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Climate change impact on hydrological extremes along rivers and urban drainage systems in Belgium

«CCI-HYDR»

P. Willems, P. Baguis, V. Ntegeka, E. Roulin

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FINAL REPORT

CLIMATE CHANGE IMPACT ON HYDROLOGICAL EXTREMES ALONG RIVERS AND URBAN DRAINAGE SYSTEMS IN BELGIUM

«CCI-HYDR»

SD/CP/03

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SUMMARY

A. Context

Flood risk is in Belgium as well as in other European countries of considerable importance. This is due to dense populations and high industrialization along river banks. Since last decades, sewer systems are being built at a large scale. Drought risks are less significant in the country, due to the humid climate and the limited length of the dry spells in summer. However, extreme low flows may occur along rivers, causing severe problems of water shortage for drinking water supply, for agriculture and for the environment.

There is strong evidence that due to global change, the risks of inundations and low flows are changing. The consequences of these changes in potential hazards are to be assessed in a perspective of sustainable development. Water managers have to anticipate these changes, as to limit the flood and drought risks of the inhabitants to acceptable risk levels. In addition to the water administrations, the insurance industry needs quantification of their related risks, as well as the different water users and policy makers so as to develop and adapt policies (e.g. CO_2 emission reduction).

The concerns about the impact of climate change on the hydrological water cycle (including floods and droughts) have triggered specific studies since the 80s. The Royal Meteorological Institute of Belgium (RMI) has been pioneering in putting into evidence differences in the sensitivity of catchments with contrasted characteristics to a $2xCO_2$ scenario (e.g., Bultot et al., 1988). They extended their study to a larger set of catchments and used the first set of climate change scenarios made available by IPCC (Gellens and Roulin, 1998). The scope was further extended to the whole Meuse river basin (Roulin et al., 2001) and Scheldt river basin (Roulin and Arboleda, 2002) using a new set of climate scenarios based on transient experiments, for instance based on the results of Global Circulation Models (GCMs) forced with an increasing greenhouse gas content. However, the GCMs have since improved, and high resolution regional climate models (RCMs) have been nested within to downscale the climate variables to regional scale. This has sparked new research related to regional impacts relevant at local scales. Hydrological impact assessments can now be performed with increased confidence.

B. Objectives

The CCI-HYDR research project investigated in a detailed objective way and based on the most recent data and climate modelling results, the climate change impact on the risk of hydrological extremes along rivers and urban drainage systems in Belgium. For

rivers, the risk of both floods and low flows has been considered. For urban drainage systems, only the impact on flood risks has been studied. The study required the simulation results from GCMs and RCMs to be downscaled to the time and space scale necessary for the hydrological impact analysis. The modelling approach was based on ensemble modelling and probabilistic analysis of simulation results, enabling the uncertainty on the climate model-based results to be taken into account. The climate change scenarios furthermore were to be compared / verified with the results from a statistical analysis on the present and past climate and flow records. This subtask aimed to bring together the two separate science domains of physically-based climate modelling and statistical hydrology.

The project consisted of two main phases. In Phase 1, the climate change scenarios were being developed after statistical analysis of trends and cycles in long-term series of historical rainfall, evapotranspiration and river flow, and after the analysis and statistical downscaling of climate model simulation results. Phase 2 focused on the impact modelling towards flood risks and low flows risk along rivers, and flood risks along urban drainage systems, making use of hydrological and hydrodynamic models.

C. Conclusions

Development of climate change scenarios

Historical trends and oscillations in rainfall extremes and evapotranspiration (ETo) and river flow patterns showed deviant behaviour from the long term average. There is a reason to be concerned as the recent significant trends in rainfall and ETo suggest. In particular, winter showed pronounced changes during the most recent decade: positively significant rainfall and ETo amounts. The future predictions (2071-2100) also point to a continuation of the same trends; the winters generally get wetter and the summers get drier. ETo will increase for all the seasons.

The future predictions were based on a set of about 30 simulations derived from 10 RCMs nested in two main GCMs. The experiments were run for the IPCC regional A2 and B2 future greenhouse gas emission scenarios. Since the PRUDENCE RCM models were based on only the A2 and B2 scenarios, scaling factors were required to make the scenarios more exhaustive (thus better taking into account the emissions uncertainty) by including changes from extra scenarios (notably the A1B and B1). These were derived from GCM simulations considered for the 4th Assessment Report of IPCC.

The selected RCM simulations exhibited both negative and positive changes (-40% to +10%) in rainfall during the hydrological summer, and positive changes during the hydrological winter (+5% to +50%). There were no significant regional differences in the climate change signals over Belgium; with the exception of the coastal region. The rainfall increases are for the main Belgian lands around 10% lower than the ones over the coastal area.

From the large set of climate model projections, three probabilistic scenarios were extracted to allow end users to investigate the range of changes. The scenarios were appropriately named high, mean and low.

The climate change scenarios were to be translated to changes in the historical rainfall and ETo input series of hydrological models. To support this task, a Perturbation Tool has been developed. The tool applies perturbations to the rainfall and ETo series. For the rainfall series, the perturbations involve both changes in the frequency of rain storms and changes in the rainfall intensity. The changes are being made in a variable way, depending on the month in the year, and on the return period or storm frequency. For the ETo series, only intensities are perturbed, but also depending on the month and the return period. The series to be perturbed can be daily or hourly and can have any length (typical lengths vary from a few years to 100 years). The perturbations can be made for time horizons till 2100 (e.g., for 2020, 2030, …, 2100).

Hydrological impact analysis

Hydrological impacts of the rainfall and ETo change scenarios were investigated at large scale in the Meuse and Scheldt basins (SCHEME hydrological model of RMI) and at local scale for the river basins of Dender and Grote Nete – Grote Laak (VHM, NAM and MIKE-SHE hydrological models and MIKE11 river hydrodynamic model by K.U.Leuven). In cooperation with the Flanders Hydraulics authority, also the impacts in 67 other subbasins of the Scheldt basin have been studied. In order to separate in the river flow trends the contributions from climate change and the non-meteorological trends (i.e. land use trends), the impact of recent land use trends also has been investigated. It has been concluded that river total and overland runoff volumes linearly increase with the increase in urban paved (impermeable) areas, while the number of extreme low flow or flood days depend in a quadratic way on the urban land use area in the basins.

Climate change impacts on hydrological extremes (floods and low flows) (scenario period 2071-2100 versus control period 1961-1990) indicated that this impact weakly depends on the topographical and soil type characteristics of the catchments. In general, low flows significantly decrease in all studied catchments and reaches up to 80 till 90% reduction in the low scenario where almost all decreases are more than 50%. The increase in hourly river peak flow extremes is less strong, and limited to around 35%. Results indicate that low flow or drought problems will increase and might become more severe in comparison with flood risk problems induced by extreme precipitation.

Uncertainties in the results are, however, still very high. Depending on the ratio between the increase in rainfall versus the increase in ETo, and the ratio between the

increase in winter rainfall versus the decrease in summer rainfall, the hydrological impact results for high flows might turn over from a positive trend into a negative trend.
While the climate change impacts tend towards wetter winters and drier summers, the hydrological response appears similar throughout the entire area. The findings show that the intensity of the impacts is only slightly dependent on the location.
The implications of the changes in flood and drought risks continued to be investigated through a collaboration with the ADAPT project. The implications to society, water managers and policy makers were assessed.

For urban drainage systems, it has been found that systems designed for a 2 years return period of flooding would flood twice that frequent for the most pessimistic climate scenario (scenario period 2071-2100 versus control period 1961-1990). Regarding the design of local source control measures (storage facilities, rainwater tanks, infiltration reservoirs, etc), 15% to 35% increase in the storage capacity would be needed for the same climate scenario if one wants to limit the overflow frequency of the facility to the current level. Correspondingly, storage facilities with a current overflow return period of 2 years would overflow approx. twice per year; facilities with an overflow return period of 5 years would (for the same scenario) overflow approx. once per 1 - 1.5 years. The latter results indicate that there is a need for more and larger local stormwater storage. In case this storage is built by means of infiltration ponds, the stormwater stored in the ponds will enhance the groundwater infiltration and consequently will help to solve the enhanced low flow problems expected for river catchments.

More information

More detailed technical information about the CCI-HYDR project, the methodologies and results can be found in the five technical reports, uploaded together with all other documents produced as part of the CCI-HYDR project on the project website: http://www.kuleuven.be/hydr/CCI-HYDR.htm.

D. Contribution of the project in a context of scientific support to a sustainable development policy

The project results provided important support to sustainable policy development especially related to sustainable water management and planning, risk and risk insurance management, the Kyoto Protocol and its successor to be discussed in December in Copenhagen.
The CCI-HYDR climate change scenarios developed in the project (incl. the statistical downscaling technique and CCI-HYDR Perturbation Tool) are currently being applied by several national water and environmental authorities. They investigate impacts of

projected climate changes on flood and low flow risks, water availability, environmental conditions, needs for adaptation measures, etc. This shows that there was a great need for the results obtained within the scope of the CCI-HYDR project. The CCI-HYDR project consequently (almost immediately) supported policy implementation and related sustainable development of the region.

E. Keywords

Climate change, floods, hydrology, low flows, precipitation, rivers, urban drainage

1 INTRODUCTION

1.1 The CCI-HYDR project

With the advent of new advances in climate science, climate models have morphed from Global Circulation Models (GCMs) to Regional Circulation Models (RCMs). This has opened up new research opportunities for impact analysts interested in small scale regional impacts. The CCI-HYDR project was supported by the Belgian Science Policy Office through their Science for Sustainable Development programme to exploit the latest data from the new climate change models. The key aim of the project was to investigate the climate change impact on the risk of hydrological extremes along rivers and urban drainage systems in Belgium. The research was primarily based on results from the high resolution PRUDENCE regional climate models and later extended to include the GCM models from the Fourth Assessment Report (AR4) of the United Nations Intergovernmental Panel on Climate Change (IPCC). The climate models from the PRUDENCE project were arguably among the first models that were primarily set up to investigate regional impacts. The collaborations from various modelling centres and climate experts increased confidence in the use of the outputs from the project. The PRUDENCE project also made a substantial contribution to the latest IPCC AR4 report. The CCI-HYDR project engaged a collaborative team of meteorological, hydrological and water engineering researchers from the Katholieke Universiteit Leuven and the Royal Meteorological Institute (RMI) of Belgium. However, a collaboration was also arranged with the ADAPT project, which is responsible for examining the wider implications of the CCI-HYDR outcomes to the society, water managers, and policy makers.

1.2 Context

Flood risk is in Belgium as well as in other European countries of considerable importance especially due to the dense populations and high industrialization along the river banks. Also, since the last decades, sewer systems are being built at a large scale. Drought risks are less significant in the country, due to the humid climate and the limited length of the dry spells in summer. However, extreme low flows may occur along rivers, causing severe problems of water shortage for drinking water supply, for agriculture and for the environment.

There is strong evidence that due to global climate change, the risks of inundations and low flows are changing. Water managers have to anticipate these changes so as to limit the flood and drought risks of the inhabitants to acceptable risk levels. In addition to the water administrations, the insurance industry needs quantification of their related risks, as well as the different water users, and policy makers so as to develop and adapt policies (e.g. CO2 emission reduction).

The concerns about the impact of climate change on the hydrological water cycle (including floods and droughts) have triggered specific studies since the 1980s. RMI has been pioneering in putting into evidence differences in the sensitivity of catchments with contrasted characteristics to a 2xCO2 scenario (e.g. Bultot et al., 1988). They extended their study to a larger set of catchments and used the first set of climate change scenarios made available by IPCC (Gellens and Roulin, 1998). The scope was further extended to the whole Meuse river basin [Roulin et al., 2001] and Scheldt river basin (Roulin and Arboleda, 2002) using a new set of climate scenarios based on transient experiments, for instance based on the results of Global Circulation Models (GCMs) forced with an increasing greenhouse gas content. However, the GCMs have since improved, and high resolution regional climate models have been nested within to downscale the climate variables to regional scale. This has sparked new research related to regional impacts relevant at local scales. Hydrological impact assessments can now be performed with increased confidence.

