Impact of urban WWTP and CSO fluxes on river peak flow extremes under current and future climate conditions

Ingrid Keupers and Patrick Willems

ABSTRACT

The impact of urban water fluxes on the river system outflow of the Grote Nete catchment (Belgium) was studied. First the impact of the Waste Water Treatment Plant (WWTP) and the Combined Sewer Overflow (CSO) outflows on the river system for the current climatic conditions was determined by simulating the urban fluxes as point sources in a detailed, hydrodynamic river model. Comparison was made of the simulation results on peak flow extremes with and without the urban point sources. In a second step, the impact of climate change scenarios on the urban fluxes and the consequent impacts on the river flow extremes were studied. It is shown that the change in the 10-year return period hourly peak flow discharge due to climate change (−14% to +45%) was in the same order of magnitude as the change due to the urban fluxes (+5%) in current climate conditions. Different climate change scenarios do not change the impact of the urban fluxes much except for the climate scenario that involves a strong increase in rainfall extremes in summer. This scenario leads to a strong increase of the impact of the urban fluxes on the river system.

Key words | climate change, combined sewer overflow (CSO), extreme value analysis, peak flows, river modelling, waste water treatment plant (WWTP)

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INTRODUCTION

The climate is changing and a significant change of rainfall patterns and temperature has been observed and is expected to continue in the future (IPCC 2012). The impact of these changing climate patterns on sewer system flows and river catchment hydrology is currently being studied by researchers worldwide (e.g. Semadeni-Davies *et al.* 2008; Ntegeka 2011; Willems *et al.* 2012). However, the impact analysis of the changing Waste Water Treatment Plant (WWTP) and Combined Sewer Overflow (CSO) outflows on the receiving rivers faces particular difficulties that require integrated models. Study of the potential impact of climate change on urban fluxes, together with the relative contribution of these urban fluxes on the downstream river system, is critical to support adaptation measures that will mitigate assumed effects.

Impervious areas, in combination with storm water drainage and wastewater treatment infrastructure, can exert several types of pressure on the hydrological cycle. Shorter lag times between onset of precipitation and subsequently higher runoff peaks and volumes in receiving waters can be observed (Shuster *et al.* 2005). This augmented discharge can increase the risk of flooding along the river. It is thought that this pressure of urbanization on the river hydrology might be intensified due to climate change, as many climate models predict more intense summer storms (IPCC 2012; Willems *et al.* 2012) thus making it more likely that CSO events will occur. Quantification of this impact, considering the extreme events in a proper statistical way, requires a long-term series of urban fluxes to be simulated as point sources into a hydraulic river model in order that interactions between the two systems, the urban drainage and river system, are taken into account. After all, an increase in urban flux extremes does not necessarily lead to an increase in river discharge extremes as the concentration times of the two systems are different (Kandori & Willems 2008).

STUDY AREA

The case study selected for this study is the Grote Nete catchment, located in the northeast of Belgium (Figure 1). The catchment has a total area of 386 km^2 and is flat, with an average slope of 3‰. Within the catchment there is an area of 27 km^2

