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RESEARCH ARTICLE

How climate proof is real-time control with regard to combined sewer overflows?

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ABSTRACT

A question arising when considering the changing climate is whether real time control (RTC) can be considered as a 'No Regret' measure, i.e. can RTC maintain its proven current added-value to reduce emissions from sewage systems in the future under altered rainfall patterns and often higher extreme rainfall intensities. This study explored four climate scenarios relevant for the lowland area of North-western Europe under two time horizons and proved that RTC's performance only marginally decreased for a representative Flemish catchment under study. Based on this case study, it was found that effects of climate change will lead to, on average, 30–40% more overflow volume in 2050 and 35–65% more overflow volume in 2085. To restore the current situation, additional measures need to be taken, but RTC preserves its contribution to the reduction of overflows. The elaborated methodology is transposable to other locations provided that the necessary information is available.

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KEYWORDS
Combined sewer overflow; real time control; climate change; no regret measure

Introduction

Nowadays, real time control (RTC) is identified as a cost-effective measure to reduce impact from combined sewer overflows (CSO) and flooding (e.g. Dirckx *et al*. 2011). Usually, algorithms aim to optimize the existing storage potential present in the sewer systems, and especially in the collection sewers and storage tanks (Schilling 1989). These facilities were typically constructed in the past 50 years often following different static design rules (Schütze *et al*. 2003) and also based on different rainfall input information from earlier precipitation registrations. Climate change could potentially burden the positive effect of such a sewer system equipped with RTC and the question arising is whether RTC will still be effective when exposed to the (at least for North Europe) expected elevated rainfall patterns (EEA 2014). This study wants to anticipate the future changes and investigate the 'No Regret' value or robustness of RTC regarding the expected upcoming climate change by comparing the results of RTC with 'No Control'-scenarios for the current climate and for eight future climate scenarios. 'No Regret' measures are activities that yield benefits even in the absence of climate change (Climate-ADAPT 2015). The 'No Control' scenarios describe the status quo situation and thus allow verification of the effect of future rainfall patterns as such (without measures like RTC). Former studies show varying results but commonly they indicate an increase in CSO's spill volume in the future, following an increase in rainfall. Krieger *et al*. (2012) for example predict an increase in overflow volume of 40–50% in the Hamburg catchment (Germany) in 2071–2100, while Gooré Bi *et al*. (2015) expect an increase of spilled volume of 15–500% in summer (May–October) for the Longueil catchment (Québec) by 2050. Two Norwegian studies found an 83% increase in annual CSO discharge for years with maximum annual precipitation in Oslo (Nilsen *et al*. 2011) and 36%–54%–89% in Frederikstad following an average rainfall increase of 20%–30%–50% respectively (Nie *et al*. 2009).

Material and methods

In order to assess the effect of climate change on urban drainage infrastructure, a validated hydrodynamic sewer model on the one hand and future rainfall time series on the other hand were used. The outcomes are determined on a regional scale with local rainfall and sewer model, but the elaborated methodology can be easily transferred to any other region.

Case study Antwerpen Noord

The catchment of Antwerpen Noord (Figure 1) situated north of the city of Antwerp (Flanders, Belgium) was chosen for this analysis, as sub-optimal functioning was detected in its current state. Four municipalities (Stabroek, Hoevenen, Kapellen and Ekeren) are draining to the waste water treatment plant, in total receiving a load of 72,300 PE. The sewer system is more than 90% of the combined type, and is substantially influenced by infiltration and inflow (more than half of the dry weather flow on average). Some 34% of the 1700 ha connected area is impervious (roofs and streets). Key figures of the sewer system can be read from the chart in Figure 1. A downstream pumping station (PS) Havenweg serves as the feeding PS of the wastewater treatment

