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Use of integrated models to minimize the impact of urban wastewater systems on a Mediterranean stream

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Abstract: In some regions, like in the Mediterranean area, streams are characterized by harsh hydrological fluctuations, with very low flow rates in summer and high in autumn. During low river flow conditions, wastewater treatment plant (WWTP) discharges contribute significantly to the total river flow and hence their impact is higher. The objective of this paper is to find solutions to confront this typical problematic situation by means of integrated modelling. The benefits of modelling the whole urban wastewater system (UWS) to evaluate multiple operational strategies are shown. The model includes two sewer systems, two WWTPs, a connection channel between the two WWTPs, storage tanks and a river stretch. The methodology is based on Monte Carlo simulations, used to conduct a Sensitivity Analysis to identify the most important operational settings and to perform a screening of the best combinations of settings with respect to immission-based criteria. The results show that properly using the storage tanks before the two WWTPs and the connection between them, as well as setting adequate aeration and recycle flow rates, allow to reduce the ammonia peak concentrations in the river by almost 30% and to increase the DO concentration in the river by about 10%, with a negligible increase in the operational costs.

Keywords*:* Integrated modelling; urban wastewater system; operational strategies; Monte Carlo simulations; global sensitivity analysis.

1 INTRODUCTION

The EU Water Framework Directive (WFD) (2000/60/EEC) established an innovative approach for water management based on Integrated River Basin Management (IRBM). This approach also applies to urban wastewater systems (UWS), promoting a shift from the individual to the integrated management of the different UWS infrastructures, including sewer system (SS), wastewater treatment plants (WWTP), storage tanks (ST) and receiving water bodies (RWB). This approach increases the complexity for water managers but results in more degrees of freedom during the evaluation of operational strategies, which can lead to a better allocation of economic resources in pollution abatement.

UWS mainly discharge organic matter, suspended solids and nutrients into the rivers. In some cases, the effluent from WWTPs accounts for more than 50% of stream flow and river N and P loads regardless of the climatic region where streams are located (Brooks et al., 2006; Carey et al., 2009). Dilution capacity of the river varies frequently for small rivers in Mediterranean regions and can significantly decrease during summer periods.

The goal of this study is to show the benefits of modelling the whole UWS to evaluate multiple operational strategies to improve its management. Also, this work contributes to the discussion on how to conduct sensitivity analysis on integrated models. From the application point of view, this paper analyses a significant decrease of river flow from 0.4 $m^3 \cdot s^{-1}$ to 0.01$m^3 \cdot s^{-1}$, and suggests operational changes to improve the RWB quality.

2 MATERIALS AND METHODS

2.1 Case-study

A particularity of the system under study is that the two WWTPs that discharge to the evaluated river streatch (15 km long) are connected through a pipe in such a way that the WWTP located upstream (treating 27480 $m^3 \cdot d^{-1}$) can send wastewater to the WWTP downstream (treating 76800 $m^3 \cdot d^{-1}$) if necessary.

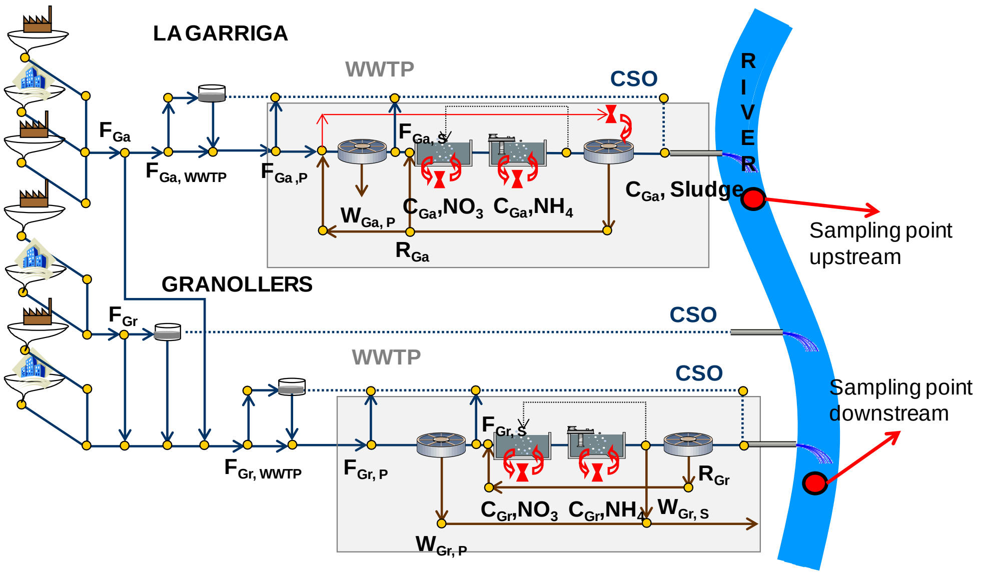

Figure 1. Main elements of the integrated model.

