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Wastewater treatment plant design and modeling for the city of Erzurum

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ABSTRACT

Currently large amounts of wastewater are produced by domestic and industrial activities. Discharge of wastewater to the receiving environment without treatment causes significant health and environmental problems. Modeling and optimization of Wastewater Treatment Plants (WWTP) developed to treat domestic wastewater play key roles in determining unit components, design parameters and operation conditions. Several models were proposed to predict the treatment performance in WWTP. The Activated Sludge Model No. 1 (ASM1) is one of the commonly-used standard models developed to better understand removal of carbonaceous and nitrogenous materials. In this study, a WWTP is proposed for domestic wastewater using grit chamber, circular primary and secondary clarifiers, completely-mixed aeration tank, sludge thickener, sludge dewatering and anaerobic digestion processes together. The WWTP was modeled with ASM1 noting the topographic and meteorological features of the city. The treatment performances with wastewater temperatures of 10°C and 20°C were investigated for this plant, operating at high elevation. Removal efficiencies at 20°C were 95.7%, 92.2%, 97.9% and 99.2% for MLSS, COD, BOD and NH_4, while effluent concentrations were 14.83, 48.51, 6.55 and 0.3 mg L^{-1}, respectively. At 10°C, removal efficiencies were 88.9%, 88%, 93.2%, and 26.9%, while effluent concentrations were 38, 75, 21.83 and 26.13 mg L^{-1}, respectively. A clear reduction was observed in nitrogenous material removal at low temperatures. Additionally, keeping dissolved oxygen concentration in the aeration tank at 1.5 mg L^{-1} with PID control increased nitrification efficiency by 30%. The findings reveal the importance of modeling studies during planning of WWTP.

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1. Introduction

In spite of 70% of the Earth's surface being covered with water, only 0.5% of this amount can be used as drinking water. Due to rapid population increase and unplanned urbanization, limited water resources are rapidly polluted and the demand for clean water is increasing every day. Uncontrolled discharge of domestic and industrial wastewaters into receiving environments negatively affects human health and the ecological balance. The correlation between the use of drinking water sources polluted by wastewater and diseases was determined for the first time by Dr. John Snow in 1854 [1, 2]. Since this date, intense research began to focus on wastewater treatment. Firstly the focus was on removal of carbonaceous organic matter. However, discharge of this partially treated water into still waters like lakes and estuaries caused eutrophication due to high nitrogen and phosphorus content. As a result, wastewater treatment plants founded in later years targeted the removal of carbonaceous material along with nitrogenous and phosphorous materials. The activated sludge process (ASP) developed by Ardern and Lockette in 1914 was a turning point in terms of biological treatment [3]. ASP is based on biologically-useful material in wastewater being consumed by microorganisms for energy acquirement or structural change [4]. These systems, named "active or activated" biomass produced to stabilize waste under aerobic conditions, became rapidly popular from the 1940s due to success in treating wastewater [5]. Activated sludge (AS) is a mixture containing living and dead microorganisms along with organic and inorganic materials. ASP comprises two separate stages of aeration and precipitation. In the first stage, sludge aerated by mixers or diffusers is not permitted to precipitate. Theoretically full mixing is ensured for organic matter, oxygen and microorganisms. In this environment, called suspended growth systems, organic matter in wastewater is degraded, while continuous active biomass sludge develops. After this stage, though organic matter is removed, the treatment process is not complete. Wastewater is a solid-fluid mixture in suspension containing suspended solid matter with organic and inorganic form. For separation of treated water and sludge, this mixture is transferred to the second stage. In the clarification tank, mixing is not performed and water speed is very low. As some of the precipitated sludge may continue wastewater treatment in the first stage, it is returned to the completely-mixed aeration tank, while the remaining portion is removed from the system to be used in sludge dryers or biogas units [6]. Nearly every wastewater treatment plant (WWTP) includes ASP, which is the most commonly chosen biological treatment system in the present day [7]. Though several studies have been performed to date about the operation of this process, which has an overly complicated biological mechanism, it still involves several unsolved problems [8]. The population distribution of microorganisms in the process, the seasonal and hourly differences in flow rate and organic load amounts in the system, yearly and daily changes in independent external factors like temperature, pH and waste content are among the leading reasons making it more difficult to understand AS systems [9]. The lack of detailed analysis of water entering the plant, lack of sufficient investigation of external environmental conditions and not performing accurate modeling studies may cause deficiencies or unnecessary scaling in process design and mistaken applications in operating procedures. Currently most ASP are constructed with dimensions that are able to deal with much higher flow than the wastewater flow rate entering the system. Additionally, it appears that even plants operating well cannot provide effluent water standards within certain periods of the operating duration [10].

To be able to better understand ASP, one of the most complicated microbial systems designed for a certain purpose, it is crucial important to model process dynamics. Several different heterotroph and autotroph bacterial groups must act together to fulfil different functions like stabilization of organic carbon, nitrification, denitrification and advanced biological phosphorus removal. Currently, metabolic activities of microorganisms can be predicted through modeling and system parameters can be separately checked to ensure optimum performance of the process [11]. In the early period, the three-component activated sludge model (ASM) focusing on oxygen use, substrate consumption and biomass production was used. However, this basic approach remained inadequate to assess wastewater treatment performance and to predict sludge amounts most of the time. As a result, the International Association on Water Pollution Research and Control (IAWPRC) created a working group in 1983 with the aim of ensuring implementation of more practical and realistic modeling for both the design and operation stages of ASP. This study group published their work with the name activated sludge model no. 1 (ASM1) in 1987 [12]. This model is a very comprehensive ASM comprising 13 components and 8 processes. In later periods, two new models were developed comprising many more components than ASM1 and were more explanatory for determination of biological phosphorus removal, nitrification, and denitrification processes [13]. However, ASM1 is a widely-accepted model that successfully explains removal of carbonaceous and nitrogenous material in single sludge systems for domestic wastewater [14].

The rapid development of computer and electronic technologies in the present day have made it possible for personal computer users to access equipment that used to be expensive, difficult to access and require large spaces. Software technology has adapted to these developments. New generation computer software has begun to be used with advanced visual interfaces, able to solve more complicated mathematical models in a short duration, making it possible to run a variety of scenarios, using open-source code and open to development. As in every area, new generation software has become popular for the modeling and simulation of wastewater treatment plants and more comprehensive computer software is offered to the market with every passing day. ASM models developed by IWA have been successfully applied using diverse design, simulation and optimization software like GPS-X (Hydromantis Environmental Software Solutions, Inc. Hamilton, ON, Canada), BioWin (EnviroSim associates LTD. Hamilton, ON, Canada), ASIM Activated Sludge SIMulation Program (Swiss Federal Institute of Aquatic Science and Technology Eawag, Dübendorf, Switzerland), SIMBA (IFAK-Institut für Automation und Kommunikation e.V. Magdeburg, Germany), WEST (DHI A/S Hørsholm, Denmark), STOAT (WRc plc. Wiltshire, UK) and Sumo (Dynamita, Sigale, France) [15, 16]. Among these, GPS-X software developed by the Canadian Hydromantis firm founded in 1985 is among the most commonly chosen at present and this software has features with broad scope for modeling and simulation of wastewater treatment plants. The GPS-X software includes nearly all processes that may occur in a WWTP. Additionally, it offers great possibilities for design and operation of WWTP with unrivaled features like useful interface, advanced graphic applications, determination of interactions between processes, optimization of critical parameters during design, and the ability to offer dynamic solutions to topics about reactions during special situations that may be encountered in WWTP.