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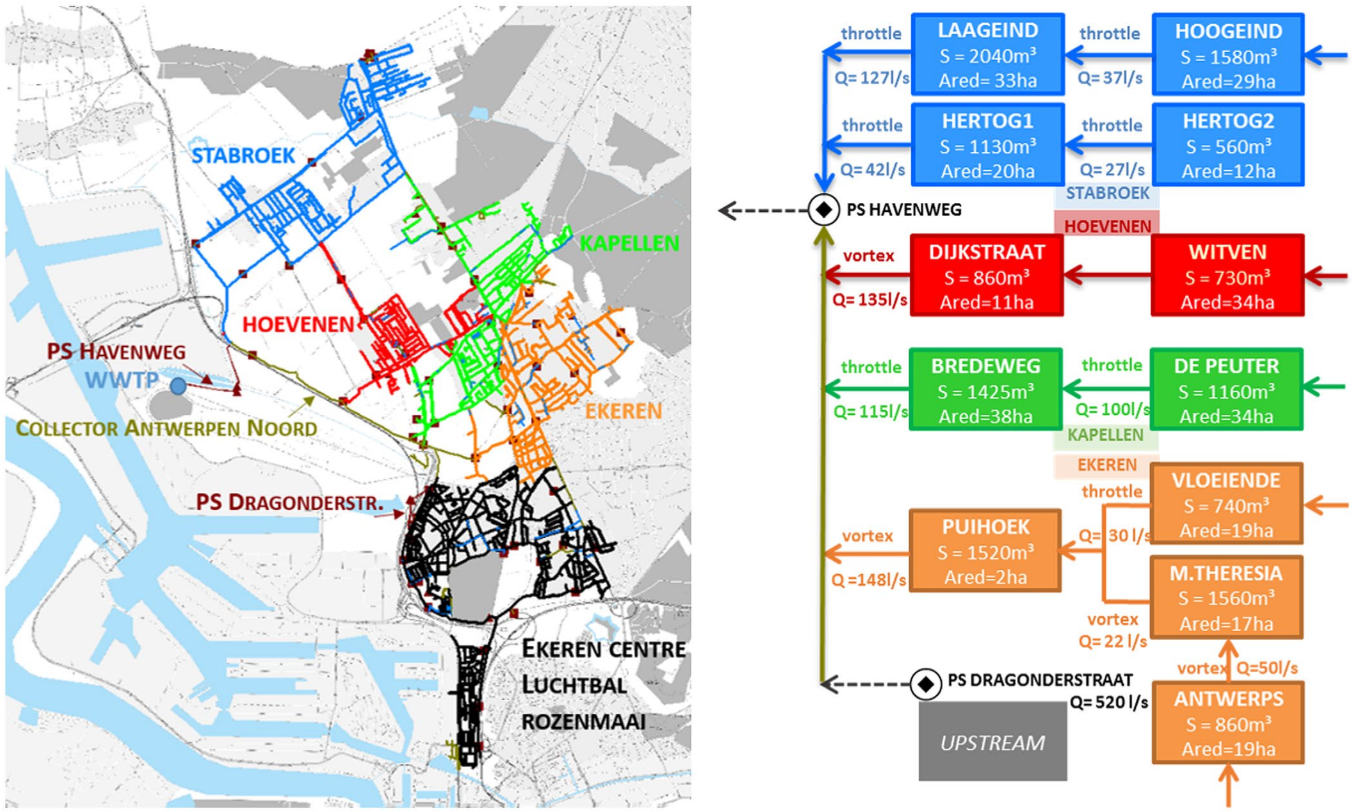


Figure 1. Catchment of Antwerpen Noord connecting the sewer system of the municipalities Stabroek, Hoevenen, Kapellen and Ekeren via PS Havenweg to the WWTP situated in the harbour area of Antwerpen (left). Schematic representation of the catchment with CSO catchments and indication of maximum storage S (m^3), connected sealed area (Ared) and (typical) throttle flow Q (right).

plant (WWTP), which is situated in the harbour area of Antwerp. Despite the region's heavy industrial activity, it receives no industrial wastewater; all treated water originates from household activities, including the extra load of septage brought to the WWTP. An important upstream PS Dragonderstraat (equivalent to 29,800 PE) drains the upstream part of the catchment, including the centre of the village of Ekeren and of the areas Rozenmaai and Luchtbal on the premises of the city of Antwerp. The downstream area can be divided into 12 CSO catchments (some less relevant upstream ones are omitted). A CSO catchment comprises that part of the sewer system that drains to a certain CSO until a next one is met (see Figure 1).

Model scenarios

Sewage system design rules in Flanders

Before discussing model scenarios it is important to highlight Flemish design rules and terminology. Default hydraulic design of urban waste water infrastructure (i.e. both WWTP and hydraulic structures within the sewer systems such as pumping stations and throttle structures) in Flanders follow the rule that the flow must be limited to $6Q_{14}$, a figure corresponding to six times the peak dry weather flow. This peak flow is indicated by the subscript '14' and refers to the 14/24-quantile of a day. Despite this default rule, hydraulic capacity of older infrastructure sometimes does not yield this $6Q_{14}$ design flow. This is also the case for the Havenweg pumping station and consequently for the Antwerpen Noord treatment plant that are operated at a $3Q_{14}$ regime (of the current loading) only, due to a long history of changed design views. This implies a considerable discrepancy in the daily operation of this entire sewage system as hydraulic structures within the transport (collection) system do follow the $6Q_{14}$ design rule. Due to the assumed overcapacity of the WWTP (of the current $3Q_{14}$ loading), this however opens new opportunities to also adjust the WWTP loading.

No control scenarios

Hydrodynamic simulations with the sewer model of the Antwerpen Noord catchment were carried out with InfoWorks CS™ (v14.5) following 3x2 model scenarios. The base scenario 'ASIS' constitutes of the status quo scenario describing the situation as is. Next to this two other model scenarios were considered comprising either an adjustment of PS Havenweg to double capacity 'Haven$6Q_{14}$' or of the upstream PS Dragonderstraat to halve capacity 'Drag$3Q_{14}$' as this aligns the systems processes in a more logical way. The latter can be achieved by decreasing the rotational speed of the existing pumps. Extending the capacity of PS Havenweg will need more substantial investments. In both cases potential (extra) flooding induced by these measures was carefully checked in order to avoid a possible shift from CSO spills to flooding.

