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Full-scale modelling of a food industry wastewater treatment plant in view of process upgrade

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Abstract

A mathematical model for the aerobic part of a food industry wastewater treatment plant (WWTP) was developed and used to assess possible upgrade options. This aerobic part of the WWTP treats two streams. The direct stream is treated in an anaerobic reactor after pre-treatment. The bypass stream is sent directly from the production facility to the aerobic part of the WWTP, without anaerobic treatment. The plant upgrade consists of installing additional volume for nitrification and denitrification, a so-called post-denitrification.

An influent characterization translated the available influent measurements into data useful for modelling.

It was shown by simulations with the developed model that the physical plant upgrade will result in a 99% decrease in effluent ammonium concentration. In addition a 5% decrease in COD concentration was obtained. However, the effluent nitrate concentration and total nitrogen increased drastically because of the upgrade. Additional control actions, more specifically the increase of the bypass flow rate, were necessary for decreasing this effluent total nitrogen concentration. This was also demonstrated with the developed model.

Keywords: Food industry WWTP; ASM; Model based optimisation; Scenario analysis; Calibration

1. Introduction

Mathematical modelling of wastewater treatment processes is an elegant and cost-effective tool to study these treatment processes [1]. Modelling offers the possibility to investigate certain engineering questions without time-consuming and expensive laboratory tests.

Different goals exist when a wastewater treatment plant (WWTP) is modelled [2]. Simulations with WWTP models can in the first place be applied in different ways to increase process understanding. Brdjanovic et al. [3], for example, used a model for better understanding of full-scale biological phosphorus removal. Models can also be used to evaluate different design options. Salem et al. [4] for example used a model to evaluate different alternatives for the upgrade of a biological nitrogen removal plant.

Ladiges and Günner [5] used the ASM1 model [6] to examine the upgrade options for the municipal WWTPs of Hamburg (Germany). Van Hulle and Vanrolleghem [7] used an extended ASM1 model to model a chemical industry WWTP. First, an alternative plant lay-out was investigated. Further, a large set of possible production schedules in the chemical production site were simulated. This allowed predicting which schedules meet the effluent standards and which do not.

The study presented here tackles the model based optimisation of a food industry WWTP treating water coming from a frozen potato products producing enterprise located in West-Flanders, a province in Flanders, the Northern part of Belgium. This region is the European gravity point of the frozen food industry as 25% of all frozen food products in Europe are produced in the region. Further, the region is one of the most important potato producing regions in Europe.

The aim of the study was two-fold. First a reliable model of the aerobic part of the WWTP was developed. Second, the upgrade options of the aerobic part of the WWTP were investigated with the developed model, because the installation of additional reactor volume is planned to further decrease the pollutant discharge. As such, the aim of this study was to evaluate this WWTP extension and to obtain more insight in the WWTP operation.

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Nomenclature

ASM1 Activated Sludge Model nr. 1
$BCOD_{Bypass\ influent}$ total biodegradable COD in the bypass influent (mgBOD/l)
$BCOD_{Direct\ influent}$ total biodegradable COD in the direct influent (mgBOD/l)
BOD biological oxygen demand
$C_1, C_2, C_3, C_4, C_5, C_6$ constants used for influent characterization
COD chemical oxygen demand
$COD^{Filtered}_{Bypass\ influent}$ filtered COD concentration in the bypass influent (mgCOD/l)
$COD^{Total}_{Bypass\ influent}$ total COD concentration in the bypass influent (mgCOD/l)
$COD^{Centrifuged}_{Direct\ influent}$ COD concentration in the centrifuged influent (mgCOD/l)
$COD^{Filtered}_{Direct\ influent}$ filtered COD concentration in the direct influent (mgCOD/l)
$COD^{Total}_{Direct\ influent}$ total COD concentration in the direct influent (mgCOD/l)
$COD^{Filtered}_{Effluent}$ filtered COD concentration in the effluent (mgCOD/l)
$COD^{Total}_{Effluent}$ total COD concentration in the effluent (mgCOD/l)
DO dissolved oxygen (mgO_2/l)
f_{BOD} factor used to calculate the BCOD
f_{ns} non-settleable fraction of the biomass
K_{BOD} the first order rate constant of the organic matter degradation during the BOD test
S_I non-biodegradable, soluble fraction of the COD
S_{NH} ammonium concentration
S_{NO} nitrate concentration
S_S biodegradable, soluble fraction of the COD
SVI Sludge Volume Index (ml/l)
TIC Theil's inequality coefficient
WWTP wastewater treatment plant
X_I non-biodegradable, particulate fraction of the COD
X_S biodegradable, particulate fraction of the COD
y_i simulated data points
$y_{i,m}$ measured data points

2. Methods

2.1. Description of the WWTP

2.1.1. Existing design

The food industry WWTP treats on average 1550 m^3 of wastewater coming from the production facility per day. This wastewater is highly loaded with COD and ammonium. The COD content of the wastewater is mainly removed in an anaerobic UASB reactor, to which the wastewater is first send after pre-treatment (oil and grease skimmer, lamellar settling and flotation). The optimisation of the UASB reactor is not the goal of this study, as this study focuses on the optimisation of the aerobic part of the WWTP. After treatment in the UASB reactor the wastewater is sent to the aerobic part of the WWTP. This stream will further be denoted as the direct stream.

A bypass exists to make sure that wastewater can be send directly to the aerobic part of the WWTP after pre-treatment. This stream is identical to the stream that is sent to the UASB reactor and will further be denoted as the bypass stream. In the present operation schedule, on average 50 m^3/day is bypassed. The effect of varying this bypass flow rate will be investigated in this contribution.

Both streams, the direct stream and the bypass stream are mixed before entering the aerobic part of the WWTP. This aerobic part of the WWTP consists of parallel trains. The first train consist of two anoxic reactors, with a respective volume of 600 and 1000 m^3, put in series before an aerobic reactor with a volume of 3100 m^3. This aerobic reactor is operated with intermittent aeration: the aeration is put on for 5 h and the dissolved oxygen concentration (DO) is controlled at 3 mgO_2/l after which the aeration is put off for 5 h. Currently, about 40% of the influent flow is treated in this train. The second train was only started on day 405 (of 630, see further) of this study and consists of one anoxic reactor and one aerobic reactor, with respective volumes of 541 and 2700 m^3. After start-up this train, about 60% of the flow is treated in this train. In both trains an internal circulation exists from the aerobic reactor to the first anoxic reactor. The flow rate of this internal recycle is, respectively, 400 m^3/h for the first train and 250 m^3/h for the second train.