Through analysis of seasonal precipitation anomalies and low flow indicators, de Wit et al. (2007) have shown that multi-seasonal droughts had generated severe low flows in the river Meuse in 1921 and 1976. These authors did not find an increase of occurrence of such multi-seasonal drought in the results of the regional climate change simulation of the PRUDENCE project (e.g. Räisänen et al., 2004). Instead, there was a large increase of the occurrence of extremely dry summers. The impact of such scenarios on the discharges of Belgian rivers deserved further detailed investigation with the use of hydrological and hydrodynamic models.

1.3 Project objectives

The CCI-HYDR research project was set up to investigate in a detailed objective way and based on the most recent data and climate modelling results, the climate change impact on the risk of hydrological extremes along rivers and urban drainage systems in Belgium. To accomplish the project objectives, the research was subdivided into two phases. Phase 1 of the project focused on the selection of the RCM scenarios and the long-term historical investigation of rainfall and potential evapotranspiration (ETo). Climate change scenarios were developed for both rainfall (including extreme conditions) and ETo. In Phase 2 of the project, the implications of the scenarios on the hydrological extremes were studied. This involved investigation of flood and low flow risks along rivers and flood risks along selected urban drainage systems in Belgium. The project results provide useful additional support for policy development especially related to sustainable development such as the Kyoto Protocol and its successor to be discussed in December in Copenhagen.

2 METHODOLOGY AND RESULTS

2.1 Development of climate change scenarios

During Phase 1 of the CCI-HYDR project both the theoretical and practical contexts of the climate change impacts on hydrological extremes were established. The theoretical contexts involved literature studies that were influential in understanding the past and future changes in the Belgian climate. The practical context involved applying the extracted changes from the climate model projections to the hydrological models. This required comprehensive assessment of the state-of-the-art climate model data relevant for hydrological impact analysis. Thus, there was a need for investigating the historical trends from observed series and the future predictions from the most recent RCMs. The latter was accomplished by evaluating the RCM model outputs relevant to the hydrological impact through statistical tests while the former was studied by applying a trend analysis technique that combines the frequency and magnitude of extremes.

Historical trend analysis

Long-term temporal analysis of trends and cycles is essential in understanding the natural variability within the climate system (Türkes et al., 2002). The historical trends also provide a basis for verifying the consistencies of the climate model predictions for the future changes (Casty et al., 2005). Investigation was made on whether the recent historical changes in frequency and amplitude of rainfall extremes can be considered statistically significant under the hypothesis of no trend or temporal clustering of rainfall extremes. The analysis was based on a unique 10-minute rainfall series for the period 1898-2005 (108 years) and a daily ETo series for the period 1901-2005, both obtained from the Uccle station in Belgium and made available by the IRM. Previous studies have examined the Uccle rainfall series albeit with varying record length, statistical properties and different analytical tools (Vaes et al., 2002 ; De Jongh et al., 2006 ; Blanckaert and Willems, 2006). The existence of trends and cycles based on previous studies has been somewhat unclear.

In this project, the trend and cycle historical characteristics were assessed through an alternative method based on frequency-perturbations or quantile-perturbations of extremes (Ntegeka and Willems, 2008). While frequency techniques focus on how often an event (a quantile) may occur, perturbation techniques determine the relative magnitudes of events based on a certain baseline. The frequency- or quantile-perturbation analysis compounds the two concepts thereby making it possible to study the changes in the extremes for particular return periods. This approach provides an insightful temporal assessment of the trends and oscillations of rainfall extremes.

Nearly independent extremes have been extracted from the long-term series, as well as for subperiods (called block periods with given block size) of the full available long-term series. All extremes in a block period are compared with the corresponding quantiles derived from the full series. The mean factor difference (called "perturbation factor") is calculated for all quantiles above a specific mean recurrence interval of 0.1 years. These quantiles reflect the most extreme conditions in the series. They correspond for rainfall to the most extreme rain storms in the series: the ones that induce flooding along rivers and sewerage systems. Block sizes of 5 to 15 years were considered and the analysis was made based on the four climatological seasons: winter (December, January and February), spring (March, April, May), summer (June, July, August) and autumn (September, October and November). Based on the Uccle series and the perturbation factor in extreme rainfall quantiles, oscillations are observed (Figure 1, Figure 2) with higher extreme rainfall quantiles in the 1910s-1920s, the 1960s and recently during the past 15 years. Lower extreme rainfall quantiles are observed in the 1930s-1940s, and in the 1970s. During the past 108 years, the multidecadal oscillations in rainfall extremes appear in a nearly cyclic manner with periods of 30 to 40 years (Figure 1, Figure 2). A period with only 3 cycles is too short to draw statistically strong conclusions on this property, but results clearly indicate the presence of long-term temporal persistence in the rainfall extremes, with a cluster of rainfall extremes during the past 15 years. These conclusions are consistent for all time scales varying from 10 minutes to the monthly scale, and both for the winter and the summer season (Figure 1). For the summer period, highest extreme rainfall quantiles are observed in the 1960s, slightly higher than the more recent ones from the past 15 years. These results suggest that the recent increase in the number of heavy showers causing sewerage system flooding, is caused by hydrometeorologic conditions which are less or equally extreme than what was observed during the 1960s. Of course, in the mean time, land use strongly changed (e.g. urban areas expanded and sewerage systems were built at a large scale) such that hydrological effects nowadays strongly differ from the ones in the 1960s.

For the winter period, observations are different. Extreme rainfall quantiles during the past 15 years are 25% higher in comparison with the 108 years average (Figure 1, Figure 2), which is 9% (for monthly rainfall volumes) to 19% (for 10 min rainfall intensities) higher than during previous cluster periods of the past century. Results show an increase in extreme rainfall quantiles for the winter period, but no clear increase for the summer season (however, summer extremes at larger time scales show a decreasing trend). The high perturbation factors in the 1910s-1920s, 1960s and 1990s and the low factors in the 1930s-1940s and 1970s are significant at the 5% significance level. They appear to be explained both by an increase/decrease in the number of extreme rainfall events and by a higher/lower rainfall intensity per event, although the former factor is most important.

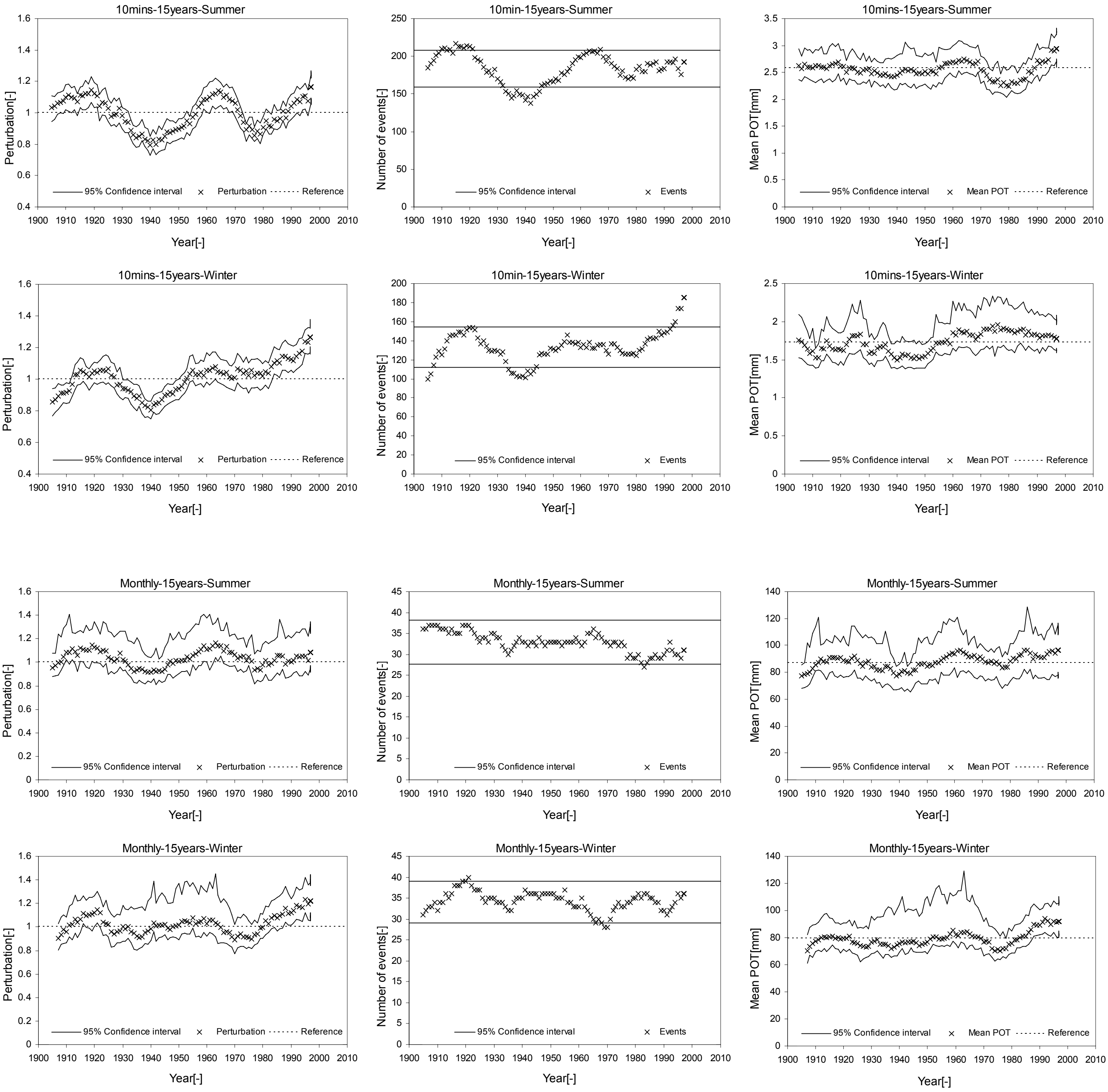


Figure 1: Estimates of average quantile perturbations, number of events and mean POT values for 10 minutes and monthly rainfall extremes, and 15-year blocks for summer and winter periods, together with 95% confidence intervals under the hypothesis of no trends or oscillations. The points are plotted centrally within each block.

In Figure 2, approximate cyclic patterns have been fitted to the average quantile perturbations, using Fourier analysis. For the winter season, the cyclic component is subtracted from the total perturbation to eliminate the oscillation component from the time series leaving only the trend component.

