No-regret selection of effective control handles for integrated urban wastewater systems management under parameter and input uncertainty

J. M. Ledergerber, T. Maruéjouls and P. A. Vanrolleghem

ABSTRACT

Regulatory water quality limits are extended from the wastewater resource recovery facility (WRRF) to the sewer system. It is thus necessary to properly integrate those systems for the evaluation of the overall emissions to the receiving water. The integration of the sewer system and the WRRF, however, leaves us with multiple potential options to reduce these emissions. The proposed approach builds on previous research using global sensitivity analysis (GSA) as a screening method for available control handles. It considers parameter and input uncertainty to select control handles that generate large benefits even if the model differs from reality. Results from a real-life case study indicate that the three top-rated handles are comparably effective for all considered uncertainty and variability scenarios. But the results also showed that this does not apply to lower-rated handles.

Key words | control authority, integrated modelling, particle settling velocity distribution, sensitivity analysis

J. M. Ledergerber (corresponding author)
P. A. Vanrolleghem
modelEAU and CentrEau,
Université Laval,
Québec,
Canada
E-mail: *julia-margrit.ledergerber.1@ulaval.ca*

T. Maruéjouls
Le LyRE, Suez Eau France SAS,
Talence,
France

INTRODUCTION

Integrated modelling is a powerful tool for the evaluation of the interactions between different subsystems (Rauch *et al.* 2002). Such integrated evaluation is of increasing interest, as water quality standards no longer apply to the wastewater resource recovery facility (WRRF) only, but are expanded 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. Assessing the overall pollutant emission to the natural environment allows evaluation of the compliance with regulations for both the sewer system and the WRRF. An integrated model also allows evaluation of potential strategies to reduce these emissions considering the effects on the entire catchment instead of conducting a local analysis of, for instance, one particular CSO.

If the objective is to improve the quality of the receiving water, an integrated approach, however, leaves us with plenty of potential modifications to different subsystems, named here after control handles. Since all of those control handles could be used to reduce the overall emissions, it seems reasonable to concentrate the efforts on the most effective ones. It is therefore useful to use a screening technique for this selection. Only once those handles are identified does the development of the specific strategies, for example to reduce the emissions, start.

Global sensitivity analysis (GSA) has been proposed as a model-based tool to perform such control handle selection (Benedetti *et al.* 2012; Langeveld *et al.* 2013; Corominas & Neumann 2014; Sweetapple *et al.* 2014; Saagi *et al.* 2018), as it allows identification of the most influential parameters for a given objective. For the ranking of the control handles these studies conducted a GSA on the settings of the control handles, basically a specific subset of model parameters, which allows ranking them. The current research builds on these approaches for ranking the control handles. However, in comparison with previous studies, the methodology is extended to consider parameter uncertainty and input variability. This is important as the model is not a perfect representation of reality and the control authority may depend on the particular reality modelled. Such

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considerations gain importance when costly infrastructure decisions are based on the model's results. To account for potential deviation between model and reality, variable model input and parameter uncertainty have to be considered. The proposed procedure allows working towards a no-regret selection of the control handles by accepting only those handles that will work effectively for a wide range of parameter and input conditions.

The proposed procedure is validated with a case study. For the case study, pollutant emission towards the receiving water is limited with respect to total suspended solids (TSS). It is thus of interest to identify the most effective control handles that reduce the TSS flux to the receiving water. Since a well-performing model is not a perfect representation of reality by far and the model input is variable, it is important to consider this when selecting control handles. This will help to avoid regret decisions, such as investing in a wrongly ranked handle.

PROPOSED PROCEDURE

The proposed procedure to evaluate control handles under parameter uncertainty and input variability is presented in Figure 1. As in the approaches proposed in the literature, the first step is to define the objective function allowing evaluation of the potential of the control handles and then identification of the control handles to be studied.

Instead of directly ranking the control handle with the calibrated and validated model, in the second step *n* different scenarios are developed representing parameter uncertainty and input variability. The scenarios are created based on prior knowledge of the modeller resulting from developing, calibrating and validating the model.

In the third step, a GSA is carried out for each of the scenarios. For each GSA, the control handles are ranked according to the GSA results.

This then allows evaluation of the consistency of the ranking of the control handles in the last step by comparing the results from the different scenarios representing parameter uncertainty and input variability.

