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No-Regret Selection of Effective Control Handles for Integrated Urban Wastewater Systems Management under Parameter and Input Uncertainty

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Abstract: Water quality limits are extended from the wastewater resource recovery facility (WRRF) to the sewer system. Integration of these systems, however, leaves us with multiple potential options to reduce overall emission. The proposed approach builds on previous research using global sensitivity analyses (GSA) as a screening method for available control handles. It considers parameter and input uncertainty to select control handles that lead to large benefits even if the model differs from reality (no-regret selection). Results on a real-life case study indicate that the three top-rated handles are comparably effective under uncertainty, but for lower-rated handles further analysis is necessary.

Keywords: Sensitivity analysis; Control authority; Particle settling velocity distribution

Introduction

Integrated modelling is a powerful tool for the evaluation of the interactions between different sub-systems (Rauch et al., 2002). Integrated evaluation is of increasing interest, as water quality standards no longer apply to the wastewater resource recovery facility (WRRF) only, but start to be extended to the sewer system, in particular to combined sewer overflows (CSO). An example is France, where each utility has to choose one out of three compliance criteria. One of the three choices includes water quality limits for CSOs: the overflow pollutant flux has to be smaller than 5% of the total pollutant flux per year (JORF, 2015). Integrated modelling covering the sewer system as well as the WRRF is therefore more important than ever as it allows evaluating the overall pollutant emission to the natural environment. With an integrated model, potential strategies to reduce pollutant emission can be evaluated for the whole catchment instead of a local analysis of, for instance, one particular CSO.

If the objective is to improve the quality of the receiving water to comply with legislation, an integrated approach leaves us with plenty of potential control handles in the integrated system. All of those control handles could be used to reduce the overall emissions. It seems however reasonable to concentrate the efforts on the most effective control handles. It is therefore useful to use a screening technique of all potential control handles and identify the best handles prior to the development of any strategies. Global sensitivity analysis (GSA) has been proposed as a model-based tool to perform such control handle ranking (Langeveld et al., 2013, Sweetapple et al., 2014, Saagi et al., 2018).

This research builds on previous approaches for ranking control handles with GSA. To do so, each control handle is given a distribution with potential values the control handle can take. However, in comparison to previous studies, it also considers parameter and input uncertainty as the used model is not perfect and the control authority may depend on the particular reality within the uncertainty range studied. The objective of the case study is to select the most effective control handles for the development of strategies that reduce the total suspended solids (TSS) flux to the receiving water. Input and parameter uncertainty are considered by developing scenarios with a different input or set of parameters and for each of the scenarios a GSA is carried out. The GSA allows ranking the control handles for each scenario. The ranking of the control handles for the different scenarios is then compared. This allows no-regret decisions with respect to the selection of the control handles by selecting those that will work effectively for a wide range of parameter and input conditions and can thus be implemented in practice with confidence.

Material and Methods

The case study "Clos de Hilde" (CdH) is located in the southern parts of Bordeaux, France and covers a catchment of about 8 000 ha. Major pumping stations and CSOs exist on both sides of the Garonne river (see Figure 1). These represent all potential control handles for the reduction of TSS emission to the Garonne. Regulations for the WRRF include TSS, COD and BOD_5 and, importantly, contain for the first time CSO water quality standards that cities will have to comply with in the near future (JORF, 2015).

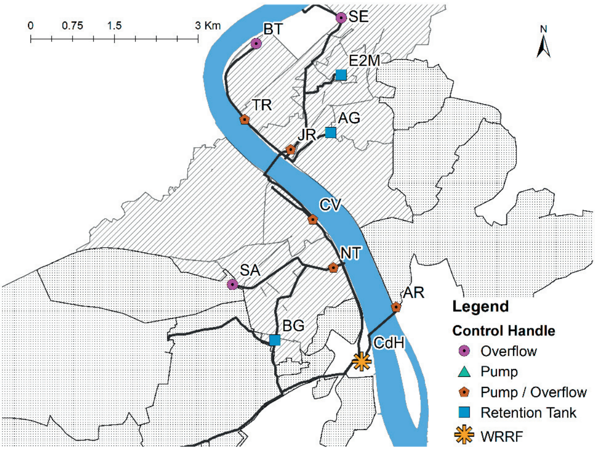

Figure 1 Map of the case study Clos de Hilde with identified potential control handles.