After the aerobic part of the WWTP the wastewater is sent to a secondary clarifier. The effluent of this clarifier is partly discharged after tertiary treatment and partly re-used in the production facility. In this tertiary treatment flocculant and coagulant is dosed to the waste stream after which the stream is sent to an additional settler. In this settler the additional formed sludge is separated from the effluent that will be discharged. The purpose of this tertiary treatment is the removal of phosphate and the further reduction of effluent COD.

The existing WWTP lay-out is presented schematically in Fig. 1 (top). The WWTP was implemented graphically in the modelling and simulation environment WEST® [8] (www.hemmis.com) as shown in Fig. 1 (bottom). In the figure return streams are indicated with dotted lines.

2.1.2. WWTP upgrade

The WWTP upgrade aims at increasing the WWTP capacity and treatment efficiency. The following modifications are planned. First, the two anoxic tanks of train 1 are combined to one reactor with a volume of 1600 m^3. Second, the volume of the aerobic tank in train 1 is increased to 3600 m^3. Third, the recycle flow rate in train 1 is increased from 400 to 1400 m^3/h. Fourth, the water coming from train 1 and train 2 is sent to an additional anoxic tank with a volume of 400 m^3 and an additional aerobic tank with a volume of 200 m^3 in which the DO is controlled at 3 mgO_2/l. The goal of installing this additional volume was to provide additional capacity for nitrification and denitrification in this so-called post-denitrification in order to increase ammonium and nitrate removal.

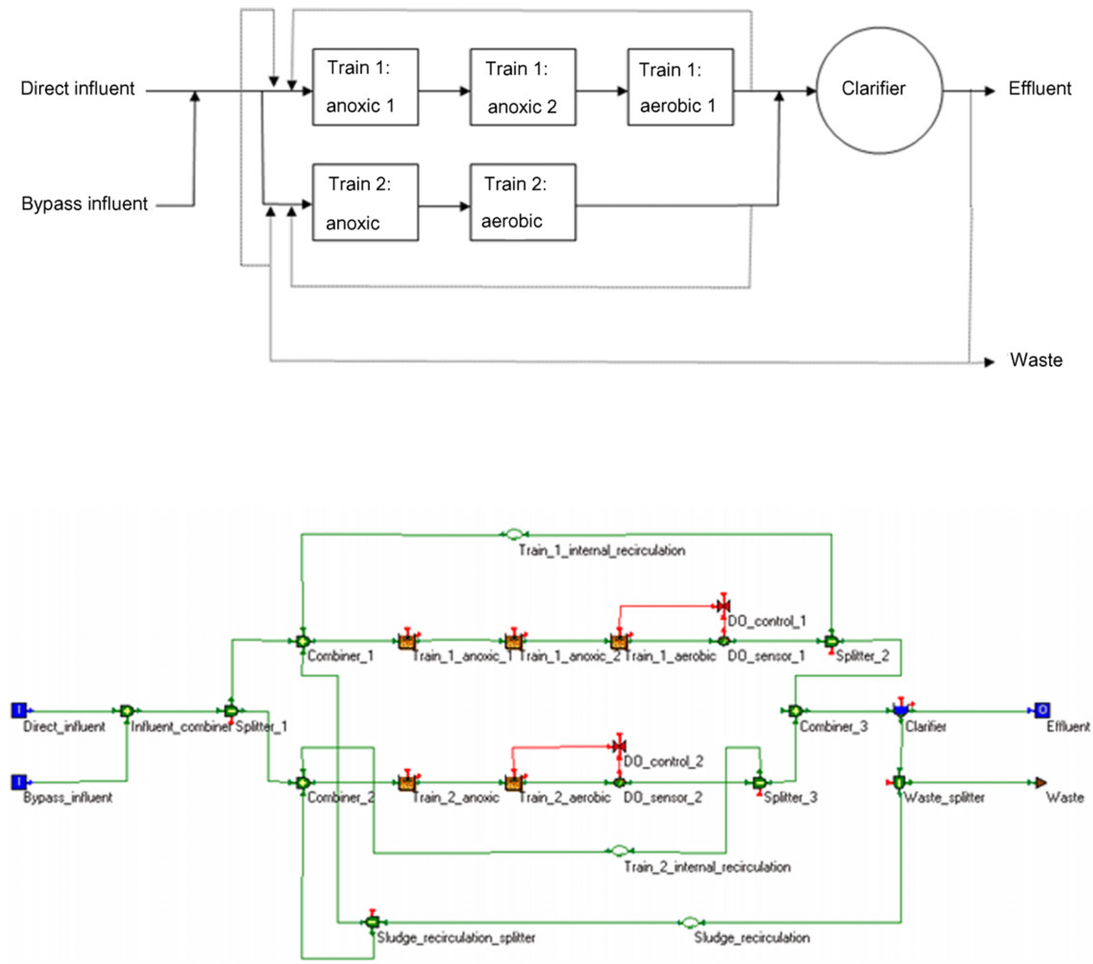

Fig. 1. The schematic lay-out of the WWTP under study (top) and the implementation in the modelling and simulation software WEST® (bottom).

Train 2 is left unchanged. The schematic representation of the upgraded WWTP is presented in Fig. 2 (top). This upgrade was implementation graphically in the modelling and simulation environment WEST® as shown in Fig. 2 (bottom). In the figure return streams are indicated with dotted lines.

2.2. WWTP modelling

The Activated Sludge Model nr. 1 [6] was chosen as the standard model for the description of bacterial growth and decay processes. The default values as proposed by Henze et al. [6] were used for the different kinetic and stoichiometric parameters. This is in contrast to several other studies such as Van Hulle and Vanrolleghem [7], where parameter values were adapted.

Temperature dependency of the biological reactions was not considered as the WWTP temperature does not vary significantly during the year because of the increased temperature of the wastewater coming from the production facility.

All the WWTP reactors were considered as completely mixed and are therefore modelled as completely stirred reactors (CSTR).

An ideal point settler with a non-settleable fraction of the biomass (f_{ns}) is considered as an appropriate model for the secondary settler, similar to the work of Van Hulle and Vanrolleghem [7]. The non-settleable fraction of the biomass (f_{ns}) was set to 0.5%.An almost 2-year long historic data-set (630 days) was made available by the plant operators for modelling and simulation purposes.