2.2 Model

The integrated model was implemented on a single modelling and simulation platform, WEST (www.mikebydhi.com; Vanhooren et al., 2003), which allowed the integrated system to be in a single executable model with fast simulation speed.

The sub-model used for the catchment and the sewer system is a modified version of the KOSIM model (ITWH 2000) implemented in the WEST model library (Solvi 2007). This includes the following units (see Figure 1): (1) urban catchment, which generates domestic or industrial wastewater patterns; (2) pipes; and (3) wastewater tanks and combined sewer overflows (CSO). The models included in the KOSIM model are pipes modelled as a series of tanks, and wastewater tanks supposed to be ideally mixed. They are modelled off line inside the sewer network, and once they are full they generate a CSO. A pump sets the flow that goes to the WWTP. Water quality components included in the model are COD (soluble and particulate), total nitrogen (TN), ammonia (NH_4^+), total phosphorus (TP) and orthophosphates (PO_4^{3}).

The two WWTPs were modelled using the IWA Activated Sludge Model no.2d (Henze et al., 2000) and the river stretch was modelled with a simplification of the IWA River Water Quality Model no.1 (Reichert et al., 2001). Consumers and chemical equilibria are not included in this simplified version. The integrated model was constructed taking into account the information coming from Devesa et al. (2009).

2.3 Methodology to minimize the impact of UWS

The methodology described by Benedetti et al. (2009) and applied by Prat et al. (2012) was used to solve the problem stated before. This methodology uses sensitivity analysis to define the most sensitive parameters among the available operational settings (in this case 18, Table 1), which are further optimized to find best operating conditions with respect to a set of evaluation criteria calculated in two sampling points in the river stretch (in this case 9, Table 2). The proposed methodology has two main steps: i) the identification of the most sensitive model parameters, and ii) the selection of best operational settings. In the first step, Monte Carlo (MC) simulations are launched to evaluate how the system performs for a wide range of operational settings combinations, the output of the simulations are the criteria to evaluate the system performance (Table 2). Global sensitivity analysis (GSA) is conducted to rank the most influential operational parameters.

The second step consists on a screening methodology (including a Pareto front calculation) applying a multi-criteria analysis to select the best combinations of operational settings.

Table 1. Operational settings

Short name	Description	Unit
C_{Ga}, NH_4	NH_4 set-point of the DO cascade controller La Garriga	$g \cdot m^{-3}$
C_{Gr}, NH_4	NH_4 set-point of the DO cascade controller Granollers	$g \cdot m^{-3}$
C_{Ga}, NO_3	NO_3 set-point of the internal recirculation controller La Garriga	$g \cdot m^{-3}$
C_{Gr}, NO_3	NO_3 set-point of the internal recirculation controller Granollers	$g \cdot m^{-3}$
$W_{Ga, P}$	Wastage flow rate of primary settler La Garriga	$m^3 \cdot d^{-1}$
$W_{Gr, P}$	Wastage flow rate of primary settler Granollers	$m^3 \cdot d^{-1}$
$W_{Gr,S}$	Wastage flow rate of secondary treatment Granollers	$m^3 \cdot d^{-1}$
R_{Ga}	Recycle flow rate after secondary treatment La Garriga	$m^3 \cdot d^{-1}$
R_{Gr}	Recycle flow rate of secondary settler Granollers	$m^3 \cdot d^{-1}$
$F_{Ga,S}$	Flow going to activated sludge La Garriga, overflow goes to river	$m^3 \cdot d^{-1}$
$F_{Gr,S}$	Flow going to activated sludge Granollers, overflow goes to river	$m^3 \cdot d^{-1}$
$F_{Ga, P}$	Flow going to primary settling La Garriga, overflow goes to river	$m^3 \cdot d^{-1}$
$F_{Gr,P}$	Flow going to primary settling Granollers, overflow goes to river	$m^3 \cdot d^{-1}$
C_{Ga},Sludge	Ratio between settled activated sludge and recycle flow La Garriga	
F_{Ga}	Flow going to La Garriga, overflow is bypassed to Granollers system	$m^3 \cdot d^{-1}$
$F_{Ga, WWTP}$	Flow going to La Garriga WWTP, overflow is bypassed to tank in La Garriga	$m^3 \cdot d^{-1}$
F_{Gr}	Flow going to Granollers WWTP, overflow is bypassed to a bigger tank in Granollers	$m^3 \cdot d^{-1}$
$F_{Gr, WWTP}$	Flow going to Granollers, overflow is bypassed to small tank in Granollers	$m^3 \cdot d^{-1}$

