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Mathematical modeling of a conventional wastewater treatment plant in Gamasa- Egypt

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ABSTRACT

This study explores the use of mathematical modeling to evaluate the performance of conventional activated sludge systems at wastewater treatment plants (WWTPs). With expanding objectives and increasingly strict regulations, mathematical modeling provides a valuable tool for evaluating WWTP performance. The research focuses on Gamasa WWTP located in the Dakahlia governorate. Historical data, design reports, and additional analyses were collected through site visits and a comprehensive sampling campaign. The wastewater was characterized, and the plant-wide model was calibrated following the protocol of the Dutch Foundation of Applied Water Research STOWA. Sensitivity analysis is done to identify the most important kinetic and stoichiometric parameters to be adjusted during the calibration process. The most sensitive parameters were aerobic yield, anoxic yield, ordinary heterotrophic maximum specific growth rate, ordinary heterotrophic substrate half saturation, ordinary heterotrophic aerobic decay rate, soluble unbiodegradable COD, COD: VSS ratio, endogenous residue COD: VSS ratio, non-colloidal slowly biodegradable COD, ammonia oxidizing bacteria maximum specific growth rate, ammonia to total kjheldahl nitrogen fraction, ammonification, soluble unbiodegradable TKN, aerobic yield, N in biomass, ammonia oxidizing bacteria substrate half saturation, ammonia oxidizing bacteria aerobic decay rate, nitrite oxidizing bacteria maximum specific growth rate and aerobic yield, and phosphate to total phosphorus fraction. The model's validity was assessed using different validation periods, with average relative deviation (ARD) values below 20% considered acceptable. Overall, this study demonstrates the effectiveness of mathematical modeling in evaluating the performance of current WWTPs and developing a mathematical model which can be used for the improvement of the WWTP to meet stringent wastewater treatment regulations.

Keywords: Wastewater treatment, Mathematical modeling, BioWin software, Sensitivity analysis

1. Introduction

Historically the primary objective for collecting wastewater was sanitation to prevent the spread of water borne diseases. Since the beginning of wastewater treatment, the objectives regarding treatment have expanded and the regulations are continuously getting stricter. At the same time there is a strong pressure on wastewater utilities to recover resources, increase energy efficiency and reduce greenhouse gas (GHG) emissions, while maintaining the effluent constraints, all of this under a constant pressure to minimize costs [1].

Biological treatment is the most common method for treating wastewater and among the different types of biological treatments, the activated sludge process is the method most often applied as it can remove organic matter and nutrients from the wastewater. Anaerobic digestion is the most widely-used biological process for sludge stabilization and energy recovery in wastewater treatment plants [2].

Optimization the operation of wastewater treatment plant is not an easy task. The influent load is constantly varying in flow and concentration, is naturally uncontrolled and arrives every hour of the day, all year round. Under such conditions mathematical modelling is a good tool for evaluating performance of WWTPs. The various biological treatment processes used to treat wastewater can be described by using mathematical equations and models. The models describe the processes and their interactions in detail considering the ambient conditions. Thereby, the plant-wide effects are captured so that the overall result can be analyzed. In wastewater treatment, models are used to gain insight into plant performance, evaluate plant designs and improvement, and develop or evaluate alternative control strategies.

Different mathematical models for biological wastewater treatment have evolved in recent decades. Among them, activated sludge models (ASMs) are those used most often in optimization studies for municipal and industrial WWTPs [3]. ASM is a representation of microbial growth and substrate utilization within an activated sludge system through a dynamic mathematical expression. ASMs are incorporated at different recent simulation platforms such as BioWin, Simba, GPS-X, etc. All of these programs, incorporate versions of the activated sludge model (ASM), activated sludge-digestion model (ASDM) or general models in their simulations that are primarily used for aerobic activated sludge and anaerobic digestion of sludge in conventional wastewater treatment plants (WWTP).

BioWin is a wastewater model simulator software that can tie together biological, chemical, and physical processes to provide insight on wastewater treatment plant operations. BioWin can be used for many applications such as selection of optimal treatment processes, reduce capital investments, energy consumption and operating costs, or for developing a process for achieving the highest effluent quality levels [4].

So, in this study, BioWin was used to evaluate Gamasa WWTP, which is located in Dakahlia, Egypt. It treats wastewater with an activated sludge process. The effluent is discharged into a nearby agricultural drain which is already suffering from environmental problems. Operational decisions for such plants should not be taken lightly since they directly impact the receiving bodies of water.

The aim of the research is to develop a plant-wide model for simulating the performance of the WWTP which can be used in the futute for the improvement of the WWTP in terms of effluent quality, energy efficiency and resource recovery, and still maintaining control of the operational costs.

2. Material and methods

For the purposes of Gamasa WWTP modeling, historical data and design reports have been collected and some site visits have been made, in addition to a sampling campaign for performing important analyses that are not included in the plant's routine analyses for proper wastewater characterization, and a successful model calibration. The wastewater characterizations, as well as the COD fractionation were conducted following the protocol for wastewater characterization of the Dutch Foundation for Applied Water Research (STOWA)[5], **Fig. 1**.

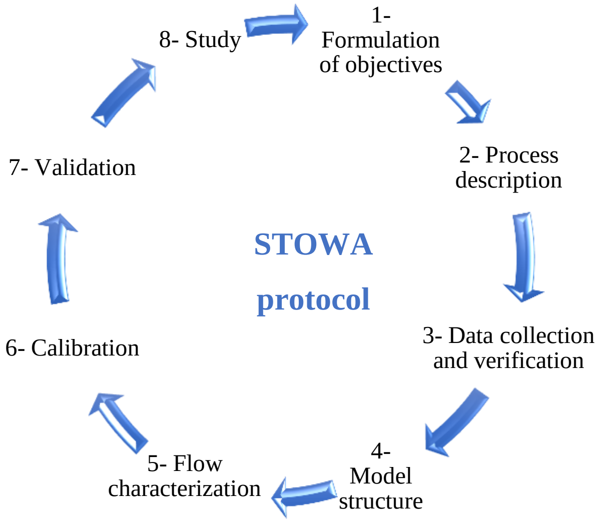


Fig. 1. Main structure of STOWA protocol

2.1. WWTP process description

The treatment in Gamasa wastewater treatment plant is done by conventional activated sludge process with capacity 40000 m^3/d, **Fig. 2**. The activated sludge process in Gamasa wastewater treatment plant consists of two grit removal chambers, four primary settling tanks (PST) (25.7 m in diameter), four aeration tanks (30 × 30 × 3) m, four secondary settling tanks (FST) (29.7 m in diameter), a chlorination tank (48.5 × 13.5) m, two sludge-thickeners (14.7 m diameter) and 88 sludge-drying beds (each 7.5 × 12.5) m.