2.3. Influent characterization

Influent characterization is one of the dominant factors for the quality of model predictions [9]. This influent characterization consists of translating the data available in the WWTP to data that can be used in the model. For example, the total COD concentration, a value frequently measured in treatment facilities, needs to be divided into a biodegradable, soluble COD fraction (S_S), a non-biodegradable, soluble COD fraction (S_I), a biodegradable, particulate COD fraction (X_S) and a non-biodegradable, particulate COD fraction (X_I).

For the WWTP under study the available influent plant data is presented in Table 1. As such, the goal of the influent characterization is to translate this data into the variables used in the Activated Sludge Model nr. 1 [6], which are also presented in Table 1. Next to the influent data, also the effluent COD concentration was used for influent characterization, as proposed by [9].

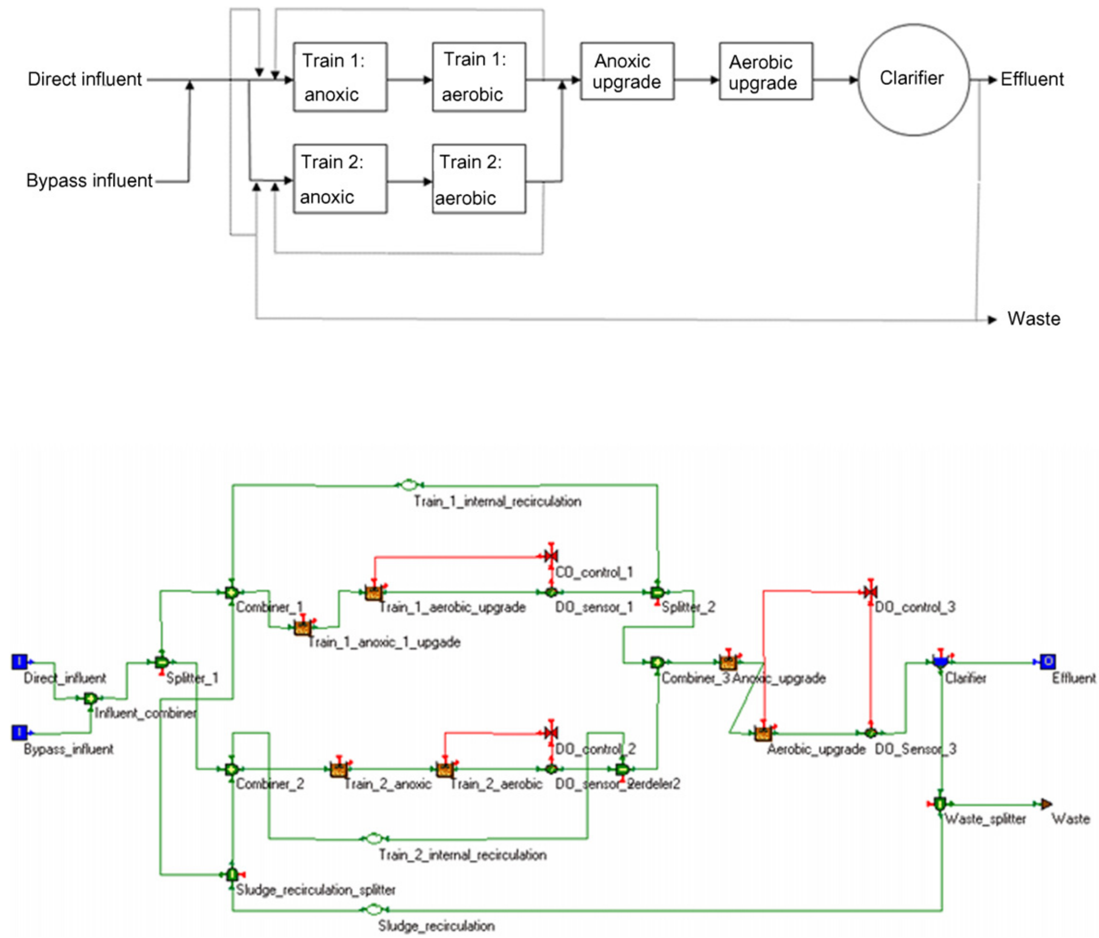

Fig. 2. The schematic lay-out of the upgraded WWTP (top) and the implementation in the modelling and simulation software WEST® (bottom).

The concentration of heterotrophic and autotrophic biomass was not included in the table because it was assumed that the concentration of active biomass was negligible in the influent. Also no organic nitrogen was considered in the influent, because the Kjeldahl nitrogen concentration measured during the measurement campaign almost equalled the ammonium concentration.

In this study influent characterization was supported by a 1-week measurement campaign. The influent characterization was based on the physical–chemical method [9], but instead of the proposed 0.1 μm filters, 0.45 μm filters were used. These filters are used to distinguish between soluble and particulate material. All material that passes through the filter is considered as soluble, while all material that is retained is considered as particulate.

In this measurement campaign six direct influent, six bypass influent and six effluent grab samples were analysed. The total influent COD concentration, the centrifuged influent COD concentration, the filtered influent COD concentration, the total effluent COD concentration, the centrifuged effluent COD concentration, the filtered effluent COD concentration and the SVI were measured. For four out of these six measurements also a BOD measurement was performed. All these measurements were necessary to characterize the influent as discussed below.

As two streams, the direct stream and the bypass stream, are treated together in the aerobic part of the plant it is difficult to use the proposed method directly. Hence, influent characterization was also based on operator experience.

Table 1
Available influent plant data and necessary ASM1 model variables

	Direct influent	Bypass influent	ASM variables
COD	Centrifuged COD ($COD^{Centrifuged}_{Direct\ influent}$)	Total COD ($COD^{Total}_{Bypass\ influent}$)	S_S
			S_I
			X_S
			X_I
N	Ammonium	Ammonium	S_{NH}
	Nitrate	Nitrate	S_{NO}
Other	Flow rate	Flow rate	Flow rate
	SVI		

2.3.1. Direct influent characterization

In the historic data-set only COD concentrations of influent samples that were centrifuged first are available. However for ASM modelling the total COD values needs to be assessed. In order to correlate total COD concentration and the centrifuged COD concentration the following relation was used as proposed by the plant operators:

$$\mathrm{COD}^{\mathrm{Total}}_{\mathrm{Direct\ influent}} = \mathrm{COD}^{\mathrm{Centrifuged}}_{\mathrm{Direct\ influent}} + C_1\,\mathrm{SVI} \tag{1}$$

where $\mathrm{COD}^{\mathrm{Total}}_{\mathrm{Direct\ influent}}$ is the total COD concentration in the influent, $\mathrm{COD}^{\mathrm{Centrifuged}}_{\mathrm{Direct\ influent}}$ the COD concentration in the centrifuged influent, SVI the influent Sludge Volume Index (ml/l), which is determined on a daily basis and C_1 is a constant.