Real time control scenarios

An RTC scenario was developed by equipping the 12 CSO catchments (as mentioned in Figure 1) with controllable penstocks (sluice gates) just in front of the existing throttle and applying an

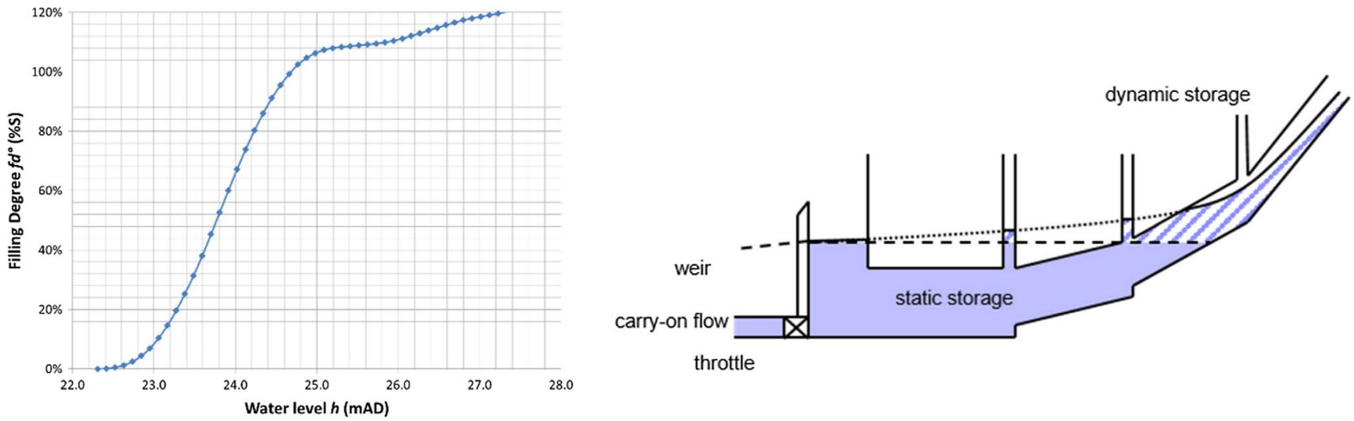


Figure 2. Example of filling degree curve (left) and principle of static and dynamic storage (right).

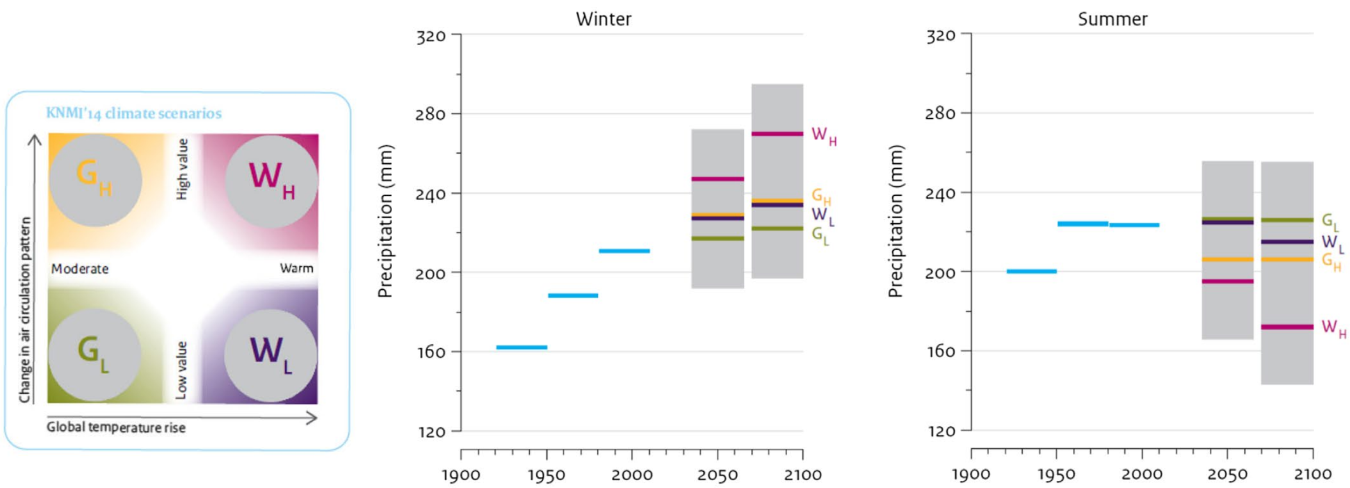


Figure 3. The KNM'14 climate scenarios (left) and precipitation observations of the past century (averages over some decades) and the scenario predictions for 2050 and 2085 (right) (KNMI'14).

RTC algorithm based on the equal filling degree. This algorithm aims to fill every CSO catchment to an equal extent at any time. The sluice gates can be proportionally controlled but in the first instance they will be either closed or opened completely. Water levels are registered at all actuator locations (sluice gate location in this case), and sent to a central controller that converts this information into filling degrees via so-called storage-height curves (Figure 2). A filling degree of a CSO catchment is the used (static) storage in this part of the system relative to the maximum storage when the water level reaches the CSO's crest (i.e. when a filling degree of 100% is reached). All filling degrees are compared to the average filling degree of all controlled CSO catchements in order to decide if either water has to be released (local filling degree higher than average) or to be backed up (local filling degree lower than average). More specific details about this setup can be found in Dirckx *et al*. (2011). This was also implied for the Haven6Q_{14} and Drag3Q_{14} sub-scenarios, resulting in three model scenarios with RTC and three without RTC (denoted as 'NoCon'). Note that it is beyond the scope of this work to find the most optimal performing control algorithm. The equal filling degree algorithm or variants have however been succesfully implemented in several Flemish catchments (e.g. Kroll *et al*. 2015) proving its quality, also because it is - by its nature - comprehensible for the operating staff.

