Real-time Control and Effluent Ammonia Violations Induced by Return Liquor Overloads

Peter A. Vanrolleghem*, Lluís Corominas and Xavier Flores-Alsina

model*EAU*, Département de génie civil et génie des eaux. Université Laval. 1065, avenue de la Médecine. Québec (QC) G1V 0A6, Canada
* To whom correspondence should be addressed: E-mail: peter.vanrolleghem@gci.ulaval.ca

ABSTRACT

Whole plant modeling and control has received increasing attention in recent years and as a result the Benchmark Simulation Model No 2 (BSM2) platform was developed to compare control strategies. The objective of this paper consists of evaluating whether MLSS concentration control (with changing set-points in summer and winter time to maintain nitrification capacity) could lead to effluent ammonia violations due to return liquor overloads and how such violations could be minimised by introducing alternative control systems. In this study three different control strategies have been implemented in the BSM2 platform, simulated and evaluated from a whole plant perspective. The results show that with the implementation of the MLSS controller a large overload is applied to the digester at the end of the winter period, but the large retention time of the anaerobic digester sufficiently dampens this overload. On the other hand, the flows can be treated more efficiently when storing the nitrogen-rich return flows during day time and releasing them at night using a simple timer-based controller.

KEYWORDS: Automatic control, Sludge digestion, Wastewater treatment, Whole plant modeling

INTRODUCTION

Since the early works of Gujer and Erni (1978) whole plant modeling has received increasing attention in the research community and it is also spreading in the wastewater industry, especially during the last decade (Filipe et al., 2001). A WWTP should be thought of as one completely integrated system, where primary/secondary clarification units, activated sludge reactors, anaerobic digesters, thickeners, dewatering systems and other sub-processes are linked together and considered not only on a local level as individual processes but as a whole taking into account all the interactions between the processes "within the fence". In case the interactions between WWTP units are not considered, sub-optimal plant operation will be an unavoidable outcome, leading to 'lower than possible' effluent quality and/or higher operational costs.

The work reported in this paper aims to evaluate whether MLSS concentration control (meant to maintain winter nitrification capacity) could lead to effluent ammonia violations due to return liquor overloads and how such violations could be minimised by introducing alternative control systems. This work fits within the overall idea of objectively evaluating control strategies at whole plant level as set out in the Benchmark Simulation Model No 2 platform initially described by Jeppsson et al. (2006). The particular MLSS control strategy considered is a two set-point MLSS controller by which the biomass concentration in winter is maintained higher than in summer. When transiting from winter to summer conditions, sludge is wasted at an accelerated rate to get the MLSS concentration down to summer values. This leads to increased anaerobic digester loading and thus to increased return liquor nitrogen loads to the water line. The question was whether this would negatively affect effluent quality during these periods of the year.

Copyright ©2010 Water Environment Federation. All Rights Reserved.

MATERIALS AND METHODS

Benchmark Simulation Model No. 2

Plant performance evaluation was based on a one-year simulation using the BSM2 plant-wide model of Jeppsson et al. (2007), using dynamic influent data generated according Gernaey et al. (2006).

The Benchmark Simulation Model No 2 (BSM2) is a detailed protocol for implementing, analysing and evaluating the impact and performance of both existing and novel control strategies applied to WWTPs. The on-going research and development of BSM2 is being performed within the framework of the IWA Task Group on Benchmarking of Control Strategies for WWTPs, established in 2005 (see www.benchmarkwwtp.org). BSM2 has been under development for several years with the preliminary concepts first introduced to a general audience at IWA's Watermatex2004 symposium (Jeppsson et al., 2006). Since then, the development has continued and a more complete version was presented at Watermatex2007 (Jeppsson et al., 2007). Recently (Nopens et al., 2010), final modifications to the plant layout and evaluation criteria were adopted and this is summarized below.

