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Research article

Reducing energy costs of the wastewater treatment plant by improved scheduling of the periodic influent load

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ABSTRACT

The wastewater treatment plant (WWTP) is a major actor of the water-energy nexus. This study proposes to partially store in available WWTP tank infrastructure the wastewater received during the day-time and schedule the purification of the stored wastewater at night-time. The intended operational approach aims to shift part of the WWTP electrical energy consumption from day-time into the night-time period when the energy has lower prices, also contributing to the balance of the electrical power generation system. This research presents the case study of a Romanian WWTP with Anaerobic-Anoxic-Oxic (A^2O) process configuration. A proposed control strategy was implemented and tested on the dynamic calibrated WWTP model, based on the Activated Sludge Model No. 1 and the secondary settler Takács model. Simulations of the proposed scheduling program for the storing and processing time-periods of the influent wastewater, associated to the designed control strategies, demonstrate the reduction of the operational costs and energy savings, while keeping the effluent quality within the requested regulation limits and improving the plant sustainability. In the most favorable case and considering the overall WWTP performance, the operational costs are reduced by 47% and the effluent quality is improved by 25%. To achieve this performance a part of the influent wastewater is stored from 2 p.m. in the available tanks (day-period) while the beginning of the stored wastewater treatment is scheduled at 12 a.m. (night-period). Air flow rate distribution in the nitrification zone and the two water recirculation flow rates are also found by optimization.

1. Introduction

Sustainable development is a process and an organizational principle that satisfies the needs of the present population without reducing the opportunities for the future generations to satisfy their own needs. Water-energy-environment nexus plays an important role in achieving the Sustainable Development Goals (SDGs) for saving energy and water (Dai et al., 2018) and promoting environmental sustainability. In the recent years, Lubega and Farid (2014) have developed a quantitative energy-water-environment nexus systems model, while Meng et al. (2019) have highlighted the importance on focusing on all three aspects of the water-energy-carbon nexus. Su et al. (2018) have developed an integrated model based on Computable General Equilibrium concept, incorporating the management of water, energy and carbon in order to evaluate by simulations the energy – socio-economic – water environment interactions. Renewable energy is a main actor for accomplishing the SDGs, and the water feeding the hydropower plants plays a major role on this scene. Research efforts were devoted to increase the energy contribution of the run-of-river hydropower plants, but also considering the environmental flows alteration. Maximizing the energy production, while taking care of the ecosystem conservation, has been investigated (Kuriqi et al., 2019a, 2019b). Ali et al. (2019) have researched the influences of a cascade dams located in China by collecting, processing and analyzing data before and after the system of dams were constructed.

Large amount of energy is required at the municipal water management systems considering water supply, distribution, sewage and wastewater treatment. Hu et al. (2013) have shown that the consumed electricity in the water supply chain of Beijing was 4–6% of the total municipal energy consumption. Filion (2008) has studied the relationship between the water distribution networks form and the energy use. Malik et al. (2015) have evaluated the environmental performance of the wastewater treatment based on the United Nations (UN) statistical data of 183 countries, highlighting the UN Sustainable Development Goals by 2030. UN aims the management of water in order to sustain people and the environment by means of three components: access to

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water supply and sanitation, sustainable use and development of water resources, improve water quality and wastewater management. Padilla-Rivera and Güereca (2019) have emphasized the importance of considering the comprehensive environmental, economic and social sustainability indicators and proposed evaluation metrics for the wastewater treatment systems. Wastewater treatment requires a significant amount of energy, and this energy need is substantially increasing due to the population growth. Satisfying this demand involves the use of advanced technologies and control systems for pollutants removal. In European countries 1% of the electricity consumption may be assigned to the WWTPs (Di Fraia et al., 2018; Longo et al., 2016). The mean specific electric energy consumption of a typical municipal wastewater treatment plant (WWTP), using activated sludge technology for the water and anaerobic digestion of the sludge, is estimated to have a value of 0.6 kWh/m^3 of treated wastewater (Gude, 2015). Longo et al. (2019) have proposed an estimation methodology for analyzing the energy efficiency at the WWTPs.

A large number of studies were published in the recent years on the wastewater treatment topic and its associated energy or environmental aspects. Mo and Zhang (2013) have reviewed the available and exploited recovery resources of the WWTPs, using both onsite and offsite methods. For evaluating the WWTP techno-economic efficiency several studies consider the data envelopment analyses while the impact of the pollutants is also addressed (Gómez et al., 2018). For example, according to the case study of Spanish WWTPs, the data envelopment analyses ranked the energy costs to have the largest potential of economic saving, besides the staff costs (Castellet and Molinos-Senante, 2016). Different energy cost models for municipal WWTPs are reported in literature (Castellet-Viciano et al., 2018), including new energy cost modelling methodologies based on machine-learning algorithms (Torregrossa et al., 2018).

The water processing capacity of the WWTP has been continuously growing during the last decades and the circular economy has revealed its potential to become a water resources recovery facility. It was observed the decrease of the specific electricity consumption with the increase of the plant size (Belloir et al., 2015). One of the energy efficiency trends is highlighted in the specialized literature as the necessity to reach the energy autonomy level in the municipal WWTPs (Gu et al., 2017). According to other perspectives, the electricity recovery could be increased by new biological, electrochemical or bio-electrochemical technologies to be implemented at the municipal WWTPs (Tang et al., 2019). A representative research example presents the optimization of the energy balance at municipal WWTPs based on the Austrian advanced municipal WWTPs experience (Nowak et al., 2015). Other research results reported studies on renewable energy obtained from wastewater. They describe the possibility of feeding the available energy excess of the WWTP into community energy distribution grids with the scope of supplying external consumers (Kollmann et al., 2017). Solar photovoltaic systems are installed in some municipal WWTPs without and with anaerobic digestion and depending on the treated quantity of wastewater (Strazzabosco et al., 2019). A survey results on Italian WWTPs highlight that energy recovery exists only at large plants in Italy (Papa et al., 2017).

Instrumentation, control and automation also play an important role in the energy savings at the municipal WWTPs (Olsson, 2012). Monitoring WWTPs is appreciated for evaluating the operation and the effluent quality. In recent years, different fault detection approaches were designed, one of them being a deep belief network model associated to a one-class support vector machine (Harrou et al., 2018). In several studies Life Cycle Assessment was performed, including the aim of evaluating different control alternatives (Corominas et al., 2013).

