Optimisation of a large WWTP thanks to mathematical modelling

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Abstract Better controlling and optimising the plant's processes has become a priority for WWTP (Wastewater Treatment Plant) managers. The main objective of this project is to develop a simplified mathematical tool able to reproduce and anticipate the behaviour of the Tougas WWTP (Nantes, France). This tool is aimed to be used directly by the managers of the site. The mathematical WWTP model was created using the software WEST®. This paper describes the studied site and the modelling results obtained during the stage of the model calibration and validation. The good simulation results have allowed to show that despite a first very simple description of the WWTP, the model was able to correctly predict the nitrogen composition (ammonia and nitrate) of the effluent and the daily sludge extraction. Then, a second more detailed configuration of the WWTP was implemented. It has allowed to independently study the behaviour of each of four biological trains. Once this first stage will be completely achieved, the remainder of the study will focus on the operational use of a simplified simulator with the purpose of optimising the Tougas WWTP operation.

Keywords Activated sludge process; calibration; modelling; optimisation; WWTP management

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Introduction

The more and more strict standards for treatment plant effluents require better process control. The use of mathematical models is also crucial to elaborate optimised management strategies. The major aims of the control options in WWTPs can be summarised as follows (Schütze *et al.*, 2002):

- Avoiding discharge of biomass into the effluent.
- Maintaining performance of the plant processes.
- Meeting the overflow discharge and effluent standards.
- Minimisation of operation and maintenance costs.

It is within this framework that a study started in Nantes (Pays de la Loire, France) in 2002, in partnership with Anjou-Recherche, Générale des Eaux and Loire 21. The objective is to develop a model able to predict and optimise the operation of the biological treatment train. This tool will become integrated in a global methodology of process control.

This project is divided into two stages. The first part consists of calibrating and validating the WWTP model with in-situ measurements. The second part aims at developing a simplified tool on top of an advanced simulator, like WEST®, especially made for operational use. This paper presents the simulation results and the conclusions of the first stage.

Materials and methods

Site description

The Tougas WWTP in Nantes was built in 1998. This activated sludge treatment plant receives the wastewater of approximately 600,000 inhabitant equivalents from a combined sewer system. It is an extended aeration plant with both biological nitrogen and phosphorus removal. A schematic overview of the Tougas WWTP is shown in Figure 1.

The maximal flow from the sewer networks that can be accepted by the WWTP is 6 m^3/s. Above this value, a bypass discharges flows directly in the river La Loire. At the same time, the biological train cannot treat more than 3 m^3/s. The surplus is stored in three storm tanks (total volume of approximately 20,000 m^3) to be released later when the hydraulic peak has passed. Next, the Tougas WWTP consists of a coarse and fine grit, sand removal, grease removal, seven anaerobic tanks (total volume of 28,000 m^3), seven oxidation ditches (total volume of 91,000 m^3), four basins of degassing-distribution, seven secondary settlers (diameter: 53 m; working height: 3.8 m) and a combined outlet in the river La Loire. Each biological train runs by couple, except for the G train.

Nitrification and denitrification processes take place in the same basin. The aeration system is made up of two turbo-compressors and ten ramps of fine bubble diffusers per ditch. It is controlled by a redox potential (ORP) measurement. Each oxidation ditch is equipped with three sensors (dissolved oxygen (DO), ORP and total suspended solids (TSS) sensors). The return of activated sludge (RAS) to the anaerobic tanks is fundamental for a good operation of the activated sludge process. The applied method in this WWTP consists of relating the RAS to the clarifier outflow rate by a constant factor. In this case, the RAS rate is increased with increasing flow. The goal of the control action is to maintain the sludge concentration in the oxidation ditches, which is about 4 g TSS/l, of which about 70% is organic. The pumping of waste activated sludge (WAS) is controlled by a clock. By increasing the waste activated sludge, settling limitations may be overcome, but at the same time, the biological performance may be affected. The effluent has to respect the following legal limits: 30 mg/l of TSS, 25 mg/l of BOD, 90 mg/l of COD, 20 mg/l of TN and 5 mg/l of NH_4-N. The yearly percentage of biological phosphorus removal must be at least 50%. These characteristics have to be respected 95% of the time in accordance with the French Regulation.