The simulations were run for 50 days without inducing any perturbation (with the river flow rate of 0.4 $m^3 \cdot s^{-1}$) and with average and constant input values, until steady-state was achieved. Afterwards, two weeks of perturbation (decreasing the river flow rate down to 0.01 $m^3 \cdot s^{-1}$) using dynamic influent conditions were simulated. The last week of results was used for evaluation purposes.

Table 2. Criteria

Description of the criteria	After discharge of LA GARRIGA	After discharge of GRANOLLERS	
Dissolved oxygen average	DO av Ga	DO av Gr	$gO_2\cdot m^{-3}$
Dissolved oxygen minim	DO min Ga	DO min Gr	$gO_2\cdot m^{-3}$
Ammonium maxim	NH_4 max Ga	NH_4 max Gr	$gN\cdot m^{-3}$
River Quality Index	RQI Ga	RQI Gr	Kg pollutant$\cdot d^{-1}$
Total cost	TC		€$\cdot d^{-1}$

The River Quality Index (RQI) has been calculated with the following formula:

$$RQI = COD + 30 \cdot (TON + S_{NH}) + 10 \cdot (NO_3 + NO_2) + 30 \cdot TP + 2 \cdot BOD$$

[kg pollutant] (E.q. 1)

Where: COD is chemical oxygen demand
TON is total organic nitrogen
S_{NH} is NH_4^+ + NH_3 nitrogen
TP is total phosphorus
BOD is biochemical oxygen demand

Total cost includes aeration, pumping and sludge costs.

3 RESULTS

3.1 Sensitivity analysis

Table 3 summarizes the ranking of the operational settings for the 9 criteria. The parameters are judged as sensitive or not on the basis of the calculation of the absolute value of the t-statistic on the partial correlation coefficients (PCC), which allows the parameters to be classified as significant at the 5% level with a t-statistic larger than 1.96 (Morrison, 1984). The larger the tPCC, the more sensitive the parameter is. The signs specify whether the linear relationship between the operational setting and the criteria is positive or negative.

The three most sensitive operational settings for the sampling point after the discharge of La Garriga are the ammonia set-point of the DO cascade controller at the La Garriga WWTP ($C_{Ga,\ NH4}$), the parameter that defines the flow going from La Garriga to Granollers (F_{Ga}) and the parameter that limits the flow treated biologically at La Garriga WWTP ($_{FGa,\ WWTP}$). In the case of the sampling point located downstream of Granollers, the most important settings are again F_{Ga}, the ammonia set-point of the DO cascade controller at the Granollers WWTP ($C_{Gr,\ NH4}$), the parameter that limits the flow treated biologically at Granollers WWTP ($F_{Gr,\ WWTP}$) and activates the use of a storage tank, and the wastage flow rate in Granollers WWTP ($W_{Gr,\ S}$). When looking at the RQI criteria, the nitrate setpoint of the internal recirculation controller in the anoxic tank of Granollers WWTP ($C_{Gr,\ NO3}$) becomes important together with the parameter that limits the flow going to the Granollers system (F_{Gr}) (sending the excess water to a storage tank). Overall, the aeration capacity of the two WWTPs, the limitation of the flow entering the WWTPs and the use of the connection are the key operational elements.