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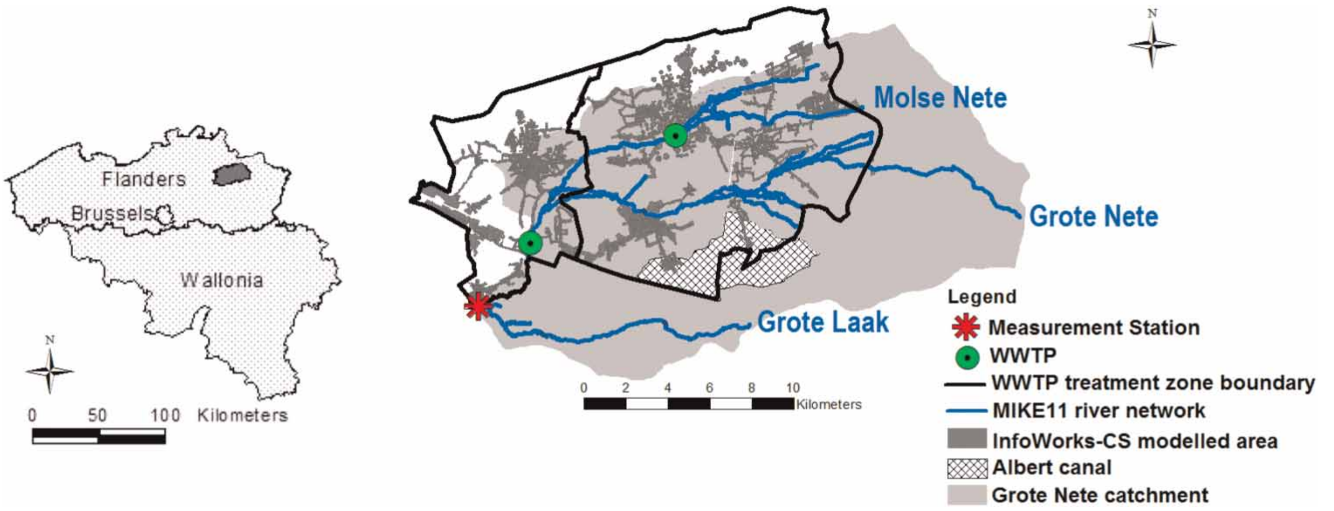

Figure 1 | Location of the Grote Nete catchment in Belgium (left); modelled catchment and river network with indication of the location of the WWTPs, discharge measurement station and modelled river and sewer network (right).

which does not drain to the network of rivers; the rainfall over this area drains instead to a canal (Albert Canal). This part of the basin is therefore not included further in the modelling.

The Grote Nete catchment was chosen as being representative of a moderately urbanized catchment. Most of the area receives a strong impact from anthropogenic activities, i.e. agriculture, including grassland and cropland, comprises 52% of the total catchment area while urban development covers 19% of the area. The catchment has two WWTPs that treat the water from the urban drainage systems of the cities of Geel (27,000 Inhabitant Equivalent (IE)) and Mol (54,900 IE). Both sewer systems consist predominantly of combined sewers with many CSO structures (23 for Geel and 101 for Mol) to divert excess water to the Grote Nete river system during rainfall events. The modelled runoff area for the city of Geel comprises a total of 15 km^2 of which 4 km^2 is impervious, which means that 28% of the catchment is impervious. The city of Mol comprises a total of 38 km^2 of which 7 km^2 (17%) is impervious.

METHODOLOGY

A flow chart of the methodology that was applied is shown in Figure 2. Each model component of the modelling chain is explained next.

Rainfall–runoff model for rural areas

To convert the available rainfall time series to a rainfall–runoff time series that enters the network of rivers, a catchment rainfall–runoff model is needed. The model has been implemented using the VHM approach of Willems (2000), previously also applied for hydrological climate change impact analysis by Taye *et al.* (2011), Liu *et al.* (2011) and Van Steenbergen & Willems (2012). VHM (Vereenvoudigd Hydrologisch Model) is a Dutch abbreviation for 'generalized lumped conceptual modelling approach'. The approach is based on a step-wise procedure to determine (identify and calibrate) the equations that control the split of the rainfall for input in the different conceptual reservoirs, namely soil moisture (which is emptied by evapotranspiration), overland flow, interflow and baseflow. Calibrated recession constants of the conceptual reservoirs of the three flow components determined the magnitude of the subflows, which were added together to determine the total rainfall runoff.

The model needs both rainfall and evapotranspiration time series as input. The average areal rainfall is calculated with the Thiessen polygon method based on six rain gauges with hourly measurements for the period 14 September 2001 to 31 December 2008. For the same period daily measurements performed by the KMI/IRM (Royal Meteorological Institute of Belgium) at Uccle were being used for the evapotranspiration time series. The model was calibrated against the measured hourly discharge at the basin outlet, after subtraction of the discharges from industries and WWTPs located in the catchment. The latter discharges artificially increase the natural rainfall runoff and were treated separately in the river model as point sources.

