MODELING OF RIYADH SEWAGE TREATMENT PLANT: 1-MODEL DEVELOPMENT, VERIFICATION AND SIMULATION

A.S. Al-Mozini

Riyadh Sewage Treatment Plant (RSTP), North Plant, King Saud University
P.O. Box 800, Riyadh, Saudi Arabia
Mozini08@yahoo.com

*I.S. Al-Mutaz and A.E. Abasaeed**

Department of Chemical Engineering, King Saud University
P.O. Box 800, Riyadh, Saudi Arabia
almutaz@ksu.edu.sa - abasaeed@ksu.edu.sa

*Corresponding Author

(Received: June 18, 2008 – Accepted in Revised Form: July 2, 2009)

Abstract In Saudi Arabia, the Riyadh Sewage Treatment Plant (RSTP) uses the activated sludge technology as the secondary treatment process for sewage. Due to the complex nature of the process, a rather simplified, yet practical, steady state model that captures the most important features of the RSTP was developed. Actual operating and design conditions were obtained from RSTP data bank. The monthly average plant data obtained in 1997 was used to calibrate the model by adjusting four parameters: $\mu_{max,H}$, $\mu_{max,A}$, b_H and b_A (seasonal variation of temperature are therefore embedded within these values) A computer program was developed to solve the resulting model equations. The predictive nature of the proposed model was verified (without further tuning) using five sets of plant data collected in 2003. Model predictions were found to be in excellent agreement with the plant data (within±5%). Simulation results revealed the sensitivity of model predictions to the values parameters.

Keywords Activated Sludge Process, Modeling, Wastewater Treatment, Sewage

چکیده در عربستان سعودی، نیروگاه تصفیه پساب ریاض (RSTP) از تکنولوژی رسوب (پسماند) فعال به عنوان فرآیند تصفیه دوم برای فاضلاب استفاده می‌کند. به دلیل طبیعت پیچیده این فرآیند، یک مدل پایدار نسبتا ساده شده و همچنان عملی که اغلب ویژگی‌های RSTP در آن در نظر گرفته شده، ایجاد شد. شرایط طراحی و عملکرد واقعی از بانک داده‌های RSTP دریافت شد. از داده‌های میانگین ماهانه نیروگاه در سال ۱۹۹۷ برای کالیبره کردن مدل با استفاده از چهار پارامتر $\mu_{max,H}$، $\mu_{max,A}$، b_H و b_A استفاده شد (تغییرات فصلی دما در این عوامل مستتر است). یک برنامه کامپیوتری برای حل معادلات مدل به دست آمده نوشته شد. طبیعت پیش‌بینی کننده مدل پیشنهادی با ۵ سری داده‌های جمع آوری شده از نیروگاه در سال ۲۰۰۳ (بدون انطباق دادن) مورد بررسی قرار گرفت. نتیجه این‌بود که پیش‌بینی‌های این مدل هم‌خوانی بسیار خوبی (۵٪±) با داده‌های نیروگاه دارد. نتایج شبیه‌سازی، حساسیت پیش‌بینی‌های این مدل به پارامترها را نشان می‌دهند.

1. INTRODUCTION

The main objectives of the biological treatment of wastewater e.g. the activated sludge process, are: to convert the organic matter into colloidal biomass, to coagulate and remove the non-settleable colloidal solids and to stabilize the organic matter. In a conventional activated sludge process, wastewater is brought into contact with a previously developed biological floc particles (a great variety of microorganisms come into play that include bacteria, protozoa, rotifers, nematodes, fungi and algae) in an aerated tank. Part of the organic matter in wastewater becomes a carbon and an energy source for cell growth. The biological mass is discharged from the aeration tank to secondary gravity clarifier for separation of the suspended solids from the treated wastewater [1-2]. Due to the continuous production of biomass, some of the biomass is recycled to the aeration tank while the remaining part is discarded to avoid buildup of biomass in the system [2]. Also, the activated sludge process removes carbonaceous Biological Oxygen Demand (BOD) and oxidized ammonia. Nitrification occurs when nitrifying bacteria called nitrosomas oxidize ammonia to nitrite and nitrobacter continues the oxidation to nitrate. A denitrification process is then employed to convert the formed nitrate to nitrogen gas. This occurs in an anoxic environment [2-6]. This process configuration is used in the north plant in Riyadh Sewage Treatment Plant (RSTP).