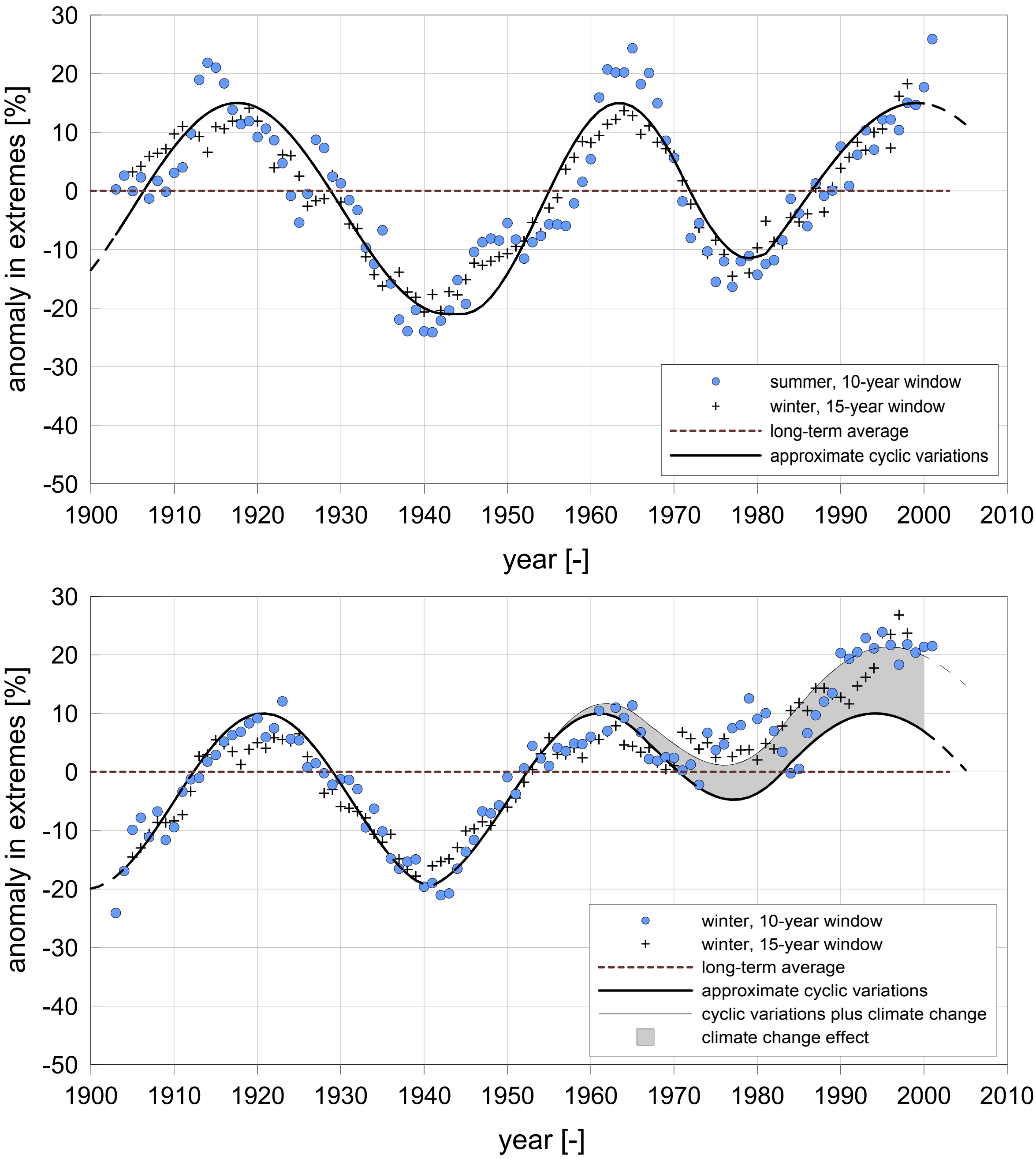


Figure 2: Estimates of average quantile perturbations for 10 minutes rainfall extremes, and 10 and 15-year blocks for summer (top) and winter (bottom) periods, together with cyclic approximations. The points are plotted centrally within each block.

Similar analysis has been done for the ETo series at Uccle. Evapotranspiration plays a key role in hydrological impact studies as it represents the loss of water from the hydrological system. It also provides a nexus in the hydrological cycle between the hydrosphere and the atmosphere. As a result, ETo changes are correlated with other climatological variables; thus, findings can be used to explain changes in other variables. Unlike precipitation which is highly variable, ETo is considered less sporadic. Therefore the analysis of ETo is somewhat less complicated.

The ETo trend analysis revealed periods of increasing or decreasing trends, which can be used to infer changes in climatic and hydrologic systems. For example, ETo and precipitation can be used for studying the dryness of periods. Coincident decreasing trends of ETo and increasing rainfall trends would signal a risk of floods. Conversely, increasing ETo trends and decreasing rainfall trends would trigger droughts and low flows. As for rainfall, the trend analysis for ETo is also important for checking historical ETo trends with expected future trends from the climate models. Climate models indeed may be assessed for suitability by checking if they reproduce the trends of the observed ETo. This, however, is still difficult due to the imperfectly modelled physics related to evapotranspiration. In particular, the physics in soil-water models present a conundrum for climate modellers.

Evapotranspiration has hitherto not been extensively studied for climate change studies partly due to its invariable seasonal nature, and the paucity of reliable long records of the various variables required for calculating ETo: wind speed, air pressure, humidity, temperature, and solar radiation. Also, ETo assessment is difficult, as direct measurements are usually expensive, and sophisticated. ETo studies have been simplified by approximate methods which provide reasonable estimates. For instance, approximate methods exist for estimating ETo primarily based on temperature differences but such methods tend to make spurious estimations especially in humid climates and thus require bias corrections. The climate of Western Europe is highly dependent on the atmospheric circulation. Wind speed is an important driving force for ETo. The Penmann-Monteith equation, which among other variables includes wind speed, is currently favoured for estimating ETo; but for more reliable results the parameters need to be calibrated. From a rigorous study, Bultot (1983) calibrated the Penman-Monteith equation for the local conditions in Belgium. The ETo trends were studied for a long-term time series for Uccle (1901-2005) generated from this Bultot method. This series was examined following a similar procedure for analyzing trends for precipitation, and this for all the climatological seasons: summer, autumn, winter, and spring (Figure 3).

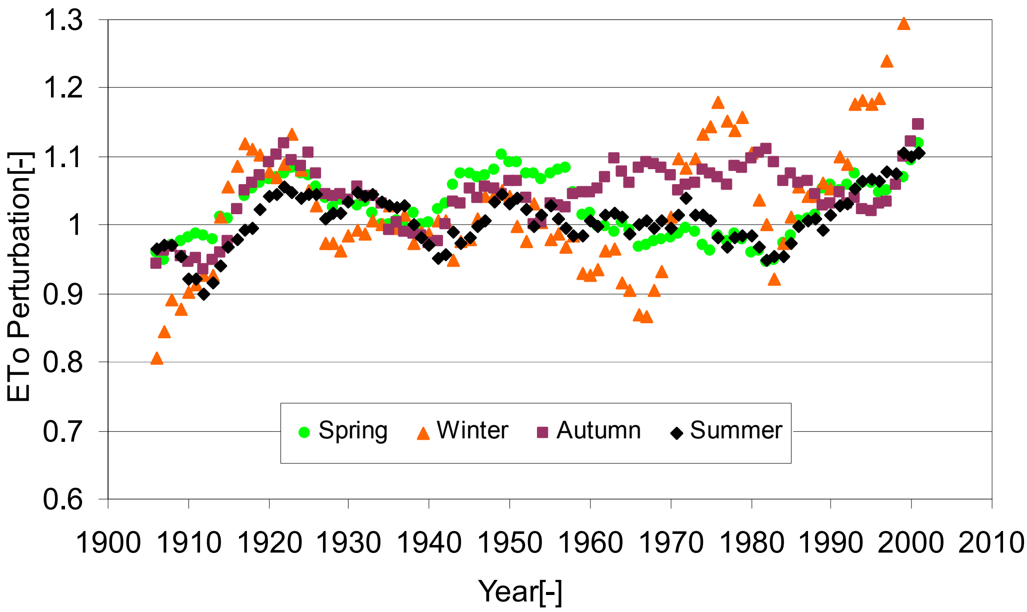


Figure 3: Estimates of average quantile ETo perturbations for monthly data covering the period 1901-2005 for summer, autumn, winter, and spring seasons.

The summer season did not show significant trends as most of the perturbations were fluctuating around the long term perturbation of 1. Typically, ETo is highest during summer but the relative changes indicate that on average ETo was fairly constant (before the 1990s). Maximum perturbations of about 10% were observed for the most recent decade. Overall the perturbations were 10% above and below the long-term average.

Autumn experienced slightly higher perturbations than summer and spring especially since the 1960s. A maximum of around 15% for the most recent decade was observed at the monthly time scale. The perturbations were ranging between -10% and 15%.

The winter season showed the most significant changes with the most recent decades appearing more pronounced. There have been some significantly high perturbations notably the 1970s and the most recent decade (1990s) showing the highest perturbations of up to 30%. The low perturbations were found in the 1960s and were 15% lower than the long term average.

The spring perturbations were similar to the summer perturbations albeit generally slightly higher. A maximum of 10% (1920s and 1950s) and a minimum of -5% were observed.

All in all, since the 1980s there have been increasing ETo trends especially during the most recent decade with winter showing the most pronounced changes. These changes are consistent with the current temperature trends which have shown warmer winters than previously recorded. Various studies have also indicated that the future winters will become milder which implies that ETo rates will increase further. This will increase the amount of water vapour in the atmosphere and therefore lead to an increased rainfall potential in winter.

Climate model projections

The PRUDENCE project produced RCM based climate projections specifically for Europe and was consequently chosen as the main source of climate change scenarios. PRUDENCE is an acronym for Prediction of Regional scenarios and Uncertainties for Defining EuropeaN Climate change risks and Effects (e.g. Räisänen et al., 2004; Christensen, 2005; Christensen et al., 2007). It is a project with many European partners, funded by the EU 5th Framework Program and having as goal the evaluation of climate change risks over Europe in the end of the current century, as predicted by the most recent (at the project time) climate models. The project applied dynamic downscaling to generate climate data over Europe at small scales (12-60km). The PRUDENCE project carried out a series of 30-year long climate simulations for the reference period (1961-1990) and at the end of the 21st century (2071-2100). The models were run using A2 and B2 SRES scenarios (IPCC, 2001) and coupled with two Atmosphere Ocean Global Circulation Models (AOGCMs). The results of these simulations were then used to drive geographically more detailed RCM-based simulations (11 RCMs in total). The results of these simulations were used in the present study. Table I shows the 21 PRUDENCE control experiments (1961-1990) that were used. Table II shows the 31 RCM scenarios (2071-2100) for the future projections.

In particular, the study used outputs with direct relevance to hydrological impacts such as rainfall and ETo. Unlike rainfall which is provided as a direct output from the climate models, ETo is not directly available. Instead, it is derived from other inputs: wind speed, humidity, cloud covering, pressure, temperature, and radiation. However, only temperature and rainfall were extensively tested due to the scant data for other observed variables.

Since the PRUDENCE RCM model simulations were based on only the A2 and B2 future greenhouse gas emission scenarios (IPCC, 2001), additional GCM simulation results were used, derived from the AR4 GCM database of IPCC. The GCM experiments were required to account for the extra uncertainty related to emission scenarios. However, given the differences in priorities, the IPCC AR4 models did not necessarily fit the same criteria for the CCI-HYDR project analysis; the control and scenario periods of the AR4 GCMs do not in general coincide with those of the PRUDENCE RCMs. Nonetheless, many of the GCMs fit the criteria which allowed for checking the estimated PRUDENCE projections which were only based on the A2 and B2 scenarios. Table III shows the GCMs that were used from the AR4 GCM database

Table I: PRUDENCE control series (1961-1990) used in the project.

PRUDENCE PARTNER	MEMBER	CONTROL	GCM	RCM
Météo France (France)	CNRM	DA9	Observed SST	ARPEGE
Danish Meteorological Institute (Denmark)	DMI	ECC	ECHAM5	HIRHAM
		ecctrl	ECHAM4/OPYC	HIRHAM
		HC1	HadAM3H	HIRHAM
		HC2	HadAM3H	HIRHAM
		HC3	HadAM3H	HIRHAM
		F25	HadAM3H	HIRHAM
Swiss Federal Institute of Technology (Switzerland)	ETH	HC_CTL	HadAM3H	CHRM
GKSS Forschungszentrum Geesthacht GmbH (Deutschland)	GKSS	CTL	HadAM3H	CLM
		CTLsn	HadAM3H	CLM (improved)
Met. Office Hadley Centre (United Kingdom)	HC	adeha	HadAM3P	HadRM3P
		adehb	HadAM3P	HadRM3P
		adehc	HadAM3P	HadRM3P
The Abdus Salam Intl. Centre for Theoretical Physics (Italy)	ICTP	ref	HadAM3H	RegCM
Koninklijk Nederlands Meteorologisch Instituut (The Netherlands)	KNMI	HC1	HadAM3H	RACMO
Norwegian Meteorological Institute (Norway)	METNO	HADCN	HadAM3H	HIRHAM
Max-Planck-Institut für Meteorologie (Deutschland)	MPI	3003	HadAM3H	REMO
Swedish Meteorological and Hydrological Institute (Sweden)	SMHI	HCCTL	HadAM3H	RCAO
		MPICTL	ECHAM4/OPYC	RCAO
		HCCTL_22	HadAM3H	RCAO (High res.)
Universidad Complutense de Madrid (Spain)	UCM	control	HadAM3H	PROMES

Table II: PRUDENCE scenario series (2071-2100) used in the project.