Finally, the operational settings affecting the TC are related to pumping and sludge treatment (R_{Gr}, $C_{Gr,\ NO3}$; $C_{Ga,\ Sludge}$ and $W_{Gr,\ S}$). Operational settings in Granollers WWTP have larger effect compared to the La Garriga WWTP, as Granollers is a larger plant. R_{Gr} and $C_{Ga,\ Sludge}$ are the external flow recirculation at the WWTP, and recycle flow rates are normally 1.5 times greater than influent flow, so they are the main contributors to pumping costs. Wastage flow rate of secondary treatment in Granollers also contributes significantly to the sludge costs and finally, $C_{Gr,\ NO3}$ also determines the internal recirculation in the Granollers WWTP and contributes to the pumping cost. The case study has a conventional gravity sewer system, therefore the hydraulic parameters ($F_{Ga,}$ $F_{Ga,\ WWTP}$, and others) are not sensitive in the TC criteria.

One limitation of the sensitivity analysis is about the R^2 (coefficient of determination) values of the multi-linear regressions. According to Saltelli et al (2000), when R^2 values are above 0.7, these correlation coefficients can be considered a reliable measure of sensitivity, and in this case, the values range from 0.49 to 0.71 depending on the criteria. Non-linear multi-regression might improve these results.

3.2 Best operational settings

Under normal conditions (river flow values around 0.4 $m^3 \cdot s^{-1}$) the NH_4^+ concentrations in the river are always below 3.5 $g \cdot m^{-3}$ and the DO always higher than 5 $g \cdot m^{-3}$ (results not shown). Current operation results with NH_4^+ peaks higher than 3.5 $gN \cdot m^{-3}$ in the river and DO concentrations below 4 $gO_2 \cdot m^{-3}$. Figure 2 shows the DO and NH_4^+ concentrations at the two sampling points for the current and the proposed operation. The integrated model allows to evaluate the benefits of including storage tanks before the two WWTPs (7000 m^3 upstream and 35000 m^3 downstream), to properly use the connection between the two WWTPs and to better use the WWTP aeration systems and recycle pumps. With the proposed strategy, DO and NH_4^+ concentrations are maintained at the levels under normal conditions.

Table 4. Criteria values compared to reference situation

	LA GARRIGA				GRANOLLERS				TC
	DO_{av}	**DO_{min}**	**$NH_{4,max}$**	**RQI**	**DO_{av}**	**DO_{min}**	**$NH_{4\ max}$**	**RQI**	
Best strat.	5.43	4.07	1.18	320.06	5.81	4.45	2.59	510.02	2307.81
Reference	5.10	3.62	3.19	347.55	5.92	3.96	7.11	550.78	2322.06
% Improv.	6	12	63	8	-1	12	64	7	1

Table 4 shows that $NH_{4,max}$ in la Garriga and Granollers improves by 63% and 64% respectively. DO average in La Garriga improves 6% and DO in Granollers remains similar, but the minimum values improve by 12% in La Garriga and 12% in Granollers.

Table 3. Global sensitivity analysis results for the 18 parameters on the 9 evaluated criteria. tPCC is used to rank the parameters.