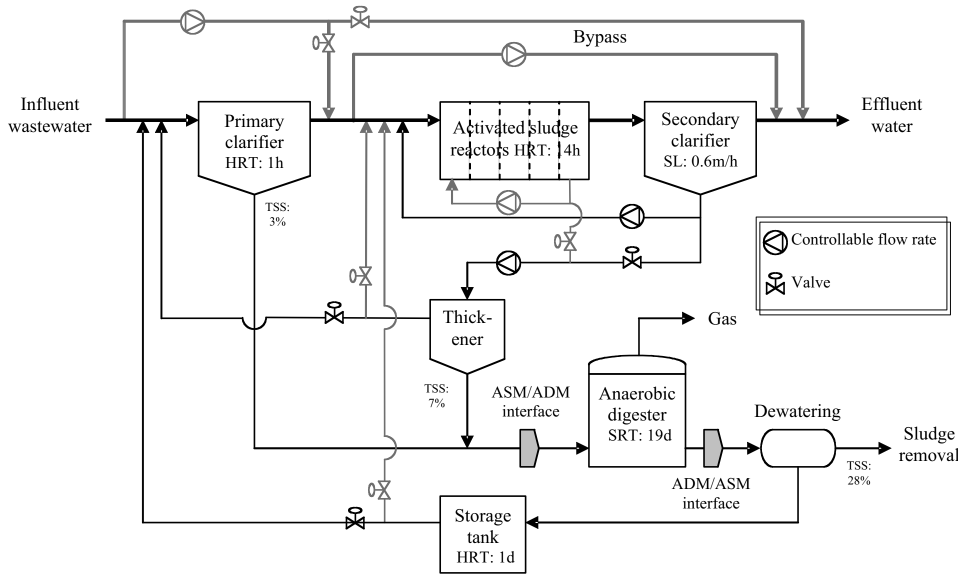

Figure 1. Plant layout for Benchmark Simulation Model No 2.

After thorough evaluation of the behaviour of the original BSM2 plant, two actions were undertaken to decrease the load of the treatment plant. First, the incoming wastewater nitrogen load was reduced by 15% (approximately offsetting the load from the recycled reject water in BSM2). The second action involved re-evaluating the tank volumes. To do this, the design guidelines from both the German Association for Water Economy, Wastewater and Waste (ATV A131, 2000) and US Environmental Protection Agency (Harris et al., 1982) were used. Both guidelines suggested that the aerobic volume should be increased by approximately a factor 2.5 compared to the original design. Anoxic tanks were increased from 1000 m^3 to 1500 m^3, aerobic tanks from 1333 m^3 to 3000 m^3, resulting in a total plant volume increase from 6000 m^3 to 12000 m^3. Due to these changes also some flow rates had to be updated to maintain a reasonable sludge residence time (SRT): the recycle flow rate was changed to 20648 $m^3.d^{-1}$ (i.e. the same as the average incoming flow rate); the internal recirculation rate was changed to 3 times the average incoming flow (61944 $m^3.d^{-1}$). These changes also resulted in changes in certain plant specifications. The hydraulic residence time (HRT) of the primary clarifier decreased from 1.2 h to 1 h, whereas the overall (aerobic + anoxic) HRT of the biological reactors was increased from

Copyright ©2010 Water Environment Federation. All Rights Reserved.

8 h to 14 h while the sludge loading to the secondary clarifier increased from 0.5 $m.h^{-1}$ to 0.6 $m.h^{-1}$. These changes also caused a drop in the SRT of the anaerobic digester from 20 to 19 d. The final plant layout including these changes is depicted in Figure 1. The main simulation platforms in which BSM2 implementation is available to date are SIMBA®, WEST®, FORTRAN and MATLAB®/SIMULINK®. These versions are ring-tested, i.e. their implementations have been verified to give the same results under steady state and dynamic conditions (Nopens et al., 2010).

A dissolved oxygen (DO) controller is installed that controls the DO set point in the second aerated tank (ASU4) to 2 g $O_2.m^{-3}$ by manipulating the aeration intensity of that tank, K_La_4. The aeration intensity in the first and third aerated tanks (ASU3 and ASU5) are set to the same value ($K_La_3 = K_La_4$) and half that value ($K_La_5 = 0.5\ K_La_4$). An external carbon source is fed into the first of the two anoxic reactors at a constant flow rate of 2 $m^3.d^{-1}$ (COD concentration = 400.000 $g.m^{-3}$).