In this study, modelling was performed for a WWTP proposed for domestic wastewater treatment in Erzurum city center, located at high elevation in continental climate conditions, using the GPS-X software. While modeling ASP, ASM1 was chosen, which is most commonly used in the literature to model the performance of full-scale domestic wastewater treatment plants. The wastewater components of COD, dissolved COD, BOD, MLSS and nitrogen parameters were characterized in the model. Literature screening was performed for other parameters and values widely used for domestic wastewater were accepted. The type, number, and physical features of treatment processes included in the plant and influent properties were mathematically modeled with the aid of GPS-X software. The effect of wastewater temperature on effluent concentration was researched to investigate whether the calculated value met the effluent standards or not. Later, the correlation between dissolved oxygen concentration in the aeration tanks, fixed to a certain value with PID control, with carbonaceous and nitrogenous material removal was investigated.

2. Materials and methods

2.1 Study area and wastewater characteristics

Erzurum city center, chosen as study area, is located in the Northeast Anatolian region in Türkiye. The city is divided into three central counties of Aziziye, Palandöken and Yakutiye and is home to 428,302 people according to 2021 Turkish Statistical Institute (TÜİK) data. The city center is located at 1853 m above sea level and is the country's most crowded city at high elevation [17]. The main industries linked to the urban wastewater system in Erzurum are the organized industrial zone, slaughterhouse and milk processing industries. Table 1 presents the characterization of wastewater from Erzurum.

In plants where biological treatment will be performed, the biologically degradable and non-degradable (inert) parts play important roles in terms of operation and modeling of ASP. COD, showing the total carbonaceous matter in influent, comprises the total of soluble inert organic matter (S_I), readily biodegradable substrate (S_S), particulate inert organic matter (X_I) and slowly biodegradable substrate (X_S) values. As the readily biodegradable substrate in wastewater comprises volatile fat acids, carbohydrates, alcohols, peptones and amino acids, it can be rapidly absorbed by heterotroph microorganisms under aerobic and anoxic conditions. According to research, the slowly biodegradable substrate comprises 35-60% of wastewater and is formed of relatively more complicated molecules, so microorganisms require a longer time to convert it to simple molecules [18]. The concentration of slowly biodegradable substrate is important in terms of modeling the hydrolysis process, while it partly plays a role in determining the age of sludge. Particulate inert organic matter is held by clarifiers and discarded from the system. Soluble inert organic matter has great importance in terms of determining the performance of the system as it is included in the effluent COD concentration [19]. Nitrogenous components include soluble nitrite and nitrate nitrogen (S_{NO}), soluble free and ionized ammonia nitrogen (S_{NH}), soluble biodegradable organic nitrogen (S_{ND}) and particulate biodegradable organic nitrogen (X_{ND}). Due to these parameters, used to be able to better understand plant operation, total nitrogen (TN) may be investigated in inert, readily degradable and slowly degradable portions.

Table 1. *Wastewater characteristics of Erzurum city center.*

Parameter	Unit	Value
Q_{design}	$m^3\ h^{-1}$	5329
Q_{mean}	$m^3\ h^{-1}$	3468
Q_{min}	$m^3\ h^{-1}$	2210
Q_{max}	$m^3\ h^{-1}$	7265
pH	-	6.99-8.87
MLSS	$g\ m^{-3}$	343
COD	$g\ m^{-3}$	631
BOD	$g\ m^{-3}$	321
TKN	$g\ m^{-3}$	54
TP	$g\ m^{-3}$	13
S_I	$g\ m^{-3}$	30
S_S	$g\ m^{-3}$	149.36
X_S	$g\ m^{-3}$	332.45
X_I	$g\ m^{-3}$	112.39
S_{NO}	$g\ m^{-3}$	0
S_{NH}	$g\ m^{-3}$	35.75
S_{ND}	$g\ m^{-3}$	1.93
X_{ND}	$g\ m^{-3}$	9.68

2.2. Wastewater treatment processes

In this study, the WWTP used grit chambers, distribution and collection structures, circular primary and secondary clarifier tanks, completely-mixed aeration tank, sludge thickener and dewatering tanks and anaerobic digesters. Wastewater was sent to the aerated grit chambers after preliminary physical processing. Sand was removed to prevent unwanted accumulation in other units and wear on machinery. All types of organic matter were removed from sand by passing through separators and washers before it is transferred to containers. Grease was removed from the surface of the wastewater and pumped to grease collection units. Wastewater was divided through distribution structures linked to the number of reactors in the treatment plant. Additionally, backups were present considering any possible breakdown of the distribution valves. Water coming from the secondary clarifier tank was sent to the recycling line with this distribution structure. In the circular primary clarifier tank, suspended solid matter and organic matter is removed. The clarified wastewater is discharged through weirs and the precipitated primary sludge is thickened in sludge cones. The distributed wastewater passing from the reactors is combined using collecting structures and thus becomes homogeneous. Wastewater passing through the circular primary clarifier tank is sent to the ASP to remove organic matter and nutrients after passing through a pumping station. AS tanks are aerated by fine bubble disc diffusors. Additionally, submerged mixers are used with the aim of ensuring that both suspended solid matter precipitate and better aeration within the tank. Wastewater is sent to the circular secondary clarifier tanks from the aeration tanks. The circular secondary clarifier tanks, where suspended solid matter and treated water are separated, are one of the most important components of ASPs. Some of the precipitated sludge is returned to the AS tanks to check sludge age and sludge thickening. Excess sludge taken from the system is concentrated through sludge thickeners working with the traditional gravity method. Thickened sludge from the circular primary and secondary clarifiers is converted into end products like carbon dioxide and methane in the anaerobic tank. Sludge is sent continuously or in batches and kept in the reactor for varying durations. Sludge removed from the reactor has reduced concentrations of organic matter and pathogenic microorganisms. Sludge passing through the anaerobic tanks is dried by being centrifuged or pressed. Later it is stored in containers or buried. When creating the model in GPS-X software, the ASP and units affecting the operation of this process were included. The plant uses 4 grit chambers, 4 circular primary clarifier tanks, 5 fully mixed completely-mixed aeration tanks and 6 circular secondary clarifier tanks. Four sludge thickener tanks are used each for excess sludge from the circular primary and secondary clarifiers. The thickened sludge is sent to anaerobic digesters with the aim of gas production. Water from the sludge thickener tanks is recycled to the circular primary clarifier input and aeration tank input. The design parameters and technical information for units included in the WWTP modeling study are shown in Table 2.