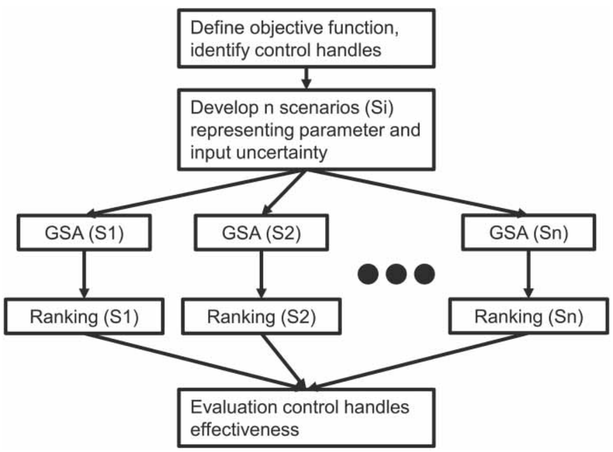

Figure 1 | Proposed procedure to evaluate control handles under parameter and input uncertainty.

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 CSOs, pumping stations, and retention tanks (RTs) exist on both sides of the Garonne river (see Figure 2). These represent all potential control handles for the reduction of TSS emissions to the Garonne. Regulations for the WRRF include TSS and chemical and biochemical oxygen demand and, importantly, potentially contain for the first time CSO water quality standards that cities will have to comply with by 2020 (JORF 2015).

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 with 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 RTs are represented by 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 *et al.* (2016) are implemented. It is important to note that this conceptual approach is very efficient from a computational point of view: the evaluation of the whole integrated urban wastewater system has on average a simulation time of less than one minute for a whole day of simulation (including WWF).

The aim is to select control handles for the development of scenarios to reduce TSS emission in comparison with the current default status. Since the default emission for a

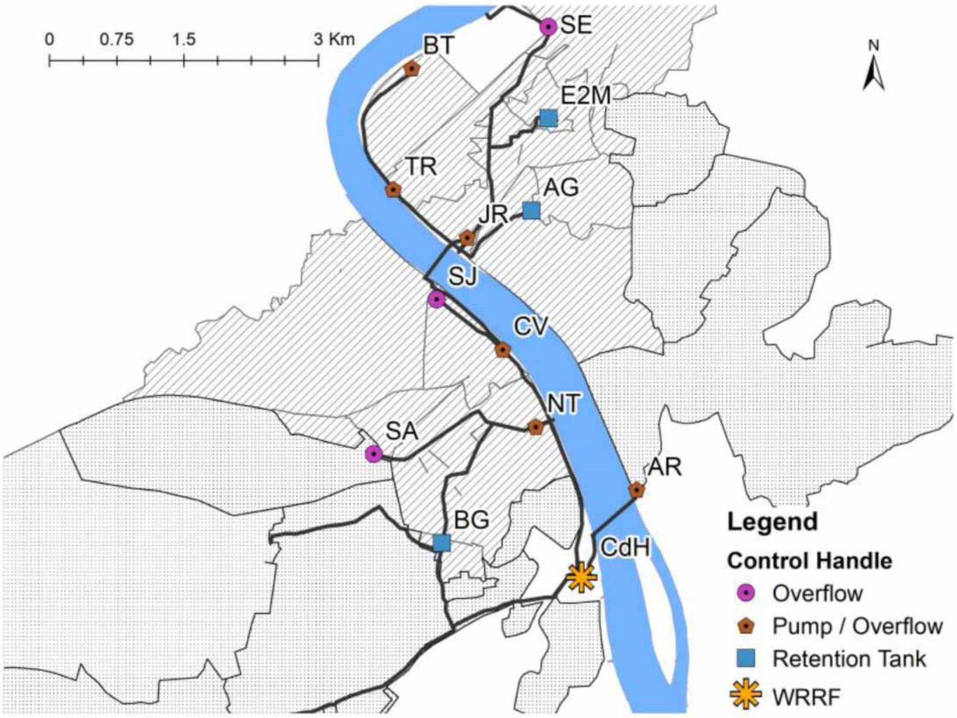

Figure 2 | Map of the case study Clos de Hilde (CdH) with identified potential control handles.