Modeling of activated sludge processes is complicated by the vast number of bioreactions that take place. A great deal of research efforts was devoted to developing models that describe the activated sludge process [6-15]. Henze, et al [13] proposed a mathematical model to predict degradation of organic matter as well as nitrification and denitrification in suspended growth wastewater treatment. Perhaps the recently developed model by Gujer, et al [10] which predicts oxygen consumption, sludge production, nitrification and denitrification of the activated sludge process, provides a rather detailed and comprehensive model. Despite all efforts and refinements in the models, part of the final outcome remains empirical [12]. Therefore, the best approach is to produce a model that is simple mathematically, yet, captures the documented important events in the system. This is particularly true and more convenient when applying practical control strategy to real systems [6,8,12].

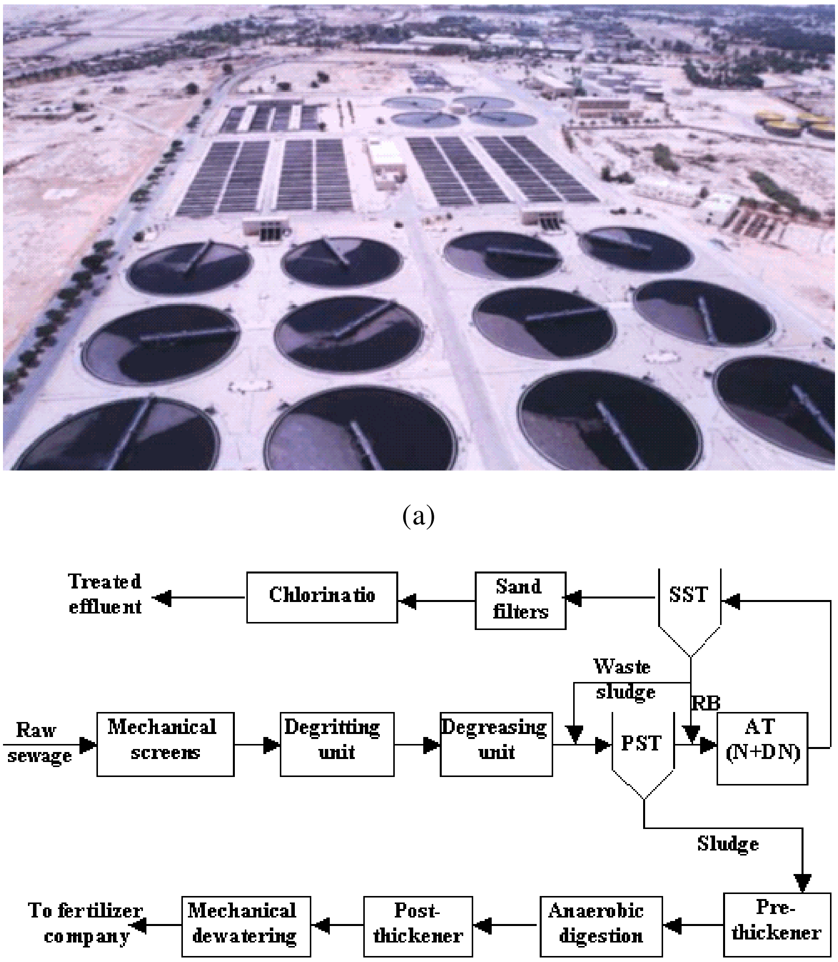
In this contribution, we present a rather simplified, yet very practical, model to describe the performance of an activated sludge plant operated in Riyadh. The actual plant data over a period of one year is used to calibrate some of the model parameters. The model is, then, tested against other plant data without further adjustment of the parameters.

2. PLANT DESCRIPTION

Figures 1a,b show, respectively, a top view and a block diagram of Riyadh Sewage Treatment Plant [16].

The block diagram can be divided into five main sections: (1) preliminary, (2) primary, (3) secondary, (4) tertiary and (5) sludge treatment sections. Raw wastewater (crude sewage) enters the plant (middle section) through the preliminary treatment section which is composed of (a) mechanical screens to remove trash, coarse solids and floating matters, (b) a degritting unit to remove gravel, sands and any particle of size greater than 200 μm and (c) a degreasing unit to remove oil and grease and serves as a backup unit for the degritting unit. Pretreated wastewater is then passed to the primary sedimentation tank (PST). In the PST, readily settleable solids and floating particles are removed. The unit also serves as the basin that receives wasted sludge from the secondary sedimentation tank (SST). The complete draw-off the sludge to the sludge treatment section (bottom section) occurs in this unit. The partially treated wastewater is then passed to the secondary treatment section to coagulate and remove the nonsettleable colloidal solids and to reduce the BOD and nutrients such as phosphorous and nitrogen. This section is composed of (a) aeration tanks (AT) in which the wastewater passes alternating aerobic (for nitrification, N) and anoxic (for denitrification, DN) zones and (b) secondary sedimentation tank (SST) in which the mixed liquor is separated from the activated sludge synthesized in the aeration tanks. The separated sludge is split into two parts: one part (RB) is sent to the aeration tank (AT) and the remaining part (wasted sludge) is sent to the primary sedimentation tank (PST). In the tertiary treatment section, the treated water from the SST is percolated through sand filters. Chlorine solution is used to disinfect the treated water before sending it from the plant for reuse (treated effluent). The bottom part of the RSTP block diagram is the sludge handling section which is composed of:

(a) Pre-thickeners to adjust the water content,
(b) An anaerobic digestion unit in which biogas (methane and carbon dioxide) and a fertilizer-rich sludge are produced,
(c) Post-thickeners,
(d) A mechanical dewatering unit to reduce the volume of the sludge before shipping to fertilizers' companies.



