Simulation of municipal-industrial full scale WWTP in an arid climate by application of ASM3

Abdelsalam Elawwad, Mohamed Zaghloul and Hisham Abdel-Halim

ABSTRACT

In developing countries, and due to the high cost of treatment of industrial wastewater, municipal wastewater treatment facilities usually receive a mixture of municipal wastewater and partially treated industrial wastewater. As a result, an increased potential for shock loads with high pollutant concentrations is expected. The use of mathematical modelling of wastewater treatment is highly efficient in such cases. A dynamic model based on activated sludge model no. 3 (ASM3) describing the performance of the activated sludge process at a full scale wastewater treatment plant (WWTP) receiving mixed domestic–industrial wastewater located in an arid area is presented. ASM3 was extended by adding the Arrhenius equation to respond to changes in temperature. BioWin software V.4 was used as the model platform. The model was calibrated under steady-state conditions, adjusting only three kinetic and stoichiometric parameters: maximum heterotrophic growth rate ($\mu_H = 8\ d^{-1}$), heterotrophic aerobic decay rate (b_H, $O_2 = 0.18\ d^{-1}$), and aerobic heterotrophic yield ($Y_{H,O2} = 0.4$ (gCOD/gCOD)). ASM3 was successful in predicting the WWTP performance, as the model was validated with 10 months of routine daily measurements. ASM3 extended with the Arrhenius equation could be helpful in the design and operation of WWTPs with mixed municipal–industrial influent in arid areas.

Key words | biological treatment, BioWin, mathematical modelling, wastewater

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INTRODUCTION

The most widely used biological wastewater treatment method is activated sludge, due to its flexibility, reliability, and high efficiency. As efficient as the activated sludge method is, this method is notably sensitive to many factors such as temperature, type of wastewater, dissolved oxygen concentration, and plant operation (Tchobanoglous *et al.* 2003). This sensitivity makes the successful operation of wastewater treatment plants (WWTPs) a challenging task, especially in the case of shock loads or changes in wastewater type. Mathematical modelling of the biological treatment offers an excellent tool to simulate activated sludge plants, predict the effluent quality under any circumstances and obtain a better understanding of the factors affecting the process.

Mathematical modelling requires formulating the bacterial growth and decay rates (WEF 2013). The activated sludge model (ASM) family is a group of models for simulating activated sludge-based treatment methods developed by the IWA task group. The first model, the ASM1, was first developed and advanced through the ASM2, ASM2d, and the recent simplified ASM3 model. Activated sludge model no. 3 (ASM3) was developed to overcome certain defects of ASM1 and proposed to become a new standard for future modelling (Henze *et al.* 2000).

For efficient process simulation, many protocols for activated sludge modelling, such as STOWA, WERF, BIOMATH, HSG, and GMP unified protocol (WEF 2013), were developed and widely used by researchers. Two important steps involved in process simulation are calibration and validation. The primary effective kinetic and stoichiometric parameters in calibration are the maximum heterotrophic

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growth rate, the heterotrophic decay rate, the half saturation coefficient, and the heterotrophic yield. Calibrated model parameters differ significantly from the default values, usually showing mistakes in the model formulation or the hydraulics of WWTPs (Hulsbeek *et al.* 2002).

ASM3 was widely applied and became established in developed countries, especially European countries. ASM-family kinetic parameters are temperature dependent and were originally developed and applied to municipal wastewater at cold and moderate temperatures ranging from 10 to 25 °C (Henze *et al.* 2000). However, publications and case studies from developing countries with arid areas are limited. Most of the WWTPs in developing countries are designed for suspended solid and organic matter removal only. Usually, there are no legal constraints regarding nutrient removal (Brdjanovic *et al.* 2007).

The aim of this paper is to evaluate the capability of ASM3 to describe the performance of full scale WWTPs that usually receive mixed domestic and industrial wastewater in developing countries with arid climates, such as in Egypt. Moreover, WWTP performance must be optimized to face stricter environmental regulations in the future.

