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Discussions

Water displacement by sewer infrastructure in the Grote Nete catchment, Belgium, and its hydrological regime effects

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Abstract

Urbanization and especially impervious areas, in combination with wastewater treatment infrastructure, can exert several pressures on the hydrological cycle. These pressures were studied for the Grote Nete catchment in Belgium (8.18 % impervious area and 3.89 % effective impervious area), based on a combination of empirical and model-based approaches. The effective impervious area, combined with the extent of the wastewater collection regions which do not coincide with the natural catchment boundaries, was used as an indicator for the urbanization pressure. Our study revealed changes in the total upstream areas of the subcatchments between −16 % and +3 %, and in upstream impervious areas between −99 % and +64 %. These changes lead to important inter-catchment water transfers. Based on simulations with a physically-based and spatially-distributed hydrological catchment model, profound impacts of effective impervious area on infiltration and runoff were found. The model results show that the changes in impervious areas and related water displacements in and between catchments due to the installation of the wastewater treatment infrastructure severely impacted low flows, peak flows and seasonal trends. They moreover show that it is difficult, but of utmost importance, to incorporate these pressures and artificial processes in an accurate way during the development of hydrological models for urbanized catchments.

1 Introduction

Urbanization significantly impacts flow regimes and water quality of river systems (Paul and Meyer, 2001; Jacobson, 2011). In particular, impervious areas exert several pressures on the hydrological cycle of catchments (Shuster et al., 2005). They can affect infiltration, surface runoff, and evapotranspiration making the lateral processes potentially more important in urban settings then the vertical processes (Arnold and Gibbons, 1996; Becker and Braun, 1999; Brabec, 2009). These alterations in hydrological processes increase runoff peak flows and flood flashiness in rivers (Sheeder et al., 2002; Baker et al., 2004).

Whereas the effects on peak flows are well investigated, potential effects of urbanization on baseflow and low flow events are less understood (Price, 2011). Baseflow represents streamflow fed from deep subsurface and delayed shallow subsurface storage (Ward and Robinson, 1989), while low flow addresses dry season minimum flows (Smakhtin, 2001; Price, 2011). Because of urbanization a reduction in infiltration and recharge is generally expected which in turn affects river baseflow e.g. Simmons and Reynolds (1982); Kauffman et al. (2009). But baseflow, however, can also be strongly influenced by various types of anthropogenic activities in the basin, such as drinking water importation, water abstractions and sewer leakage or ground water intrusion (Seiler and Rivas, 1999; Smakhtin, 2001; Brandes et al., 2005; Wittenberg and Aksoy, 2010). There is no predictable response of the proportion of baseflow to total streamflow or the annual low flow to urbanization, but a weak tendency of baseflow decline seams to exist (Price, 2011).

Sewers collect wastewater and (for combined sewer systems) rainstorm water from pavements. But it can also intercept groundwater or leak wastewater to the groundwater system (Dirckx et al., 2009). The collected water is transported to a wastewater treatment plant (WWTP) and, after treatment, discharged into the receiving river. The WWTP thus aggregates water from the entire wastewater collection region (WWCR) and returns it to the environment at one single river location. Moreover, the WWCRs usually do not coincide with the river basin boundaries as they are mostly based on administrative borders. Consequently the associated sewer infrastructure might transport water between different (sub)catchments and further affect the natural hydrological processes in the basin (Simmons and Reynolds, 1982).

Total impervious area (TIA) is considered to be an important indicator of the urban disturbance and an important land use characteristic in physically-based hydrological models. Imperviousness of urban areas is, however, very heterogeneous. Infiltration of impervious areas may not always be zero (Ragab et al., 2003). Impervious areas that are directly connected to the receiving water have a much larger effect on the receiving waters (Boyd et al., 1994; Walsh et al., 2009). Some studies therefore suggest that the subset of impervious surfaces that route storm water runoff directly to streams via storm water pipes, also called effective impervious area (EIA), may be a better predictor of stream ecosystem alteration (Shuster et al., 2005; Roy and Shuster, 2009). But measurements of EIA are much more difficult and therefore less addressed in hydrological studies (Walsh et al., 2009).

Some studies have accounted for the difference between TIA and EIA in impact studies (Lee and Heaney, 2003; Shuster et al., 2005). The traditional calculation of TIA and EIA might, however, be erroneous since the difference in boundaries between the natural river catchment and the WWCRs is generally disregarded. Although impervious areas are situated within a river catchment, the surface runoff from these areas might drain to a WWTP located outside the catchment. The impervious areas in that case do not take part of the considered catchment.

Another method to study the impact of changes in pervious and impervious areas on catchment hydrology is by means of hydrological models. Such models indeed can help in complementing existing data and obtaining a better insight in the catchment hydrological behavior and the hydrological impact of changes in the catchment (e.g. impact of urbanization). To allow spatial (e.g. land use related) scenarios to be studied, fully spatially distributed hydrological process models (FDPM) are required. Such models give a spatially detailed and potentially reliable description of the hydrological processes in the catchment (Abbott et al., 1986; Boyle et al., 2001; Ajami et al., 2004; Carpenter and Georgakakos, 2006), but require a high amount of spatially-explicit input data. They may be difficult to calibrate because of parameter identifiability problems when limited input and calibration data are available (Beven, 1989; Jakeman and Letcher, 2003; Muleta and Nicklow, 2005). These factors limit the applicability of such models. The FDPMs perform well in catchment areas where the hydrological processes are still close to natural run-off conditions, but are typically less accurate in urban areas due

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to the several (unknown or difficult to model) human influences (Vansteenkiste et al., 2012).

Discarding these anthropogenic influences can lead to significant bias in the design of the catchment hydrological processes in the model. In an urbanized environment with sewer infrastructure, this might not only affect the performance of the catchment runoff and river flow simulation, but can also have indirect effects on parameterization of other land-uses and over- and underestimate individual runoff components (Vansteenkiste et al., 2012). It has previously been demonstrated that if one does not differentiate between TIA and EIA in the hydrological model, this may result in a large analytical model bias (Alley and Veenhuis, 1983; Brabec, 2009). EIA is the most sensitive flow parameter in urban drainage models. Some authors have shown that calibration of this parameter may completely eliminate the bias in the results of these models (Willems and Berlamont, 1999; Kleidorfer et al., 2009).

This paper aims to quantify the importance of the above-mentioned impacts of WWTPs on downstream river flows, for a selected river catchment in Belgium. The study makes use of measured river flows and effluent discharges from the different WWTPs installed in and outside the catchment. We evaluate the relative contribution of these WWTPs to the rivers' flow. To understand the origin of the WWTP effluent discharges and the WWTP induced water transfers between catchments, the sewer infrastructure and the EIA are assessed in a GIS environment, and compared with simulations in a FDPM of the catchment. When implementing the FDPM, the above-mentioned modeling issues are considered. Based on the GIS- en model-based results, we demonstrate the magnitude and importance of:

- water transfers across the catchment boundaries;
- water transfers across subcatchments within the catchment;
- the impact of EIA on the performance of a FDPM and the different hydrological properties.

We also discuss the implications the water transfers have on the FDPM based impact analysis.

2 Material and methods

2.1 Study area

The research was conducted within the Grote Nete catchment (350 km^2), situated in the north of Belgium. It has a maritime, temperate climate with an average precipitation of 800 mm yr^{-1}. The catchment is composed of a mosaic of semi-natural, agricultural and urbanized areas, with a total population of 218 815 (Belgium, 2011). Urbanized areas are mainly situated around the town centers, but important parts of the urbanization spreads along the main roads that connect the different towns. As a result the development of the sewer infrastructure is difficult, costly and time consuming. Although the first wastewater treatment plant in the catchment dates back from 1964, serious investments in the sewer infrastructure only started 15 to 20 yr ago (Dirckx et al., 2009). Nevertheless, large numbers of households are yet to be connected to the sewer infrastructure resulting in a mixture of connected and not-connected houses, roads and other impervious areas. Not-connected houses are generally connected to the nearest stream with, most of the times, a septic tank in-between.

2.2 River flow and WWTP discharges

Daily mean river flow data ($m^3\,s^{-1}$) were obtained for the river gauging station situated at the outlet of the catchment (Varendonk) from the Flemish Environment Agency (FEA) for the period 2004–2008, as well as wastewater discharge data were obtained for the different WWTPs that are related to the catchment (Fig. 1). To evaluate the overall impact of the WWTPs that discharge into the catchment (Mol and Geel) relative contributions of the WWTPs to the daily discharge of the Grote Nete were calculated for the period 2004–2008. No discharge data were available for the WWTP of the military camp of Leopoldsburg. However, because of its small size (0.69 % of total EIA), its impact on the river system is considered to be negligible.

