Mathematical modelling of the trickling filters of the WWTP of Tudela

<u>Year 2021: DEVELOPMENT OF A HYDRAULIC MODEL FOR TRICKLING FILTERS</u>

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1. Objective of the document

The main objective of this document is to present the first approach of the mathematical model developed to reproduce the hydraulic behaviour of trickling filters. First of all, the main characteristics of trickling filters are described and the interested in developing a mathematical model is argued.

Trickling filters are fixed film secondary treatments that are simple and robust to build and have low energy consumption. The principle of operation of a trickling filter is to pass wastewater through a solid filler that supports the attached bacterial layer. Bacteria attached to this packing (biofilm) feed on the pollutant load and grow on it. Trickling filters are widely used on large sites.

The water quality obtained from this apparently simple operation is in fact a combination of complex internal biological mechanisms described elsewhere and an unknown hydraulic behaviour (hydraulic short-circuits). The uncertainty associated to the combination of both effects has made historically difficult to predict and understand the performance of trickling filters. However, there is no simulation tool (mathematical model) to optimise and fully understand this technology.

NILSA and Ceit are collaborating within the framework of the Project LIFE16 IPC/ES/000001: “LIFE IP NADAPTA-CC - Towards an integrated, coherent, and inclusive implementation of Climate Change Adaptation policy in a region: Navarre.” on a line of R&D projects aimed to thoroughly understanding the mechanisms of a wide range of wastewater treatment technologies using advanced mathematical modeling tools. In this context, the construction of a mechanistic mathematical model that describes in detail the hydraulic behaviour of trickling filters will be developed. This model will help to understand the operation of the technology. In this document, the hydraulic model describing the behaviour of a trickling filter has been calibrated using data from a real WWTP with trickling filters with plastic packing media located in Tudela, Navarra for three different situations.

2. Methodology

In this section the developed hydraulic model is explained. Firstly, the experimentation done to calibrate the hydraulic trickling filter model is explained. Then, the development of a finite difference-based model is described. In this model, the trickling filter is conceptualised as a series of interconnected continuously stirred-tank reactors (CSTR). This is done in a spreadsheet.

I. Experimentation

In order to calibrate the hydraulic model, three different experiments are done. All of them consist of introducing a constant flow rate in an empty filter for a given time and then, observing the behaviour of the outflow until the filter was completely emptied. Table 1 gathers all the data from the three experiments. To obtain the data, flow meters were placed at the inlet and outlet of the trickling filter.

Table 1. Description of the experimentation.

Experiment	*Flow (m^3/min)*	*Flow (m^3/h)*	*Time (h)*
1	7.5	450	24
2	8.2	490	1.5
3	6.65	400	24

Figure 1 shows the inflows for the three experiments carried out to calibrate the hydraulic mathematical model for trickling filters.

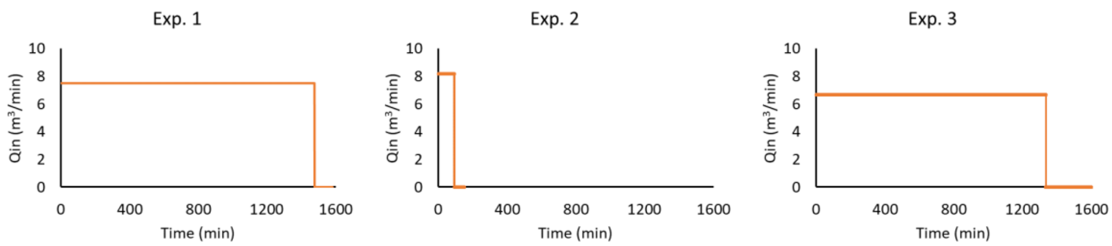

Figure 1. Profiles of the inflows for the experiments.

II. Mathematical model

Trickling filters show a complex hydraulic behaviour. The water goes through the reactor, but it does not leave the system immediately. When water is poured into an empty filter, it takes a long time to reach the outlet and the outlet flow rate needs even more time to reach the inlet value. In addition, the quality of the outlet water is different when backwashing is carried out. Therefore, it is concluded that the hydraulic part affects the performance of the system considerably. With this in mind, there are at least two paths or two ways of descending through the filler. These paths aim to reproduce the existence of hydraulic short-circuits and retained water in the system. The first it is called the circulating path and the latter the retained path. Furthermore, the water from the hydraulic short-circuits (circulating path) is in contact for a short time with the biofilm of the system, so the water that passes through that path is hardly treated. Whereas the retained water is completely biodegraded.

The random distribution of the plastic carriers makes possible the water to go from one path to another, this leads to the consideration of different levels in height of the reactor to reproduce this behaviour. All these considerations lead to model a single trickling filter as 8 virtual tanks. On one hand, the total height of the filter is divided in four levels. On the other hand, two paths are considered. Figure 2 shows a schematic diagram, where f is the fraction of the water flow that goes to the circulating path, the letter in the subscript ($_C$ for circulating path and $_R$ for retained path) indicates the path and the number the corresponding level. Both flows are mixed and distributed when every level is crossed.

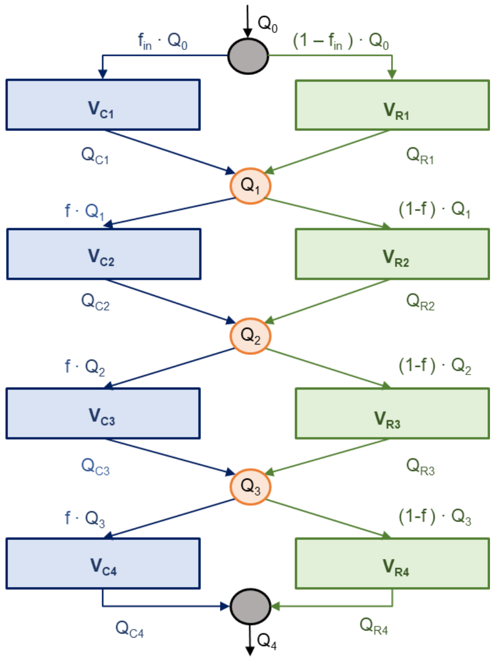

Figure 2. Schematic view of the trickling filter hydraulic model.

The mass conservation equation is used to reproduce the variation of the water volume in each tank. This mass balance can be expressed as a volume variation, and considering constant the density of the water, the following equation is obtained, Eq. (1).

$$\frac{dv(t)}{dt} = Q_{in}(t) - Q_{out}(t) \qquad \text{Eq. (1)}$$

Where v is the volume of the fluid in the control volume, Q_{in} and Q_{out} the inflow and the outflow rate of the control volume, respectively. The outflows of each tank are modelled by a weir equation, Eq. (2), where k is the opening coefficient of the valve and α is the exponent that regulates the emptying of the tank.

$$Q_{out}(t) = k \cdot V^{\alpha} \qquad \text{Eq. (2)}$$

A different opening coefficient and emptying exponent are defined for both paths. In total, 5 different parameters are needed to describe the hydraulic behaviour of a trickling filter: f, k_C, k_R, α_C and α_R.

The mathematical model is calibrated jointly for all experimental cases. In other words, a single set of values of the aforementioned parameters reproduces the hydraulic behaviour of the filter. This is done by sweeping through a range of parameter values, with each case comparing the model’s response (the value of the outlet flow) with the experimental value. This resolution is done automatically in the spreadsheet. Finally, the set of parameters that minimises the difference for all tests is selected.

3. Results and discussion

This section includes the main results obtained during the first year of the project. Firstly, the calibration of the hydraulic mathematical model is shown and then, some results implicit in the hydraulics are depicted. These implicit results have an impact on the understanding of the biological treatment process of this technology. Finally, a discussion of the results and the implications of the mathematical model is done.

I. Mathematical model calibration

Once the single set of parameters is defined, the values of the outflows obtained with those parameters are compared with the experimental results. Figure 3 shows how the model reproduces the experiments. Figure 4 helps in the comparison as the details of the filling of the filter are more easily distinguished. It is observed how the calibrated single set of parameters is able to reproduce the results in the three different cases. Furthermore, the model follows the main trends during the filling (Figure 4), steady-state operation and emptying.

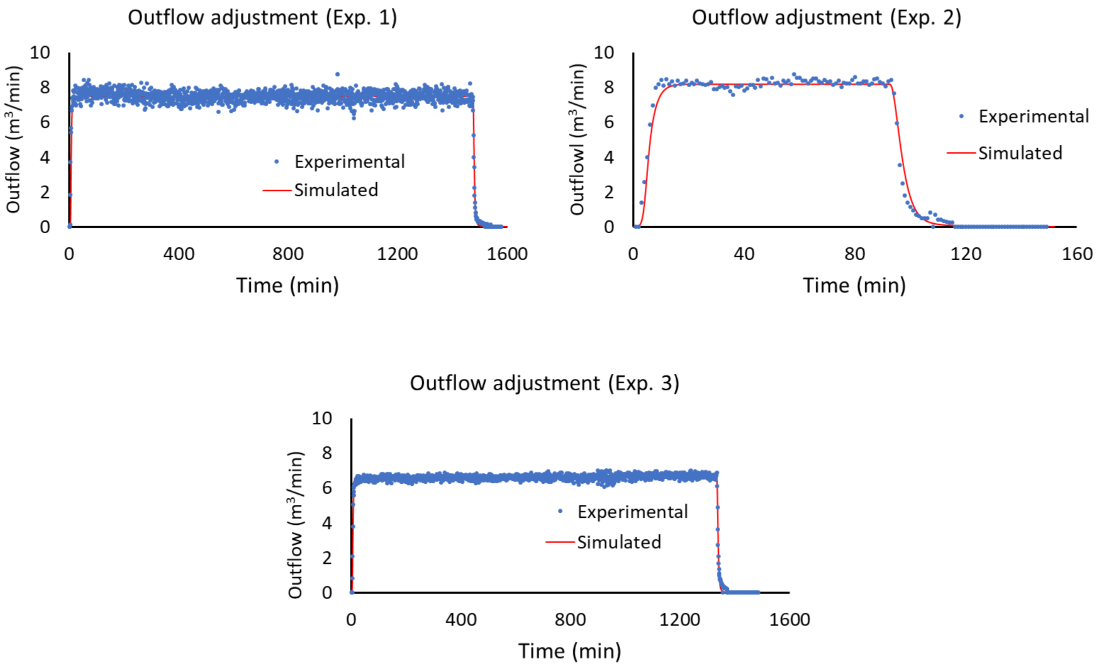

Figure 3. Comparison of the mathematical model results with the experimental results.

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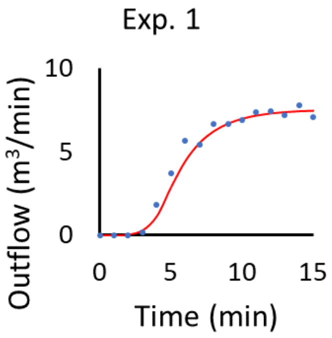


Figure 4. Zooming of the results comparison for experiments 1 and 3.

II. Hydraulic implications in the overall performance

Thanks to the developed model, a simulation tool of the hydraulic performance of a trickling filter is obtained. But not just that, thanks to the hydraulic model the retained amount of water can be determined, which is a value usually unknown. By calculating the area under the tail of the emptying of the outflow, it can be known which is the amount of water kept inside the trickling filter. This can be observed in Figure 5 for experiment 1 and in the Appendix for experiments 2 and 3.

