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Improving the operational performance of a wastewater treatment plant by using GPS-X simulations: a case study in northern Taiwan

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Abstract

Empirically optimizing the design of a wastewater treatment plant to achieve higher efficiencies of pollutant removal is an extremely time-consuming process. Digital model simulations serve as an effective solution to this problem. The current study used the GPS-X simulation software to simulate five scenarios for improving the oxidation ditch treatment process at the Guishan Wastewater Treatment Plant, which was selected as a case study. The simulation results of the five scenarios revealed that Scenario E, involving a simultaneous increase in flow velocity and aeration of oxidation ditch along with returned flow from the secondary sedimentation tank to the anoxic section of the oxidation ditch, resulted in the most significant improvement in the removal efficiencies for ammonia (36 to 95%) and total nitrogen (51 to 86%). Moreover, among the five scenarios, Scenario E had the lowest carbon emissions but achieved the same increases in removal efficiencies for biological oxygen demand, chemical oxygen demand, ammonia, and total nitrogen.

Keywords Simulation, GPS-X, Wastewater treatment plant, Oxidation ditch, Energy consumption, Carbon emissions

1 Introduction

Wastewater treatment plants (WWTPs) play a critical role in preventing the introduction of organic pollutants, nitrogen, and phosphorus derived from municipal wastewater into the surrounding environment [1]. The growing emphasis on protection of aquatic environments in recent years has resulted in stricter discharge standards for wastewater, and therefore, several WWTPs have been required to upgrade their processes and configurations [2]. The nitrogen present in sewage primarily exists in four forms, namely, organic nitrogen, ammonia (NH_4^+), nitrite, and nitrate. The total nitrogen (TN) content in sewage is typically 40–50 mg L^{-1}. Excessive nitrogen content in water can lead to eutrophication and deterioration of water quality, which can affect the growth and reproduction of aquatic organisms. To reduce the amount of NH_4^+ entering water bodies, on December 25, 2017, the Ministry of Environment in Taiwan added discharge standards for NH_4^+ and TN to existing WWTP effluent standards, and the new standards were implemented in 2021. These standards are planned to gradually become stricter; the NH_4^+ standard for municipal domestic WWTPs was lowered to 6 mg L^{-1} in 2024, and the NH_4^+ standard for industrial WWTPs will be lowered to 30 mg L^{-1} in 2027.

The current study focused on the Guishan WWTP, located in Guishan District of Taoyuan City in Taiwan. This facility processes both industrial wastewater and domestic sewage, and therefore, the NH_4^+ discharge standard for the Guishan WWTP will be 30 mg L^{-1} by

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2027. The discharge from the Guishan WWTP is released into the Nankan River, a key municipal river in the city of Taoyuan. According to data from seven water quality monitoring stations maintained by the Department of Water Resources, Taoyuan, the average river pollution index of the Nankan River was 5.4 in 2020, with pollution levels ranging from moderate to severe. River pollution index is ranging from 1 to 10 with 10 being the worst water quality. This suggests that although the water discharged from the Guishan WWTP meets current standards, the effluent quality can still be improved.

The main treatment process deployed at the Guishan WWTP is the oxidation ditch process. First implemented in Voorschoten, the Netherlands, in 1954, this process has become increasingly popular over time; more than 9,200 municipal oxidation ditches are currently installed in the United States [3], and 11 municipal WWTPs in Taiwan use the oxidation ditch process. The oxidation ditch is a modified activated-sludge biological treatment process that utilizes long solids retention times to remove biodegradable organics and ammonia [4]. However, effectively optimizing the operation performance of WWTPs to achieve higher rates of pollutant removal is extremely time-consuming and involves a high degree of uncertainty, even for experienced engineers.

Digital model simulations serve as an easily applicable and effective means of optimizing complex biological treatment processes and have been recognized as an indispensable tool for improving and managing the operations of WWTPs [1]. Numerous types of commercial numerical simulation software (e.g., Simba, GPS-X, BioWin, and WEST) that incorporate activated-sludge models (e.g., ASM1, ASM2, ASM2d, and ASM3) have been developed for engineering practice [5]. GPS-X, developed by the Canadian firm Hydromantis Environmental Software Solutions, is a simulation system for WWTPs that is commonly used worldwide. GPS-X simulates the operation of municipal and industrial WWTPs and includes all models approved by the International Water Association, including ASM1, ASM2, ASM2d, and ASM3. Table 1 presents the details of the different activated-sludge models. In addition to modeling the traditional activated-sludge process, GPS-X simulations model oxidation ditch units and membrane bioreactor units. Therefore, GPS-X can be used to simulate and analyze the nitrogen removal efficiency of an entire wastewater treatment process and optimize its operation. The advanced graphical user interface of GPS-X helps facilitate and simplify model development, simulation, and the interpretation of results. Therefore, GPS-X has been widely applied in simulations of WWTP operations to improve WWTP performance [6–8]. Nasr et al. [9] used GPS-X to simulate the operation of a sequencing batch reactor in six scenarios, successfully reducing the concentration of TN in effluents from 13.0 to 8.3 mg L^{-1}.

The nitrogen removal potential of a WWTP depends on the existence of alternate aerobic and anoxic zones; NH_4^+ is converted into nitrate (nitrification) in the aerobic zone, and nitrate is subsequently used to remove organic carbon (denitrification) in the anoxic zone [10]. Therefore, dissolved oxygen (DO) content is a crucial parameter in the nitrogen removal process. In addition, the design flow velocity of an oxidation ditch is generally 0.25–0.30 m s^{-1}, which ensures that solids remain in suspension [11]. This can facilitate biological reactions, including nitrification and denitrification. Nitrogen removal can be improved by replacing the traditional activated-sludge wastewater treatment process with the modified Ludzack–Ettinger wastewater treatment process, wherein flow is returned from the secondary settling tanks to the anoxic sections of oxidation ditches [12].