Table 2. *Technical specifications of the processes in the wastewater treatment plant.*

Process	Parameter	Unit	Value
Grit chamber	Number of units	-	4
	Volume per unit	m^3	209
	Hydraulic retention time, (Q_{max})	minute	7
	Sand production per volume	$g\ m^{-3}$	20
Circular primary clarifier	Number of units	-	4
	Volume per unit	m^3	1130
	Hydraulic retention time, (Q_{mean})	hour	1
	Diameter	m	24
	Height	m	2.5
	Surface load, (Q_{max})	$m^3\ m^{-2}\cdot day^{-1}$	100
	Sludge load	$kg\ day^{-1}$	14010
Completely-mixed aeration tank	Number of units	-	5
	Volume per unit	m^3	17578.2
	Hydraulic retention time, (Q_{max})	hour	12
	Sludge age	day	13
	Oxygen flow rate	$m^3\ hour^{-1}$	12000
	MLSS concentration	$kg\ m^{-3}$	3.7
Circular secondary clarifier	Number of units	-	6
	Volume per unit	m^3	5273.67
	Hydraulic retention time, (Q_{max})	hour	4.4
	Diameter	m	38
	Height	m	4.65
	Surface load, (Q_{max})	$m^3\ m^{-2}\cdot day^{-1}$	25.7
	Sludge flow rate	$m^3\ day^{-1}$	2700
	Recycle sludge rate	$m^3\ m^{-3}$	0.75
Primary sludge thickener	Number of units	-	4
	Volume per unit	m^3	353.45
	Diameter	m	10
	Concentrated sludge flow rate	$m^3\ day^{-1}$	200
Secondary sludge thickener	Number of units	-	4
	Volume per unit	m^3	450
	Diameter	m	11.3
	Concentrated sludge flow rate	$m^3\ day^{-1}$	400
Anaerobic digester	Number of units	-	4
	Volume per unit	m^3	4342
	Temperature	°C	35
	Hydraulic retention time	day	25

2.3. Activated Sludge Model No. 1 (ASM1)

The ASM developed by the study group founded by IAWPRC was published under the name ASM1 in 1987. The first aim when developing the model was to create a consensus about a simple model to investigate available models and to be able to realistically predict the performance of carbon-removal, nitrification and denitrification systems. In later years, the IAWPRC took the name International Association on Water Quality (IAWQ) and developed ASM2 in 1995, ADM2d in 1999 and ASM3 in 2000 [20]. However, ASM1 developed by Henze et al. (1987) is a comprehensive model comprising 13 components and 8 processes that is adequate for biological treatment of domestic wastewater [12]. Table 3 shows the explanations of the components and units used in the model. In this notation, S symbolizes soluble compounds, while X symbolizes insoluble compounds. B, S and O subindexes represent biomass, substrate and oxygen, respectively. A and H show autotrophic and heterotrophic microorganisms. In the model, the COD parameter is chosen in terms of making connections between organic matter, biomass and electron receivers. Organic matter is separated into two main groups of biodegradable and non-degradable matter. Biodegradable matter is grouped as readily degradable (S_S) and slowly degradable matter (X_S); while non-degradable matter is grouped as inert (S_I) and particulate (X_I). The particulate matter emerging with degradation of biomass (X_P) comprises slowly biodegradable substrate as a result of the decay of microorganisms. Though alkalinity (S_{ALK}) is not one of the basic components of the model, it is important in terms of revealing pH changes in the model. In the model, ammonium nitrogen (S_{NH}), organic nitrogen (S_{ND}) and particulate nitrogen (X_{ND}) are accepted as being biodegradable. Particulate nitrogen may be hydrolyzed to soluble nitrogen during hydrolysis of the slowly biodegrading substrate. Soluble organic nitrogen may be converted to ammonium nitrogen by heterotrophic bacteria. Later ammonium nitrogen is used as a nitrogen source for heterotrophic bacteria, while it is used as an energy source and for new cell synthesis by autotropic bacteria. Particulate nitrogen emerges as a result of the decay of both heterotrophic and autotrophic bacteria [21].

Table 3. *ASM1 state variables.*

Component	State variable	Symbol	Unit
1	Soluble inert organic matter	S_I	g COD m^{-3}
2	Readily biodegradable substrate	S_S	g COD m^{-3}
3	Particulate inert organic matter	X_I	g COD m^{-3}
4	Slowly biodegradable substrate	X_S	g COD m^{-3}
5	Active heterotrophic biomass	X_{BH}	g COD m^{-3}
6	Active autotrophic biomass	X_{BA}	g COD m^{-3}
7	Particulate products arising from biomass decay	X_P	g COD m^{-3}
8	Dissolved oxygen	S_O	g O_2 m^{-3}
9	Nitrate and nitrite nitrogen	S_{NO}	g N m^{-3}
10	Free and ionized ammonia nitrogen	S_{NH}	g N m^{-3}
11	Soluble biodegradable organic nitrogen	S_{ND}	g N m^{-3}
12	Particulate biodegradable organic nitrogen	X_{ND}	g N m^{-3}
13	Alkalinity	S_{ALK}	Molar units

ASM1 comprises 8 processes encompassing proliferation and decay of microorganisms, ammo-nitrification of soluble organic nitrogen, and hydrolysis of slowly degrading substrate and particulate organic nitrogen. The relationships between the parameters and compounds used to create these processes are mentioned in brief below [22].

- Aerobic proliferation of heterotrophs: This is accepted as the main process for COD removal. In this process using oxygen as an electron acceptor, in the process the readily degraded substrate and ammonium nitrogen are consumed to obtain energy and synthesize new cells.
- Anoxic proliferation of heterotrophs: The denitrification event occurs in this process. Heterotrophs consume nitrate as electron acceptor while using the readily degraded organic matter as substrate. In this process, ammonium nitrogen is used for synthesis of new cells. Since substrate removal under anoxic conditions occurs more slowly than under aerobic conditions, the rate expression is multiplied by the correction factor η_g which is less than 1.
- Aerobic proliferation of autotrophs: In this process, oxygen and ammonium nitrogen are consumed to produce nitrifying microorganisms and nitrate emerges at the end of the process. Additionally, autotrophs cause

a pronounced effect on alkalinity when proliferating aerobically.