Performance criteria

A set of 19 criteria (X_j) was used to evaluate the different alternatives. Flow-weighted average effluent concentrations of Total Kjeldahl Nitrogen (TKN), Total Nitrogen (TN), COD, BOD_5 and total suspended solids (TSS) are calculated during the one year evaluation period. Total sludge production is calculated from the wasted sludge and the effluent TSS flux.

To obtain an overall view on effluent quality, a weighted effluent quality index (EQI) is calculated according:

$$EQI = \frac{1}{1000\, t_{obs}} \int_{t_{start}}^{t_{end}} \left[PU_{TSS}(t) + PU_{COD}(t) + PU_{BOD}(t) + PU_{TKN}(t) + PU_{NO}(t) \right] Q_e(t)\, dt$$

where t_{obs} represents the total evaluation time (= t_{end} - t_{start}), Q_e is the effluent flow rate and the pollution units PU_{xxx} are calculated as the product of weights β_{xxx} and the concentration of compound *XXX* at time *(t)*. The weights β_{xxx} were determined based, in part, on empirical effluent component weightings from a paper by Vanrolleghem *et al.* (1996). Jeppsson *et al.* (2007) showed that the original criterion (*EQI*) does not reward - from an environmental perspective - any effort to go below the effluent limits for ammonium (i.e. identical β for *TKN* and nitrate nitrogen (S_{NO}) = 20). Therefore, for better agreement with ecological aspects related to discharge of ammonium (S_{NH}) versus S_{NO}, the weights in the *EQI*-expression were changed by Nopens et al. (2010) from 20 to 30 for *TKN* and from 20 to 10 for S_{NO}. Finally, the BOD_5 of any bypassed water is computed as 65% of the biodegradable COD, whereas that in the settler effluent only contains 25% BOD_5.

To get an idea on the overall operation costs of the plant, an Operational Cost Index (OCI) is calculated via:

$$OCI = AE + PE + 3 \cdot SP + 3 \cdot EC + ME - 6 \cdot MP + HE^{net}$$

where *AE* represents aeration energy, *PE* is pumping energy, *SP* is sludge production, *EC* is external carbon addition, *ME* is mixing energy, *MP* represents methane production and HE^{net} is the net heating energy needed to heat the anaerobic digester (normally zero thanks to available heat generated by the electricity production from methane). *AE*, *PE* and *ME* are calculated based on specific sub-models.

Other criteria include the percentages of time when effluent limits are violated. The effluent limits are defined as: $N_{tot,e}$ < 18 g $N.m^{-3}$, COD_e < 100 g $COD.m^{-3}$, $S_{NH,e}$ < 4 g $N.m^{-3}$, TSS_e < 30 g $TSS.m^{-3}$ and $BOD_{5,e}$ < 10 g $BOD_5.m^{-3}$. More details about the "time plant in violation" (TIV) criterion can be found in Copp (2002).

A detailed description of all BSM2 evaluation criteria can be found in Gernaey et al. (2010).

Copyright ©2010 Water Environment Federation. All Rights Reserved.

RESULTS AND DISCUSSION

As indicated in **Table 1** three different sludge handling control strategies (A_i) have been implemented, composed of one of the two MLSS controllers (i = 1 & 2) and one controller in the sludge line that stores return liquors and releases them when influent nitrogen concentrations are low (i = 3), similar to the Gujer and Erni (1978) controller. The first MLSS controller just maintains the sludge concentration at a fixed set-point, whereas the second controller implements the summer-winter MLSS shift. Thus, A_1 uses a fixed set-point MLSS controller, A_2 includes a temperature-dependent MLSS controller and, finally, A_3 extends A_2 with a storage volume controller.

Table 1. Control strategies evaluated in this case study

Characteristics	**MLSS Controller I**	**MLSS Controller II**	**$V_{storage}$ Controller**
Measured variable(s)	MLSS in AER3	MLSS and T in AER3	time
Setpoint/critical value	3300 g MLSS·m^{-3}	4300 g MLSS·m^{-3} (if T< 15 ^{o}C) 3300 g MLSS·m^{-3} (if T> 15 ^{o}C)	$Q_{storage}$ = 450 m^3·day^{-1} (if 12am < time < 8am) $Q_{storage}$ = 0 m^3·day^{-1} (if 8am < time < 12am)
Manipulated variable	Q_w	Q_w	$Q_{storage}$
Control algorithm	PI	Cascaded PI	ON/OFF
Applied in control strategies (Ai)	A_1	A_2 & A_3	A_3