2.3 Land use map and impervious area

The land use map used in this study was obtained from the National Geographical Institute (NGI) (NGI, 2007) and has a spatial accuracy of one meter. This land use map (1 : 10 000 vector-layers) is based on aerial photographs from 1998 (1 : 21 000) and on ground verification and adjustment in the following years until 2007. For hydrological simulation purposes, only a set of predefined, significantly different land use classes are applied, which are defined on the basis of their impact on hydrological processes. These follow the IGBP-classification system and default land use parameters are used (Liu and De Smedt, 2004). Therefore, the 47 different land uses were reduced to 9 categories: Evergreen Needle leaf Forest, Broad-leaved woodland, Mixed Forest, Open Scrublands, Grasslands, Permanent Wetlands, Croplands, Impervious area and Water Bodies. In order to plan further investments in sewer infrastructure, the Flemish Government approved zoning plans in 2008. These zoning plans indicate which buildings currently are connected to a WWTP, which will be connected in the future and which buildings will have to install individual wastewater treatment plants (FEA, 2008a). Using these maps we were able to select the houses from the impervious areas that are connected to a sewer and to the different WWTPs. Maps of the sewer infrastructure were used to select the roads that are connected to each WWTP (FEA, 2008b). Combining these methods resulted in one map that gave us the EIA of the WWCRs relevant to the catchment.

2.4 Upstream area calculations

Subcatchments were delineated for the Grote Nete catchment based on a 1 : 5000 digital elevation model (DEM) expressed as a 5 m-raster (FEA, 2005, 2006). For each

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stream junction ($n = 131$), upstream areas were calculated using the method discussed in Jenson and Domingue (1988) (in this article called “run off method”). By combining these upstream areas with the 1m-raster of the land-use map we calculated upstream impervious area for each stream junction. Next the sewer infrastructure was considered (“sewer method”) (Fig. 2). In this method, the subcatchments and upstream areas were recalculated by removing the EIAs from their natural subcatchments and adding these EIAs to the subcatchment of the stream into which the WWTP discharges. As zoning maps also indicate which houses have yet to be connected to the WWTPs, expected upstream areas for the near future were obtained as well. Differences in upstream impervious areas and total areas between the “runoff method” and the “sewer method” could be considered as indicators of how strong the catchment is affected by the sewer infrastructure. All GIS-calculations were performed in ArcGIS 9.3 (ESRI Inc., 2009). To make an evaluation of the impact of the sewer infrastructure on the catchment’s overall water balance, the changes in upstream area and upstream impervious areas between both methods were calculated.

2.5 MIKE SHE model set-up

MIKE SHE is a spatially distributed, physically based, hydrological model (Abbott et al., 1986). It simulates the terrestrial water cycle including evapotranspiration (ET), overland flow, unsaturated soil water, and groundwater-water movements (Refsgaard and Storm, 1995; Feyen et al., 2000; DHI Water and Environment). The MIKE SHE model has been used worldwide for a wide range of applications (Refsgaard, 1997; Sun et al., 1998; Thompson et al., 2004; Sahoo et al., 2006; Zhang et al., 2008). The representation of watershed characteristics and input data in MIKE SHE are provided through raster information. The MIKE SHE model for the Grote Nete catchment was built on a 250 m grid. It was developed with physics-based flow descriptions only for the processes that are important for the purposes of this study, i.e. overland and unsaturated flow. The saturated zone was implemented through simplified lumped process descriptions, given that the groundwater flow is not affecting the surface runoff process and study objectives in this study (Graham and Butts, 2006).

Six (hourly) rainfall stations were considered to describe the spatial variability of the rainfall over the catchment and used to create meteorological input Thiessen polygons. Only one potential evapotranspiration series was acquired from the national meteorological station located at Uccle, 30 km west of the study area, and applied. The growing cycle of the different crops were considered by means of a vegetation database that included leaf area index (LAI) and root depth (RD) series and were based on Rubarenzya et al. (2007). Additional empirical parameters for determining the evapotranspiration of the crops were assessed from literature (Kristensen and Jensen, 1975; DHI Water and Environment). The overland flow component was determined by the Strickler roughness coefficient, detention storage and initial water depths. The surface roughness is based on values from literature (Chow, 1964), as a function of land use. Standard values were taken for the detention storage and initial water depths and are considered constant over the entire catchment (DHI Water and Environment). The MIKE SHE model was coupled to a full hydrodynamic river model, implemented in MIKE 11 to route MIKE SHEs overland flow to the basin outlet and account for the hydraulic effects of the river network and its infrastructure. The river network comprised the main branches in the basin, which were extracted from the Flemish hydrological atlas (FEA, 2005). The geometry of each river branch was specified in terms of cross sections obtained from field survey data. Most rivers are clean and straight but with many weeds. Therefore the manning river bed roughness coefficient was considered equal to 0.035 (Chow et al., 1988). All infrastructures that were expected to have a significant impact on the river flow, such as bridges, culverts, weirs. . . , were implemented in the model. The unsaturated zone was built on the soil map of Flanders obtained from the Flemish institute for geographical information (AGIV). Soil characteristics were derived from the USDA soil parameters classification system (Graham and Butts, 2006). Saturated zone flow was simulated using the linear reservoir method. The entire groundwater system was divided into a series of shallow interflow reservoirs plus two deep baseflow reservoirs. These reservoirs allowed differentiating between fast and slow components of baseflow discharge and storage. Water was routed through the linear reservoirs as interflow and baseflow and subsequently added to the MIKE11 river network as lateral inflow in the lowest interflow reservoir (Graham and Butts, 2006).

2.6 MIKE SHE model calibration

The model was calibrated against hourly streamflow measurements at the catchment outlet for the time period 2004–2006, while the years 2007 and 2008 were used for model validation. The parameters, mainly surface roughness and saturated zone parameters were iteratively adjusted until maximal correspondence between measured and predicted runoff downstream the catchment was achieved. The model correspondence was evaluated both qualitatively by visual comparison of the runoff series and quantitatively using the goodness-of-fit statistics, including mean error (ME), root mean squared error (RMSE), correlation coefficient (R) and Nash-Sutcliffe efficiency (NSE) (Nash and Sutcliffe, 1970). Because the aim of this study was to investigate the impact on both high and low river flow conditions, also peak and low flows, extracted from the time series using the method of Willems (2009) were explicitly validated. This was done in scatterplots of simulated versus observed values but also by means of ME and RMSE statistics. The model was verified for the present situation before being applied for the analysis of the effects of the WWTP discharges and water transfers. Additional verification of the model performance was done analysing data on peak and low flows within a multi-criteria model evaluation protocol included in the WETSPRO tool (Willems, 2009).

2.7 Implementing the hydrological influence of the sewer infrastructure in MIKE SHE

To model the effect of the EIA on the hydrological regime of the Grote Nete basin, the detailed land use map (1 : 5000) and EIA had to be resampled to the MIKE SHE model grid specifications (250 m). The land use resampling was performed with high detail for preserving the land use distributions. But an overestimation of TIA by 4.25 % in the model remained. For each WWCR the urban area and EIA were extracted and the percentage EIA per urban area WWCR was assessed. These EIAs were used in combination with the resampled urban area per WWCR in MIKE SHE to define the fraction of rainfall which would be discharged by the sewer infrastructure to the river. Table 1 presents the percentage of EIA per WWCR and its urban area.

There are two possibilities for simulating the impact of the sewer infrastructure with the MIKE-SHE model. The first possibility basically involves the removal of the surface runoff to the sewer network from the catchment runoff and addition of this sewer surface runoff in a concentrated way, after accounting for the sewer – WWTP routing time delivery delay, to the river network at the WWTP effluent location. For the sewer runoff removals a solution is to take out, from the modeling domain, the grid cells that cover impervious areas that contribute to the sewer system. The problem encountered here is that none of the 250 m grid cells are fully covered by that type of impervious surfaces. Only fractions of the grid cell areas contribute to the sewer system, making the removal of the grid cells impossible. For that reason, we opted for the second solution: reducing the rainfall input proportional to the fraction of the sewer runoff contribution.

The different rainfall series were reduced based on the overlap between their Thiessen polygons, WWCR regions and corresponding rainfall fractions, and implemented in the model. The difference in runoff discharges between the initial model result and the simulation with reduction of rainfall gave us indications about the impact of the sewer infrastructure on the catchment runoff. These results were then compared with the measured discharge data of the different WWTPs. Different scenarios of reduced rainfall were applied within the model to assess its impact in the model. Scenario 1 considered a reduction in rainfall within the WWCRs that discharge within the catchment to assess the impact of the RWZI's on the river flow. Scenario 2 implemented a reduction in rainfall within the WWCRs that discharge outside the catchment to assess the impact of water transport outside the catchment. Scenario 3 took a reduction in

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rainfall across the entire catchment to evaluate the impact of all the sewers on the river system (Table 1).

