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Assessing impacts of urbanization and climate change on urban flood risks: A case study on Turnhout in Belgium

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Abstract

The combined effect of urbanization and climate change on catchment runoff has been drawing attention in the recent years to assess the impact of climate change on urbanizing catchments. There has been extensive development of paved areas within the city of Turnhout in Belgium in combination with several modifications of the neighbouring rivers. Moreover, the city authority has decided to encourage more densification of housing and industries within or next to the cores, which would lead to frequent overflows out of the existing combined sewer system. This combination leads to a faster flow of larger quantities of water which physically cannot be retained by the valleys over this region and thus causes increasingly frequent and harmful flood events affecting agricultural lands. The situation could be indisputably exacerbated under climate change scenarios. This study focuses on assessing the effects of urban development and climate change on flood risks in the downstream of Turnhout. For this study, a lumped conceptual hydrological model NAM was developed for generating runoff from the catchment. The CCI-HYDR perturbation tool, developed by Katholieke Universiteit Leuven, was applied to generate time series of future rainfall and evapotranspiration. The time series of urban runoff were obtained from the correlation between rainfall and urban runoff under both current and climate change (A1B, A2, B1 and B2) scenarios. Rainfall-runoff was then uniformly distributed along the river reaches and urban runoff was applied as point source boundary conditions in the calibrated and validated MIKE 11 river flood model. Composite hydrographs with different return periods for all the boundary conditions were generated through extreme value analysis. The results show intensified and more frequent peak runoff resulting from combined effect of urbanization and climate change, in comparison to the individual effect of urbanization or climate change each. Urban runoff seems to characterize the hydrograph by an increase in the peak with an indication of quick response to the rainfall event. So, urban runoff can be considered as a component of total rainfall-runoff; in addition to base flow, interflow and overland flow, with further investigations.

Keywords: Urbanization, climate change, river flood model, urban runoff, composite hydrograph

List of acronyms and abbreviations

CCI-HYDR	Climate Change Impact on hydrological extremes along rivers and urban drainage systems
DHI	Danish Hydraulic Institute, Water & Environment
ETo	Evapotranspiration
IW-CS	InfoWorks-Collection System
IW-RS	InfoWorks-River System
K.U.Leuven	Katholieke Universiteit Leuven
NAM	Nedbør-Afstrømnings-Model
NSE	Nash-Sutcliffe Efficiency
POT	Peak Over Threshold
QDF	Discharge/Duration/Frequency
VMM	Vlaamse MilieuMaatschappij
WETSPRO	Water Engineering Time Series PROcessing tool

1. Introduction

The hydrological system within a catchment is governed by a number of factors, climate change and urbanization being the two most important ones. Significant alteration in the volume and timing of runoff may be caused by the changes in either or both of these factors (Franczyk and Chang, 2009). Many previous studies, assessing the impact of climate change on hydrology, found that there is a close association between streamflow variability and climate change. A significant impact of land use changes, especially caused by urbanization, on hydrology has been found in most of the previous studies (Tu, 2009). However, only some limited studies have been conducted to analyze the combined effects of climate change and land use changes on streamflow (Tu, 2009; Franczyk and Chang, 2009). Climate change projections for Belgium state that there will be rise in temperature from 1.7 to 4.9 ºC in winter and from 2.4 to 6.6 ºC at the end of 2100 in relation to the end of 2000 (Ntegeka, 2006). The change in rainfall as projected previously shows a rise from 6% to 23% for winter and a drop of up to 50% for summer until the end of 2100 (Ypersele, 2004). A resulting intensified global and regional hydrologic cycle is expected by these predicted temperature rises (Huntington, 2006). Urbanization causes dramatic environmental changes as vegetation is removed, soils become covered by impervious surfaces and streams are replaced by pipes which are illustrated by rapid flow responses and high peak flows following even modest rainfalls due to decreased infiltration and increased runoff (Semadeni-Davies et al., 2008; White et al., 2006). Increase in runoff occurs in proportion to the cover of impervious surface in a catchment (Arnold et al., 1996) which increases peak discharges and flood extents. Land cover change, especially urbanization, within a watershed is also recognized as an important factor affecting runoff (Chang, 2007), and it is possible that the transformation of land across the globe could have a greater influence on runoff than climate change (Vorosmarty et al., 2000). Urbanization, as well as changes in land uses and vegetation, within a watershed may further exacerbate the effect of climate change on runoff from the watershed (Georgiyevsky and Shiklomanov, 2003 cited in Franczyk and Chang 2009). Until now, climate change impact assessment for urban areas has been focused on flood risk from river systems alone rather than storm- and wastewater drainage (Semadeni-Davies et al., 2008). In the city of Turnhout in Belgium, the urban development within the city and modifications of the riverbed over the years caused increasingly frequent and harmful flood events affecting agricultural lands downstream. Any further expansion of urban fabric together with climate change impact may aggravate the situation beyond the existing water management capacity.