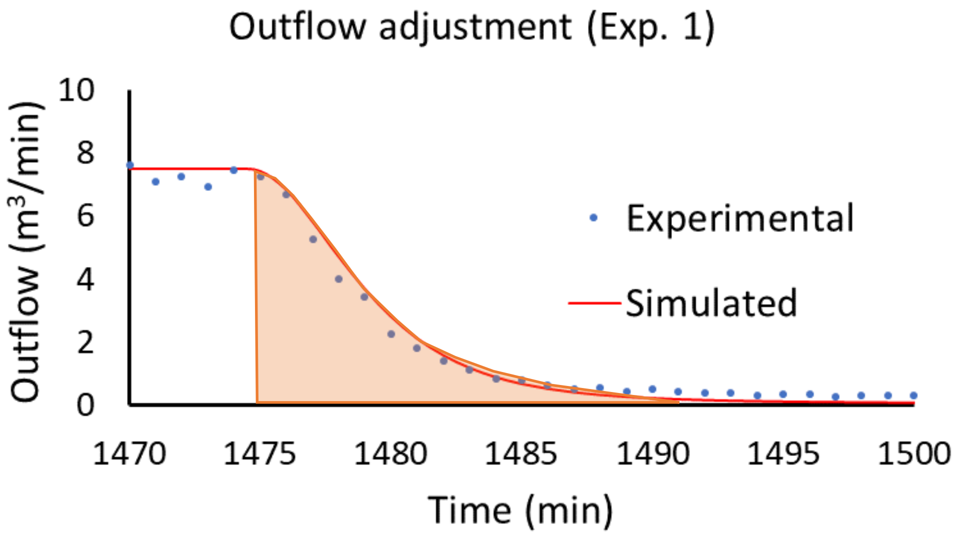


Figure 5. Emptying profile for experiment 1 of the hydraulic behaviour of the trickling filter.

The area observed under the graph represents the total volume of water kept inside of the trickling filter. This volume is different for each experiment as the water inflow is different for each case. This fact, leads to determining an equation that allows to calculate the amount of water kept inside in any situation. This equation has the following structure, Eq. (3):

$$V = 5 \cdot Q_{in} + 7 \qquad \text{Eq. (3)}$$

Where V is the accumulated water volume (m^3) and Q_{in} is the water inflow to the trickling filter (m^3/min).

This equation applied to each experiment gives the following graph, Figure 6, where the trend of the volume can be observed. This equation is only valid for the trickling filter used in these experiments.

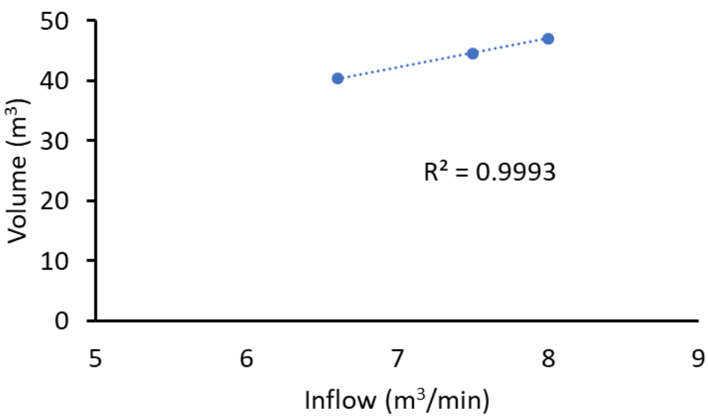


Figure 6. Water volume accumulated in a trickling filter for different inflows.

III. Discussion

The hydraulic mathematical model for a trickling filter developed and calibrated in this document is an important step in order to understand more precisely the behaviour of a trickling filter. The definitions of two different ways or paths of flowing inside the reactor allows the reproduction of hydraulic short-circuits. Furthermore, the distribution of the height of the reactor in 4 reactors (levels) allows to reproduce the mixing of the water of both paths and that way, reproduce the filling profile of the trickling filter. The assumption of using this number of levels must be analysed in more detail in the continuation of the project.

In addition, the hydraulic model helps in the determination of some values often unknown, such as the water volume kept inside of the trickling filters. When more water is retained, more time is in contact with the biofilm, leading to a better degradation of nutrients and organic matter. This way, thanks to the developed hydraulic mathematical model hydraulics implication in the biological process can be determined, this will be further studied in the following months.

The hydraulic mathematical model is an interesting tool to understand the behaviour of a trickling filter, but it needs the inclusion of biological phenomena in order to better understand the overall process. Furthermore, the impact of hydraulics will be better appreciated. Therefore, the next step will be to create a combined hydraulic and biological model for trickling filters.

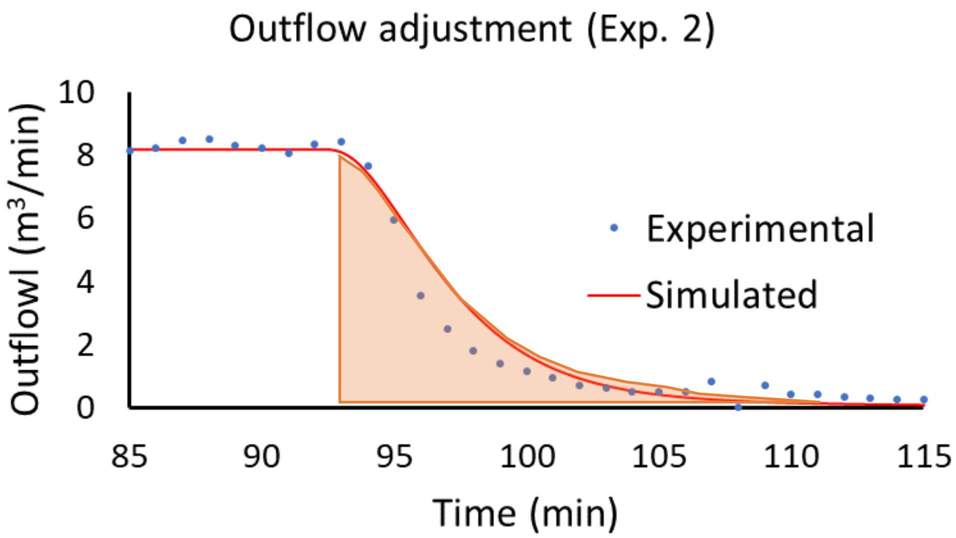
4. Conclusions

In this document, the development and calibration of a hydraulic mathematical model for trickling filters is described. This model is able to reproduce the outflow profile observed in a trickling filter of the WWTP of Tudela in three different situations (three different inflows). Furthermore, the three situations are reproduced with the same set of parameters.

The proposed model for a trickling filter is composed of 8 virtual tanks. 4 different levels are considered to reproduce the vertical gradients of the system. Furthermore, the developed model includes the presence of two different water paths, the circulating path to reproduce the hydraulic short-circuits and the retained path, where the water gets in contact with the biofilm. Weir equations are used to model the flow of the water and the mass conservation equation is employed to described the volume in each virtual tank.

The developed model is ready to be combined with a biological model to reproduce the global behaviour of the system.

5. Appendix



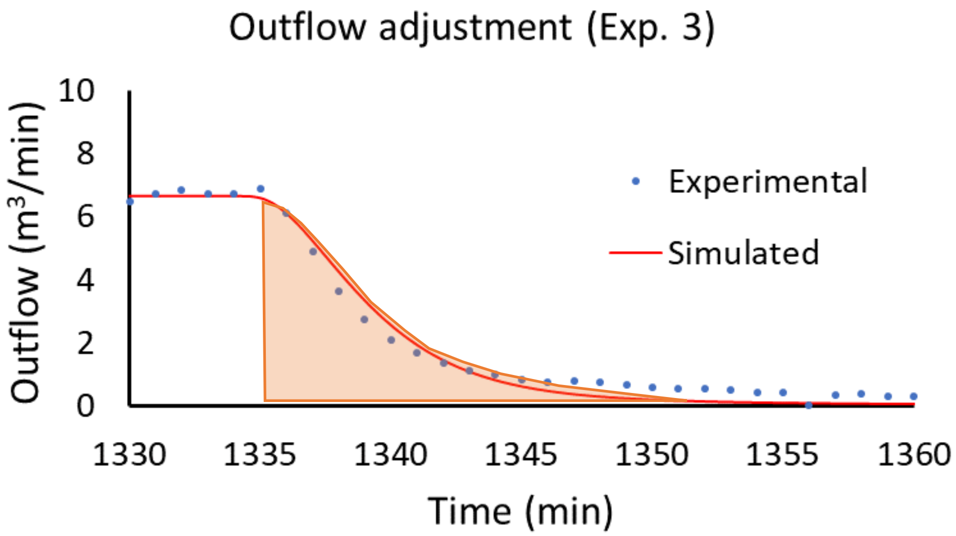


Figure 1A. Emptying profile for experiments 2 and 3 of the hydraulic behaviour of the trickling filter.

Mathematical modelling of the trickling filters of the WWTP of Tudela

Year 2022: DEVELOPMENT OF A HYDRAULIC AND BIOLOGICAL MODEL FOR TRICKLING FILTERS. FULL-SCALE IMPLEMENTATION AND VALIDATION

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1. Objective of the document

The main objective of this document is to present the combined hydraulic and biological model developed to reproduce the overall performance of a trickling filter. The hydraulic mathematical model developed in the previous year of the project is introduced in WEST-DHI software. The latter is known for being a common programme used in wastewater treatment simulations. By introducing the hydraulics of the process, the biokinetic transformations will be affected reproducing more faithfully the experimental results. NILSA and Ceit are collaborating within the framework of the Project LIFE16 IPC/ES/000001: "LIFE IP NADAPTA-CC - Towards an integrated, coherent, and inclusive implementation of Climate Change Adaptation policy in a region: Navarre." on a line of R&D projects aimed to thoroughly understanding the mechanisms of a wide range of wastewater treatment technologies using advanced mathematical modelling tools.

Once the combined model is developed is calibrated with experimental results obtained in the WWTP of Tudela, Navarra, during a whole year. This way, the mechanistic model developed by NILSA and Ceit-BRTA will help to understand the operation of the technology and to optimise the operation of any WWTP with trickling filters.

Besides the main objective, in this document the hydraulic model is studied in detail, analysing different possible combinations of paths and levels and their impact on the residence time and the model outputs.

2. Wastewater treatment plant (WWTP) of Tudela

The wastewater treatment plant (WWTP) of Tudela is operated by NILSA, a public identity of the Government of Navarra. This WWTP treats 10% of Navarra's wastewater and approximately 30% of the sludge. This sludge is generated at the facilities itself, as well as sludge generated at other WWTPs managed by NILSA itself.

The WWTP of Tudela is made up of two lines: the water treatment line and the sludge treatment line. The load of this plant is 100,000 population equivalents. Figure 1 shows the WWTP of Tudela as seen from the air.

Figure 1. Aerial view of the WWTP of Tudela.

The water treatment line consists of a pumping system, pre-treatment, primary treatment and secondary treatment. The average flow to be treated by this line is 22000 m^3/d. The pre-treatment consists of a screening system and a grit removal system. The aim of both is to remove particles larger than 3 mm and sand. After the pre-treatment, the primary treatment begins, which consists of two settlers where the settled solids are diverted to the sludge line. In this WWTP, the settling also performs the function of thickening.