- Decay of heterotrophs: This process is modeled according to the death-renewal hypothesis. According to this approach, some of the active biomass converts to slowly decaying particulate matter and inert particulate products. In the death renewal approach, an electron acceptor like O_2 or NO_3 is not used and it is accepted that COD removal does not occur.
- Decay of autotrophs: This is modeled with the death-renewal approach as for degradation of heterotrophic microorganisms. Autotrophic biomass decays and is converted to slowly degrading particulate matter and inert particulate matter.
- Ammo-nitrification of soluble organic nitrogen: In this process, biodegradable nitrogen is converted to ammonium nitrogen by heterotrophic microorganisms. During ammo-nitrification, alkalinity variations occur as hydrogen ions are consumed.
- Hydrolysis of captured organics: This event is the conversion of slowly biodegradable substrate captured in sludge to readily degraded substrate by extracellular enzymes. Hydrolysis rate is connected to the delay in electron acceptor consumption during substrate removal.
- Hydrolysis of captured organic nitrogen: This is the hydrolysis of particulate organic nitrogen to soluble organic nitrogen. Hydrolysis rate is accepted as being dependent on the ratio of particulate organic nitrogen to the slowly biodegradable substrate.

Table 4 includes the matrix view of the components and processes in ASM1. The matrix view allows the opportunity to more readily understand complicated models involving many parameters [23]. Here, the i variable are column components, while the rows shown by j represent processes. The rate equation for each process is included in the rightmost column. The conversion rate equation (r_i) for each component in the model is calculated with the aid of the following equation (Eq.1).

$$r_i = \sum_j \nu_{ij} \rho_j \tag{1}$$

In this equation, ν is the component coefficient and ρ is the process rate equation.
For example, the readily biodegradable substrate (S_S) may be expressed as follows with this method (Eq. 2).

$$r_{S_S} = \frac{dS_S}{dt} = \nu_{2,1}\rho_1 + \nu_{2,2}\rho_2 + \nu_{2,7}\rho_7 = -\frac{1}{Y_H}\left(\mu_{Hmax}\left(\frac{S_S}{K_S+S_S}\right)\left(\frac{S_O}{K_{OH}+S_O}\right)X_{BH}\right) - \frac{1}{Y_H}\left(\mu_{Hmax}\left(\frac{S_S}{K_S+S_S}\right)\left(\frac{K_{OH}}{K_{OH}+S_O}\right)\left(\frac{S_{NO}}{K_{NO}+S_{NO}}\right)\eta_g X_{BH}\right) + k_h \frac{X_S/X_{BH}}{K_X+(X_S/X_{BH})}\left[\left(\frac{S_O}{K_{OH}+S_O}\right) + \eta_h\left(\frac{K_{OH}}{K_{OH}+S_O}\right)\left(\frac{S_{NO}}{K_{NO}+S_{NO}}\right)\right]X_{BH} \tag{2}$$

Table 4. *Matrix representation of ASM1.*

Component → (i)	1	2	3	4	5	6	7	8	9	10	11	12	13	Process rate, ρ_j $[ML^{-3}T^{-1}]$
Process ↓ (j)	S_I	S_S	X_I	X_S	X_{BH}	X_B	X_P	S_O	S_{NO}	S_{NH}	S_{ND}	X_{ND}	S_{ALK}	
1 Aerobic growth of heterotrophs		$-\frac{1}{Y_H}$			1			$-\frac{1-Y_H}{Y_H}$		$-i_{XB}$			$-\frac{i_{XB}}{14}$	$\hat{\mu}_H\left(\frac{S_S}{K_S+S_S}\right)\left(\frac{S_O}{K_{O,H}+S_O}\right)X_{B,H}$
2 Anoxic growth of heterotrophs		$-\frac{1}{Y_H}$			1				$-\frac{1-Y_H}{2.86Y_H}$	$-i_{XB}$			$\frac{1-Y_H}{14\times 2.68Y_H}-\frac{i_{XB}}{14}$	$\hat{\mu}_H\left(\frac{S_S}{K_S+S_S}\right)\left(\frac{K_{O,H}}{K_{O,H}+S_O}\right)\left(\frac{S_{NO}}{K_{NO}+S_{NO}}\right)\eta_g X_{B,H}$
3 Aerobic growth of autotrophs						1		$-\frac{4.57-Y_A}{Y_A}$	$\frac{1}{Y_A}$	$-i_{XB}-\frac{1}{Y_A}$			$-\frac{i_{XB}}{14}-\frac{1}{7Y_A}$	$\hat{\mu}_A\left(\frac{S_{NH}}{K_{NH}+S_{NH}}\right)\left(\frac{S_O}{K_{O,A}+S_O}\right)X_{B,A}$
4 Decay of heterotrophs				$1-f_P$	-1		f_P					$-i_{XB}-f_P i_{XP}$		$b_H X_{B,H}$
5 Decay of autotrophs				$1-f_P$		-1	f_P					$-i_{XB}-f_P i_{XP}$		$b_A X_{B,A}$
6 Ammonification of soluble organic N										1	-1		$\frac{1}{14}$	$k_a S_{ND} X_{B,H}$
7 Ammonification of soluble organic N		1												$k_h \frac{X_S/X_{B,H}}{K_X+(X_S/X_{B,H})}\left[\left(\frac{S_O}{K_{O,H}+S_O}\right) + \eta_h\left(\frac{K_{O,H}}{K_{O,H}+S_O}\right)\left(\frac{S_{NO}}{K_{NO}+S_{NO}}\right)\right]X_{B,H}$
8 Hydrolysis of entrapped organic N											1	-1		$\rho_7\left(\frac{X_{ND}}{X_S}\right)$

The rates of change of components in ASM1 are linked to the basic features of the microorganisms and wastewater, environmental conditions and a variety of correction coefficients, as well as the relationship of the components with each other. In the model a total of 19 parameters were used, with 5 stochiometric and 13 kinetic parameters. The explanations and symbols for these parameters are included in Table 5. The stochiometric parameters include substrate removal and biomass formation yield, conversion coefficients and carbon:nitrogen (C:N) ratio. The kinetic parameters include a variety of coefficients and correction factors related to microorganism proliferation and decay rates, ammonization and hydrolysis. The values determined for these parameters by the IAWQ at temperatures of 10°C and 20°C and intervals in the literature are shown in Table 6 [12].