(b)

Figure 1. (a) A top view of riyadh sewage treatment plant and (b) A block diagram of RSTP where (SST=secondary sedimentation tank, PST=primary sedimentation tank, RB=returned biomass, AT (N+DN)=aeration tank (with nitrification and denitrification zones).

The basic design characteristics of RSTP are: nominal flow rate is $2x10^5$ m^3/day, peak flow rate is 3.2 x 10^5 m^3/day, average influent and effluent soluble solids are 400 and 10 mg/l respectively and average influent and effluent BOD are 300 and 10 mg/l respectively.

3. MODELING AND SIMULATION

This section contains the details of model development, calibration and validation as well as the results of model simulation.

3.1. Model Development A simplified schematic diagram of the secondary treatment unit which is composed of an aeration tank (AT) and a secondary sedimentation tank (SST) is shown in Figure 2.

The steady state model considered here accounts for substrate, ammonia, heterotrophic and autotrophic biomass. It is important to mention here that there exists two identical main secondary treatment lines in the actual plant, so the total influent flow rate, Q_T is equally split between the two lines, Q_o which are combined later.

The reaction rate and the material balance equations for the biological events that take place in this process are given below.

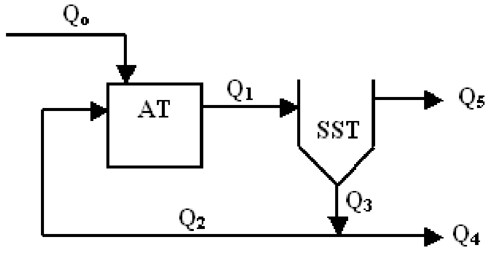


Figure 2. Schematics of the secondary treatment unit.

Equation 1 gives the rate of aerobic growth of heterotrophs (R_H) and the rate of decay of heterotrophs (D_H) is given by Equation 2

$$R_H = \mu_{max,H} * \frac{S_1}{(S_1 + K_S)} * \frac{O_2}{(K_{OH} + O_2)} * X_{H1} \quad (1)$$

$$D_H = b.X_{H1} \quad (2)$$

Equation 3 gives the rate of aerobic growth of autotrophs (R_A), while Equation 4 gives the rate of decay of autotrophs (R_A)

$$R_A = \mu_{max,A} * \frac{A_1}{(A_1 + K_A)} * \frac{O_2}{(K_{OA} + O_2)} * X_{A1} \quad (3)$$

$$D_H = b.X_{H1} \quad (4)$$

The mass balance equations around aeration tank (AT) are given by:

(a) Equation 5 for substrate removal,
(b) Equation 6 for ammonia removal,
(c) Equation 7 for heterotrophic biomass and
(d) Equation 8 for autotrophic biomass.

$$\frac{d(V_1 S_1)}{dt} = Q.S. + Q_2.S_2 - Q_1 S_1 - V_1 \frac{R_H}{Y_H} \quad (5)$$

$$\frac{d(V_1 A_1)}{dt} = Q.A. + Q_2 A_2 - Q_1 A_1 - V_1.R_A \left(\frac{1}{Y_A} + Y_{AH}\right) - Y_{AH} V_1 R_H \quad (6)$$

$$\frac{d(V_1 X_{H1})}{dt} = Q_0 X_{H0} + Q_2 X_{H2} - Q_1 X_{H1} + V_1.R_H - V_1 b_H X_{H1} \quad (7)$$

$$\frac{d(V_1 X_{A1})}{dt} = Q_0 X_{A0} + Q_2 X_{A2} - Q_1 X_{A1} + V_1.R_A - V_1 b_A X_{A1} \quad (8)$$

The main function of the settler is to separate the biomass from the treated liquor, therefore, the concentrations of the soluble substrate and ammonia entering or leaving the unit is similar, thus the mass balance equations around settler (SST) are given by Equations 9-12 for heterotrophic biomass, autotrophic biomass, substrate and ammonia respectively.