The model results were compared for the different scenarios and assessed on an hourly, daily and monthly basis. The reductions in flow because of reduced rain were compared to the measured WWTP discharges and their relative contributions to the overall flow. Differences in relative contributions were calculated between the reference scenario and the rain scenarios 1 and 3. Changes in peak and low flows were evaluated in relation to the empirical return period (mean recurrence interval of these flows).

3 Results

3.1 River flow contribution of WWTPs

Between January 2004 and December 2008 the Grote Nete had an average observed discharge of $3.95\,m^3\,s^{-1}$ at the catchment outlet. The upstream WWTPs had for the same period an average discharge of wastewater to the Grote Nete of $0.31\,m^3\,s^{-1}$ or 7.90 % of the river flow. Discharges of both the river and WWTPs however vary substantially in time (Fig. 3). Rain events always lead to strong changes in river flow. For example, in 2007 there was a strong reduction in baseflow during spring and summer, followed by a strong recharge during the winter period. In 2008 several rain periods lead to a higher average flow during spring and summer. Monthly mean discharges of WWTPs and monthly mean river flows were found to be well correlated ($r^2 = 0.72$; $p < 0.001$). Correlation between daily mean WWTP discharges and daily mean river flow was lower ($r^2 = 0.60$; $p < 0.001$).

The WWTPs were found to contribute between 5.52 % and 13.14 % of the monthly average river flow at the Grote Nete catchment outlet (Fig. 4). On a daily basis the contribution of the WWTPs to the river flow could decrease to 5.52 % during wet periods or increase up to 23.59 % in summer. The highest relative contributions were observed

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for rain events that occurred during low river flow (e.g. convective thunderstorm periods after long dry summer periods).

3.2 Water transfers between catchments and subcatchments

3.2.1 Current situation

From the analysis of the WWCRs we concluded that there are significant water transfers between the Grote Nete catchment and adjacent catchments. In total, 2836 ha of TIA are present in the catchment. Of those, 1661 ha are currently connected to the WWTPs, 1175 ha are not. This gives an initial ratio of 0.59 between TIA and EIA. Of those 1661 ha, 761 ha, mostly situated in the southern parts of the catchment, drains surface water outside the catchment by the sewer infrastructure. Only 900 ha (54 %) of the EIA drains water that remains inside the catchment. At the same time waste, ground- and rainwater from 461 ha, mostly from the north, is transported from outside to inside the catchment. If the difference in boundaries between catchment and WWCRs is taken into account the EIA is considered to be 1361 ha instead of 1661ha. These 1361 ha represent 3.91 % of the entire catchment area and give a ratio of 0.54 between the TIA and EIA.

Upstream impervious areas and total upstream area change substantially when the WWCRs are incorporated in the calculations. By taking the WWCRs into account total upstream impervious areas could decrease up to 99 % or increase up to 64 % depending on the assessed stream junction (Fig. 5a).The change in total upstream area varies between −16 % and +3 % (Fig. 5b).

3.2.2 Future developments

When the WWCR zoning plans are fully implemented within the Grote Nete catchment another 245 ha of impervious areas will be connected to a WTTP. Of those 245 ha, the surface run off of 141 ha will be transported to other catchments, while the surface run

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off of 148 ha will be imported from neighboring catchments. This will result in a 7 ha increase of the upstream impervious area.

When all subcatchments are evaluated most of the stream junctions will experience an extra reduction in upstream area by 1 or 2 % (Fig. 6). Ten stream junctions however will experience an increase of their upstream area by 1 or 2 % because of the upstream presence of a WWTP.

3.3 Model calibration and validation

Table 2 shows the model performance statistics ME, RMSE, *R* and NSE. These demonstrate the good general model performance. The statistics however demonstrate that the model performance is slightly better in the calibration period, than in the validation period. Figure 7 shows the observed and simulated hourly runoff series. Additional verification of the model performance for the high and low flow extremes is presented in Fig. 8. The observed independent high and low flow extremes are plotted against the simulated ones after Box-Cox transformation. These validation plots allow evaluation of the model for its ability to predict extreme conditions. The model is able to simulate the extreme peak flows well, while the low flow extremes are slightly overestimated by the model. The mean bias is very small (0.05 $m^3 s^{-1}$) for the peak flows and larger (0.14 $m^3 s^{-1}$) for the independent low flow extremes. Based on the good general model performance for total flows in both calibration and validation periods and for peak flows, the model was considered applicable for assessing the impact of the water transfers on these flow variables due to the WWTPs.

3.4 Comparison with model impact results

3.4.1 River flow impact of WWTPs

Comparison is made between the model based impact results and an alternative empirical approach of Sect. 3.1, where the river flow at the outlet of the catchment are adjusted for the connected areas. Overall lower river flow values are obtained in comparison with the empirical approach where the flow is reduced with the EIA percentages (Fig. 9). The mean hourly river discharge between 2004 and 2008 reduces by $0.180\,m^3\,s^{-1}$ and vary between a maximum reduction of $1.192\,m^3\,s^{-1}$ or an increase up to $0.069\,m^3\,s^{-1}$. Scenario 2 which evaluates the effect of the water transported outside the catchment, shows during the same period a decrease in mean hourly discharge of $0.15\,m^3\,s^{-1}$. Reductions in hourly modeled flow vary up to $1.143\,m^3\,s^{-1}$. Scenario 3 results in a decrease of mean hourly discharge of $0.33\,m^3\,s^{-1}$ whereas the change in the individual hourly discharges varies between $0.031\,m^3\,s^{-1}$ and $1.375\,m^3\,s^{-1}$.

Figure 10 shows the model based differences in mean monthly river flows between the reference scenario and the scenario with adjusted rain. Based on this difference, the relative contributions of the EIA to the total river flow could be calculated. Relative contributions for scenario 1 vary between 2.19 % and 7.15 % of the flow of the reference scenario. For scenario 2 these contributions vary between 2.77 % and 6.07 %. Scenario 3 resulted in a contribution between 5.28 % and 12.68 %. Compared to the empirical approach (see Sect. 3.1), scenario 1 and 2 gave a lower impact of the impervious areas, whereas scenario 3 resulted in higher impact of the relative contribution in the years 2004 and 2005. There was a better agreement for 2006.

3.4.2 Seasonal variation in river flow impact

A seasonal change in relative contribution of the WWTP infrastructure to the river flow was found. The largest contributions to the overall flow were found during summer and lowest during winter periods. But the effect is again less pronounced compared to the relative contribution based on the empirical approach (Fig. 10).

There is a strong seasonal pattern in the difference between the model based and empirical approaches (Fig. 11). Especially during the period of declining flows (flow recession periods) in spring and the beginning of summer, the model simulates much lower relative contributions. The difference is less pronounced or absent for the summer of 2008.

3.4.3 Impact on peak and low flows

The model based impact results of the scenarios resulted in a decrease of both peak (Fig. 12a) and low flows (Fig. 12b). For events above a return period of 1 yr, peak flows of scenario 1 decrease on average with 0.332 $m^3 s^{-1}$ or 3.00 % compared to the reference scenario, scenario 2 with 0.299 $m^3 s^{-1}$ or 2.75 % and scenario 3 with 0.615 $m^3 s^{-1}$ or 5.96 %. Low flows of scenario 1 decrease on average with 0.126 $m^3 s^{-1}$ or 5.49 %, scenario 2 with 0.105 $m^3 s^{-1}$ or 4.85 % and scenario 3 with 0.23 $m^3 s^{-1}$ or 10.65 %.

4 Discussion

4.1 Impact of WWTPs on the river baseflow

The overall impact of the WWTPs on the river flow depends on the time scale (days, months or years). On average, the WWTPs are responsible for about 10 % of the catchment's discharge. The high WWTPs effluent contribution to the total mean river discharge is probably due to different sewer infrastructure related processes: wastewater collection, rain water runoff and groundwater intrusion. WWTPs were found to be important point sources of water that, despite the absence of rain, discharge significant amounts of water. Particularly during dry periods the impact of the WWTPs on the river flow is very high (Fig. 6). During these periods the sewer infrastructure collects both wastewater from households and industry, but probably also important amounts of parasitic groundwater (Dirckx et al., 2009). Due to this draining of the groundwater table, drought related problems induced by the urbanization will further increase. Climate change scenarios for Flanders predict a strong decrease in river low flows during summer (Baguis et al., 2010; Vansteenkiste et al., 2012). The impact of the WWTPs on the overall flow is thus expected to increase in the future. While the impact of a WWTP on a river can be evaluated relatively easy, the impact of connected impervious area on

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the flow regime of smaller reaches within the WWCR is more complex. Often the roofs of buildings and pavements of a catchment are connected to sewers that transport rain and wastewater to a WWTP (which might be outside the catchment). If we would like to evaluate these changes, long term river flow data need to be available that encompass also river flow data from before the sewer development and a detailed inventory of the gradual expansion of the sewer infrastructure.