MATERIALS AND METHODS

The case study in the first part of this paper is the western 6th of October WWTP, located at the 6th of October City, Egypt. Egypt has a hot desert climate with rare rainfall, hot summers and mild winters. The raw sewage temperature is in the range 13–34 °C with an annual average of approximately 23 °C.

The WWTP under study receives 150,000 m^3/d of wastewater, 35% of which is industrial wastewater. The industrial waste comes from an industrial area of 1,400 factories, incorporating furniture, metals and galvanization, food industries, medical and chemical industries, and textiles. The WWTP is designed for organic removal only and consists of three identical treatment trains with a capacity of 50,000 m^3/d each.

Sewage treatment is based on a conventional configuration, containing screens, grit chambers, primary settlers, biological tanks with surface aeration, and final clarifiers. Most of the settled sludge is returned to the beginning of the aeration tank after wasting excess sludge from the final clarifiers (Figure 1). The plant operator found no reason to change return sludge and excess sludge quantities. Therefore, excess and return sludge pumping was continuous over 24 hours at a constant rate. This strategy resulted in fluctuating sludge retention time (SRT) over the validation period to be between (11.4 ± 4) days. Excess sludge was returned to primary settling tanks to improve their settling performance.

The effluent disposal standards at present are: $BOD_5 \leq 60$ mg/L, TSS ≤ 50 mg/L and COD ≤ 80 mg/L (where BOD_5 is biochemical oxygen demand, TSS is total suspended solids, and COD is chemical oxygen demand) with no legal constraints regarding nutrient removal. The biologically treated effluent does not meet

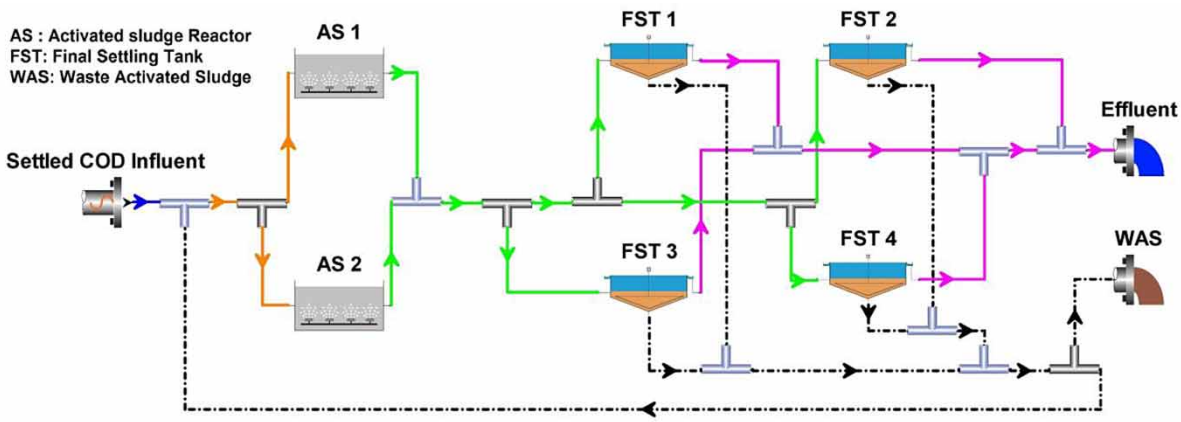


Figure 1 | Simplified plant process schematic from BioWin software.

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the legal requirements. Therefore, biologically treated effluent is passing through sand filters and chlorine steps and subsequently being used for planting non-edible trees.