MEMBER	SCENARIO	RESOLUTION (Km)	SCENARIO	GCM	RCM
SMHI	SMHI-MPI-A2	49	A2	ECHAM4/OPYC	RCAO
	SMHI-MPI-B2	49	B2	ECHAM4/OPYC	
	SMHI-HC-22	24	A2	HadAM3H	
	SMHI-A2	49	A2	HadAM3H	
	SMHI-B2	49	B2	HadAM3H	
KNMI	KNMI	47	A2	HadAM3H	RACMO
METNO	METNO-A2	53	A2	HadAM3H	HIRHAM
	METNO-B2	53	B2	HadAM3H	
DMI	DMI-S25	25	A2	HadAM3H	HIRHAM
	DMI-ecsc-A2	50	A2	ECHAM4/OPYC	
	DMI-ecsc-B2	50	B2	ECHAM4/OPYC	
	DMI-HS1	50	A2	HadAM3H	
	DMI-HS2	50	A2	HadAM3H	
	DMI-HS3	50	A2	HadAM3H	
ETH	ETH	55	A2	HadAM3H	CHRM
HC	HC-adhfa	50	A2	HadAM3P	HadRM3P
	HC-adhfe	50	A2	HadAM3P	
	HC-adhff	50	A2	HadAM3P	
	HC-adhfd-B2	50	B2	HadAM3P	
MPI	MPI-3005	55	A2	HadAM3H	REMO
	MPI-3006	55	A2	HadAM3H	
CNRM	CNRM-DC9	59	A2	ARPEGE	ARPEGE
	CNRM-DE5	59	A2	ARPEGE	
	CNRM-DE6	59	A2	ARPEGE	
	CNRM-DE7	59	A2	ARPEGE	
GKSS	GKSS-SN	55	A2	HadAM3H	CLM
	GKSS	55	A2	HadAM3H	CLM
ICTP	ICTP-A2	52	A2	HadAM3H	RegCM
	ICTP-B2	52	B2	HadAM3H	RegCM
UCM	UCM-A2	52	A2	HadAM3H	PROMES
	UCM-A2	52	B2	HadAM3H	

Table III: GCM experiments from the AR4 GCM database (IPCC Data Distribution Centre) used in the project.

CENTRE	MODEL	CONTROL	A2	A1B	B1
BCCR	BCM2.0	•			•
CCCma	CGCM3 (T47)	•		•	•
CNRM	CM3	•	•	•	•
CSIRO	Mk3.0	•	•	•	•
MIUB, METRI, M&D	ECHO-G	•	•	•	
LASG	FGOALS-g1.0			•	
GFDL	CM2.0		•	•	•
	CM2.1		•	•	•
GISS	AOM	•		•	•
	E-H	•		•	
	E-R	•	•		
INM	CM3.0	•		•	
IPSL	CM4	•	•	•	•
NIES	MIROC3.2 hires			•	•
	MIROC3.2 medres		•	•	•
MRI	CGCM2.3.2	•	•	•	•
NCAR	PCM		•	•	
	CCSM3		•	•	•
UKMO	HadCM3	•	•	•	•
	HadGEM1	•	•	•	

Evaluation of the climate models

The climate models were tested for their ability to reproduce the meteorological characteristics including mean statistics, seasonality, spatial variability, inter-annual variability, and trends. If a model performs poorly, it can either be rejected or given a low weight to reduce its impact on the overall uncertainty. Several performance tests were carried out at both a local scale (comparing with the Uccle series) and the regional scale (for the whole of Belgium).

At the regional scale, the models were tested for their performance based on the difference of the statistical spatial dependences between the climate model simulations and the observations obtained by integrating the rainfall measurements over the grid boxes of the corresponding climate model. At the local scale, the RCM data were statistically checked for inconsistencies by quantifying the differences between the models and the historical time series for mean, maximum and minimum temperature and rainfall obtained by the RMI at Uccle. The data were checked for the number of days with given temperature or rainfall classes (including extreme events) and for monthly, seasonal and annual differences. For the assessed models, it has been found that the climatological profile of temperature is simulated better than rainfall. Rainfall, being inherently less predictable, is less well captured in the simulations. It is interesting to observe that the higher-resolution simulations (at 25 km) do not necessarily perform better than the high-resolution simulations (at 50 km); generally the errors are lower in the higher resolutions (25 km), but there are some simulations at 50 km with even less error. The bias for both rainfall and temperature alternates around zero with more wide variations for the rainfall. However, the overall mean of the bias per model simulation is not far away from zero: 6.04% for the rainfall annual totals and 3.54% for the mean annual temperature. So, based on an ensemble mean, the models have a small positive bias for both variables.

When focusing on the extreme events, it was found that all models have some difficulty of capturing the climatic behaviour of such events. There is a tendency for overestimation of extreme rainfall events and for underestimation of the number of dry days during winter. During summer, however, there is a general negative frequency bias of events. For temperature, there is a general underestimation of the frequency of freezing or hot days. The relative error ranged from 30.60% up to 81.98% for the freezing days, and from 115.55% up to 287.50% for the hot days.

The RCM time series were also assessed based on standard statistical tests to detect the existence of trends or change-points in the model simulations and in the reference historical time series from the RMI at Uccle. In particular, the Kendall coefficient, Pettit (1979), and Lombard (1988) tests were performed. It has been found that the model simulations capture well the absence of trends in the observed times series, for both rainfall and temperature.

Comparing all these model performance results, only seven control series (from six RCMs) appear to be ideal (no apparent faults) for the Belgian climate: DMI-HC1, DMI-HC2, DMI-F25, KNMI, MPI, METNO and SMHI-HCCTL. They simulate the present climate well and would provide the best estimates for climate change. These six models would make the best selection but having only six models would greatly reduce the number of models. Since it is not guaranteed that a climate model, which simulates well the present climate, would simulate well the future climate it is better to take a more cautious approach. There is a need of more models because the increased number of models can provide insights concerning climate model spatial and temporal variability, and uncertainty. The combination of areal and point performance measures of the regional climate models led to a selection of climate models suitable for the Belgian climate. These are the models listed in Table I, Table II and Table III, except the RCMs ICTP (RegCM) and GKSS (CLM). The latter appeared most anomalous and were omitted from the list.

Trend consistency check for the PRUDENCE RCMs

Climate models can only produce credible projections if they succeed to simulate realistic future trends consistent with the past (observed) trends. It also would be useful to check whether the RCM simulation results are consistent with the historical climate. It would have been ideal to rerun the climate models for longer periods to check whether the models reproduce the observed trends and oscillations. However, this is impractical as it has implications for the calculation times considering the number of models involved. Therefore, a different approach was to check whether the projected changes are realistic in retrospect. The future trends thus were projected backwards towards the observed trends. If a portion of the observed trends is not within the projection, the model is biased for trends. This would implicitly be linked to the errors in the internal dynamics or physics of the climate model which would suggest down-weighting or exclusion of the model from the selected group.

For a comparison with the model projections to be valid, the historical perturbations were recalculated for 30 year block sizes; RCM experiments are indeed run for 30 year periods. The new trends and oscillations were compared to the future projections. Since the perturbations had a cyclic component, the perturbations were first de-oscillated (as explained earlier on the basis of Figure 2) such that only the trends would be compared. The historical perturbations, recalculated for 30-year blocks, thus have been processed to subtract the cyclic component from the total perturbation to eliminate the oscillation component from the time series leaving only the trend component. It is important to keep in mind that comparisons with the historical perturbations are only possible after 1961, which is the beginning period of the control simulations.

With the quantile-perturbation approach, average extreme perturbations are calculated for the RCMs by comparing the 30 year control series (1961-1990) with the 30 year scenario series (2071-2100). The perturbations calculated here depend on two series, which is different from the historical trend and oscillation analysis where the perturbations are based entirely on the historical series. Calculating the average perturbations for the period 2071-2100 for all the models leads to a range of factors. These factors represent the average increase or decrease in the extremes relative to the control period (1961-1990). By plotting a line joining the 1975 (centre of 1961-1990) and the factor at 2085 (centre of 2071-2100), a trend is traced. Instead of tracing all the trends for all the models, only the extreme trends have been shown in Figure 4. The perturbation represents a change relative to the baseline 1961-1990, which has a perturbation of 1. The analysis was repeated for both winter and summer. For both seasons, the historical trends are consistent (or at least not inconsistent) with the global warming impact predictions by regional climate models; the historical trends are enveloped by the range of future projections. Therefore, in retrospect, the projected changes from the climate models are credible.

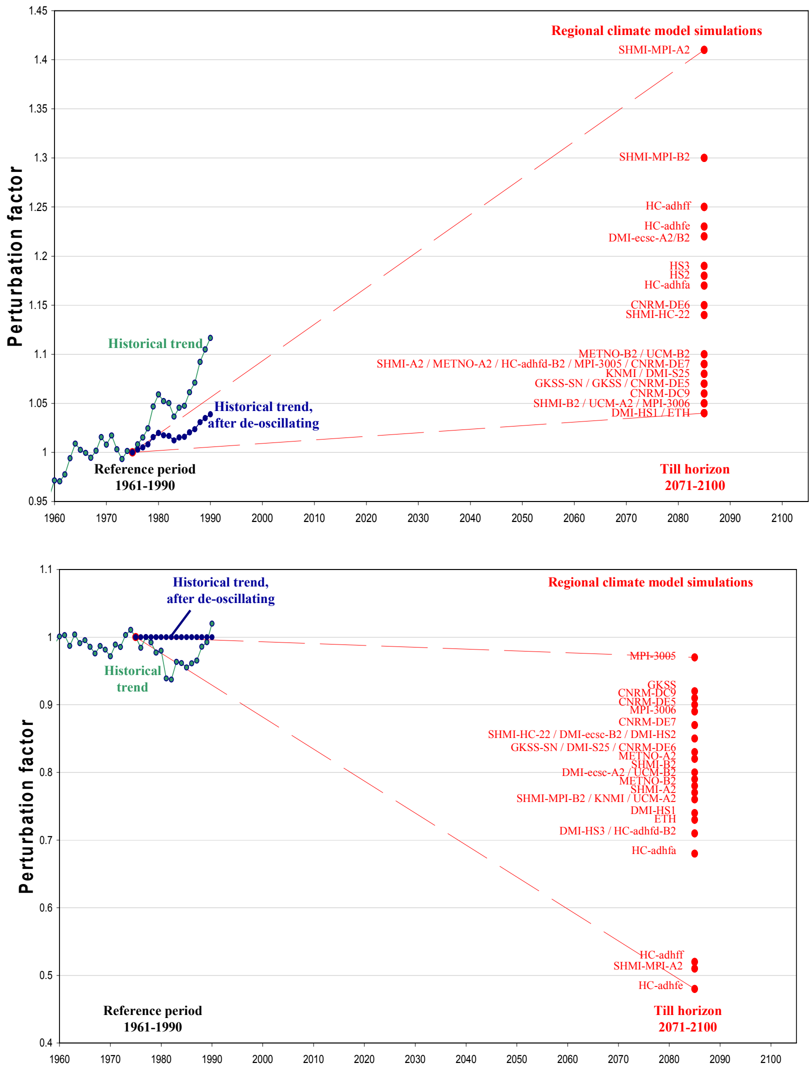


Figure 4: Comparison of the recent historical trends of daily rainfall extremes at Uccle for 30 years block size (from 1961-1990 till 1976-2005), before and after elimination of the approximate cyclic multidecadal oscillation contribution, with PRUDENCE RCM simulation results from the reference period 1961-1990 till 2071-2100, for winter (top) and summer (bottom) season.