Mechanistic model description and simulation procedure

The mathematical model was created using the software WEST® (Hemmis, 2002). The modelling and simulation package WEST® provides the modeller with a user-friendly platform to use existing models or to implement and test new models (Vanhooren *et al.*, 2002). The treatment plant has been modelled using an extended ASM1-model (Henze *et al.*, 1986), for the activated sludge conversion part, while the settling model of Takács *et al.* (1991) was used to describe the behaviour of clarifiers. This extended ASM1-model was developed by Anjou-Recherche (Lesouëf, 1990) and recently implemented in the WEST®

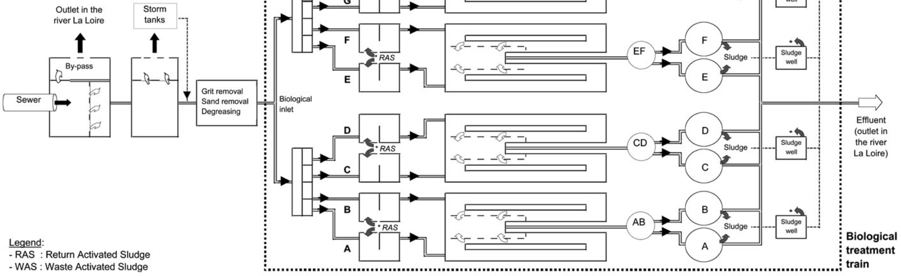

Figure 1 A schematic overview of the Tougas WWTP

environment (Printemps *et al.*, 2002). Its main strength is to take into account a specific fractionation of TSS and a process of mineral TSS dissolution, which allow to correctly reproduce sludge production. The effect of water temperature on kinetics and the effect of a low alkalinity concentration on nitrification were also integrated. Note that this model is not able to describe biological phosphorus removal.

The first step in the simulation procedure is to simulate the system under study to steady state using an influent of constant flow and composition. This ensures a consistent starting point and should eliminate the influence of starting conditions (Copp, 2002). Then, starting from the steady state solution, a dynamic simulation using an influent of hourly flow and composition can be carried out. Two Tougas WWTP models were implemented in WEST®. The first one is a very simple description of the WWTP (see Figure 2). The aim is to compare the WEST® results with those calculated by the software SIMBA/SIMBAD (Lesouëf, 1990), which does not allow to build a configuration with several parallel trains. The second more detailed plant model has then been built in order to increase the precision of the predictions.

The first Tougas WWTP model

The seven biological treatment trains have been summarised in one train. The activated sludge unit (ASU) No 1 constitutes the anaerobic zone and the four following units are the aerated basins. ASU3 and ASU5 are aerated, in contrast to ASU2 and ASU4. The goal of this description is to take into account the aeration ramps distribution within the tanks (see Figure 3). We judged that the anoxic zone represented about 10% of the total volume. The DO concentrations of the aerated basins are regulated using two PI-controllers. A nitrate return loop has been implemented in the WWTP model with the purpose of reproducing the circulation within the aerated ditches. A ratio control of 10 was chosen. This high number indicates good mixing. The clarifier was controlled using the actual measurements of the RAS flow, the WAS flow and the sludge volume index (SVI). A daily sample is taken for each train and analysed for SVI.

The measurement campaign

The WWTP model was mainly calibrated and then validated on the basis of a measurement campaign, which was performed between May 3, 2002 and July 31, 2002 at the Tougas WWTP, with the aim of completing the analyses of self monitoring. Daily composite samples were taken at the WWTP inlet and analysed for dissolved COD and VSS (Volatile Suspended Solids). To follow continuously the ammonia and nitrate concentrations in the combined outlet, two on-line analysers were placed during the measurement campaign. At the same time, a second DO sensor was installed in the G ditch in order to study the oxygen distribution in the basin. Figure 3 shows the distribution of aeration ramps, the position of both DO sensors in the G ditch and the DO measurements obtained between June 17 and 23,