	DO_{av} Ga		**DO_{min} Ga**		**$NH4_{max}$ Ga**		**DO_{av} Gr**		**DO_{min} Gr**		**$NH4_{max}$ Gr**		**RQI Ga**		**RQI Gr**		**TC**	
	R^2=	**0.55**	**R^2=**	**0.55**	**R^2=**	**0.56**	**R^2=**	**0.70**	**R^2=**	**0.56**	**R^2=**	**0.54**	**R^2=**	**0.49**	**R^2=**	**0.53**	**R^2=**	**0.71**
	tPCC	**rank**	**tPCC**	**rank**	**tPCC**	**rank**	**tPCC**	**rank**	**tPCC**	**rank**	**tPCC**	**rank**	**tPCC**	**rank**	**tPCC**	**rank**	**tPCC**	**rank**
CGa, NH4	***-14.94***	***1***	***-7.20***	***2***	***14.49***	***1***	0.37	15	-0.15	15	1.40	9	***8.10***	***2***	1.44	9	5.76	5
CGr, NH4	-0.46	11	0.11	18	-0.40	11	***-7.07***	***2***	***-8.26***	***3***	***4.42***	***3***	0.07	16	-1.57	6	0.08	16
CGa, NO3	0.51	10	0.16	15	-0.11	17	0.74	10	0.63	8	-1.00	12	-0.73	8	-1.15	10	4.46	7
CGr, NO3	0.08	17	0.48	14	0.46	9	-0.24	18	0.62	9	-2.06	7	0.63	10	***-7.09***	***3***	***8.43***	***2***
WGa, P	0.63	9	0.48	13	-0.24	15	-0.39	14	0.07	17	-0.08	16	-0.55	13	0.49	13	-0.09	15
WGr, P	0.66	8	0.99	5	-0.28	13	2.74	5	1.29	6	-1.47	8	0.03	18	-1.45	8	1.43	9
RGr	0.31	14	0.53	8	-0.49	7	1.46	8	-0.27	14	-1.04	10	-0.48	14	-0.99	12	***11.78***	***1***
RGa	-0.43	12	***-1.32***	***4***	0.08	18	-0.91	9	-0.35	12	1.01	11	-1.06	6	0.30	15	0.90	10
WGr,S	-0.24	15	-0.52	9	-0.47	8	***6.32***	***3***	***6.82***	***4***	***3.49***	***4***	-0.60	11	-1.75	5	***7.10***	***4***
FGa,S	-0.78	6	0.48	12	***-2.74***	***4***	0.25	17	0.30	13	0.34	14	***-3.16***	***4***	0.14	17	0.37	12
FGr,S	-0.81	5	-0.54	7	-0.43	10	2.43	6	0.14	16	***-6.03***	***2***	-0.77	7	***-9.43***	***2***	4.73	6
FGa, P	0.03	18	0.13	17	0.25	14	-0.56	12	0.38	11	-0.01	18	0.59	12	0.13	18	-0.06	17
FGr,P	0.20	16	0.49	10	-0.13	16	-0.70	11	-0.44	10	0.06	17	0.04	17	-0.29	16	0.02	18
CGa,Sludge	***-2.23***	***4***	-0.49	11	-2.27	5	-0.26	16	0.00	18	-0.18	15	-2.29	5	-0.47	14	***7.74***	***3***
FGa	***-9.27***	***2***	***-15.28***	***1***	***7.32***	***3***	***13.23***	***1***	***9.48***	***2***	-2.25	6	***14.66***	***1***	-1.49	7	0.20	14
FGa, WWTP	***4.67***	***3***	***-7.16***	***3***	***8.15***	***2***	0.46	13	3.55	5	-0.84	13	***4.09***	***3***	1.01	11	-0.33	13
FGr, WWTP	-0.74	7	0.56	6	-0.35	12	***6.12***	***4***	***-10.69***	***1***	***16.09***	***1***	-0.15	15	***13.11***	***1***	2.03	8
FGr	-0.37	13	-0.14	16	-0.55	6	2.11	7	-0.66	7	2.66	5	-0.65	9	***2.14***	***4***	-0.83	11