specific scenario results in a discrete value, the total TSS flux with varying control handle values can be chosen as the objective function of the GSA, as it approximates the flux reduction potential. The control handles are thus ranked based on their influence on total TSS flux. The potential control handles identified are mainly pumping and throttle capacities that limit the flow to the WRRF at pumping stations and overflows. Increasing a pumping, respectively a throttling, capacity towards the WRRF will reduce the overflow at the particular CSO. These modifications would require either the installation of new pumps or modifications of the throttle device. The 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. To change the filling of the RT, the crest of the weir would need to be modified, whereas for the emptying flow rate the currently installed pumps would need to be controlled differently. The locations of the control handles are shown in Figure 2. Table 1 summarizes the control handles with their currently implemented values and the range over which they will be studied in the GSA. The range generally corresponds to ±50% of the currently implemented value with the exception of the RT control handles. For those parameters, only smaller values than the currently implemented values are studied. At present, the RTs are exclusively filled for flood protection control and are thus only very rarely in use. The operators, however, want to extend their service to the control of CSOs. Thus, lowering those values allows operation of the RTs also for smaller rain events. The lower limits are selected with respect to both the implemented pumps and thus the operational feasibility as well as the RT's storage capacity in comparison with the connected surface.

For the development of the scenarios representing parameter uncertainty, the model parameters considered 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 ($Conc_{TSS}(WWF)$) for the two available measurement points in the sewer system, CdH and NT respectively. These measurement points are also indicated in Figure 2. 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). For the development of the uncertainty scenarios the values of the parameters are varied by ±20% of their calibrated value, as indicated in Table 2.

The inputs to the model are the rain intensity time series. Thus, to represent the variability of the input, different rain

Table 1 | Potential control handles for total suspended solids flux reduction to the receiving water with currently implemented values and upper and lower limits for the global sensitivity analysis evaluation. RT = retention tank

#	Abbreviation	Description	Value (m^3/d)	Lower limit (m^3/d)	Upper limit (m^3/d)
1	$Q_{P,AR}$	Max. pumping capacity at Arcins	5,182	2,590	7,770
2	$Q_{P,BT}$	Max. pumping capacity at Bastide	840	420	1,260
3	$Q_{P,CV}$	Max. pumping capacity at Carle Vernet	21,600	10,800	32,400
4	$Q_{P,JR}$	Max. pumping capacity at Jourde	21,600	10,800	32,400
5	$Q_{P,NT}$	Max. pumping capacity at Noutary	26,957	13,500	40,400
6	$Q_{Empt,AG}$	Emptying flow rate RT Alfred Giret	65,000	19,500	65,000
7	$Q_{Empt,BG}$	Emptying flow rate RT Bergonié	4,320	2,160	4,320
8	$Q_{Empt,E2M}$	Emptying flow rate RT Entre deux mers	38,000	4,320	38,000
9	$Q_{T,SA}$	Throttle capacity at Siphon d'Ars	38,880	19,400	58,300
10	$Q_{Fill,AG}$	Flow filling RT Alfred Giret	95,000	9,500	95,000
11	$Q_{Fill,BG}$	Flow filling RT Bergonié	5,000	2,500	7,500
12	$Q_{Fill,E2M}$	Flow filling RT Entre deux mers	5,900	2,950	8,850
13	$Q_{P,SE}$	Max. pumping capacity at St. Émilion	7,344	3,670	11,000
14	$Q_{P,TR}$	Max. pumping capacity at Thiers	3,456	1,730	5,180

Table 2 | Default parameter values and their variation values representing parameter uncertainty for the development of the different scenarios. CdH = Clos de Hilde; DWF = dry weather flow; TSS = total suspended solids

		Value		
Parameter	**Unit**	**Default**	**Var 1**	**Var 2**
$Conc_{TSS}$(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

events are chosen. The characteristics of the chosen rain events are given in Table 3. Since the overall goal is to reduce the TSS flux towards the receiving water, rain events are chosen with a return period for which CSO control is typically targeted (events appearing several times over a summer). An additionally quite heavy rain event (expected less than every other year) is chosen to push the boundaries.

The resulting scenarios of the case study are thus as follows. The first scenario analysed is the default scenario, combining the default rain event (RE1) with the default model parameter values. An additional 20 scenarios are evaluated to consider parameter uncertainty. For all of the ten indicated parameters a scenario is run by combining the lower, respectively upper, variation (Var 1 and 2) of a specific parameter with the other default parameters and the default rain event. The last four scenarios are run to consider input variability. For this, the default parameters are combined with the four additional rain events chosen (REs 2 to 5). This means that a total of 25 scenarios is analysed, resulting in the evaluation of 25 GSAs.