Heterotrophic biomass:

$$\frac{d(V_2 X_{H3})}{dt} = Q_1 X_{H1} - Q_3 X_{H3}$$

Where

$$X_{H3} = X_{H2} = X_{H4} \quad (9)$$

Autotrophic biomass:

$$\frac{d(V_2 X_{A3})}{dt} = Q_1.X_{A1} - Q_3 X_{A3}$$

Where

$$X_{A3} = X_{A2} = X_{A4} \quad (10)$$

Substrate:

$$S_1 = S_2 = S_3 = S_4 = S_5 \quad (11)$$

Ammonia:

$$A_1 = A_2 = A_3 = A_4 = A_5 \quad (12)$$

It is clear from Figure 2 that the flow rates can be related by:

$$Q_1 = Q_o + Q_2 = Q_3 + Q_4$$

and

$$Q_3 = Q_2 + Q_4 \quad (13)$$

The steady state equations are obtained by setting the left hand sides of Equations 5-10 equal to zero.

3.2. Model Calibration The steady state model equations (modified Equations 5-10) together with the rate Equations 1-4 and Equations 11-13 are used to calibrate the model against plant data obtained over a one year period as shown in Table 1 for the year 1997.

The plant data in Table 1 is used to adjust four model parameters, namely, $\mu_{max,H}$, $\mu_{max,A}$, b_H and b_A. These parameters are chosen because of (a) the large variance in their values reported in the literature and (b) their values are strongly dependent on temperature e.g., $\mu_{max,A} \in [0.35,1.0]$. Values of other parameters are obtained from literature as listed in Table 2.

TABLE 1. Actual Plant Data (Monthly Average) for the Year 1997.

Month	Q_T	S_o	S_1	A_o	A_1	X_{H1}	X_{A1}
1	211404	359	30.0	18.9	0.6	2577.5	79.7
2	220102	368	42.0	17.8	0.4	2471.3	76.4
3	215374	334	49.0	18.0	0.3	2531.7	78.3
4	203347	345	46.0	18.0	0.8	2428.4	75.1
5	204552	338	41.0	18.0	0.6	2667.0	82.5
6	187747	352	57.0	18.8	1.0	2474.2	76.5
7	207358	350	47.8	17.4	0.7	2467.7	76.3
8	197247	355	36.8	18.8	0.6	2471.3	76.4
9	198005	324	51.7	19.4	0.5	2607.4	80.6
10	194279	344	51.0	20.1	1.9	2515.0	77.8
11	194500	367	55.0	21.8	1.1	2504.8	77.5
12	199609	386	47.0	22.0	0.9	2582.6	79.9
Average	202794	351.8	46.2	19.1	0.785	2524.9	78.1
Maximum	220102	386	57	22	1.9	2667.0	82.5
Minimum	187747	324	30	17.4	0.3	2428.4	75.1
% Difference	17.2	19.1	90.0	26.4	533.3	9.8	9.8

TABLE 2. Parameters Values from Literature [9,13].

Parameter	Value	Parameter	Value	Parameter	Value
K_{OH}	0.2 g/m^3	K_{OA}	0.5 g/m^3	K_s	60 g/m^3
K_A	1.0 g/m^3	Y_H	0.63 g/g	Y_A	0.24 g/g
Y_{AH}	0.001 g /g				

Initially, an algorithm that uses the capabilities of Excel spread sheet (Goal seek and Solver) was written to determine the optimum values of the four parameters based on the method of least squared errors. Later, a Fortran coded program was written to check results obtained by Excel, both programs gave the same results. The optimum values of the parameters are given in Table 3.

Table 3 reveals the importance of calibrating laboratory's values of key parameters to conditions of an actually operating plant. While the values for maximum growth rate ($\mu_{max,A}$) and the rate constant of the decay (b_A) of the autotrophic biomass fall within the reported literature ranges, the maximum growth rate of heterotrophic biomass ($\mu_{max,H}$=0.691) is much lower than the literature range ($3<\mu_{max,H}<6$). The constant for the rate of heterotrophic decay (b_H) is also lower than that obtained from the literature. Differences in adjusted parameters values from literature values may be attributed to the fact that the data used in model's calibration over a one year period spans hot and cold weathers whereas laboratory's data are usually obtained under controlled operating conditions (specially temperature).

3.3. Model Validation Five sets of data (Table 4) obtained in the plant during the year 2003 were used to check the predictive nature of the model. The table shows the values of the influent and effluent concentrations of the four state variable respectively (the concentrations of the substrate (S), ammonia (A), heterotrophic biomass (X_H) and autotrophic biomass (X_A) into and out of the aeration tank). The values of the four parameters were set and the model was used without further adjustment.