High, mean and low climate change scenarios for hydrological impact analysis

The local and spatial assessment culminated in the selection of climate models for hydrological impact modelling. The selected climate models could now be used for climate change studies in Belgium with increased confidence. It is notable that despite the dynamic downscaling of the selected RCMs, there was still a need for further downscaling. The statistical evaluations of the PRUDENCE model results revealed that the direct use of the biased model results would subsequently lead to biased impact analysis. Even so, the large set of models implied that the interpretations would be difficult for the impact analysts. Therefore, three scenarios were identified which would simplify the interpretation and at the same time account for the overall uncertainty from the selected models. The three scenarios were deduced through a statistical downscaling method that involved the transfer of the changes estimated from the climate models to an observed time series. The changes were mainly considered for the number of wet days and the intensities of the wet days. Based on the entire set of the models the high, mean and low scenario cases were selected to represent the overall expected range of changes. These were extracted from a probabilistic analysis of the entire set of the model projections.

The three-case scenario approach was then used to transform the observed series of rainfall and ETo, which are the key factors for impact modelling in hydrological models. The flow outcomes from the three climate scenarios that are categorised as high, mean, and low should match the range that would have been simulated if all the selected models were applied. The high case defines the most extreme scenario (most pessimistic high flow impact); thus the most severe case for flood risk analysis. The mean case represents the expected average scenario (mean flow impact), while the low scenario (stongest low flow impact) in contrast to the high scenario reflects the most pessimistic change in the low flow situation. However, since the PRUDENCE RCM models were based on only the A2 and B2 future greenhouse gas emission scenarios (IPCC, 2001), scaling factors were required to make the scenarios more exhaustive by including changes from extra scenarios (notably the A1B and B1). These were derived from the IPCC AR4 models.

The high, mean and low statistically probed climate change scenarios for the Belgian climate are crucial for hydrological and hydrodynamic impact studies in the country. Also, ecological impact assessments benefit from the outputs of the hydrological-hydrodynamic models, which are based on the generated scenarios. The impact results can also support the study of adaptation measures.

Before discussing the hydrological impact results obtained in Phase 2 of the project, more details will be provided first on the high, mean and low scenarios derived and the statistical downscaling of these scenarios.

Dependence on return period and time scale

As outlined above, projections based on the selected models were statistically processed by comparing the control simulations (1961-1990) with their respective future simulations (2071-2100). Based on the frequency analysis of quantiles, perturbation factors were calculated for each day in the scenario period. The perturbation factor is the ratio of the value in the scenario period versus the corresponding value (with the same empirical return period, or with the same rank number after sorting) in the control series. The perturbation factors are then plotted against the return period and the dependency of the perturbation factor on the return period investigated. For the higher return periods (more extreme conditions; typically for return periods higher than 0.1 years), mean perturbation factors are calculated for aggregation levels of 1 day, 1 week, 1 month, winter, and summer season. In Figure 5 the control and scenario rainfall quantiles are plotted for the winter and summer seasons. During winter, the scenario quantiles are above the control quantiles for the extremes, which implies that the intensity for a given return period increases; but for a given intensity, the return period decreases. Therefore, during winter, the future will experience an increase in frequency (reduced recurrence intervals) and an increase in intensity of the extremes. Summer presents an opposite response with reduction in frequency (increased recurrence intervals) and reduction in intensity. The patterns shown in Figure 5 are only for one model; other models may show a mixture of results with the scenario and control curves exchanging positions for different ranges of return periods. Figure 5c shows the perturbation factor which combines the frequency and intensity properties. A positive perturbation means that there is an increase in intensity and/or frequency while a negative factor implies a decrease in intensity and/or frequency. This explains the positive winter perturbations and the negative (perturbation < 1) perturbations for summer. Also, the sharp bend shown during summer demonstrates the importance of a threshold. By selecting a 0.1 year threshold, the influence of the sharp bend is eliminated. This bend is somewhat linked to the positive feed backs within the climate models which lead to excessive drying of the soils in the soil-water models.

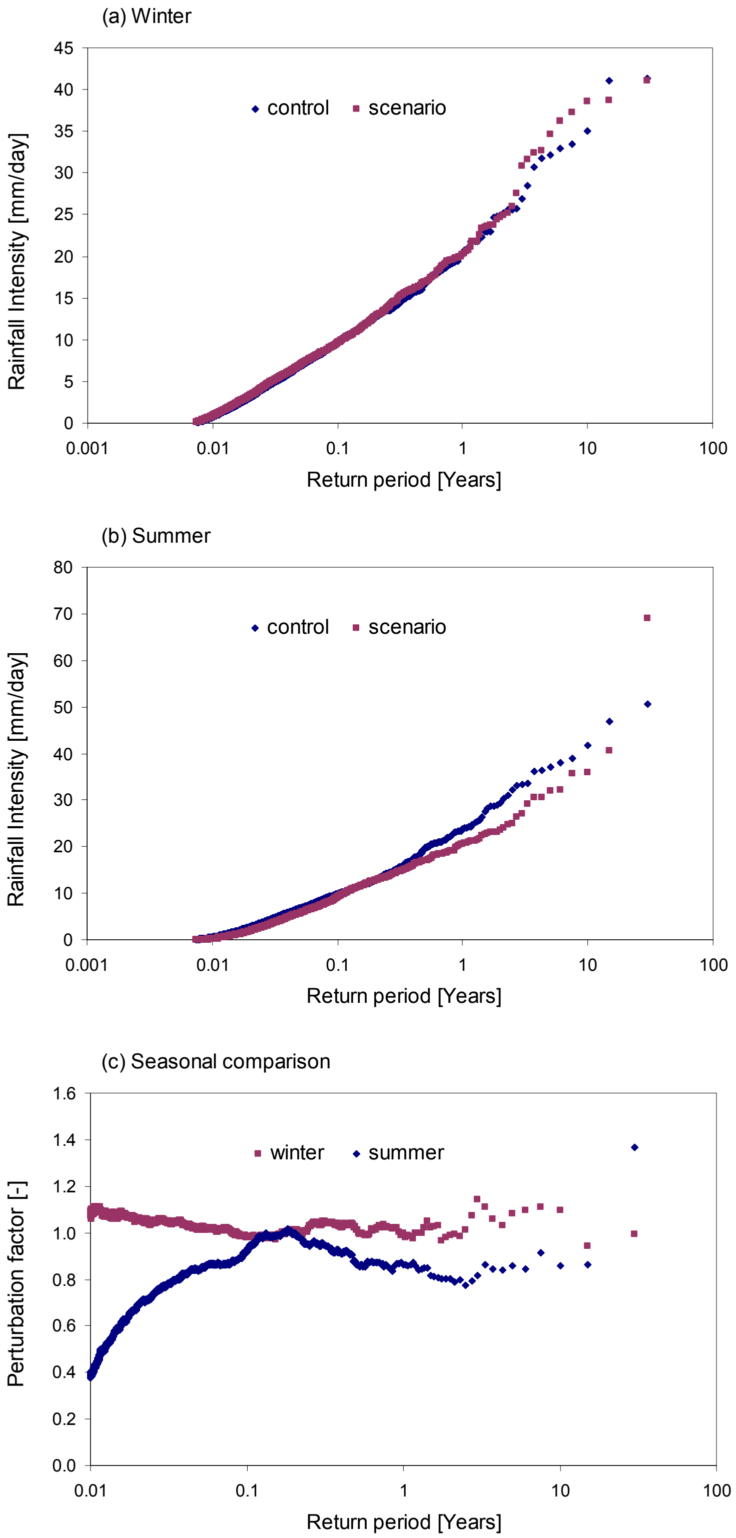
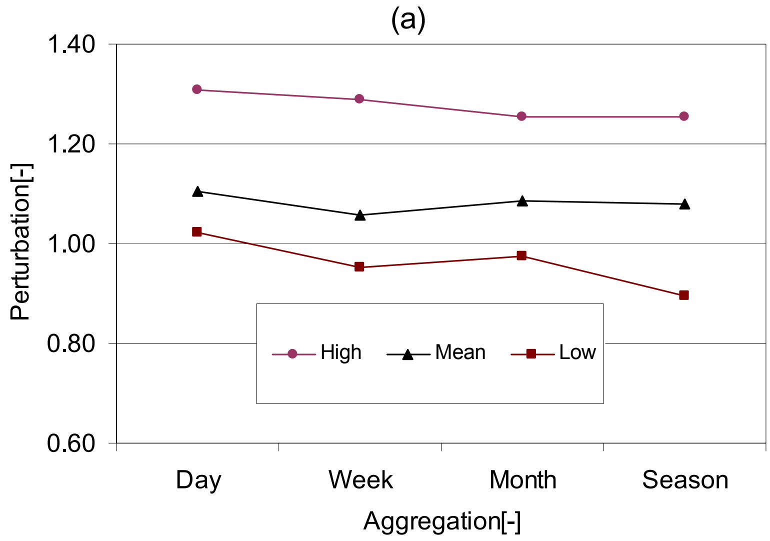


Figure 5: Daily rainfall distributions for winter (a) and summer (b), and the corresponding perturbations (c). The control (1961-1990) and scenario (2071-2100) series are shown for only one RCM run (DMI-HS1) to illustrate the typical perturbation patterns during the two seasons.

The quantile-perturbation analysis for the different aggregations was aimed at understanding the temporal variability of the perturbations. By definition, aggregations require the summation of values which implies a volumetric summation of rainfall quantities. By studying how the perturbations vary with aggregations it is possible to distinguish the internal variability of the base time series (the daily time step). Aggregation at different time scales implies a daily accumulation of quantities. By separating the daily values in seasonal time series, volumes for winter and summer were estimated at daily, weekly, monthly and seasonal scales. This was done for the control and scenario series after which the frequency perturbation technique was applied and an average perturbation calculated for values with recurrence intervals greater than 0.1 years. This was repeated for all the climate model runs for the rainfall and ETo series. The perturbation patterns across the different time scales revealed distinct seasonal behaviour.

It is apparent from Figure 6, in which only the highest, mean and lowest perturbations are represented, that the rainfall changes are somewhat constant for a given scenario during the winter season. This suggests that the number of wet days during winter does not significantly change. The perturbations during summer are generally lower than 1 (for the mean and low scenario) indicating that during summer all models predict reductions in perturbations. However, the reductions are highest during the seasonal aggregation. This suggests that by aggregating to seasonal scale the perturbations reduce mainly due to a reduction in seasonal volumes. This reduction in perturbations is perhaps explained by both the reduction in number of wet days and general reduction of intensity. The former factor appears to be more important as summer extremes were found to have increased and not decreased. Even so, the extremes make up a small percentage of the total number of wet days. The reduction in volumes can mainly be explained by an aggregation which includes the less extreme events hence leading to lower volumes. It follows that during summer, the reduction of wet days is important for climate change. The changes at different aggregations point to important characteristics which are relevant for downscaling which include the changes in both the number of wet days (for rainfall) and the intensities.

The perturbations for ETo have somewhat dissimilar features (Figure 6). The seasonal volumes tend to increase (with perturbations above one) for both winter and summer. The increase may be linked to the positive temperature perturbations in both seasons. The increase is more important during winter as there appears to be a significant increase from the monthly timescale to the seasonal timescale. This indicates that ETo changes are larger during winter due to the possibly higher temperature changes which can be inferred from the increased number of warm days. The higher temperature changes lead to higher ETo changes during winter. Whether the ETo changes will have a significant impact on the hydrological system will depend on the sensitivity of the impacts to ETo (see also later). Floods tend to be less determined by the ETo changes but low flows are considerably affected by ETo.