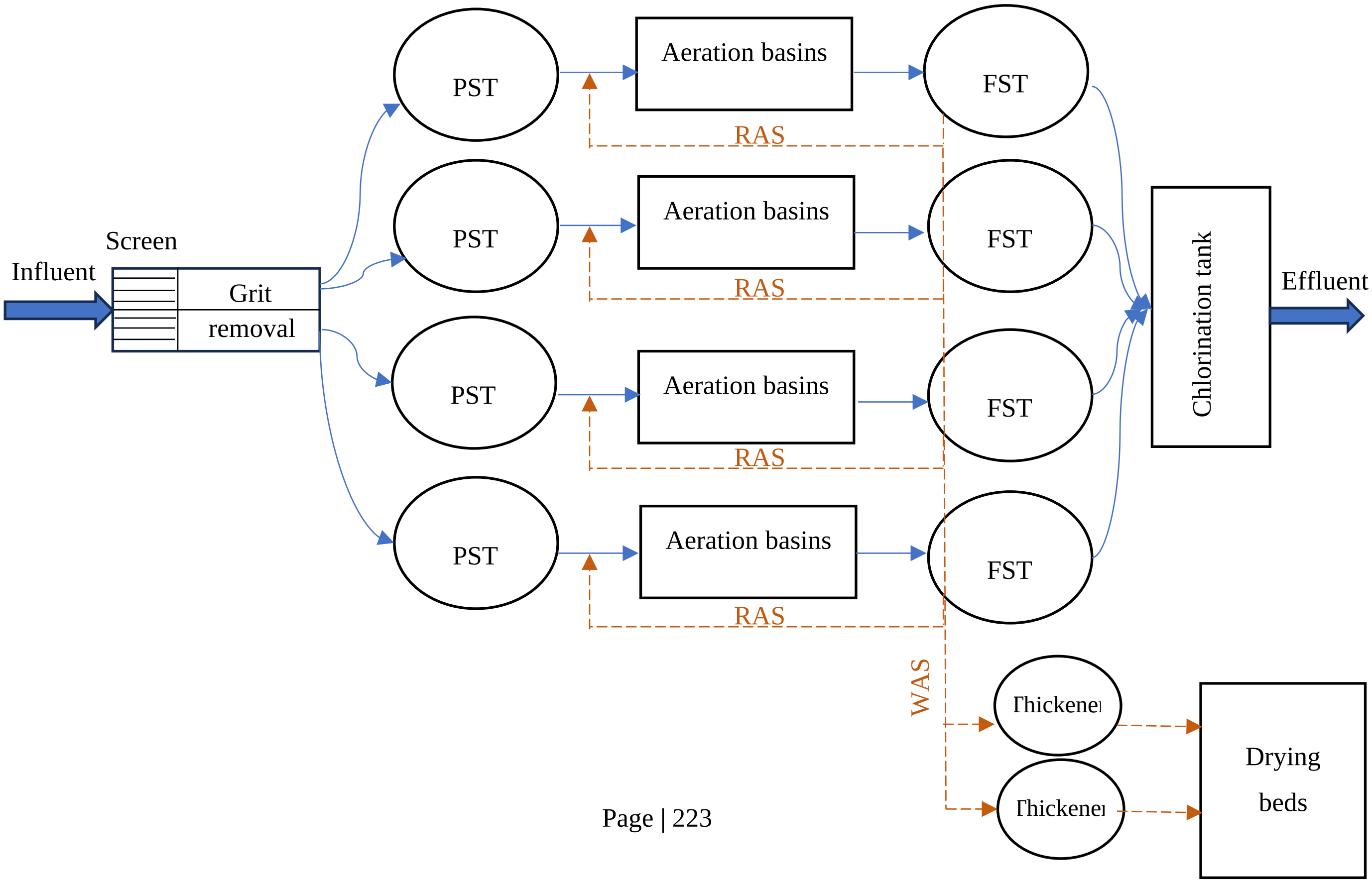


Fig. 2. Layout of Gamasa WWTP

2.2. Historical analysis and sampling campaign

i. Data collection

Before the sampling program, there is a significant stage, which is the data collection stage. This stage took place during two months prior to the sampling program. In order to obtain a general overview of the WWTP, data regarding the components of the treatment systems, operation, and performance are collected through several visits to the WWTP, observations and interviews with officials and chemists working at the WWTP.

ii. Data verification

After completing the data collection stage, it was found that there is still a lack of data required for the model. One of the most important missing data, which is considered the first step in building the model, is related to flow, **Fig. 3**, thus a flow balance should be conducted to calculate those unknown flows and to evaluate and verify the collected data. The other part of the missing data is related to wastewater characteristics and this will be covered during the sampling campaign.

The return and waste-activated sludge flow results were obtained through a number of Gamasa wastewater treatment plant visits and questionnaires, the return-activated sludge flow results due to the visits and questionnaires was in the range of 25000 m^3/d and the waste sludge flow from both primary and secondary sedimentation tanks was in the range of 2000 m^3/d which is discharged to the thickeners. The average dried volume of sludge in the drying beds is approximately 50 m^3/d. Gamasa WWTP has been redesigned according to its current conditions and the return and waste activated sludge flow results due to equations from 1 to 12 [6] was consistent with the results collected from Gamasa WWTP through visits and questionnaires as shown in **Fig. 4**.

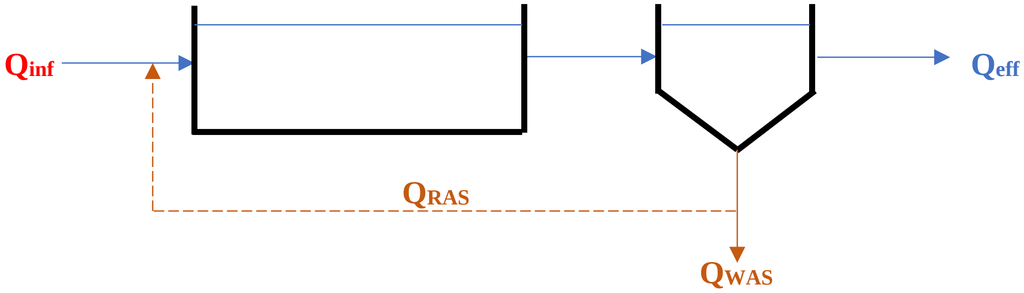


Fig. 3. Main flows in the Activated sludge system

$$Q_{inf} - Q_{eff} - Q_{was} = 0 \tag{1}$$

$$\text{Heterotrophic biomass}\,(P_{X,VSS}\ (A)) = \frac{1.1 * Q_{av} * y * (S_o - S_e)}{1 + k_d * SRT} \tag{2}$$

$$\text{Cell debris}\,(P_{X,VSS}\ (B)) = \frac{f_d * k_d * 1.1 * Q_{av} * y * (S_o - S_e) * SRT}{1 + k_d * SRT} \tag{3}$$

$$\text{Nitrifying bactertia biomass}\,(P_{X,VSS}\ (C)) = \frac{1.1 * Q_{av} * y_n * NO_x}{1 + k_{dn} * SRT} \tag{4}$$

$$\text{Nonbiodegradable VSS in influent } (P_{X,VSS}\ (D)) = 1.1 * Q_{av} * nbVSS \tag{5}$$

$$P_{X,TSS}\ (\text{total}) = \frac{A+B+C}{VSS/TSS} + D + 1.1 * Qav * (TSS_{primary,eff} - VSS_{primary,eff}) \tag{6}$$

$$XR = \frac{10^6}{SVI} \tag{7}$$

$$Q_W = \frac{P_{X,TSS}}{XR * \gamma} \tag{8}$$

$$Q_{RAS} = \frac{1.1 * Qav * X}{XR - X} \tag{9}$$

$$RAS\% = \frac{1.1 * X}{XR - X} * 100 \tag{10}$$

$$\text{Thickened sludge flow} = \frac{\text{thickened sludge weight}}{\text{Thickened solids concentration} * \gamma} \tag{11}$$

$$\text{Dried sludge volume} = \frac{\text{thickened sludge weight}}{\text{Sludge solids concentration} * \gamma} \tag{12}$$

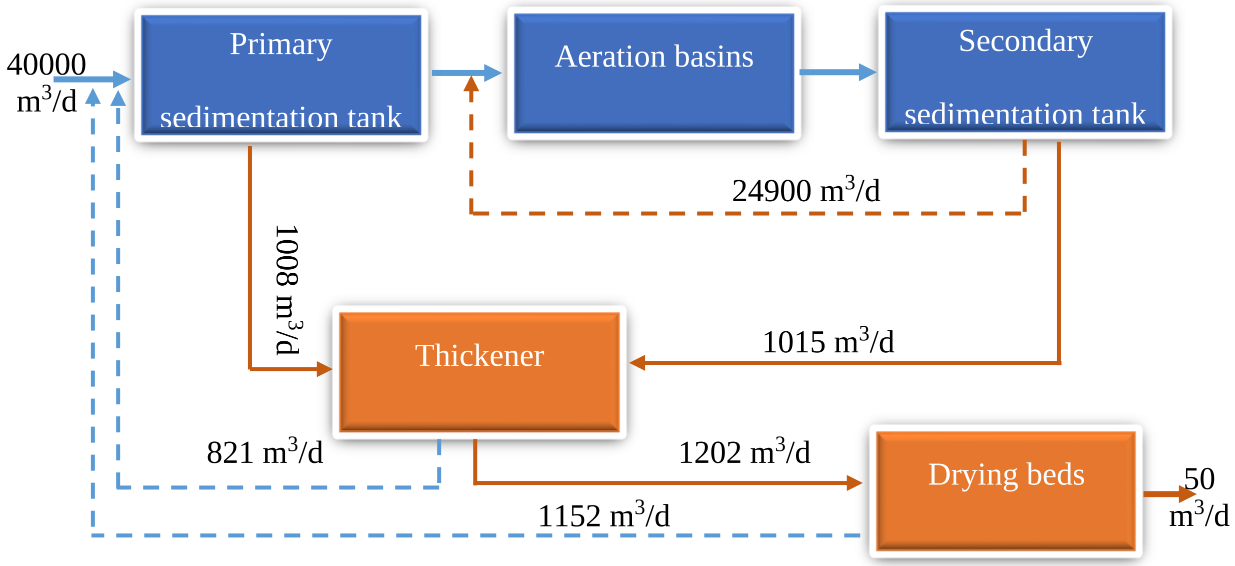


Fig. 4. Verification results for RAS and WAS in Gamasa WWTP

iii.Sampling campaign

This stage is considered the most important stage in building the model and it is done for many reasons, including; verification of the historical data, completing the plant's routine data, measuring the influent characterization; measuring the effluent characterization; and setting up a good base for model calibration. The sampling program is carried out from 1 to 25 June, 2018. The influent and effluent wastewater characteristics obtained from the sampling campaign are summarized in **Table 1**.