The filtered influent concentration was correlated to the total influent concentration by the following equation:

$$\mathrm{COD}^{\mathrm{Filtered}}_{\mathrm{Direct\ influent}} = C_2(\mathrm{COD}^{\mathrm{Total}}_{\mathrm{Direct\ influent}} - C_1\,\mathrm{SVI}) \tag{2}$$

where $\mathrm{COD}^{\mathrm{Filtered}}_{\mathrm{Direct\ influent}}$ is the filtered COD concentration in the influent and C_2 is a constant.

The filtered effluent COD concentration was correlated with the total effluent COD by the following equation:

$$\mathrm{COD}^{\mathrm{Filtered}}_{\mathrm{Effluent}} = C_3\,\mathrm{COD}^{\mathrm{Total}}_{\mathrm{Effluent}} \tag{3}$$

where $\mathrm{COD}^{\mathrm{Filtered}}_{\mathrm{Effluent}}$ is the filtered COD concentration in the effluent, $\mathrm{COD}^{\mathrm{Total}}_{\mathrm{Effluent}}$ the total COD concentration in the effluent and C_3 is a constant.

The total biodegradable COD (BCOD) in the influent was determined from a BOD_{20} test. From such a test the total BOD ($\mathrm{BOD}_{\mathrm{tot}}$) of the wastewater can be calculated by the following equation:

$$\mathrm{BOD}_{\mathrm{tot}} = \frac{1}{1-\mathrm{e}^{-K_{\mathrm{BOD}}t}}\mathrm{BOD}_t \tag{4}$$

where K_{BOD} is the first order rate constant of the organic matter degradation during the BOD test and BOD_t is the evolution of the BOD over time.

During the BOD measurement there is an interaction of growth and decay of biomass, which resulted in the conversion of a part of the biodegradable COD into an inert fraction in long-term BOD measurement. Therefore, a correction factor f_{BOD} (0.15) was used to calculate the BCOD (Eq. (5)):

$$\mathrm{BCOD} = \frac{1}{1-f_{\mathrm{BOD}}}\mathrm{BOD}_{\mathrm{tot}} \tag{5}$$

The following equation was used to correlate the total influent COD concentration and the total biodegradable COD (BCOD) in the influent:

$$\mathrm{BCOD}_{\mathrm{Direct\ influent}} = C_4\,\mathrm{COD}^{\mathrm{Total}}_{\mathrm{Direct\ influent}} \tag{6}$$

where C_4 is a constant.

Based on Eqs. (1)–(6) the division of the total COD concentration into S_{S}, S_{I}, X_{S} and X_{I} can be performed according to [10]:

$$S_{\mathrm{I}} = 0.9 \times \mathrm{COD}^{\mathrm{Filtered}}_{\mathrm{Effluent}} \tag{7}$$

$$S_{\mathrm{S}} = \mathrm{COD}^{\mathrm{Filtered}}_{\mathrm{Direct\ influent}} - S_{\mathrm{I}} \tag{8}$$

$$X_{\mathrm{S}} = \mathrm{BCOD}_{\mathrm{Direct\ influent}} - S_{\mathrm{S}} \tag{9}$$

$$X_{\mathrm{I}} = \mathrm{COD}^{\mathrm{Total}}_{\mathrm{Direct\ influent}} - S_{\mathrm{S}} - S_{\mathrm{I}} - X_{\mathrm{S}} \tag{10}$$

2.3.2. Bypass influent characterization

Values for the total influent COD concentrations of the bypass influent ($\mathrm{COD}^{\mathrm{Total}}_{\mathrm{Bypass\ influent}}$) were available in the historic data-set, in contrast to the direct influent. The filtered influent concentration was again correlated to the total influent concentration by the following equation:

$$\mathrm{COD}^{\mathrm{Filtered}}_{\mathrm{Bypass\ influent}} = C_5\,\mathrm{COD}^{\mathrm{Total}}_{\mathrm{Bypass\ influent}} \tag{11}$$

where $\mathrm{COD}^{\mathrm{Filtered}}_{\mathrm{Bypass\ influent}}$ is the filtered COD concentration in the bypass influent and C_5 is a constant.

The total biodegradable COD (BCOD) in the bypass influent was determined again from a BOD_{20} test similar to the direct influent. From the measurement campaign a correlation between the total influent COD concentration and the total biodegradable COD (BCOD) in the influent was established:

$$\mathrm{BCOD}_{\mathrm{Bypass\ influent}} = C_6\,\mathrm{COD}^{\mathrm{Total}}_{\mathrm{Bypass\ influent}} \tag{12}$$

where C_6 is a constant.

The effluent COD concentration of the wastewater treatment plant was not used for characterization of the bypass influent as the bypass influent flow is too low (50 m^3/day) compared to the total influent flow. As such the contribution of the bypass stream is not high enough. Hence additional data needs to be collected for further characterization of the bypass influent. This was done by estimating the X_{S} concentration in the bypass influent. Behaviour of the WWTP was simulated based on the initial 30 days of the historic data-set. The X_{S} concentration that yielded the best agreement between the measured and simulated data was 1000 mgCOD/l and hence this value was selected.

Based on Eqs. (11) and (12) and the fact that the X_{S} concentration was estimated to be 1000 mgCOD/l the division of the total COD concentration into S_{S}, S_{I}, X_{S} and X_{I} can be performed for the bypass influent, similar to the direct influent:

$$X_{\mathrm{S}} = 1000\,\mathrm{mgCOD/l} \tag{13}$$

$$S_{\mathrm{S}} = \mathrm{BCOD}_{\mathrm{Bypass\ influent}} - X_{\mathrm{S}} \tag{14}$$

$$S_{\mathrm{I}} = \mathrm{COD}^{\mathrm{Filtered}}_{\mathrm{Bypass\ effluent}} - S_{\mathrm{S}} \tag{15}$$

$$X_{\mathrm{I}} = \mathrm{COD}^{\mathrm{Total}}_{\mathrm{Bypass\ influent}} - S_{\mathrm{S}} - S_{\mathrm{I}} - X_{\mathrm{S}} \tag{16}$$

Daily measurements of the influent flow rate as well as the influent ammonium concentration are available in the historic data-set. Several grab samples revealed that the influent nitrate concentration was also on average 2 mgN/l, while no nitrite was detected. Hence for the flow rate and the nitrogen components no additional measurements were necessary.