Mathematical modelling and simulation are very useful tools for the study of activated sludge processes operating at the municipal WWTPs (Borzooei et al., 2019; Gernaey et al., 2004). They may both serve for the investigation of different control systems designs (Guerrero et al., 2011) which may contribute to: improvements of the WWTP operation (Nair et al., 2018; Kuriqi, 2014) by reducing the operational cost while ensuring the required effluent quality (Ostace et al., 2013, 2012), analysis of different construction designs of the WWTP (Mannina et al., 2016) and evaluation of greenhouse gases emission (Flores-Alsina et al., 2014). Four main activated sludge models were developed and are used by the wastewater treatment community. They are the Activated Sludge Models (ASMs) No. 1, 2, 2 d and 3 (Henze et al., 2000). These models describe the organic matter, nitrogen pollutants and phosphorus removal from wastewater. The Benchmark Simulation Models, developed on the basis of the ASMs, also contain models for the physical separation of the solid particles by means of the primary and secondary settler units. Stable and efficient operation of the plant may be obtained by automatic control. Typically, two control loops are considered in the real plants and in the BSMs. They are the control of the dissolved oxygen in the aerated reactors with the air flow rate used as the manipulated variable and the control of the nitrates concentration in the anoxic reactor by manipulating the nitrate recirculation flow rate (Alex et al., 2008). These control loops play an important role in the total energy consumption of the WWTP (Jeppsson et al., 2007).

The novelty of the present work consists in the synergy of merging waste water treatment plant control and optimization with the idea of scheduling the partial storage of the wastewater during the day-time and its subsequent processing in the night-time period. The paper presents this new solution and methodology aimed at achieving the improved operation of the WWTP for reducing the energy costs, environmental impact and enhancing effluent water quality. The daily time moments, duration and the flow rates of the storing and stored-wastewater processing, the air flow rate distribution in the nitrification reactor and the recirculation flow rates were obtained by optimization and the design of the associated control system was made in order to provide stable and smooth operation against disturbances.

The main objectives of the present research were to: i) develop a new way of operating the WWTP by storing a part of the influent wastewater during day-time, when the electricity prices are higher, and subsequently treating the stored wastewater during the night-time period, when electricity tariffs are lower, ii) propose different scheduling algorithms for the storing-treatment time and flow rates of this operating approach, iii) design the structure of the control system aimed to support the scheduling algorithms by controlling the effluent quality, iv) optimize the storing-treatment time and flow rates, the air distribution in the aerated zone of the biodegradation basins and the recirculation flow rates weighting factors for each scheduling algorithm and v) assess the performance of the optimized scheduling algorithms for reducing the energy costs and enhancing the effluent water quality, while improving the environmental impact.

2. Materials and methods

2.1. Case study of the Romanian municipal WWTP

2.1.1. WWTP layout

The activated sludge process under study is operating at the Romanian municipal WWTP and has an Anaerobic-Anoxic-Oxic (A^{2}O) configuration, as it is presented in the layout of Fig. 1. The water line consists of gross filtration, fine filtration, fats separation, storm water accumulation, primary sedimentation, biological treatment in anaerobic, anoxic, aerobic bio-reactors and secondary sedimentation.

The urban sewage network is of a mixed type and for this reason it has a spillway for overflows when the WWTP influent flows exceed the maximum hourly processing capacity of the plant (12,872 m^3/h). In the aerated basins the main process of ammonia oxidation to nitrates and nitrites takes place. The nitrates and nitrites formed in the aerobic zone are returned from the outlet of the aerated tanks into the anoxic zone by the nitrate recirculation (NR) flow. Separation of the mixed-liquor leaving the aeration basins is performed in secondary settler. Part of the activated sludge is recycled to the inlet of the water line by the return

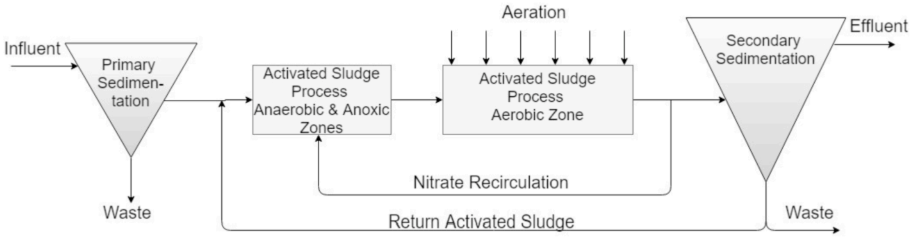

Fig. 1. Configuration of the investigated Romanian municipal WWTP.

activated sludge (RAS) flow and part of it is sent as waste to the anaerobic digestion unit. The cleaned water is fed to the emissary river.

2.1.2. WWTP construction and process measured data

The investigated municipal WWTP accomplishes online measurements, coupled with chemical laboratory analyses, in order to monitor and control the plant for achieving the required performance. The online measurements of the flow rates, influent and effluent components concentration are collected with a sampling time of 10 s by the Supervisory Control and Data Acquisition (SCADA) system, while the chemical laboratory of the plant makes analytical measurements on the daily or weekly average collected samples.

The data used in the present study were collected during the month of May 2016. The influent and effluent concentration of the Chemical Oxygen Demand (COD), Total Nitrogen (N_{total}), free and saline ammonia (S_{NH}), Nitrates and Nitrites (S_{NO}), Total Suspended Solids (TSS), together with the wastewater influent, water effluent, air entering the biodegradation tanks, return activated sludge and nitrate recirculation flow rates, are all measured and considered in the present study. The average measured influent, effluent and operational values for the first 22 days of the month are presented in Table 1. The period chosen for investigations and used as case study to assess the proposed scheduling approach performance, i.e. the 22 days of month May, may be considered representative for the yearly operation of the WWTP, as it is an intermediate season between the coldest winter season (month February) and the hottest summer one (month July).

The dimension and construction data of the primary clarifiers, biodegradation tanks and secondary settlers are presented in Table 2.

2.2. Dynamic WWTP model and components

The dynamic simulator of the investigated WWTP was built using as basis the Benchmark Simulation Model No. 1 (BSM1), developed by the COST Action 624 & COST Action 682 (Copp, 2002).

Table 1
Influent, effluent and operating data, averaged for the first 22 days of month May 2016.