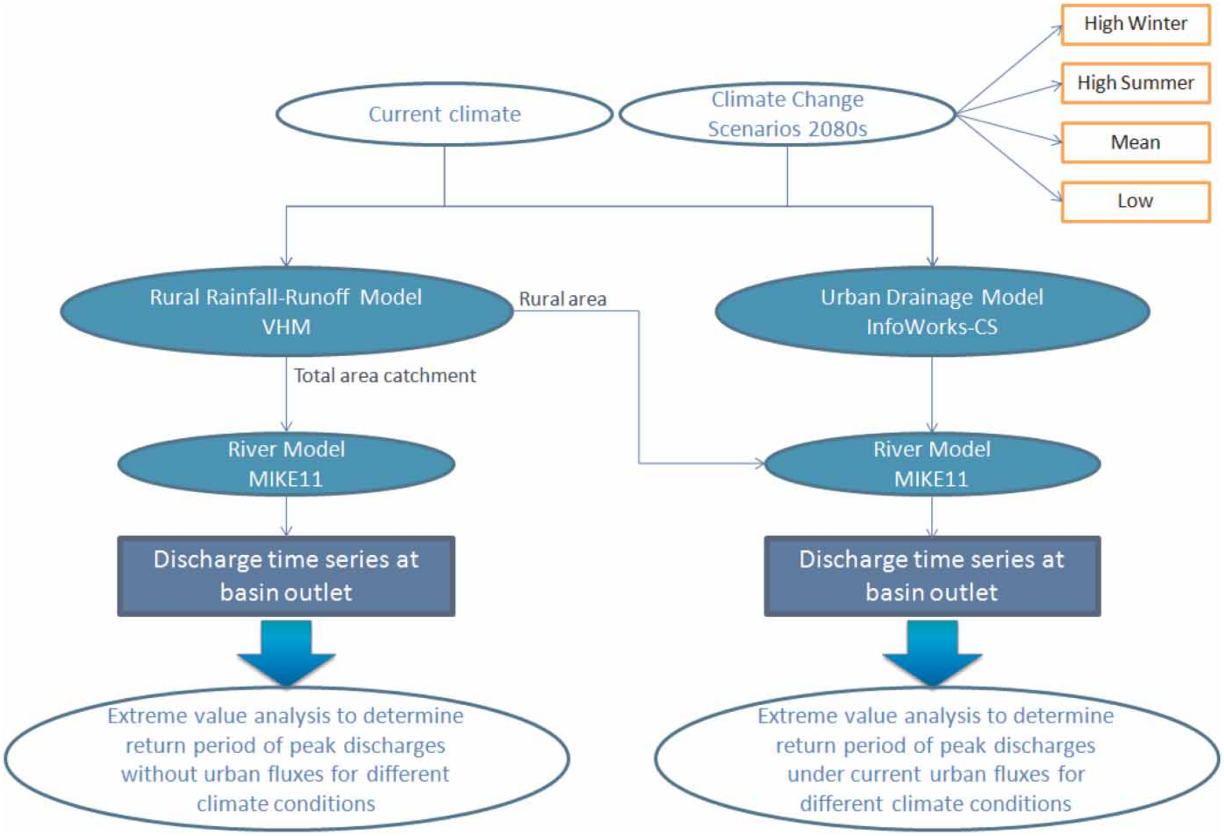

Figure 2 | Schematic overview of model setup.

Urban contributions to river flow

To model the impact of the combined sewer system overflows and WWTPs of the two cities (Mol and Geel) on the river flows, detailed full hydrodynamic sewer models for both cities were used. These models have been set up in InfoWorks-CS and validated with sewer flow measurement data by the Flemish water company Aquafin NV. The rainfall over the drained urban area is routed to the sewer system using the Wallingford routing model. Default parameters have been considered for the different surfaces such as streets and rooftops, but subcatchment areas were validated and adjusted based on the measurement data.