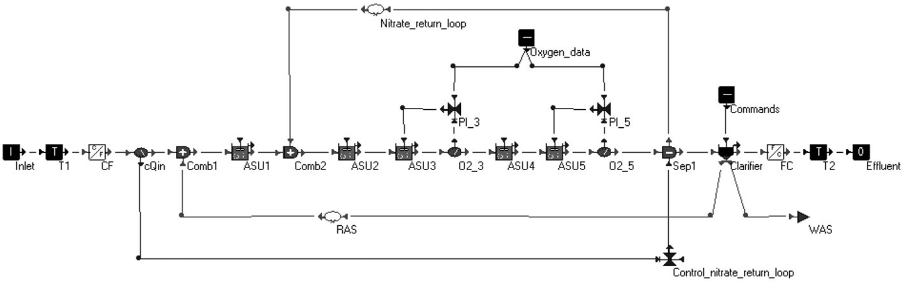

Figure 2 First WEST® implementation of the Tougas WWTP

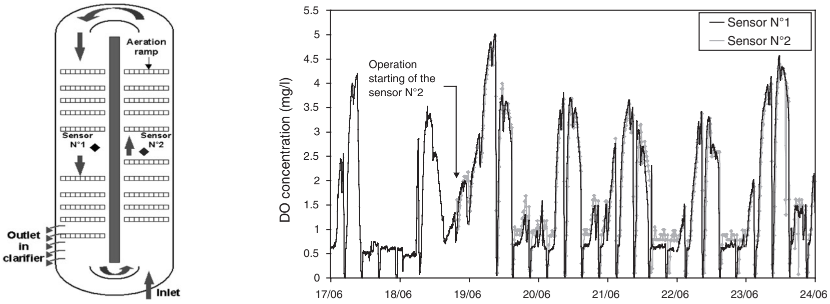

Figure 3 Measurements of the dissolved oxygen concentration in the G oxidation ditch

2002. Similar values were measured on both DO sensors along this period. Only a few differences can be observed for the lowest concentrations (0.5 to 1.0 mg/l). Thus, we have applied the same setpoint values of DO concentration in ASU3 and ASU5.

Results and discussion

Calibration stage

The calibration and validation stage mainly focused on the nitrogen composition of the combined outlet and the sludge quantity extracted for sludge treatment. The WWTP model was calibrated with the data set of May 3 to 19, 2002. The results obtained on nitrogen pollutant emissions are presented in Figures 4 and 5. A large difference between the ammonia concentrations measured with the on-line analyser, and those measured with the self monitoring can be observed, while there is a good reproducibility of the nitrate data. The model

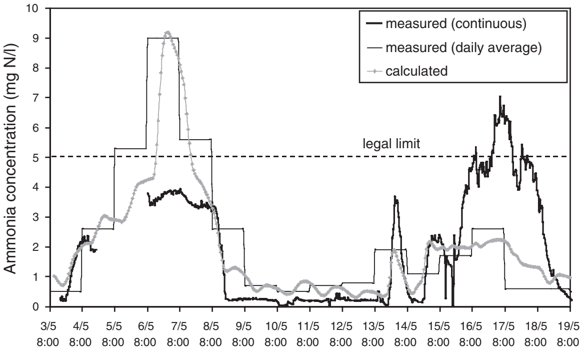

Figure 4 Calibration – May 3 to 19, 2002

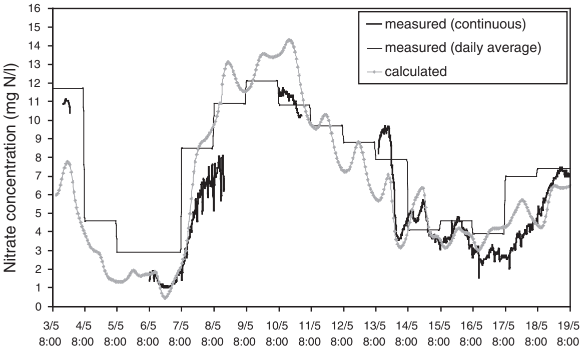

Figure 5 Calibration – May 3 to 19, 2002

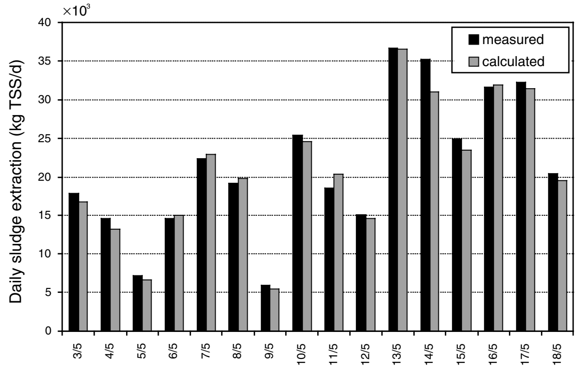

Figure 6 Calibration – May 3 to 18, 2002

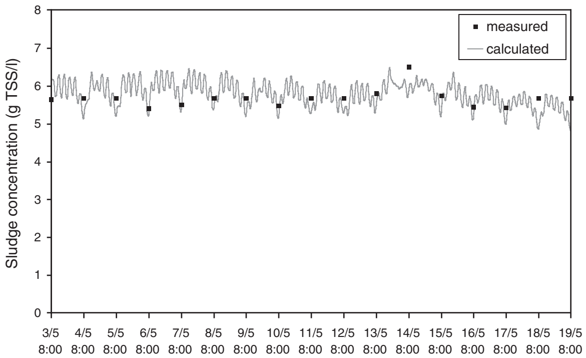

Figure 7 Calibration – May 3 to 19, 2002

was calibrated taking mainly into account the daily average of the ammonia concentration and the continuous nitrate measurement.