Climate scenarios and rainfall series

Future climate

Future climate - according to the KNMI'14 climate change scenarios - was used, as developed by the Dutch Meteorological Institute KNMI (KNMI 2014). Climate change models project milder but wetter winters and warmer summers, with potentially less rainfall, for the lowland area covered by the Netherlands and the Flemish region of Belgium (Figure 3). Transformation programmes follow the delta method that makes use of historic rainfall series as input. Details can be found in Bakker and Bessembinder (2012). The climate scenarios consist of combinations of two possible values for the global temperature increase 'Moderate' (G) and 'Warm' (W), and two possible changes in air circulation patterns, 'Low value' (L) and 'High value' (H). (KNMI 2014). The changes are determined for two different time horizons: around 2050 and around 2085. The W_H and W_L scenarios were identified as most crucial regarding the reaction to the urban drainage system. Finally, two sub-scenarios called 'upper'

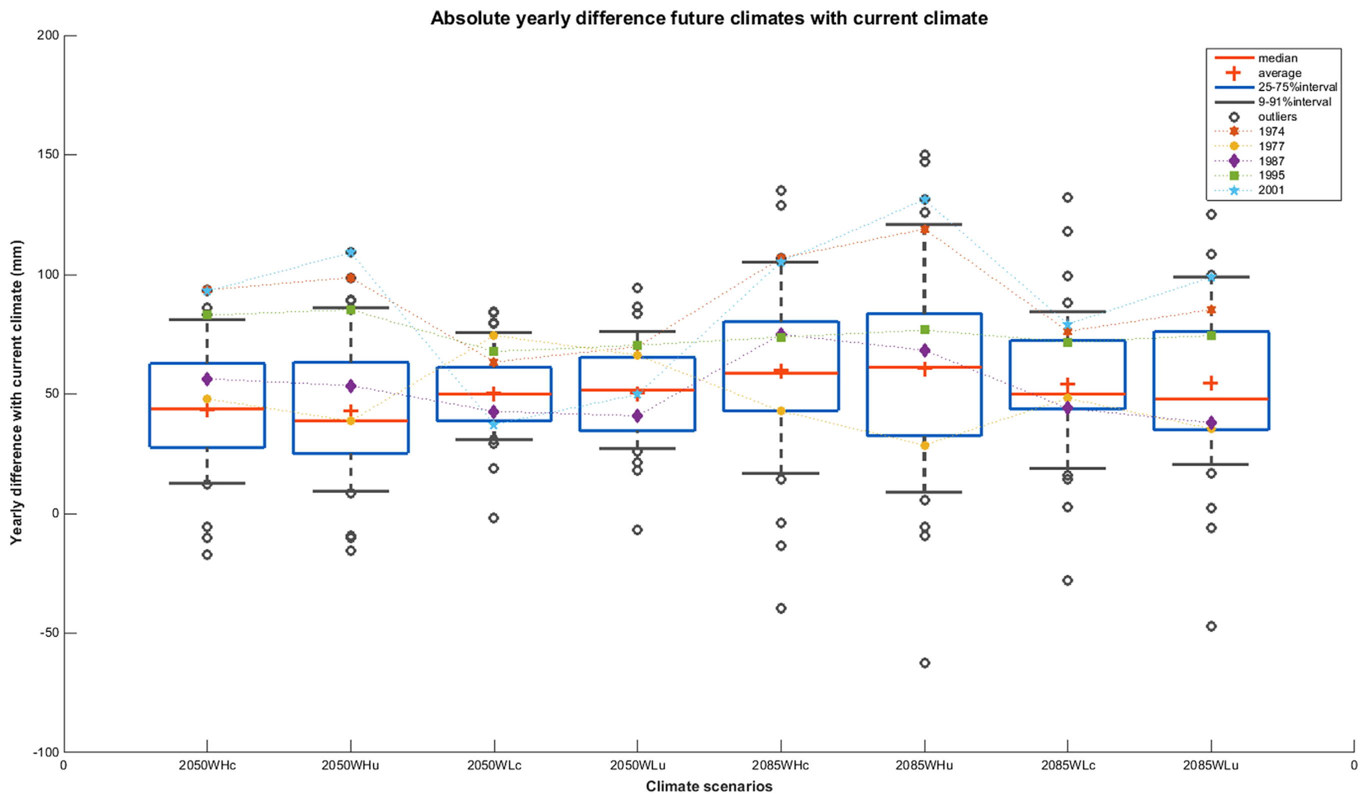


Figure 4. Boxplot including outliers of the annual differences (mm) in yearly precipitation sum between a climate scenario and the current climate. The years that were used for the overflow analysis are indicated separately.

Table 1. Relative average seasonal differences in total rainfall between climate scenarios and current climate.