Table 1
Raw influent and effluent sampling campaign analysis average results.

Parameter	Unit	Influent	Effluent

BOD	mg/l	215	29
COD	mg/l	352	58
TSS	mg/l	225	39
NH_4	mg/l	27.4	24.5
PO_4	mg/l	5.02	4.5
T	˚C	25.2	-

2.3 Wastewater fractionation and characterization

The STOWA proposes an influent characterization based on physical-chemical methods to determine the wastewater fractions [7]. **Fig. 5** shows the principles of the fractionation of COD components using a physical-chemical method [8].

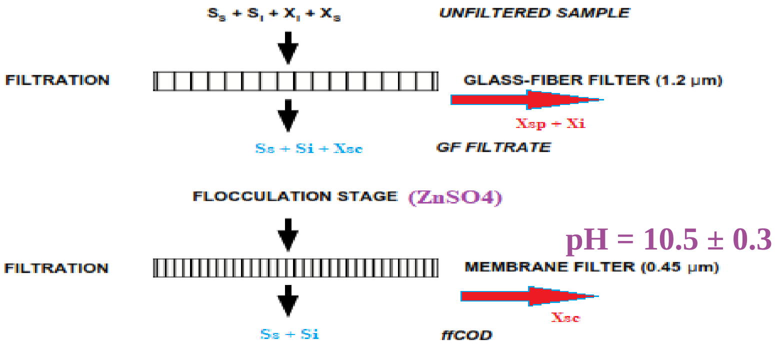


Fig. 5. Retaining/passage of COD components from influent wastewater through consecutive 1.2 m glass fiber filtration, flocculation, and 0.42 m membrane filtration.

The COD in wastewater has two main components: the biodegradable and unbiodegradable COD. The biodegradable COD is divided in two different components, the readily biodegradable RBCOD (S_S), which is divided in complex COD (S_C) and the short chain fatty acid COD (S_a), and the slowly biodegradable COD, SBCOD (X_S), which is composed of colloidal COD (X_{SC}) and particulate COD (X_{SP}). In addition, the unbiodegradable COD has two components, the soluble (S_i) and particulate (X_i) unbiodegradable COD. **Fig. 6** shows the relationship between these components:

Wastewater fractions were determined based on the measured data during the sampling program. The ammonia and phosphate fractions were determined from the results of sampling program. The fractionation results covering the sampling period were as shown in

Table *2*.

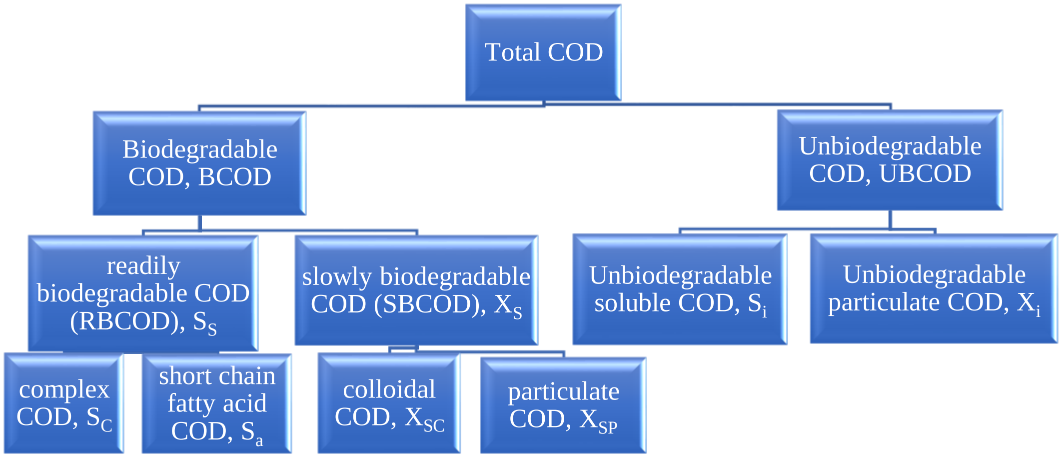


Fig. 6. Scheme of fractionation of COD components in wastewater.

Table 2

Organic fractions average in the influent of Gamasa WWTP during the sampling campaign.

Parameter	**Unit**	**BioWin default fractions values**	**Measured fractionatior prameters**
Readily biodegradable including Acetate, F_{bs}	[gCOD/g of total COD]	0.16	0.15
Acetate, F_{ac}	[gCOD/g of readily biodegradable COD]	0.15	0.2
non-colloidal slowly biodegradable, F_{xsp}	[gCOD/g of slowly degradable COD]	0.75	0.62
non-biodegradable soluble, F_{us}	[gCOD/g of total COD]	0.05	0.03
non-biodegradable particulate, F_{up}	[gCOD/g of total COD]	0.13	0.08
Ammonia, F_{na}	[gNH_3-N/gTKN]	0.66	0.7
Phosphate, F_{po4}	[gPO_4-P/gTP]	0.5	0.62

2.4 Model Structure

BioWin software is used to build the model for Gamasa WWTP using the data collected from the plant and the flow balance results. The model simulates the primary sedimentation tanks, biological aeration tanks, secondary sedimentation tanks, and gravity thickeners. **Fig. 7** shows the BioWin model structure for Gamasa WWTP.

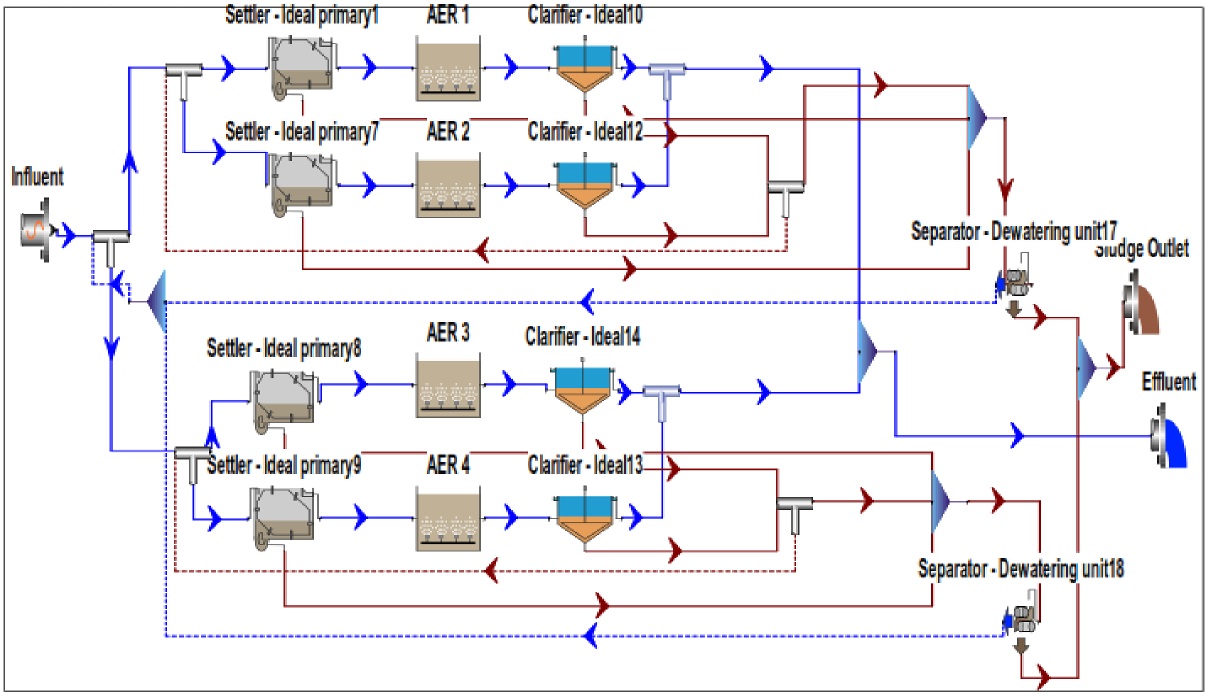


Fig. 7. Gamasa WWTP Model structure.