Finally, the secondary treatment consists of the biological purification process of the wastewater, which in the case of Tudela is carried out in two-stage trickling filters. In these systems, the water is distributed over the upper surface by means of four rotating distributor arms, after which the water flows downwards through a cylinder filled with plastic material thanks to the action of gravity. The water comes into contact with the air inside the filter and the degradation takes place thanks to the bacterial biofilm that is generated on the plastic material during the degradation itself. The first stage of the secondary treatment consists of three trickling filters with a useful volume of about 3500 m^3. The filling of these filters has a specific surface area of 100 m^2/m^3. After collecting the water at the bottom of the filter, the water is directed to an intermediate settling tank where the settled biological sludge is mixed with the primary sludge in the primary settling tank. Finally, the water is directed to the second stage. This second stage consists of two trickling filters with a usable volume of 1500 m^3 and a specific surface area of 200 m^2/m^3 of plastic filler material. The water is collected in a perimeter channel and directed to the final settling. The outlet water is the treated effluent from the water line and the biological sludge generated is recirculated to the primary settling tanks in the same way as in the intermediate settling.

The sludge treatment line at the WWTP of Tudela is an autothermal thermophilic aerobic digestion system (ATAD), where the sludge is aerobically stabilised at temperatures of 60-70 ºC. At present, the sludge arriving at the facility is 200% of the sludge estimated in its design and, therefore, the sludge retention time in the digesters is less than that required for optimum treatment to take place under thermophilic conditions. The WWTP of Tudela also has two pilot-scale anaerobic digesters, one operated under mesophilic conditions (35 ºC) and the other under thermophilic conditions (55 ºC). Each of these reactors has a volume of 2 m^3.

3. Methodology

During this year of the project two different topics have been developed. In the first case, the hydraulic model previously developed have been analysed in detail. The structure of the model is compared with other possible structures. In the second case, the mathematical model is introduced in the WEST-DHI software and it is combined with a Ceit version of the IWA-ASM2d model. Then the combined model is validated with experimental results of the WWTP.

I. Analysis of the hydraulic model of a trickling filter

The mechanistic mathematical model of a trickling filter developed in the previous year of this project was composed of 8 virtual tanks, divided in 2 paths and 4 levels. That model reproduces faithfully the results obtained experimentally. Despite that, different model configurations are to be analysed to prove if considering more or less levels it would reproduce the experimental results.

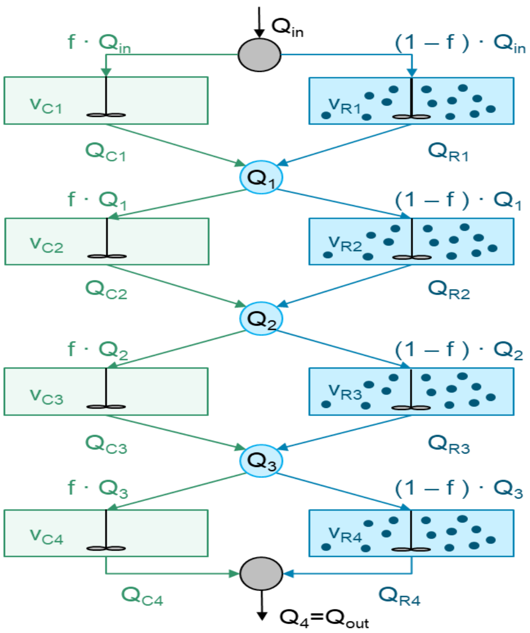

Figure 2. Schematic view of the trickling filter hydraulic model.

Figure 2 shows how a trickling filter is reproduced in the model with the circulating path (in green on the left) and the retained path (in blue on the right). The circulating path represents the hydraulic short-circuits and the retained path reproduces the water in contact with the biofilm that is being treated. In contrast to this scheme, there are two other options, the first using only two levels and the second using 8 levels.

These options are depicted in Figure 3. The contact time of the water with the biofilm is analysed for each case study.

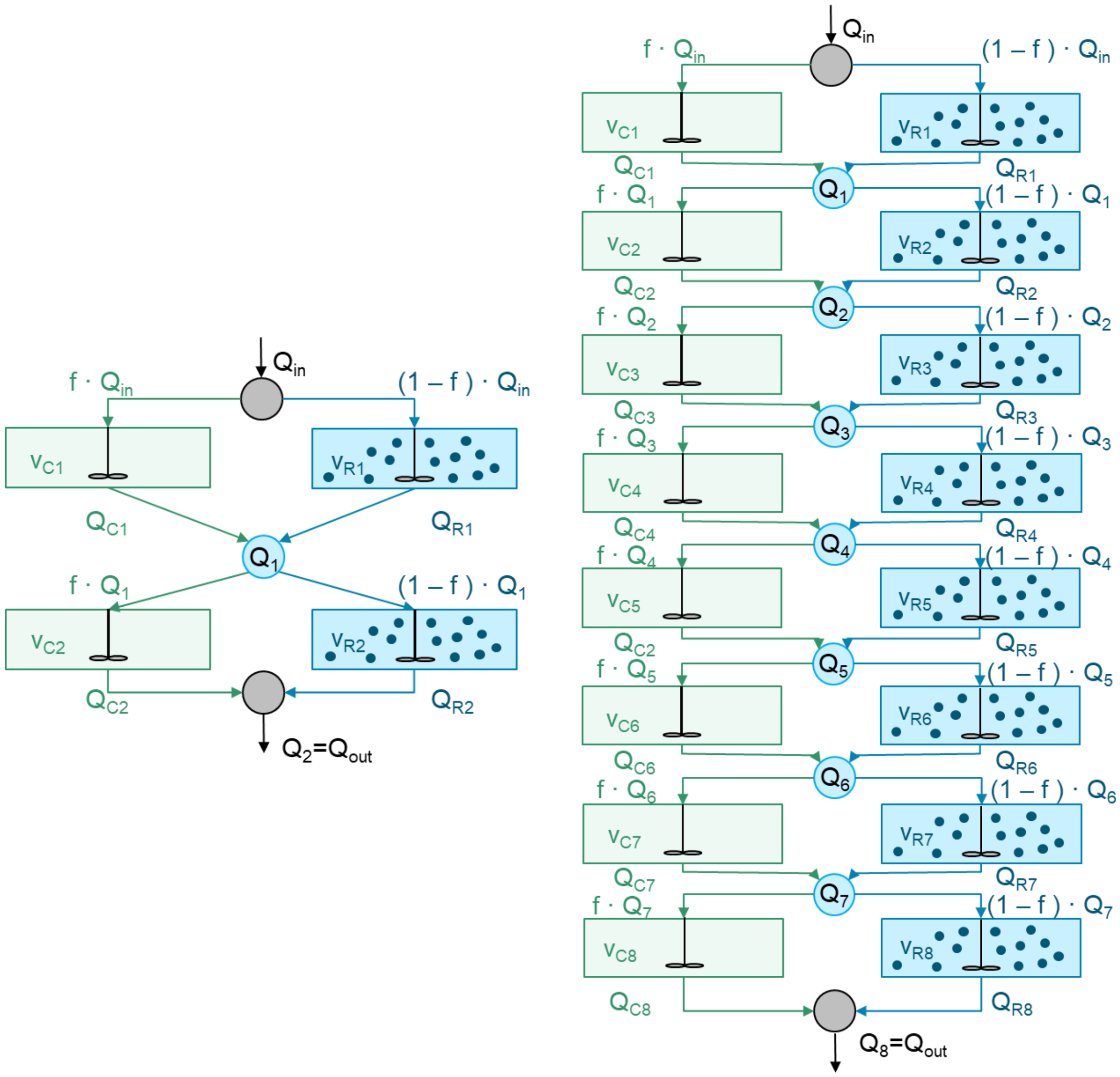

Figure 3. Schematic view of the different options of the hydraulic model of a trickling filter.

II. Combination of the hydraulic mathematical model with the biokinetic transformations

In this section the combination of the previously developed hydraulic mathematical model of a trickling filter with a biochemical model is shown. Figure 4 shows how these models are combined. The water entering the trickling filter is distributed between the two paths. The water flowing through the retained path is being degraded as it is in contact with the air and the biofilm. Once the level 1 (closest to the upper side) is crossed, both flows are mixed and distributed again. This occurs at the end of every level. This creates different fractions of treated water.

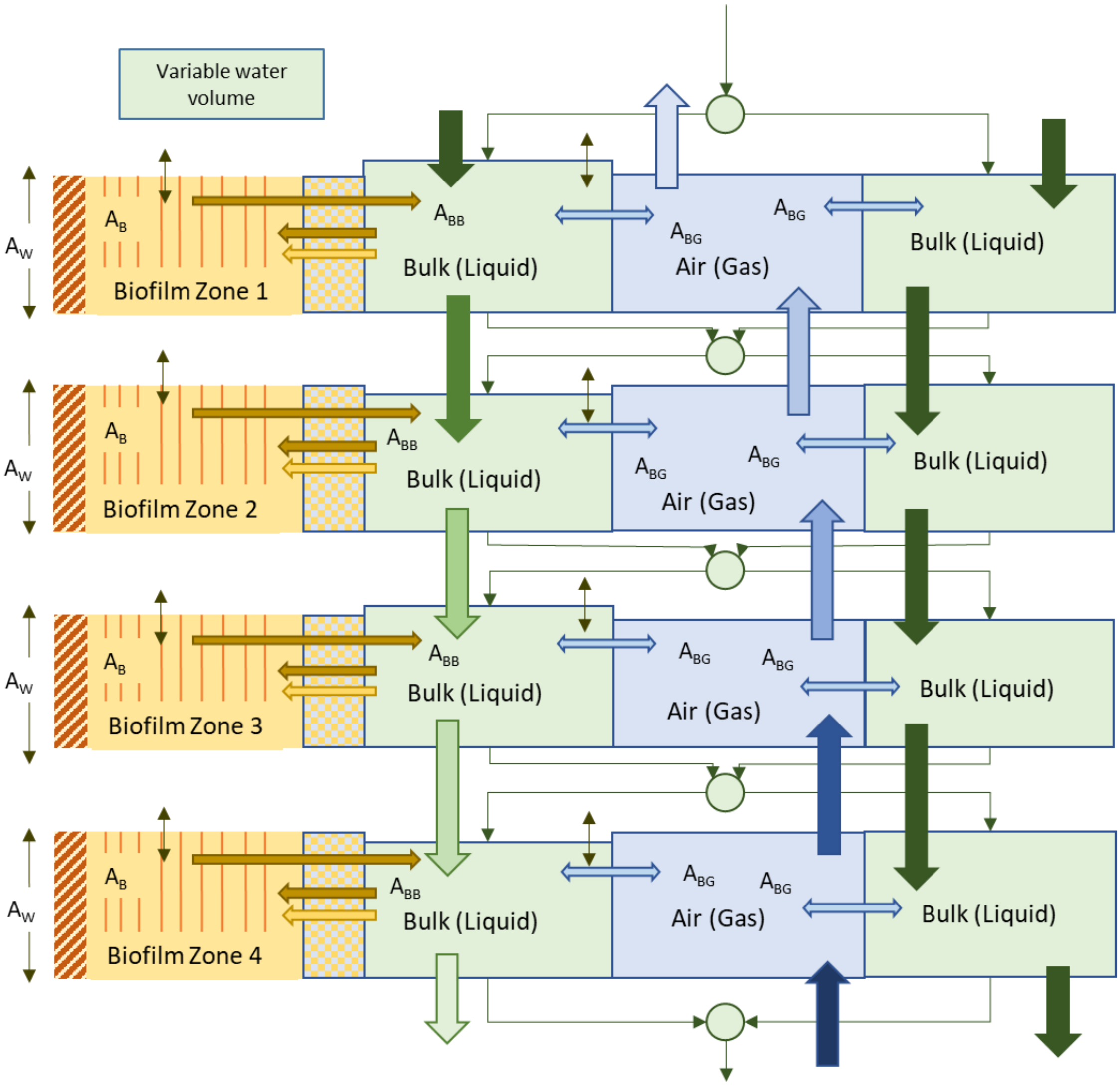

Figure 4. Schematic representation of the combination of hydraulic and biological models.