4.2 TIA versus EIA

Impervious area is a landscape metric that is widely used as a predictor of water quality, quantity and stream ecosystem health (Jacobson, 2011). In the empirical approach, the impact of the sewer infrastructure on the impervious areas within the catchment was evaluated. The proposed method allowed us to make a distinction between TIA and EIA and evaluate both transfers between catchments and subcatchments. Both upstream TIA and EIA have found to be an indicator of hydrological and ecological disturbance. But in general EIA is considered to be a better indicator for the anthropogenic impact on the hydrological regime. The EIA of the catchment decreased significantly when the different WWCRs were incorporated in the calculation. Large parts of the connected impervious areas within the catchment do not really take part of the catchment but are in fact connected to a neighbouring catchment. As a result the overall impact of urbanization within the catchment can be over- or underestimated. At the same time large amounts of wastewater are transported from outside the catchment. These changes have a spatial impact on the hydrology of the catchment through their impact on travel time, spatial distribution, response on local rain events, etc. The changes in the total upstream areas, between −16 % and +3 %, and upstream impervious areas, between −99 % and +64 %, in our study were found to be large. For most of the subcatchments of our research both, total upstream area and upstream impervious area, decreased significantly. Although these subcatchments were found not to have actual upstream EIA, they are affected by the reduction of the upstream impervious areas and the resulting decreased total upstream area. These reductions in impervious areas and the

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transfer of rain and wastewater to other reaches can lead to changes in flow regime and related river characteristics. As the removal of the entire impervious area from the catchment by the sewer system can strongly affect the river flow, the actual absence of upstream impervious areas in the recalculated areas might be more important than the presence of only a small portion of upstream impervious area. In contrast to many other studies we were able to use high resolution data that are based on manual field observations instead of less accurate remote sensing data. The use of proxies for impervious areas, as used in other studies (Chabaeva et al., 2009), was not necessary. The same counts for the calculation of the EIA. As a result we expect that both metrics, TIA and EIA, are close to the actual situation.

4.3 Model impact results

As opposed to the empirical approach, the model based approach allows to explicitly consider the catchment runoff dynamics, the highly non-linear hydrological responses to the changes in impervious areas and the interactions between different runoff components. However the use of hydrological models has, like all models, limitations. Traditional hydrological models impose restrictions on how to deal with sewer infrastructure. Advanced spatially distributed, physically models are required. In this study we evaluated the impact of the WWTPs within an existing, calibrated MIKE SHE hydrological model. To enable the simulation of model functioning versus the impact of the surface runoff from impervious areas transferred from the natural catchment runoff to the sewer system, rainfall series were reduced relative to the EIAs within the catchment. However, by this method it is not possible to evaluate the impact of the EIA situated outside the catchment. The latter impact evaluation would require sewer models to be integrated with the catchment hydrological model.

As expected, the different scenarios resulted in a decreased flow, compared to the reference scenario, proportional to the amount of EIA taken into account. The scenario with the lowest amount of EIA (scenario 2) resulted into the smallest change in flow. Besides an overall decrease in flow, both peak flows and low flows decreased. But low

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flows were proportionally more heavily affected by the rain reduction scenarios. These results confirm the higher impact of EIA during summer low flows from the empirical approach and again illustrate the high impact of EIA on the flow regime and its importance to the model. The modeled river flows after consideration of the scenarios were higher than the measured river flow adjusted for the EIA, this despite the fact that the rain was reduced for a same amount within the different scenarios. Apparently other processes like evapotranspiration within the model compensate for the reduced rainfall, leading to a lower reduction in flow.

The compensation for EIA in the model does only occur at the mouth of the catchment. Because of the spatial distribution of the WWTPs and the related changes in upstream areas in the catchment, the reliability of the flow along the different reaches in the model and its spatial variability could not be validated. This may have its effect on the accuracy of the impact results. It also would be useful to compare the approach based on rain reduced scenarios with an alternative approach where the impervious areas giving runoff to the sewer system sewer system are removed from the model domain. This is however technically difficult to achieve. Areas that are situated outside the catchment should somehow be integrated in the model; e.g. by integrating it with sewer models.

Another problem is the coarse spatial resolution of the model. Due to this resolution, there is a general overestimation of the TIA and EIA in the model compared to the high resolution data. Nevertheless discharges of WWTPs and the reduction in flow in scenario 3 are comparable. Impervious runoff generated by remote urban areas has long travel distance towards the stream and partial or even full losses take place. The surface runoff losses, due to the hydrological "disconnectivity" are in the model probably compensated by this general overestimation of the actual impervious area. In this perspective, impervious area configuration might play an equal important role as effective impervious area. Because of the overestimation of the actual TIA and EIA in the catchment the same errors might be made as when no distinction is made between EIA and TIA (Alley and Veenhuis, 1983). At the same time the overestimation

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of the impervious surfaces may have biased the hydrological model parameters during the calibration (e.g. underestimation of the surface runoff coefficient). This means that when the model would be used for impact analysis of urbanization and climate change scenarios, the impacts on peak flows and flood frequencies may be underestimated. This problem is further investigated by Vansteenkiste et al. (2012) for the MIKE-SHE model of the same catchment considered in this study.

An important aspect is the seasonal variation in the relative contribution of the EIA. Both scenario 1 and 3 resulted in an underestimation of the EIA impact during months with low flow and an overestimation during months with high flow. Hydrological models are often used to evaluate peak discharges and related flood risks. Climate change scenarios for Flanders, however, indicate an increase in frequency and duration of dry periods, making low flow events more common (Boukhris et al., 2009). Therefore the importance of these low flow events and their evaluation in hydrological models will increase. A better incorporation of the impervious areas and WWTPs might be crucial for a better performance of the models in evaluating both peak and low flow events.

Hydrological models are frequently used to predict changes in the hydrological regime. But if we want to use these to assess changes in climate, land-use or other future developments within the catchment, consideration of the sewer transfers discussed in this paper becomes increasingly important. Our results show that the further development of the sewer infrastructure will have a profound impact on the upstream areas.

5 Conclusions

This paper presented a methodology to calculate EIA in a way that incorporates the effects of WWCRs that do not coincide with natural catchment boundaries. It allows us to evaluate rain- and wastewater transfers between different catchments and indicate how strongly the catchment's hydrology is impacted by the sewer infrastructure. Comparisons between histograms or differences in histograms of catchment areas can display the vulnerability of the catchments to impervious area impacts and potential peak and low flow events. The method also allows the study on how rivers that have no WWTP upstream are impacted by the upstream presence of EIA. These upstream impervious areas can have profound impacts on infiltration, runoff and the hydrology of the catchment. We also simulated the impacts of the changes in impervious areas and WWTPs in FDPMs. By applying different rain scenarios the impact of wastewater transfers in the catchment were simulated and evaluated. At the same time we could analyze the impervious area parameterization within the model. Our results show that water displacements in and between catchments may severely impact the hydrological model results. Hence it may also be important to take these displacements into account in the hydrological model development. The correct incorporation of impervious areas in models is of utmost importance as impervious areas have an impact on catchment delineation and different aspects of the flow regime. With increasing urbanization and sewer development the impact of these processes within the hydrological regime are expected to further increase in the future. Important areas of further research remain amongst others: (a) how to incorporate impervious areas from outside the catchment into the model (b) how to remove the areas that are transported outside the catchment from the model domain (c) how to better represent the seasonal variation in impervious area and WWTP impact in the model.

Acknowledgements. This research was supported by the University of Antwerp (UA-BOF fund), the Flanders Hydraulics Research ("Waterbouwkundig Laboratorium", division of the Authorities of Flanders) and The Belgian Federal Science Policy Office (SUDEM-CLI cluster project, program "Science for a Sustainable Development").

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Table 1. Different variables used to implement the rain reduced scenarios: EIA in the catchment (ha), EIA per WWCR (%) and EIA per urban area unit (%) based on the NGI data. × indicates the WWRCs for which the rain was reduced in each scenario.

WWTP	EIA (ha) per WWCR	EIA per WWCR (%)	EIA per urban area WWCR (%)	Scenario 1	Scenario 2	Scenario 3
Mol	782.07	5.17	72.77	×		×
Geel	284.31	7.2	67.42	×		×
Leopoldsburg	32.04	6.99	48.5	×		×
Tessenderlo	418.85	6.58	76.21		×	×
Westerlo	182.96	4.77	67.22		×	×
Beverlo	41.14	5.43	87.34		×	×
Lommel	145.43	2.75	47.57		×	×
Eksel	101.6	2.27	74.04		×	×

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Table 2. Statistical performance of total runoff flows for model calibration and validation.