1.1 General aims of the study

The general aim of this study is to understand the effect of urbanization and climate change on the river flow causing severe urban flooding.
Specifically it can be summarized as:

1. Hydrological modelling for the sub-catchments using NAM (Nedbør-Afstrømnings-Model), a lumped conceptual hydrological model;
2. Development, calibration and validation of a one-dimensional hydrodynamic model for the two rivers, the Aa and the Visbeek, using MIKE 11 hydrodynamic software;
3. Simulation of an existing Sewer System Model ‘InfoWorks-CS’ to generate urban drainage scenario; and
4. Extreme value analysis to generate composite hydrographs with different return periods both under existing and future climate change conditions of the river flow and urban runoff

1.2 Study area description

The study focuses on the city of Turnhout in the Province of Antwerp, North of Flanders in Belgium. The city is located on a plateau between two small rivers, the Aa and the Visbeek, belonging to the Kleine Nete basin. The Aa river has a length of 19 km with a contributing area of 52.52 km^2 while the Visbeek river has a length of 11 km with a contributing area of 19.19 km^2. The study area has been displayed in Fig. 1.

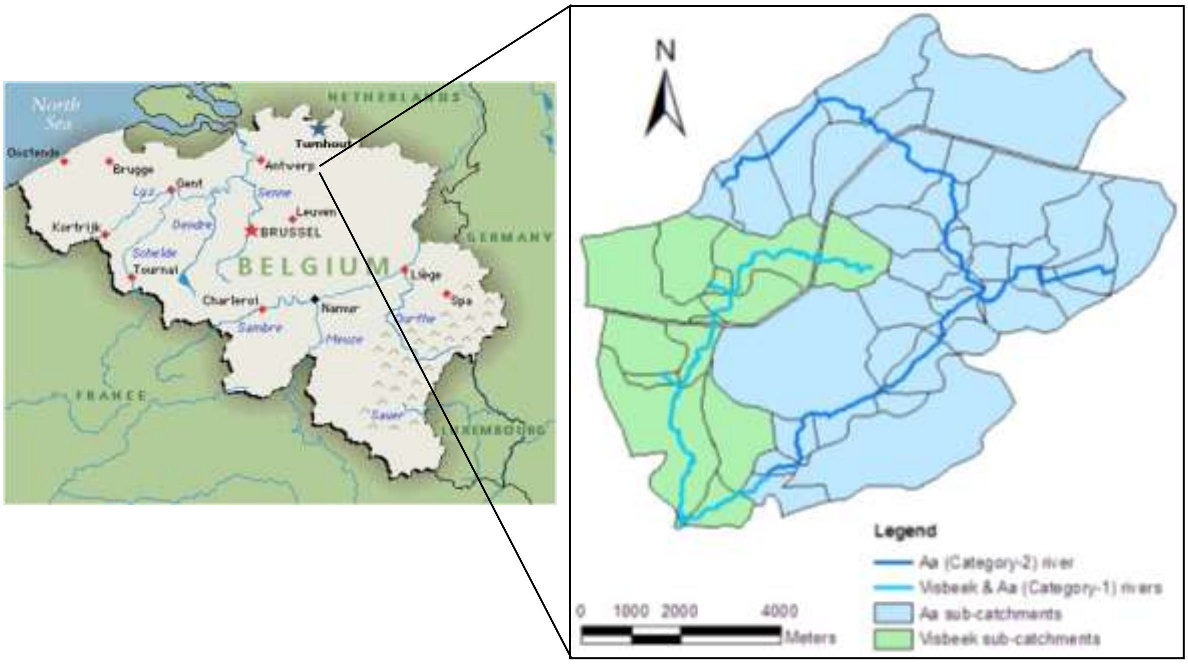

Fig. 1. Location of the city of Turnhout in Flanders, the sub-catchments and the rivers

1.3 Available data

The basic input requirements for a Hydrological model consist of meteorological data, hydrological data, model parameters and initial conditions. The basic meteorological inputs are rainfall and potential evapotranspiration averaged over the whole catchment. The required hydrological data is the discharge at the outlet of the catchment required for model calibration and validation. The necessary input data; point rainfall and discharge; were originally obtained from HYDRONET database operated by Vlaamse MilieuMaatschappij (VMM), while evapotranspiration data were obtained from Royal Meteorological Institute (KMI) for the Uccle station. The time series of discharge is observed at Turnhout flow gauging station on the Aa river (station ID L10_064).

2. Methodology

2.1 Hydrological Modelling using NAM

NAM is the abbreviation of the Danish "Nedbør-Afstrømnings-Model", meaning precipitation-runoff-model. This model was originally developed by the Department of Hydrodynamics and Water Resources at the Technical University of Denmark. NAM is a lumped conceptual hydrological model, describing the hydrological system taking into account four linear reservoirs in series. The NAM hydrological model simulates the rainfall-runoff processes occurring at the catchment scale. NAM forms part of the rainfall-runoff (RR) module of the MIKE 11 river modelling system (DHI, 2008). NAM includes parameters of an empirical and conceptual nature. In NAM model both manual and auto calibration methods are included for adjusting the parameters. The manual calibration is a method of trial and error which usually starts by adjusting the water balance in the system. While in automatic calibration, the calibration objectives have to be formulated as numerical goodness-of fit measures that are optimized automatically (DHI, 2008). Four numerical performance measures are used for the four objective functions included in the model.