Because of the small response time of sewer systems, especially when compared to the catchment rainfall runoff, a higher resolution rainfall time series (Δt 15 min) measured at the basin outlet for the same time period was used as input for the sewer model. The daily potential evapotranspiration data at Uccle were considered as evapotranspiration input. The modelled time series (Δt 10 min) of urban fluxes at each WWTP and CSO within the catchment were input as point sources in the river model.

Hydraulic river model

To model the hydrodynamic behaviour of the river system, a full hydrodynamic model, implemented in MIKE11, has been set up. The model includes the three main river branches of the catchment, namely the Molse Nete, the Grote Nete and the Grote Laak, and its main tributaries, which cover a total river length of 139 km. Cross-section information is included approximately every 50 m, except where there are hydraulic structures that require a smaller spatial resolution. This high spatial resolution of the computational model requires a small time resolution for the simulation (Δt 30 seconds) to avoid numerical instability, hence long calculation times are obtained.

Climate change scenarios

Both the catchment runoff and the sewer models were driven by measured values of precipitation and potential evapotranspiration. In order to study the effect of changing climatic conditions on the hydrological regime, the impact of climate change on these two variables was assessed. It is commonly accepted that such climate change impact analysis requires an 'ensemble approach' considering a set of climate models and climate model simulations (Willems *et al*. 2012). For Belgium, statistical downscaling and intrinsic bias correction have been applied before to a large set of more than 30 different Regional Climate Model (RCM) runs and more than 20 different Global Climate Model (GCM) runs, based on the quantile perturbation method (Willems & Vrac 2011). Simulating each of these available climate model runs, after statistical downscaling, in the river and sewer hydrological and hydrodynamic models would imply an extremely long calculation time. Therefore, in order to simplify the analysis, use was made of a limited number of tailored climate scenarios, based on the method and tool developed by Ntegeka & Willems (2009). These scenarios aim to cover the range of impact results obtained if the full set of available climate model runs were to be considered.

The tool was used to generate perturbed time series for both the 15 min and hourly rainfall and daily evapotranspiration time series for the projected climate around the 2080s (2071–2100) for four different scenarios, namely high summer, high winter, mean and low. The signal covariations that were used to generate these perturbed time series can be found in Ntegeka (2011). All four scenarios were considered in this study to account for the overall uncertainty that is present in the GCM/RCM projections used to develop these scenarios.

Extreme value analysis

An extreme value analysis was performed on the simulated hourly peak discharges at the basin outlet for each climate scenario. This analysis enabled the calculation of the expected peak discharge for given return periods. In this way, the analysis provides information on the changes in extremes, which are of higher relevance to water engineering and the design of adaptation measures than changes in mean flows.

From the whole discharge time series, nearly independent peak events were selected by applying a Peak-Over-Threshold (POT) method as described in Willems (2009). A Generalized Pareto Distribution (GPD) was calibrated to these peak flows, based on a qq-plot regression method as described in Willems *et al*. (2007). From the calibrated extreme value distribution, peak flow return periods were calculated as defined in Rosbjerg (1985).

RESULTS

The simulation result after recent historical rainfall and evapotranspiration time series and including the contribution of the urban fluxes was compared to measured discharges at the basin outlet to validate the model setup. The correlation coefficient between model results and measurements of all hourly river flows equals 0.84, indicating that a good agreement between model results and measurements is obtained and that the model can be used for scenario analysis (Figure 3).