Historical data routinely collected by the staff of the plant were obtained from HCWW, Egypt. The data include a detailed description of the processes, plant components, and historical daily measurements from raw sewage, settled sewage, and biologically treated effluent. Data for one treatment train (out of three treatment trains) were selected over 10 months (from April 2014 to February 2015) for model validation. The selected treatment train operated continuously without interruption or major maintenance over these 10 months. Fortunately, the operator was operating this treatment train with semi-constant flow, which is not common in municipal WWTPs. The incoming flow was pumped to the studied treatment train with a constant flow of 50,000 m^3/day, and any overflow was sent to the rest of the treatment trains in the WWTP. Historical data lacked certain measurements, such as filtered COD, alkalinity, phosphorus, and nitrogen compounds (nitrates, nitrites and total Kjeldahl nitrogen (TKN)). SRT was estimated based on Equation (1) (Tchobanoglous *et al.* 2003). Tables 1 and 2 show the average historical daily routine measurement and operating conditions.

$$SRT = \frac{V * \mathrm{MLVSS}}{(Q_{Ex} * \mathrm{VSS_{Ex}}) + (Q_{eff} * \mathrm{VSS_{eff}})} \quad (1)$$

where SRT, sludge retention time (days); V, reactor volume (m^3); MLVSS, mixed liquor volatile suspended solids (g/m^3); Q_{ex}, excess sludge quantity (m^3/d); Q_{eff}, effluent flow rate (m^3/d); VSS_{ex}, volatile suspended solids in excess sludge (m^3/d), and VSS_{eff}, volatile suspended solids in effluent (m^3/d).

Table 1 | WWTP average of historical daily routine measurements over 10 months

Test	Raw sewage	Settled effluent	Biologically treated effluent
Flow (m^3/d)	49,106 ± 633		
BOD_5 (mg/l)	506 ± 91	263 ± 47	36 ± 5
COD_{tot} (mg/l)	1,459 ± 279	462 ± 82	95 ± 17
TSS (mg/l)	452 ± 94	182 ± 36	36 ± 5
VSS (mg/l)	401 ± 75	128 ± 33	30 ± 6
Temp. (°C)	25 ± 5.3	–	–
pH	8.3 ± 0.6	8.2 ± 0.6	8.2 ± 0.45

Table 2 | Average of historical operational data of activated sludge process over 10 months

Test	Biological treatment
MLSS (mg/l)	4,010 ± 697
MLVSS (mg/l)	2,730 ± 687
F/M ratio	0.16 ± 0.15
SRT	11.5 ± 4
DO (mg/l)	1.6 ± 0.44
RAS flow (m^3/d)	50,112 ± 0
WAS flow (m^3/d)	864 ± 0
RAS TSS (mg/l)	7,264 ± 1,244
RAS VSS (mg/l)	5,610 ± 1,785

For calibration purposes, an intensive sampling program was performed for 7 days at the WWTP to perform accurate wastewater characterization. Because this study focussed on the biological stage only, the WWTP performance was monitored for settled sewage (inlet to the biological process) and biologically treated effluent. The temperature was optimum during the sampling program (sewage temperature approximately 29 °C). The analyses were performed according to *Standard Methods for the Examination of Water and Wastewater* (APHA 2005). Mass and hydraulic balances at the plant were performed based on hydrometer readings and flow rates of pumps for the inflow, outflow, waste and return sludge, TSS and COD measurements. The information obtained through the sampling program was combined with the historical daily routine measurements of the plant. Wastewater characterization was performed based on the STOWA method (Roeleveld & van Loosdrecht 2002). Tables 3 and 4 show the averaged measurements and wastewater characterization during the sampling program, respectively.

A steady-state model for the biological process was built using BioWin 4 software (Figure 1), which is a semi-open platform software that allows the user to introduce the model equations and parameters. The modelling work was based on the GMP unified protocol proposed by the GMP

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Table 3 | Averaged measurements during the sampling program