In the case of Aa sub-catchment the basic three components are considered since there is negligible occurrence of snow in the area. The input data for the modelling process was meteorological daily data of precipitation and potential evapotranspiration. The period from 1st January 1997 to 31st December 2001 was considered for calibration.

Using the provided input data the NAM model simulates catchment runoff. The optimum values of parameters that represent the entire catchment were determined by calibrating the model against the observations. While conducting manual calibration the nine basic model parameters were adjusted by trial and error and then the optimum values were obtained through auto-calibration. At first the maximum amount of water in the surface storage, U_{max}, and the root zone storage, L_{max}, were adjusted to arrive at a smallest water balance error possible. Values of 19 mm and 116 mm for U_{max} and L_{max} respectively gave better result for this catchment.

The parameter CQ_{OF} was used to adjust the volume of the peaks, where this parameter indicates the amount of water that contributes to the overland flow. A higher value is expected as the catchment is a highly urbanized area and the paved area contributes more to the overland flow although the principal soil type is sandy and loamy sand. The amount of the interflow is determined by CK_{IF} parameter. This parameter was also adjusted to have reasonable amount of interflow in the catchment.

Afterwards the shape of the hydrograph for the peaks was adjusted by the time constant for routing parameter ($CK_{1,2}$). As the size of the catchment is relatively small, the response to the rainfall is expected to be fast. The shape of the recession was then adjusted using base-flow time constant (CK_{BF}). The threshold values TOF, TIF and TG were calibrated to further fine tune the total amount of the flow components.

The calibration of the ungauged Visbeek sub-catchment was done based on the relationships between the model parameters of the gauged sub-catchment characteristics, which are important for the runoff response such as shape, slope, land use and soil type (Timbe, 2007). The characteristics of gauged and ungauged sub-catchments were compared; and finally, the same NAM model parameters were used for the ungauged sub-catchment.

2.2 Hydrodynamic Modelling using MIKE 11

The essence of river flow modelling is the description and forecasting of maximum stages in rivers subject to phenomena such as precipitation runoff, tidal influences, hydraulic structure operations and possible structure or dike failure. Moreover, discharge and stage hydrographs, velocities of anticipated currents and duration of flooding are of interest. MIKE 11 (DHI, 2008) and InfoWorks RS (Wallingford, 2009) are some of the examples of one dimensional hydrodynamic software models. These models solve the Saint-Venant equations for shallow water waves in open channel using a finite-difference scheme. The models require data on river geometry (cross-sections perpendicular to the flow direction), the stream bed resistance factors (Manning coefficient) and the time series of upstream and downstream flow discharge or stage height boundary conditions. So, for each grid point (cross-section) average water depth and velocity is then calculated using the finite-difference approximation (Timbe, 2007). In this study 1D hydrodynamic MIKE 11 (DHI, 2008) model was used and the calibration and validation of the model was performed using the river flow data obtained from the Province of Antwerp.

2.3 InfoWorks-CS Model

InfoWorks CS is a comprehensive, easy-to-use and flexible system for the management of urban drainage network models, including stormwater or wastewater drainage systems or a combined stormwater and wastewater system. A network contains all the information needed to describe the drainage system. Each network is modelled as a collection of sub-catchment areas that drain to nodes (manholes or grade breaks) which are joined by links (conduits, pumps etc.) (Wallingford, 2009).

The software incorporates the sophisticated HydroWorks modelling engine for simulating the behaviour of the network under many different conditions. When a network is set up, event data (real or synthetic) representing the volume of water entering different points can be supplied on the network over a period of time. The modelling engine then runs a simulation to demonstrate the effect of the water on the network, so that weak points in the network can be identified.

Many different models can be created for the same network, based on different event data and various periods of time, from a few hours to a number of years. For this study, an existing model for the collector system, InfoWorks CS, generated by Province of Antwerp using composite storms based on the IDF relationships of the rainfall data at Uccle station operated by the Royal Meteorological Institute of Belgium (KMI) for the period 1967-1993 with a time step of 10 minutes for Flemish design applications determined in 1996, was available. The model includes the present sewer system, consisting of a combined (rain+waste) water system and the new parallel (piped) rainwater collector system, according to the plan of water management in partnership with the river basin coordinator in order to study new solutions to prevent prevailing flooding problems.

2.3 Urbanization and climate scenario development

The main purpose of calibrating the NAM model is to investigate the possible changes in the discharge of the rivers due to urbanization and climate change. Simulation of InfoWorks-CS model generates short time series of urban runoff for different storm events in both sub-catchments. These time series of urban runoff were not long enough for the extreme value analysis to be carried out in order to construct composite hydrographs for flood analysis. To generate long time series of urban runoff, several correlations were checked for a simple conceptualization of the runoffs, such as correlation between rainfall and; runoff discharge and urban runoff etc. A high correlation was found between rainfall at Turnhout station and urban runoff from the Aa sub-catchment, while a high correlation was observed between rainfall at Uccle station and urban runoff from the Visbeek sub-catchment. Fig. 2 shows the correlation between rainfall and two urban runoffs from two different areas in the city, for example, that were derived from IW-CS model.