	Calibration	Validation
ME [$m^3\,s^{-1}$]	0.6	0.72
RSME [$m^3\,s^{-1}$]	0.84	0.93
R [–]	0.88	0.84
NSE [–]	0.72	0.63

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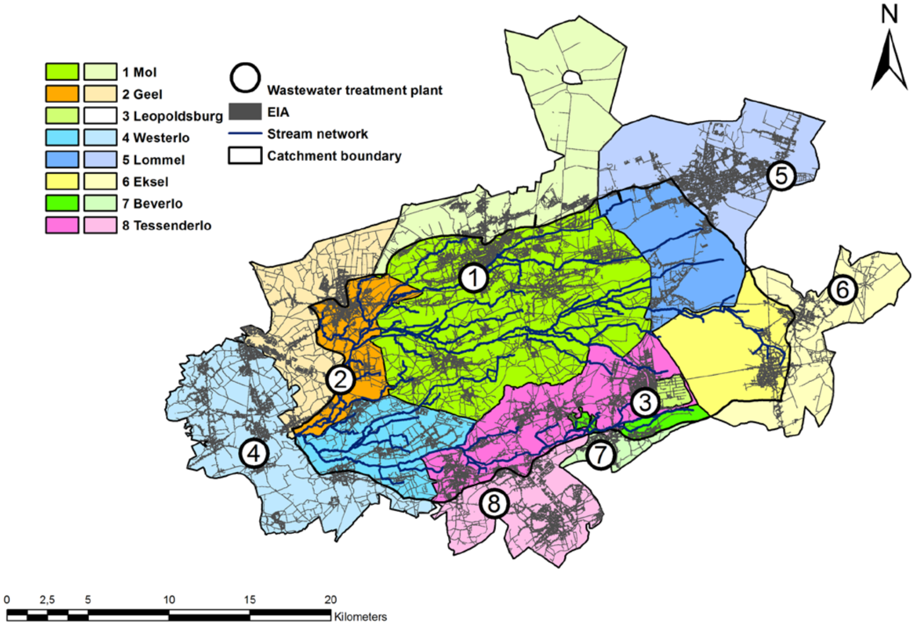

Fig. 1. Overview of the different WWTPs that are situated within the Grote Nete catchment (1–3) and the WWTPs that receive wastewater from impervious areas that are situated within the Grote Nete catchment but discharge in another catchment (4–8).

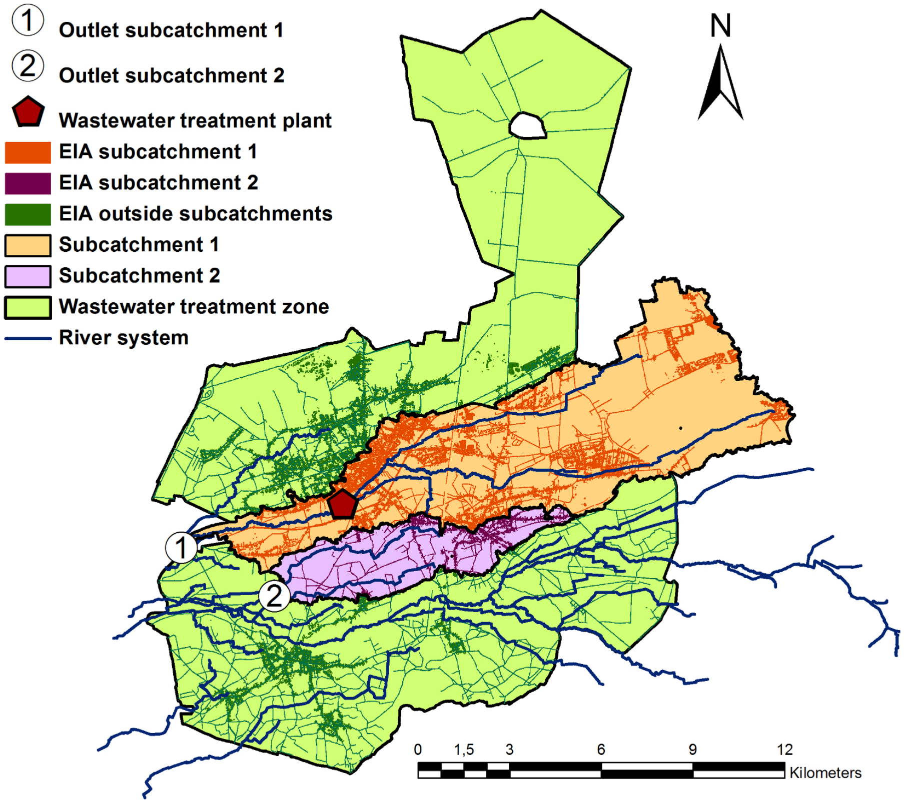

Fig. 2. Example on the calculation of the upstream areas. The WWTP discharges into subcatchment 1 (orange colored). Therefore the EIA within the WWCR, but outside subcatchment 1 (green and purple colored), are included in the upstream area of subcatchment 1. As a result the area of the subcatchment increases with 404.6 ha of impervious area or with 5.10 % of the total area. Because the EIA is removed from subcatchment 2 (purple color), the area of subcatchment 2 decreases with 68.73 ha or 4.31 % of the total area.

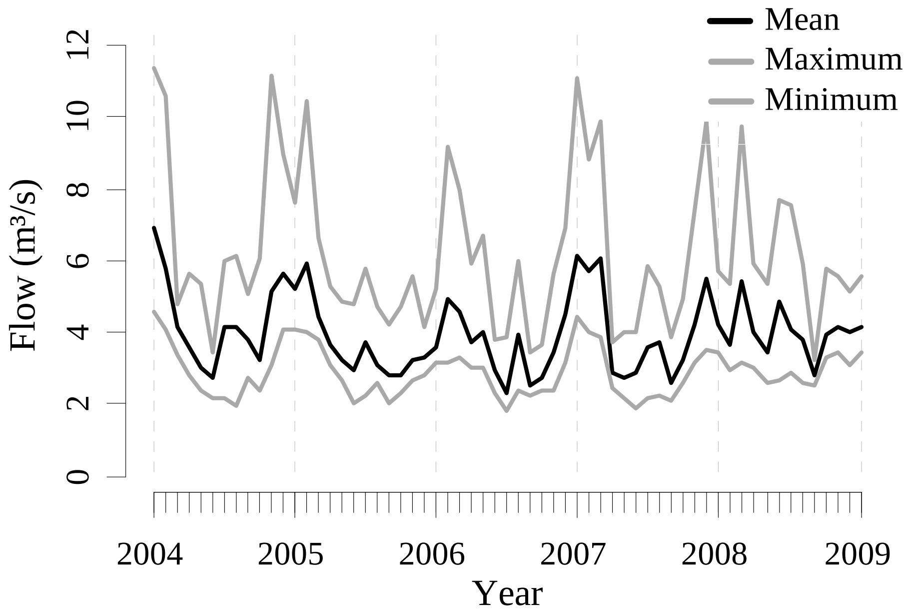

Fig. 3. Monthly mean, minimum and maximum of the daily measured flow ($m^3 s^{-1}$) for the period 2004–2008 at the outlet (Varendonk) of the Grote Nete catchment.

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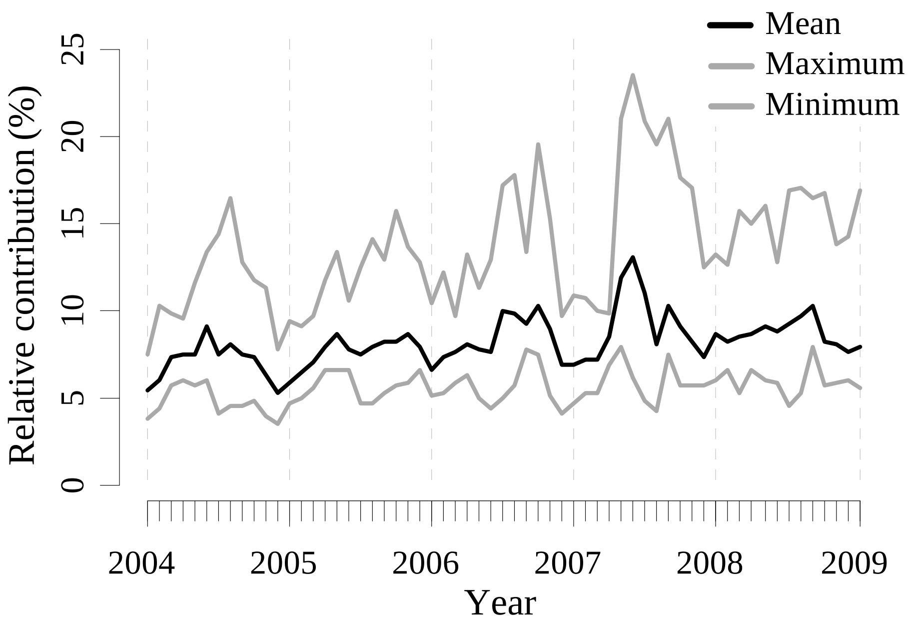

Fig. 4. Monthly mean, minimum and maximum relative contribution of the WWTPs (Mol and Geel) to the river flow at the outlet (Varendonk) of the Grote Nete catchment.