Variable	Average value	Unit
Influent Measured Data		
Influent Chemical Oxygen Demand	264.17	g COD/m^3
Influent Total Suspended Solids	132	g SS/m^3
Influent Free and Saline Ammonia	24.98	g N/m^3
Influent Nitrates and Nitrites	2.34	g N/m^3
Influent Total Nitrogen	35.23	g N/m^3
Influent Alkalinity	6.81	–
Influent Flow Rate	119,221	m^3/day
Influent Temperature	15.83	°C
Effluent Measured Data		
Effluent Soluble Chemical Oxygen Demand	4.84	g COD/m^3
Effluent Total Suspended Solids	12.00	g SS/m^3
Effluent Free and Saline Ammonia	0.17	g N/m^3
Effluent Nitrates and Nitrites	3.76	g N/m^3
Effluent Total Nitrogen	5.70	g N/m^3
Operating Measured Data		
Flow Rate of the Air Entering the Tanks	383,325	Nm^3/day
Flow Rate of Nitrate Recirculation	138,345	m^3/day
Flow Rate of Return Activated Sludge	112,523	m^3/day
Flow Rate of Waste	889	m^3/day

The WWTP model is composed of: i) a primary clarifier with equations presented by Otterpohl and Freund (1992), ii) one anaerobic bioreactor, iii) one anoxic bioreactor, iv) three aerobic bioreactors connected in series (with all bioreactors based on the Activated Sludge Model No. 1 (ASM1)) (Henze et al., 2000) and v) a secondary settler considering the double-exponential velocity function reported by Takács (Takács et al., 1991). The dynamic municipal WWTP model was developed in Matlab software and Simulink simulation environment. The equations of the biodegradation basins and settlers were written in C programming language. The issued C files were implemented in the simulation environment as S-function blocks. The model was updated, calibrated and validated based on the collected measured data and dimensional characteristics of the municipal WWTP under study (Várhelyi et al., 2019).

2.3. Control strategy and the proposed storage algorithms

This research proposes the partial storage of the influent wastewater during the day-time and the treatment of the stored wastewater during the night-time. Different configurations of this operation approach were tested by simulation, using available and collected data from the Romanian municipal WWTP under study and considering in the performance assessment the averaged values for a period of 10 min. An associated control system is also proposed for maintaining stable and efficient operation of the plant.

2.3.1. Proposed control system structure

The previously calibrated WWTP model was extended with appropriate control systems. Firstly, the calibrated model was coupled with the Ammonia Based Aeration Control (ABAC) system (Åmand et al., 2013), whose role is to control the free and saline ammonia concentration at the outlet of the aerated biodegradation basins by manipulating the flow rate of air entering in the aerobic zone of the bioreactors (Rieger et al., 2014). In order to carry out this control task, the concentration of ammonia is measured in the fifth (last) of the ASM1 bioreactors and it is compared with the setpoint value of 1 g N/m^3. In the cascaded control loops of the new control structure are implemented three dissolved oxygen controllers. The last dissolved oxygen controller

Table 2
The dimension specifications of the investigated municipal WWTP units.

Variable	Averaged value	Unit
Primary Settler		
Total Area	2125	m^2
Height	3.5	m
Biodegradation Tanks		
Total Volume of the Anaerobic Zone	9015	m^3
Total Volume of the Anoxic Zone	12,678	m^3
Total Volume of the Aerobic Zone	33,066	m^3
Total Area of the Aerobic Zone	6012	m^2
Secondary Clarifier		
Total Area	67,824	m^2
Height	3	m

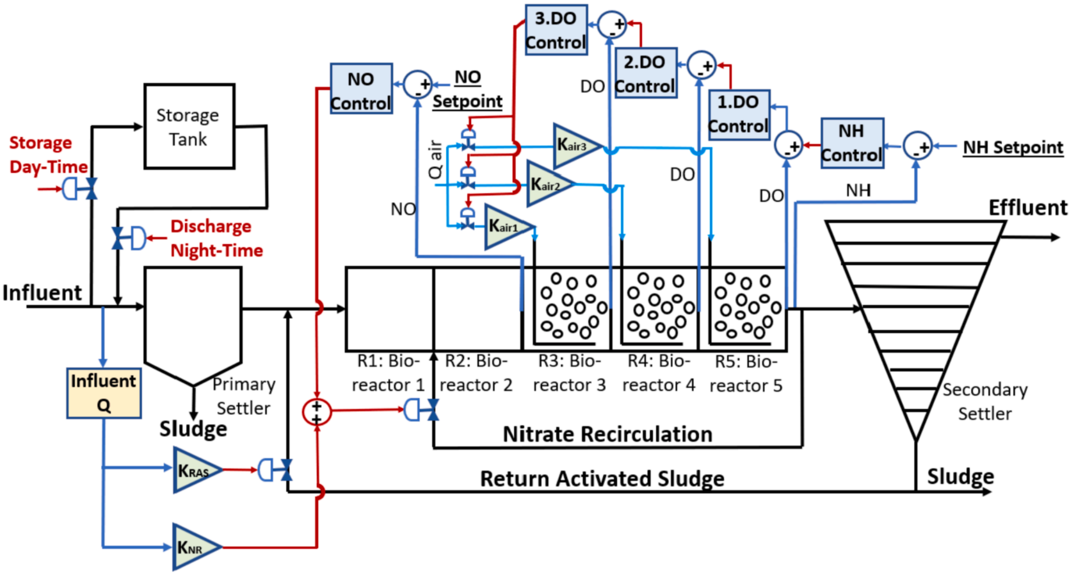

Fig. 2. Ammonia Based Aeration Control associated to Nitrate Recirculation and Return Activated Sludge Control proposed and tested for the calibrated WWTP model.

calculates and the control valve manipulates the necessary flow rate of air. Secondly, in order to control the denitrification process the feedback control system of the nitrates and nitrites (NO) concentration in the anoxic zone was introduced. To this control system it was associated a feedforward control component, based on the influent flow rate disturbance. This NO controller manipulates the nitrate recirculation flowrate. The flow rate of the nitrate recirculation is computed based on the sum of two components. They are the flow rate of the influent flow, multiplied with an appropriately chosen factor (k_{NR}), i.e. the feedforward control component, and the control signal of the nitrates and nitrites controller (feedback component). The return activated sludge flow rate is also manipulated based on the influent flow rate, using another selected factor (k_{RAS}). Fig. 2 presents the proposed control system structure.

2.3.2. Storage and stored wastewater treatment at constant flow rates and fixed time moments

For the WWTP having associated the control system presented in Fig. 2 it was proposed a new operation approach. It consists in partially storing the wastewater that enters the plant between 7 a.m. and 10 p.m. in the available tanks, with a total volume of 11,173 m^3, and then treating the stored water during night-time when the electricity has lower prices than the day-time tariffs. Different storage scheduling designs were tested by dynamic simulations.