2.4. Chemical analyses

All chemical analyses, COD concentration, BOD_{20} concentration, ammonium concentration, nitrate concentration, oxygen concentration and Sludge Volume Index (SVI) were performed according to standard methods [10].

3. Results and discussion

3.1. Influent characterization

Several correlations between values available in the data-set and data necessary for the ASM1 model were established during the measurement campaign. These correlations allowed calculation of the data necessary for the ASM1 model from the values available in the 630-day data-set.

In Fig. 3 the influent flow rate, the total influent COD concentration, the influent SVI and the influent ammonium concentration of the direct influent are depicted together with the total effluent COD concentration. In Fig. 4 the influent flow rate, the total influent COD concentration and the influent ammonium concentration of the bypass influent are depicted.

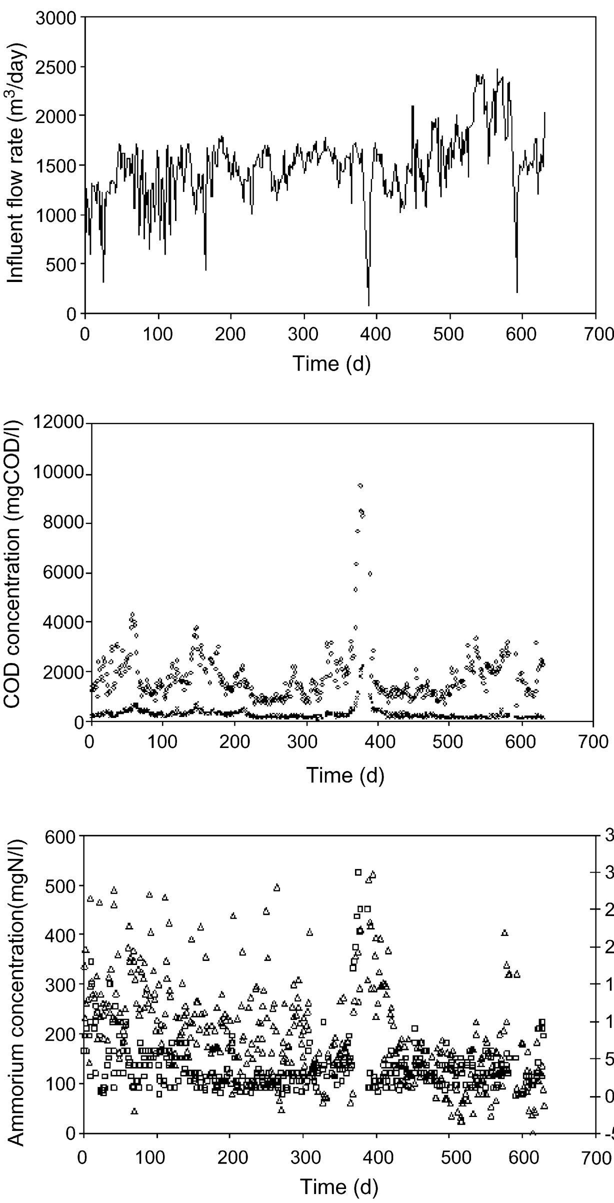

Fig. 3. The influent flow rate (top, -), the total influent COD concentration (middle, ◊), the influent SVI (bottom, □) and the influent ammonium concentration (bottom, △) of the direct influent and the total effluent COD concentration (middle, ×).

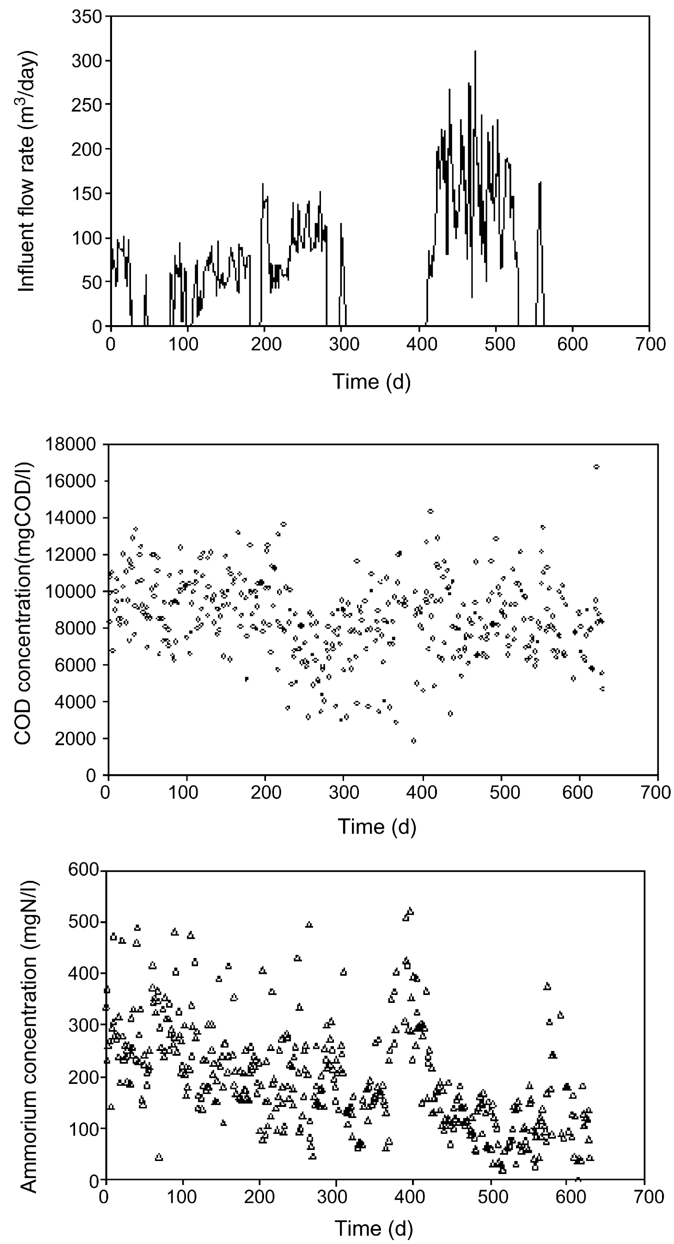

Fig. 4. The influent flow rate (top, -), the total influent COD concentration (middle, ◊) and the influent ammonium concentration (bottom, △) of the bypass influent.