Table 5. *Description of ASM1 parameters.*

Description	Symbol
Stoichiometric parameters	
Yield for heterotrophic biomass	Y_H
Yield for autotrophic biomass	Y_A
Fraction of biomass leading to particulate products	f_P
Mass of nitrogen per mass of COD in biomass	i_{XB}
Mass of nitrogen per mass of COD in endogenous biomass	i_{XE}
Kinetic parameters	
Maximum specific growth rate for heterotrophic biomass	μ_{Hmax}
Half-saturation coefficient for heterotrophic biomass	K_S
Oxygen half-saturation coefficient for heterotrophic biomass	K_{OH}
Nitrate half-saturation coefficient for denitrifying heterotrophic biomass	K_{NO}
Decay coefficient for heterotrophic biomass	b_H
Correction factor for μ_H under anoxic conditions	η_g
Correction factor for hydrolysis under anoxic conditions	η_h
Maximum specific hydrolysis rate	k_h
Half-saturation coefficient for hydrolysis of slowly biodegradable substrate	K_X
Maximum specific growth rate for autotrophic biomass	μ_{Amax}
Ammonia half-saturation coefficient for autotrophic biomass	K_{NH}
Oxygen half-saturation coefficient for autotrophic biomass	K_{OA}
Ammonification rate	k_a
Decay coefficient for autotrophic biomass	b_A

For a WWTP model to be applicable, it is necessary to make some assumptions and acknowledge limitations. Some of these are related to the physical structure of the system, while some are related to the mathematical model. The assumptions and limitations, though ignored when creating the model, can be added to the model if desired by the user. The assumptions and limitations of ASM1 are listed below [10, 12, 22]:

- As temperature variations will affect the processes and coefficients, the system is assumed to operate at fixed temperature. If a correlation of parameters in the model with temperature is to be made, the Arrhenius equation may be used.
- The pH value is fixed and close to neutral. Though affected by several parameters, the statements related to pH are limited. To be able to monitor the effect of pH in the model, the alkalinity component (S_{ALK}) may be used.
- The variations caused to organic matter in wastewater within the reactor are not reflected in the model. For this reason, the parameters related to organic matter are fixed.
- In situations where nitrogen, phosphorus and other inorganic matter is limited, it should be checked whether inorganic nutrients have sufficient amounts, as the model does not include how organic matter removal and cell growth will be affected.
- The values for the correction factors for the denitrification process of η_g and η_h are assumed to be fixed for wastewater. Though it is possible that these parameters are affected by system structuring, this is ignored in the model.

- The coefficients for nitrification are assumed to be fixed. These coefficients are determined to reflect the inhibitory effects of other compounds in wastewater.
- The heterotrophic biomass is assumed to be homogeneous and there is no change in species over time. As parameters related to heterotrophic biomass are assumed to be fixed, the effects of substrate concentration gradient, reactor structuring and sludge precipitation features are not included in the model.
- Adhesion of organic matter with particulate structure to biomass is accepted as instantaneous.
- Hydrolysis of organic matter and organic nitrogen is assumed to occur at equal rates and simultaneously in connection with each other.
- The electron acceptor type is not affected by losses occurring due to decay of active biomass.

Table 6. *Typical values of ASM1 parameters.*

Symbol	Unit	Value at 10°C	Value at 20°C	Range
Y_H	g cell COD formed (g COD oxidized)$^{-1}$	0.67	0.67	0.38-0.75
Y_A	g cell COD formed (g N oxidized)$^{-1}$	0.24	0.24	0.07-0.28
f_P	dimensionless	0.08	0.08	-
i_{XB}	g N (g COD)$^{-1}$ in biomass	0.086	0.086	-
i_{XE}	g N (g COD)$^{-1}$ in endogenous mass	0.06	0.06	-
μ_{Hmax}	day^{-1}	3	6	0.6-13.2
K_S	g COD m^{-3}	20	20	5-225
K_{OH}	g O^2 m^{-3}	0.2	0.2	0.01-0.2
K_{NO}	g NO_3-N m^{-3}	0.5	0.5	0.1-0.5
b_H	day^{-1}	0.2	0.62	0.05-1.6
η_g	dimensionless	0.8	0.8	0.6-1
η_h	dimensionless	0.4	0.4	-
k_h	g slowly biodegradable COD (g cell COD·day)$^{-1}$	1	3	-
K_X	g slowly biodegradable COD (g cell COD)$^{-1}$	0.01	0.03	-
μ_{Amax}	day^{-1}	0.3	0.8	-
K_{NH}	g NH_3-N m^{-3}	1	1	-
K_{OA}	g O_2 m^{-3}	0.4	0.4	0.4-2
k_a	m^3·COD (g. day)$^{-1}$	0.04	0.08	-
b_A	day^{-1}	0.1	0.2	0.05-0.2

2.4. GPS-X software

The GPS-X software, containing nearly all processes that may occur in a WWTP developed by the Canadian Hydromantis firm, is among modeling and simulation software commonly used both academically and commercially. The GPS-X software allows the opportunity to mathematically model processes in the plant, in addition to investigating the reactions in the plant by trialing simulations, checks and a variety of scenarios. The modeling and simulation screen images for the GPS-X software are shown in Figure 1 [24].

The GPS-X software contains 6 libraries prepared according to the system to be modeled and the detail of the model. Explanations related to these libraries are given below.

- Carbon-nitrogen (cnlib): The basic library containing 12 state variables related to carbon oxidation, nitrification and denitrification processes.
- Advanced carbon-nitrogen (cn2lib): This is similar to the cnlib; however, it also models nitrite and nitrate. It has 19 state variables.
- Carbon-nitrogen-phosphorus (cnplib): A library containing 17 state variables including biological and chemical phosphorus removal.
- Carbon-nitrogen-industrial pollutant (cniplib): A library containing the cnlib library and 30 user-defined state variables.
- Advanced carbon-nitrogen-industrial pollutant (cn2iplib): This is a library containing the cn2lib and 30 user-determined state variables.

- Carbon-nitrogen-phosphorus-industrial pollutant (cnpiplib): This is a library containing the cniplib and 30 user-defined state variables.