A comparison between model's predictions and the corresponding values for the five sets of real plant data (2003 data) is shown in Table 5. Also, a 5 % parity plot between measured and predicted values is shown in Figure 3. It is clear from, both, Table 5 and Figure 3 that the model predictions are very close to real plant data. They all (except for ammonia removal which showed fluctuations reaching 9 % of the measured values) fit within a 5 % margin as shown in Figure 3.

TABLE 3. Adjusted Parameters Values and the Literature Range.

Parameter	Value	Range
$\mu_{max,A}$	0.571	0.35 – 1.0
b_A	0.068	0.048 – 0.144
$\mu_{max,H}$	0.691	3.0 – 6.0
b_H	0.138	0.192 – 0.382

TABLE 4. Real Plant Data in 2003.

Sets	Q_0	Input Data (Influent)				Measured Values (Effluent)			
		S_0	A_0	$X_{H,2}$	$X_{A,1}$	S_1	A_1	$X_{H,1}$	$X_{A,1}$
Set 1	203294	350	19.2	4089.5	126.5	46.7	0.8	2523.1	78.0
Set 2	203404	352	20.0	4177.6	129.2	47.0	0.79	2577.5	79.7
Set 3	198490	340	19.1	3912.4	121.0	44.0	0.78	2429.9	75.2
Set 4	211320	350	19.9	4213.9	130.3	47.5	0.82	2553.5	79.0
Set 5	207358	320	20.0	4623.2	143.0	45.0	0.78	2822.7	87.3

TABLE 5. Comparison Between Predicted Effluent Values and Plant Data in 2003.

Sets	Measured Values				Predicted Values			
	S_1	A_1	$X_{H,1}$	$X_{A,1}$	S_1	A_1	$X_{H,1}$	$X_{A,1}$
Set 1	46.7	0.80	2523.1	78.0	46.7	0.80	2523.8	78.0
Set 2	47.0	0.79	2577.5	79.7	45.7	0.83	2581.0	79.9
Set 3	44.0	0.78	2429.9	75.2	45.2	0.81	2440.1	75.5
Set 4	47.5	0.82	2553.5	79.0	48.2	0.89	2566.1	79.4
Set 5	45.0	0.78	2822.7	87.3	42.8	0.73	2831.3	87.6

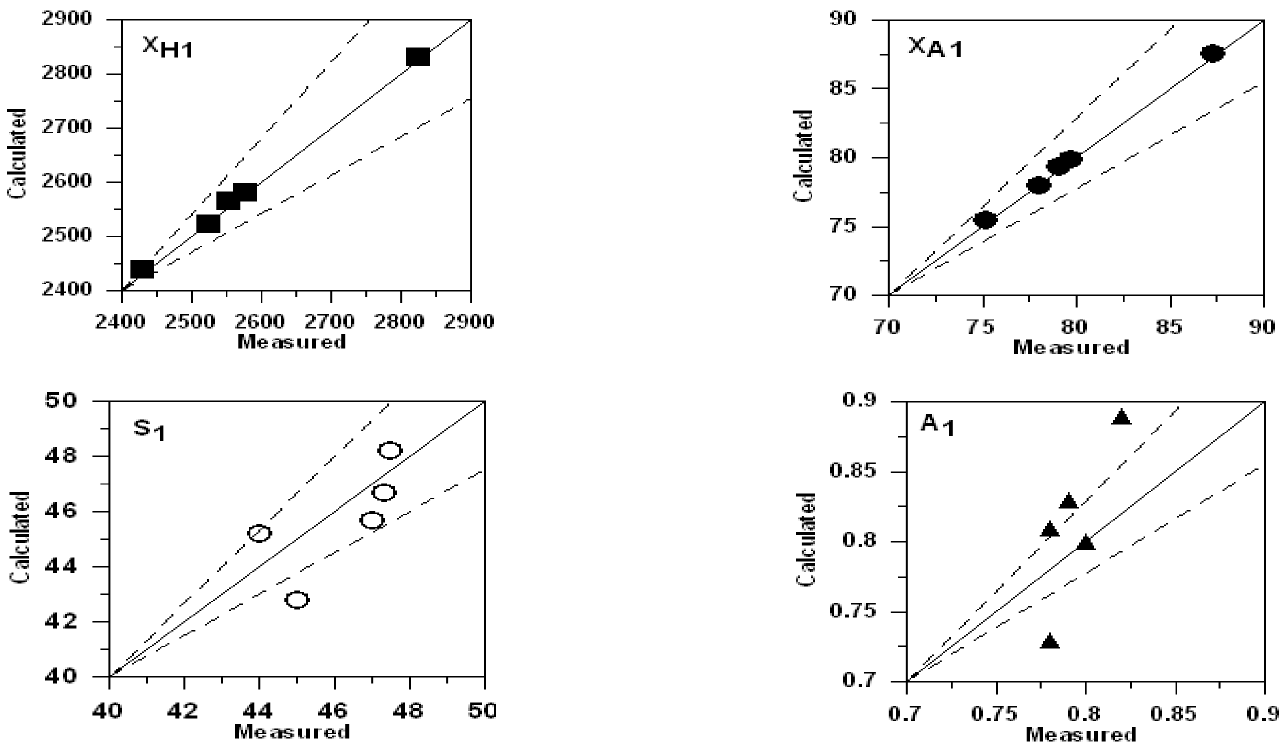


Figure 3. 5 % parity plots for the five sets (dashed line is±5% off solid line).