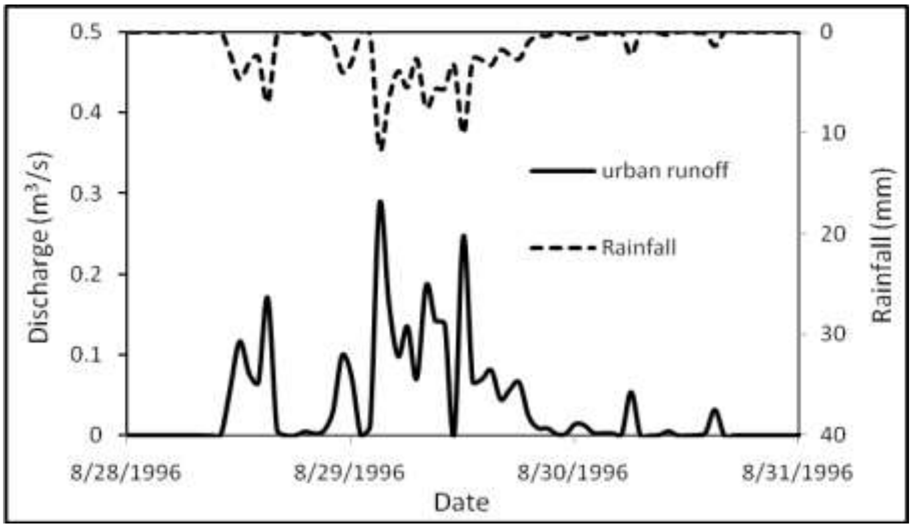

Fig. 2. Correlations between rainfall and urban runoff

The relation between rainfall and urban runoff is that a certain percentage of rainfall contributes to the urban runoff which has been checked and calculated for all the runoff coming from different sources in the city of Turnhout. Finally, the correlation of an urban runoff with rainfall was expressed as an average percentage of rainfall to generate urban runoff for long time period.

The climate change scenarios were obtained using the perturbation algorithm developed in the CCI-HYDR project at Hydraulics Laboratory of K.U. Leuven for facilitating the climate change impact assessment in Belgium. The algorithm imparts a perturbation to an observed series to generate future time series. In this tool the observed time series are perturbed on the basis of four SRES scenarios (A1B, A2, B1 and B2) (Ntegeka and Willems, 2008). So, the perturbation of rainfall from the Turnhout station and evapotranpiration from the Uccle station was performed by using this CCI-HYDR Perturbation Tool to generate the future time series of the same for 2100s. These time series were then used as the input in the calibrated hydrological model NAM to generate the rainfall-runoff from the sub-catchments under future climate conditions. The future urbanization scenarios are based on the correlation found out between the urban runoffs and the rainfall representing current climate condition. The perturbed rainfall was then used to generate the urban runoffs from different sources in the city using different correlations established previously. The simulation results from NAM and generated urban runoff based on the correlations were statistically processed (extreme value analysis) and compared with the current values to assess the change in only the high peak values for the analysis of flood frequency towards the end. This comparison is performed as follows:

1. The current and climate change scenario period results are ranked in descending order giving rank one to the highest value in the series;
2. The empirical return period for the ranked runoffs is calculated (using formula n/m) where n is the number of years for the time series and m is the rank number.

The time series of the rainfall-runoff and urban runoff both under current and future climate conditions were then statistically analyzed to construct composite hydrographs with different return periods.

2.4 Generation of composite hydrographs

The composite hydrographs for each sub-catchment and boundary were generated using the extreme value analysis applied to a long-term time series of rainfall-runoff discharges. The time series for the catchments were generated by the lumped conceptual hydrological model NAM (DHI, 2008), using the long rainfall and evapotranspiration series available in and around the catchment.

The results, rainfall-runoff discharges, from the hydrological model were then analyzed for the flood frequency distributions with different aggregation-levels which vary from 1 hour to 3 days. These distributions were summarized in the form of 'discharge/duration/frequency' (QDF) relationships and more advanced, in the form of 'composite hydrographs'. These constructed composite hydrographs are synthetic hydrographs which refer to an average discharge corresponding to a specific return period for all the durations that are considered centrally in the hydrograph (Vaes et al., 2000). For both the rivers, the composite hydrographs were first generated for the rainfall-runoff of the two sub-catchments, for 5 upstream boundary conditions and for the 11 point source boundaries of urban runoff.

2.5 Selection of Peak Over Threshold (POT)

Since independent extreme values are necessary for further analysis, extreme values from the rainfall-runoff time series were extracted as peak-over-thresholds (POT) in 'nearly independent' quick runoff events using WETSPRO tool ((Willems, 2009). The moving average approach was used for five different aggregation levels of 1, 6, 12, 24 and 72 hours. The extremes have to be independent in the extreme value analysis and the extraction of independent values is done using one of the 'independency criteria' available in the tool. The number of extremes to be selected is determined by one of these criteria. According to Willems, 2009 two subsequent peak events are considered nearly independent when the following three conditions are fulfilled:

(i) The time length τ of the decreasing flank of the first event exceeds a time k_p:

$$\tau > k_p \tag{1}$$

(ii) The discharge drops down – in between the two events – to a fraction lower than f of the peak flow:

$$\frac{q_{\min}}{q_{\max}} < f \tag{2}$$

or close to the base-flow q_{base}:

$$\frac{q_{\min} - q_{base}}{q_{\max}} < f \tag{3}$$

(iii) The discharge increment $q_{max} - q_{min}$ has a minimum height q_{lim}:

$$q_{\max} - q_{\min} > q_{\lim} \tag{4}$$

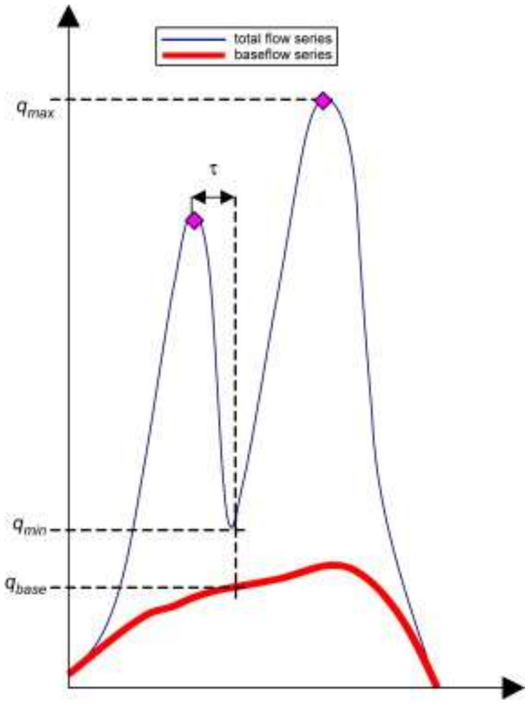

Fig. 3. Parameters for selecting nearly independent POT values (Adapted from Willems, 2009)

This procedure for peak flow selection has three parameters: k_p, f and q_{lim}. It is based on the concept that a peak flow event can be considered largely independent from the next one, when the inter event discharge drops down to a low flow condition or almost to the base-flow level. The method and the parameters used for selection of POT values of the rainfall-runoff of Aa sub-catchment are presented in Table 1.

Table 1
The POT selection criteria for the rainfall-runoff discharges from the Aa sub-catchment for different aggregation levels

Aggregation level (hr)	1	6	12	24	72
Parameter, f (-)	0.8	0.8	0.8	0.9	0.9
Independency period, k (days)	6	6	6	6	6
Min peak height, q_{lim} (m^3/s)	0.25	0.25	0.2	0.15	0.1

2.6 Extreme value analysis

The next step after selecting the nearly independent POT values for the different aggregation level is the analysis of these data separately for distribution plots. And, this was done by using Hydrological extreme value analysis tool ECQ (Willems, P., 2004). The parameters of the extreme value analysis were then determined through subjective judgment based on the least MSE of the extreme value Q-Q (quantile-quantile) plot. The QDF relationships for the Turnhout station are shown in Fig. 4. Finally the composite hydrographs for all the rainfall-runoff discharges and urban runoff both for current and climate change scenarios were constructed for return periods of 5, 10, 25, 50 and 100 years; and 50 and 100 years respectively .

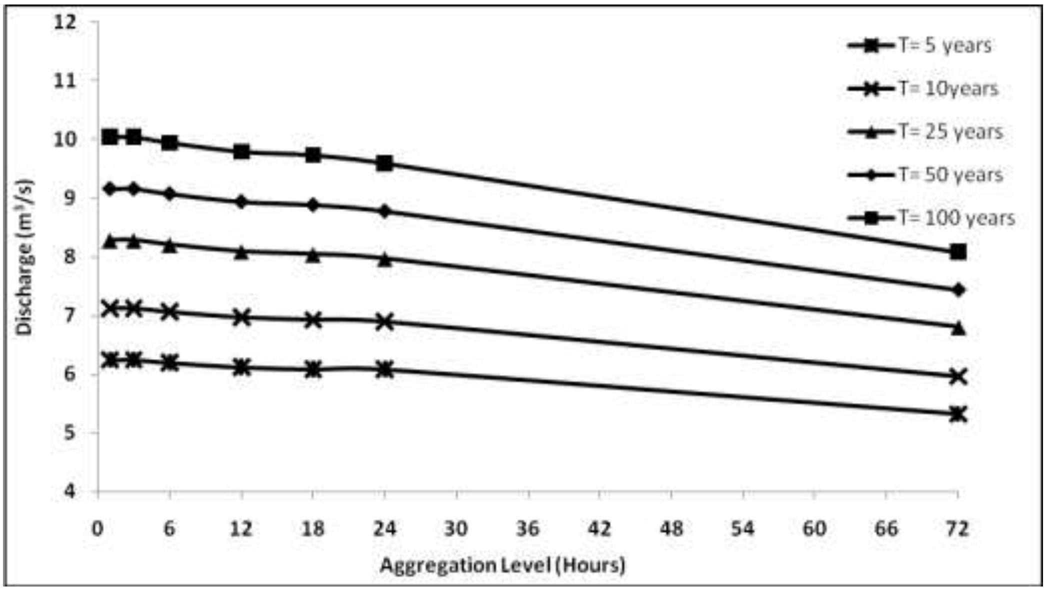

Fig. 4. Generated QDF relationships for the Turnhout station

3. Results and discussion

3.1 Hydrological modelling using NAM

The final simulation result of Aa sub-catchment has the following optimum values for the nine NAM parameters.