	$2050W_{Hc}$	$2050W_{Hu}$	$2050W_{Lc}$	$2050W_{Lu}$	$2085W_{Hc}$	$2085W_{Hu}$	$2085W_{Lc}$	$2085W_{Lu}$
Winter	+18%	+17%	+8%	+8%	+28%	+28%	+11%	+11%
Spring	+9%	+9%	+11%	+11%	+12%	+13%	+13%	+13%
Summer	−13%	−13%	+2%	+1%	−24%	−24%	−5%	−5%
Autumn	+8%	+7%	+3%	+3%	+12%	+11%	+5%	+5%

and 'central' were added to partially meet potential uncertainty regarding extreme rainfall.

Climate scenarios

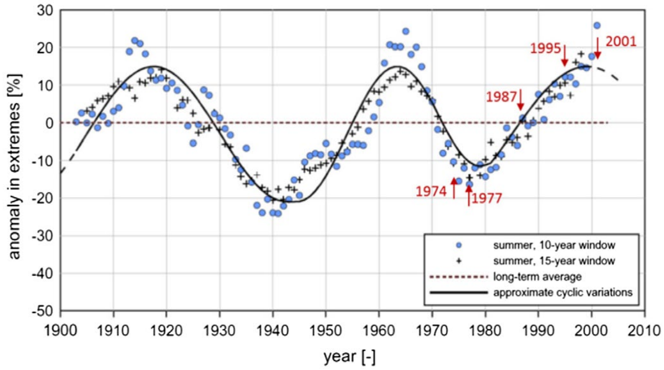
A rainfall time series of 47 historic years (1967–2013) of 10 min rainfall intensity for Ukkel (Brussels) was perturbed with the KMNI'14 transformation program[1], together with the registered daily evaporation values, resulting in eight (2×2×2) future series combining scenarios W_H and W_L, time horizons 2050 and 2085 and sub-scenarios central (c) and upper (u), describing the lower and upper values of the range for extreme hourly rainfall. As these nine climate rainfall times series were used as input to the hydrodynamic simulations, it is useful to have a deeper look into the changing rainfall patterns first.

On an annual aggregation level, Figure 4 shows that the total yearly amount of precipitation will increase according to the climate scenarios with on average 5–6% around 2050 and with 6–7% around 2085 compared with the current climate. A yearly average of 829 mm was recorded over the 47 year period of 1967–2013. However, major seasonal differences in climate change can be observed between the scenarios (Table 1). Overall, the trend is that the amount of precipitation increases in winter (January, February, December), to a lesser extent in spring (March to May) and autumn (September to November) but decreases in summer (June to August) except for $2050W_L$.

Finally, on a detailed level, i.e. 10 min registrations, the main conclusion is that - contrary to certain trends in yearly or monthly precipitation, rainfall extremes will increase in all seasons, including the summer period. This effect is the main difference between the 'c' and 'u' sub-scenarios: the 'upper' extremes tend to be higher than the 'central' extremes.

Simulation aspects

A standard simulation with the sewer model of Antwerpen Noord (4000+ nodes, 1 year rainfall, time step 60 sec, DWF multiplier = 32 to speed up simulations during dry weather flow) takes up to more than 11 h in simulation time (PC type: Intel® Xeon® CPU E5–1620 0 @ 3.60 GHz, 16 Gb RAM memory in octo-core multi-threading mode). In order to keep overall simulation time manageable, five representative years (1974, 1977, 1987, 1995, 2001) showing diverse rainfall extreme values and total annual volume were selected from the original 47 year times series available (Figure 5). As rainfall extremes seem to exhibit temporal clustering at multi-decadal scales, analysis has shown



YEAR	Extreme values	Yearly average
1974	Low	High
1977	Low	Moderate
1987	Moderate	High
1995	Low	Low
2001	Low	High

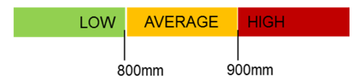


Figure 5. Multi-decadal oscillations in Ukkel rainfall (Willems 2013) (left) and properties of the years selected for analysis (right).

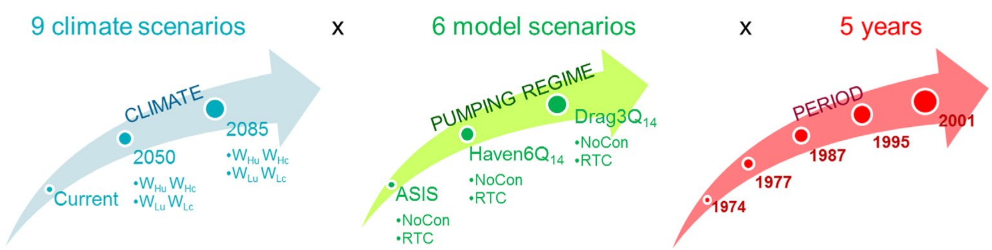


Figure 6. Schematic overview of simulations: nine climate scenarios (one current, four for 2050, four for 2085), six model scenarios (situation as is, PS Havenweg at $6Q_{14}$, PS Dragonderstraat at $3Q_{14}$, each time with or without RTC) and five selected years.

that the 1960s and the 1990–2000s had a higher frequency and amplitude of high rainfall intensities at various time scales (Willems 2013). These years also showed different yearly total rainfall depths in the range of 600 mm (low) to 1100 mm (high). Resuming all scenarios, a total of 270 simulations combining six model scenarios, nine climate (one current and eight future) and 5 years of rainfall (see Figure 5) were run. This is schematically represented in Figure 6.