3.1.1. Direct influent characterization

Table 2 lists the constants that were determined during the measurement campaign for the characterization of the direct influent. The values listed for the constants were calculated as an average for the six measurements.

From this analysis it was determined that about 75% of the total COD concentration was biodegradable and soluble (S_S), about 6% was non-biodegradable and soluble (S_I), about 13% was biodegradable and particulate (X_S) and about 6% was non-biodegradable and particulate (X_I).

Table 2
Direct influent characterization constants

Constant	Unit	Value (±S.D.)
C_1	mgCOD/ml	10.05 ± 0.31
C_2	–	0.69 ± 0.05
C_3	–	0.95 ± 0.02
C_4	–	0.88 ± 0.07
BOD_{tot}	mgCOD/l	1782 ± 111
K_{BOD}	day^{-1}	0.21 ± 0.03

3.1.2. Bypass influent characterization

Table 3 lists the constants that were determined during the measurement campaign for the characterization of the bypass influent. The values listed for the constants were calculated as an average for the six measurements.

From this analysis it was determined that about 36% of the total COD concentration was biodegradable and soluble (S_S), about 15% was non-biodegradable and soluble (S_I), about 48% was biodegradable and particulate (X_S) and about 1% was non-biodegradable and particulate (X_I).

3.2. Simulation of the current situation

The developed model was used to simulate the behaviour of the current plant lay-out (Fig. 1). In Fig. 5 the measured and calculated COD concentrations in the aerobic reactors of both WWTP trains is depicted. In Fig. 6 the measured and calculated nitrate concentrations in the aerobic reactor of the first WWTP train is depicted. It can be seen that an excellent agreement exists between measured and calculated values.

In Fig. 7 measured effluent COD and nitrate concentration are compared with simulated data. Again an excellent agreement is obtained. This is however not the case for the effluent ammonium concentration because of the low measurement frequency compared to the dynamics of the production facility and the WWTP (Fig. 8).

Calculated effluent suspended solids concentration was on average 15 mg/l, which is very similar to the measured value (data not shown). The suspended solids discharge limit was not violated during the 630-day period.

The goodness-of-fit of the simulations was further quantified by calculating Theil's inequality coefficient (TIC [11]), which is expressed as follows:

$$\mathrm{TIC} = \frac{\sqrt{\sum_i (y_i - y_{i,\mathrm{m}})^2}}{\sqrt{\sum_i y_i^2} + \sqrt{\sum_i y_{i,\mathrm{m}}^2}} \quad (17)$$

Table 3
Bypass influent characterization constants

Constant	Unit	Value (±S.D.)
C_5	–	0.78 ± 0.06
C_6	–	0.85 ± 0.06
BOD_{tot}	mgCOD/l	4682 ± 1086
K_{BOD}	day^{-1}	0.59 ± 0.11

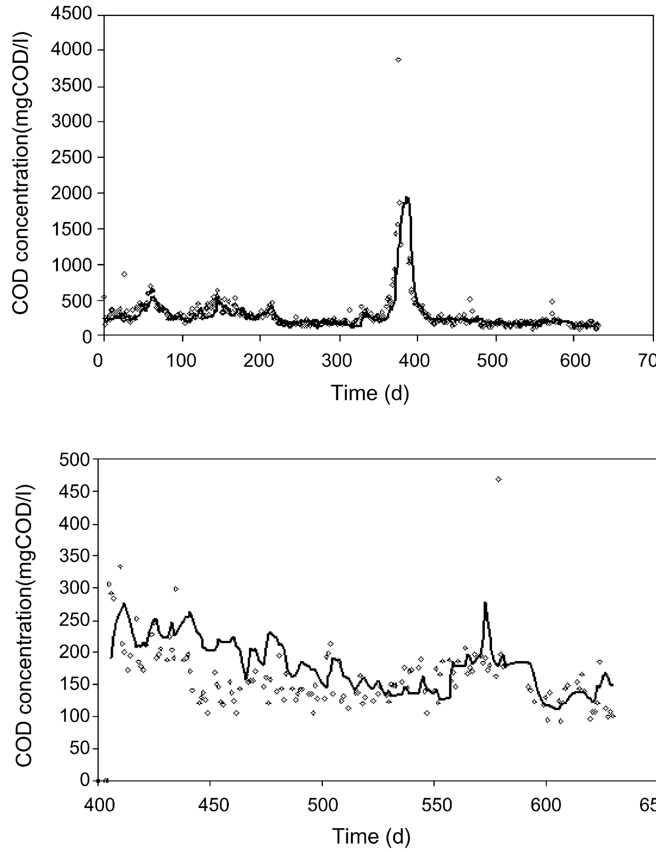

Fig. 5. Comparison between the measured (◇) and calculated COD (-) concentration in the aerobic reactors of both WWTP trains (top: train 1; bottom: train 2).

where y_i represents the simulated data points and $y_{i,\mathrm{m}}$ representing the measured data points.

For the data available in this study a TIC value of 0.23 was calculated. A value of the TIC lower than 0.3 indicates a good agreement with measured data [12]. As such, the simulations demonstrate the developed model describes the behaviour of the WWTP properly and thus this model can be used for further scenario and upgrade analysis.

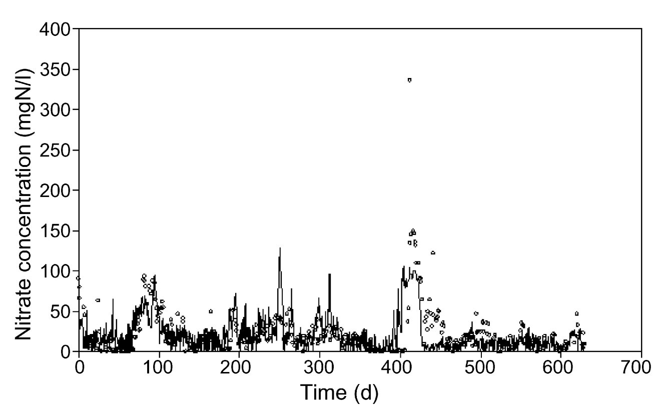

Fig. 6. Comparison between the measured (◯) and calculated (-) nitrate concentration in the aerobic reactor of train 1.