The integrated model of the case study covers the system starting at the catchments down to the effluent of the primary clarifiers. It uses the particle settling velocity distribution (PSVD) approach for water quality modelling of TSS (Maruéjouls et al., 2015). The catchment model is based on the KOSIM-WEST model (Meirlaen, 2002), coupling a module for wet weather flow (WWF) and a module for dry weather flow (DWF). In comparison to the original model, WWF routing can be split into a fast and a slow component (Pieper, 2017). The TSS is fractionated into ten classes according to measured settling velocity distributions. The sewer conduits are modelled with PSVD linear reservoirs in series (Ledergerber et al., 2019). The retention tanks (RT) are represented with a simplified version of the PSVD RT model, without the detailed pumping chamber model that the original model has (Maruéjouls et al., 2012). For the grit chamber and the primary clarifiers adaptations of the model described by Bachis et al. (2015) and Tik and Vanrolleghem (2017) are implemented.

The control handles considered are mainly pumping and throttle capacities limiting the flow to the WRRF at pumping stations and overflows. Additional control handles are related to the three RTs. The flow rates at which the filling of the RT starts, and the emptying flow rate are considered for all RTs. The locations of the control handles are shown in Figure 1. Table 1 summarizes the control handles with their currently implemented values and the range over which they will be studied in the GSA.

Table 1 Potential control handles for TSS flux reduction to the receiving water with currently implemented values and upper and lower limits for the GSA evaluation

#	Abbr.	Description	Value (m^3/d)	Lower limit (m^3/d)	Upper limit (m^3/d)
0	$Q_{P,AR}$	Max. pumping capacity at Arcins	5 182	2 590	7 770
1	$Q_{P,BT}$	Max. pumping capacity at Bastide	840	420	1 260
2	$Q_{P,CV}$	Max. pumping capacity at Carle Vernet	21 600	10 800	32 400
3	$Q_{P,JR}$	Max. pumping capacity at Jourde	21 600	10 800	32 400
4	$Q_{P,NT}$	Max. pumping capacity at Noutary	26 957	13 500	40 400
5	$Q_{Empt,AG}$	Emptying flow rate RT Alfred Giret	65 000	19 500	65 000
6	$Q_{Empt,BG}$	Emptying flow rate RT Bergonié	4 320	2 160	4 320
7	$Q_{Empt,E2M}$	Emptying flow rate RT Entre deux mers	38 000	4 320	38 000
8	$Q_{T,SA}$	Throttle capacity at Siphon d'Ars	38 880	19 400	58 300
9	$Q_{Fill,AG}$	Flow filling RT Alfred Giret	95 000	9 500	95 000
10	$Q_{Fill,BG}$	Flow filling RT Bergonié	5 000	2 500	7 500
11	$Q_{Fill,E2M}$	Flow filling RT Entre deux mers	5 900	2 950	8 850
12	$Q_{P,SE}$	Max. pumping capacity at St. Émilion	7 344	3 670	11 000
13	$Q_{P,TR}$	Max. pumping capacity at Thiers	3 456	1 730	5 180

In contrast to Saagi et al. (2018), the standardized regression coefficient (SRC) method (Saltelli et al., 2008) is preferred over the Morris method for the GSA, as convergence problems are known with the latter (Vanrolleghem et al., 2015). The GSA is performed for the objective function of total TSS emission to the natural environment from the sewer system via CSOs and the WRRF after primary treatment. The ranking of each control handle is evaluated using the absolute value of the obtained SRC. For the control handles, a uniform distribution with generally ± 50% of the currently implemented limit is tested (Table 1). For the potential control handles regarding the RTs, only values smaller than the currently implemented values were considered. Indeed, the RTs are currently in operation for extreme rain events only. Testing smaller values allows evaluating the interest to activate them also for rain events with shorter return periods. Quality control of the GSA was performed by evaluating the quality of the regression ($R^2 > 0.7$; Consenza et al, 2013) and the Variance Inflation Factor ($VIF < 5$; Rogerson, 2014).

The consistency of the ranking of the control handles is evaluated for different scenarios representing parameter uncertainty and the uncertainty related to the selection of the input rain event. A schema of the approach is presented in Figure 2.

