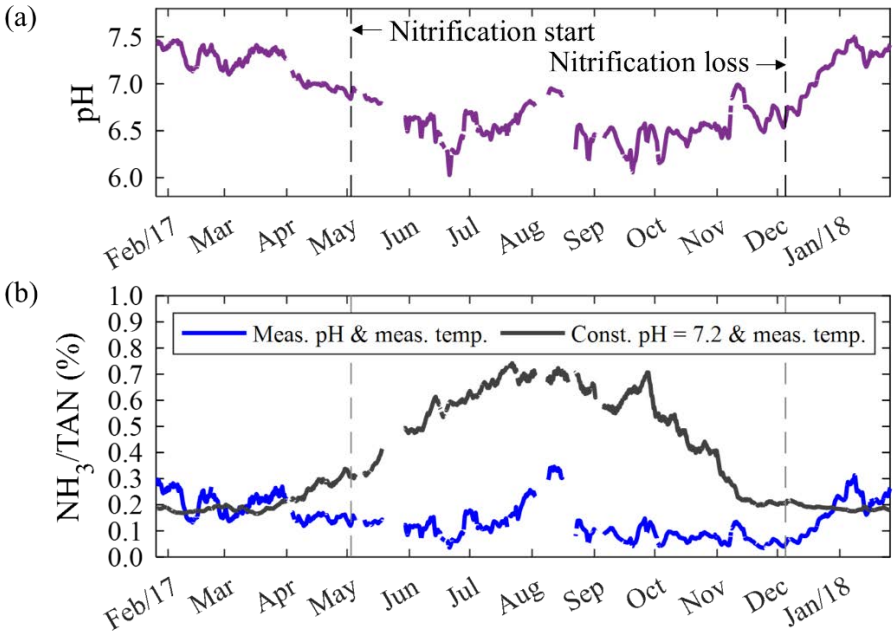

Figure 6: Effect of (a) effluent pH on (b) percent NH_3 relative to TAN concentration

CONCLUSIONS

The data collected during this study help demonstrate that adding a fixed biofilm support media in an aerated lagoon is beneficial for increasing the duration of seasonal nitrification even if the system is subject to a high average organic loading rate (5.8 $gCBOD_5/m^2 \cdot d$). Indeed, a comparison of the studied system's performance with simulated performance for a suspended growth system showed that a significant extension of the nitrification period was made possible thanks to the presence of biofilm. The extension is observed at the end of the nitrification period. During the nitrification period, un-ionized ammonia percent and therefore effluent toxicity is also reduced. During the colder months, however, competition for DO and space between heterotrophs and nitrifying autotrophs combined with the lack of thermal energy make it challenging to nitrify. A quantity of nitrates representing 4% of influent TN were produced on

average during this period, suggesting a retention of active autotrophic nitrifying biomass in the biofilm during winter. The collected data also show that nitrification is sensitive to the presence in the reactors of significant quantities of particulate matter originating from the resuspension of sediments during their anaerobic digestion after winter. Nitrification loss was observed during the warmer months (digestion active period) because of either a lack of DO in the biofilm caused by an increase of biofilm thickness or a decrease of the SRT caused by an increase of biofilm detachment or a combination of both. Model-based analysis of the complete system should be conducted to validate these mechanisms and quantify their importance. The model would also be useful to better understand autotrophic biomass activity in the biofilm at cold temperature.

ACKNOWLEDGEMENTS

This project was funded by a Collaborative Research and Development grant from the Natural Sciences and Engineering Research Council of Canada (NSERC), Bionest Technologies and Primodal. The project was also financially supported by the Quebec consortium for industrial bioprocess research and innovation (CRIBIQ). The authors would also like to thank the research and development team of Bionest for the provided technical and logistics support. Peter Vanrolleghem holds the Canada Research Chair on Water Quality Modelling.

REFERENCES

Alferes, J. & Vanrolleghem, P. A. (2016). Efficient automated quality assessment: Dealing with faulty on-line water quality sensors. *AI Communications*, 29 (6), 701-709. *doi*: 10.3233/AIC-160713

Boutet, E., Baillargeon, S., Patry, B. & Lessard, P. (2018). Simultaneous organic matter removal and nitrification of an inert self-supporting immersed media to upgrade aerated lagoons. *Water Science and Technology*, 77 (1), 51-59. *doi*: 10.2166/wst.2017.511

Choi, Y., Johnson, K., Hayes, D. & Xu, H. (2008). Pilot-scale aerated submerged biofilm reactor for organics removal and nitrification at cold temperatures. *Water Environment Research*, 80 (4), 292-297. *doi*: 10.2175/106143008X307566

Emerson, K., Russo, R. C., Lund, R. E. & Thurston, R. V. (1975). Aqueous ammonia equilibrium calculations: Effect of pH and temperature. *Journal of the Fisheries Research Board of Canada*, 32 (12), 2379-2383. *doi*: 10.1139/f75-274

Figueroa, L. A. & Silverstein, J. (1992). The effect of particulate organic matter on biofilm nitrification. *Water Environment Research*, 64 (5), 728-733. *doi*: 10.2175/WER.64.5.10

Hem, L. J., Rusten, B. & Ødegaard, H. (1994). Nitrification in a moving bed biofilm reactor. *Water Research*, 28 (6), 1425-1433. *doi*: 10.1016/0043-1354(94)90310-7

Henze, M., Gujer, W., Mino, T. & van Loosdrecht, M. C. M. (2006). *Activated Sludge Models ASM1, ASM2, ASM2d and ASM3*. London, UK: IWA Publishing.