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 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). Quality control of the GSA was performed by evaluating the quality of the regression ($R^2 > 0.7$; Cosenza *et al.* 2013) and the variance inflation factor (<5; Rogerson 2014).

RESULTS AND DISCUSSION

For each of the 25 uncertainty scenarios a GSA was conducted and the calculation of the absolute SRC value allowed ranking of the control handles according to their

Table 3 | Characteristics of the different rain events (REs) with which uncertainty scenarios were built

Event	Start date [dd.mm.yy]	End date [dd.mm.yy]	Cumulative rain [mm]	Duration [h]	Return period
RE 1 (Default)	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

effectiveness. Since 25 different GSAs were conducted, 25 different rankings are available. This allows study of the effect of uncertainty and variability, represented as scenarios, on the ranking. An option to visualize the control handle ranking under uncertainty and variability is to count how often a control handle takes a specific rank. Figure 3 indicates this for the case study, where 14 different control handles were studied, thus resulting in 14 different ranks. Since 25 scenarios were analysed, each handle can take 25 positions. If the rank of a handle is indifferent to the uncertainty scenario analysed, it will take the same position 25 times. If, however, the ranking of a handle depends quite heavily on the scenario chosen, the 25 counts will be distributed over a wide range of ranks. 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 and 14, respectively 5 and 13 (highlighted in blue). This means that depending on the scenario studied, the control handle can be quite important, respectively unimportant. Interesting are also control handles that show two fairly opposed peaks, meaning that, depending on the uncertainty scenario,

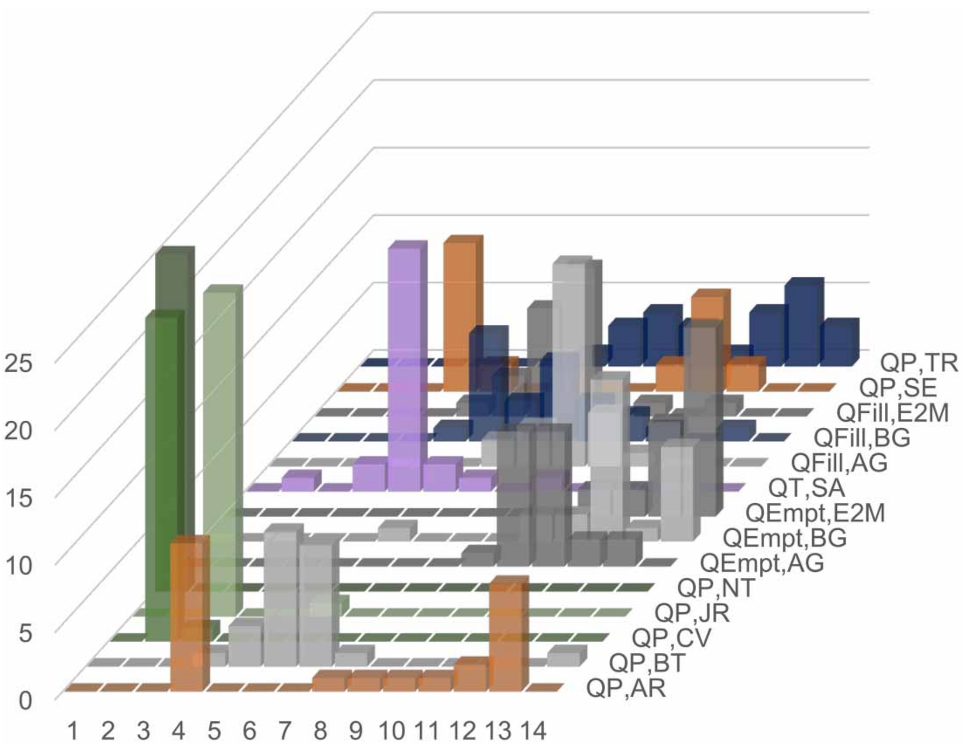

Figure 3 | Distribution of the rank of control handles (1–14) resulting from the 25 different uncertainty scenarios.

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 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^{-5} 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). Comparing these findings with the currently implemented capacities at the pumping stations in Table 1 shows that the installed pumping capacity at NT is highest. It is, however, interesting to note that the same increase in the pumping capacity at CV would have a more important effect than at JR, since those pumping stations have currently the same pumping capacity installed (see Table 1).