The one-year simulation results depicted in **Figure 1a** clearly show that the MLSS=3300 g m^{-3} controller (strategy A_1) leads to important winter excursions of effluent ammonia concentrations (**Figure 1d**). Strategy A_2 properly tackles this by applying its summer-winter switch controller. As can be seen in **Table 2**, changing from A_1 to A_2 reduced the sludge production (due to the longer sludge age in winter conditions) (criterion X_7) and increased nitrification efficiency (X_1 and X_{17}). However, the higher biomass concentrations in winter increased the clarifier solids loading rate, leading to increased effluent organic matter related criteria (X_3, X_4 and X_5) and the TIV-values for COD, TSS and BOD_5 (X_{16}, X_{17} and X_{19}).

Now, would the extra wastage when moving from winter to summer MLSS concentrations affect effluent ammonia concentrations? Surprisingly, the effect of the MLSS set-point change in the aerobic reactor did not have a drastic effect on the sludge treatment line. **Figure 1b** confirms that indeed a large overload is applied to the digester at the end of the winter period, but **Figure 1c** implies that the large retention time of the anaerobic digester sufficiently dampens this overload. Thus, neither incurs a step change in the return liquor nitrogen load to the water line, nor does it increase the effluent ammonia concentrations (**Figure 1d**). Next to the large retention time in the anaerobic digester, the absence of negative impacts can also be explained by the fact that the sludge mass that is still present at the time the wastage is increased provides sufficient nitrification capacity to handle the increased N peaks. On top of that the temperature has already increased to spring values at that time, also helping to deal with the increased N-load.

When the $V_{storage}$ control is implemented (compare A_3 to A_2) a further decrease of the EQI (X_6) and the TIV for S_{NH} (X_{17}) can be observed. This reduction is attributed to the storage tank's smoothing effect on the overall nitrogen loads. The nitrogen-rich return flows are stored during day time when the plant is highly loaded (see **Figure 2a**), and are released at night when the influent nitrogen load is lower (**Figure 2b** and **c**). As a result the combined flows can be treated more efficiently (**Figure 2d**).

Copyright ©2010 Water Environment Federation. All Rights Reserved.

Table 2. Evaluation criteria for the different control strategies

X_i	Evaluation criteria	A_1	A_2	A_3	UNITS
X_1	Total Kjeldahl Nitrogen (TKN)	3.8	3.5	3.3	$g\ N \cdot m^{-3}$
X_2	Total Nitrogen (TN)	11.3	10.9	11.1	$g\ N \cdot m^{-3}$
X_3	Chemical oxygen demand (COD)	48.9	60.3	60.2	$g\ COD \cdot m^{-3}$
X_4	Biochemical oxygen demand (BOD_5)	2.7	3.9	3.9	$g\ COD \cdot m^{-3}$
X_5	Total suspended solids (TSS)	14.9	23.7	23.5	$g\ TSS \cdot m^{-3}$
X_6	Effluent quality index (EQI)	5673	6106	6075	$kg\ poll \cdot day^{-1}$
X_7	Sludge production (P_{sludge})	2710	2523	2525	$kg\ TSS \cdot day^{-1}$
X_8	Aeration energy (AE)	3619	3779	3800	$kWh \cdot day^{-1}$
X_9	Pumping energy (PE)	445.6	439.9	439.9	$kWh \cdot day^{-1}$
X_{10}	Carbon addition (CS)	800.0	800.0	800.0	$kg\ COD \cdot day^{-1}$
X_{11}	Mixing energy (ME)	768.1	768.1	768.1	$kWh \cdot day^{-1}$
X_{12}	Heating energy (HE)	4247	4085	4086	$kWh \cdot day^{-1}$
X_{13}	Methane production (MP)	1089	1033	1034	$kg\ CH_4 \cdot day^{-1}$
X_{14}	OCI	8828	8757	8782	-
X_{15}	Time in violation for TN (TIV_TN)	0.32	0.95	1.20	%
X_{16}	Time in violation for COD (TIV_COD)	0.06	1.07	1.05	%
X_{17}	Time in violation for ammonium (TIV_S_{NH})	16.21	1.41	0.55	%
X_{18}	Time in violation for TSS (TIV_TSS)	0.27	2.20	2.20	%
X_{19}	Time in violation for BOD_5 (TIV_BOD_5)	0.82	1.17	1.17	%