4. SENSITIVITY ANALYSIS

Figures 4 and 5, respectively, show the effect of the maximum growth rate of heterotrophic biomass ($\mu_{max,H}$) and the crude sewage influent flow rate (Q_o) on the performance of the units. It is clear from Figure 4 that increasing $\mu_{max,H}$ leads to an increase in the concentration of the heterotrophs (X_{H1}) and a decrease in substrate concentration (S_1) while insignificantly affecting X_{A1} (<0.01%) and A_1 (<1.5%). Figure 5 shows significant increase of S_1 and A_1 which is accompanied by significant drop in X_{H1} and X_{A1} as the fresh feed flow rate, Q_o, is increased.

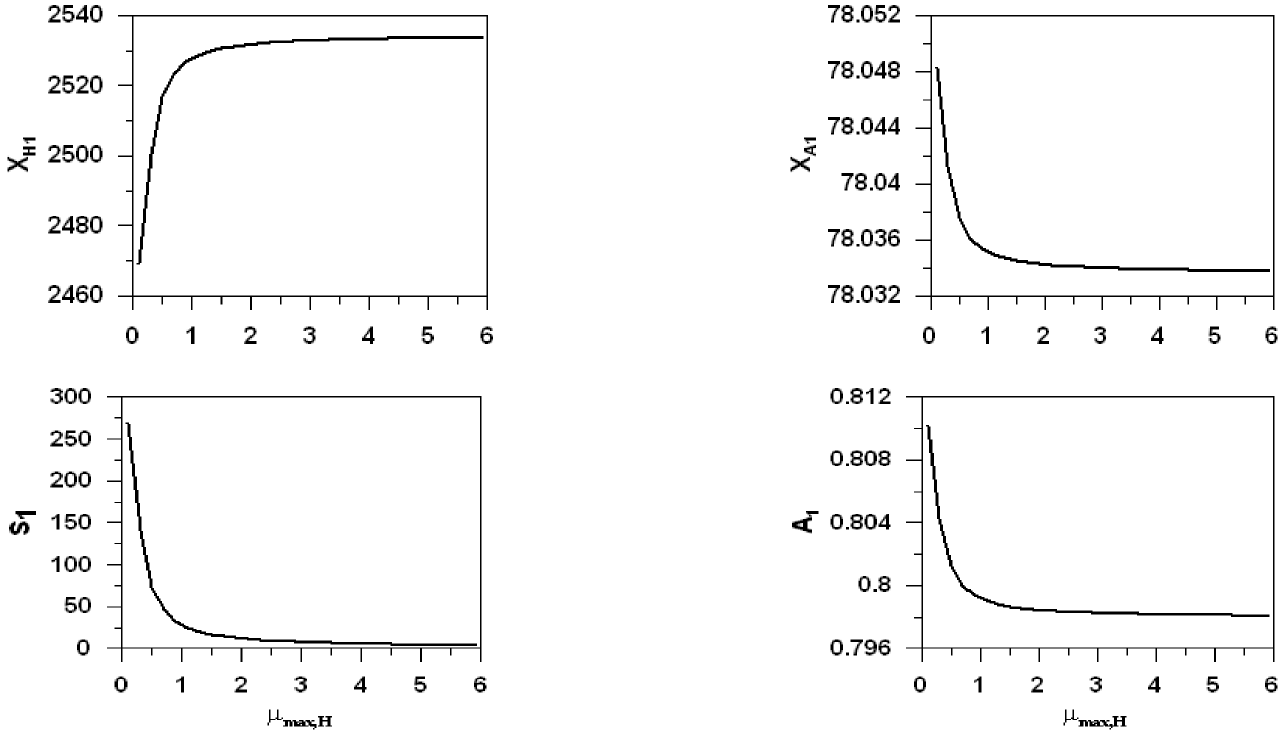


Figure 4. Effect of $\mu_{max,H}$ on S_1, A_1, X_{H1} and X_{A1}.