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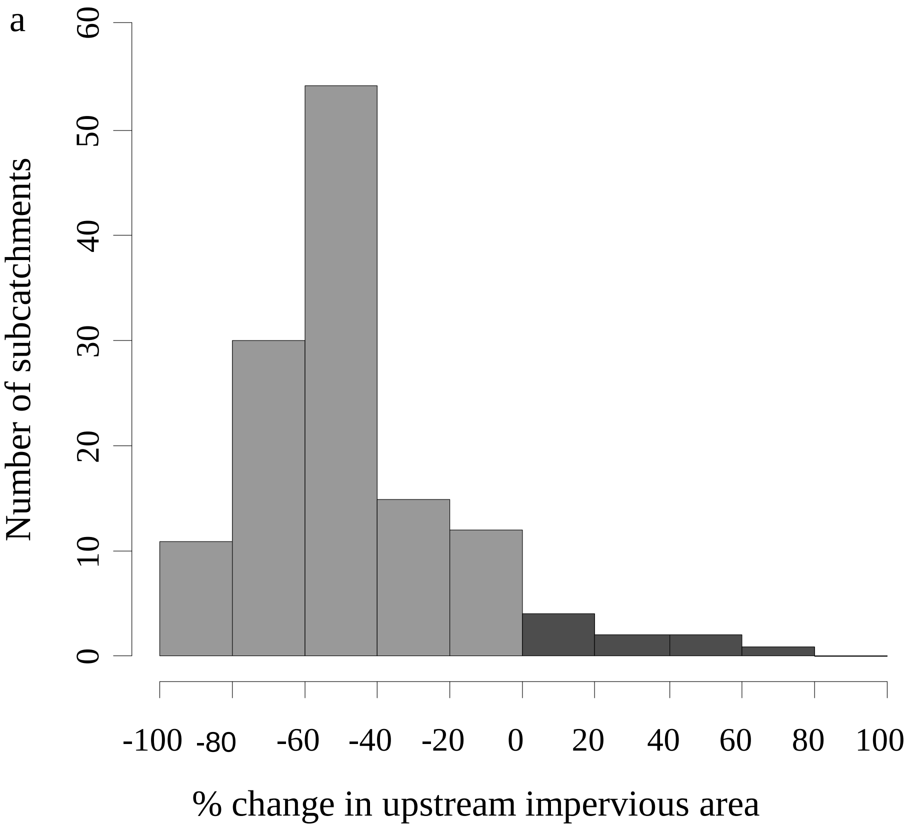

Fig. 5. Histogram of the change in upstream impervious areas between the "natural catchment" calculation and after integration of the WWTPs ($n = 131$).

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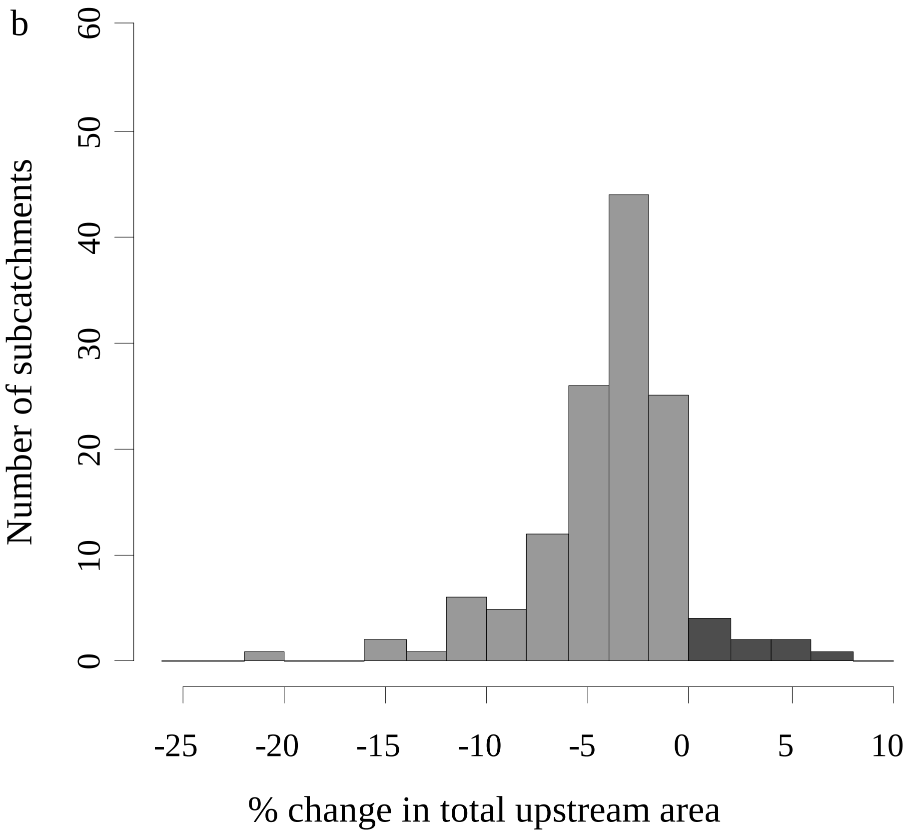

Fig. 5. Histograms of the change in total upstream areas between the "natural catchment" calculation and after integration of the WWTPs (n = 131).

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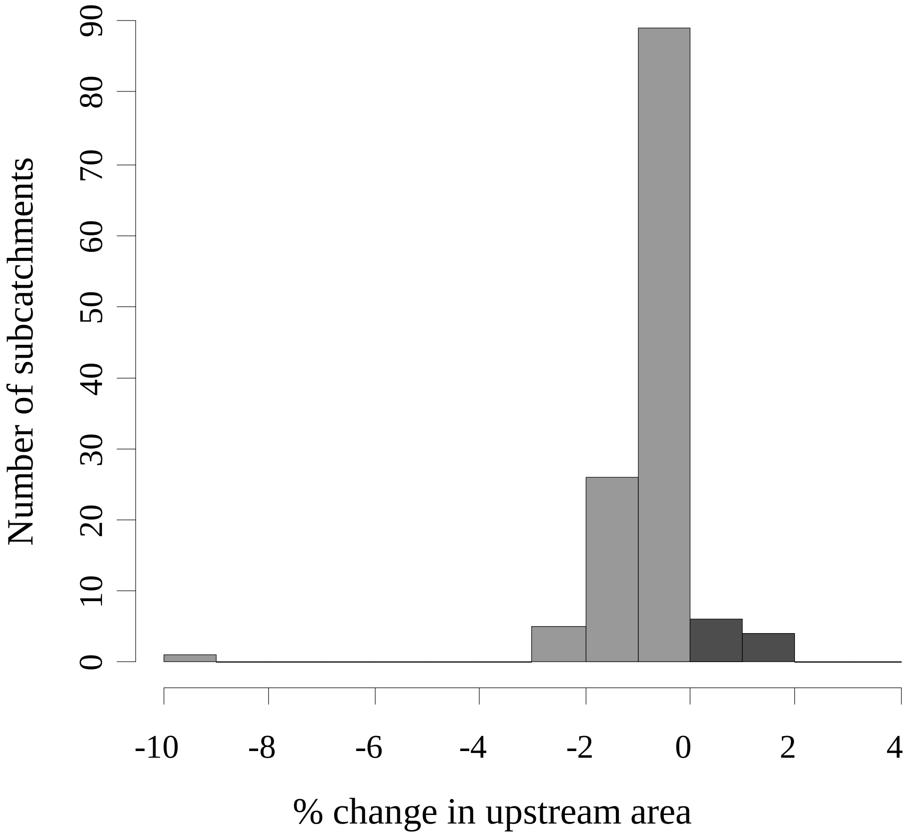

Fig. 6. Histogram of the change in upstream areas after full implementation of the zoning plans (n = 131).

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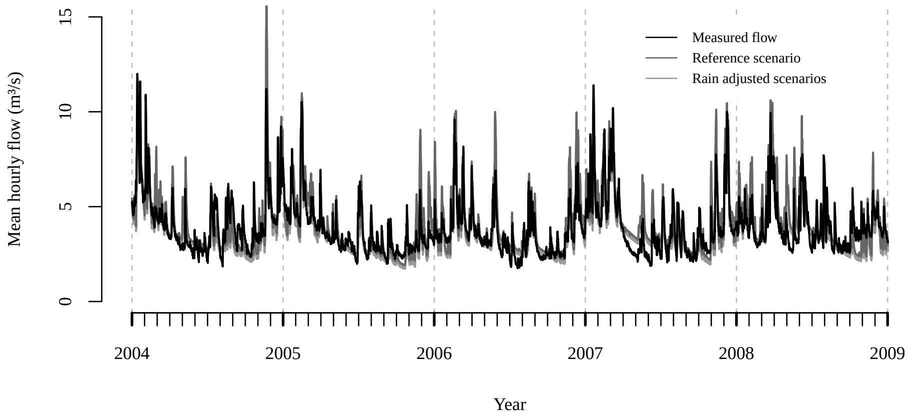

Fig. 7. Observed and simulated runoff series for model calibration and validation (= 0.25).