The current study not only improved the efficiency of removal of NH_4^+ and TN at the Guishan WWTP through the use of GPS-X but also identified the most energy-efficient method across the following five simulated scenarios: Scenario A, increased flow velocity; Scenario B, increased aeration in oxidation ditches; Scenario C, returned flow from the secondary settling tanks to the anoxic sections of oxidation ditches; Scenario D, a combination of scenarios A and B; and Scenario E, a combination of scenarios A, B, and C.

Table 1 Activated-sludge mathematical models commonly used in GPS-X software

Approved unit	Model	Nitrification + Denitrification	Biological phosphorus removal	Number of parameters	Reaction program
IWA	ASM1	●		13	8
	ASM3	●		13	12
	ASM2	●	●	19	19
	ASM2d	●	●	19	21
	ASM3 + Bio-P	●	●	17	23
TU Delft	TUDP	●	●	17	21
	B&D	●	●	19	36

2 Materials and methods

2.1 Description of the case study

The Guishan WWTP, located in Guishan District of Taoyuan City, Taiwan, was selected as a case study for exploring strategies to enhance removal efficiencies of NH_4^+ and TN (Fig. 1). According to the Department of Water Resources, Taoyuan, the Guishan WWTP, which was built in 1992, employs an oxidation ditch system designed to treat daily 27,000 m^3 wastewater, with the wastewater originating from the Gongsan and Gongsi Industrial Parks as well as the villages of Dagang, Gongxi, Wenhua, Dahua, Dahu, Jiulu, and Leshan within Linkou New Town. The main treatment units within the Guishan WWTP are an aerated grit chamber, an oxidation ditch, a secondary sedimentation tank, and disinfection and discharge units. The oxidation ditch is the key unit for removing NH_4^+ and TN during the wastewater treatment process. Sludge treatment at the WWTP includes sludge thickening and sludge dewatering.

2.2 Data acquisition

Data were obtained from the wastewater treatment data management system maintained by the Sewage System Office of the Construction and Planning Agency, Ministry of the Interior, Taiwan. Table 2 presents the mean influent and effluent flow rates and the values of various water quality indicators at the Guishan WWTP in 2021. The mean data in Table 2 were obtained from a total of 12

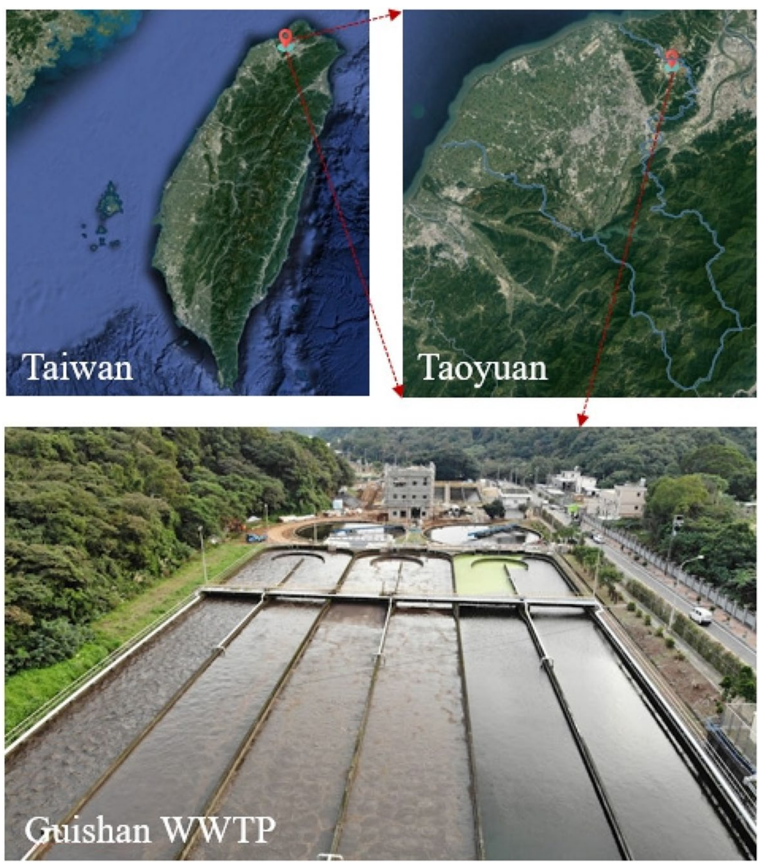

Fig. 1 Geographical location of Guishan WWTP

Table 2 Mean quality data for the influent into and effluent out of the Guishan WWTP from January to December, 2021 (12 datasets)

Parameters	Mean flow rate (m^3 d^{-1})	BOD (mg L^{-1})	SS (mg L^{-1})	COD (mg L^{-1})	NH_4^+ (mg L^{-1})	TN (mg L^{-1})
Influent	23,810 ± 4,333	110 ± 24	90 ± 11	210 ± 36	30.4 ± 8.7	42.6 ± 8.8
Effluent	21,800 ± 4,245	12.3 ± 2.3	12.4 ± 3.3	33.7 ± 8.1	14.3 ± 8.6	20.7 ± 9.4
Removal efficiency (%)	-	88 ± 2	86 ± 2	84 ± 1	53 ± 18	51 ± 14