Table 3 presents the set of investigated cases when at 7 a.m. the wastewater starts feeding the available storage tanks, at a chosen constant flow rate, until 90% of the tanks volume is filled. At 10 p.m. the stored wastewater is sent, at the same constant flow rate, to the water line inlet in order to be treated. Ammonia based aeration control coupled with nitrates and nitrites control were used in all of these simulation cases. They consider: i) equal air distribution in the biodegradation basins of the aerobic zone, ii) equal flow rates of the return activated sludge (Q_{RAS}) and the influent flow (k_{RAS} is considered 1), as presented in Eq. (1), iii) nitrate recirculation flow rate (Q_{NR}) computed by the summation between the influent flow rate ($Q_{Influent}$) multiplied by the 0.7 (k_{NR}) factor and the control signal of the nitrate controller ($y_{c\_NOcontroller}$), as described in Eq. (2). The different values of the investigated flow rate cases for the wastewater storage and for the treatment of the stored wastewater are described in Table 3 by Eqs. (3-10), $Q_{storage\_wastewater}$ representing the flow rate of the storing wastewater in the available storage tanks, while $Q_{treat\_stored\_wastewater}$ denoting the flow rate which is used to transport the stored wastewater from the storage tanks to the water line in order to treat it.

$$Q_{RAS} = k_{RAS} \cdot Q_{Influent} \tag{1}$$

$$Q_{NR} = y_{c\_NOcontroller} + k_{NR} \cdot Q_{Influent} \tag{2}$$

2.3.3. Storage and stored wastewater treatment at constant flow rates and different time moments

Scheduling the partial storage time moment and the stored wastewater processing time may have positive or negative effects on the performance of the water treatment. Twelve proposed investigation cases are shown in Table 4 and they are described by Eqs. (11-22), $time_{storage\_wastewater}$ representing the beginning of the storage period for the influent wastewater, while $time_{treat\_stored\_wastewater}$ denoting to the stored wastewater treatment starting time. ABAC and the other presented control strategies were also implemented. The flow rate, both for wastewater storage and for stored wastewater discharge into the water line, was equal to 30,000 m^3/day. The particular value of this flow rate was chosen based on the results presented in section 4.2.

2.3.4. Energy costs and effluent quality optimization

Different storage cases were investigated by optimization considering the storage flow rate, the air distribution among the three aerobic bioreactors (Q_{air} (R3):Q_{air} (R4):Q_{air} (R5)), the RAS and NR flow rates,

Table 3
Investigated cases of the wastewater storage - treatment, at different constant flow rates and WWTP using the ABAC, Nitrate Recirculation and Return Activated Sludge control.

Case	Description	Eq. no.
Storage Case 1	$Q_{storage\_wastewater} = 0\ m^3/day$ $Q_{treat\_stored\_wastewater} = 0\ m^3/day$	(3)
Storage Case 2	$Q_{storage\_wastewater} = 10,000\ m^3/day$ $Q_{treat\_stored\_wastewater} = 10,000\ m^3/day$	(4)
Storage Case 3	$Q_{storage\_wastewater} = 20,000\ m^3/day$ $Q_{treat\_stored\_wastewater} = 20,000\ m^3/day$	(5)
Storage Case 4	$Q_{storage\_wastewater} = 30,000\ m^3/day$ $Q_{treat\_stored\_wastewater} = 30,000\ m^3/day$	(6)
Storage Case 5	$Q_{storage\_wastewater} = 40,000\ m^3/day$ $Q_{treat\_stored\_wastewater} = 40,000\ m^3/day$	(7)
Storage Case 6	$Q_{storage\_wastewater} = 50,000\ m^3/day$ $Q_{treat\_stored\_wastewater} = 50,000\ m^3/day$	(8)
Storage Case 7	$Q_{storage\_wastewater} = 60,000\ m^3/day$ $Q_{treat\_stored\_wastewater} = 60,000\ m^3/day$	(9)
Storage Case 8	$Q_{storage\_wastewater} = 70,000\ m^3/day$ $Q_{treat\_stored\_wastewater} = 70,000\ m^3/day$	(10)

Table 4
Investigated cases of the wastewater storage followed by subsequent stored water treatment, at constant flow rates but with different starting storage and subsequent treatment time moments.

Case	Description	Eq. no.
Storage-Treat Time Case 1	$time_{storage\_wastewater} = 7$ a.m. $time_{treat\_stored\_wastewater} = 10$ p.m.	(11)
Storage-Treat Time Case 2	$time_{storage\_wastewater} = 10:30$ a.m. $time_{treat\_stored\_wastewater} = 10$ p.m.	(12)
Storage-Treat Time Case 3	$time_{storage\_wastewater} = 12$ p.m. $time_{treat\_stored\_wastewater} = 10$ p.m.	(13)
Storage-Treat Time Case 4	$time_{storage\_wastewater} = 2$ p.m. $time_{treat\_stored\_wastewater} = 10$ p.m.	(14)
Storage-Treat Time Case 5	$time_{storage\_wastewater} = 7$ a.m. $time_{treat\_stored\_wastewater} = 12$ a.m.	(15)
Storage-Treat Time Case 6	$time_{storage\_wastewater} = 10:30$ a.m. $time_{treat\_stored\_wastewater} = 12$ a.m.	(16)
Storage-Treat Time Case 7	$time_{storage\_wastewater} = 12$ p.m. $time_{treat\_stored\_wastewater} = 12$ a.m.	(17)
Storage-Treat Time Case 8	$time_{storage\_wastewater} = 2$ p.m. $time_{treat\_stored\_wastewater} = 12$ a.m.	(18)
Storage-Treat Time Case 9	$time_{storage\_wastewater} = 7$ a.m. $time_{treat\_stored\_wastewater} = 3$ a.m.	(19)
Storage-Treat Time Case 10	$time_{storage\_wastewater} = 10:30$ a.m. $time_{treat\_stored\_wastewater} = 3$ a.m.	(20)
Storage-Treat Time Case 11	$time_{storage\_wastewater} = 12$ p.m. $time_{treat\_stored\_wastewater} = 3$ a.m.	(21)
Storage-Treat Time Case 12	$time_{storage\_wastewater} = 12$ p.m. $time_{treat\_stored\_wastewater} = 3$ a.m.	(22)

the storage and the treatment starting time as decision variables. The investigated cases are presented in Table 5 and described by Eqs. (23-32). All the presented optimization problems consider as total objective function the sum between the sub-objective weighted term of the costs of energy (i.e. aeration and pumping energy), multiplied by the weighting factor of 11.875, and the effluent quality sub-objective term. The introduction of the 11.875 weighting factor was necessary for balancing the sub-objective terms importance.

In Cases 2–5 the storage starting time was set to 2 p.m., while the treatment starting time of the stored wastewater was considered to be at 12 a.m. These starting time values were chosen based on the previously performed simulations, presented in section 4.3. In Case 2 the storage and treatment flow rates, the air distribution and the k_{RAS} and k_{NR} factors, used for controlling the RAS and NR flow rates on the basis of the influent flow rate, were determined by optimization. For the k_{RAS} factor, one value was considered for the whole period of 22 days of the study. In Case 3, the decision variables remain the same, but the k_{RAS} factor was considered with daily changes. In Case 4, the flow rate of the return activated sludge was considered to be equal with the influent flow rate, while the k_{NR} was set to 0.7. As decision variables were chosen the storage and treatment flow rates, associated to the air distribution among the aerated biodegradation basins. In Case 5 all of the air flow rates entering in the aerated bioreactors were considered to be equal, while k_{RAS} was fixed to 1 and k_{NR} to 0.7. For this case, as decision variables of the total optimization index were chosen the storage and discharge flow rates.