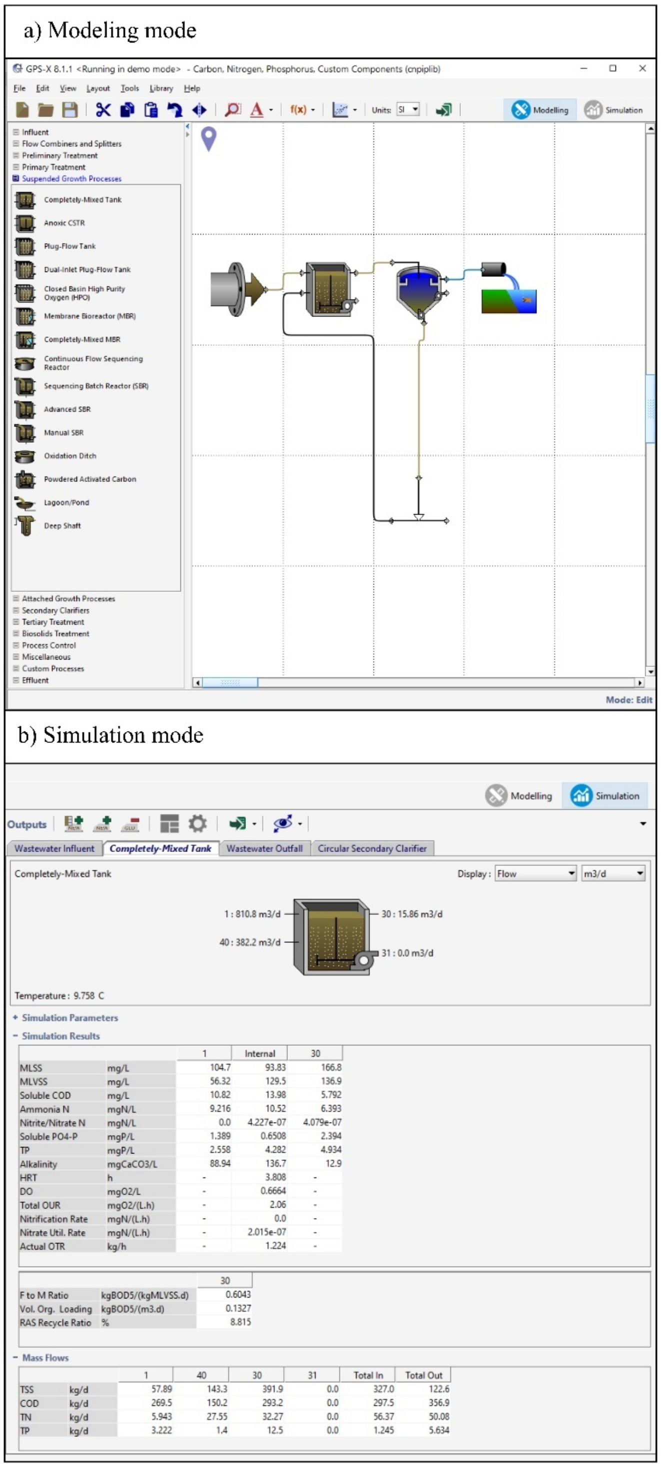

Figure 1. *Screenshot of (a) modeling and (b) simulation panels of GPS-X software.*

The software includes many units including batch and continuous wastewater input into the wastewater treatment plant, combination and distribution structures, pumping station, equilibrium tank, grit chamber, full mixed and piston flow reactors, drop filters, oxidation trench, pure oxygen tank, rotating biodiscs, lagoon, clarifying tanks, anaerobic sludge digesters, sludge dewatering and drying devices, sand filtration, membrane filters and disinfection unit. The GPS-X contains some modules where the flow scheme is prepared, reviewed and the simulation is completed. These modules are mentioned in brief below.

- Simulator: This module creates a flow diagram for units in the wastewater treatment plant and is the module determining the physical features of the processes. Additionally, model selection for operation of processes is performed in this module.
- Builder: The flow diagram developed by the user is converted to computer code in this module. The previously-chosen models are converted to mathematical model equations. This software previously used Fortran and new versions use Python and it makes the model statements operable as computer software. There are 4 types of build choices. This selection should be made appropriate to the dimension of the plant to be modeled and the number of processes.
- Analyzer: This module in the GPS-X software is able to investigate the effect of stochiometric, kinetic or physical parameters on dependent variables in the processes. This module may use 3 types of analysis methods to investigate the status of variables, according to steady state by ignoring the time variable, process dynamics and time showing the effect of the independent variables on the dependent variable at any time.
- Optimizer: This module calculates the optimum values for the independent variables to be able to determine certain intervals for certain parameters in the plant to be modelled.

Additionally, the software contains additional modules like dynamic parameter estimator, advanced control, multiple sampling license and scenario manager.

In this study, the cnlib library containing the basic features of domestic wastewater, and 12 state variables related to carbon oxidation, nitrification and denitrification processes was used. Influent characterization was defined by the BOD-based model called bod-based. All processes and connections in the plant were created using elements found in the Process table toolbox. The flow diagram for the model prepared in GPS-X software is shown in Figure 2.