The simulation case must be constructed. For that purpose, the WWTP of Tudela is created in the WEST-DHI simulation platform. The process units considered in the simulations are observed in Figure 5.

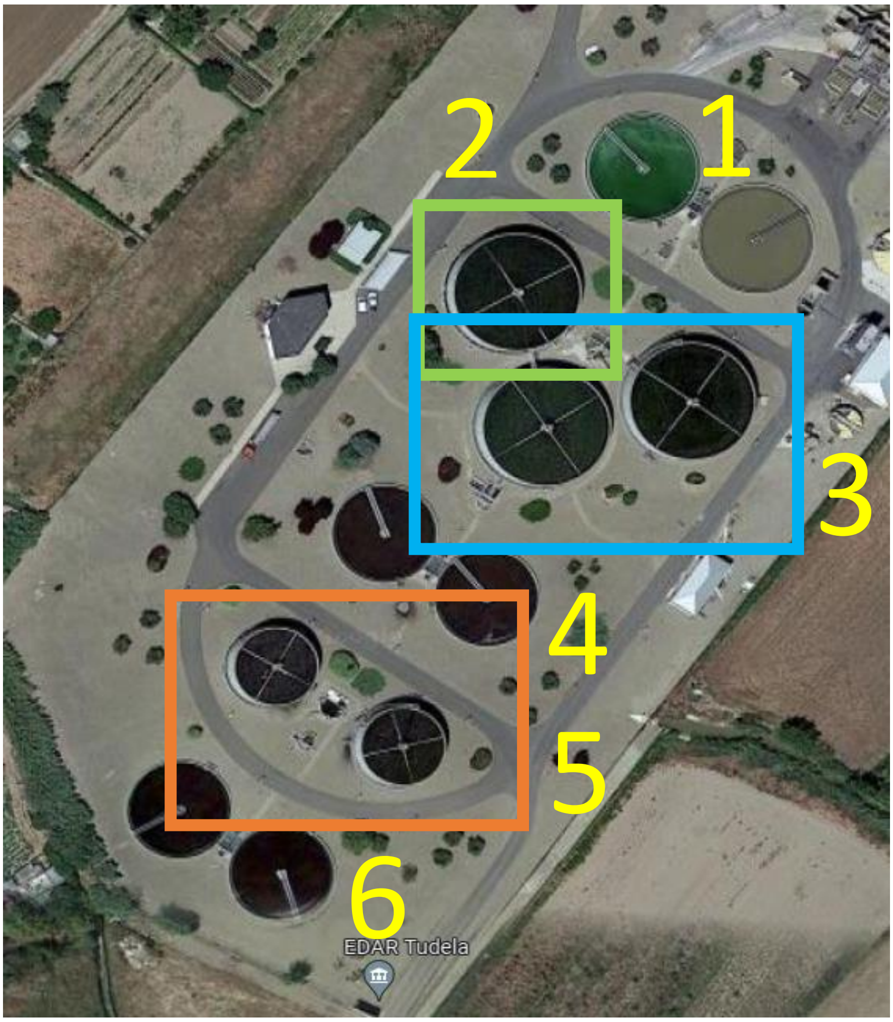

Figure 5. Description of the water treatment line of the WWTP of Tudela.

The main process units are the primary settlers (PS) (no. 1 in Figure 5), the first primary trickling filter (no.2 in Figure 5), the second primary trickling filters (no. 3 in Figure 5), the intermediate settling (IS) (no. 4 in Figure 5), the secondary trickling filters (no. 5 in Figure 5) and final settling (FS) (no. 6 in Figure 5).

In total, 6 process units are distinguished, those referenced in Figure 5, which are the ones to be transferred to the case study to be simulated in the WEST-DHI platform. This software is widely used for the modelling and simulation of the biological and physico-chemical processes that take place in wastewater treatment plants. Ceit has extensive experience with this tool and it is mainly with this tool that it develops and simulates the different processes or plants.

This process units and the hydraulic model of a trickling filter are combined and the WWTP of Tudela is constructed and simulated as seen in Figure 6.

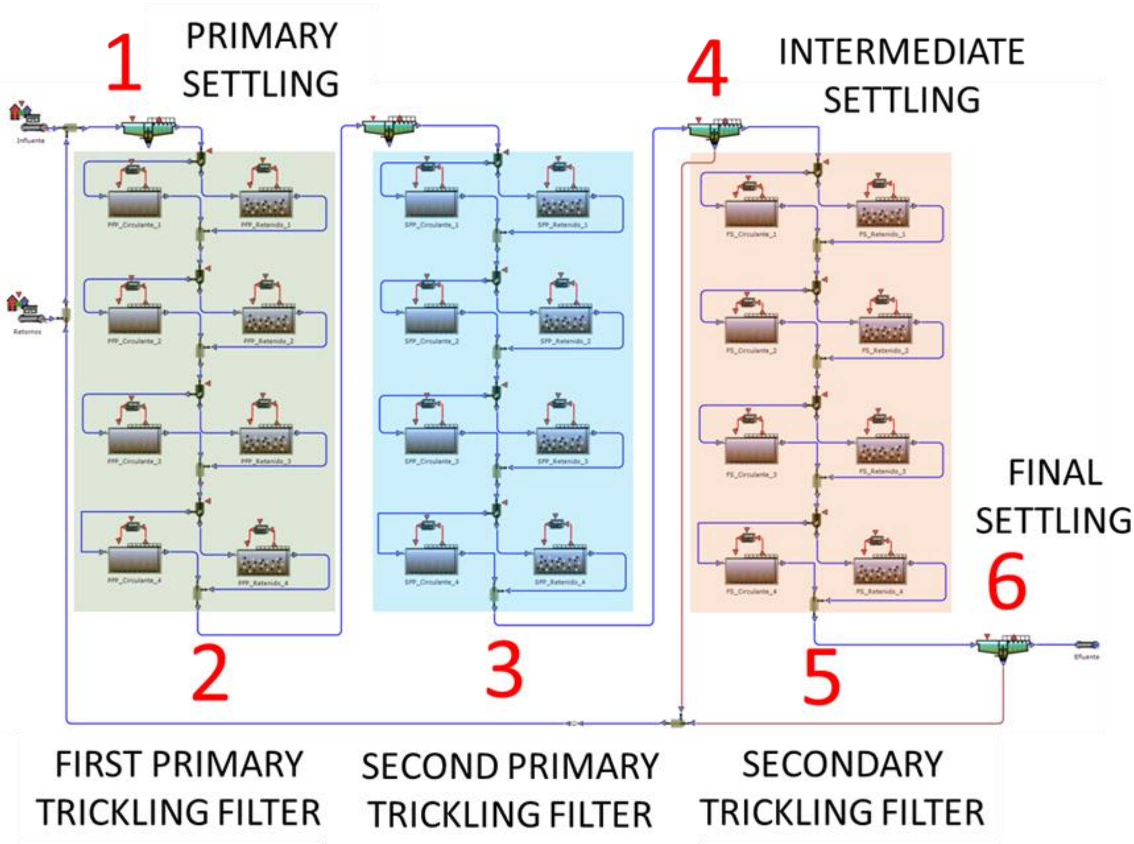

Figure 6. WWTP of Tudela in WEST-DHI simulation platform.

Once the WWTP is constructed, the model is compared with the experimental data gathered during a whole year in three different points of the facility. These points are the outlet of the PS, the outlet of the IS and the outlet of the FS, which is the effluent water of the plant. In each point composite measures are made. Ammonium (N-NH4), nitrates (N-NO3), total nitrogen (TN), phosphates (P-PO4), total phosphorus (TP), chemical oxygen demand (COD), soluble chemical oxygen demand (CODs) and total suspended solids (TSS) are measured.

To validate the model, firstly, steady-state simulations are performed to check that the model is able to reproduce the average values of the WWTP and then the whole year is simulated dynamically. The dynamic simulation is used to check that the model response is valid for time-varying inputs.

4. Results and discussion

In this section the results from the analysis of the hydraulic model of the trickling filter are shown. These results help in the definition of the proposed model as an independent model that is able to reproduce as close to reality as possible the hydraulic characteristics and overall behaviour of trickling filters. Then, the hydraulic model is combined and implemented in WEST-DHI with a biochemical transformations model to simulate the hydraulic and biological performance of the WWTP of Tudela, which has trickling filters. Finally, a discussion of the results and model implications is made.

I. Analysis of the hydraulic model of a trickling filter

The analysis done in this section is a comparison of the amount of water in contact with the biofilm and for how long for the 3 cases presented in the methodology section Analysis of the hydraulic model of a trickling filter. The three different cases differ in the number of levels. As the number of levels increases the number of possible combinations of paths is increased too.

Firstly, the three different configurations are calibrated to reproduce the experimental results. In the previous document, the calibration of the 4-level configuration is shown.

Each configuration has different "amounts" of water in contact with the biofilm. For example, the 2-level configuration has 3 different groups, the fraction of water that is not in contact with the biofilm, the group that is in contact with the biofilm half of the time and finally, the amount that is always in contact. These fractionation of the groups of water increases with the number of levels. For the 4-level configuration five different groups are found, whereas for the 8-level configuration there are nine different cases.

The three configurations have the same maximum contact time with the biofilm. Figure 7 shows the different contact time distributions for the 3 cases. The most critical fact is the amount of water that is never in contact for each configuration. The 2-level configuration shows that the 36 % of the water passes through the trickling filter without being treated by the biofilm, whereas this percentage is reduced to 12 % and 2 % for the 4-level and 8-level configuration, respectively. The 36 % of water not being treated automatically eliminates the possibility of using that configuration as it is able to reproduce the hydraulic behaviour, but not the biochemical performance.

The distribution of the contact times of the 4-level and 8-level configurations has a similar shape. In the latter case, the shape of the distribution is smoother, but involves a higher computational cost. As both configurations can reproduce the biochemical performance, the 4-level configuration is chosen to reproduce the behaviour of a trickling filter.