datasets and represent the mean value for each parameter over the period from January to December, 2021. For the influent, the daily flow rate was 23,810 ± 4330 m^3 d^{-1}, the biological oxygen demand (BOD) was 110 ± 24 mg L^{-1}, the chemical oxygen demand (COD) was 210 ± 36.8 mg L^{-1}, the suspended solids (SS) content was 90 ± 11 mg/L, the NH_4^+ content was 30.5 ± 8.6 mg L^{-1}, and the TN content was 42.6 ± 8.8 mg L^{-1}. For the effluent, the daily flow rate was 21,800 ± 4,245 m^3/day, the BOD was 12.3 ± 2.3 mg L^{-1}, the COD was 33.7 ± 8.1 mg L^{-1}, the SS content was 12.4 ± 3.3 mg L^{-1}, the NH_4^+ content was 14.3 ± 8.6 mg L^{-1}, and the TN content was 20.7 ± 9.4 mg L^{-1}. The BOD removal efficiency was 88 ± 2%, the COD removal efficiency was 84 ± 1%, the SS removal efficiency was 86 ± 2%, the NH_4^+ removal efficiency was 52 ± 18%, and the TN removal efficiency was 51 ± 13%. The influent and effluent water quality data obtained for the Guishan WWTP are similar to those for other WWTPs across Taiwan. The removal efficiency for BOD, COD, and SS were satisfactory, whereas those for NH_4^+ and TN can be further improved.

2.3 Process design description

The ASM1 model was used for simulations. ASM1 simulates eight essential stages of the wastewater treatment process: (i) aerobic growth of heterotrophic biomass, (ii) anoxic growth of heterotrophic biomass, (iii) aerobic growth of autotrophic biomass, (iv) heterotrophic biomass decay, (v) autotrophic biomass decay, (vi) ammonification of soluble organic nitrogen, (vii) hydrolysis of entrapped particulate organic matter, and (viii) hydrolysis of entrapped organic nitrogen. Figure 2 illustrates the simulation developed using GPS-X for the treatment process deployed in the Guishan WWTP. The rate of sludge return from the secondary sedimentation tanks to the oxidation ditches was set to 132% of influent flow rate according to the actual operation. Aeration in the oxidation ditch was controlled by three surface aerators, each having a rating of 27 kW.

For the GPS-X simulation, the Guishan WWTP model was calibrated using measured effluent water quality data (BOD, COD, SS, NH_4^+, and TN) from January to December of 2021 and validated against daily data from 2021. The simulations were performed under dynamic conditions and steady-state for calibration and validation, respectively. The model was calibrated under dynamic conditions because 12 input datasets were available. A difference of less than 20% between the measured quality data (COD, BOD, SS, NH_4^+, and TN) and the simulated results was deemed to be acceptable. Subsequently, the calibration parameters were applied to validation simulations performed over a different dataset from the Guishan WWTP (e.g., daily data from 2021). The procedure for calibration and validation is described in the following.

1. Fig. 2 illustrates a flowchart of the main processing units at the Guishan WWTP.
2. The carbon and nitrogen custom library within the GPS-X software was selected.
3. The GPS-X Influent Advisor was used to characterize the influent flow by inputting the influent quality data, including the values for COD, BOD, SS content, NH_4^+ content, and TN content.
4. If the mass balance calculations (i.e., organic, nitrogen, and Model-Augmented Neural neTwork with Incoherent k-space Sampling (MANTIS) fractions) of the GPS-X Influent Advisor were satisfactory, the study proceeded to the next step.

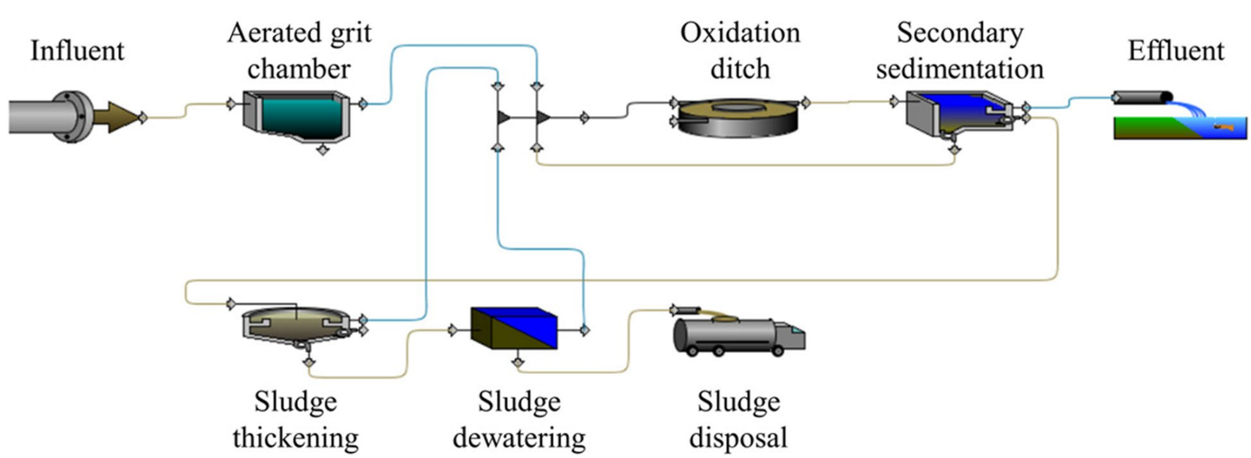

Fig. 2 Flowchart of main processing units at the Guishan WWTP

If the mass balance calculations were imbalanced, the organic, nitrogen, and MANTIS fractions were manually adjusted until the balance was satisfactory.

5. The model was calibrated using data from 2021 and the default values of the kinetic and stoichiometric parameters in GPS-X. The calibration was deemed to be complete when the model prediction fit the data on all effluent quality indicators within acceptable limits.
6. If the default GPS-X model failed, an initial screening was conducted to identify the most sensitive parameters by running the activated sludge process and clarifier models using data from 2021. The values of the relevant default parameters were manually and individually adjusted, and the corresponding GPS-X predictions of the effluent quality parameters were monitored to ascertain whether the simulated results reflected the effluent water quality data measured in 2021 (BOD, COD, SS, NH_4^+, and TN).
7. The model was recalibrated using data from 2021 by changing the values of the parameters that were screened and identified in step 6 to further optimize the prediction abilities of the model.
8. The parameter values that yielded the best modeling prediction for the standard effluent quality parameters were selected. These values represented the final calibrated parameters.
9. The performance of the developed model was validated against a different dataset from the Guishan WWTP (e.g., daily data from 2021). The validation result is shown in Table S1.