Table 2
Summary of calibrated NAM model parameters for Aa sub-catchment

Parameters	*Umax* (mm)	*Lmax* (mm)	*CQOF* (-)	*CKIF* (hours)	*CK1,2* (hours)	*TOF* (-)	*TIF* (-)	*TG* (-)	*CKBF* (hours)
Values	19	116	0.90	681	44	0.006	0.92	0.15	3610

The optimum values of these parameters lie between the range of values as recommended by the NAM manual (DHI 2008). *CQOF* and *CK1,2* values are reasonable according to the characteristics of the catchment. Since the size of the catchment is small, the fast response to the rainfall input is expected. Besides, since the area is highly urbanized leading to more impervious area, the infiltration capacity of the area is expected to be lower and in turn higher proportion of the excess rainfall goes to the overland flow component.

The reliability of the NAM was evaluated based on the Nash-Sutcliffe Efficiency (NSE) which evaluates the percentage of accuracy or goodness of the simulated values with respect to their observed values. The NSE obtained from the final simulation result is 0.61. The discrepancy of water balance is -2.1%. The graphical comparison of simulated and observed flow for the whole calibration period is presented in Figure 5. The less accurate results might be related to the input data uncertainty. Further evaluation of the models was performed with graphical methods as presented in the next section.

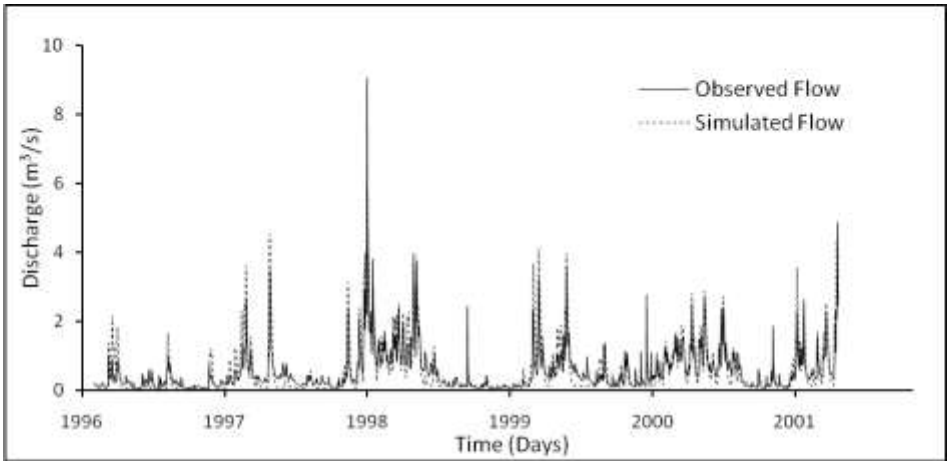

Fig. 5. Calibration result of NAM for the period 1997-2001

3.2 *Validation of MIKE 11 model*

The simulated rainfall-runoff from NAM was used to validate the MIKE 11 model for the period of 25 October 1998-7 November 1998. The simulated average maximum water level in the floodplains from MIKE 11 is 22.71 m as compared to 22.89 m as obtained from the Water Management Division of the Province of Antwerp with an average variation in the maximum water levels by 0.71% and by 2.47% in the minimum water levels. The model performance is also satisfactory for water levels in all the floodplains with an R value of 0.99 and a NSE value of 0.97 for the validation period with NAM results.

3.3 *Impact of urban runoff on flooding*

Total eleven urban runoffs were considered to assess their impact on peak runoff from two sub-catchments; out of these urban runoffs, seven are planned to be buffered in future by the city authority. It is planned that runoff collected through rainwater collector system would be stored during the high flow periods in the green spaces at the transition of the city and the river and it is expected to have positive implication on flooding in the downstream of the city. It is there imperative to ascertain their impact on the peak runoff from the sub-catchments they belong to. In order to assess this impact, the ‘peak over threshold (POT)’ runoff values, the simulated runoff results of NAM, were selected for subsequent extreme value analysis. Then extreme value analysis reveals that there is an average increase of 36% in the peak runoff from two sub-catchments due to these urban runoffs. Fig. 6 indicates that the frequency of an extreme high event will be increased (i.e. decreasing the return period) if these urban runoffs continue to be added to the total runoff.