Results and discussion

The following section discusses the results of the scenario analyses. First the effect of applying structural changes in the current situation is considered, followed by the results of the altered rainfall patterns on the (future) spill characteristics. Finally the effect of RTC in the current and future climates is evaluated.

Effect of different NoCon model scenarios on spill characteristics

Without taking RTC into account yet, bringing PS Dragonderstraat to $3Q_{14}$ has virtually no effect (1% on average less spill volume). It seems that spill volumes are shifted from the downstream to the upstream part, while no (extra) flooding occurred in this area. The $3Q_{14}$ scenario(s) will therefore not be further discussed. Conversely, upgrading PS Havenweg to $6Q_{14}$, has a considerable effect: 40% less spill volume on average. This beneficial result is probably due to the fact that twice as much water is pumped out of the system during storm conditions. Consequences of this measure on the capacity and structural aspects of PS Havenweg and the WWTP will be outlined further.

Effect of climate change on spill characteristics

The boxplots in Figure 7 summarize the effect of the climate change on the sewerage system of Antwerpen Noord by showing the range and average difference between the climate scenarios and the current climate (for the remaining model scenarios ASIS and Haven$6Q_{14}$, without RTC). It is striking that, despite a limited increase in yearly rainfall (5% to 7%), overflow volumes seem to rise much more over time. This is partially due to the rise in rainfall extremes.

In 2050 on average 27–46% more overflow volume is expected, further rising in 2085 to 32–67%. This non-linear effect was also found by Gooré Bi *et al.* (2015) while Nie *et al.* (2009) found the increase in spill volume to be around 80% higher than the increase in rainfall volume. The figures determined in this study are deemed to slightly overestimate the effect because the five selected years seem to cover the upper yearly total range of transformation values as can be seen in Figure 4. *A posteriori* simulations with the full time series (of 47 years of rainfall) for some climate scenarios indeed confirmed overestimations in the range of 1% to 5%. Still, the rise in CSO spill volume is much higher than the increase of rainfall volume.

The upper scenarios have a significantly stronger effect compared to the central scenarios due to the higher increase of extreme precipitation amounts. Detailed seasonal analysis showed that overflow volumes are rising for all seasons in all scenarios, except for 2085W_{Hc} in summer where on average spill volumes decrease (see Table 2). The overall increase of spill volume is due to a rise in rainfall extremes for all scenarios also for those (like the W_H-scenarios) for which a volumetric decrease of the average rainfall over the summer period is projected. Further detailed investigations revealed that for many events with relatively small

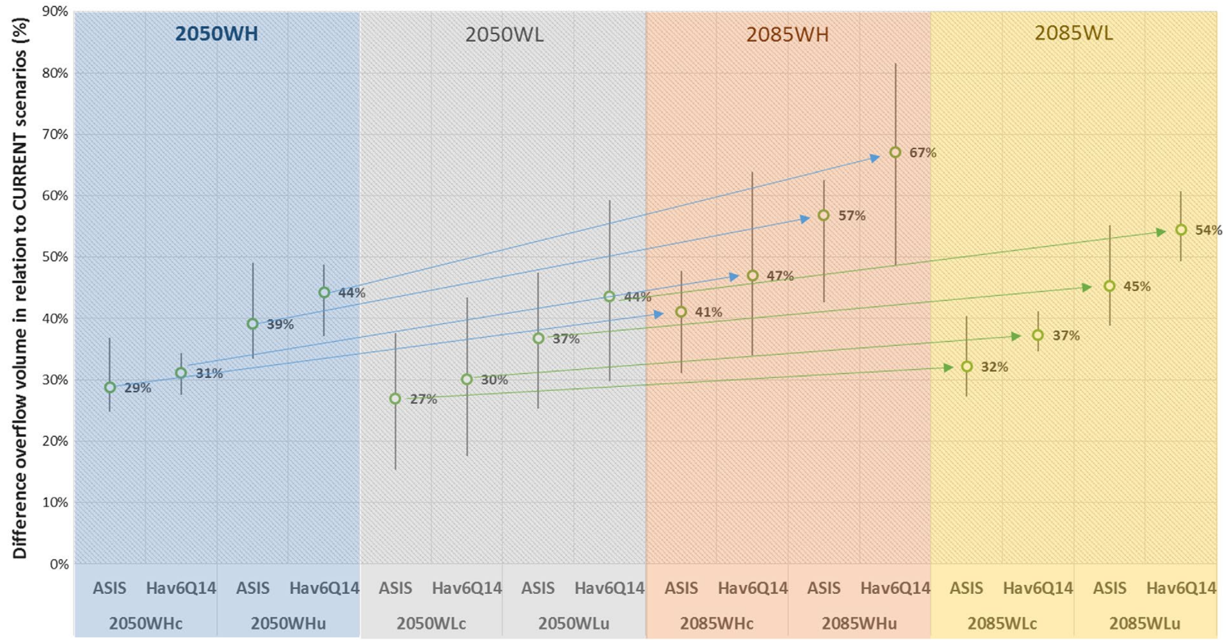


Figure 7. Relative change in overflow volume of the various climate scenarios compared to the reference period: boxplots for five simulated years as increase of overflow volume in relation to current situation, and two model scenarios ASIS and Hav6Q14. All without RTC.