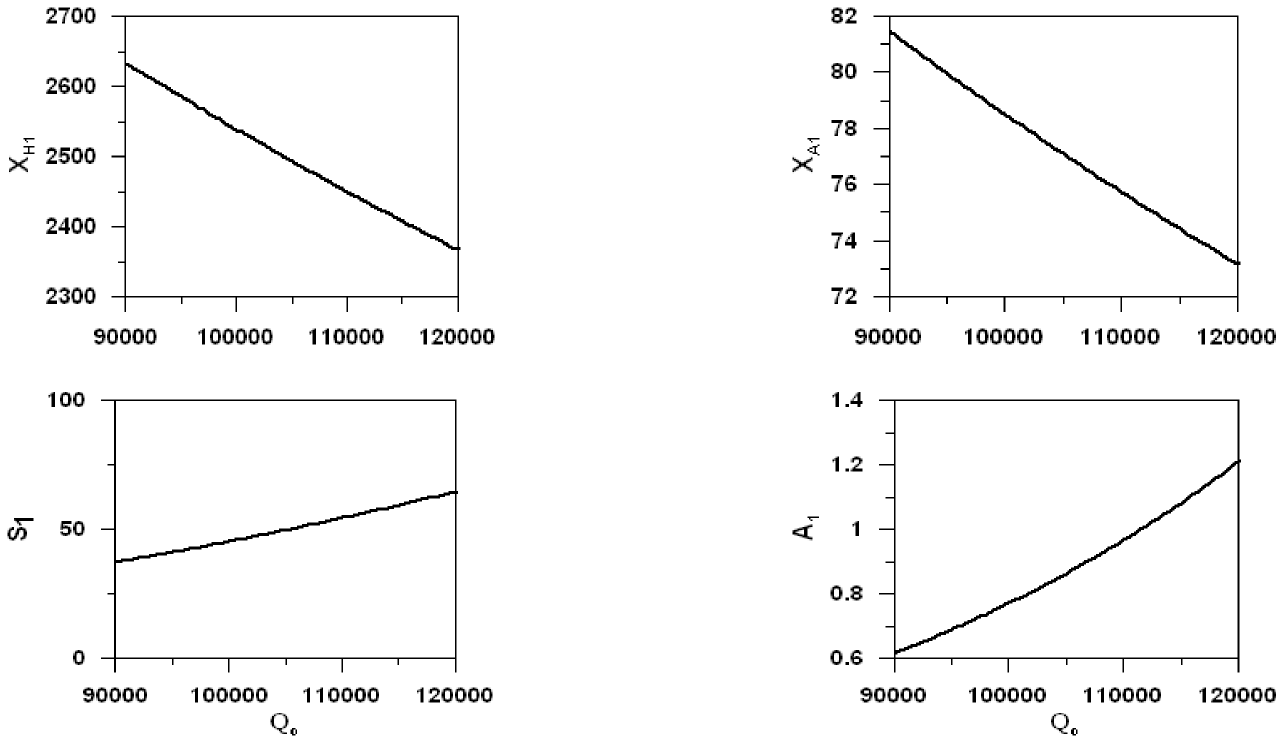


Figure 5. Effect of influent flow rate, Q_o, on S_1, A_1, X_{H1} and X_{A1}.

5. CONCLUSIONS

Riyadh sewage treatment plant (RSTP) uses the activated sludge process to treat sewage. A simplified steady state model was developed for the plant. Plant data collected in 1997 was used to calibrate the model by adjusting four of its associated parameters. The predictive nature of the calibrated model was then tested (without further adjustment) against five sets of plant data collected in 2003. Model predictions were very close (within +5% margins) to real plant data. Sensitivity of model predictions to parameters values analysis was also assessed. It is important to note that this model was calibrated using data spanning summer and winter seasons, therefore, temperature effects are implicitly considered.

6. NOMENCLATURE

A_0 Fresh feed ammonia concentration, g/m^3
A_1 Aeration tank effluent ammonia concentration, g/m^3
A_2 Effluent ammonia concentration, g/m^3
b_A Decay rate of nitrifiers, day^{-1}
b_H Heterotrophic decay rate, day^{-1}
K_A Ammonia half saturation, gN/m^3
K_S Substrate half saturation, gCOD/m^3
K_{OH} Oxygen half saturation for heterotrophs, gO_2/m^3
K_{OA} Oxygen half saturation for autotrophs, gO_2/m^3
S_0 Fresh feed substrate concentration, g/m^3
S_1 Aeration tank effluent substrate concentration, g/m^3
S_2 Effluent substrate concentration, g/m^3
Q_0 Fresh feed flow rate, m^3/d
Q_1 Aeration tank effluent flow rate, m^3/d
Q_2 Return activated sludge flow rate, m^3/d
Q_3 Sludge withdraw from secondary clarifier, m^3/d
Q_4 Secondary sedimentation tank liquor flow rate, m^3/d
Q_5 Wasting flow rate, m^3/d
X_{H1} Heterotrophic biomass concentration, g/m^3
X_{A1} Autotrophic biomass concentration, g/m^3
X_{H2} Return heterotrophic biomass concentration, g/m^3
X_{A2} Return autotrophic biomass concentration, g/m^3
R_H Aerobic growth of heterotrophic organism
R_A Aerobic growth of autotrophic organism
Y_{AH} N content of biomass, gN/gCOD
O_2 Oxygen concentration, g/m^3
V_1 Volume of aeration tank, m^3
Y_H Heterotrophic yield coefficient, gCOD/gCOD
Y_A Autotrophic yield coefficient, gCOD/gN