The contribution of the urban fluxes to the river discharges at the basin outlet ranges from 8% to 10% (average for all hourly time steps). This contribution does not change much under different climate change scenarios. This average contribution, however, does not reflect the highly variable contribution of urban fluxes with a minimum

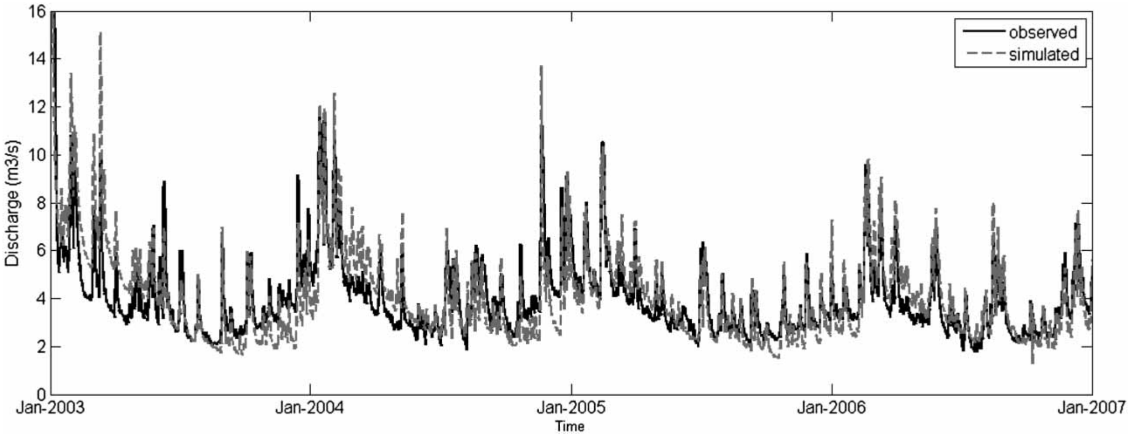

Figure 3 | Observed (black full line) versus simulated (grey dashed line) discharges at the basin outlet for the current urbanized conditions and current climate.

of 1% and a maximum of up to 80% of the hourly river discharge at the basin outlet.

For the effect on the (POT) river peak flows Figure 4 shows the impact of the urban fluxes and Figure 5 the impact of the climate scenarios for the current (historical) conditions for the urban fluxes. The results shown in these figures are after calibration of the GPD to the simulated peak flow extremes.

DISCUSSION

The impact results are hereafter discussed for a return period of 10 years, as this return period is commonly used for the design of sewer systems. For a return period of 10 years, the increase in river peak flow extremes due to the urban fluxes is 8% under current climatic conditions. The impact of the urban fluxes does not change significantly for the low, mean and high winter scenarios. In the high summer scenario, however, an increased impact of 20% is obtained. Under this scenario, which involves a strong increase in the intensity of summer storms, the increased CSO discharges from the sewer system lead to a more significant increase in river peak flow extremes in the natural river system (the river system without the urban fluxes), compared to the current impact.

The magnitude and direction of the impact of the different climate scenarios on the river peak flow extremes is more difficult to determine than the impact of the urban fluxes. This is due to the high uncertainty in the future climate projections. The projected changes in river peak flow extremes vary between −14% for the low scenario, and