Cases 6–9 are similar to the presented Cases 2–5. The only difference consists in the starting time of the wastewater storage and of the stored wastewater discharge.

In the last Case 10, the selected decision variables were the storage and discharge flow rates, the starting time of the storage, the air distribution and the recycle stream factors. The discharge from the storage tanks was scheduled to begin at 10 p.m. In all optimized storage cases lower and upper boundaries were considered for the decision variables.

The storage solutions presented in Table 5 were computed based on solving the constrained optimization problem, using a gradient based algorithm embedded in the *fmincon* function of the Matlab software.

Table 5
Investigated cases for the optimization of energy, operational costs and effluent quality, using storage flow rate, air distribution and recycle flow rates as decision variables.

Case	Description	Eq. no.
Optimized Storage Case 1	$Q_{storage\_wastewater} = 9957\ \mathrm{m}^3/\mathrm{day}$ optimized value $Q_{treat\_stored\_wastewater} = 42,546\ \mathrm{m}^3/\mathrm{day}$ optimized value $Q_{air}(R3) : Q_{air}(R4) : Q_{air}(R5) = 2.15 : 2.14 : 1$ optimized air distribution $k_{RAS} = 0.4043;\ k_{NR} = 0.7993$ optimized values for the whole period of time Storage from 8:38 a.m., treat stored wastewater from 1:34 a.m. optimized storage and treatment time values Objective function: $11.875 \cdot \mathrm{EnergyCost} + \mathrm{EQ} \overset{!}{=} MIN$	(23)
Optimized Storage Case 2	$Q_{storage\_wastewater} = 35,349\ \mathrm{m}^3/\mathrm{day}$ optimized value $Q_{treat\_stored\_wastewater} = 32,400\ \mathrm{m}^3/\mathrm{day}$ optimized value $Q_{air}(R3) : Q_{air}(R4) : Q_{air}(R5) = 3.01 : 2.43 : 1$ optimized air distribution $k_{RAS} = 0.3956;\ k_{NR} = 0.4579$ optimized values for the whole period of time Storage from 2 p.m., treat stored wastewater from 12 a.m. Objective function: $11.875 \cdot \mathrm{EnergyCost} + \mathrm{EQ} \overset{!}{=} MIN$	(24)
Optimized Storage Case 3	$Q_{storage\_wastewater} = 25,317\ \mathrm{m}^3/\mathrm{day}$ optimized value $Q_{treat\_stored\_wastewater} = 25,602\ \mathrm{m}^3/\mathrm{day}$ optimized value $Q_{air}(R3) : Q_{air}(R4) : Q_{air}(R5) = 2.77 : 1.21 : 1$ optimized air distribution $k_{RAS} -$ optimized values each day; $k_{NR} = 0.7$ Storage from 2 p.m., treat stored wastewater from 12 a.m. Objective function: $11.875 \cdot \mathrm{EnergyCost} + \mathrm{EQ} \overset{!}{=} MIN$	(25)
Optimized Storage Case 4	$Q_{storage\_wastewater} = 59,979\ \mathrm{m}^3/\mathrm{day}$ optimized value $Q_{treat\_stored\_wastewater} = 27,459\ \mathrm{m}^3/\mathrm{day}$ optimized value $Q_{air}(R3) : Q_{air}(R4) : Q_{air}(R5) = 3.24 : 3.29 : 1$ optimized air distribution $k_{RAS} = 1; k_{NR} = 0.7$ Storage from 2 p.m., treat stored wastewater from 12 a.m. Objective function: $11.875 \cdot \mathrm{EnergyCost} + \mathrm{EQ} \overset{!}{=} MIN$	(26)
Optimized Storage Case 5	$Q_{storage\_wastewater} = 29,943\ \mathrm{m}^3/\mathrm{day}$ optimized value $Q_{treat\_stored\_wastewater} = 31,425\ \mathrm{m}^3/\mathrm{day}$ optimized value $Q_{air}(R3) : Q_{air}(R4) : Q_{air}(R5) = 1 : 1 : 1$ $k_{RAS} = 1;\ k_{NR} = 0.7$ Storage from 2 p.m., treat stored wastewater from 12 a.m. Objective function: $11.875 \cdot \mathrm{EnergyCost} + \mathrm{EQ} \overset{!}{=} MIN$	(27)

(*continued on next page*)

Table 5 (*continued*)

Case	Description	Eq. no.
Optimized Storage Case 6	$Q_{storage\_wastewater} = 114\ \mathrm{m}^3/\mathrm{day}$ optimized value $Q_{treat\_stored\_wastewater} = 7728\ \mathrm{m}^3/\mathrm{day}$ optimized value $Q_{air}(R3) : Q_{air}(R4) : Q_{air}(R5) = 3.96 : 1.3 : 1$ optimized air distribution $k_{RAS} = 0.5026;\ \ k_{NR} = 0.7909$ optimized values for the whole period of time Storage from 7 a.m., treat stored wastewater from 10 p.m. Objective function: $11.875 \cdot \mathrm{EnergyCost} + \mathrm{EQ} \overset{!}{=} MIN$	(28)
Optimized Storage Case 7	$Q_{storage\_wastewater} = 59,850\ \mathrm{m}^3/\mathrm{day}$ optimized value $Q_{treat\_stored\_wastewater} = 29,772\ \mathrm{m}^3/\mathrm{day}$ optimized value $Q_{air}(R3) : Q_{air}(R4) : Q_{air}(R5) = 2.01 : 1.01 : 1$ optimized air distribution k_{RAS} − optimized values each day; $k_{NR} = 0.7$ Storage from 7 a.m., treat stored wastewater from 10 p.m. Objective function: $11.875 \cdot \mathrm{EnergyCost} + \mathrm{EQ} \overset{!}{=} MIN$	(29)
Optimized Storage Case 8	$Q_{storage\_wastewater} = 19,197\ \mathrm{m}^3/\mathrm{day}$ optimized value $Q_{treat\_stored\_wastewater} = 15,573\ \mathrm{m}^3/\mathrm{day}$ optimized value $Q_{air}(R3) : Q_{air}(R4) : Q_{air}(R5) = 2.14 : 1.86 : 1$ optimized air distribution $k_{RAS} = 1;\ \ k_{NR} = 0.7$ Storage from 7 a.m., treat stored wastewater from 10 p.m. Objective function: $11.875 \cdot \mathrm{EnergyCost} + \mathrm{EQ} \overset{!}{=} MIN$	(30)
Optimized Storage Case 9	$Q_{storage\_wastewater} = 11,325\ \mathrm{m}^3/\mathrm{day}$ optimized value $Q_{treat\_stored\_wastewater} = 15,351\ \mathrm{m}^3/\mathrm{day}$ optimized value $Q_{air}(R3) : Q_{air}(R4) : Q_{air}(R5) = 1 : 1 : 1$ $k_{RAS} = 1;\ k_{NR} = 0.7$ Storage from 7 a.m., treat stored wastewater from 10 p.m. Objective function: $11.875 \cdot \mathrm{EnergyCost} + \mathrm{EQ} \overset{!}{=} MIN$	(31)
Optimized Storage Case 10	$Q_{storage\_wastewater} = 35,034\ \mathrm{m}^3/\mathrm{day}$ optimized value $Q_{treat\_stored\_wastewater} = 0.079\ \mathrm{m}^3/\mathrm{day}$ optimized value $Q_{air}(R3) : Q_{air}(R4) : Q_{air}(R5) = 1.4 : 1.4 : 1$ optimized air distribution $k_{RAS} = 0.6577;\ k_{NR} = 0.5113$ optimized values for the whole period of time Storage from 8:01 a.m., treat stored wastewater from 10 p.m. optimized storage time value Objective function: $11.875 \cdot \mathrm{EnergyCost} + \mathrm{EQ} \overset{!}{=} MIN$	(32)