Hoang, V., Delatolla, R., Abujamel, T., Mottawea, W., Gadbois, A., Laflamme, E. & Stintzi, A. (2014). Nitrifying moving bed biofilm reactor (MBBR) biofilm and biomass response to

long term exposure to 1 °C. *Water Research*, 49 (0), 215-224. *doi*: 10.1016/j.watres.2013.11.018

Horn, H. & Hempel, D. C. (1997). Growth and decay in an auto-/heterotrophic biofilm. *Water Research*, 31 (9), 2243-2252. *doi*: 10.1016/S0043-1354(97)00081-X

Houweling, C. D., Kharoune, L., Escalas, A. & Comeau, Y. (2005). Modeling ammonia removal in aerated facultative lagoons. *Water Science and Technology*, 51 (12), 139-142. *doi*: 10.2166/wst.2005.0448

Houweling, D., Kharoune, L., Escalas, A. & Comeau, Y. (2008). Dynamic modelling of nitrification in an aerated facultative lagoon. *Water Research*, 42 (1–2), 424-432. *doi*: 10.1016/j.watres.2007.07.034

Mattson, R. R., Wildman, M. & Just, C. (2018). Submerged attached-growth reactors as lagoon retrofits for cold-weather ammonia removal: performance and sizing. *Water Science and Technology*, 78 (8), 1625-1632. *doi*: 10.2166/wst.2018.399

Morgenroth E. (2003). Detachment: an often-overlooked phenomenon in biofilm research and modeling In Wuertz S., Bishop, P. & Wilderer, P. (Eds.), *Biofilms in Wastewater Treatment: An Interdisciplinary Approach* (pp. 264-290). London, UK: IWA Publishing.

Ouldali, S., Leduc, R. & Nguyen, V.-T. (1989). Uncertainty modeling of faculative aerated lagoon systems. *Water Research*, 23 (4), 451-459. *doi*: 10.1016/0043-1354(89)90136-X

Patry, B. Ridyard, G., Boutet, É. Lessard, P. & Vanrolleghem, P. A. (2018). Particulate matter accumulation and energy recovery potential in highly loaded enhanced aerated lagoons. In: *Proceedings 4th IWA Ecotechnologies for Wastewater Treatment Conference (ecoSTP 2018)*. London, ON, Canada, June 25-27.

Patry, B. (2019). *Monitoring, understanding and modelling of a biofilm technology to increase the capacity of aerated lagoons* (Doctoral thesis in preparation). Université Laval, Québec, Québec, Canada.

Québec (2015). *Municipal infrastructure*, Databank of Official Statistics on Québec [database]. Retrieved from http://www.bdso.gouv.qc.ca/pls/ken/ken2122_navig_niv_2.page_niv2?p_iden_tran=REPERCVK0BO4227792409817m$(Yd&p_lang=2&p_id_ss_domn=1039

Rich, L. G. (1999). *High Performance Aerated Lagoon Systems*. Annapolis, MD: American Society of Environmental Engineers.

Rieger, L., Gillot, S., Langergraber, G., Ohtsuki, T., Shaw, A., Takács, I. & Winkler, S. (2012). *Guidelines for Using Activated Sludge Models*. London, UK: IWA Publishing.

Roeleveld, P. J. & van Loosdrecht, M. C. M. (2002). Experience with guidelines for wastewater characterisation in The Netherlands. *Water Science and Technology*, 45 (6), 77-87. *doi*: 10.2166/wst.2002.0095

Rusten, B., Xf, Rn, Hem, L. J., Xd & Ødegaard, H. (1995). Nitrification of municipal wastewater in moving-bed biofilm reactors. *Water Environment Research*, 67 (1), 75-86. *doi*: 10.2175/106143095X131213

Särner, E. & Marklund, S. (1985). Influence of particulate organics on the removal of dissolved organics in fixed-film biological reactors. *Water Science and Technology*, 17 (2-3), 15-26. *doi*: 10.2166/wst.1985.0116

U.S. Environmental Protection Agency (USEPA) (2011). *Principles of Design and Operations of Wastewater Treatment Pond Systems for Plant Operators, Engineers, and Managers* (EPA/600/R-11/088). Retrieved from https://www.epa.gov/sites/production/files/2014-09/documents/lagoon-pond-treatment-2011.pdf

Vanrolleghem, P., Insel, G., Petersen, B., Sin, G., De Pauw, D., Nopens, I., Dovermann, H., Weijers, S. & Gernaey, K. (2003). A comprehensive model calibration procedure for activated sludge models. In: *Proceedings 76th Annual WEF Conference and Exposition*. Los Angeles, CA, October 11-15.

Wang, J., Jin, P., Bishop, P. L. & Li, F. (2012). Upgrade of three municipal wastewater treatment lagoons using a high surface area media. *Frontiers of Environmental Science & Engineering*, 6 (2), 288-293. *doi*: 10.1007/s11783-011-0280-z

Wanner, O., Eberl, H., Morgenroth, E., Noguera, D., Picioreanu, C., Rittmann, B. & van Loosdrecht, M. C. M. (2006). *Mathematical Modelling of Biofilms*. London, UK: IWA Publishing.

Wastewater Systems Effluent Regulations (2012). *Canada Gazette, Part II, June 29, 2012, Vol. 146, No. 15.* (SOR/2012-139). Retrieved from http://www.gazette.gc.ca/rp-pr/p2/2012/2012-07-18/html/sor-dors139-eng.html

Young, B., Delatolla, R., Ren, B., Kennedy, K., Laflamme, E. & Stintzi, A. (2016). Pilot-scale tertiary MBBR nitrification at 1°C: Characterization of ammonia removal rate, solids settleability and biofilm characteristics. *Environmental Technology*, 37 (16), 2124-2132. *doi*: 10.1080/09593330.2016.1143037