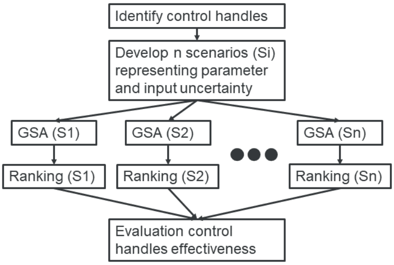

Figure 2 Methodology to evaluate control handles under parameter and input uncertainty

The rain events and the water quality model parameters considered to build the uncertainty scenarios are listed in Table 2. The parameters are all related to the water quality model: the mean TSS concentration for DWF generation in the catchment ($Conc_{TSS}$(DWF)) and event mean TSS concentration for WWF ($Conc_{TSS}$(WWF)). The last three parameters are related to the TSS propagation in the sewer model and affect the resuspension function of the TSS ($r_{resusp,max}$, f_{Qhalf}, n_{resusp}). The sewer water quality model is described in more detail in Ledergerber et al. (2019). Two calibration points (CdH and NT) were available for the water quality model, resulting in two sets of values for each parameter. For the development of the uncertainty scenarios the values of the parameters are varied by ±20% of their calibrated value (also indicated in Table 2). The characteristics of the different rain events chosen are given in Table 3. This results in the default scenario and 24 additional uncertainty scenarios.

Table 2 Default and variation values for model input and parameters to develop different uncertainty scenarios representing parameter and input uncertainty

Parameter	**Unit**	**Value**				
		Default	**Var 1**	**Var 2**	**Var 3**	**Var 4**
Rain Event	-	RE1	RE 2	RE 3	RE 4	RE 5
$Conc_{TSS}$(DWF,CdH)	mg/l	350	420	218		
$Conc_{TSS}$(DWF,NT)	mg/l	440	528	352		
$Conc_{TSS}$(WWF,CdH)	mg/l	50	60	40		
$Conc_{TSS}$(WWF,NT)	mg/l	80	96	64		
$r_{resusp,max}$(CdH)	1/d	24	29	19		
$r_{resusp,max}$(NT)	1/d	48	58	38		
f_{Qhalf}(CdH)	-	1.4	1.7	1.1		
f_{Qhalf}(NT)	-	1.5	1.8	1.2		
n_{resusp}(CdH)	-	4	5	3		
n_{resusp}(NT)	-	8	10	6		

Table 3 Characteristics of the different rain events with which uncertainty scenarios were built

Event	**Start Date**	**End Date**	**Cumulative Rain**	**Duration**	**Return period**
	[dd.mm.yy]	**[dd.mm.yy]**	**[mm]**	**[h]**	
RE 1	01.05.17	04.05.17	19.2	14.0	2 months
RE 2	17.05.17	21.05.17	37.3	24.6	8 months
RE 3	29.05.17	01.06.17	7.5	7.7	0.5 months
RE 4	27.06.17	02.07.17	105.0	46.3	> 24 months
RE 5	14.06.17	16.06.17	4.0	2.4	0.5 months

Results and Discussion

For each of the 25 uncertainty scenarios a GSA was conducted and the calculation of the absolute SRC allowed ranking the control handles according to their effectiveness. Figure 3 summarizes the results by showing how often a control handle takes a specific rank. The ranking distributions of the top three control handles ($Q_{P,NT}$, $Q_{P,CV}$, $Q_{P,JR}$) are highlighted in green. The distributions are narrow, meaning that these control handles are ranked high constantly, i.e. irrespective of the uncertainty scenario analysed. Figure 3 also shows that some of the control handles have a very wide distribution of their rankings. $Q_{P,TR}$ and $Q_{Fill,BG}$, for example, show ranks between 7-14, respectively 5-13 (highlighted in blue). Interesting are also control handles that show two fairly opposed peaks, meaning that, depending on the uncertainty scenario, they are rather effective or rather ineffective control handles. Examples of this distribution are highlighted in orange in Figure 3 ($Q_{P,SE}$ and $Q_{P,AR}$). An analysis of the results in more detail showed that they have the tendency to take opposing ranks in the same scenario, meaning that if $Q_{P,SE}$ is ranked high, $Q_{P,AR}$ is usually ranked low.

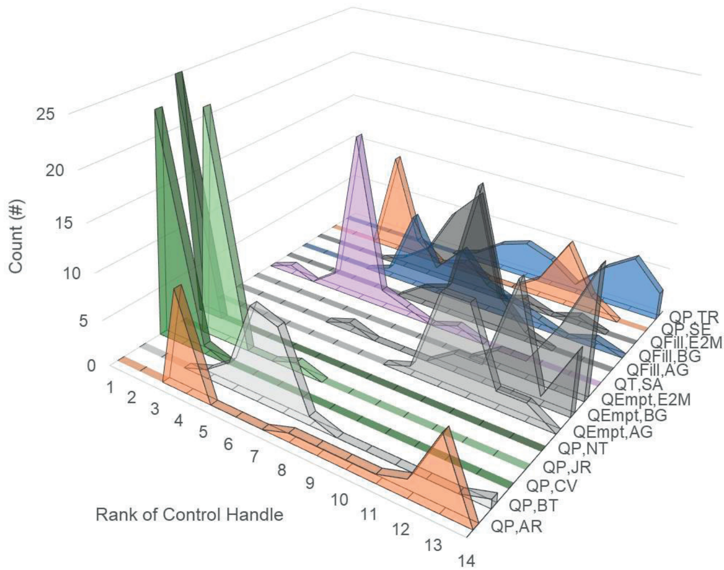

Figure 3 Distribution of the rank of control handles resulting from the different uncertainty scenarios.