Test	Settled sewage	Biologically treated effluent
Flow (m^3/d)	49416.7 ± 276	–
Temp. (°C)	28.93 ± 0.6	–
pH	8.92 ± 0.2	8.77 ± 0.07
Total alkalinity	290 ± 81.6	–
TSS (mg/l)	349 ± 38	33.7 ± 7
VSS (mg/l)	287 ± 39	26.8 ± 7.7
BOD_5 (mg/l)	207 ± 19	33.7 ± 6
COD (mg/l)	483 ± 58	81.3 ± 8
Filtered COD (mg/l)	234 ± 28	32 ± 3
DO (mg/l)	0.13 ± 0.1	–
TKN (mg/l)	34.2 ± 1	–
NH_4-N (mg/l)	–	26.2 ± 0.5
NO_2-N (mg/l)	0.05 ± 0.03	0.24 ± 0.09
NO_3-N (mg/l)	1 ± 0.8	7.4 ± 4

Table 4 | COD fractions for settled sewage

Parameter	Name	Value gCOD/m^3	Ratio to total COD
S_I	Soluble inert organic matter	14.6	3%
S_S	Soluble substrates	219.1	45%
X_I	Particulate inert organic matter	144.3	30%
X_S	Slowly biodegradable substrate	105.1	22%

Task Group was selected for this study (Rieger *et al.* 2012). For the simulation of a WWTP, the ASM3 (Henze *et al.* 2000) was used.

To model the effect of temperature, the Arrhenius equation (Equation (2)) was added to the reaction rates in ASM3. The Arrhenius equation gives a generalized estimate of temperature effects on biological reaction rates (Tchobanoglous *et al.* 2003),

$$k_T = k_{20} * \theta^{(T-20)} \quad (2)$$

where k_T is the rate at the desired temperature (T), and k_{20} is the rate at 20 °C.

RESULTS AND DISCUSSION

Model calibration

Calibration of the ASM3 model was performed using steady state data on treatment plant operation. Calibration of the model was adjusted in two steps, calibrating the TSS followed by the COD. The TSS calibration depended mainly on the accuracy of the wastewater characterization, because the model calculates the suspended solids using the ratio of soluble, particulate COD to total COD. Then, the TSS removal efficiency in the final sedimentation tanks was adjusted to 99.8%, as this determines the amount of suspended solids in the returned sludge. The second step is to calibrate the COD by adjusting the ASM3 kinetic and stoichiometric parameters. The model was calibrated adjusting only three parameters: maximum heterotrophic growth rate, heterotrophic aerobic decay rate, and aerobic heterotrophic yield. Table 5 shows the calibrated parameters and their default values for the ASM3. The parameters were compared to the available parameters in the literature (Table 5). The rest of the parameters showed a negligible effect on the outcome of the model, therefore, the default ASM3 values were set for them. The calibrated value for heterotrophic aerobic decay rate (b_H, $O_2 = 0.18\ d^{-1}$) was not far from the default value and the values stated in the literature. Meanwhile, the calibrated values for maximum heterotrophic growth rate ($\mu_H = 8\ d^{-1}$) and aerobic heterotrophic yield ($Y_{H,O2} = 0.4$ (gCOD/gCOD)) were far from the default values (Table 5). However, the stated values in the literature for maximum heterotrophic growth rate and aerobic heterotrophic yield are extensive and depend on the conditions of each research. ASM-family kinetic parameters and their default values are originally developed and applied for municipal wastewater at a cold and moderate temperatures range between 10 and 25 °C (Henze *et al.* 2000). However, the results from this research and many other studies (Table 5) suggest that default values especially for maximum heterotrophic growth rate and aerobic heterotrophic yield can fall in an extensive range. The use of default values for the heterotrophic growth rate and aerobic heterotrophic yield suggested by wastewater processes programs can lead to

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Table 5 | Calibrated ASM3 kinetic and stoichiometric parameters