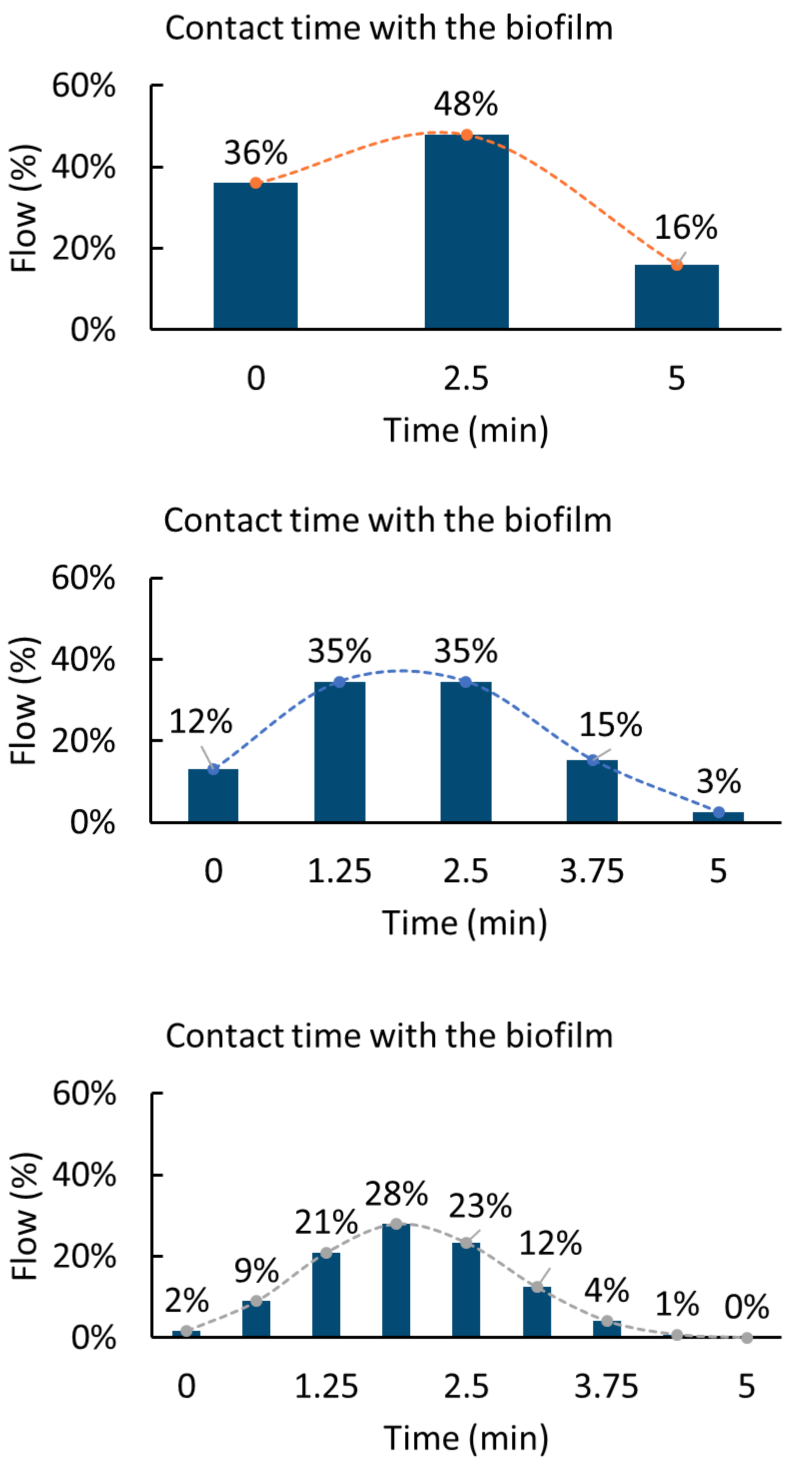

Figure 7. Contact time with the biofilm for each hydraulic model configuration. 2-level (Top), 4-level (Middle) and 8-level configurations (Bottom).

II. Validation of the combined mathematical model for trickling filters

This section shows the results of the steady-state and dynamic simulation compared to values of the measurements taken over one year. For the steady-state simulations the average values are used and whenever possible, the concentrations are plotted at four different points of the plant: influent, PS, IS and FS. Whereas for the dynamic case just the effluent water quality is compared. In this way, it is possible to observe the evolution of the compounds at all times and thus interpret what is happening at each point of the facility. Firstly, the graphs of the different compounds analysed for the steady-state simulations, while in Appendix a table showing all the values is included.

Firstly, Figure 8 shows the evolution of ammonium throughout the WWTP. It can be seen how the external returns contribute to an increase in the concentration of NH4 in the PS. Then, it can be seen that during the first stage of the secondary biological treatment, between the PS and the IS, nitrification starts to occur. This means that in this stage a large part of the COD is degraded. Finally, it can be seen how at the outlet of the FS (effluent water quality) the model manages to reproduce the concentration of N-NH4 measured experimentally. In this second stage, the trickling filters continue to nitrify.

Figure 8 shows the behaviour of N-NO3 in the WWTP. The value in the influent is not shown because there is no N-NO3 in it. However, a certain concentration can be seen at the outlet of the PS, which the model is not able to reproduce. After the first stage of the secondary treatment, when N-NH4 is consumed during nitrification, N-NO3 is formed. Finally, the second stage of the biological treatment continues nitrifying, so the NO3 concentration increases. It can be seen that nitrates do not decrease at any point in the WWTP. This occurs because the filters are never in anoxic conditions, they are under aerobic conditions as they are naturally aerated. The model reproduces the results obtained experimentally.

Biological trickling filters are used for nitrification and even denitrification, but always under the same conditions. In order to remove phosphorus biologically, the growth of PAO bacteria (polyphosphate accumulating organisms) must be promoted. These grow under alternating aerobic/anoxic and anaerobic conditions. The filters of Tudela are always aerated so they are not able to remove phosphorus biologically. Figure 8 shows how P-PO4 remain practically constant in the plant. The model does not reproduce any type of phosphorus consumption or storage.

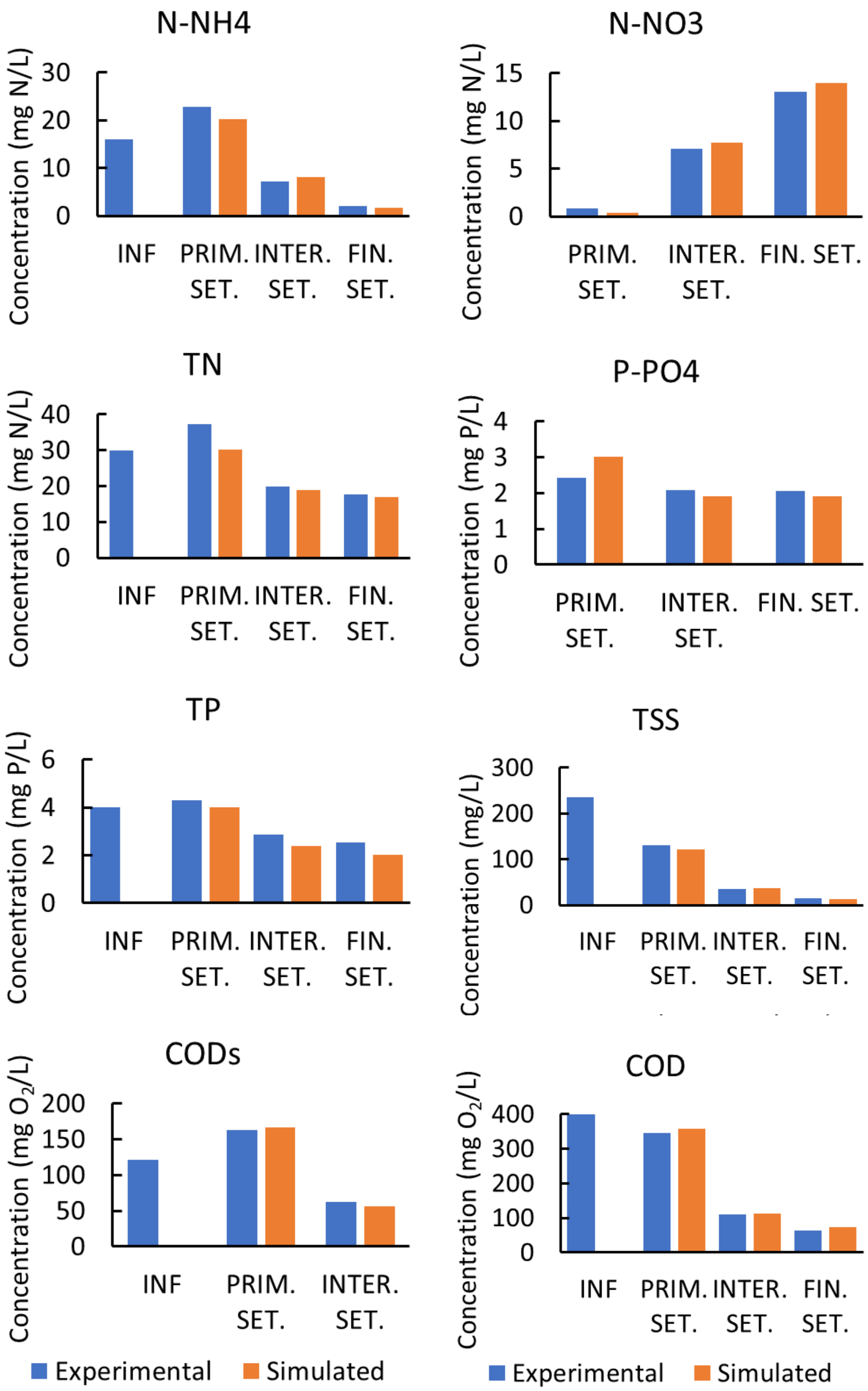

Figure 8. Evolution of N-NH4, N-NO3, TN, P-PO4, TP, TSS, CODs and COD in the WWTP of Tudela (Comparison between steady-state simulation and experimental results in the influent, at the outlet of the primary settling (PS), at the outlet of the intermediate settling (IS) and at the outlet of the final settling (FS)).

Figure 8 also shows the evolution of COD throughout the plant. In the PS, a good part of the solids are settled, as the external returns contribute a large amount of COD. It can be seen that the first stage of the biological filters consumes a large amount of COD, while between the IS and FS it continues to be degraded, but to a lesser extent. In addition, Figure 8 shows how CODs is consumed during the first stage of secondary biological treatment. The model is able to reproduce this consumption in a satisfactory way.

Finally, Figure 8 shows the evolution of TSS in the plant. The model shows a very similar behaviour to all the WWTP settlers.

Once the steady-state simulation results are compared with the average values, the dynamic simulation is carried out to verify the model's capability to work under time-varying inputs. The concentrations of the effluent water, outlet of the FS, are shown.

Figure 9 shows the N-NH4 profile obtained in the simulation versus the different experimental points. In general, the model is able to capture the main trends observed experimentally. Discrepancies at some points in time may be due to erroneous treatment of the data (lack of outlier removal), measurement errors or temporal effects such as sampling time.

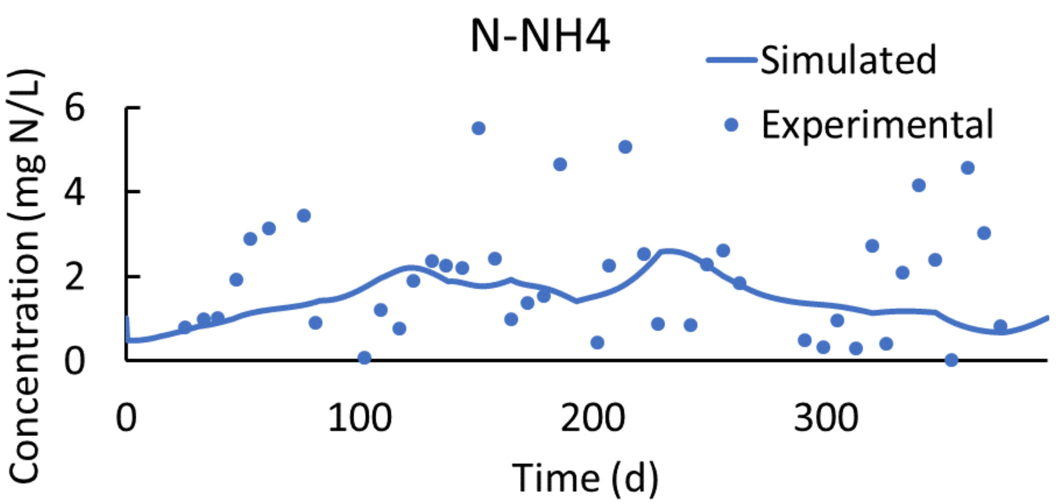

Figure 9. Evolution of N-NH4 in the effluent of the WWTP of Tudela (Comparison between the results of the dynamic simulation and the experimental values at the outlet of the final settling (FS)).