Table 2. Relative average seasonal changes in total CSO spill volume between climate scenarios and current climate.

	$2050W_{Hc}$	$2050W_{Hu}$	$2050W_{Lc}$	$2050W_{Lu}$	$2085W_{Hc}$	$2085W_{Hu}$	$2085W_{Lc}$	$2085W_{Lu}$
Winter	+52%	+62%	+29%	+36%	+84%	+101%	+43%	+54%
Spring	+38%	+52%	+30%	+40%	+63%	+82%	+45%	+60%
Summer	+6%	+15%	+30%	+40%	−7%	+5%	+17%	+29%
Autumn	+35%	+45%	+24%	+34%	+56%	+74%	+35%	+50%

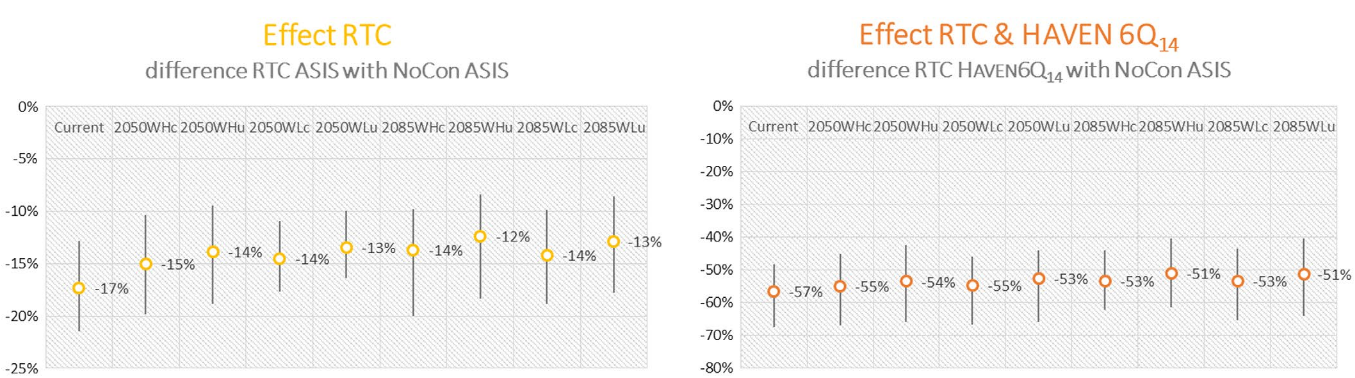


Figure 8. Relative effect of RTC on spill volume with a changing climate: small drop in efficiency with time. Difference between RTC with NoCon model for ASIS situation (left) and for $6Q_{14}$ upgrade of PS Havenweg (right).

rainfall volumes in summer time the spill volumes are indeed decreasing, but the extreme events mean that total spill volume over the (entire) summer period is increasing or decreasing to a lesser extent than the decrease in average rainfall.

Effect of RTC under a changing climate

The robustness of RTC is investigated both for the RTC ASIS situation and for the combination of RTC with a potentially interesting structural upgrade ($Haven6Q_{14}$). System alignment by downgrading the PS Dragonderstraat to $3Q_{14}$ was not further considered due to the less promising initial results ($Drag3Q_{14}$).

Situation ASIS

Regarding the current climate, RTC proves to be beneficial with 17% less overflow volume on average, which has to be seen in the light of a considerably sub-optimal working sewage system due to the hydraulic imbalance as explained before. However combining RTC with an upgrade of the WWTP's feeding PS Havenweg to the Flemish standard $6Q_{14}$ results in a 57%

decrease of overflow volume on average. Effects of both measures can almost linearly be totalled up.

Figure 8 shows the effect of RTC on the spill volume under a changing climate. The ASIS situation is compared with RTC ASIS (or with RTC Haven6Q_{14} for the right figure) scenarios for each climate scenario. A small decrease in efficiency can be observed over time (around 13–15% in 2050 and around 12–14% in 2085). The decrease is probably caused by the extra input of rainfall in a system already under failure. Especially during events where the system is already completely overloaded in the current climate, any surplus of rainfall in the future climate will cause supplementary overflowing, which will result in a slightly more negative balance. Sometimes a little extra rainfall linked to the changing climate will cause spilling where the system was just not under failure in the current climate. Bearing these aspects in mind, it can be concluded that RTC retains its added value as these results remain in the same order of magnitude. The same conclusions go for the combination of RTC with an upgrade of PS Havenweg to 6Q_{14} as also shown in Figure 8.

Upgrading PS Havenweg and effect on the WWTP

On an engineering level, it is interesting to consider potential upgrades of PS Havenweg as this clearly has a positive effect on the RTC performance as well. Initial simulations of the 3Q_{14} and 6Q_{14} regimes showed a 17% and 57% decrease of the CSO spill volume (Figure 9).