Disparities between measured data and simulated data are often related to the fractionation of organic matter, stoichiometric parameters [13], and kinetic parameters [14]. However, data records maintained by Taiwanese WWTPs generally lack information on such parameters. Therefore, their values were set to the default values in the GPS-X software (Table 3). The model inputs for influent water quality and influent volume were based on the corresponding measured values at the Guishan WWTP in 2021. The simulated effluent quality data for a 1-yr period were compared with the measured effluent quality data. Table 4 presents a comparison of the measured mean effluent quality data with the simulation results obtained from 12 datasets. Figure 3 displays the temporal trends in both measured data (dots) and simulated data (lines) from January to December, 2021. The simulated

Table 3 Default values of stoichiometric and kinetic parameters for GPS-X simulations

Classification	Parameter	Unit	GPS-X Default	January to March	April to June	July to September	October to December
Composite Variable Stoichiometry							
Organic Fractions	i_{cv}	g COD g^{-1} VSS	1.48				
	f_{bod}	-	0.66				
Nutrient Fractions	i_{XB}	g N g^{-1} COD	0.086				
Model Stoichiometry Parameters							
Active Heterotrophic Biomass	Y_H	g COD g^{-1} COD	0.666				
	U_H	g COD g^{-1} COD	0.08				
Active Autotrophic Biomass	Y_A	g COD g^{-1} N	0.24				
	U_A	g COD g^{-1} COD	0.08				
Kinetic Parameters							
Active Heterotrophic Biomass	$\mu_{max,H}$	d^{-1}	6	4.2	7.0	5.5	8.0
	$K_{S,S}$	mg COD L^{-1}	20				
	$K_{O,H}$	mg O_2 L^{-1}	0.2				
	η_g	-	0.8				
	K_{NO}	mg N L^{-1}	0.5				
	b_H	d^{-1}	0.62				
Active Autotrophic Biomass	$\mu_{max,A}$	d^{-1}	0.8				
	K_{NH}	mg N L^{-1}	1.0				
	$K_{O,A}$	mg O_2 L^{-1}	0.4				
	b_A	d^{-1}	0.04				
Hydrolysis	k_h	d^{-1}	3				
	K_x	g COD g^{-1} COD	0.03				

Table 4 Comparison of measured mean effluent quality data with simulated effluent quality data obtained using GPS-X

	BOD	COD	SS	NH_4^+	TN
Measured mean effluent quality in 2021 (mg L^{-1})	12.3 ± 2.3	33.6 ± 8.1	12.4 ± 3.3	14.3 ± 8.6	20.7 ± 9.4
Simulated mean effluent quality for 2021 (mg L^{-1})	10.8	40.4	11.3	17.4	21.1

results for COD, BOD, and SS content exhibited poor alignment with the corresponding measured data.

2.4 Scenario description

2.4.1 Scenario A: increased flow velocity

The design flow velocity of an oxidation ditch is generally 0.25–0.30 m s^{-1}, which ensures that solids are maintained in suspension [11], which can facilitate biological reactions, including nitrification and denitrification. We conducted an on-site investigation and discovered that the flow rates