Figure 10, Figure ***11***, Figure ***12***, Figure ***13***, Figure ***14*** and Figure ***15*** show how the model reproduces N-NO3, TN, P-PO4, TP, TSS and COD against the experimental results, respectively. As in the case of N-NH4, the model reproduces satisfactorily the trends and most of the values observed in the experimental tests, replicating the most significant peaks and troughs of the cases.

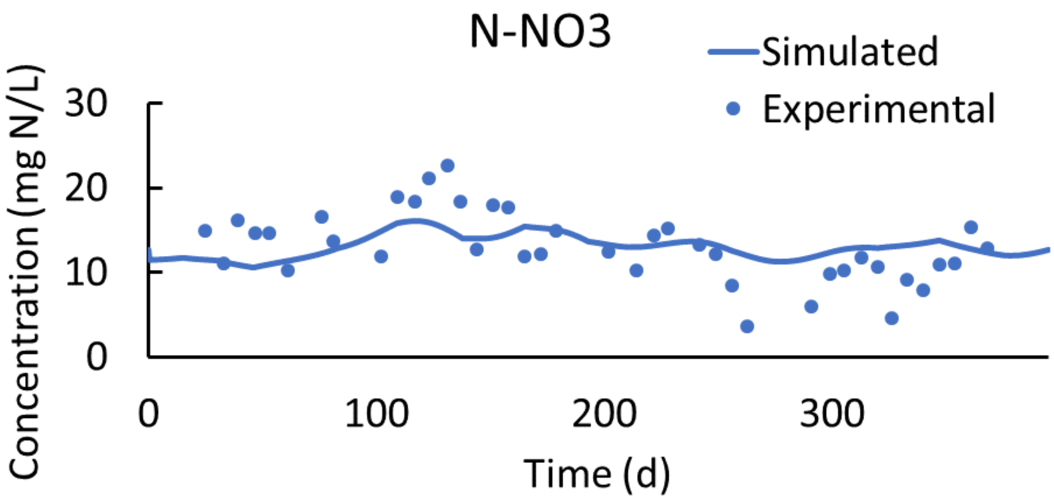

Figure 10. Evolution of N-NO3 in the effluent of the WWTP of Tudela (Comparison between the results of the dynamic simulation and the experimental values at the outlet of the final settling (FS)).

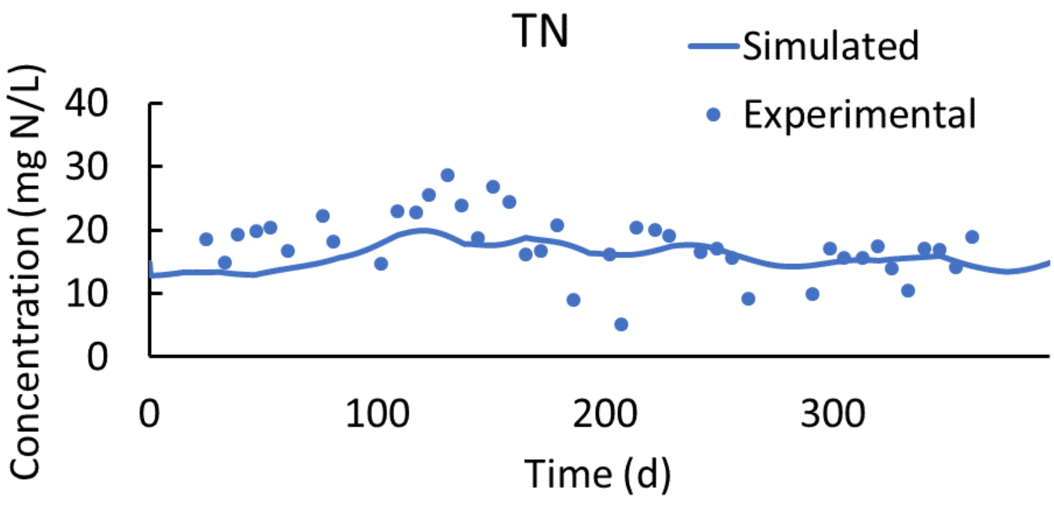

Figure 11. Evolution of TN in the effluent of the WWTP of Tudela (Comparison between the results of the dynamic simulation and the experimental values at the outlet of the final settling (FS)).

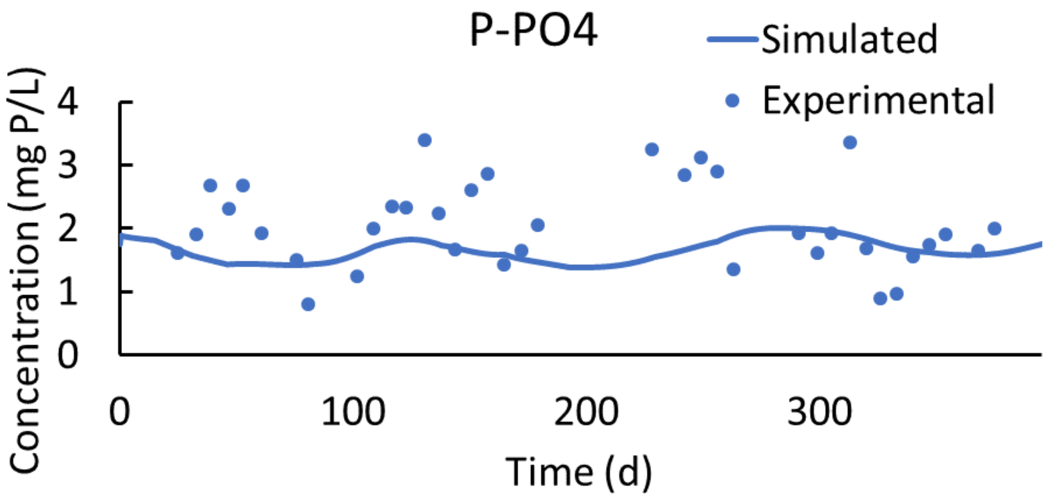

Figure 12. Evolution of P-PO4 in the effluent of the WWTP of Tudela (Comparison between the results of the dynamic simulation and the experimental values at the outlet of the final settling (FS)).

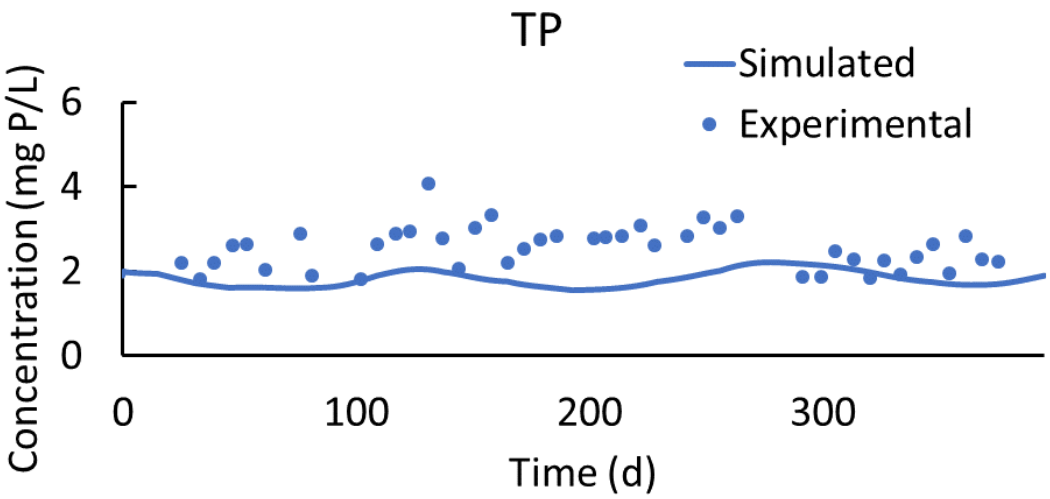

Figure 13. Evolution of TP in the effluent of the WWTP of Tudela (Comparison between the results of the dynamic simulation and the experimental values at the outlet of the final settling (FS)).

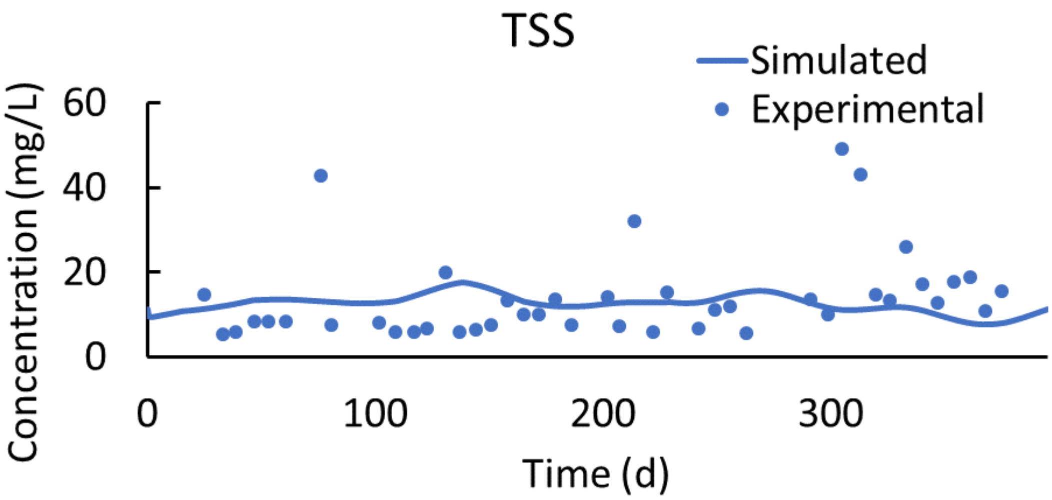

Figure 14. Evolution of TSS in the effluent of the WWTP of Tudela (Comparison between the results of the dynamic simulation and the experimental values at the outlet of the final settling (FS)).