Even if the use of on-line analysers can be sometimes a complex operation, the continuous measurement is so important for the calibration of a model that it appears essential. Figures 6 and 7 show the results obtained concerning the daily extracted sludge masses and the TSS concentration of return activated sludge. Similar for the ammonia and nitrate concentrations of the effluent, the simulation follows the data set.

Validation stage

The WWTP model was then validated with the data set of June and July, 2002. All results were calculated with the set of parameters determined at the end of the calibration stage. The results obtained on nitrogen pollutant emissions are shown in Figures 8 to 11.

These simulation results show that a correctly calibrated and validated WWTP model is able to supply good predictions concerning the evolution of the effluent nitrogen composition. The use of a simulation tool seems also to be very interesting for the WWTP managers. For example, it could be used to predict how to optimise the biological treatment in order to limit the ammonia peaks and to avoid violation of the effluent standards.

Figures 12 and 13 show the results obtained concerning the daily sludge extractions. No sludge was extracted from the secondary clarifiers on June 22, June 30 and July 6, 2002. The measured and calculated monthly extracted masses are shown in Table 1. These calculations do not take into account the values of May 1 and 2, 2002. The daily average error between simulation and measurement data is less than 6%. This prediction constitutes interesting information, which could be used to better manage the sludge treatment of the WWTP.