3. Results and discussion

3.1. Model calibration

The calibration process was carried out in three stages through 3 simulations of Gamasa WWTP. wastewater fractions, kinetic and stoichiometric parameters were determined based on the measured data combined with the sensitivity analysis. Initially, the default values for the wastewater influent fractions, kinetic and stoichiometric parameters were used in the first simulation. In the second simulation, the default values of the kinetic and stoichiometric were applied, and only the wastewater influent fractions were modified according to the measured values. In the last simulation, the values of wastewater influent fractions, kinetic and stoichiometric were modified according to the results of sensitivity analysis.

i. Sensitivity analysis

Kinetic and stoichiometric parameters were determined based on the sensitivity analysis. The sensitivity analysis allowed the identification of the most important parameters which are needed to be adjusted during model calibration. The calibration of the model in the third simulation was done by running a series of simulations that amounted to approximately 300 run and carrying out sensitivity analysis on the model.

In this study, about 40 kinetic and 30 stoichiometric parameters of the Biowin AS model were subjected to sensitivity analysis. Sensitivity analysis showed that among all the studied parameters, 24 can be regarded as sensitive. There are several sensitivity analyses have been conducted in order to identify the values for the parameters such as AOB Maximum specific growth rate, NOB maximum specific growth rate, OHOs maximum specific growth rate, and some common parameters. BioWin parameters were altered up and down by about 50 to 100% from the default values provided in the model to determine the parameters with impact on wastewater characteristics.

Sensitivity analysis was also done to confirm the parameters that were used in the second simulation and also to study the effect of the factors that were difficult to obtain in the data collection stage. sensitivity analysis was done for both WWTP influent and effluent. In most studies, a sensitivity analysis is done for the effluent of WWTP only, but unusually in this study, a sensitivity analysis was done for both the effluent and influent, where through the results it was found that there are some parameters that affect influent simulated results, which are not directly entered into the model, and most of these parameters were from fractionation parameters.

To evaluate the impact of these parameters, two different measures of sensitivity are calculated: the normalized sensitivity coefficient ($S_{i,j}$) and the deviation of wastewater characteristics due to the change in these parameters. When $S_{i,j}$ is less than 0.25, a parameter is thought to have little impact on a particular model output; when $S_{i,j}$ is between 0.25 and 1, the parameter is thought to be influential; and when $S_{i,j}$ is between 1 and 2, the parameter is thought to have significant impact, and if $S_{i,j}$ is equal or greater than 2, it is regarded as being very influential [9]. The results of normalized sensitivity coefficient and the results deviation percentage for influent are shown in

Table *3* and **Table 4** respectively.

Table 3
Normalized sensitivity coefficient for influent results.

	BOD	**TSS**	**VSS**	**NH_4**	**PO_4**
F_{bs}	0.05	0.12	0.19		
F_{xsp}		0.34	0.53		
F_{xi}	0.15	0.04	0.07		
F_{na}				0.89	
F_{po4}					1
Part. inert COD: VSS		0.08	0.13		
Part. Subs. COD: VSS		0.59	0.94		
Aer. yield	0.53				

Table 4

Approximate values for the results deviation percentage due to the impact of fractionation, kinetic and stoichiometric parameters on wastewater influent characteristics**.**

	BOD	TSS	VSS	NH_4	PO_4
F_{bs}	2.85 ± 0.25 (D)	7.35 ± 0.75 (I)	11.65 ± 1.15 (I)	-	-
F_{xsp}	-	20.3 ± 11 (D)	32.2 ± 17.3 (D)	-	-
F_{xi}	11.65 ± 2.35 (I)	3.35 ± 0.65 (D)	5.35 ± 1.05 (I)	-	-
F_{na}	-	-	-	60.65 ± 24.25(D)	-
F_{po4}	-	-	-	-	70 ± 10 (D)
Part. inert COD: VSS	-	4.15 ± 2.35 (I)	6.55 ± 3.75 (I)	-	-
Part. Subs. COD: VSS	-	30.5 ± 18.4 (I)	48.25 ± 29.05 (I)	-	-
Aer. yield	32.05 ± 5.25 (I)	-	-	-	-

D : directly proportional

I : inversely proportional

It is clear from the results of sensitivity analysis for the influent that the impact of the parameters is mostly in BOD, TSS, VSS, NH4, and PO4. The most effective parameter for influent BOD is aerobic yield, regarding TSS and VSS the most effective parameter is COD: VSS ratio and to a slightly lesser extent non-colloidal slowly biodegradable. For ammonia and phosphate, the most effective parameter is ammonia to total kjheldahl nitrogen fraction and phosphate to total phosphorus fraction respectively.

The results of normalized sensitivity coefficient and the results deviation percentage for effluent are shown in **Table *5*** and **Table 6** respectively.

Table 5

Normalized sensitivity coefficient for effluent results.

Parameter	BOD	COD	TSS	VSS	ISS	TN	TKN	NH4	NO3	TP	PO4	MLSS	MLVSS

Fxsp	0.59	0.13	0.11	0.18	0.03	0.07	0.01	0.07	0.08	0.09	0.11	0.12	0.18
Fsi	0.03	0.70	0.02	0.04	0.00	0.01	0.00	0.01	0.02	0.02	0.02	0.02	0.04
Fxi	0.08	0.03	0.09	0.18	0.01	0.01	0.00	0.00	0.01	0.02	0.03	0.09	0.18
Fna	0.03	0.00	0.00	0.01	0.00	0.16	0.57	3.42	0.17	0.01	0.01	0.01	0.01
Fpo4	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.02	0.00	0.35	0.35	0.00	0.00
Fnus	0.00	0.00	0.00	0.00	0.00	0.01	0.35	0.02	0.02	0.00	0.00	0.00	0.00
Ammonif.	0.00	0.00	0.00	0.00	0.00	0.00	0.54	0.04	0.04	0.00	0.00	0.00	0.00
Max spec (amm)	0.02	0.00	0.01	0.01	0.00	0.00	3.81	19.33	0.32	0.01	0.01	0.01	0.01
Sub half sat (amn	0.01	0.00	0.00	0.00	0.00	0.00	0.22	1.11	0.02	0.00	0.00	0.00	0.00
Aer dec rate (amr	0.02	0.00	0.00	0.00	0.00	0.00	0.19	0.98	0.02	0.00	0.00	0.00	0.00
Max spec (nit)	0.01	0.00	0.00	0.01	0.00	0.02	0.15	0.75	0.59	0.00	0.00	0.00	0.01
Max spec (ord)	0.67	0.11	0.01	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.01
Sub half sat (ord)	0.34	0.06	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Aer dec rate (ord	0.31	0.05	0.25	0.40	0.06	0.06	0.22	0.03	0.05	0.21	0.23	0.25	0.40
denitrif N2 prod	0.01	0.00	0.00	0.01	0.00	0.11	0.02	0.10	0.11	0.01	0.00	0.01	0.01
P in end res	0.00	0.00	0.00	0.00	0.02	0.00	0.00	0.00	0.00	0.12	0.13	0.01	0.00
End res COD:VSS	0.00	0.00	0.16	0.29	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.16	0.29
Part. inert COD: VSS	0.00	0.00	0.09	0.16	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.09	0.16
Aer. yield	3.88	0.64	0.89	1.43	0.22	0.60	0.27	0.42	0.64	0.78	0.84	0.89	1.43
Anox yield	0.03	0.01	0.04	0.07	0.01	0.26	0.04	0.19	0.28	0.04	0.04	0.04	0.07
COD: VSS	0.00	0.00	0.32	0.58	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.32	0.58
N in biomass	0.00	0.00	0.00	0.01	0.00	0.11	0.27	0.12	0.14	0.00	0.00	0.00	0.01

Table 6
Approximate values for the percentage of the impact of fractionation, kinetic and stoichiometric parameters on wastewater effluent characteristics.