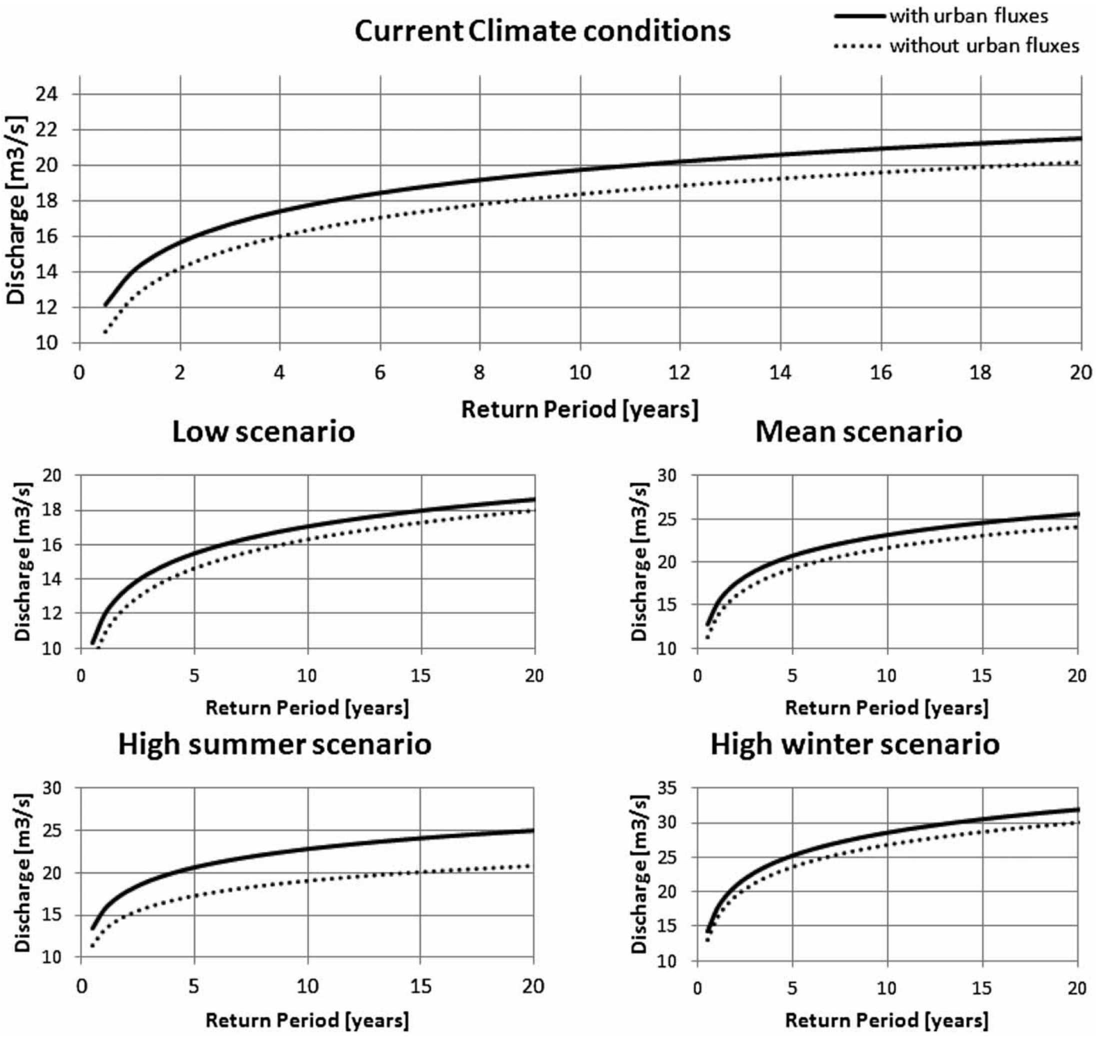

Figure 4 | Impact of the urban fluxes for the current (historical) climate conditions and for the four climate scenarios.