Parameter	μ_H Max. growth rate of heterotrophic biomass	$b_{H,O2}$ Aerobic endogenous respiration of heterotrophic biomass	$Y_{H,O2}$ Aerobic yield of heterotrophic biomass
This study	**8**	**0.18**	**0.4**
Default value	2	0.2	0.63
Koch (2000)	3	0.3	0.8
Ni *et al.* (2008)	0.58	0.016	0.68
Liwarska-Bizukojc *et al.* (2008)	7.5–21.4	0.22–0.28	0.44–0.79
Henze *et al.* (1987)	3–6	0.2–0.62	0.67
Solfrank & Gujer (1991)	1.5	0.24	0.64
Kappeler & Gujer (1992)	1–8		
Henze *et al.* (1995)	3–6	0.2–0.4	0.63
Bjerre (1997)	6.8		0.55
Hvited-Jacobsen *et al.* (1998)	3.25		0.55
Almeida & Butler (2002)	6.3	–	0.57
Sin & Vanrolleghem (2007)	2	–	
Karahan *et al.* (2008)	2	0.1	0.68
Trojanowicz *et al.* (2009)	6.1	0.18	0.58

inaccurate designs. Therefore, default values for the heterotrophic growth rate and aerobic heterotrophic yield have to be categorized and recommended for wastewater modelling based on the conditions of the wastewater process studied.

Model validation

COD analysis

The influent COD is entered into the BioWin software as the influent COD is measured at the plant. As shown in Figure 2, ASM3 provided good representation for WWTP performance. The modelled effluent COD is consistent with the measured COD values. COD is the main parameter in the ASM models, so adjusting the COD represents most of the work performed to calibrate the model.

A dynamic simulation was run before and after adding the Arrhenius equation to ASM3 equations, and the results were compared to ensure that the model responded to changes in the temperature. Adding the Arrhenius equation showed lower COD effluent values, and an easier calibration was obtained. Under arid climate conditions, a higher temperature is expected to enhance the kinetics of the biological processes. This enhancement was important as the temperature range during the validation period (10 months) was wide, ranging from 12.8 to 33.9 °C with an average of 22.8 °C, and the temperature was mostly above 20 °C.

During the validation period, shock loads occurred. The shock loads were used to test the model response to a sudden change in influent quality. The shock loads happened on different days as shown in Figure 2. The model was very successful in predicting the WWTP performance in these situations.

TSS analysis

The model also describes the suspended solids concentrations in the influent, effluent and in return activated sludge (RAS). Calibrating the influent TSS, as shown in Figures 3 and 4, depended mainly on adjusting the wastewater characterization, as the wastewater characterization is the only tie between the COD and the TSS, hence the ASM3 and the TSS. However, the TSS of the effluent and the RAS have another factor affecting their values in the model. The TSS removal efficiency in the final sedimentation tanks plays a major role in the TSS values in the

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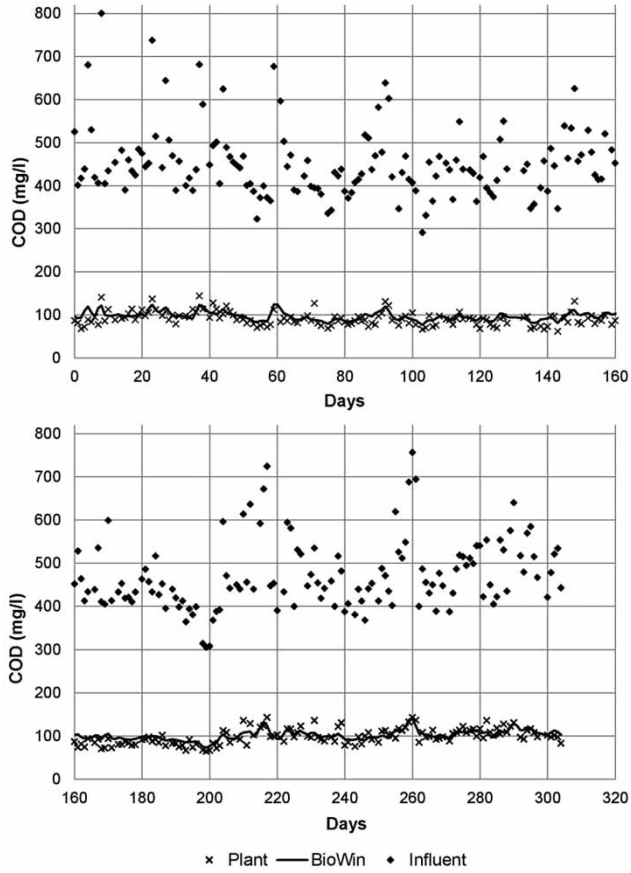


Figure 2 | Influent and effluent COD – plant vs model data for days 0 to 160 (upper graph), and days 160 to 305 (lower graph).