	BOD	COD	TSS	VSS	ISS	TN	TKN	NH4	NO3	TP	PO4	MLSS	MLVSS
F_{xsp}	24.5 ± 11.7 (I)	5.45 ± 2.65 (I)	5 ± 2.7 (I)	7.9 ± 4.3 (I)	1.45 ± 0.75 (I)	3.05 ± 1.65 (D)			3.3 ± 1.8 (D)	4.15 ± 2.35 (D)	4.55 ± 2.45 (D)	5.05 ± 2.75 (I)	7.95 ± 4.35 (I)
F_{si}		63.15 ± 6.95 (D)				1.35 ± 0.15 (D)			1.45 ± 0.15 (D)	1.85 ± 0.25 (D)	2 ± 0.1 (D)	2.1 ± 0.2 (I)	3.45 ± 0.35 (I)
F_{xi}	6 ± 1.2 (I)	2.65 ± 0.45 (D)	7.1 ± 1.4 (D)	13.85 ± 2.85 (D)								7.15 ± 1.45 (D)	13.75 ± 2.75 (D)
F_{na}						10.05 ± 4.25 (D)	46.15 ± 28.25	222.8 ±202.3 (D)	11.05 ± 5.95				
F_{po4}										23.7 ± 3.5 (D)	24.25 ± 3.65 (D)		
F_{nus}							25.75 ± 8.75 (D)		1.75 ± 0.55 (I)				
Ammonif.						0.9 ± 0 (I)	47.1 ± 37.2 (I)		3.9 ± 3.1 (D)				
Max spec (amm)	1.75 ± 1.05 (D)	0.3 ± 0.3 (D)	0.9 ± 0.7 (D)	1.5 ± 1.2 (D)		0.5 ± 0.4 (I)	479.4 ± 469.5 (I)	2431.85 ±2379.55 (I)	40.25 ±39.25 (D)			0.95 ± 0.75 (D)	1.6 ± 1.2 (D)
Sub half sat (amm)							16.35 ± 5.15 (D)	82.95 ± 26.15 (D)	1.45 ± 0.35 (I)				
Aer dec rate (amm)							17.25 ± 7.85 (D)	88.65 ± 38.65 (D)	1.45 ± 0.65 (I)				
Max spec (nit)						2.35 ± 1.75	27.8 ± 0	140.9 ± 0	50.45 ± 49.55 (D)			0.25 ± 0.25 (D)	0.4 ± 0.4 (D)
Max spec (ord)	46.4 ± 32.6 (I)	7.6 ± 5.3 (I)										0.35 ± 0.25 (D)	0.6 ± 0.4 (D)
Sub half sat (ord)	16.2 ± 1.7 (D)	2.9 ± 0.6 (D)											

Cont. Table 6

	BOD	COD	TSS	VSS	ISS	TN	TKN	NH4	NO3	TP	PO4	MLSS	MLVSS
Aer dec rate (ord)	34.3 ± 5	5.5 ± 0.5	25.15 ± 19.05 (I)	40.45 ± 30.95 (I)	6.2 ± 4.4 (I)	6.5 ± 4.8 (D)	16.35 ± 1.15 (D)		5.7 ± 5.1 (D)	21.85 ± 16.65 (D)	23.45 ± 17.85 (D)	25.1 ± 19.1 (I)	40.55 ± 30.95 (I)
denitrif N_2 prod						9.45 ± 0.75 (I)			10.15 ± 0.85 (I)				
P in end res										8.1 ± 1.6 (I)	8.75 ± 1.75 (I)	0.6 ± 0.1 (D)	
End res COD:VSS			10.55 ± 6.25 (I)	19.05 ± 11.35 (I)								10.5 ± 6.2 (I)	19.1 ± 11.2 (I)
Part. inert COD: VSS			4.6 ± 2.6 (I)	8.35 ± 4.75 (I)								4.6 ± 2.6 (I)	8.35 ± 4.75 (I)
Aer. yield	487.3 ± 430.4	72.1 ± 50.3	47 ± 30.7 (D)	74.55 ± 51.65 (D)	13.05 ± 4.95 (D)	33.9 ± 15.8 (I)	24 ± 15 (I)	0.25 ± 0.05 (I)	35.5 ± 19.3 (I)	42 ± 26 (I)	45.2 ± 28 (I)	47 ± 30.8 (D)	74.55 ±51.65 (D)
Anox yield			3.45 ± 1.85 (D)	5.65 ± 2.95 (D)		20.75 ± 10.45 (D)	2.7 ± 0 (D)	13.6 ± 0 (D)	22.3 ± 11.4 (D)	3.05 ± 1.45 (I)	3.2 ± 1.6 (I)	3.5 ± 1.8 (D)	5.65 ± 2.85 (D)
COD: VSS			21.1 ± 12.7 (I)	38.25 ± 23.05 (I)								21.15 ±12.75 (I)	38.4 ±23.1 (I)
N in biomass						14.5 ± 5.3 (I)	36.3 ± 14.8 (D)	13.65 ± 2.25 (I)	18.85 ± 7.05 (D)			0.5 ± 0.2 (I)	0.8 ± 0.3 (I)

It is clear from the results of sensitivity analysis for the effluent that the parameters mentioned in the previous table almost impact all the effluent parameters in varying degrees. The most effective parameters for effluent BOD are aerobic yield, ordinary heterotrophic maximum specific growth rate, ordinary heterotrophic substrate half saturation, ordinary heterotrophic aerobic decay rate and non-colloidal slowly biodegradable COD. For COD the most effective parameters are soluble unbiodegradable COD and aerobic yield. Regarding TSS the most effective parameters are aerobic yield, COD: VSS ratio and ordinary heterotrophic aerobic decay rate. For VSS the most effective parameters are aerobic yield, COD: VSS ratio, ordinary heterotrophic aerobic decay rate and endogenous residue COD: VSS ratio. The most effective parameter for ISS is aerobic yield. For TN the most effective parameters are aerobic and anoxic yield. The most effective parameters for TKN are ammonia oxidizing bacteria maximum specific growth rate, ammonia to total kjheldahl nitrogen fraction, ammonification, soluble unbiodegradable TKN, aerobic yield and N in biomass. The most effective parameter for NH_4 are ammonia oxidizing bacteria maximum specific growth rate, ammonia to total kjheldahl nitrogen fraction, ammonia oxidizing bacteria substrate half saturation, ammonia oxidizing bacteria aerobic decay rate, nitrite oxidizing bacteria maximum specific growth rate and aerobic yield. Regarding nitrate the most effective parameters are aerobic yield, nitrite oxidizing bacteria maximum specific growth rate, ammonia oxidizing bacteria maximum specific growth rate and anoxic yield. Regarding TP and PO_4 the most effective parameters are aerobic yield and phosphate to total phosphorus fraction. The most effective parameters for MLSS are aerobic yield, COD: VSS ratio and ordinary heterotrophic aerobic decay rate. For MLVSS the most effective parameters are aerobic yield, COD: VSS ratio, ordinary heterotrophic aerobic decay rate and endogenous residue COD: VSS ratio.

ii. *Model calibration*

After the completion of the sensitivity analysis and fractionation process, different wastewater fractions, kinetic, and stoichiometric parameters were adjusted to calibrate the model. The final adjusted kinetic and stoichiometric parameters are shown in **Table 7** and **Table 8**.

The third simulation was run and the results extracted from the model using adjusted wastewater fractions, kinetic and stoichiometric parameters compare very well with the measured data during the sampling campaign. The results of the three simulations were compared to the measured results, and it is clear that the measured data accurately matches the BioWin data with few exceptions as there might be human error, high or low influent concentration recorded in the plant data on that particular day **Fig. 8**.

Table 7

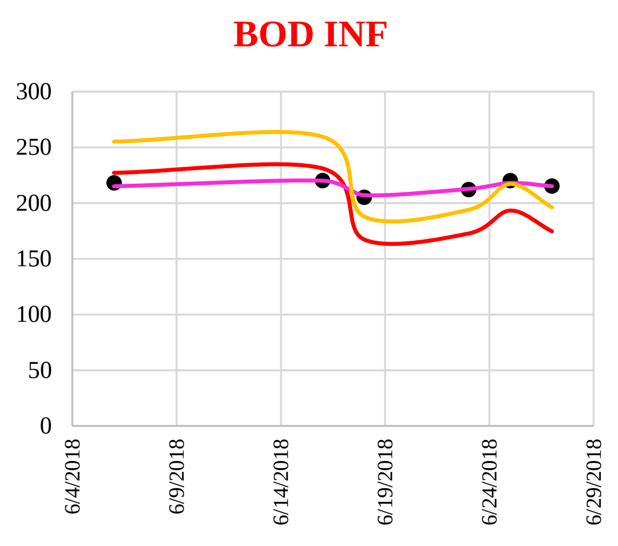
Final calibrated kinetic parameters.

Parameter	Unit	Default value	Calibrated value
COMMON			
Ammonification rate	L/mgCOD . d	0.08	0.06
Ammonia oxidizing			
Maximum specific growth rate	1/d	0.9	0.7
Substrate half saturation	mgN/L	0.7	0.9
Aerobic decay rate	1/d	0.17	0.25
Nitrite oxidizing			
Maximum specific growth rate	1/d	0.7	0.53
Ordinary heterotrophic			
Maximum specific growth rate	1/d	3.2	2.9
Substrate half saturation	mgCOD/L	5	10
Aerobic decay rate	1/d	0.62	0.75
Denit. N_2 producers	-	0.5	0.3

Table 8

Final calibrated stoichiometric parameters.