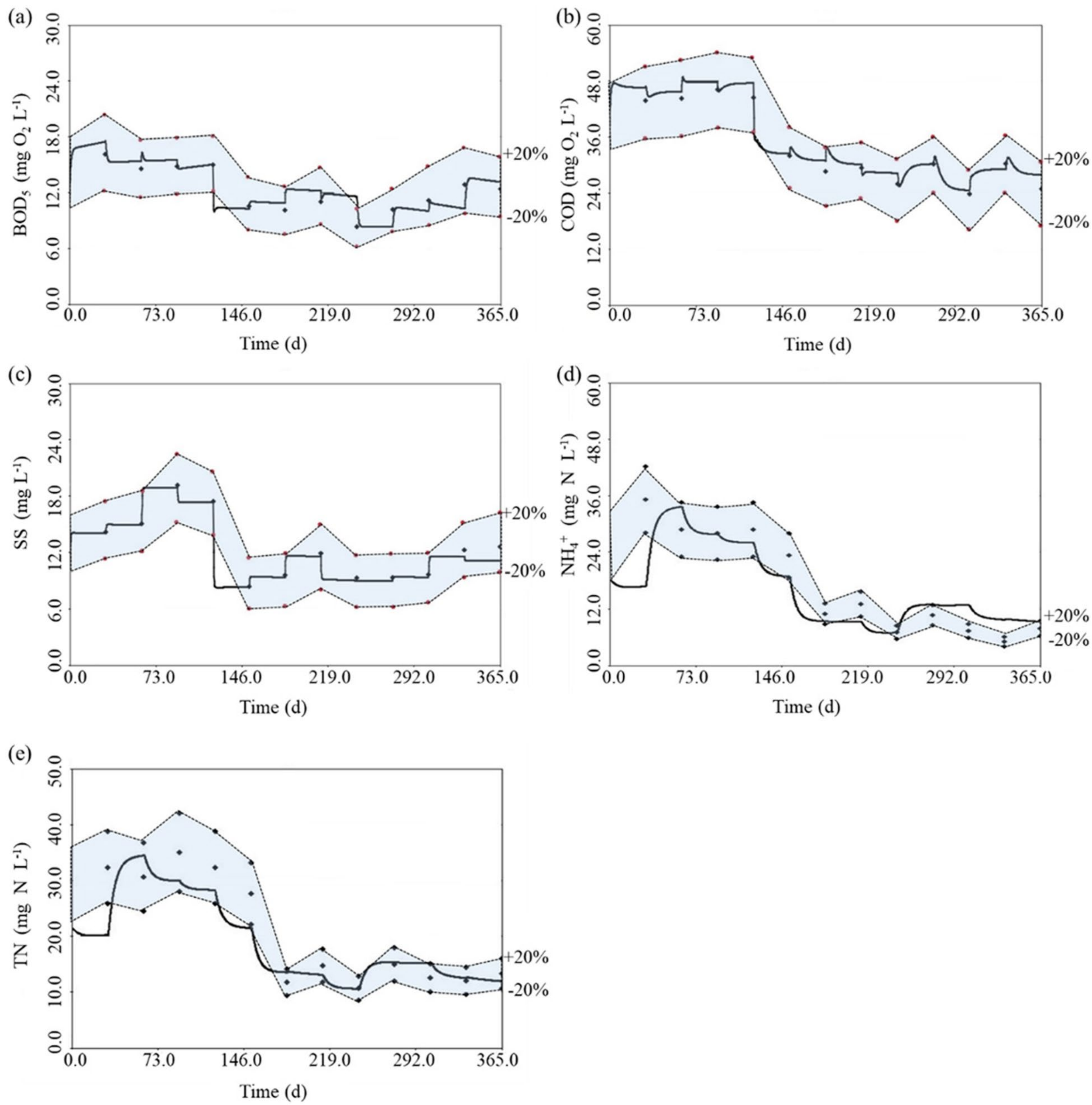

Fig. 3 Trends in simulated (line) and measured (dot) effluent data from January to December, 2021: (**a**) BOD, (**b**) COD, (**c**) SS, (**d**) ammonia, and (**e**) TN. The shadowed region means ± 20% ranged of measured data

of the oxidation ditches at the Guishan WWTP were low. Therefore, we assumed the original flow velocity of each oxidation ditch to be only 0.1 m s^{-1}, which is lower than the standard flow velocity and must be increased to 0.3 m s^{-1} in Scenario A. Moreover, a flow velocity of 0.01 m s^{-1} was selected as the experimental value of flow rate lower than 0.1 and 0.4 m s^{-1} was selected as experimental value of flow rate above 0.3 m s^{-1}.

2.4.2 Scenario B: increased aeration in oxidation ditches

The oxidation of inorganic NH_4^+ is referred to as nitrification. The nitrification reaction can be represented as follows:

$$NH_4^+ + 1.83O_2 + 1.98HCO_3^- \rightarrow 0.21C_5H_7O_2N + 0.98NO_3^- + 1.04H_2 + 1.88H_2CO_3\text{(nitrification bacteria)} \quad (1)$$

The rate of nitrification is proportional to the amount of DO in water. The aeration zone of each oxidation ditch should ideally have DO content ≥ 2.0 mg L^{-1} to facilitate nitrification [12]. The biological denitrification rate is also affected by DO. DO content < 0.2 mg L^{-1} is recommended to facilitate denitrification [12]. In the current study, the simulated concentration of NH_4^+ was close to the simulated concentration of TN (Table 4), indicating that nitrification does not progress to completion during the wastewater treatment process and is capable of being improved. Increasing DO content in the oxidation ditch can enhance nitrification. As mentioned in Sect. 2.3, aeration in the oxidation ditch is controlled by three surface aerators, each with a rate of 27 kWh. Therefore, in Scenario B, we increased the power of each surface aerator from 27 to 60 and 80 kWh, consequently increasing the DO content from 0.09 to 0.18 and 0.21 mg L^{-1} in the oxidation ditches, respectively.

2.4.3 Scenario C: returned flow from the secondary sedimentation tanks to the anoxic sections of the oxidation ditches

According to Wastewater Engineering: Treatment and Resource Recovery [15], returned activated sludge from secondary sedimentation tanks is transported to the anoxic zone. The denitrification reaction is depicted in Eq. (2) and Eq. (3). The returned flow to the anoxic zone can add to the source of available carbon, thereby enhancing denitrification. Therefore, in Scenario C, we used GPS-X to simulate the return of sludge from the secondary sedimentation tanks to the anoxic sections of the oxidation ditches.

$$NO_3^- + 1.085CH_3OH + 0.24H_2CO_3 \rightarrow 0.065C_5H_7O_2 + 0.47N_2 + 1.68H_2O + 1.88H_2CO_3\text{(denitrification bacteria)} \quad (2)$$

$$R'_{DN} = R_{DN} \times (1 - \mathrm{DO}) \quad (3)$$

where.

R_{DN}' = correction value.

R_{DN} = denitrification rate which is not affected by dissolved oxygen.

DO = dissolved oxygen (mg L^{-1}).

2.4.4 Scenario D: Scenario A + Scenario B

We hypothesize that Scenario D, which combines Scenario A and Scenario B, would have an additive effect on enhancing nitrification as well as denitrification.

2.4.5 Scenario E: Scenario A + Scenario B + Scenario C

We hypothesize that Scenario E, which combines Scenario A, Scenario B, and Scenario C, would have an additive effect, resulting in more complete nitrification and denitrification.

2.5 Increase in energy consumption and electricity cost in the simulated scenarios

In a GPS-X model, changes in the settings of equipment, such as surface aerators, do not affect the flow velocity in the oxidation ditch. In other words, the flow velocity in the oxidation ditch must be set manually. In addition, GPS-X models do not incorporate flow pushers, which are used in real-world settings to increase the flow velocity in the oxidation ditch. Therefore, to calculate the energy requirements for increasing the flow velocity in Scenarios A, D, and E, we assumed that the addition of each flow pusher to the system would consume 7.5 kWh/unit. A total of two flow pushers were added to the oxidation ditch, and they were operated throughout the day. The annual energy consumption of the flow pushers was calculated as presented in Eq. (4).

$$W_{pusher} = P_{pusher} \times t_{pusher} \times n_{pusher} \quad (4)$$

where.