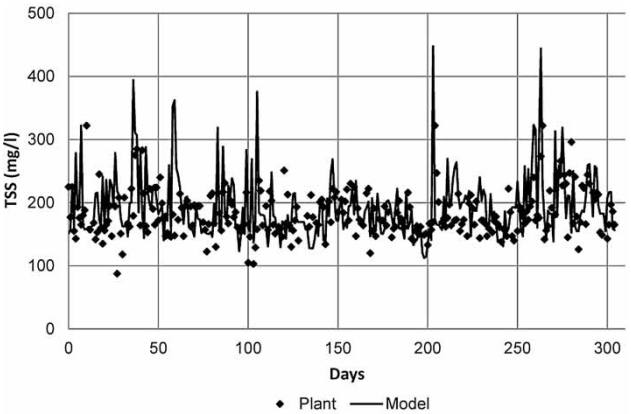


Figure 3 | Influent TSS – plant vs model data.

effluent and the RAS, and consequently affects the COD in the effluent. Final sedimentation tank removal efficiency was calibrated to 99.8%. The model was successful in validating the MLVSS values in the activated sludge reactor. The MLVSS in activated sludge reactor values (Figure 5) depends on the influent suspended solids, which depends on the wastewater characterization, and the RAS suspended solids (Figure 6), which depends on the final clarifier removal efficiency. The SRT obtained from the model was (12.0 ± 0.3) days over the validation period and shows a good representation of the plant (11.4 ± 4), considering that the plant data should not be so dispersed.

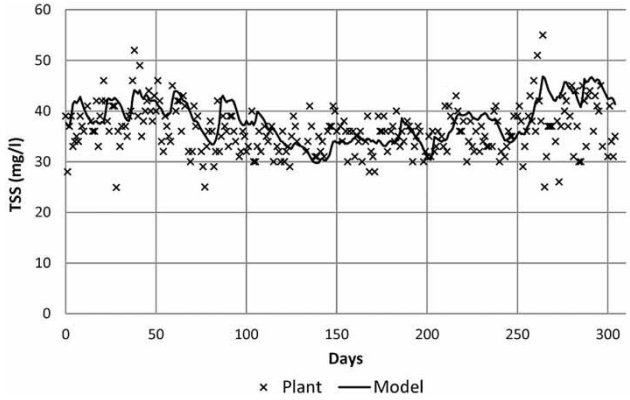


Figure 4 | Effluent TSS – plant vs model data.

Nitrification

In spite of the good sludge age of 12 days and relatively high temperature, elimination of ammonia was limited in the WWTP, as was concluded from the measurements done during sampling program. From oxygen measurements, oxygen was always above 1.5 mg/l and therefore oxygen was

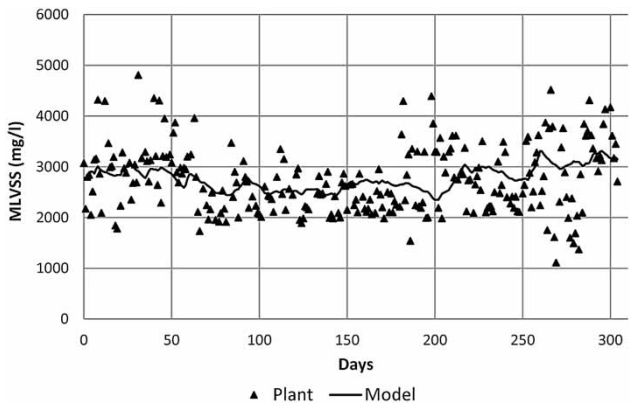


Figure 5 | MLVSS in reactor – plant vs model data.