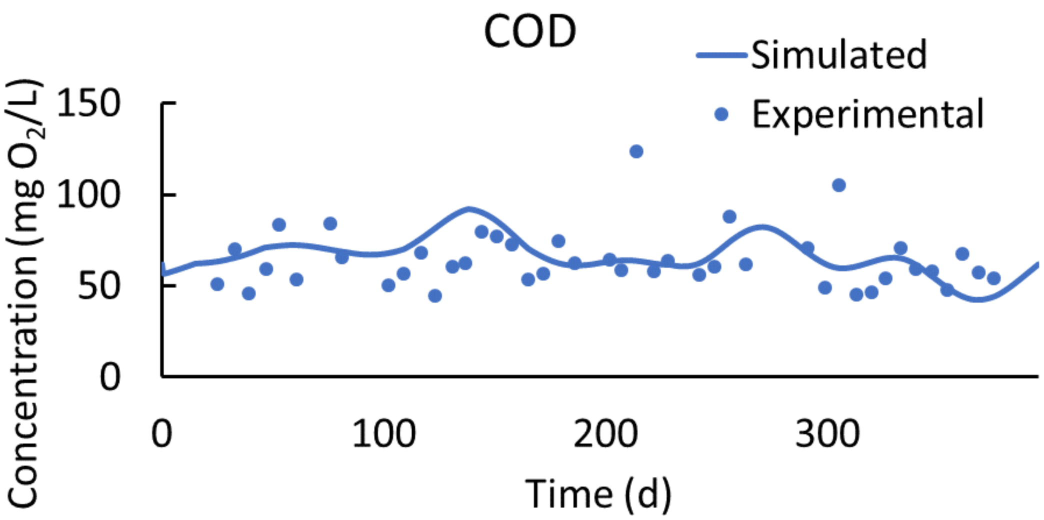

Figure 15. Evolution of COD in the effluent of the WWTP of Tudela (Comparison between the results of the dynamic simulation and the experimental values at the outlet of the final settling (FS)).

III. Discussion

The developed hydraulic model of a trickling filter has a simple enough configuration to reproduce the main trends of the technology. The different configurations analysed during this year succeed in replicating the experimental results, but the effect of those configurations in the biokinetic processes are different. The 4-level and 8-level configurations have an acceptable distribution of the contact time with the biofilm among the different fractions of water. Finally, the 4-level configuration is chosen due to computational costs reasons.

This analysis shows how hydraulics affects the biology, so if a trickling filter is being simulated, hydraulics cannot be ignored. The developed hydraulic model is implemented in WEST-DHI and combined with the biokinetic model based on IWA-ASM2d. Once the model is combined, it is calibrated. The results provided by the model are in good agreement with the observed experimental results.

This way, a complete model of a trickling filter is developed and calibrated. This model explains the hydraulic and biochemical behaviour of trickling filters. This model is a useful tool for designing new WWTP with this technology. In addition, it could help in analysing different operational strategies and finally, optimising the plant.

5. Conclusions

In this document, firstly, the analysis of the hydraulic model of a trickling filter is done. This analysis helps in the definition of the appropriate model to describe the behaviour of this technology. Thanks to this analysis the 4-level configuration proposed initially is chosen as the best option to reproduce the hydraulic and biological behaviour of trickling filters, as it the distribution of contact times is the more suitable one.

Then, the hydraulic model is implemented and combined with a biochemical transformation model included in the WEST-DHI software. The combined model is able to reproduce successfully through steady-state simulations the average experimental values obtained throughout a whole year. Then, the model is run in a dynamic simulation. This way, a useful tool for understanding and optimising the hydraulic and biological performance of trickling filters is obtained.

6. Appendix

CONCENTRATION	INFLUENT	PRIMARY SETTLING			INTERMEDIATE SETTLING			FINAL SETTLING		
		Exp	Sim	Error (%)	Exp	Sim	Error (%)	Exp	Sim	Error (%)
N-NH3 (mg N/L)	16	22	20	9	7	8	14	2	2	0
N-NO3 (mg N/L)	-	0.8	0.4	50	7	8	14	13	14	8
TN (mg N/L)	30	37	30	19	20	19	5	18	17	6
P-PO4 (mg P/L)	-	2.4	3	25	2.1	1.9	9	2.0	1.8	10
TP (mg P/L)	4	4.3	4	7	2.9	2.4	17	2.5	2	20
COD (mg O_2/L)	400	346	357	3	110	112	2	64	72	13
CODs (mg O_2/L)	121	163	166	2	62	56	10	-	51	-
TSS (mg/L)	235	130	121	7	36	37	3	14	13	7

Mathematical modelling of the trickling filters of the WWTP of Tudela

Year 2023: APPLICATION OF SIMPLIFIED NEW COMBINED HYDRAULIC AND BIOLOGICAL MODEL FOR TRICKLING FILTERS

Index

1. Objective of the document

NILSA and Ceit are collaborating within the framework of the Project LIFE16 IPC/ES/000001: "LIFE IP NADAPTA-CC - Towards an integrated, coherent, and inclusive implementation of Climate Change Adaptation policy in a region: Navarre." on a line of R&D projects aimed to thoroughly understanding the mechanisms of a wide range of wastewater treatment technologies using advanced mathematical modeling tools. The main objective of this document is to simplify the combined hydraulic and biochemical model for trickling filters. The previously developed mathematical model has a high level of hydraulic detail which is interesting in some cases, but when the overall performance of the plant has to be analysed the computational costs is high. That's why a simplified model for trickling filters is necessary.

The simplified version reduces its hydraulic detail, but keeps the biochemical performance with a reduced computational cost. In total, two different versions are analysed. This way, the simplified mechanistic model developed by NILSA and Ceit-BRTA will help to optimise the operational strategy of any WWTP with trickling filters.

2. Methodology

For the simplification of the combined hydraulic and biochemical model certain aspects have to be considered. These models will only work for steady-state conditions. The simplified models would not be able to reproduce the filling and the emptying profile of trickling filters, but they have to reproduce the biokinetic behaviour of the filters. Despite not reproducing the complete hydraulic behaviour, some hydraulic considerations must be taken into account. Within the framework of this project, new trickling filter models are developed because the previous ones did not consider certain aspects such as hydraulic short-circuits, therefore, the simplified version should also include their presence.

With these assumptions, two different cases are presented as simplified version of the complete model presented previously and brought it here in Figure 1. This Tudela's WWTP layout has 24 biological reactors, making computationally high-cost simulations.

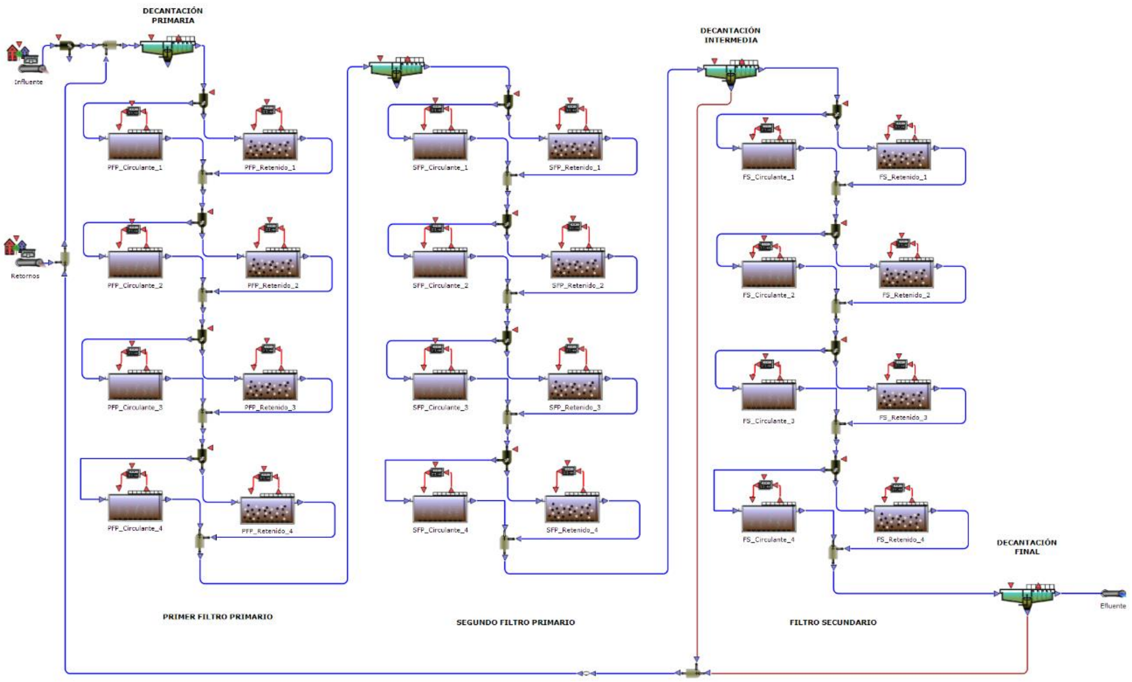

Figure 1. WWTP of Tudela with the complete trickling filter model.

The first approach for the simplification of the model is done by replacing the 8 virtual tanks by a single biofilm reactor with a virtual settling tank in series to increase the hydraulic residence time (HRT). At the same time, a by-pass is created to reproduce the water of the hydraulic short-circuits. This way, the main hydraulic limitation is maintained and the number of biological reactors is reduced up to 3. Figure 2 shows the layout of Tudela's WWTP with this simplification.

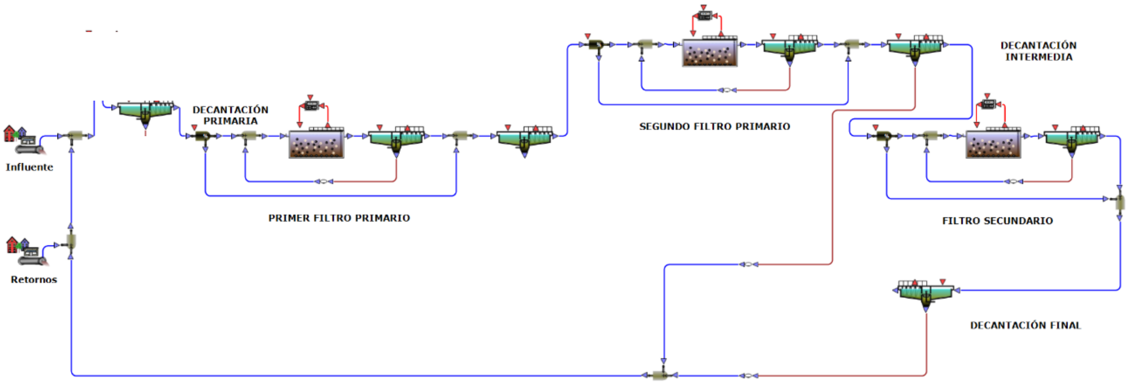

Figure 2. WWTP of Tudela with the biofilm simplified trickling filter model.

The second version of the simplified model is analogous to the first version, but instead of using biofilm reactors, it uses continuously stirred-tank reactors (CSTR) which are used to simulate activated sludge (AS). This way, 3 biological reactors are used instead of 24. Figure 3 shows the layout of Tudela's WWTP with this simplification. For both simplifications the fraction of the water that flows through the by-pass is determined as the 12 % of the incoming water. This number is obtained thanks to the hydraulic analysis done with the hydraulic model.

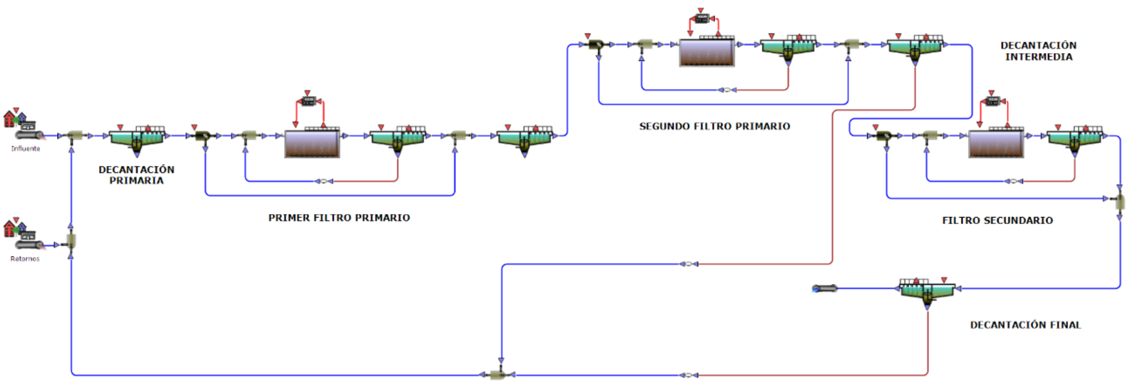

Figure 3. WWTP of Tudela with the AS simplified trickling filter model.