Parameter	Unit	Default value	Calibrated value
COMMON			
P in endogenous residue	mgP/mgCOD	0.022	0.1
Endogenous residue (COD : VSS) ratio	mgCOD/mgVSS	1.42	1.23
Particulate substrate (COD : VSS) ratio	mgCOD/mgVSS	1.6327	1.46
Particulate inert (COD : VSS) ratio	mgCOD/mgVSS	1.6	1.46
COD : VSS ratio	mgCOD/mgVSS	1.42	2.1
Ordinary heterotrophic			
Yield (aerobic)	-	0.666	0.56
N in biomass	mgN/mgCOD	0.07	0.1
Yield (anoxic)	-	0.54	0.61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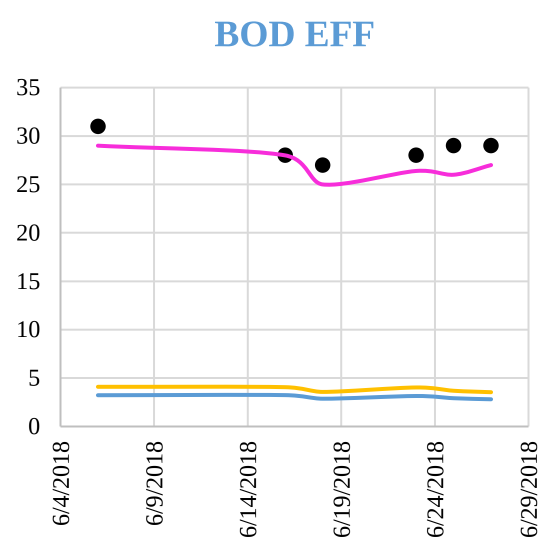
6/9/2018
6/14/2018
6/19/2018
6/24/2018
6/29/2018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20
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5
0
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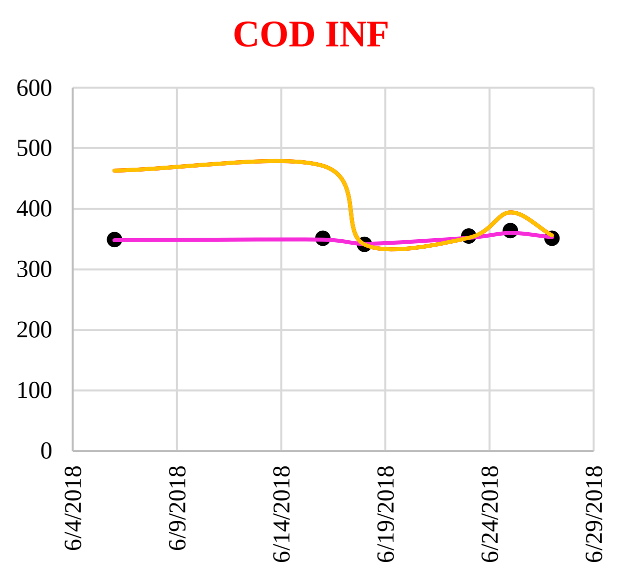
6/9/2018
6/14/2018
6/19/2018
6/24/2018
6/29/2018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0
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6/14/2018
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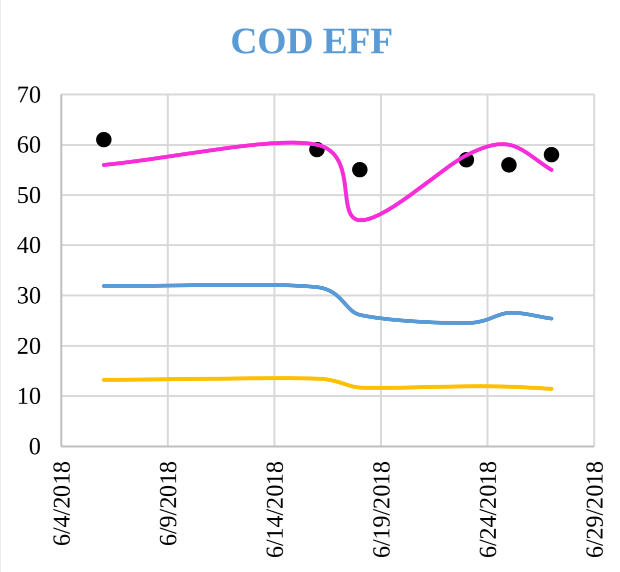
6/24/2018
6/29/2018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10
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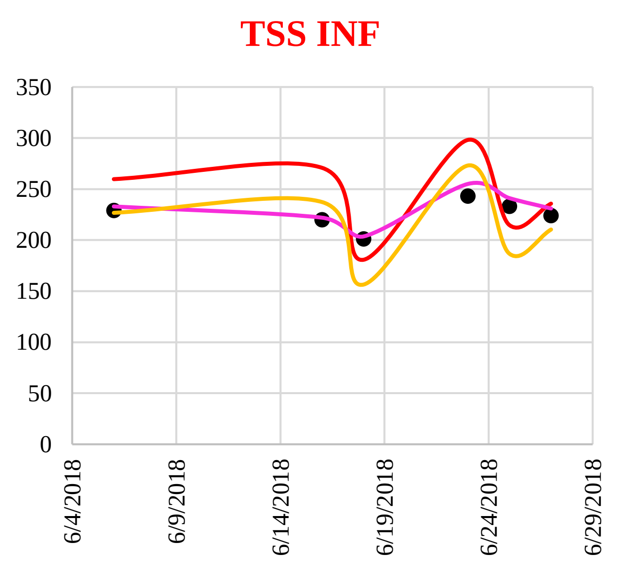
6/9/2018
6/14/2018
6/19/2018
6/24/2018
6/29/2018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200
150
100
50
0
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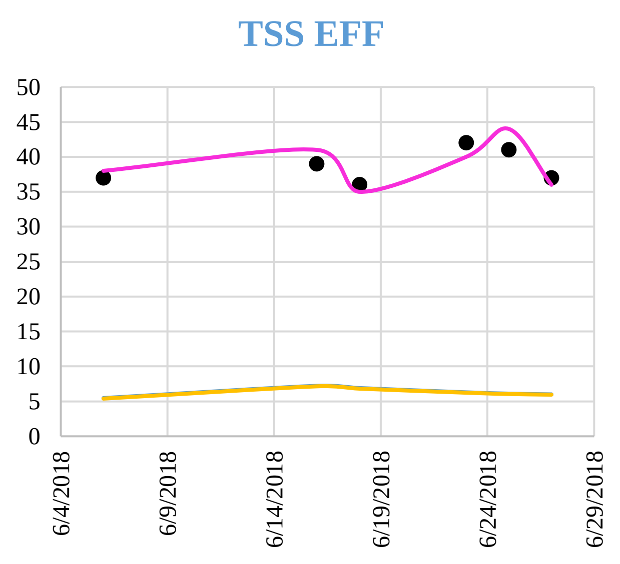
6/9/2018
6/14/2018
6/19/2018
6/24/2018
6/29/2018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30
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6/24/2018
6/29/2018