CONCLUSIONS

This paper demonstrates the importance of evaluating control strategies from a whole plant perspective by studying the effect of an MLSS controller implemented in the liquid line to the return liquor overloads. The key findings of the study can be summarized in the following points:

- The MLSS controller with different set-points during winter and summer time decreases total effluent nitrogen compared to a single set-point strategy and drastically reduces the ammonia effluent limit violations.
- The change of MLSS set-point during winter/summer period causes a sharp increase in the MLSS load entering the digester. However, the large hydraulic retention time of the anaerobic digester dampens this overload and, consequently, there are no effluent ammonia violations induced by return liquor overloads.
- The simple timer-based storage tank controller smoothes the ammonium peaks in the effluent by storing nitrogen rich return flows during day-time when the plant is highly loaded.

Copyright ©2010 Water Environment Federation. All Rights Reserved.

ACKNOWLEDGEMENT

This research is supported by a NSERC Special Research Opportunities grant as part of the Canadian contribution to the European Union 6th Framework project NEPTUNE. Lluís Corominas benefits from the postdoctoral fellowship "Juan de la Cierva" of the Government of Spain. Peter Vanrolleghem holds the Canada Research Chair in Water Quality Modelling.

REFERENCES

ATV A131 (2000). *ATV-DVWK Arbeitsblatt A 131: Bemessungen von einstufigen Belebungsanlagen ab 5000 EW*. ATV, Hennef, Germany [in German].

Copp J.B. (ed.) (2002). The *COST Simulation Benchmark: Description and Simulator Manual*. ISBN 92-894-1658-0, Office for Official Publications of the European Community, Luxembourg.

Filipe C.D.M., Crawford G., Johnson B. and Daigger G.T. (2001) Integrating ASM2d models into whole plant mass balance simulators. In: *Proceedings 74th Annual WEF Conference and Exposition.* Atlanta, USA, October 14-18 2001. (on CD-ROM).

Gernaey K.V., Jeppsson U., Vanrolleghem P.A, Copp J.B. and Steyer J.-P. (ed.) (2010). *Benchmarking of Control Strategies for Wastewater Treatment Plants*. Scientific and Technical Report. IWA Publishing, London.

Gernaey K.V., Rosen C., Jeppsson U. (2006). WWTP dynamic disturbance modelling – an essential module for long-term benchmarking development. *Wat. Sci. Tech*. **53**(4-5), 225-234.

Gujer W. and Erni P. (1978). The effect of diurnal ammonium load variation on the performance of nitrifying activated sludge processes. *Prog. Water Technol*. **10**, 391–407.

Harris R.W., Cullinane M.J. and Sun P. (eds) (1982). *Process Design & Cost Estimating Algorithms for the Computer Assisted Procedure for Design and Evaluation of Wastewater Treatment Systems (CAPDET)*. US EPA, Office of Water Program Operations.

Jeppsson U., Pons M.N., Nopens I., Alex J., Copp J.B., Gernaey K.V., Rosen C., Steyer J.P. and Vanrolleghem. P.A. (2007). Benchmark Simulation Model No 2 – general protocol and exploratory case studies. *Wat. Sci. Tech*., **56**(8), 287-295.

Jeppsson U., Rosen C., Alex J., Copp J., Gernaey K.V., Pons M.-N. and Vanrolleghem P.A. (2006) Towards a benchmark simulation model for plant-wide control strategy performance evaluation of WWTPs. *Wat. Sci. Tech*., **53**(1), 287-295.

Nopens I., Benedetti L., Jeppsson U., Pons M.-N., Alex J., Copp J.B., Gernaey K.V., Rosen C., Steyer J.-P. and Vanrolleghem P.A. (2010) Benchmark Simulation Model No 2 - Finalisation of plant layout and default control strategy. *Wat. Sci. Tech*. (in press).