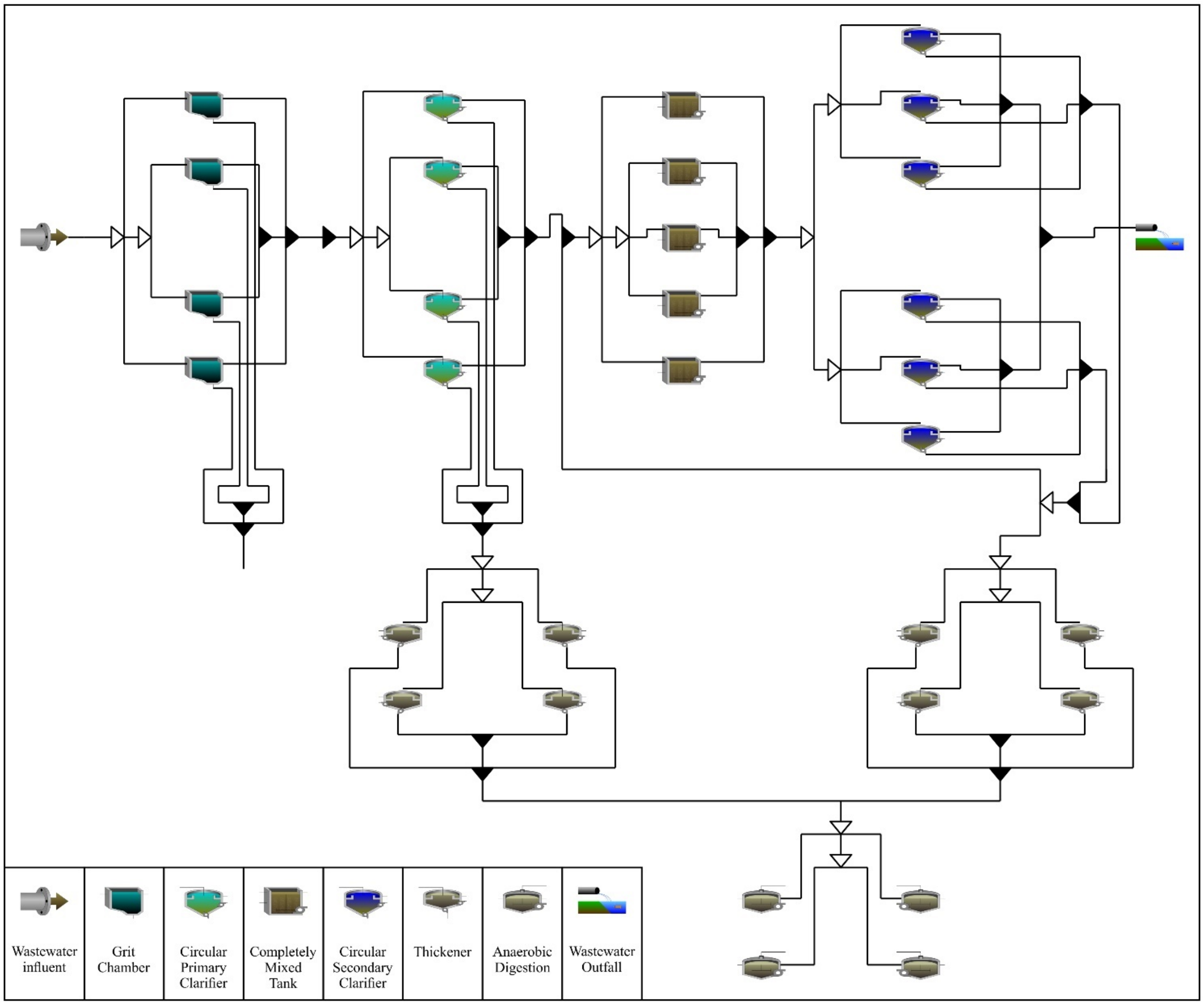

Figure 2. *Flow diagram of WWTP processes modeled in GPS-X software.*

The flow diagram was saved with the GPS-X software file format of the layout (.LYT) extension. After this, model selection was made for processes in the plant. For grit chambers, the sand amount produced per meter cube volume was determined using the standard *empiric* model in the software. It was assumed that no biological reaction occurred in the circular primary and secondary clarifiers, so the *simple1d* model was chosen. The completely-mixed aeration tanks were modeled using the ASM1 model. The sludge removed from the clarifying tanks was transferred to separate sludge thickener tanks for the circular primary and secondary clarifiers. For thickener tanks in sludge removal, the standard model in the software of the *simple1d* model was used. The water coming from the sludge thickener was recycled into the circular primary clarifier and aeration tanks. The target was to use thickened sludge to provide gas production by sending it to anaerobic digesters using the *basic* model [22]. As the software allows at most 5 distribution and collection structures, 2 and 3 distribution and collection structures were used together before and after the circular secondary clarifier, as seen in Figure 2. In the next stage, the physical features of the units in the plant like volumes, depths, surface areas and heights were input using suitable models for the WWTP in the GPS-X software. Later, information like the influent and reactor operating temperature, elevation of the plant above sea level and open-air pressure, types of precipitators, motor power of mixers used in the completely-mixed aeration tank, aeration method, amount of air used, biological treatment recycle sludge flow rate, and sludge flow rates discharged from clarifiers and sludge thickeners was entered into the relevant data entry sections. The BOD-based definitions in the carbon-nitrogen (cnlib) library and a variety of stochiometric coefficients for influent used in the ASM1 model were determined as shown in Table 7 using Influent Advisor, assisting software for the GPS-X program.

Table 7. *Basic user inputs of Influent Advisor (Library: cnlib).*

Parameter (User input)	**Unit**	**Value**
Readily biodegradable fraction of total COD (frss)	-	0.31
Ammonium fraction of soluble TKN (frsnh)	-	0.65
Ratio of particulate organic nitrogen to total organic nitrogen (fnd)	-	0.90
Ratio of particulate COD to VSS (icv)	g COD g VMLSS^{-1}	2.20
Ratio of volatile suspended solids to TSS (ivt)	g VSS g TSS^{-1}	0.60
Ratio of BOD_5 to ultimate BOD (fbod)	-	0.66
Nitrogen content of active biomass (ixbn)	g N g COD^{-1}	0.086
Nitrogen content of endogenous/inert mass (ixun)	g N g COD^{-1}	0.060

The wastewater entering the system comes to the completely-mixed aeration tanks after grit chambers and circular primary clarifier. Each of the 5 completely-mixed aeration tanks where biodegradation occurs are given 12000 m^3 h^{-1} air through diffusors. It is assumed that sludge is not discharged from the completely-mixed aeration tanks. After 7 hours in the completely-mixed aeration tanks, collection and distribution structures are used to send water to the circular secondary clarifier tank and after being left for a duration, the water is discharged into the receiving environment. The precipitated sludge is sent back to the completely-mixed aeration tanks with 0.75 recycle rate. A total of 2700 m^3 day^{-1} sludge is discharged from the circular secondary clarifier and sent to the sludge thickeners. The separately condensed sludge from the primary and secondary sludge thickeners is combined and transferred to anaerobic digesters with the aim of gas production. The WWTP simulation was created using the *Build* command which is the review process in the GPS-X software. Later the simulation was observed on the screen and a variety of scenarios are run.

3. Results and Discussion

3.1. Effect of wastewater at different temperatures on effluent

The plant operating under stable conditions had COD, BOD and NH_4 concentrations calculated for influent with temperatures 10°C and 20°C using the GPS-X software. Figure 3 shows the treatment efficiency obtained according to the ASM1 model. As the dissolved oxygen concentration was inversely correlated with temperature and due to the reduction in active biomass concentration, at 20°C the dissolved oxygen concentration was 0.7 mg L^{-1}, while at 10°C the dissolved oxygen concentration reached 6 mg L^{-1}. Additionally, the MLSS concentration in effluent was calculated as 14.83 mg L^{-1}. According to the model, MLSS is a composite parameter encompassing X_S, X_I, X_{BH} and X_{BA} components. The MLSS value is a parameter sensitive to the amount of sludge discharged from the circular secondary clarifier tank, surface load changes and hold time changes. The effluent from the plant operated at 20°C had COD concentration 48.51 mg L^{-1} and BOD concentration 6.55 mg L^{-1}. The dissolved COD concentration, calculated as 34.87 mg L^{-1}, is a composite parameter comprising the combination of the soluble inert substrate and soluble readily degradable substrate. The 30 mg L^{-1} inert portion in the influent leaves the system without any change. Theoretically, the dissolved COD value is expected to be the same as S_i. However, as a result of biochemical activity in the system, the expected readily degradable S_S value is found in effluent, though only partly. The NH_4 concentration in output water was 0.3 mg L^{-1} under stable conditions, while the NO_3 concentration was calculated as 18.2 mg L^{-1}. The nitrate and nitrite concentrations occurring as a result of the nitrification process are related to the nitrifying microorganism concentration in the completely-mixed aeration tank and dissolved oxygen concentration. According to the dissolved oxygen concentration calculated by the model for the completely-mixed aeration tank, it appears nitrification occurred. However, for nitrification to occur more efficiently, the dissolved oxygen concentration should not be lower than 1.5 mg L^{-1}. The total nitrogen concentration in effluent, comprising ammonium, nitrate, soluble organic and inert nitrogen, was calculated as 20.2 mg L^{-1}. As only nitrification occurred in the system, the nitrate concentration increased. Nitrate removal may occur with denitrification and the quality of the discharge water may be increased.