Figure 4 gives the values of the SRCs of each control handle for every uncertainty scenario evaluated. The results indicate a wide range of absolute SRC values ($2*10^{-4}$ to 0.86) meaning that the potential impact of the control handles on receiving water quality improvement varies over a wide range. The results also show that the three highest rated control handles ($Q_{P,NT}$, $Q_{P,CV}$, $Q_{P,JR}$) have an average (0.78, 0.46 and 0.26) which is considerably higher than the fourth highest average of $Q_{T,SA}$ (0.07).

A positive, respectively a negative SRC value gives us an indication in which direction a control handle needs be changed to reduce the overall TSS flux to the environment. For the three highest rated control handle the SRC value is negative, which means that increasing the pumping capacity towards the WRRF will reduce the TSS flux to the Garonne (because the TSS can be removed at the WRRF). This is, however, not the case for the limiting throttle capacity towards the WRRF of the fourth control handle $Q_{T,SA}$. In this case, the limiting capacity to the WRRF would need to be decreased, meaning that locally more overflow is created (!), to overall reduce the TSS emission. Figure 1 shows that SA is located upstream of the highly used pumping station NT. The catchment upstream SA is mainly influence by WWF and the more polluted DWF plays only a minor role. This means that it is favourable to overflow the less polluted water at SA instead of further transporting it to NT, where it is mixed with more polluted water and might cause a highly loaded overflow.

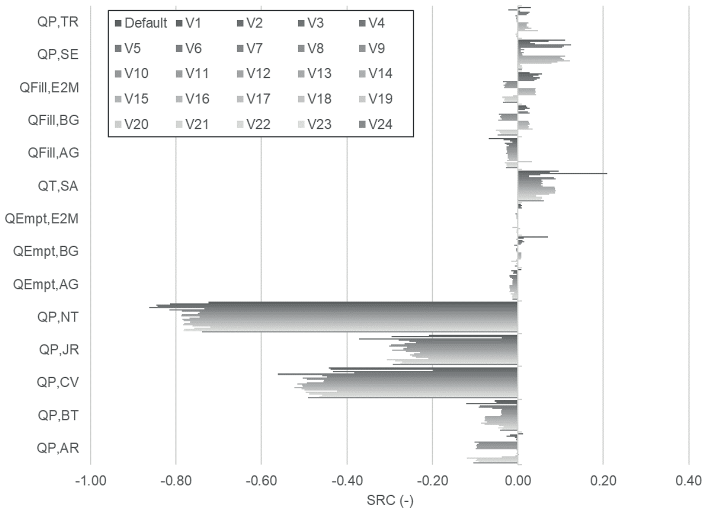

Figure 4 SRC of the evaluated control handles under the scenarios of parameter and input uncertainty.

Comparing the pumping capacity of the second and third rated control handle $Q_{P,CV}$, and $Q_{P,JR}$ shows that they have currently the same capacity installed (see Table 1). The results, however, clearly indicate that increasing the pumping capacity at CV would have a bigger effect than at JR.

Finally, Figure 4 shows for some lower ranked control handles that the SRC values switch from positive to negative depending on the scenario (for example $Q_{P,TR}$, $Q_{Fill,E2M}$ or $Q_{Fill,BG}$). This means that depending on the actual parameter values and the specific rain event, an increase of the value of the control handle might increase respectively decrease the TSS flux to the environment.