W_{pusher} = annual energy consumption of flow pushers (kWh).

P_{pusher} = power of the flow pusher (kW).

t_{pusher} = annual operation time of the flow pusher (h).

n_{pusher} = number of flow pushers.

The average electricity cost of the Guishan WWTP in 2021 was approximately NTD 2.5 kWh. The annual electricity cost of the flow pushers was calculated as presented in Eq. (5).

$$C_{pusher} = W_{pusher} \times C_{electricity} \quad (5)$$

where.

C_{pusher} = annual electricity cost of the flow pusher (NTD).

$C_{electricity}$ = average electricity cost of the Guishan WWTP (NTD kWh^{-1}).

In Scenarios B, D and E, increased aeration of the oxidation ditch was achieved by simulating an increase in the energy consumed by channel surface aerators. As mentioned in Sect. 2.5, the energy consumption of surface aerators increased from 27 to 60 kWh/unit. A total of three surface aerators were used, and each aerator was assumed to be operated throughout the day. The increase in energy consumption resulting from the increased aeration in oxidation ditches was calculated as indicated in Eq. (6).

$$\triangle W_{aerator} = \triangle P_{aerator} \times t \times n \quad (6)$$

where.

$\triangle W_{aerator}$ = increased annual energy consumption of surface aerators (kWh).

$\triangle P_{aerator}$ = increase in the power of surface aerators (kW).

$t_{aerator}$ = annual operation time of surface aerators (h).

$n_{aerator}$ = number of surface aerators.

The annual electricity cost of the surface aerators was calculated as presented in Eq. (7):

$$\triangle C_{aerator} = \triangle W_{aerator} \times C_{electricity} \quad (7)$$

where.

$\triangle C_{aerator}$ = increased annual electricity cost of surface aerators (NTD).

$C_{electricity}$ = average electricity cost of the Guishan WWTP (NTD kWh^{-1}).

The parameters used in the aforementioned equations are listed in Table 5.

2.6 Increase in carbon emissions under the simulated scenarios

The amount of carbon emissions was calculated as indicated in Eq. (8).

$$\text{carbon emissions} = W \times CFC_{electricity} \quad (8)$$

where.

$CFC_{electricity}$ = carbon emission coefficient of electricity.

Table 5 Values of parameters used in calculations

Parameter	Value	Definition
P_{pusher}	7.5	power of the flow pusher (kW)
t_{pusher}	8,760	annual operation time of flow pusher (h)
n_{pusher}	2	number of flow pusher
$C_{electricity}$	2.5	average electricity cost of Guishan WWTP (NTD kWh^{-1})
$\triangle P_{aerator}$	33	the increase of power of surface aerator (kW)
$t_{aerator}$	8,760	annual operation time of surface aerator
$n_{aerator}$	3	number of surface aerator
$CFC_{electricity}$	0.509	carbon emission coefficient of electricity in 2021 in Taiwan

The Taiwan Power Company announced that the carbon emission coefficient of electricity in 2021 was 0.509 kg CO_2e $kWh.^{-1}$

3 Results and discussion

3.1 Scenario A: increased flow velocity

The simulation results for Scenario A are illustrated in Figs. 4 and 5. Similar removal efficiencies were obtained for BOD, COD, NH_4^+, and TN at flow velocities of 0.01, 0.1, 0.3 and 0.4 m s^{-1}. Abusam et al. [16] indicated that high horizontal velocity could lead to high removal efficiencies for NH_4^+ because of an increase in the volume of the aerated zones. However, in the current case, insufficient DO may have caused incomplete nitrification because the NH_4^+ concentration in the simulated effluent was 19.4 mg L^{-1} and DO content was < 0.01 mg L^{-1}. Therefore, the removal efficiency of NH_4^+ did not improve significantly when the oxidation ditch flow velocity was increased from 0.01 to 0.3 m s^{-1}. However, the removal efficiencies of BOD, NH_4^+, and TN at flow velocity of 0.4 m s^{-1} were 17, 70, 18%, respectively, which was lower than other flow velocity. Moreover, COD and SS is even higher than the influent.

3.2 Scenario B: increased aeration in oxidation ditches

The removal efficiency under different power of surface aerator is presented in Fig. 6. The removal of BOD, COD, SS and NH_4^+ increase as the power of the surface aerator increases. Insel et al. also showed that sufficient DO can help the ammonia nutrient removal performance [17]. However, when the surface aerator power is increased to 60 kWh, the TN removal efficiency improves. Conversely, when the power is further increased to 80 kWh, the TN removal efficiency decreases. It is suggested that the excessively power of the surface aerator leads to high dissolved oxygen and insufficient anoxic area, which result the low denitrification rate. This result is consistent with the previous study [16]. Therefore, the simulation result