Table 3
Change in flooded area and volume of flooding water with the return periods of urban runoffs compared to the situation without any influence

Return period (years)	Change in flooded area (%)		Change in volume of water (%)	
	All floodplains	Lower valley	All floodplains	Lower valley
5	7.2	22.2	14.4	36.3
10	5.9	22.9	1.71	34.0
50	5.4	22.3	11.4	32.5
100	6.1	25.8	14.5	40.8

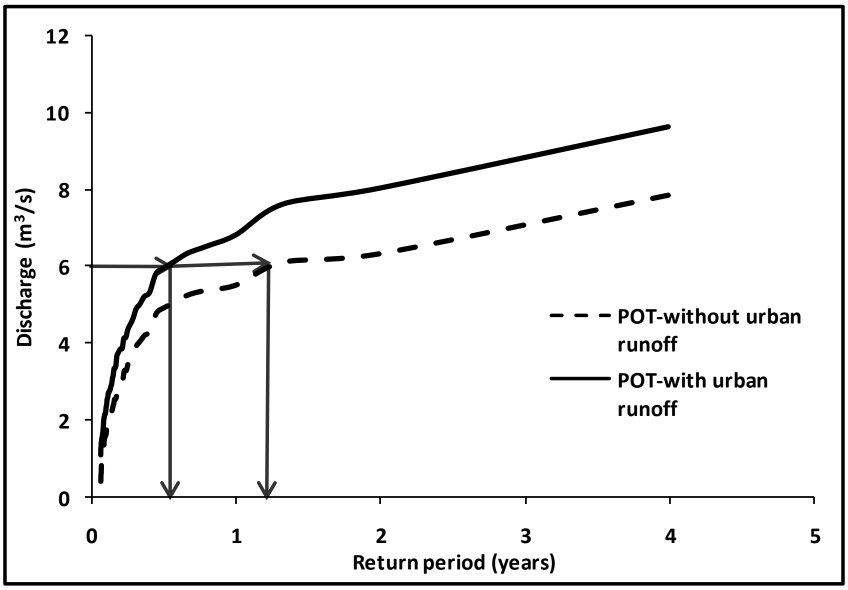

Fig. 6. Effect of urban runoff from the city on peak runoff from two sub-catchments

3.4 Impact of climate change on flooding

Since it is expected that the risk associated with flooding is higher in the high scenario, the climate change impact analysis was based on the high scenario which represents the most pessimistic scenario. The impact of climate change alone on peak runoff is presented in Fig. 7 which also shows an average increase of peak runoff by 23% for higher return periods, while an average decrease of relatively lower peak runoff by 19% for lower return periods as compared to the current conditions. The extreme value analysis reveals that the return period of a flood event will be decreased by about 3 times causing the event to be about 2 times more frequent in future with comparison to the current frequency of occurrence. This trend might be useful for the city water managers to search for the options which must be designed to be functional to combat this exacerbating impact that has not yet been taken into consideration in any of the alternatives proposed hitherto.

Table 4
Change in flooded area and volume of flooding water between current condition and climate change 'high' scenario for 2100s without considering urban effect

Return period (years)	Change in flooded area (%)		Change in volume of water (%)	
	All floodplains	Lower valley	All floodplains	Lower valley
50	47.0	62.6	61.0	66.2
100	50.0	53.8	69.0	67.7

3.5 Combined Impact of urban runoff and climate change on flooding

Since the runoff is more sensitive to climate change than to urban runoff (i.e. urbanization), the situation might deteriorate further if urban runoffs from the city are combined with climate change. The increase in peak runoff becomes higher when the impact of both the variables is taken into account concurrently than they are considered individually. The average increase of peak runoff is about 56% with comparison to the current trend as shown in Fig. 8. This intensification might cause more frequent and higher floods than the one prevailing at present and being considered in selecting an appropriate management alternative to overcome the flooding problem. The relative impact of urbanization and climate change both individually and combined is presented in Fig. 9.

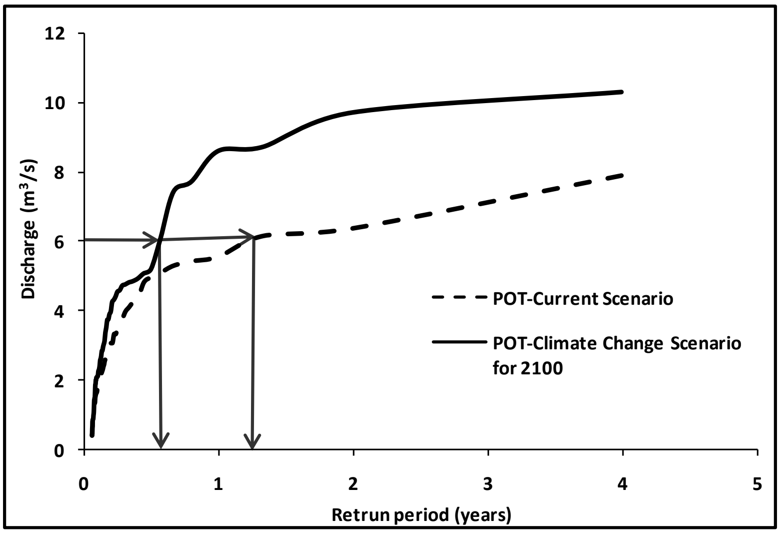

Fig. 7. Effect of climate change (high scenario) on peak runoff from two sub-catchments

Table 5
Change in flooded area and volume of flooding water between current condition without urban impact and climate 'high' scenario for 2100s combined with urban runoff

Return period (years)	Change in flooded area (%)		Change in volume of water (%)	
	All floodplains	Lower valley	All floodplains	Lower valley
50	52.6	87.6	76.8	114.7
100	58.7	92.8	87.3	124.2