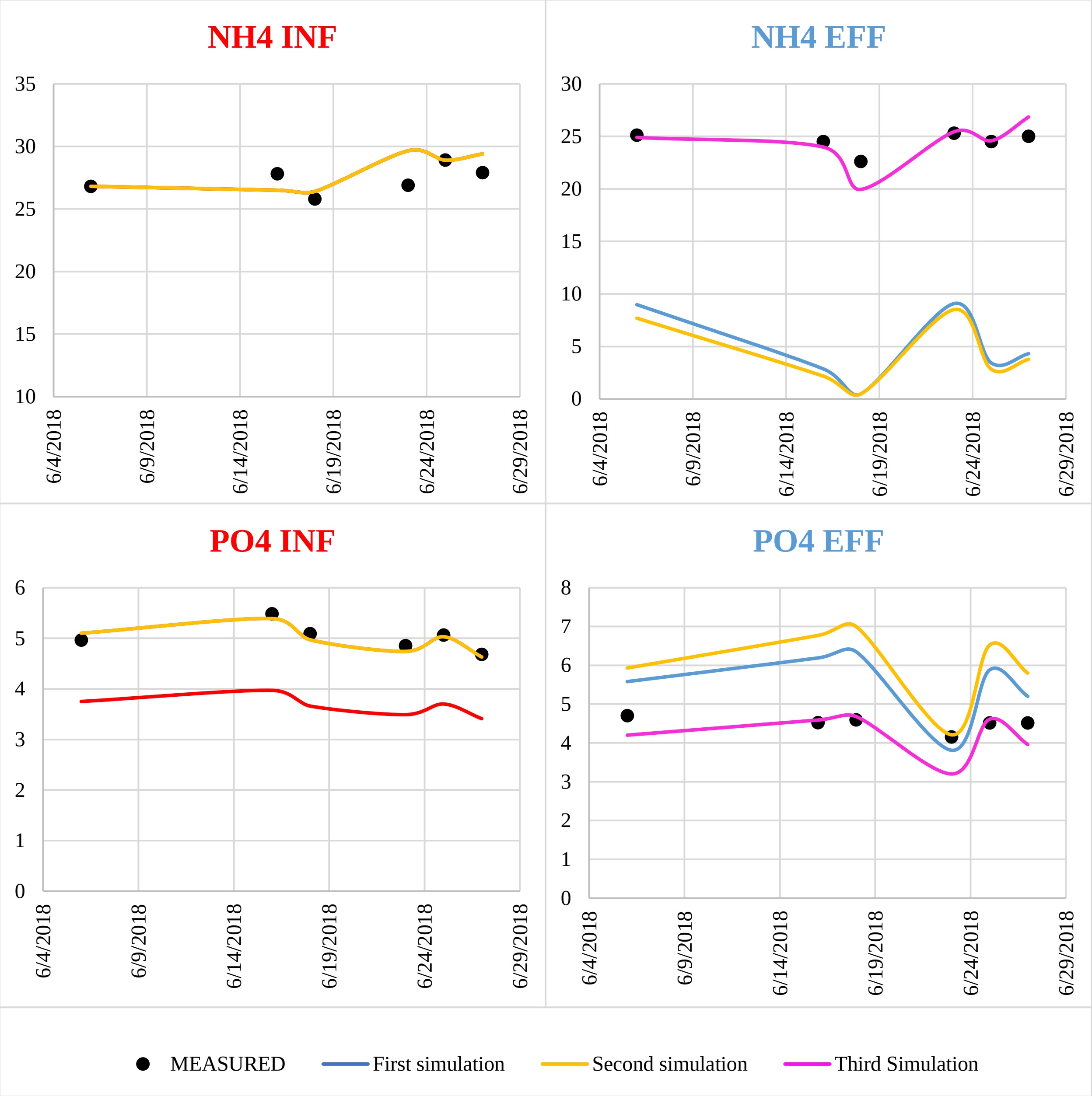


Fig. 8. Comparison between the model three simulation results and the measured data.

iii. Statistical analysis

To evaluate the results of any simulation process, deviations between measured and simulated results must be calculated. The n deviations can be summarized with statistics of the overall deviation, the most commonly used statistical metric for comparing models is average relative deviation (ARD), and this is in agreement with [9] and [10], who used ARD to evaluate their results. ARD lower than 20 % is considered to be acceptable.

$$\Delta D = \left(\frac{Y_i - X_i}{Y_i}\right) * 100$$

$$ARD = \frac{1}{n} * \sum_{i=1}^{n} \left| \Delta D_i \right|$$

Where X_i is simulated result, Y_i is measured value, n is number of measurements, ΔD is the relative deviation, ARD is the average relative deviation. ARD is calculated to evaluate the final results of the model in the third simulation, the results are shown in **Table 9**.

Table 9

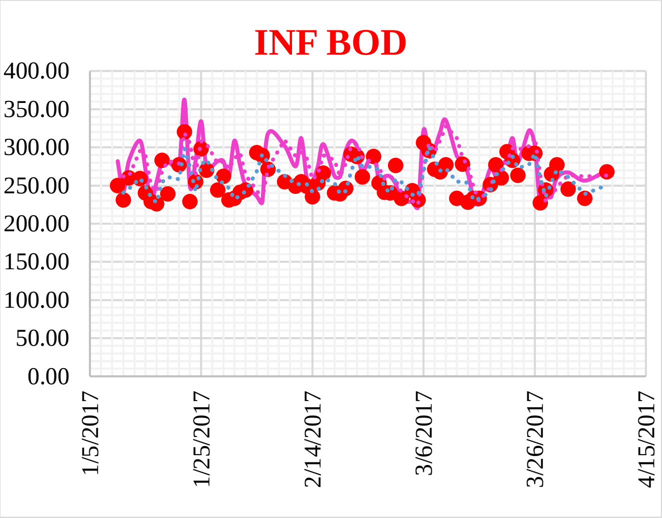
Average relative deviation (ARD) for the final simulated results of Gamasa WWTP.

Parameter	ARD	
	Influent	Effluent
BOD	1.7	4.2
COD	0	4.8
TSS	2.3	3.1
VSS	2.1	2.8
ISS	0	4.9
TN	0	1.4
TKN	0	1.2
NH4	0.2	3.8
NO3	0	5.1
TP	0	2.9
PO4	1	4.1
MLSS	3.5	
MLVSS	3.2	

From the results shown in the previous table, it is clear that most of the values ARD are less than 5 % and this indicates the great success of the model in predicting the performance of Gamasa WWTP.

3.2. Model validation

After the calibration was successfully done, the validation of the model was carried out. The available data in the period from January to April 2017 are used for validation of the model. The characteristics of wastewater, which are measured as routine in Gamasa WWTP, and were available to be used in the validation of the model, are COD, BOD, TSS, and NH_4. **Fig. 9** shows the comparison between the measured data and simulated results for the validation period.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300.00
250.00
200.00
150.00
100.00
50.00
0.00
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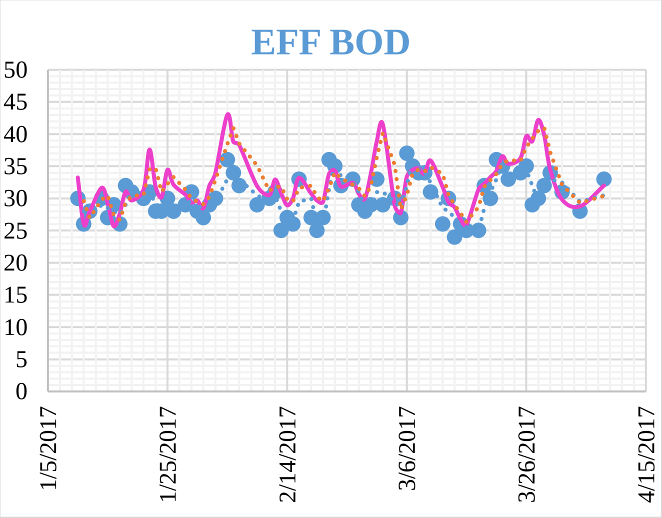
3/6/2017
3/26/2017
4/15/2017


EFF BOD
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45
40
35
30
25
20
15
10
5
0
1/5/2017
1/25/2017
2/14/2017
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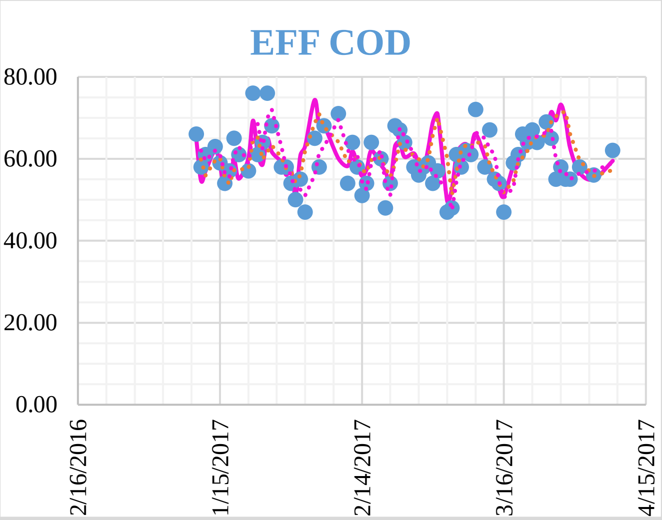
3/26/2017
4/15/2017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20.00
0.00
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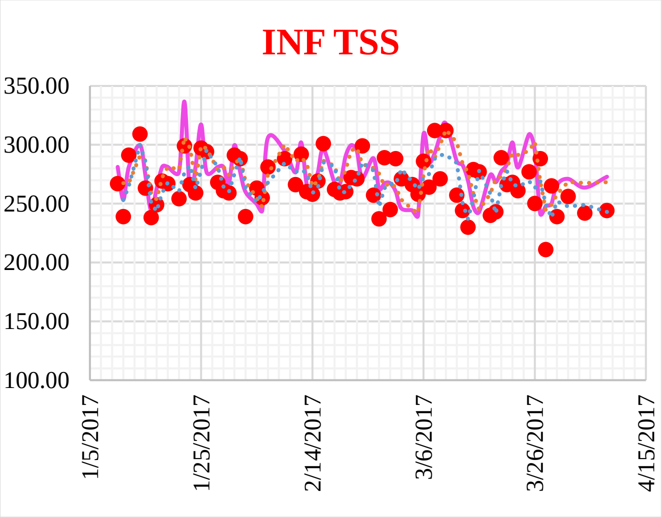
1/15/2017
2/14/2017
3/16/2017
4/15/2017