Vanrolleghem P.A., Jeppsson U., Carstensen J., Carlsson B. and Olsson G. (1996). Integration of WWT plant design and operation – A systematic approach using cost functions. *Wat. Sci. Tech.*, **34**(3-4), 159-171.

Copyright ©2010 Water Environment Federation. All Rights Reserved.

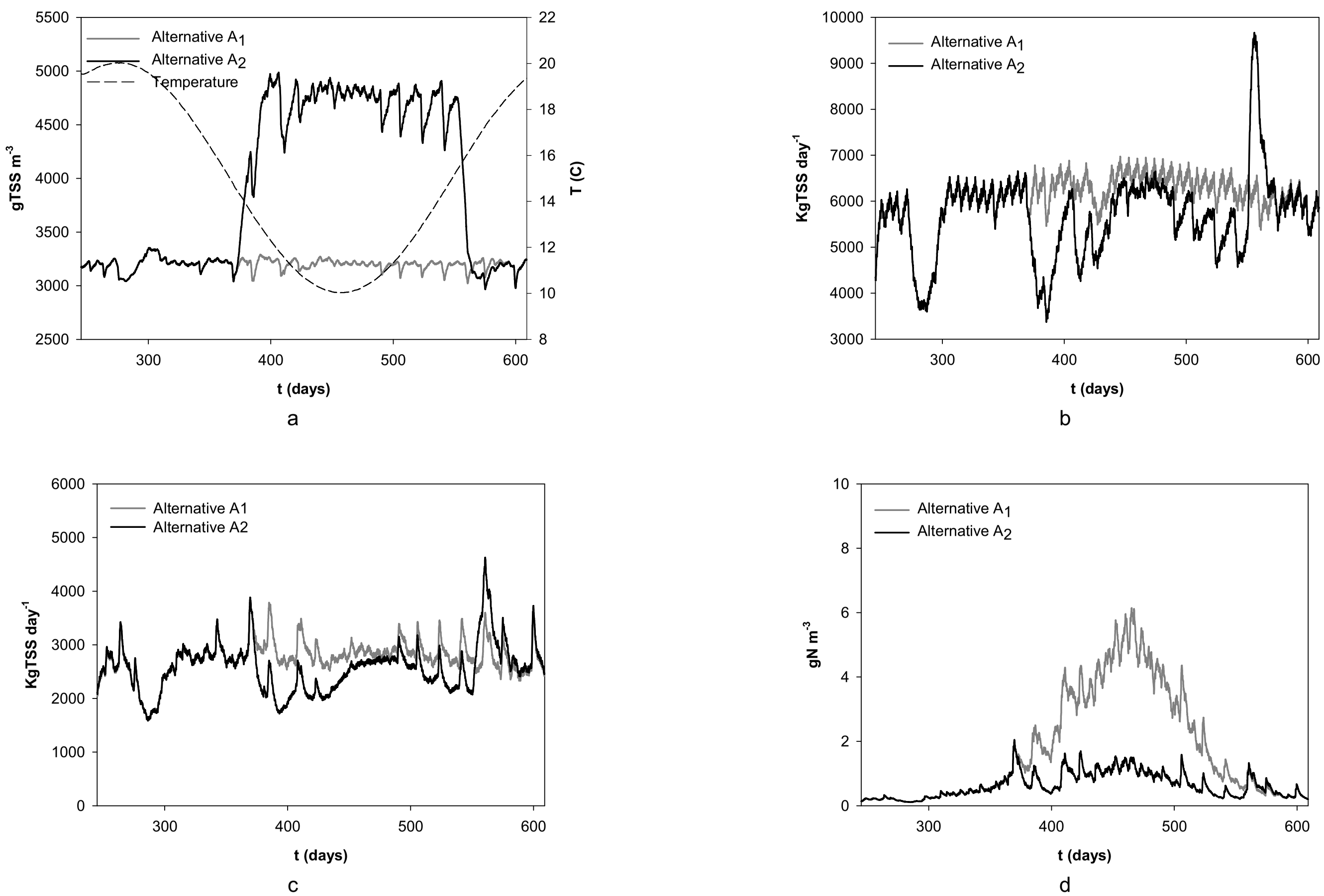

Figure 1. Yearly dynamic profile of alternatives A_1 and A_2 : (a) MLSS concentration in the third aerobic reactor, (b) TSS load before the anaerobic digester, (c) TSS after the anaerobic digester, (d) ammonium in the effluent

Copyright ©2010 Water Environment Federation. All Rights Reserved.