Extra simulations revealed a steeper gain from 3 to 4Q_{14} and a more gentle slope from 5 to 6$Q_{14,}$ which indicates that the effectiveness of an upgrade is not linear but higher in the first part than in the second. Regarding investments, upgrading to 4Q_{14} seems to be possible with a new pump only, while 'overloading' the WTTP, which is possible due to the WWTP's overcapacity. Going further to 5Q_{14} would require a new larger rising main for the PS and possibly a small storm water tank at the WWTP. The same pump as for 4Q_{14} can be used by increasing the rotational speed. When aiming for 6Q_{14} larger investments will be needed: next to a bigger storm tank, also a new wet well, a new pump and rising main for the PS. This makes the latter scenario less interesting from a perspective of cost-effectiveness. As it was shortly decided to replace the rising main anyway (because of a structural failure), the 5Q_{14} scenario becomes the optimum one considering cost-effectiveness.

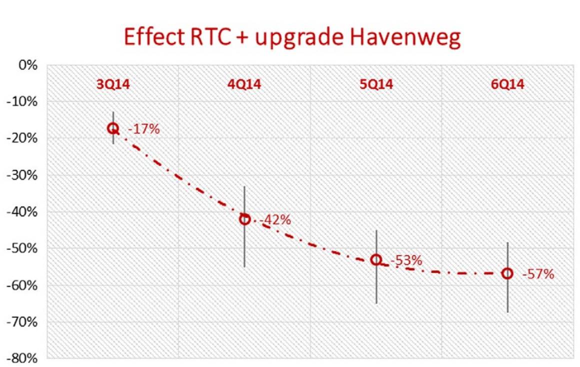


Figure 9. Effect of RTC on spill volumes in combination with pumping regimes of PS Havenweg for the current climate, including the intermediate values 4Q_{14} and 5Q_{14}.

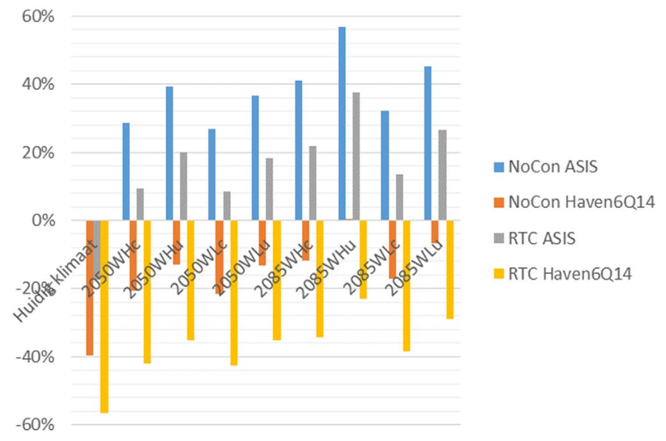


Figure 10. Overall result for relative change in spill volume of promising model scenarios compared to current climate model situation 'ASIS' for all climate scenarios.

Finally, Figure 10 concludes all interesting remaining model scenarios as a comparison between the average CSO spill from the climate and model scenarios with one scenario, i.e. the current NoCon ASIS situation. The latter scenario represents the same analysis as in Figure 7 with a predicted increase in spill volume in the future. Applying RTC can clearly (RTC ASIS) mitigate the increased amount of spill volume (because of climate change), but will still lead to higher spill volumes (due to the higher future rainfall) than for the current situation (ASIS). Only upgrading PS Havenweg to 6Q_{14} (NoCon Haven6Q_{14}) cannot restore the current situation for one climate scenario (2085W_{Hu}), while applying this measure in combination with RTC has the best overall effect (RTC Haven6Q_{14}). As simply adding up the outcomes of applying RTC and upgrading PS Havenweg seems more or less possible, it is expected that both upgrading to 4Q_{14} (-42% on average) and 5Q_{14} (-53% on average) in combination with RTC (-12–15% in the future) will at least restore the current situation.

Conclusion

Based on the case study of the catchment of Antwerpen Noord as a typical Flemish catchment and climate scenarios representative for the lowland area of North-western Europe, it was found that overflow volumes are expected to rise on average by 30–40% in 2050 and 35–65% in 2085, corresponding to a yearly average increase of precipitation of 5–6% and 6–7% respectively. The increase in overflow volume is due to the increase of rainfall volume together with the elevation in rainfall extremes. RTC however seems to maintain its relative positive effect, with only a small decrease from the average 17% in the current climate to on average 13–15% for the 2050 climate and to 12–14% for the 2085 climate. This proves that RTC can be considered as a 'No Regret' measure. Combining RTC with the upgraded flow regime at the WWTP's feeding the PS (Havenweg) avoids the climate change induced (absolute) increase of overflow volume for all future scenarios compared to the current situation. Extra subtraction of flow from the sewer system follows a non-linear behaviour. Any further abatement of CSO spills compared to the current situation will require more investment (apart from RTC).

Note

1. Version 3.0, May 2014. This transformation programme transforms at a daily level. The relative changes per day were also applied to all 10 min rainfall amount on that same day.

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Disclosure statement

No potential conflict of interest was reported by the authors.

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