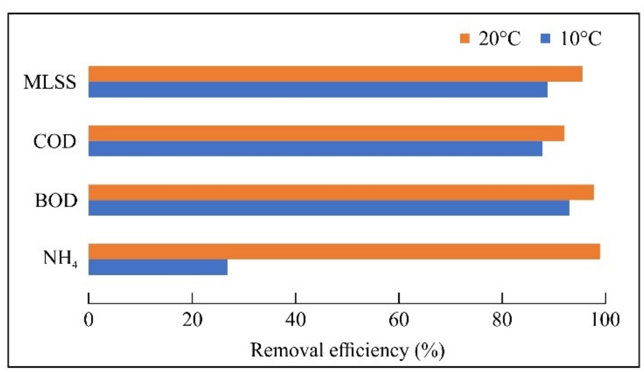

Figure 3. *Effect of wastewater temperature on effluent quality.*

The WWTP operated under stable conditions for 10 days at 10°C had mean values in effluent of 75 mg L^{-1} for COD, 21.83 mg L^{-1} for BOD and 38 mg L^{-1} for MLSS. When the concentration of wastewater entering the completely-mixed aeration tank is noted, it is possible to mention biological activity of heterotrophs, though slow. However, when the obtained results are compared with effluent concentrations at 20°C, a 30% reduction in removal of carbonaceous material is observed. As the majority of the COD concentration comprises the inert portion, negligible rates (nearly 1%) of variation were observed in COD. The value of 26.13 mg L^{-1} obtained for NH_4 shows the nitrification process reached the point of stopping. As nitrifying autotrophic microorganisms are more sensitive to environmental conditions, especially, it is not always possible for nitrification to occur at operating conditions lower than 10°C and higher than 50°C [25]. When the simulation results are investigated, it is possible to state that efficient carbon and nitrogen removal will not occur in the biological treatment units in December-January. With the aim of minimizing the effect of these temperature changes in the winter month on the ASP, completely-mixed aeration tanks may be constructed with the top enclosed.

3.2. Effect of controlling DO concentration with PID on effluent

The dissolved oxygen (DO) concentration is among the determinative parameters for carbonaceous material removal and the nitrification process in completely-mixed aeration tanks. DO concentration should be controlled using automatic control systems to balance sudden flow increases and changes in influent concentration. One of the features of the GPS-X software is proportional-integral-derivative (PID) control used to keep the dissolved oxygen level in the completely-mixed aeration tanks at 1.5 mg L^{-1}. The effect of keeping the DO concentration at 1.5 mg L^{-1} on effluent COD, BOD and NH_4 removal efficiency is shown in Figure 4.

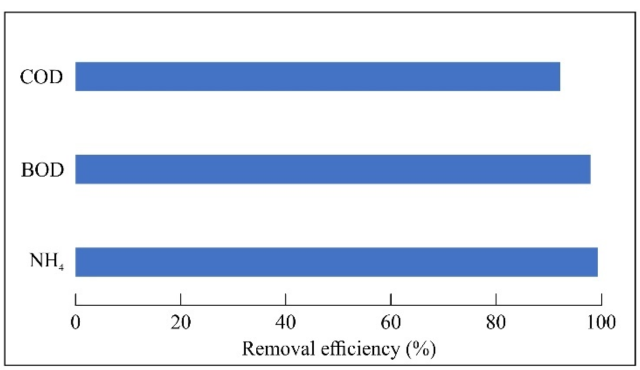

Figure 4. *Effect of PID-controlled dissolved oxygen (DO) concentration on effluent quality.*

As a result of the simulation operated under stable conditions with DO concentration fixed to 1.5 mg L^{-1}, COD was calculated as 48.37 mg L^{-1}, BOD 6.46 mg L^{-1} and NH_4 0.22 mg L^{-1}. Comparing these results with the COD and BOD values calculated using the criteria determined for plant design, it appears that 12000 m^3 h^{-1} air flow rate is sufficient for carbonaceous matter removal. The nitrate concentration was calculated as 25.72 mg L^{-1}. With PID control, the nitrification efficiency appeared to increase by 30%. This situation reveals the need to increase the amount of air for more efficient nitrification [26]. To be able to keep the DO concentration in the aeration tank at 1.5 mg L^{-1}, it was calculated that nearly 14000–15000 m^3 h^{-1} of air should be used.

4. Conclusion

It is necessary to design large-scale wastewater treatment plants to treat significant amounts of wastewater before discharge into the receiving environment. Most of the time, the treatment efficiency of these plants cannot be predicted before operation. Treatment models assist in estimating the treatment performance before building large-scale treatment plants. The ASM1 model is a successful model for prediction of carbonaceous and nitrogenous material removal from domestic wastewater especially. Additionally, it ensures determination of some operating conditions. Using a model created with GPS-X software, the typical parameters for domestic wastewater like suspended solids, carbon and nitrogen concentrations in the effluent from the operating plant were investigated. Later stages of the study researched the effect of dissolved oxygen concentration and temperature parameters. The results obtained in this study are given below:

- The effluent from the plant operated at 20°C had values of 48.51 mg L^{-1} for COD, 34.87 mg L^{-1} for dissolved COD, 6.55 mg L^{-1} for BOD and 14.38 mg L^{-1} for MLSS.
- When values of 0.3 mg L^{-1} for NH_4 and 18.2 mg L^{-1}, for nitrate are investigated, it appears nitrification partially occurred. However, it was observed that dissolved oxygen concentration around 0.7 mg L^{-1} was inadequate for nitrification.
- Effluent from the plant operated at 10°C contained 38 mg L^{-1} MLSS, 75 mg L^{-1} COD, 21.83 mg L^{-1} BOD and 26.13 mg L^{-1} NH_4. According to the results calculated with the model, biological activity slowed for heterotrophs while nitrification reached stopping point.
- Holding dissolved oxygen concentration to 1.5 mg L^{-1} using PID did not play a great role in carbonaceous matter removal; however, it was identified to cause a 30% improvement for the nitrification process. For nitrification to occur in a healthy way, it was determined to be necessary to use 14000–15000 m^3 h^{-1} air in the completely-mixed aeration tanks.

Future studies are suggested to use models encompassing phosphorus removal in addition to carbonaceous and nitrogenous material removal. Additionally, plant treatment efficiency should be investigated in other extraordinary situations like sudden changes in flow rate, and excessive carbon and nitrogen loading, apart from temperature.

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Conflict of interest

There is no conflict of interest.

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