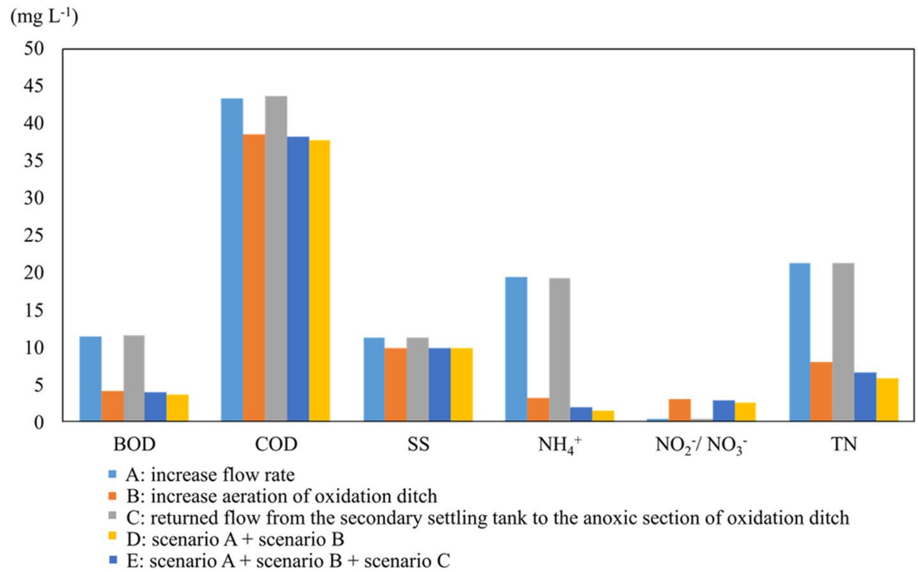

Fig. 4 Effluent water quality in each scenario

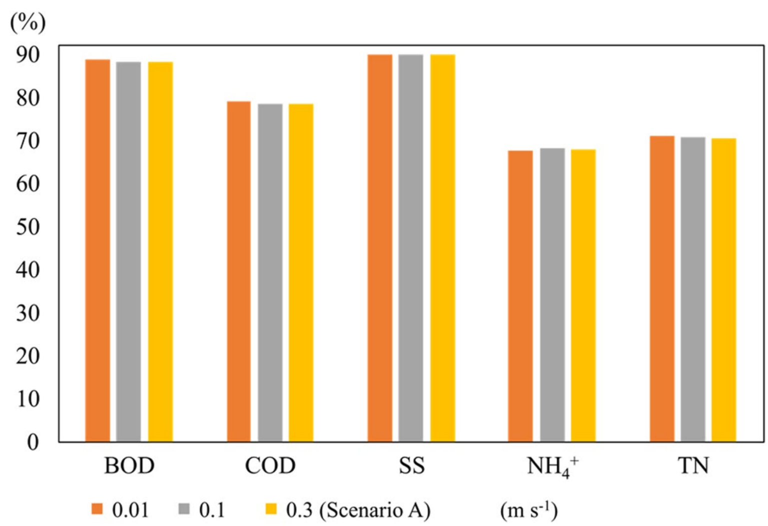

Fig. 5 Removal efficiency under different flow velocities

for 60 kWh represented Scenario B for comparison with other scenarios.

The simulation results for Scenario B are presented in Fig. 6. The removal efficiencies for BOD, COD, SS, and NH_4^+ were 96, 81, 89, 89 and 81%, respectively. The concentration of nitrite/nitrate nitrogen in the effluent increased from 0.3 to 3.2 mg L^{-1}, suggesting enhanced nitrification. These simulation results indicate that increased aeration in oxidation ditches can significantly improve the removal of BOD, NH_4^+, and TN. Fiter demonstrated that increasing DO content can promote nitrification [18]. In the current study, the amount of DO was insufficient under the original operating conditions. The GPS-X simulation revealed that the DO content in the region around the surface aerators increased from < 0.01 to 0.18 mg L^{-1}. Li et al. mentioned that the DO level in the aerobic pool should be 2–4 mg L^{-1}, while at the anaerobic pool it should be 0.20–0.50 mg L^{-1} [19], which is higher than this study. In this study the DO in aerobic pool is only about 0.18 mg L^{-1}, which not only enhanced the removal efficiency of contaminants but also saved more energy than other studies.

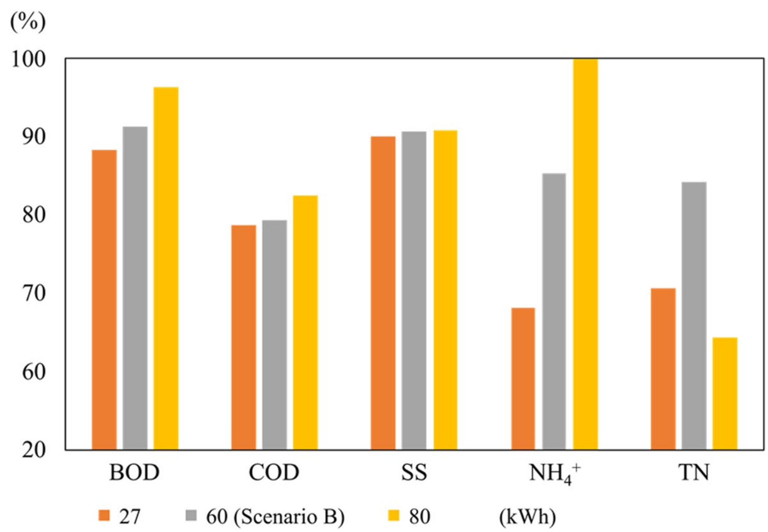

Fig. 6 Removal efficiency under different surface aerator powers

3.3 Scenario C: returned flow from the secondary sedimentation tanks to the anoxic sections of the oxidation ditches

The simulation results for Scenario C are presented in Fig. 4. The removal efficiencies for BOD, COD, SS, NH_4^+, and TN were 89, 79, 87, 36, and 50%, respectively. These simulation results indicate that effluent quality does not significantly improve when sludge from the secondary sedimentation tanks is returned to the anoxic sections of the oxidation ditches. The concentrations of NH_4^+ and DO in the effluent were 19.3 and < 0.01 mg L^{-1}, respectively, and therefore, the aforementioned observation could be the result of insufficient DO, as was true in Scenario A.