Conclusions

The proposed methodology based on multiple GSAs of control handles conducted for a (limited) set of uncertainty scenarios allows studying the sensitivity of the control handle ranking to potential deviations between model and reality, including variability of rain events. The results indicate that the three control handles that are on average ranked highest are keeping their rank for a wide range of scenarios. This means that developing scenarios for reduction of the TSS flux to the natural environment based on these handles will not only have the greatest impact but will most likely also be a no-regret decision, i.e. they will have a good impact even if the model was not a perfect description of reality or the rain events studied do not cover all possible rain events that may occur. Focusing on the lower ranked control handles would not only have a smaller positive impact on the environment and (assuming comparable investments) seems therefore less sensible. Even worse, depending on the actual parameter values and the specific rain event occurring, they might even increase the TSS flux to the environment. The evaluation of multiple GSAs representing parameter and input uncertainty showed that their effect changes from positive to negative under certain conditions. Note that this would not have been visible in a static GSA with only one parameter set and one rain event, which might have led to a regret-decision.

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References

Bachis, G., Maruéjouls, T., Tik, S., Amerlinck, Y., Melcer, H., Nopens, I., Lessard, P., and Vanrolleghem, P. A. (2015). Modelling and characterization of primary settlers in view of whole plant and resource recovery modelling. *Water Sci. Technol.*, 72(12):2251–2261.

Cosenza, A., Mannina, G., Vanrolleghem, P. A., and Neumann, M. B. (2013). Global sensitivity analysis in wastewater applications: A comprehensive comparison of different methods. *Environ. Model. Softw.*, 49:40–52.

JORF (2015). Arrêté du 21 juillet 2015 relatif aux systèmes d'assainissement collectif et aux installations d'assainissement non collectif, à l'exception des installations d'assainissement non collectif recevant une charge brute de pollution organique inférieure ou égale à 1,2 kg/j de DBO5. Journal Officiel de la République Française (in French).

Langeveld, J. G., Benedetti, L., de Klein, J. J. M., Nopens, I., Amerlinck, Y., van Nieuwenhuijzen, A., Flameling, T., van Zanten, O., and Weijers, S. (2013). Impact-based integrated real-time control for improvement of the Dommel river water quality. *Urban Water J.*, 10(5):312–329.

Ledergerber, J. M., Tik, S., Maruéjouls, T., and Vanrolleghem, P. A. (2019). A validated conceptual sewer water quality model based on the particle settling velocity distribution. In *Proceedings of the 9th International Conference on Sewer Processes and Networks (SPN)*, Aalborg, Denmark, August 27-31 2019 (in press).

Maruéjouls, T., Lessard, P., and Vanrolleghem, P. A. (2015). A particle settling velocity-based integrated model for dry and wet weather wastewater quality modeling. In *Proceedings of the WEF Collection Systems Conference*, Cincinnati, Ohio, United States, April 19-22 2015.

Maruéjouls, T., Vanrolleghem, P. A., Pelletier, G., and Lessard, P. (2012). A phenomenological retention tank model using settling velocity distributions. *Water Res.*, 46(20):6857–6867.

Meirlaen, J. (2002). *Immission based real-time control of the integrated urban wastewater system*. PhD thesis, Ghent University, Ghent, Belgium.

Pieper, L. (2017). Development of a model simplification procedure for integrated urban water system models – conceptual catchment and sewer modelling. Master's thesis, Université Laval, Québec, QC, Canada.
Rauch, W., Bertrand-Krajewski, J.-L., Krebs, P., Mark, O., Schilling, W., Schütze, M., and Vanrolleghem, P. A. (2002). Deterministic modelling of integrated urban drainage systems. *Water Sci. Technol.*, 45(3):81–94.
Rogerson, P. A. (2014). *Statistical methods for geography: a student's guide*. Sage Publications, London, UK.
Saagi, R., Kroll, S., Flores-Alsina, X., Gernaey, K. V., and Jeppsson, U. (2018). Key control handles in integrated urban wastewater systems for improving receiving water quality. *Urban Water J.*, 15(8):790–800.
Saltelli, A., Ratto, M., Andres, T., Campolongo, F., Cariboni, J., Gatelli, D., Saisana, M., and Tarantola, S. (2008). *Global Sensitivity Analysis: The Primer*. John Wiley & Sons, West Sussex, UK.
Sweetapple, C., Fu, G., and Butler, D. (2014). Identifying sensitive sources and key control handles for the reduction of greenhouse gas emissions from wastewater treatment. *Water Res.*, 62:249–259.
Tik, S. and Vanrolleghem, P. A. (2017). Chemically enhancing primary clarifiers: model-based development of a dosing controller and full-scale implementation. *Water Sci. Technol.*, 75(5):1185–1193.
Vanrolleghem, P. A., Mannina, G., Cosenza, A., and Neumann, M. B. (2015). Global sensitivity analysis for urban water quality modelling: Terminology, convergence and comparison of different methods. *J. Hydrol.*, 522:339–352.