For choosing a simplified model, the results provided by each of them are compared with the experimental results and those provided by the complete model. In addition, two other criteria are added to decide whether the simplified models are valid. The first one is the composition of the generated primary sludge and the second one is the simulation time. The first is important because the WWTP of Tudela has a sludge line, and it is wanted to be simulated in another project, while the second criteria can also be crucial when deciding to use one model or another.

3. Results and discussion

In this section the main results obtained through the comparison of the outputs of the simplified models with the experimental results and complete model are shown. Once the results are compared the composition of the obtained primary sludge in every model is compared and finally, the simulation times are studied. With these results, the most suitable simplified model is chosen after a brief discussion.

I. Comparison between the different models' outputs

The results of the simplified models are compared with the experimental and complete model results. Steady-state simulations are run in order to compare them. Several points of the WWTP are chosen as comparing sites. As it was done in the previous year, primary settling (PS), intermediate settling (IS) and final settling (FS) are the chosen places. Ammonium (N-NH4), nitrates (N-NO3), chemical oxygen demand (COD) and total suspended solids (TSS) are analysed.

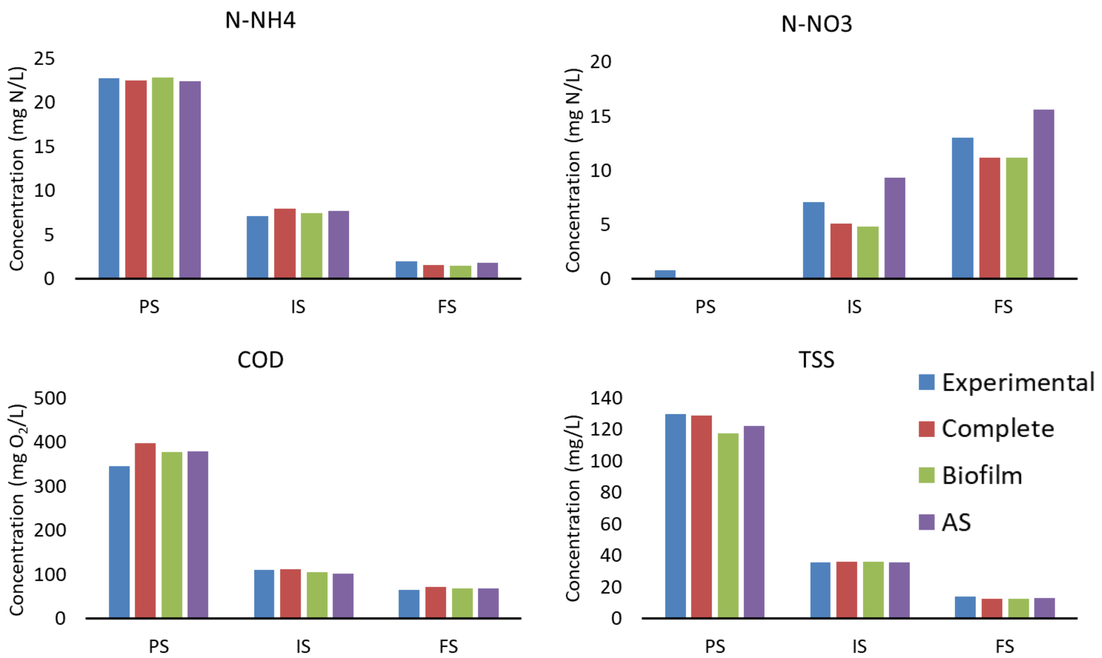

Figure 4. Comparison between the simplified models results and experimental and complete model outputs.

Figure 4 shows the outputs of the different models compared with the experimental values. All of them reproduce faithfully enough the experimental results. The main difference is found in the nitrates. Where biofilm is considered (complete and simplified biofilm model), nitrates have a lower presence in the system. This could be due to the biofilm potential of simultaneous coexistence of different conditions inside it. However, the rest of the values are correctly reproduced. At this point any simply could be use, but the simplified biofilm model is in advance.

II. Primary sludge composition

Another criterion for choosing one model over the other is the composition of the primary sludge obtained in the simulations. Biofilm technologies produce a different sludge than activated sludge technologies. In order to verify this hypothesis and its impact in the model the volatile suspended solids (VSS) and TSS are compared for the three models. Furthermore, the inert fraction of those solids and its percentage over the total are compared.

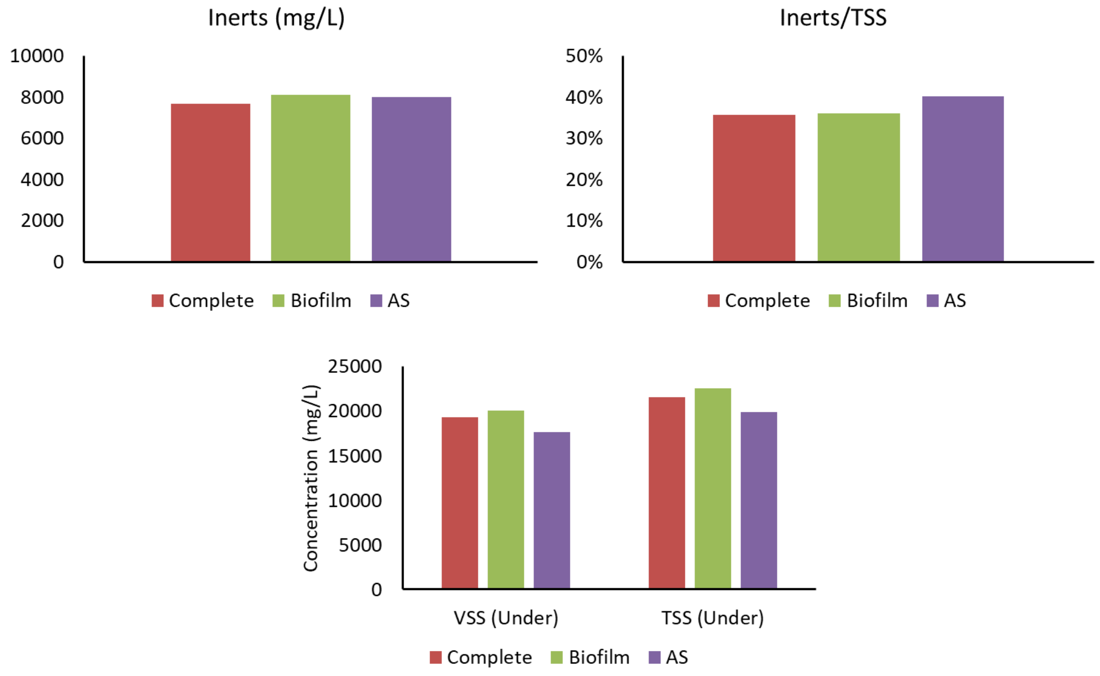

Figure 5. Comparison of the primary sludge production for the different proposed models.

Figure 5 shows the comparison between different results regarding the primary sludge production. In every case, the VSS and TSS concentration is quite similar. Those differences could be related to the definition of the HRT of the simplified versions. When the concentration of the inert solids is analysed almost no difference is found between them, however the percentage of inert in the TSS shows that the biofilm simplified version reproduces more faithfully the behaviour than the AS version. This way, the biofilm simplified version is a more suitable option.

III. Simulation time

Finally, the simulation time of the three models is compared. In order to do that the same steady-state simulation is run. In every case, 100 days are simulated.

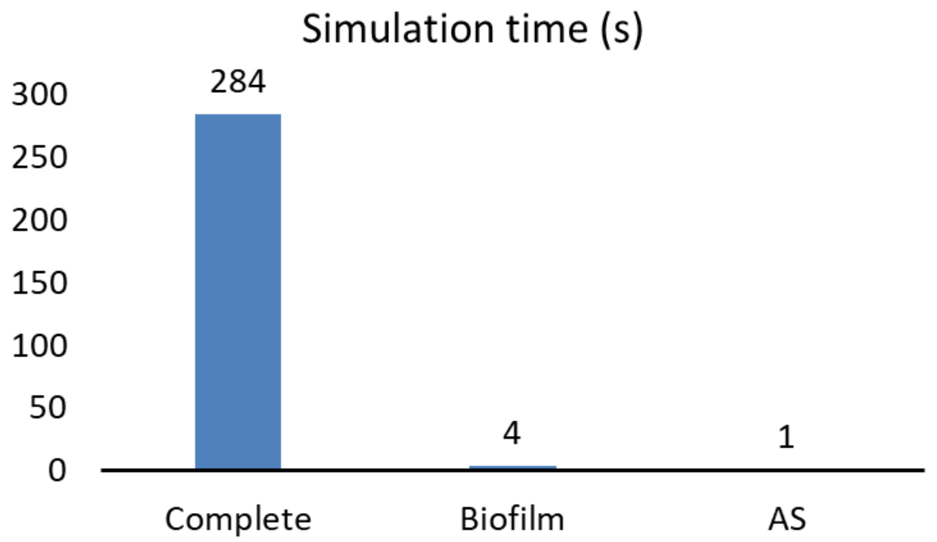

Figure 6. Comparison of the simulation time needed for each case.

Figure 6 shows the differences in the simulation time needed for each mathematical model. The complete model with 12 biofilm and 12 AS reactors needs 284 s to simulate 100 days of operation, whereas the biofilm simplified model (3 biofilm reactors) needs 4 s and the AS simplified model (3 AS reactors) needs only 1 s. With this criterion, the AS simplified model would be the best choice.

IV. Discussion

The results of the two simplified models are compared with the experimental results and complete model results. In total, three different criteria are used to choose the best option. Both simplified models reproduce the steady-state results faithfully. The results of the biofilm simplified model are more similar to the complete model as both of them used biofilm reactors. Furthermore, the primary sludge composition of the biofilm model is the same as the complete model. Finally, even though the AS model is faster the biofilm simplified model is considered fast enough.

As the results of the latter are more accurate and the simulation is 70 times faster, the biofilm simplified is chosen as a good option. This way, a very useful tool is available that provides less hydraulic detail than the complete model, but is able to reproduce the biological behaviour while maintaining the presence of hydraulic short-circuits. This simplified version of the model considerably speeds up simulations, facilitating the exploration of different operation strategies and the optimisation of different WWTP.

4. Conclusions

In this document, the combined hydraulic and biological trickling filter model is simplified. By reducing the hydraulic high detail of the complete model, two different options are proposed which have lower computational cost.

The simplified version reduces its hydraulic detail, but keeps the biochemical performance with a reduced computational cost. Between the two different proposed versions, the biofilm one is chosen. This model uses a single biofilm reactor with a virtual settler and a by-pass to reproduce the behaviour of a trickling filter. This model reproduces the experimental results for a steady-state simulation 70 times faster than the complete model. This way, the simplified mechanistic model developed by NILSA and Ceit-BRTA will help to optimise the operational strategy of any WWTP with trickling filters.