INF TSS
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200.00
150.00
100.00
1/5/2017
1/25/2017
2/14/2017
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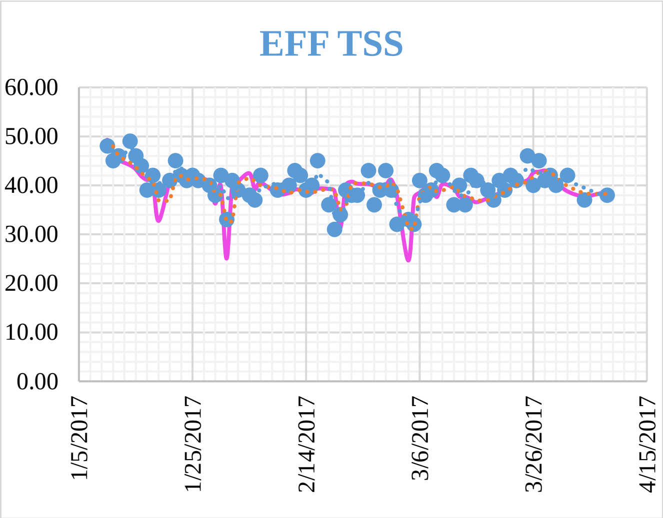
3/26/2017
4/15/2017


EFF TSS
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1/5/2017
1/25/2017
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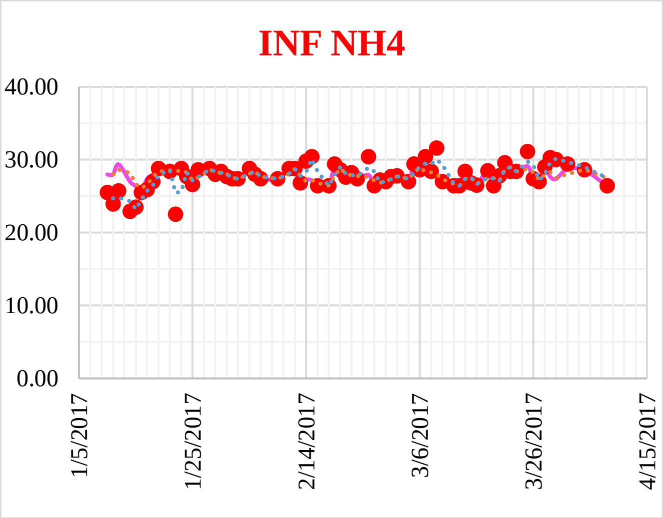
3/26/2017
4/15/2017


INF NH4
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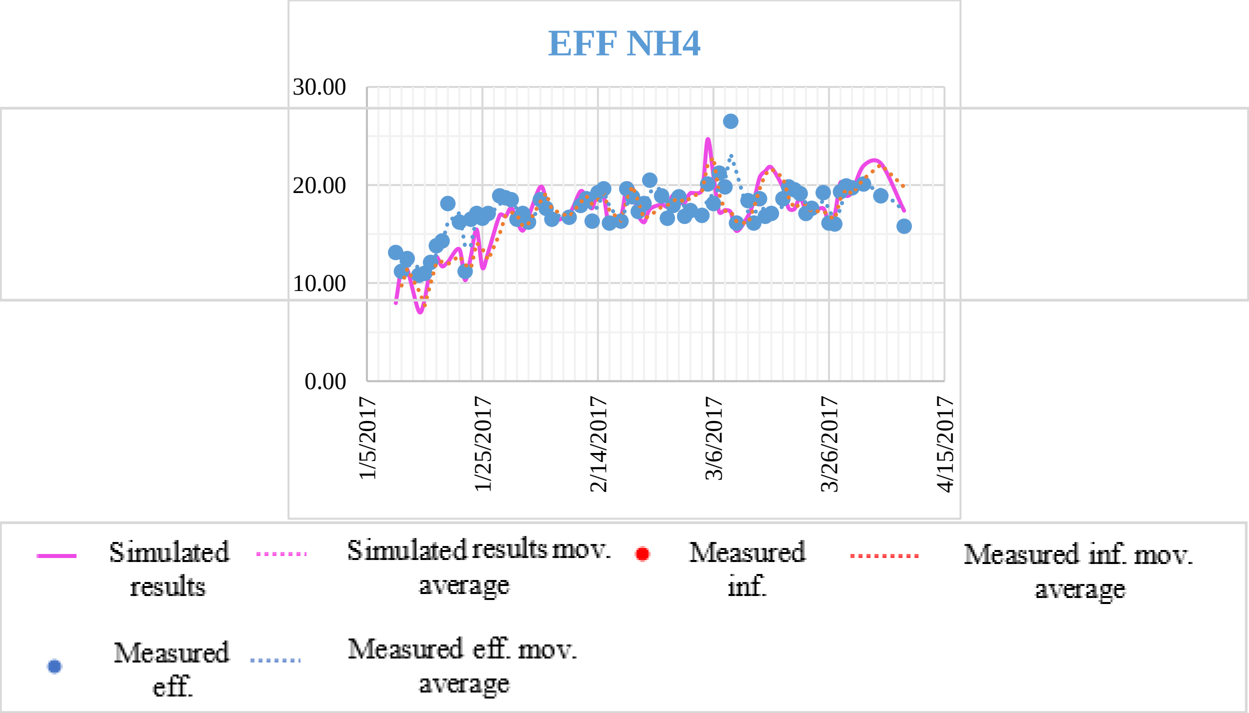
EFF NH4
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1/5/2017
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3/6/2017
3/26/2017
4/15/2017
Simulated results
Simulated results mov. average
Measured inf.
Measured inf. mov. average
Measured eff.
Measured eff. mov. average

Fig. 9. Validated model simulation results during validation period.

As you can see in **Fig. 9**, the measured data accurately matches the BioWin data, the average line of measured data almost matches the average line of simulated results, with few exceptions as there might be human error, moreover, the operational conditions vary throughout the year in terms of incoming wastewater characterization, the removal efficiency of PST and FST in the model was considered constant over the validation period, but in reality it was variable and dependent on the incoming flow's variation.

The average relative deviation between the simulated data and the measured data for the validation period was calculated, ARD values are as shown in **Table 10**. ARD values were less than 10% and were considered to be acceptable.

Table 10

Average relative deviation between the simulated data and the measured data for the first validation period.

Parameter	**ARD**	
	Influent	**Effluent**
BOD	7.6	8.7
COD	0	5.6
TSS	6.7	5.2
NH4	2.1	7.3
TKN	0	4.4
MLSS	3.8	
MLVSS	2.4	

From the results of sampling results calibration and the validation of the model, it can be said that the model has succeeded in the WWTP simulation, and now it can be used in the improvement of WWTP performance.

4. conclusion

Successful plant-wide modelling was done in this study for Gamasa wastewater treatment plant (WWTP). BioWin software and the STOWA protocol for wastewater characterization were successfully implemented in this study. A sensitivity analysis was done and it was found that the most sensitive parameters were aerobic yield, anoxic yield, ordinary heterotrophic maximum specific growth rate, ordinary heterotrophic substrate half saturation, ordinary heterotrophic aerobic decay rate, soluble unbiodegradable COD, COD: VSS ratio, endogenous residue COD: VSS ratio, non-colloidal slowly biodegradable COD, ammonia oxidizing bacteria maximum specific growth rate, ammonia to total kjheldahl nitrogen fraction, ammonification, soluble unbiodegradable TKN, aerobic yield, N in biomass, ammonia oxidizing bacteria substrate half saturation, ammonia oxidizing bacteria aerobic decay rate, nitrite oxidizing bacteria maximum specific growth rate and aerobic yield, and phosphate to total phosphorus fraction.After the calibration was successfully done, the validation of the model was carried out for two different periods of time. Average relative deviation (ARD) values between the simulated data and the measured data through calibration and validation stages, were less than 20%, This verifies the success of the model to simulate Gamasa WWTP and now it can be used in the study of the improvement of WWTP performance.

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