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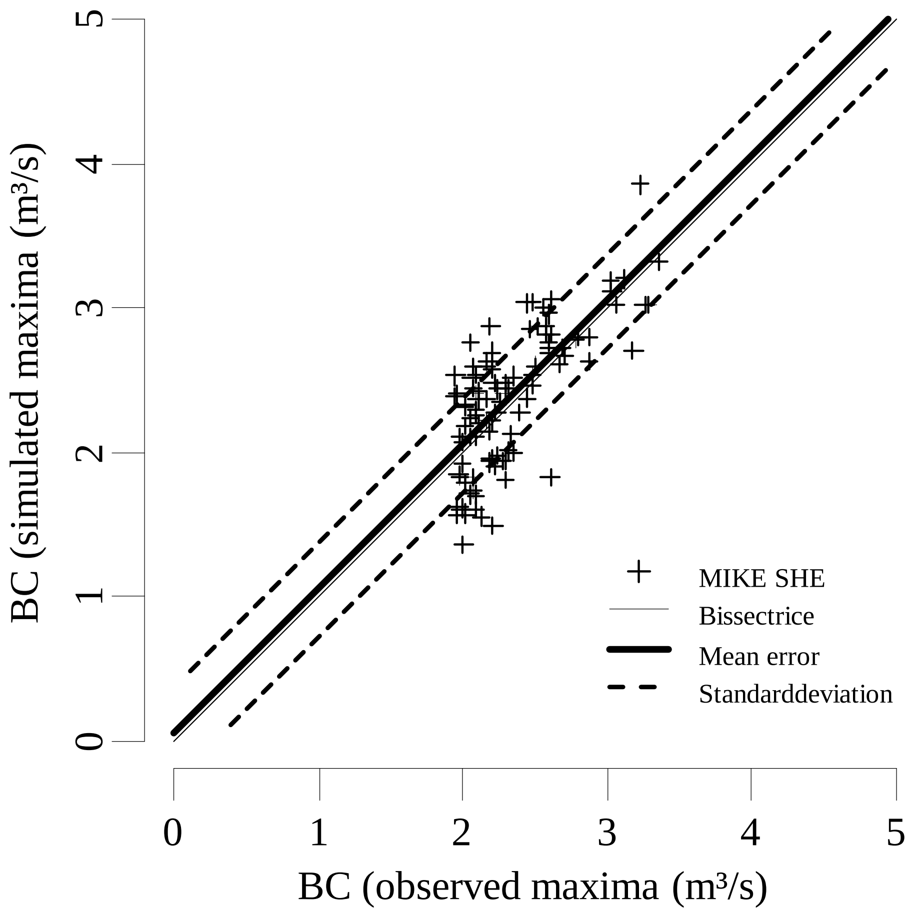

Fig. 8. Validation of nearly independent hourly peak flows after Box-Cox transformation (= 0.25).

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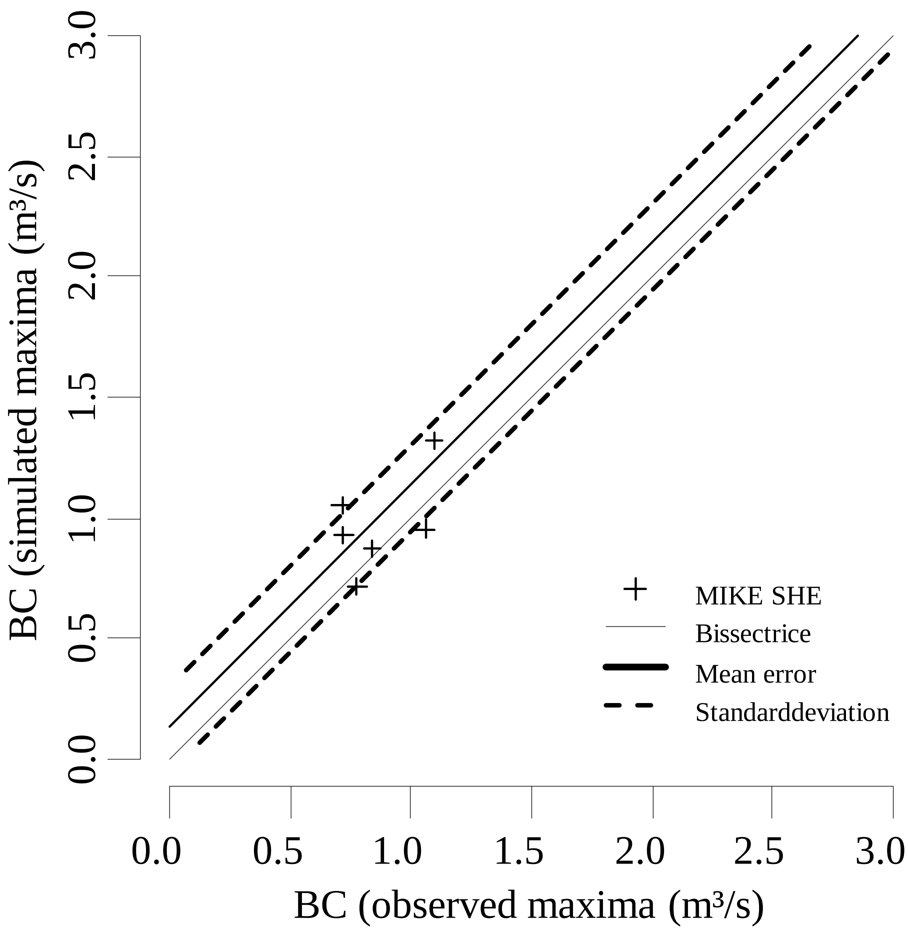

Fig. 8. Validation of nearly independent hourly low flows after Box-Cox transformation (= 0.25).

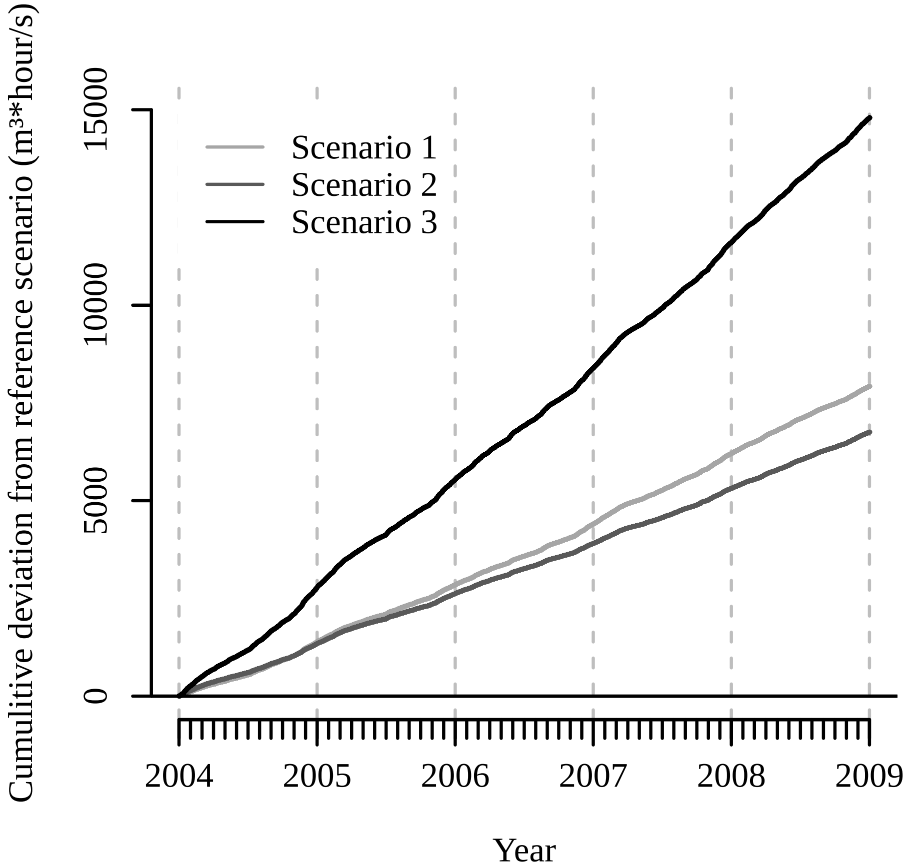

Fig. 9. Cumulative difference in modelled hourly river discharges after the rain reduced versus the reference scenario.