3.4 Scenario D: Scenario A + Scenario B

The simulation results for Scenario D are illustrated in Fig. 4. The removal rates for BOD, COD, SS, NH_4^+, and TN were 96, 81, 89, 93, and 84%, respectively. Combining Scenarios A and B resulted in significant enhancements in the removal efficiencies of BOD, NH_4^+, and TN. Furthermore, the removal efficiencies of NH_4^+, TN, and nitrite/nitrate from the effluent were more favorable in Scenario D than in Scenario B. These results are consistent with those of Gillot et al., who reported that an increase in horizontal velocity induces an increase in the kinetics of oxygen transfer [20]. Therefore, we speculate that when the amount of DO is sufficient, increasing the flow rate of the oxidation ditch increases the kinetics of oxygen transfer, which in turn increases the reaction rate and the removal efficiencies of NH_4^+ and TN.

3.5 Scenario E: Scenario A + Scenario B + Scenario C

The simulation results for Scenario E are presented in Fig. 4. The removal efficiencies of BOD, COD, SS, NH_4^+, and TN were 96, 82, 89, 95 and 86%, respectively. Combining Scenarios A, B, and C significantly enhanced the removal efficiencies of BOD, NH_4^+, and TN. Furthermore, the removal efficiencies of NH_4^+, TN, and nitrite/nitrate nitrogen were slightly higher in Scenario E than in Scenario D. We speculate that when sufficient amounts of DO are available, increasing the oxidation ditch flow velocities and returning the sludge from the secondary sedimentation tanks to the anoxic sections of the oxidation ditches can significantly enhance nitrification and denitrification, resulting in better removal of NH_4^+ and TN.

3.6 Increases in energy consumption, electricity costs, and carbon emissions in the simulated scenarios

Scenario E had the highest removal efficiencies but was also associated with the highest increases in energy consumption and carbon emissions (Fig. 7). Therefore, we identified the scenario with the optimal tradeoff between energy consumption and carbon emissions and removal efficiencies. Because carbon emissions are proportional to energy consumption, they can serve as a proxy for energy consumption. Table 6 presents the increases in carbon emissions per unit increase in removal efficiencies for all five scenarios. Scenario E had the lowest carbon emissions for the same increase in removal efficiency for COD and SS. For the same increase in BOD, SS and NH_4^+ removal, the lowest carbon emissions were obtained in Scenarios B. The

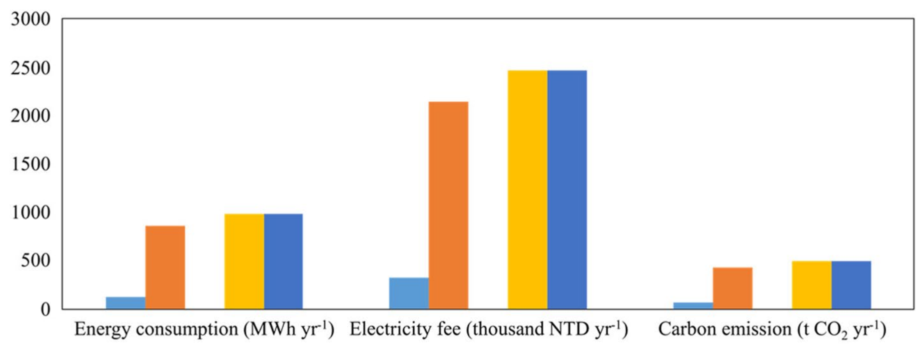

Fig. 7 Estimated increases in energy consumption and carbon emissions for each scenario

Table 6 Increases in carbon emissions under the same increased removal rates

Scenario	$\frac{\text{increase of carbon emission (t } CO_2 \text{ yr}^{-1})}{\text{increased removal efficiency (\%)}}$				
	BOD	**COD**	**SS**	**NH_4^+**	**TN**
A	0	0	0	0	0
B	72.3	233.6	289.3	8.2	14.2
C:	0	0	0	0	0
D	82.2	259.2	329.4	8.8	14.8
E	77.9	226.6	334.6	8.6	14.0

simulation results revealed that the most energy-efficient method for improving the quality of effluent water among Scenario A to E is Scenario E for COD and SS, and Scenario B for BOD, SS and NH_4^+

4 Conclusions

This study used the GPS-X water quality simulation software to evaluate whether the removal efficiencies of NH_4^+ and TN could be improved during the oxidation ditch treatment process at the Guishan WWTP. The following five scenarios were simulated: Scenario A, increased flow velocity; Scenario B, increased aeration in oxidation ditches; Scenario C, returned flow from the secondary sedimentation tanks to the anoxic sections of the oxidation ditches; Scenario D, a combination of Scenarios A and B; and Scenario E, a combination of Scenarios A, B, and C. The results indicate that Scenarios B, D, and E can significantly improve the removal efficiencies of NH_4^+ and TN. Although, Scenario E improved the removal efficiency the most, Scenarios B had the lowest carbon emissions under the same increase in the removal efficiency of BOD, NH_4^+ and TN. Therefore, from an energy efficiency point of view, Scenario B is the most energy-efficient method for improving the quality of effluent water. Although they may lead to increases in costs and carbon emissions, these scenarios indicate that up to 142 t of NH_4^+ and 121 t of TN can be prevented from entering the Nankan River each year. Improving river water quality and strengthening environmental protection measures are critical objectives that must be pursued. Therefore, WWTPs must adopt more energy-efficient measures, such as those in Scenario B, to improve effluent quality. Although we were unable to implement Scenario B at the Guishan WWTP and measure real-world outcomes in this study, we were able to confirm the credibility of our proposed improvement measures by using GPS-X simulations. In future studies, we recommend implementing Scenario B or at the pilot scale or in a real-world WWTP to test the proposed model.

Supplementary Information

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Data availability
All the data generated or analyzed during this study are available from the corresponding author upon reasonable request.

Declarations

Ethics approval and consent to participate
Not applicable.

Consent for publication
Not applicable.

Competing interests
The authors declare that they have no competing interests.

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