(a)
1.40
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1.00
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0.60
Perturbation[-]
High
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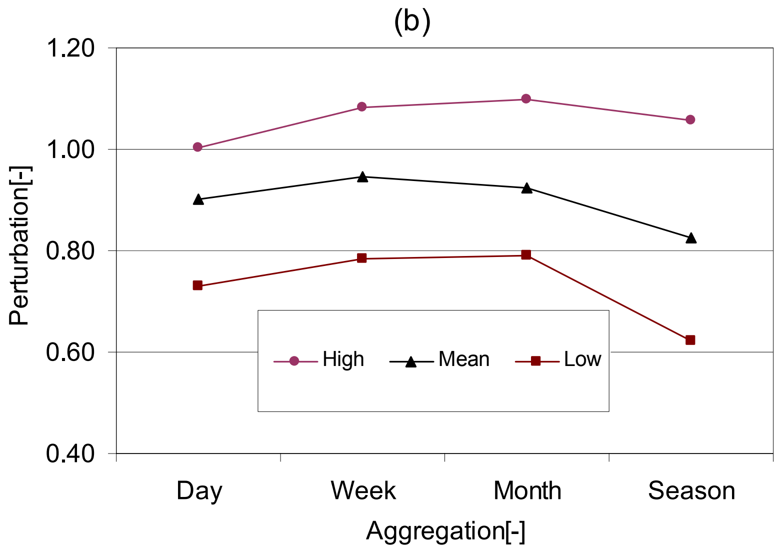
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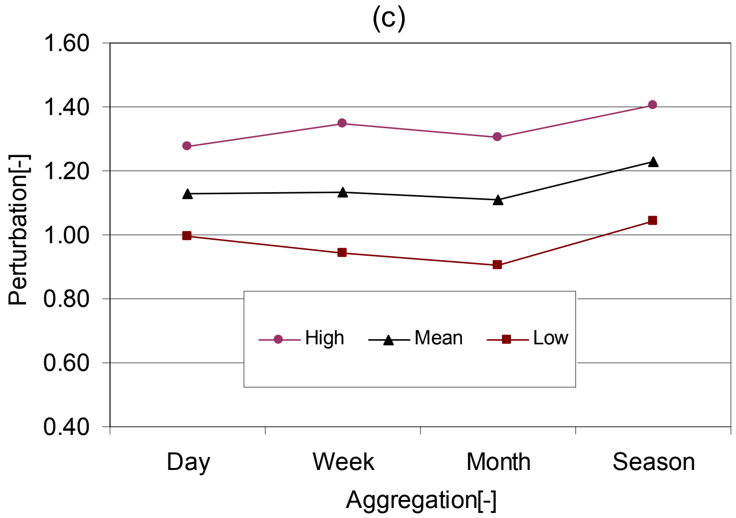


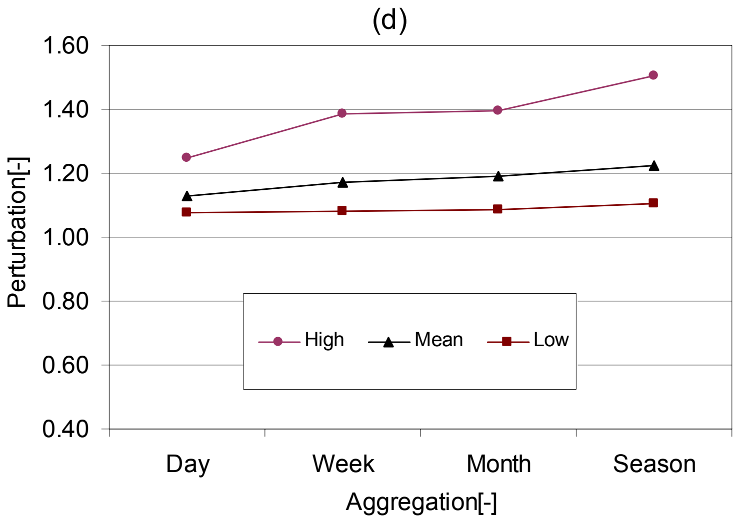
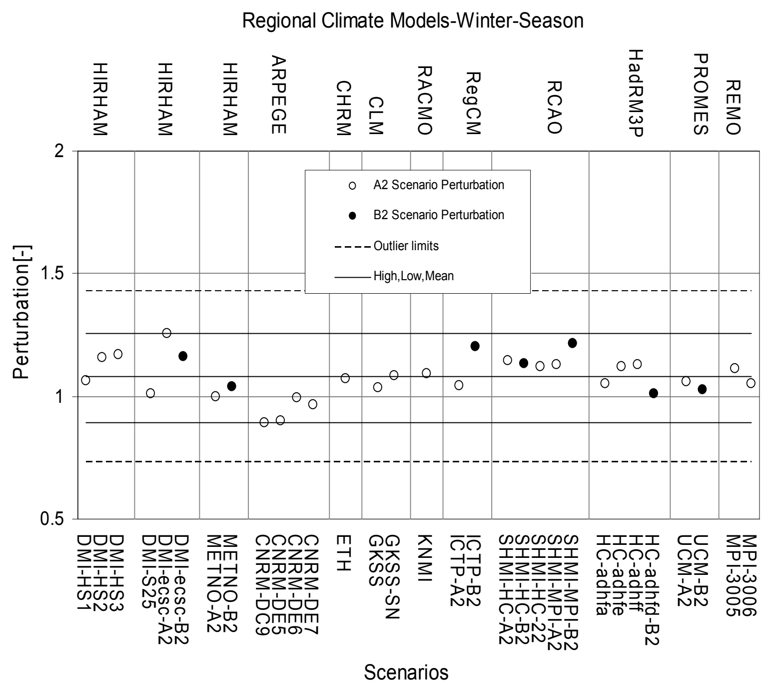


Figure 6: High, mean, and low perturbation factors for the different aggregations for rainfall in winter and summer (a and b) and ETo in winter and summer (c and d).

Projected climate change

The projections were initially determined from the control and the scenario series (close to the Uccle series) from the PRUDENCE RCMs, which were based on the regional A2 and B2 scenarios. The number of models also leads to a range of expected changes, which are a manifestation of the differences in the modelling physics of the models. Thus, a high, mean, and low projection can be provided for any future expected change. To understand the differences within the model projections, graphical interpretations are essential. With the models superimposed on the same graph systematic differences were spotted. The projected changes were first analyzed at a local scale (region close to Uccle) and then spatially (for the entire Belgium). Figure 7 shows the rainfall perturbations, which were derived as ratios of future seasonal volumes to present seasonal volumes. The discordant models identified previously (from ICTP and GKSS) have been deliberately included to highlight a remarkable observation: despite the biases, and model physics differences, the model projections are closer to each other. The outlier lines were determined using the extreme outlier boundaries of the box-and-whiskers plot (Tukey, 1977). The similar climate projections may be explained by the fact that the models have similar boundary GCMs. Indeed, most of the models have the ECHAM4/OPYC3 and HadCM3 as boundary GCMs, which were found to have similar global climate change (IPCC, 2001). However, the PRUDENCE set of models remains unique for its regional focus and thus the projected changes would be a first realistic case for future regional changes. The local changes (Figure 7) generally predict an increase of rainfall during winter (perturbation>1) and a decrease in rainfall during summer (perturbation<1). The climatological winter (December, January and February) seasonal changes are in the range of -10% to +26% while the climatological summer (June, July and August) changes are in the range of -40% to +6%. Other interpretations may also be made from the graphical plots. For instance, models may be categorized as high, mean and low. Differences in scenario projections may be quantified although for the seasonal case the A2 and B2 scenarios showed similar signals. The effects of the resolutions can also be inferred from the plots.



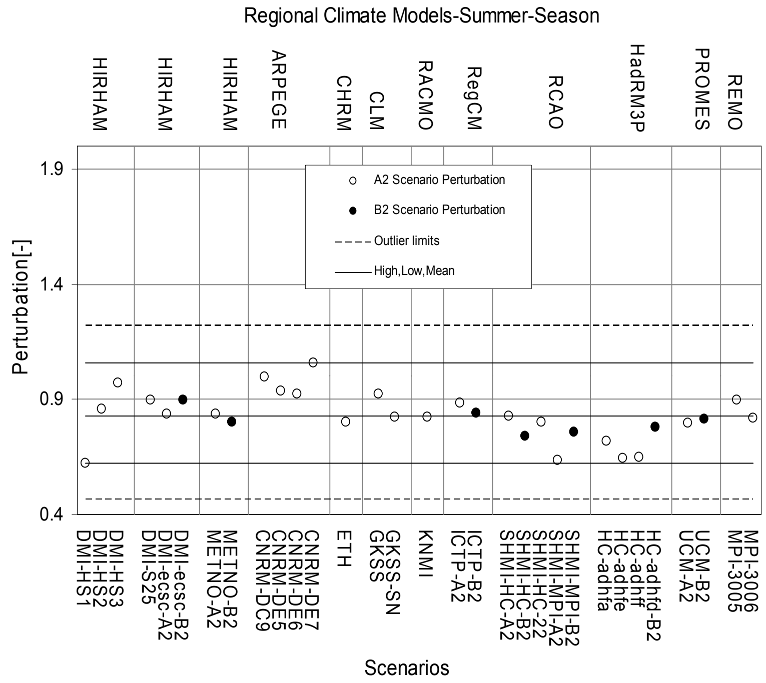


Figure 7: Local rainfall projections for winter (left) and summer (right). Dotted lines show the outlier limits (there are no outliers). The range of projections is defined by the high, mean and low factors.

Regional differences across Belgium

The climate change projections from the PRUDENCE RCM simulations were also derived at the regional level over Belgium. The meteorological variables analysed regionally are ETo, precipitation and temperature.

The approach adopted here makes use of the perturbation factors, i.e. the deviation (difference or ratio) between scenario and control climate data values. The perturbations were calculated at seasonal basis (hydrological summer and winter). The values for precipitation and temperature are provided directly by the RCM output while those for ETo are calculated using the Penman formula, specifically calibrated for Belgium at the RMI, as explained before. For each meaningful combination of control and scenario RCM data, the corresponding perturbations for ETo, precipitation and temperature were calculated. The perturbations for temperature were calculated as differences between the scenario and control values in degrees Celsius, while the ones for ETo and temperature are ratios and therefore dimensionless. The complete perturbation data from all models were collected over each cell of the common grid used by the SCHEME model (see section 3). Recall that, among the PRUDENCE climate models retained for subsequent analysis, there are eight different grids at 50 km horizontal resolution (the SCHEME hydrological model has a grid at 7 km horizontal resolution). From this perturbation sample over each grid cell of the SCHEME model, low, mean and high perturbations were defined, following the method discussed before. This leads to three levels of scenarios for each one of the three variables, ETo, precipitation and temperature. These scenarios are graphically represented in Figure 8, Figure 9 and Figure 10 respectively.