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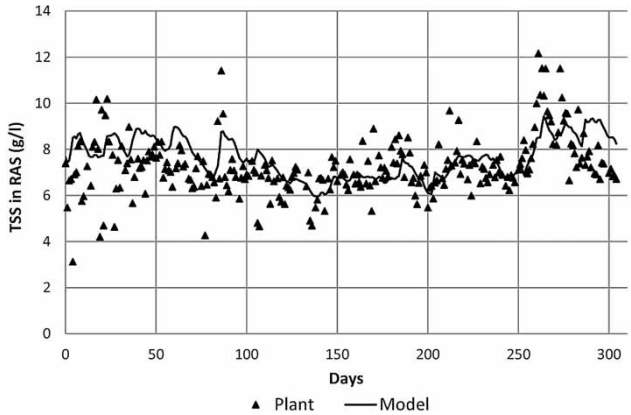


Figure 6 | TSS in return activated sludge (RAS) – plant vs model data.

not the limiting parameter for the nitrification process. Due to the low performance of the nitrification process in the WWTP under study, calibration of the nitrification process was neglected. All kinetic and stoichiometric parameters related to the nitrification process were set to the default values. The model was able to predict that no nitrification is happening.

Nitrifying bacteria responsible for the nitrification process are highly sensitive to a number of environmental factors. These include oxygen concentration, temperature, pH, elevated BOD and the presence of toxic or inhibiting substances. Nitrifying bacteria have a low growth rate compared to heterotrophic bacteria. The relatively high heterotrophic growth rate ($\mu_H = 8\ d^{-1}$) reported in this study could be the cause of wash out of nitrifying bacteria out of system.

Another reason could be that not all COD is treated. As shown in Tables 1 and 3, COD effluent is 80–100 mg/l and BOD effluent is 30–40 mg/l. High COD concentrations in the effluent could cause inhibition of the nitrification process. The WWTP receives non-toxic industrial wastewater (furniture factories, metals and galvanization industries, food industries, medical and chemical industries, and textiles). However, the composition of this mixture of municipal–industrial wastewater could be another reason for inhibition of the nitrification process.

CONCLUSIONS

In this study, modelling applications for municipal and industrial wastewater treatment were introduced in a developing country with an arid climate. The ASM3 model extended with the Arrhenius equation was used to simulate the performance of a full scale WWTP receiving mixed domestic–industrial wastewater and located in an arid area. Altered kinetic and stoichiometric parameters for the calibration were the heterotrophic organism growth rate (μ_H), the heterotrophic organism decay rate (b_H), and the heterotrophic organism yield (Y_H), which changed due to the radical variation in temperature in the plant and due to the presence of the industrial wastewater, which was not accounted for in the ASM3 default values. We concluded that the proposed model gave good correlations with measurements of COD, TSS and MLSS concentrations. We can conclude that the ASM3 model extended with the Arrhenius equation was able to describe plant operation. Although ASM-family models including the BioWin AS model were originally developed and applied to municipal wastewater, the model was demonstrated to be a useful tool in predicting performance of WWTPs receiving mixed domestic–industrial wastewater in arid climates. During the study some limitations were encountered, which provided recommendations for any future studies. The routinely collected data of the plant did not contain any nitrogen related measurements as there are no restrictions regarding nitrogen removal in Egypt until now. So it is recommended to perform long-term measurements to be able to validate the model for nitrification. ASM3 can be a reliable and flexible tool to assess the performance of WWTPs in developing countries with arid climate. Proposals for future research could include the use of mathematical modelling to upgrade and optimize the process in these areas, especially regarding nitrification. This could be important in future in light of recent trends to apply stricter environmental regulations.

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