3. Results

3.1. Performance of the municipal WWTP without influent storage and treatment scheduling

In order to analyze the WWTP performance of the proposed storage and treatment investigated cases the following assessment measures were calculated: the aeration energy and aeration cost, the pumping energy and pumping cost, the effluent quality and number of violations of the water quality upper limits which are set by regulations (Copp, 2002). The aeration energy was calculated based on the mass transfer coefficient in the aerated bioreactor (K_La), the aerated bioreactor volume and the dissolved oxygen concentration at saturation, as described by Eq. (33) (Jeppsson et al., 2007). The pumping energy took into consideration the nitrate recirculation flow rate (Q_{NR}), the return activated sludge flow rate (Q_{RAS}) and the waste flow rate (Q_{waste}), as shown in Eq. (34) (Jeppsson et al., 2007). C_{AE} and C_{PE} factors were considered for calculating the energy. The aeration and pumping energy are expressed in kWh/day units. The energy prices considered were of 0.07614 €/kWh for the day-time consumed electricity and of 0.04632 €/kWh for the night-time consumed electricity. The effluent quality computation is based on the effluent concentration of the total suspended solids (TSS), chemical oxygen demand, biochemical oxygen demand (BOD), total Kjeldahl nitrogen (TKN) and nitrates (NO). They were expressed in pollutant units (PU) and are presented by Eq. (35).

$$AE = C_{AE} \cdot \frac{SO_{sat}}{T \cdot 1.8 \cdot 1000} \int_0^T \sum_{aerated\ \ bioreactor} \left[V_{bioreactor} \cdot K_L a_i(t)\right]\ dt \tag{33}$$

$$PE = C_{PE} \cdot \frac{1}{T} \int_0^T \left[0.004 \cdot Q_{NR}(t) + 0.08 \cdot Q_{RAS}(t) + 0.05 \cdot Q_{waste}(t)\right]\ dt \tag{34}$$

$$EQ = \frac{1}{T \cdot 1000} \int_0^T \left[PU_{TSS}(t) + PU_{COD}(t) + PU_{BOD}(t) + PU_{TKN}(t) + PU_{NO}(t)\right] Q_{effluent}(t)\ dt \tag{35}$$

For all investigated cases, no violations were reported for the regulation limit concentrations of the pollutants in the effluent. This is due to the control system operation.

Based on WWTP measurements, the performance of the investigated plant is presented in Table 6 for the period of the first 22 days of month May, year 2016. They represent the reference case of the presented investigations.

Table 6 reveals that the aeration energy spent during the day-time is 62.4% of the daily total aeration energy, while the pumping energy spent during the day-time is 65.1% of the daily total pumping energy. It may be concluded that larger quantity of electricity is consumed during day-time than during night-time and this is an important reason for higher operational costs during the day-time period.

Table 6
Performance of the Romanian municipal WWTP under study during the chosen period of the 22 days of May 2016.

Municipal WWTP	Aeration Energy Day-Time [kWh/day]	Aeration Energy Night-Time [kWh/day]	Pumping Energy Day-Time [kWh/day]	Pumping Energy Night-Time [kWh/day]	Total Operation Cost [€/day]	Effluent Quality [kg PU/day]
WWTP	9260.8	5588.1	5745.5	3086.1	1544.3	18,710.2

Table 7
Aeration and pumping energy, total operation cost and the effluent quality for the 8 cases of the storage designs with the different constant storage and discharge flow rates.

Cases Storage 1-8	Aeration Energy Day-Time [kWh/day]	Aeration Energy Night-Time [kWh/day]	Pumping Energy Day-Time [kWh/day]	Pumping Energy Night-Time [kWh/day]	Total Operation Cost [€/day]	Effluent Quality [kg PU/day]
Case 1	6202.0	3204.3	6007.8	3288.7	1230.4	14,272.6
Case 2	5833.7	3508.8	5704.9	3567.1	1206.3	14,132.6
Case 3	5534.3	3831.7	5428.6	3840.7	1190.0	14,295.3
Case 4	5433.2	4016.6	5314.9	3943.2	1187.0	14,517.0
Case 5	5555.7	3982.3	5306.7	3941.3	1194.0	14,773.0
Case 6	5681.6	3928.6	5299.9	3940.3	1200.6	14,985.1
Case 7	5752.0	3912.5	5295.1	3940.5	1204.8	15,147.2
Case 8	5789.9	3918.8	5291.4	3941.3	1207.7	15,274.5

Table 8
Aeration and pumping energy, total operation cost and effluent quality for the cases of the different starting time moments of the wastewater storage and discharge, and with constant flow rates.