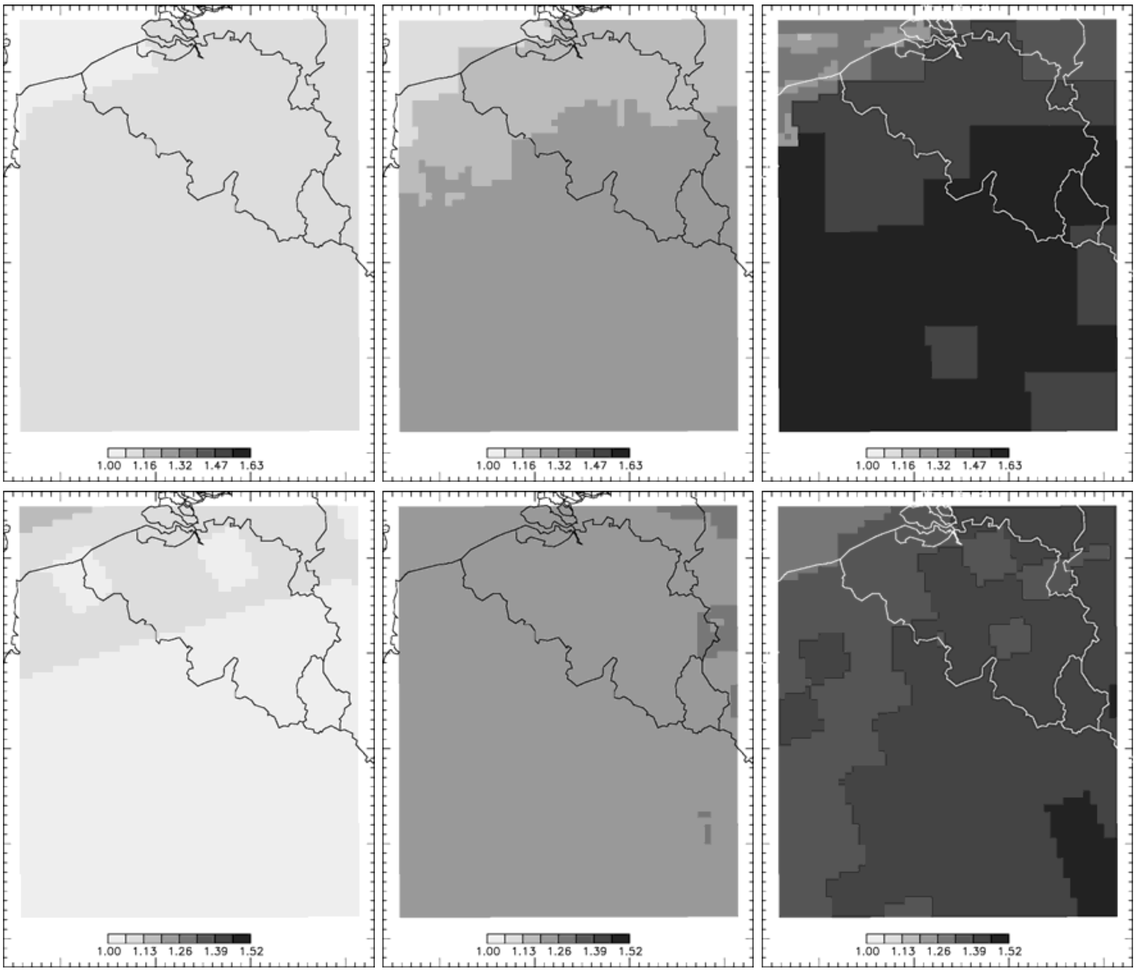


Figure 8: Perturbation-based scenarios for ETo. Upper row: hydrological summer, lower row: hydrological winter. From the left to the right: low, mean and high scenario.

Table IV: Perturbation spatial value range for ETo scenarios.

	Low	**Mean**	**High**
Summer	1.00 – 1.13	1.12 – 1.29	1.22 – 1.63
Winter	1.00 – 1.14	1.21 – 1.27	1.30 – 1.52

In the ETo scenarios and in both summer and winter, there is no perturbation value below 1. This means increase of ETo in every case. For the winter, apart the clear distinction between the three scenario levels, there is little differentiation in the spatial perturbation values at each scenario level. This differentiation is somewhat more marked in the high scenario. The same situation is observed in summer too, although in that case there seems to be more spatial differentiation with increased ETo values in the southeastern part of Belgium.

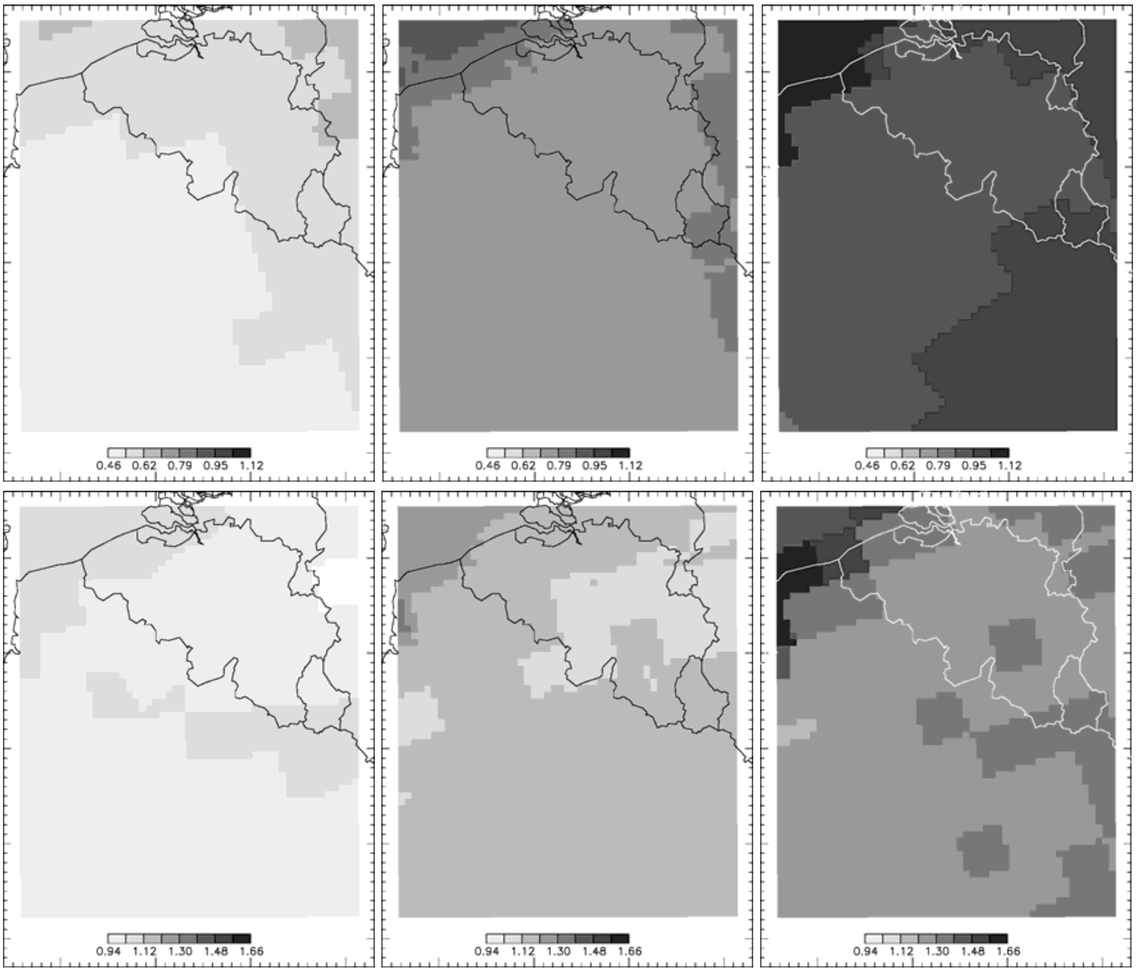


Figure 9: Perturbation-based scenarios for precipitation. Upper row: hydrological summer, lower row: hydrological winter. From the left to the right: low, mean and high scenario.

Table V: Perturbation value spatial range for precipitation scenarios.

	Low	**Mean**	**High**
Summer	0.46 – 0.64	0.71 – 0.88	0.86 – 1.11
Winter	0.94 – 1.09	1.09 – 1.32	1.21 – 1.66

The main characteristic of the precipitation scenarios is the strong decrease of precipitation amount everywhere in Belgium in the low and mean scenario levels. The decrease is projected to be less important along the coast. In the high scenario level however, the coastal precipitation appears to be unchanged or even increased with respect to the control values. During winter the perturbation values exceed the value 1 almost everywhere, so the amount of precipitation would be expected to increase. In each scenario level, the precipitation increase is stronger along the coast again. The general precipitation pattern described above using perturbations could be related to changes in the large-scale circulation over northwestern Europe and in ocean water temperature under climate change conditions.

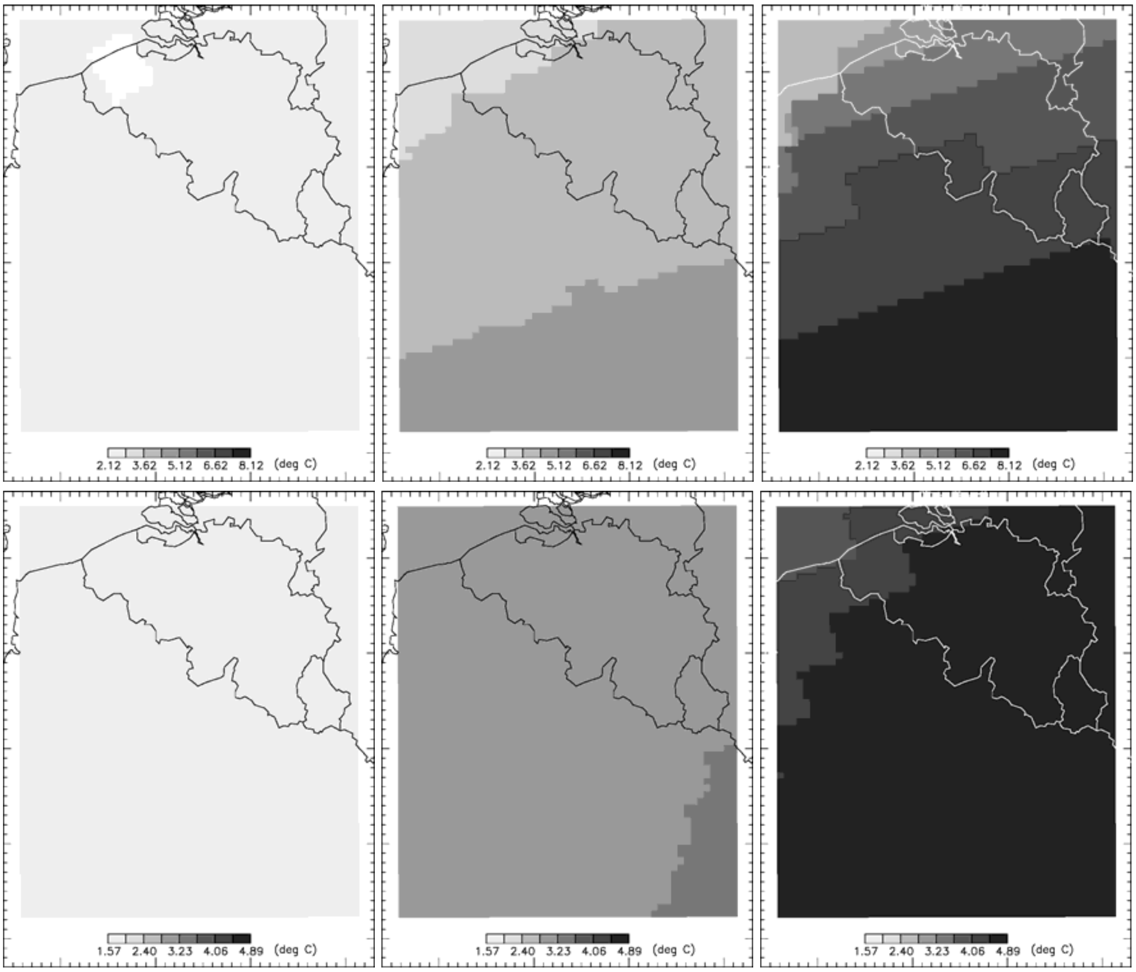


Figure 10: Perturbation-based scenarios for temperature. Upper row: hydrological summer, lower row: hydrological winter. From the left to the right: low, mean and high scenario.

Table VI: Perturbation value spatial range for temperature scenarios.