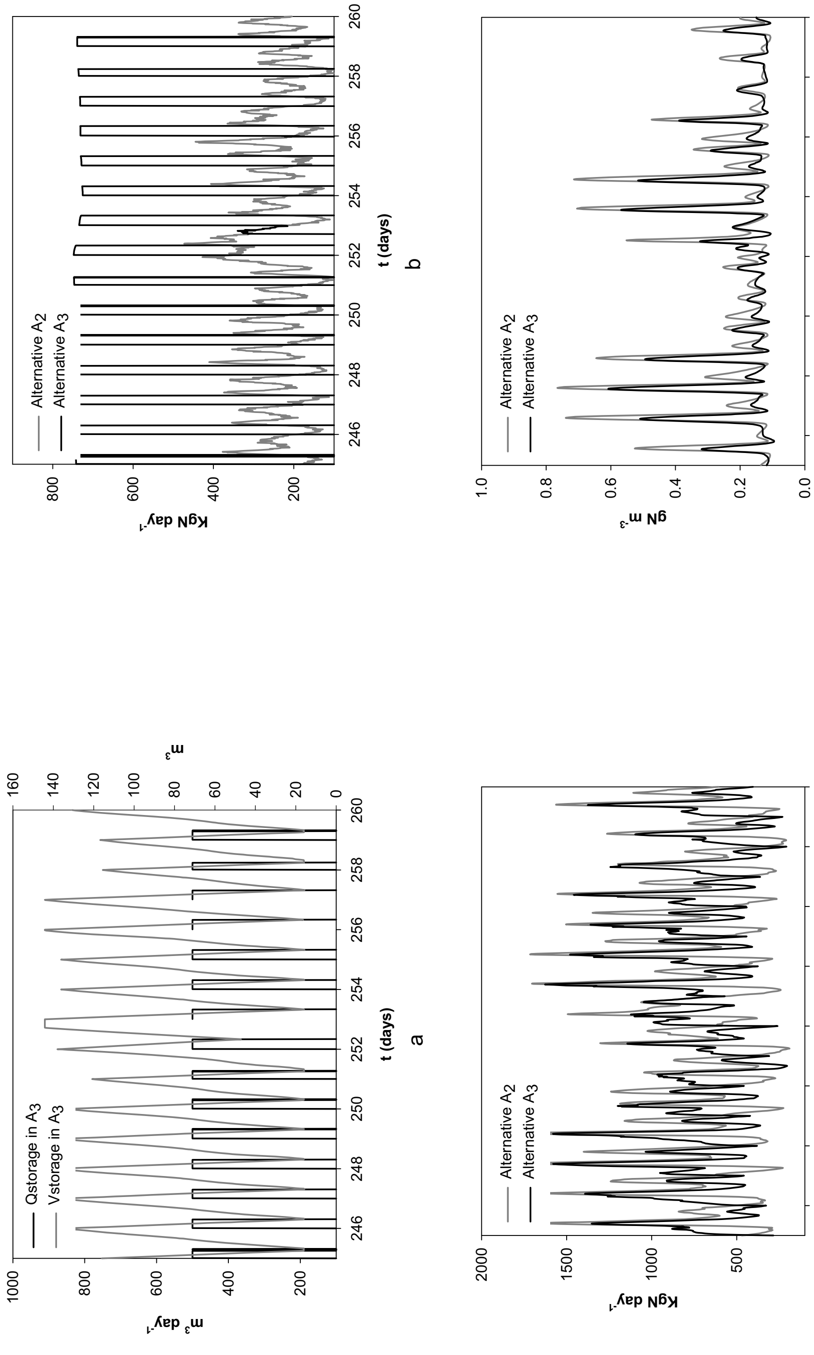

Figure 2. Snapshot of the yearly dynamic profile of alternatives A_2 and A_3:(a) outflow and volume of the storage tank, (b) N load coming from the sludge treatment line, (c) combined influent and sludge line N load and (d) ammonium in the effluent

Copyright ©2010 Water Environment Federation. All Rights Reserved.