Greek Letters

$\mu_{max,H}$ Maximum growth rate of heterotrophic organisms, day^{-1}
$\mu_{max,A}$ Maximum growth rate of autotrophic organisms, day^{-1}

7. ACKNOWLEDGEMENT

The authors are very grateful to the management of the Riyadh Sewage Treatment Plant for providing this valuable technical and operating data which was used by their employee Eng. Al-Mozini to finish his M.S. thesis.

8. REFERENCES

1. Metcalf and Eddy, Inc., "Wastewater Engineering Treatment and Reuse", 4th edition, Tata, McGraw Hill, New Delhi, India, (2003).
2. Sundstrom, D.W. and Klei,H.E., "Wastewater Treatment", Prentice-Hall Inc., Englewood Cliffs, N.J. U.S.A., (1979).
3. Dosta, J., Gali, A., El-Hadj, B., Mace, S. and Mata-Alvarez, J., "Operation and Model Description of a Sequencing Batch Reactor Treating Reject Water for Biological Nitrogen Removal Via Nitrite", ***Bioresource Technology***, Vol. 98, (2007), 2065-2075.
4. Saziye, B. and Ridvan, B., "Dynamics of an Activated Sludge Process with Nitrification and Denitrification: Start-up Simulation and Optimization using Evolutionary Algorithm", ***Computers and Chemical Engineering***, Vol. 30, (2006), 490-499.
5. Hao, O.J. and Huang, J., "Alternating Aerobic-Anoxic Process for Nitrogen Removal: Process Evaluation", ***Water Environment Research***, Vol. 68, (1996), 83-93.
6. Stare, A., Hvala, N. and Vrecko, D., "Modeling, Identification and Validation of Models for Predictive Ammonia Control in a Wastewater Treatment Plant–A Case Study", ***ISA Transactions***, Vol. 45, (2006), 159-174.
7. Moussa, M.S., Hooijmans, C.M., Lubberding, H.J., Gijzen, H.J. and Loosdrecht, M.C., "Modelling

Nitrification, Heterotrophic Growth and Predation in Activated Sludge", ***Water Research***, Vol. 39, (2005), 5080-5098.

8. Kim, H., "Temporal Activated Sludge Systems: Modeling Approach and Process Control", Ph.D Thesis. University of Maryland-College Park, U.S.A., (2000).
9. Henze, M., Gujer, W., Mino, T. and Loosdrecht, M.C., "Activated Sludge Models ASM1, ASM2, ASM2d and ASM3", IWA publishing, London, U.K., (2000).
10. Gujer, W., Henze, M., Mino, T., Loosdrecht, M.C., "Activated Sludge Model", ***Water Science Technology***, Vol. 39, No. 3, (1999), 183-193.
11. Abasaeed, A.E., "Sensitivity Analysis on a Sequencing Reactor Model: II. Effect of Stoichiometric and Operating Parameters", ***J. Chem. Technol. and Biotechnol***., Vol. 74, (1999), 451-599.
12. Ibrahim, G. and Abasaeed, A.E., "Modeling of Sequencing Batch Reactors", ***Water Research***, Vol. 29, (1995), 1761-1766.
13. Henze, M., Grady, C.P., Gujer, W., Marais, G.V. and Matsuo, T., "A General Model for Single-Sludge Wastewater Treatment Systems", ***Water Research***, Vol. 21, (1987), 505-515.
14. Dold, P.L. and Marais, G.V., "Evaluation of the General Activated Sludge Model Proposed by the IAWPRC Task Ggroup", ***Water Science Technology***, Vol. 18, (1986), 63-89.
15. Dold, P.L., Ekama, G.A. and Marais, G.V., "A General Model for Activated Sludge Process", ***Progress in Water Technoogy***, Vol. 12, (1980), 47-77.
16. Operation and Maintenance Manual (OMM) for North Plant in RSTP: Riyadh Sewage Treatment Plant Documentations, (1992).