Figure 4 also shows whether the SRC values are positive or negative. A positive, respectively a negative, SRC value gives an indication in which direction a control handle needs to be changed to reduce the overall TSS flux to the environment. For the three highest rated control handles 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 2 shows that SA is located upstream of the highly used pumping station NT. The catchment upstream SA is mainly influenced 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.

Finally, plotting the SRC values as in Figure 4 also allows evaluation of whether a control handle switches

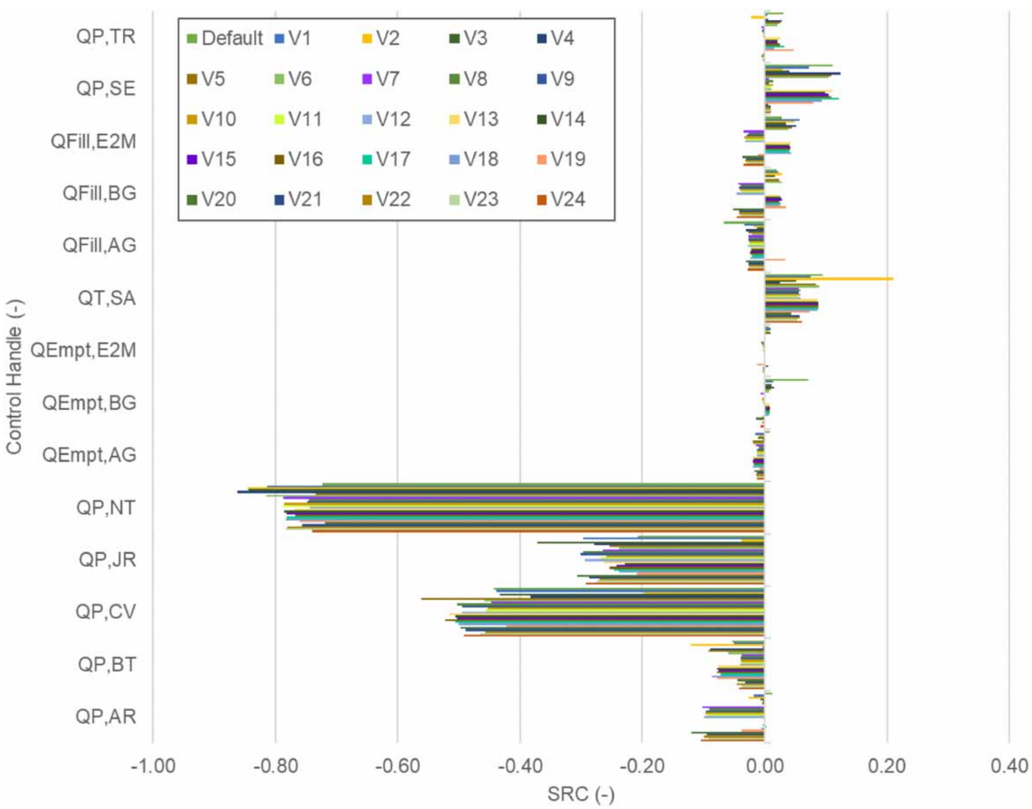

Figure 4 | Standardized regression coefficient of the evaluated control handles under the scenarios of parameter and input uncertainty.

from positive to negative values depending on the scenario. This means that depending on the actual model parameter values and the specific rain event, an increase in the value of the control handle either increases or decreases the TSS flux to the environment. Depending on the unknown reality, such a control handle can thus have the desired or the unwanted effect. For the given case study, this only occurred for control handles with generally very low SRC values and thus quite unimportant control handles, such as $Q_{P,TR}$, $Q_{Fill,E2M}$ or $Q_{Fill,BG}$.

CONCLUSIONS

The proposed methodology based on multiple GSAs of control handles conducted for a limited set of uncertainty scenarios allows study of the sensitivity of the control handle ranking to potential deviations between model and reality with respect to parameter uncertainty and input variability, here namely 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 also be robust with respect to parameter deviations between model and reality and will most likely have good impact for a wide range of rain events. 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. 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. This methodology provides a tool to help urban wastewater system operators and stakeholders to decide about the most effective control handles for further development of their management strategies. The procedure considers parameter uncertainty and input variability and is thus working towards a no-regret selection. Additional sources of uncertainty, such as measurement uncertainty and structural uncertainty are, however, neglected. Even though uncertainty and variability considerations were included in the selection of the control handles, these considerations should also be included in the next step, the evaluation of different management strategies using the selected control handles.

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