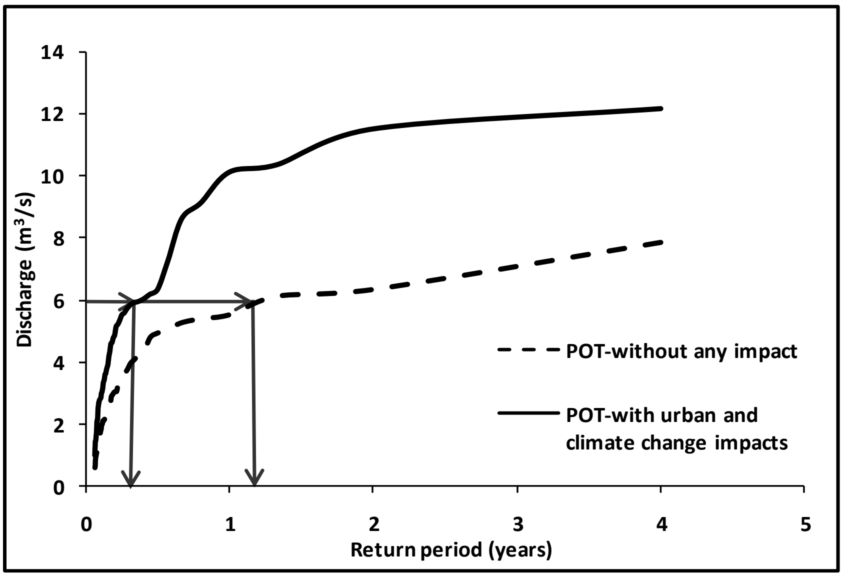

Fig. 8. Effect of both the urban runoff and climate change ‘high’ scenario on peak runoff from two sub-catchments

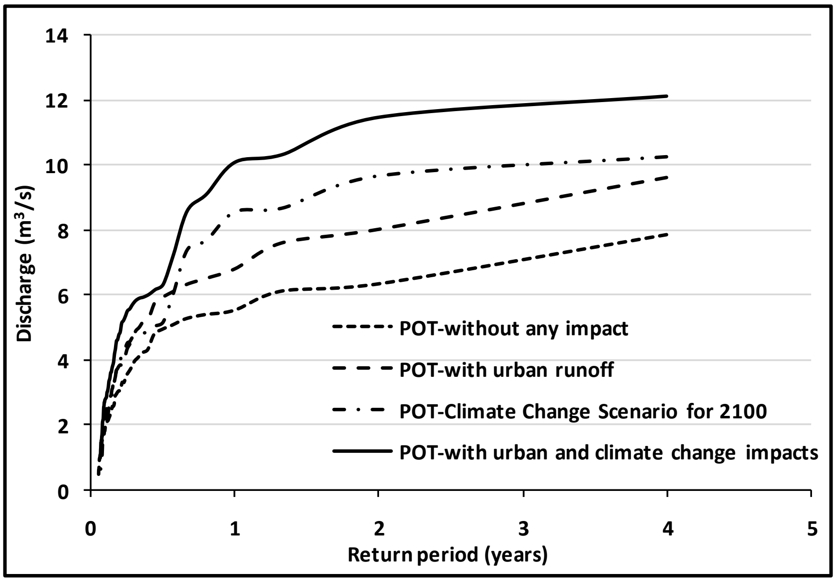

Fig. 9. Relative effect of urban runoff and climate change ‘high’ scenario both alone and together on peak runoff from two sub-catchments

3.6 Urban runoff as a flow component

In the numerical filter technique, a time series of total rainfall-runoff discharges can be split into three subflows, such as the overland flow, the subsurface flow or interflow and groundwater flow or baseflow (Willems, 2009). Urbanization does not belong to the hydrologic domain, but it has an impact on the hydrologic cycle. Urbanization causes increase in the paved area removing the vegetated surface, which reduces infiltration through the impervious surfaces. The increasing proportion of paved surface within the urban fabric transforms the hydrographs to ones that are characterized by high flow peaks and fast response to even moderate rainfall events (Semadeni-Davies et al., 2008). The results of 1D

Hydrodynamic MIKE 11 model show the effect of urban runoff (as a consequence of urbanization) on simulated river discharges which is characterizing the hydrograph by an increase in the peak with an indication of quick response to the rainfall event. With further investigations in other study areas, this urban runoff can be considered as a fourth component of total rainfall-runoff discharge to confirm the results of the present study.

4. Conclusions

Under current conditions, the average increase in peak runoff from the catchment is 36% due to the impact of urbanization in the region. On the other hand, the individual impact of climate change 'high' scenario on peak runoff from the catchment shows also a quite significant influence with an average increase in peak runoff by 23% and an average reduction of relatively lower peak runoff with lower return periods by 19% as compared to the current condition without considering the impact of urbanization. Finally, the combined impact of urbanization and climate change shows a very significant intensification of the peak runoff with an average increase in the peak runoff by 56% as compared to the current condition where no impacts are considered. With further investigations in other study areas, the urban runoff flow can be considered as a fourth component of total rainfall-runoff discharge; in addition to base flow, interflow and overland flow, to confirm the results of the present study.

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