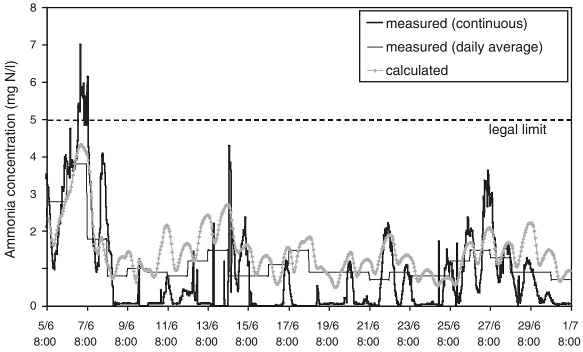

Figure 8 Validation – June, 2002

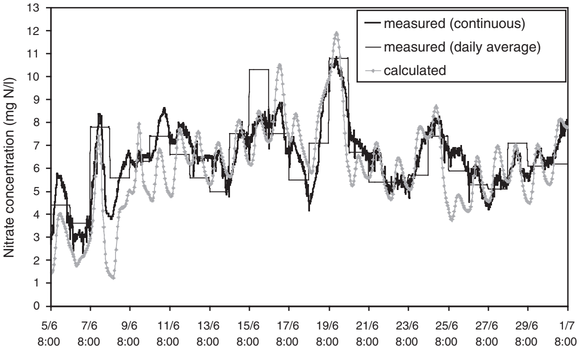

Figure 9 Validation – June, 2002

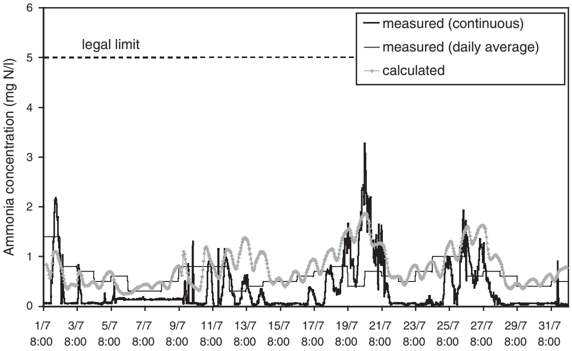

Figure 10 Validation – July, 2002

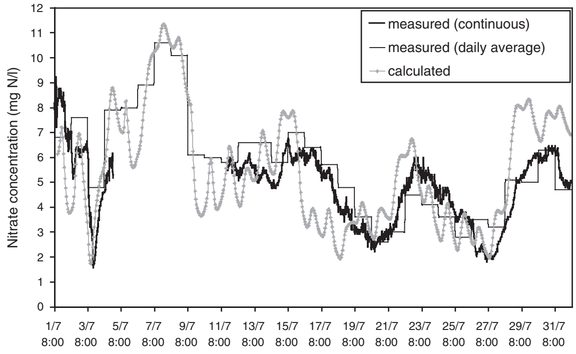

Figure 11 Validation – July, 2002

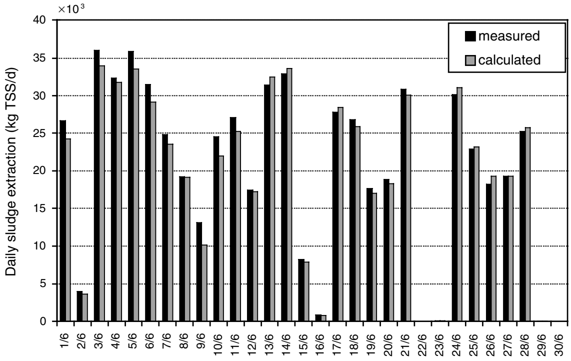

Figure 12 Validation – June, 2002

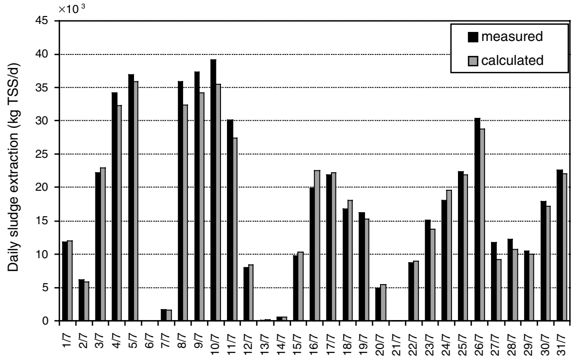

Figure 13 Validation – July, 2002

Table 1 Comparison between the measured and calculated monthly extracted sludge masses

	May, 2002	**June, 2002**	**July, 2002**
Measured mass (10^3 kg TSS)	665.0	603.7	523.3
Calculated mass (10^3 kg TSS)	677.7	573.1	505.2
Error (%)	**+1.9**	**−5.1**	**−3.5**

WEST® results are similar to those calculated by the software SIMBA/SIMBAD. The only difference concerns the aeration strategy implemented in both tools. Indeed, it does not exist any PI-controller in the node library of SIMBA/SIMBAD.

More detailed Tougas WWTP model

A second scheme of the WWTP was implemented in WEST®. This new model consists of four biological trains. The objective of this new part is to increase the precision of the prediction by elaborating a more realistic WWTP configuration able to independently simulate the behaviour of each train. This increased complexity is needed, because the different trains are loaded and almost managed differently. Indeed, the control strategies of aeration, RAS and WAS for each train are totally independent. This model was tested for the data set of July, 2002. Along this period, only the B oxidation ditch was not equipped with its DO sensor. Each biological train was modelled with the same set of parameters as the one used for the first WWTP model. As it could be expected, the overall nitrogen pollutant emissions calculated by both WWTP models are very close. To follow the behaviour of the G biological train, a daily composite sample was taken at the clarifier outflow during the measurement campaign and analysed for ammonia and nitrate. Figures 14 and 15 show that the model is able to predict the evolution of this specific effluent. With this new description of the WWTP, the model is now able to give reliable information about the TSS concentrations of mixed liquor and RAS. Figures 16 and 17 show the simulation results obtained on the G biological train.

Although the overall dynamics are correctly reproduced by the model, the quality of the simulation results for each of the four trains is not identical. Concerning the extracted sludge masses, the error between simulation and measurement data can increase up to about 10%, as shown in Table 2.