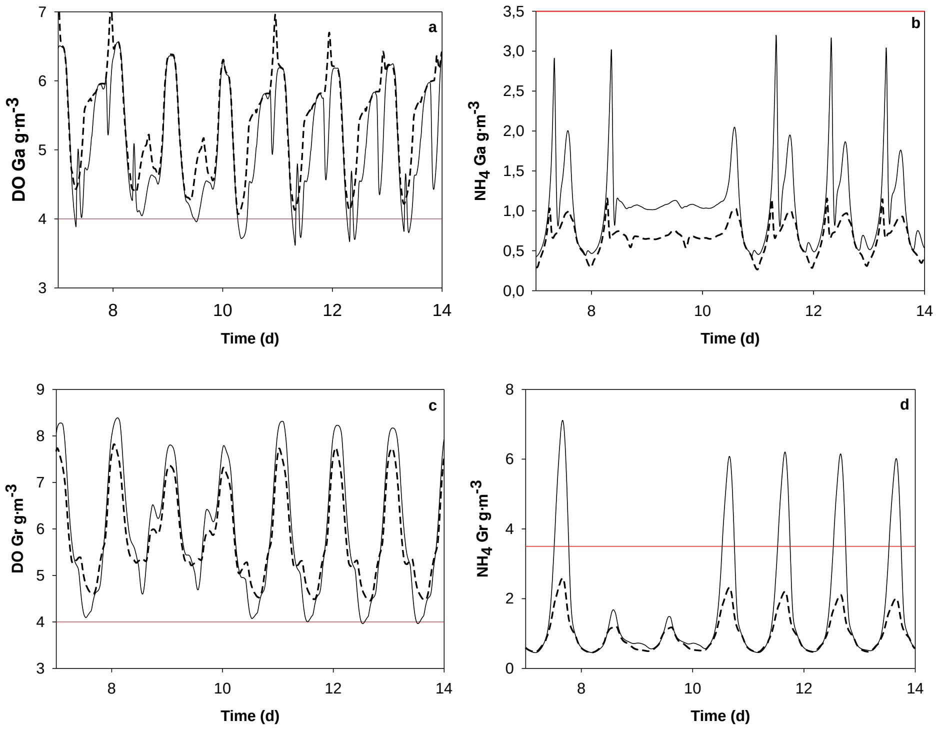

Figure 2. Dissolved oxygen (left) and ammonia concentrations (right) in the river after the upstream WWTP (top) and after the downstream WWTP (bottom) during low river flow events. Solid line is the current operational strategy, dotted line is a better operational strategy and red line is the threshold for dissolved oxygen and ammonia concentration.

The strategy selected makes use of the tanks in La Garriga and Granollers, and also activates the bypass from one system to the other. Figure 3 shows the flow distribution in La Garriga (a) and in Granollers (b) systems. The solid line refers to the total flow produced in the catchment which reaches the system just before any bypass or storage tank. The dotted line refers to the flow that enters the WWTPs. In La Garriga (Figure 3-a), the dark gray area indicates the volume bypassed to Granollers WWTP and the gray area is the volume sent to the storage tank in La Garriga. In Granollers (Figure 3-b), the dark gray area indicates the volume sent to the biggest storage tank located in Granollers. The volume sent to the smallest tank located upstream of the Granollers system is not represented in the graphic.

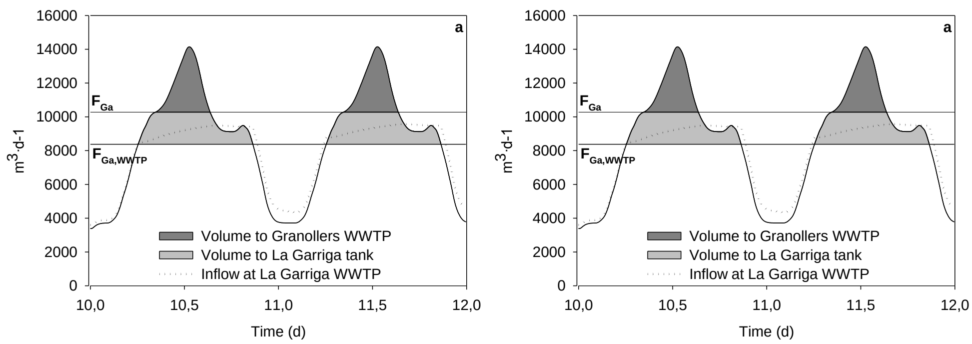

Figure 3. Flow distribution upstream (left) and downstream (right). Solid lines refer to the total flow that reaches each subsystem (before any bypass or storage tank) and dotted lines refer to the flow reaching WWTPs.

The strategy selected also decreases the set-points for the ammonia controllers in both WWTP La Garriga (from 1 to 0.6 $g \cdot m^{-3}$) and Granollers (from 1 to 0.94 $g \cdot m^{-3}$). This results in better effluent characteristics and improves the evaluation criteria. This strategy increases the wastage flow rate in the secondary settler in Granollers WWTP (R_{Gr}) (from 28800 to 29785 $m^3 \cdot d^{-1}$) and readjusts the nitrate controller in the anoxic tank also in Granollers WWTP ($C_{Gr, NO3}$) (from 1 to 2.4 $g \cdot m^{-3}$).

4 CONCLUSIONS AND RECOMMENDATIONS

Integrated models can help to improve the integrated management of UWS. An integrated model has been developed and has been used to overcome the problematic situation of having low river flows during summer periods, decreasing the dilution capacity. A MC analysis coupled with linear regression can provide useful insight into the relative influence of factors, however regressions can result with low R^2 and therefore, other methods are needed to increase the reliability of the sensitivity results. The three storage tanks and the bypass between the two WWTPs play an important role in order to improve the evaluation criteria. The operational settings related to these elements were ranked as the top 4 for all the criteria. Also, the ammonia controller set-points in both WWTPs were important. A multi-criteria decision analysis was performed to identify the best combination of operational settings that resulted with NH_4^+ and DO levels in the river similar to the normal situation.

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