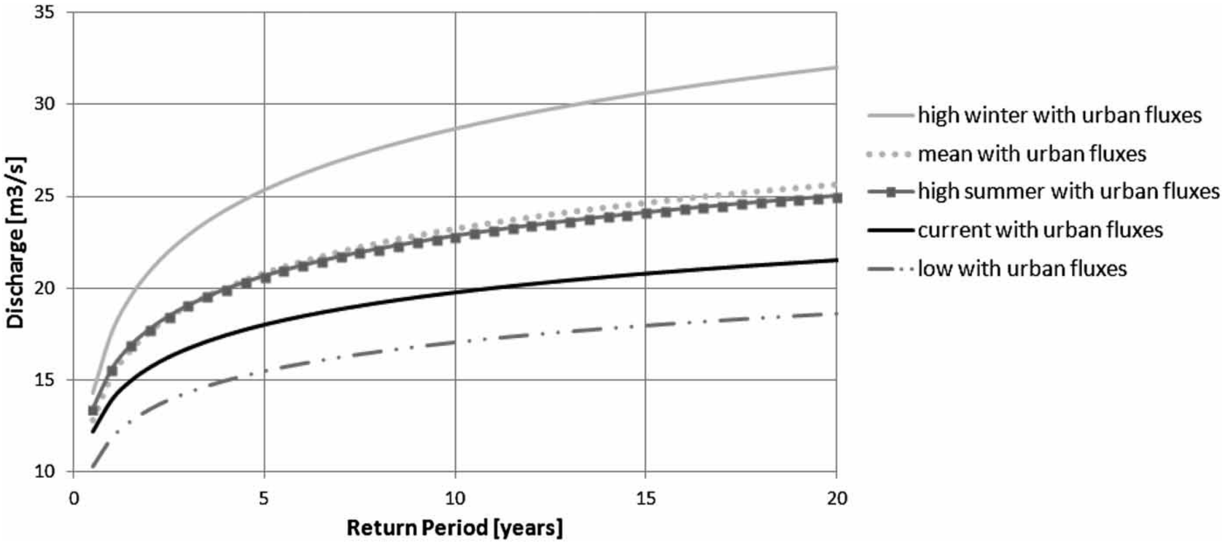

Figure 5 | Impact of the climate scenarios for the current (historical) conditions for the urban fluxes.

+16% and +18% for the high summer and mean scenario, and +45% for the high winter scenario. This high uncertainty makes it very difficult to derive adaptive measures to counteract the possible effects of climate change. Flexible designs that take the uncertainty into account will be required as was also demonstrated by Willems *et al.* (2012) and Langeveld *et al.* (2013).

The average increase in river discharge due to the urban drainage systems (+8% to +10%) does not change under the different climate scenarios. This underlines the importance of the extreme value analysis, as it is not the average flow nor the total volume difference that are important for flood-based impact analysis, but the change in the distribution of the extreme events.

CONCLUSIONS

This study investigated whether the urban drainage infrastructure built in the Grote Nete catchment (Belgium) significantly changed the downstream river peak flows and the consequent river flood hazard, and whether climate change modifies this impact. Firstly, a lumped rainfall–runoff model was coupled to the detailed full hydrodynamic river model. The model was used to simulate seven historical years, once without the urban fluxes and once with the urban fluxes (WWTPs and CSOs; calculated by a detailed full hydrodynamic sewer model) included as point sources in the hydrodynamic river model. After the simulation of the current climatic conditions, the precipitation and evapotranspiration time series were perturbed to project four climate change scenarios for the 2080s. The perturbed time series were used to assess the impact of climate change on the urban fluxes and the related impact on the receiving river.

Based on the predicted discharges for a return period of 10 years it can be concluded that the change in high flow extremes due to climate change under the current (historical) urban condition (−14% to +45%) is in the same order of magnitude as the change in extremes due to the added urban fluxes (+5% to +20%). The different climate change scenarios do not change the impact of the urban fluxes much except for the high summer scenario where the impact of the urban fluxes on the river system is increased from 8% to 20%. This is due to the increase in the frequency and magnitude of intense storm intensities for that scenario during the summer period.

The urban aspects considered in this study are limited to the WWTP and sewer system overflow contributions to the river flow. Urbanization might, however, also affect the river hydrology, for example by changing the baseflow characteristics. These effects were not included in this study. They hence need further investigation.

It is recommended that the extreme value analysis be repeated for different locations along the river network, especially at those points that are subject to river flooding. An extreme value analysis of the simulated water levels would allow conclusions to be made about the change in flood extent and depths through climate change and urbanization. This would enable flood managers to conduct a cost-benefit analysis of proposed adaptive measures against climate change for urban drainage systems. Moreover, it would be useful to extend the water quantity model with a water quality and environmental impact module such that the impact of urbanization and climate change on water quality, and related ecological consequences, can be studied as well.

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