Cases Storage Time 1-12	Aeration Energy Day-Time [kWh/day]	Aeration Energy Night-Time [kWh/day]	Pumping Energy Day-Time [kWh/day]	Pumping Energy Night-Time [kWh/day]	Total Operation Cost [€/day]	Effluent Quality [kg PU/day]
Case 1	5433.9	4011.1	5315.3	3942.8	1186.8	14,500.5
Case 2	6202.0	3204.3	6007.8	3288.7	1230.4	14,272.6
Case 3	5247.4	4082.2	5325.4	3949.1	1177.0	14,233.7
Case 4	5313.6	3990.8	5329.5	3950.0	1178.1	14,141.8
Case 5	5519.4	3859.0	5349.5	3908.7	1187.3	14,321.1
Case 6	5378.8	3933.3	5355.9	3912.8	1180.7	14,151.6
Case 7	5364.0	3921.4	5358.7	3914.5	1179.3	14,082.2
Case 8	5402.4	3864.2	5362.1	3915.3	1179.9	14,005.3
Case 9	5881.4	3519.2	5621.9	3635.8	1207.2	14,284.6
Case 10	5769.7	3553.6	5628.8	3640.1	1201.0	14,112.8
Case 11	5743.1	3553.7	5631.2	3641.5	1199.3	14,058.7
Case 12	5733.4	3543.1	5634.9	3642.5	1198.4	13,983.5

Table 9
Aeration and pumping energy, total operation cost and effluent quality for the 10 optimized complex storage cases, using as decision variables the storage flow rate, the air distribution in the three aerobic bioreactors, and the RAS and NR flow rates.

Cases Storage Optimized 1-10	Aeration Energy Day-Time [kWh/day]	Aeration Energy Night-Time [kWh/day]	Pumping Energy Day-Time [kWh/day]	Pumping Energy Night-Time [kWh/day]	Total Operation Cost [€/day]	Effluent Quality [kg PU/day]
Case 1	5551.1	3638.4	2382.1	1577.0	845.6	14,246.9
Case 2	5117.6	4018.0	2180.3	1614.2	816.5	14,000.4
Case 3	5358.9	3714.8	3411.6	2365.8	949.4	12,661.3
Case 4	5540.4	3933.6	5435.2	3875.8	1197.4	13,206.8
Case 5	5376.4	3892.1	5332.8	3944.1	1178.3	14,015.3
Case 6	6384.7	3188.7	3152.9	1731.2	954.0	13,367.3
Case 7	5557.5	3785.3	3290.7	2416.0	960.9	14,046.2
Case 8	5717.5	3623.1	5581.2	3724.5	1200.6	13,472.3
Case 9	5666.1	3659.0	5569.2	3706.7	1196.6	14,094.1
Case 10	6081.4	3138.9	3987.3	2199.4	1013.9	13,878.8

3.2. Storage and stored wastewater treatment at constant flow rates and fixed time moments

The simulation results of the proposed storage cases, when different constant flow rate values for the storage and discharge are considered at fixed time moments, may be found in Table 7.

It can be observed that with the increase of both wastewater storage flow rate (storage starting at 7 a.m.) and stored water discharge flow rate (discharge starting at 10 p.m.), the effluent quality is increasing (i.e. larger amount of pollutant in the effluent). The lowest operational costs were achieved in Case 4 when a minimum was found. It corresponds to the equal storage and the discharge flow rates of 30,000 m^3/day. It is worthy to mention that the volume of the stored and subsequently treated wastewater is the same for all cases, i.e. 90% of the total storage tank volume. There are only the flow rates and the duration of storage and discharge periods that are changing.

When implementing the control strategies, the performance of the WWTP shows benefits emerged from their implementation. Compared to the reference case of the plant operation presented in Table 6 the effluent quality is improved by 23.7% and the aeration energy is reduced by 36.7%. The total pumping energy is increased, but the total operation energy is reduced due to the reduction of the aeration energy. The total operation cost is reduced by 20.3%.

3.3. Storage and stored wastewater treatment at constant flow rates and different time moments

Table 8 shows the simulation results for the cases of the different time moments proposed for starting the wastewater storage in the available storage infrastructure of the WWTP and for the discharge of the stored water into the primary settler. The storage and discharge flow rates were considered to have the value of 30,000 m^3/day, because at this constant flow rate the results presented in Table 7 showed a minimum of the total operational cost.

Storage and treatment time scheduling of Case 8 may be ranked with the best performance among the twelve analyzed cases, when the both the overall WWTP performance of the operational cost and the effluent quality are considered. According to this case the storage starts at 2 p.m.

with 30,000 m^3/day flow rate and the stored water is sent to the treatment beginning with 12 a.m. (i.e. at midnight). Compared to the actual performance of the municipal WWTP, the total operation cost is reduced by 23.6%, and the effluent quality is improved by 25.1%. The most favorable case for the operation cost is the storage and treatment time presented in Case 3 which has the lowest operation cost value of 1177.0 €/day. In this case, the storage is scheduled to start at 12 p.m. and the treatment of the stored wastewater at10 p.m. Considering the effluent quality, Case 12 is the most favorable one as it shows the most reduced value of 13983.5 kg P.U./day. In this case, the wastewater storage is planned to start at 2 p.m., while the discharge back into the water line is scheduled to start at 3 a.m.

3.4. *Energy costs and effluent quality optimization*

Complex storage cases were proposed for energy costs and effluent quality optimization. They were implemented and their performance was assessed by simulation with the calibrated municipal WWTP model. The results are shown in Table 9.

Considering the overall performance of the municipal WWTP, the optimized storage Case 2 is the most favorable storage-discharge investigated case. The lowest operational cost was achieved for the storage flow rate value of 35,349 m^3/day, planned to start at 2 p.m. and the value of 32,400 m^3/day discharge flow rate scheduled to start at 12 a.m. The air distribution along the aerated bioreactors was given by the ratios 3.01:2.43:1 and the obtained optimized recirculation factor k_{NR} was equal to 0.4579 and k_{RAS} was equal to 0.3956. The operational cost is reduced by 47.1%. The best effluent quality is obtained in the optimized storage Case 3. These results were obtained when the return activated sludge factor was changing daily and it led to the improvement of the effluent quality index by 32.3%.

A general sensitivity analysis, which assesses the performance of the proposed solution for the WWTP operating improvement, reveals that results are depending in a decreasing order of importance on the recirculation flow rates, the moments for scheduling the treatment and storage, the air distribution in the nitrification reactors and ammonia control, the energy tariffs and the nitrate control in the anoxic zone.

4. Discussion

The goal of the municipal WWTP is to secure the removal of carbon, nitrogen and phosphorus pollutants from the wastewater and to reduce the costs implied by spenfing the aeration and pumping energy. Saving part of the energy used at the WWTP brings not only economic benefits, but also reduces the associated environmental emissions.

In order to find the storage-treatment most favorable scheduling scheme, a first set of cases for constant wastewater storage and stored wastewater discharge flow rates was investigated. Following this study, it was concluded that with the increase of these flow rates, the effluent quality index slightly increases, but without violating the effluent constrains. Notably, the operational cost could be reduced by 23.1%, when the storage flow rate and the discharge flow rate were considered to have the value of 30,000 m^3/day. Noteworthy is that this first study revealed a minimum of the operational costs.