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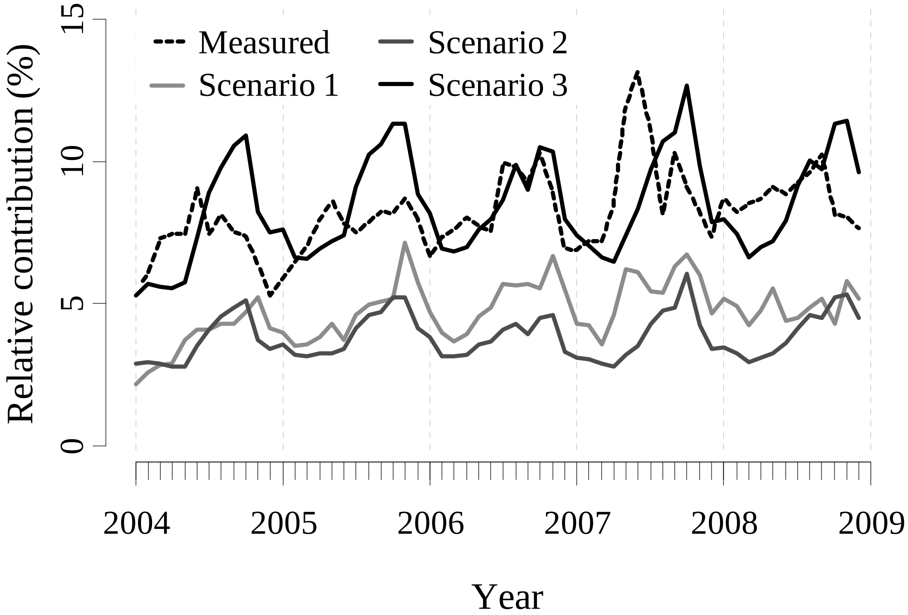

Fig. 10. Relative contribution (% monthly mean total flow) of the WWTPs to the total river flow. “Measured” refers to the empirical results obtained in Sect. 3.1.

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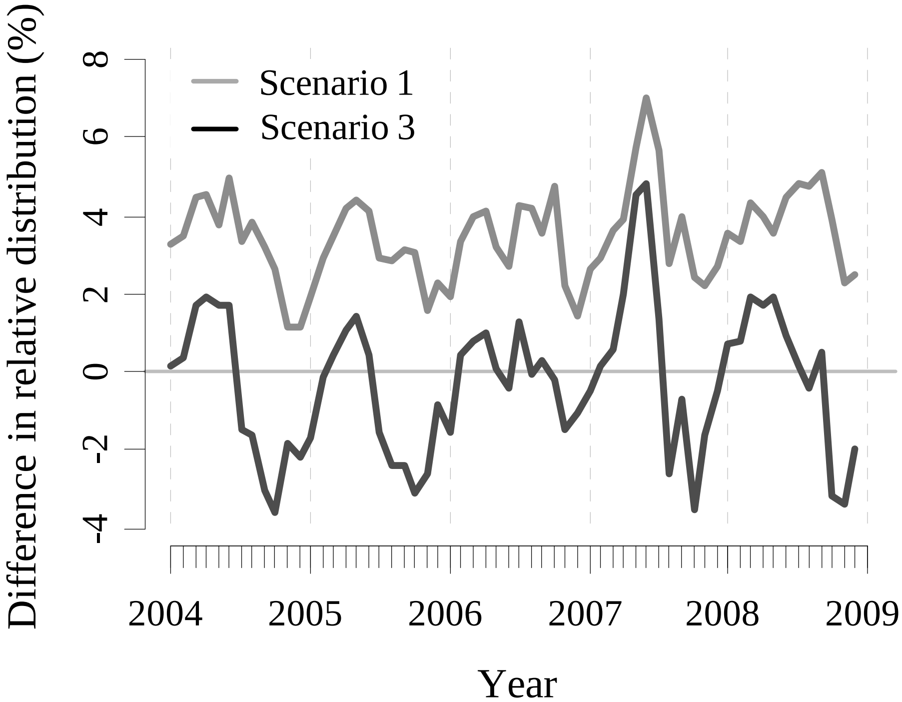

Fig. 11. Difference in relative contribution of the WWTPs to the total river flow between the model-based and empirical approaches (scenario 1 and scenario 3). The difference in contribution increases during flow recession periods.

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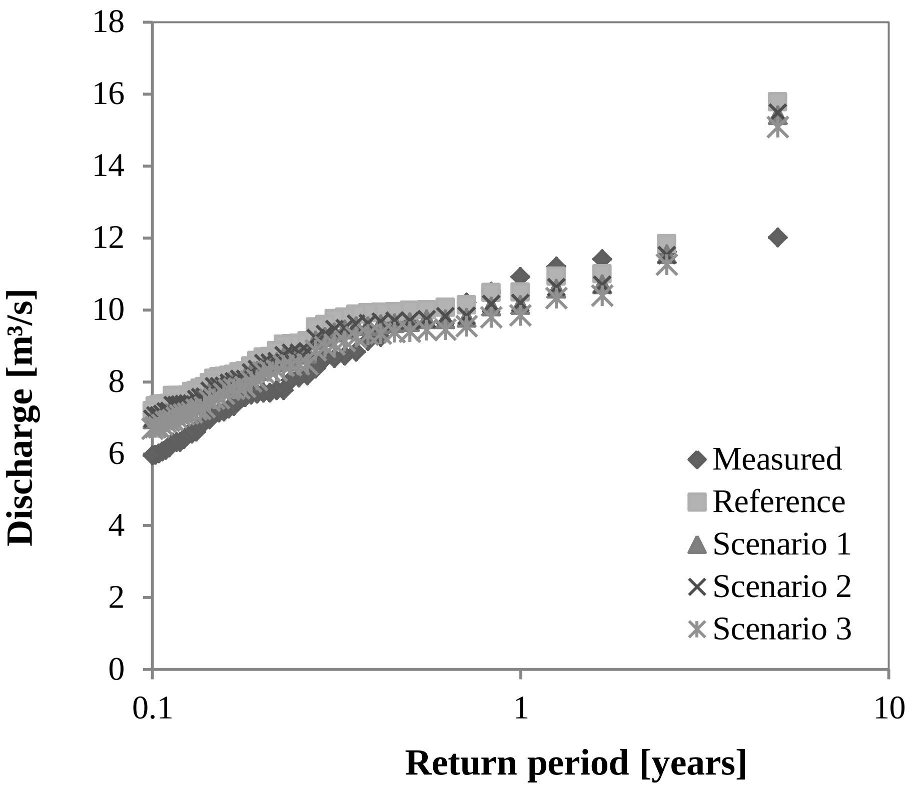

Fig. 12. Return period of hourly peak flow extremes for the Grote Nete catchment between 2004 and 2008.

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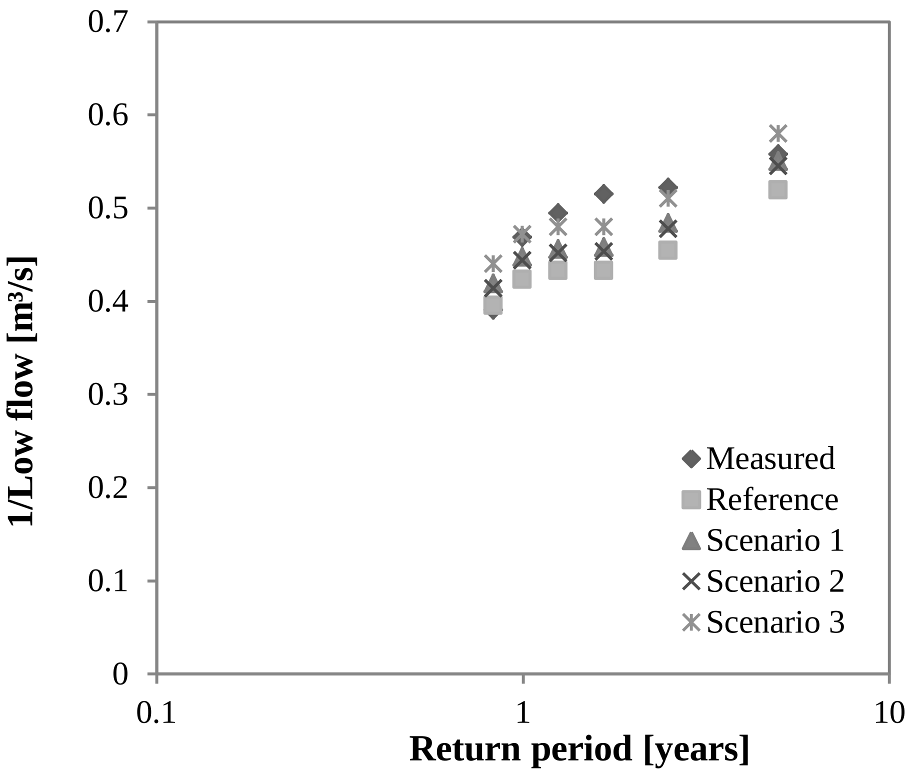

Fig. 12. Return period of hourly low flow extremes for the Grote Nete catchment between 2004 and 2008.

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