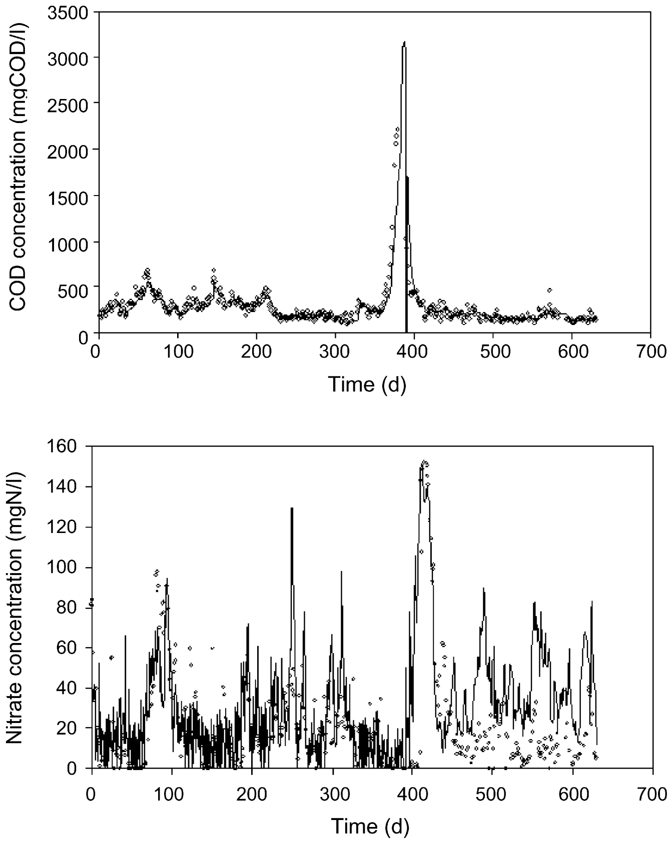

Fig. 7. Comparison between the calculated (-) and measured COD (◇, top) and nitrate (◯, bottom) effluent concentration.

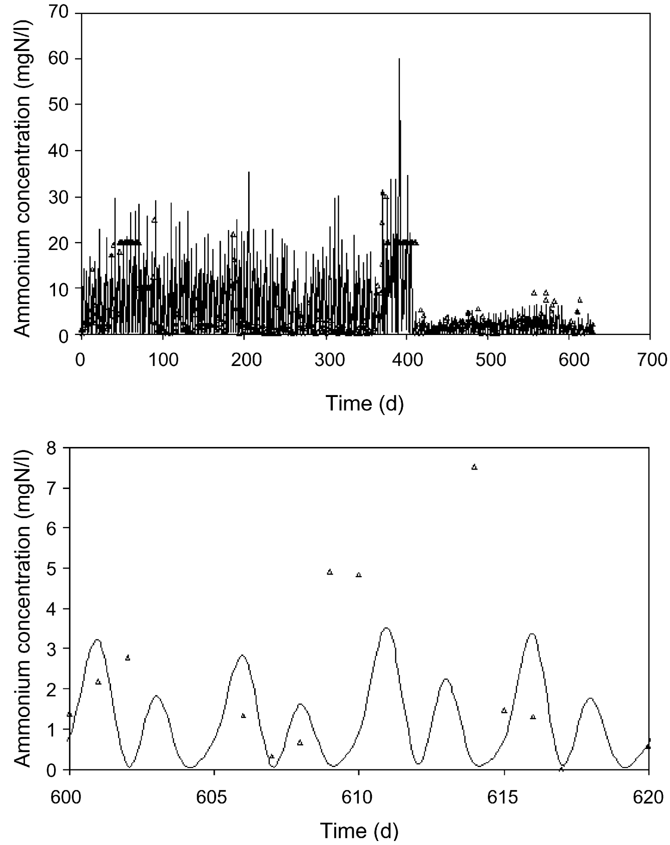

Fig. 8. Comparison between the calculated (-) and measured (△) ammonium effluent concentration during the complete period of the historic data-set (top) and comparison between the measured and calculated ammonium effluent concentration in the period from days 600 to 620 (bottom).

3.3. WWTP upgrade assessment

The performance of the upgraded WWTP was assessed by means of simulation. First, the performance of the WWTP was evaluated in case the operation of the WWTP remained unchanged, with the exception of the above discussed upgrades. Table 4 lists the relative change effluent COD, ammonium, nitrate and total nitrogen concentration.

From this table it can be seen that a small improvement in COD removal is obtained with the WWTP upgrade. A decrease of 5% is attained.

The larger volume available for nitrification results in a drastic decrease in effluent ammonium concentration. Both the effluent nitrate concentration and the total nitrogen concentration are increased, although the recycle flow rate in train 1 is tripled. This increase in recycle flow rate would normally lead to an increase in denitrification. From this simulation it can be concluded that simply upgrading the WWTP is not a guarantee for decreased effluent concentrations. Additional control actions will be necessary.

Table 4
Relative change in average effluent concentration (+: increase; −: decrease)

Component	Change (%)
COD	−5
Ammonium	−99.9
Nitrate	+121
Total nitrogen	+86

From a detailed analysis of the simulation results it became clear that the amount of biodegradable COD was not sufficient for complete denitrification. One way of dealing with this is increasing the bypass stream as this stream has a high COD content. However, it is to be expected that an increase in COD load to the WWTP will also result in a COD effluent concentration increase as not all the COD can be treated. This study identified which effect, an increase in denitrification or a decrease in COD removal will have the most impact.

Two different scenarios were analysed. In scenario 1 an increased production is simulated as the bypass flow is increased with 50, 100, 150 and 200 m^3/day, while the direct flow rate is kept constant. In scenario 2 a constant production is simulated. The bypass flow is increased with 50, 100, 150 and 200 m^3/day and the direct flow rate is decreased in such a way that the total influent stays constant. Results from simulations with these two scenarios are summarized in Table 5. In Table 5 the relative change in effluent COD, ammonium, nitrate and total nitrogen concentration is listed compared to the original WWTP lay-out.