In a second set of investigated cases, the starting moment of time for wastewater storage and the starting moment of time for the stored water treatment were studied. It was observed that significant benefits showed up when the influent wastewater was stored during the daily periods of time corresponding to the maximum influent concentrations and maximum influent flow rates, i. e at 2 p.m., and the discharge was scheduled at midnight. The operation costs for the aeration and pumping energy were reduced by 23.6%, and the effluent quality was improved by 25.1%, compared to the operational performance of the municipal WWTP under study.

In the last set of the most complex investigated cases, energy costs and effluent quality minimization were analyzed. Improved solutions for the storage flow rate, air distribution in the three aerobic bioreactors, RAS and NR flow rates were found by optimization. The cost optimal results were achieved for the storage flow rate value of 35,349 m^3/day, planned to start at 2 p.m., and for the value of 32,400 m^3/day discharge flow rate, scheduled to start at 12 a.m. Reduction of the operation costs relative to the costs of the non-optimized operation of the municipal WWTP were significant, reaching 47.1%. This was the case when the k_{RAS} factor for the return activated sludge control was determined by daily optimization. Benefits for the effluent quality could be also observed. The optimized air flow rate distribution among the three aerated reactors was described by the ratios 3.01:2.43:1. The best storage case from the effluent quality index perspective was improved from 18,710.2 kg P.U./day to 12,661.3 kg P.U./day, while the operational cost was reduced from 1544.3 €/day to 949.4 €/day.

The results of the proposed influent flow rate storage and treatment scheduled operation, associated with the new control system, show benefits for the management of municipal WWTPs by promoting sustainability at the economic and environmental level. The achievement of improved WWTP sustainability is basically emerging form the enhanced and optimized distribution of the intrinsically periodic influent flow rate and more efficient control, therefore providing smoother operation of the entire plant. This better-balanced influent flow rate is implicitly associated to a more equalized influent pollutant load which also favorizes sustainability. The following sustainability benefits may be observed:

i) economic sustainability improvement is well proved by the reduction of the operation costs, mainly represented by the electricity costs for aeration and pumping. Nevertheless, the costs with the flocculants and long-term maintenance costs will also decrease due to the more uniform operation.
ii) environmental sustainability is enhanced on different paths. First, the WWTP effluent quality is superior, directly leading to the reduction of environmental impact on the emissary river and its eutrophication hazard. Second, the Green House Gases (GHG) emissions are reduced due to the carbon dioxide emissions associated to the spared electrical energy. The decrease is originating from the optimized aeration distribution among the nitrification reactors and the lesser pumping energy used for the transport of smaller quantities of wastewater (especially by the recirculation flows). It is also expected that other GHG emissions (such as N_2O) are reduced due to the decreased operation overshoot, as revealed by Bani Shahabadi et al. (2009). They may have direct impact on the global warming process and on leaching in the atmosphere of NO_x or NH_3 gases. Third, indirect effect on the renewable energy development may be also envisaged. They consist in the increased biogas production of the anaerobic digestion unit subsequent to the WWTP water line. Additionally, by reducing the WWTP effluent flow rate fluctuations, improved hydrological conditions may be satisfied for any downstream run-of-river hydropower plant energy production plant and for maintaining the ecologically safe environmental water flow.

The sustainability benefits are accompanied by favorable impact the proposed solution has on the WWTP management, especially due to the designed control system that provides increased safety and stability to the WWTP operation.

5. Conclusions

Scheduling the operation of the WWTP by temporary storage of the wastewater during day-time, followed by its subsequent processing at night-time and associating this procedure with efficient work of a specially designed control system proved sustainable WWTP management. The economic results and environmental considerations showed incentives for reducing operational costs by energy savings, keeping or improving the WWTP effluent quality and enhancing the environmental benefits. The best overall performance obtained in the case of the investigated municipal WWTP applying the proposed storage algorithm and its associated control system has the potential to reduce the operation cost by 47% and it may improve the effluent quality by 25%, when the influent wastewater was stored from 2 p.m. in the available tanks (day-time period) and the stored wastewater treatment started at 12 a.m. (night-time period). The presented storage and control algorithms reveal an efficient management alternative for every waste water treatment plant where storage capacity is available or can be developed either in the plant or in the upstream sewer system.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

CRediT authorship contribution statement

Melinda Simon-Várhelyi: Conceptualization, Methodology, Software, Formal analysis, Data curation, Writing - original draft. **Vasile Mircea Cristea:** Conceptualization, Methodology, Validation, Data curation, Writing - review & editing, Supervision. **Alexandra Veronica Luca:** Software, Data curation, Resources.

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Nomenclature

Abbreviations

A^2O	Anaerobic-Anoxic-Oxic
ABAC	Ammonia Based Aeration Control
AE	Aeration Energy
ASM1	Activated Sludge Model No. 1
BOD	Biochemical Oxygen Demand
BSM1	Benchmark Simulation Model No. 1
C_{AE}	Correction factor for calculating the aeration energy
C_{PE}	Correction factor for calculating the pumping energy
COD	Chemical Oxygen Demand
DO	Dissolved Oxygen
EQ	Effluent Quality
K_La	Mass transfer coefficient in the aerated bioreactor
k_{NR}	Coefficient for the nitrate recirculation flow rate
k_{RAS}	Coefficient for the return activated sludge flow rate
GHG	Green House Gases
NH	Free and saline ammonia
NO	Nitrates and nitrites
NR	Nitrate Recirculation
N_{total}	Total Nitrogen
PE	Pumping Energy
PU	Pollutant units
Q	Flow Rate
$Q_{air}(R3)$	$Q_{air}(R4)$:$Q_{air}(R5)$ Air distribution among the three aerobic bioreactors
$Q_{Effluent}$	Flow rate of the effluent cleared water
$Q_{Influent}$	Flow rate of the influent wastewater
Q_{NR}	Flow rate of the nitrate recirculation
Q_{RAS}	Flow rate of the return activated sludge
$Q_{strorage\_wastewater}$	Flow rate of the wastewater transportation from influent wastewater to storage tanks
$Q_{treat\_stored\_wastewater}$	Flow rate of the wastewater transportation from storage tanks to the primary settlers
Q_{waste}	Flow rate of waste from the secondary settlers
RAS	Return Activated Sludge
SCADA	Supervisory Control and Data Acquisition
SDG	Sustainable Development Goal
S_{NH}	Free and saline ammonia
S_{NO}	Nitrates and nitrites
SO_{sat}	Oxygen saturation concentration
T	Time, number of days for calculating the aeration and pumping energy
$time_{storage\_wastewater}$	Beginning of the influent wastewater storage period
$time_{treat\_stored\_wastewater}$	Start time of the stored wastewater treatment
TKN	Total Kjeldahl Nitrogen
TSS	Total Suspended Solids
$V_{bioreactor}$	Volume of the bioreactor
WWTP	Wastewater Treatment Plant
$y_{c\_NOcontroller}$	Control signal of the nitrate controller

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