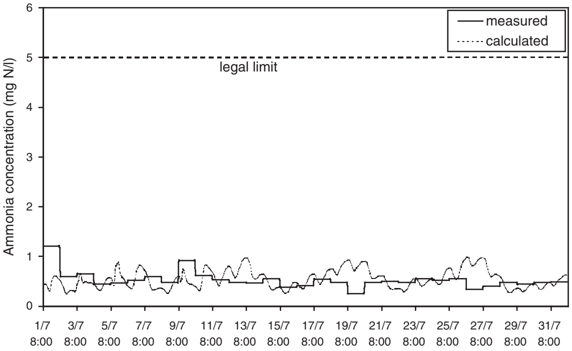

Figure 14 Outlet of G train – July, 2002

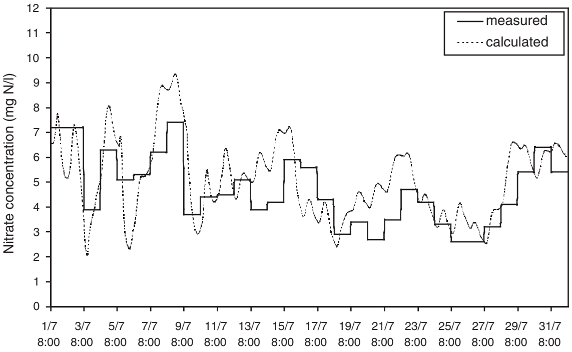

Figure 15 Outlet of G train – July, 2002

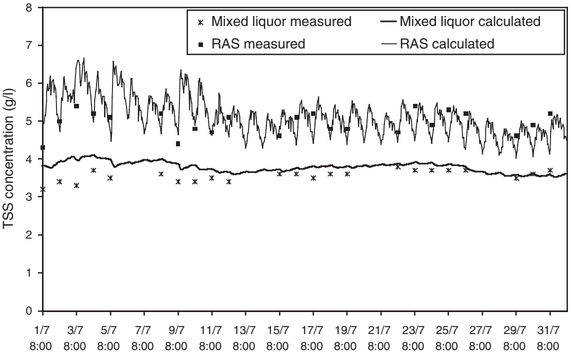

Figure 16 TSS (G train) – July, 2002

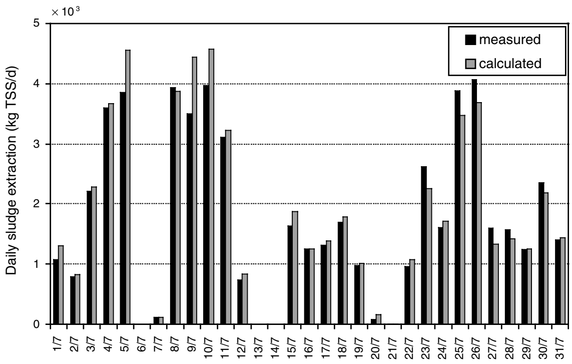

Figure 17 WAS (G train) – July, 2002

Table 2 Comparison between the measured and calculated extracted sludge masses of July

	AB train	**CD train**	**EF train**	**G train**
Average WAS flow rate (m^3/d)	1,140	1,024	656	358
Measured mass (10^3 kg TSS)	173.5	171.8	122.8	55.1
Calculated mass (10^3 kg TSS)	157.8	163.8	126.6	57.0
Error (%)	**−9.1**	**−4.7**	+**3.1**	+**3.5**

The practical management of the Tougas WWTP does not require to investigate a configuration divided into seven trains. On the contrary, to simulate with a still more detailed model would significantly increase the calculation time. In this context, a compromise has to be found.

Research perspectives

With the aim of adapting the WWTP model to its future operational use, the demonstration of a relationship between the air flow rate and the K_La' (wastewater reaeration constant) value is actually in progress. Even if the first simulation results are encouraging, it needs to be investigated further. The good results presented above show that the crucial point is to correctly reproduce the DO concentrations measured in the different oxidation ditches. If this condition is met, the model will be able to simulate the behaviour of the WWTP. To completely achieve the validation stage, the robustness of the model for different rainfall events (hydraulic peaks) and cold periods (temperature effect) must be evaluated.

Also, the Tougas WWTP operation needs to be investigated further with the second model. Once this part is realised, the objective is to develop a simplified tool from the WEST® results, especially made for a regular use by the operators of the Tougas treatment plant.

Conclusions

The purpose of this modelling is not limited to a simple comparison between simulations and measurements, but is to validate a mathematical tool whose use will allow to better understand, characterise and finally anticipate the behaviour of the biological train of the Tougas WWTP. The simulation results obtained on the measurement campaign events show that despite a first very simple description of the WWTP, the model is able to predict the evolution of the effluent composition and the daily extraction of sludge over a long period. To conclude, once the model will be completely calibrated and validated with a variety of events, it will be possible to describe the behaviour of the biological train in details under various weather conditions. A second more detailed configuration of the WWTP was implemented. It allows to study specifically the behaviour of each biological train. The remainder of this project will focus on the operational use of a simulator with the purpose of optimising the Tougas WWTP operation.

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