It can be seen from Table 5 that increasing the bypass flow rate has a positive effect on nitrogen removal on the condition that the bypass flow rate, and consequentially the COD loading,

Table 5
Relative change in average effluent concentration when bypass flow is increased (+: increase; −: decrease)

Additional bypass flow rate (m^3/day)	Change (%)			
	COD	Ammonium	Nitrate	Total nitrogen
Scenario 1				
50	3.9	−98.9	55.6	31.6
100	6.8	−98.8	7.8	−8.4
150	9.5	−98.6	−24.3	−34.8
200	12.1	−98.5	−44.7	−51.8
Scenario 2				
50	3.1	−98.9	50.0	26.8
100	6.1	−98.8	−4	−17.9
150	8.9	−98.6	−38.8	−47.2
200	12.3	−98.5	−60.5	−65.1

is higher than 100 m^3/day. However, as predicted, the increase in COD loading also results in an effluent COD concentration increase. The total nitrogen discharge limit (15 mgN/l) is much more stringent than the COD discharge limit (200 mgCOD/l). Further, the tertiary treatment, which is not studied here, further reduces the effluent COD concentration making sure that the COD discharge limit is not violated in the final WWTP effluent. This was confirmed by measurements performed by the Flemish government (www.vmm.be). Indeed, the COD concentration in the effluent of the aerobic part of the WWTP was on average 287 mgCOD/l during the period of this study, while the COD concentration after tertiary treatment was on average 119 mgCOD/l. Also at no point in time during the study was the discharge limit violated.

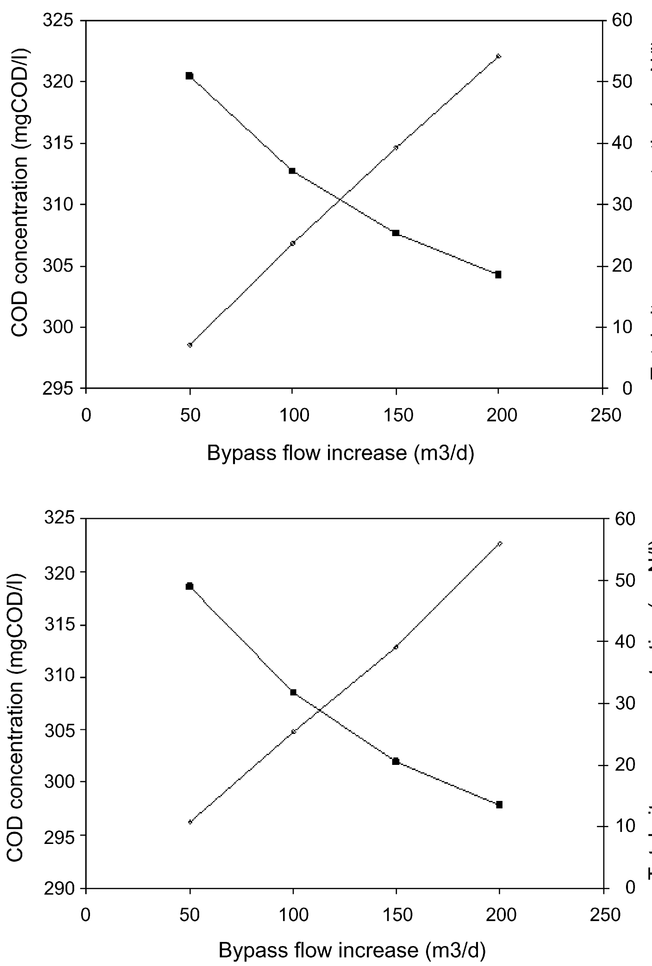

Fig. 9. Decrease in average total nitrogen concentration (■) compared to increase in average COD concentration (◊) resulting from a bypass flow rate increase (top: scenario 1; bottom: scenario: 2).

As such, an increased effluent COD concentration in the effluent of the aerobic part of the WWTP is preferred over an increased effluent nitrogen concentration as a 60–65% decrease of total nitrogen concentration can be obtained with only a 12% increase in COD concentration. At an increased bypass flow rate of 200 m^3/day the total nitrogen discharge limit is even reached by the average effluent concentration. This is illustrated in Fig. 9 where the average effluent COD and total nitrogen concentration are depicted as function of the increase in bypass flow rate. As such, the combination of an upgraded WWTP with the control of the bypass flow rate yields an improved operation of the WWTP.

4. Conclusions

A mathematical model was constructed and used to assess the upgrade of an industrial WWTP.

Before simulations with the model were performed a detailed characterization of these influent streams was performed. This characterization translated the influent measurements available in the plant to data useful for modelling. More specifically, the total COD concentration was divided into a biodegradable, soluble COD fraction (S_S), a non-biodegradable, soluble COD fraction (S_I), a biodegradable, particulate COD fraction (X_S) and a non-biodegradable, particulate COD fraction (X_I). For the direct influent it was determined that 75% of the total COD concentration was biodegradable and soluble, 6% was non-biodegradable and soluble, 13% was biodegradable and particulate and 6% was non-biodegradable and particulate. For the bypass stream it was determined that 36% of the total COD concentration was biodegradable and soluble, 15% was non-biodegradable and soluble, 48% was biodegradable and particulate and 1% was non-biodegradable and particulate.

Based on simulations with the developed model it could be predicted that the physical plant upgrade, i.e. the building of additional reactor volume which improves nitrogen removal, will results in a 99% decrease in effluent ammonium concentration. Ammonium is a component of environmental concern in view of its role in eutrophication, i.e. undesirable growth of aquatic plants and algae and its toxicity to aquatic organisms. In addition a 5% decrease in COD concentration was obtained. However the effluent nitrate concentration, and consequentially the effluent total nitrogen concentration, increased drastically because of the upgrade.

Additional control possibilities which should result in a decrease of effluent total nitrogen concentration were investigated. It was demonstrated with the mathematical model that increasing the bypass flow rate, and consequentially increasing the COD load to the reactor, will result in a substantial decrease of effluent total nitrogen concentration. This increased COD load also resulted in an increased effluent COD concentration, but this increase was not in proportion with the decrease in total nitrogen concentration. Further additional, tertiary treatment ensures the removal of this additional COD content.

It can be concluded that by combination a physical WWTP upgrade and additional flow control the performance of the WWTP can be increased. This performance increase was clearly assessed with a mathematical model.

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