	Low	**Mean**	**High**
Summer	2.12 – 2.79	3.09 – 4.68	3.74 – 8.12
Winter	1.57 – 1.84	2.92 – 3.32	3.85 – 4.88

The projected temperature changes under climate change, according to Figure 10, are above 1.5 degrees Celcius in every season and everywhere in Belgium. The temperature perturbation field represented in Figure 10 is quite homogeneous during winter, with some exceptions arising in the high level. As we see in Table VI this reflects the small spatial variation of the perturbations in the low and mean scenario levels. During summer, some temperature perturbation gradient can be detected, increasing towards the southeast, mostly in the high scenario again. This implies that the coast will experience less severe temperature increases in summer than the rest of the country, according to the climate change scenarios provided by the PRUDENCE database.

2.2 Climate change downscaling

After evaluating the available RCMs and understanding the inconsistencies therein, the analysis progressed to statistical downscaling. Statistical downscaling ensures that the now realistic projections from the RCMs are transferred to the local observations. Conventional statistical downscaling techniques require the use of statistical relationships obtained by comparing synoptic scale variables (predictors) with meso scale regional variables (predictands). These techniques, however, tend to focus on mean tendencies and overlook the changes in extremes, which are essential for impact analysis. The PRUDENCE project primarily set out to use dynamic downscaling for fine scales to better represent the regional climate in Europe. Nonetheless, the RCM evaluation revealed biases despite the dynamic downscaling methods employed from the various models. Thus, the RCM results could not be used directly; hence the downscaling methodology required further modifications particularly those relating to changes in extremes. In essence, the dynamically downscaled results required statistical downscaling.

The "delta approach" of applying the climate signals from the climate models directly to observed series is still popular chiefly because of its simplicity and the need for less data; only one variable is required. The perturbation delta approach is a combined downscaling method, combining the advantages of dynamical with statistical downscaling methods. It is the most common used method to transfer the signal of climate change from climate models to hydrological models (Bultot et al, 1988; Vehviläinen and Huttunen, 1997; Lettenmaier et al, 1999; Middelkoop et al, 2001). There have been improvements on the approach by examining various scenarios to address the demerits of the method; but there still remains a challenge of simulating changes in extremes. This study uses a variant of the delta approach which exploits the merits while improving on some of the demerits. Instead of using simple change factors, the changes in extremes and changes in wet days are explored. The changes are extracted form the RCMs and then probabilistically applied to a given series; typically the observed input series of hydrological models. The hydrological responses before applying the perturbations and after applying the perturbations determine the future climate change impacts. A schematic illustration of this modelling chain is shown in Figure 11.

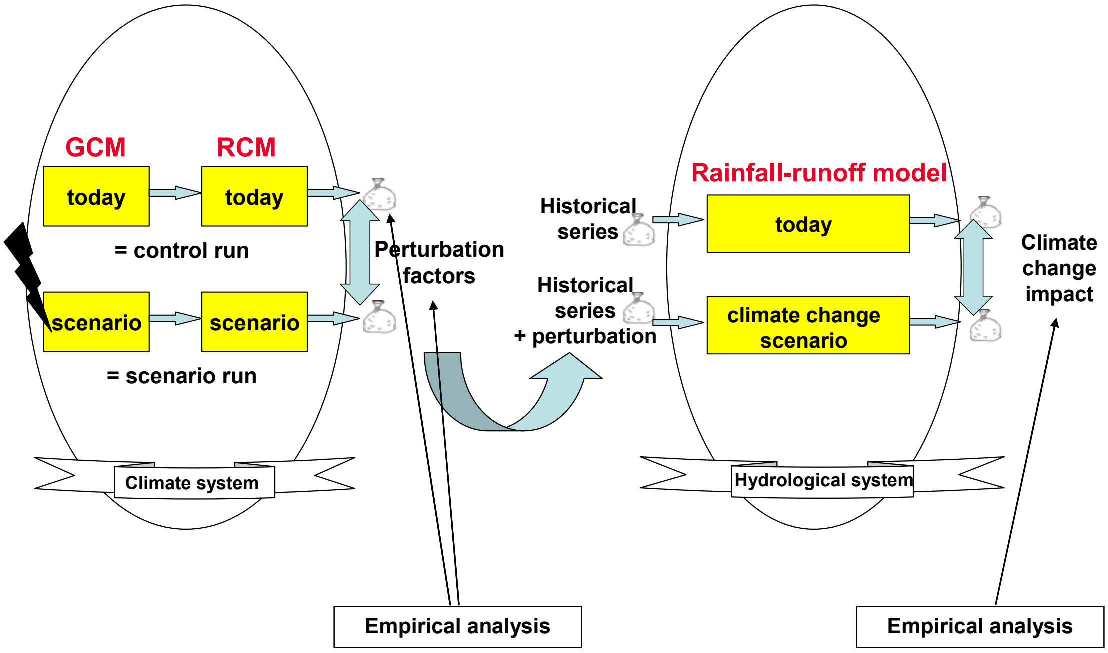


Figure 11: Schematic illustration of the standard "delta approach".

The developed downscaling approach entailed perturbations for the number of wet days and perturbations for the rainfall intensity on a wet day. The combined effect of these two perturbations leads to perturbations on the rainfall intensity for given aggregation levels. As discussed before, these perturbations were also studied for different aggregation levels and return periods. After having done so, the climate change scenarios could be represented by changes in the probability distributions, the extreme value distributions, the cumulative volumes, or summarized by changes in intensity/duration/frequency (IDF) relationships. An overview of the downscaling approach and related outcomes is shown in Figure 12.

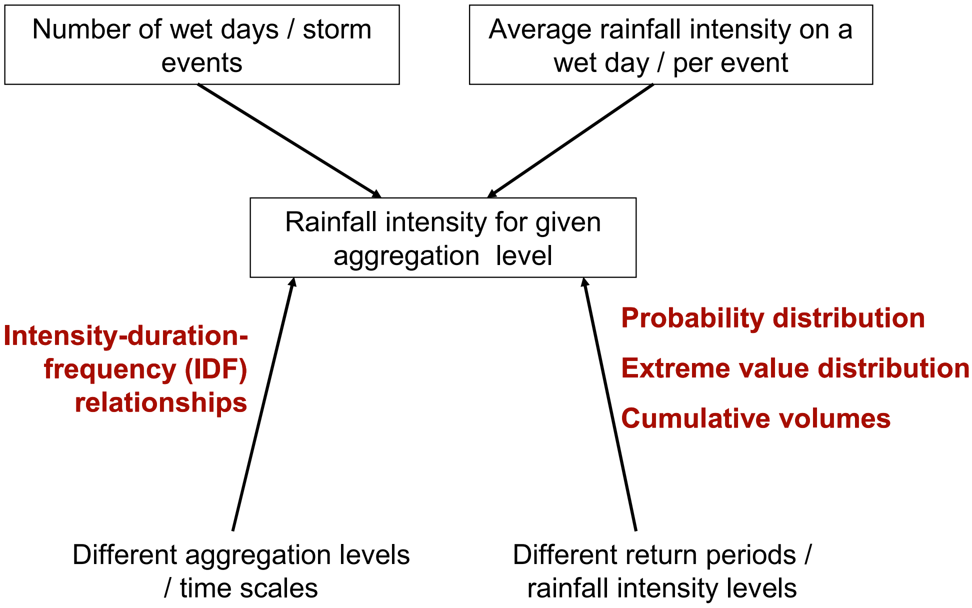


Figure 12: Downscaling approach and related outputs.

Wet day intensity and frequency perturbations

The challenge still remains as to how end users can make use of a large set of models. The available simulations yielded different outputs. Ensemble techniques are currently being widely examined by climate scientists as the convergence of results from many models would not only increase confidence but also pave way for sharing information for future adjustments. This study borrowed some concepts of ensemble modelling by making use of the probabilistic perturbations derived from the selected PRUDENCE RCMs. The set of 28 selected RCM runs (see section 2.1) implied that there were 28 possible scenarios which required close examination as all were equally plausible. Particular attention was paid to the wet day frequency perturbation, and the wet day intensity perturbation, given that these are crucial for hydrological impact analysis. The use of probabilistic techniques ensured that the expected outputs represented the spectrum of all the projections. It is worth noting that no distinction was made on the different scenarios (A2 and B2) as there were few B2 scenarios compared to A2. Even so, there appeared to be no significant differences when observing the entire range of perturbations.

Thus far, section 2.1 indicated that the wet days will get wetter and the dry days will get drier. Moreover, it is found in the project (see next) that during winter the wet days will generally increase in intensity, and the number of wet days will not significantly increase; although the number of wet days in summer will decrease. Also, it has been predicted that the intensity during both winter and summer will increase. The thunderstorms in summer may become more intense while the intensity on lower events may even decrease. These rainfall characteristics can be checked for similarities from the perturbations in wet day frequency and perturbations in the intensity of the wet days.

The wet day for this study was taken as a day with rainfall higher than 0.1 mm. The study considered only the number of wet days and the wet day intensities as they are relevant for extreme frequency analysis.

The perturbation analysis focused on monthly grouped data to capture the intrinsic daily changes within each month. The analysis could also have been done at a seasonal scale but that would lead to less realistic results due to the coarse nature of the seasons. The change in wet days was calculated as a ratio of the number of wet days in a given month during the control period (1961-1990) to number of wet days during the corresponding month in the scenario period (2071-2100). Based on the n(=28) selected RCM model simulations the calculation was repeated implying that for each month there were n wet day perturbations. The range of results represented the overall uncertainty. From that range, the high, mean and low scenarios were extracted using 95% confidence intervals, calculated based on the conclusion that the individual (wet day intensity and frequency) perturbations followed normal distributions. The upper confidence limit defined the high scenario while the lower confidence limit defined the low scenario. The mean scenario was represented by the mean of all the projected changes in the number of wet days. In esence, the high, mean and low scenarios can be seen as pseudo models derived to suitably represent the entire range of projections. This reduces on the calculation time and makes the interpretation of the results easier since the amount of data is also reduced.

Figure 13 shows the model scenarios and the normal distribution scenarios selected for high, low and mean. The high, mean and low changes based on changes of individual models have a thinner range compared to the normal distribution range. Using individual models thus would lead to lower or higher estimates of the perturbations for some months. Consequently, it would fail to represent the whole range of expected changes.

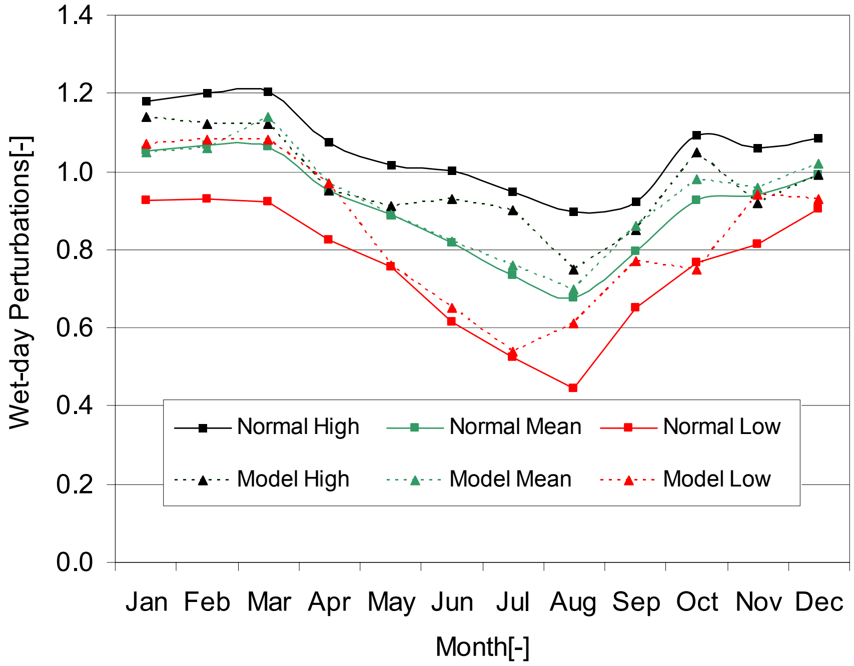
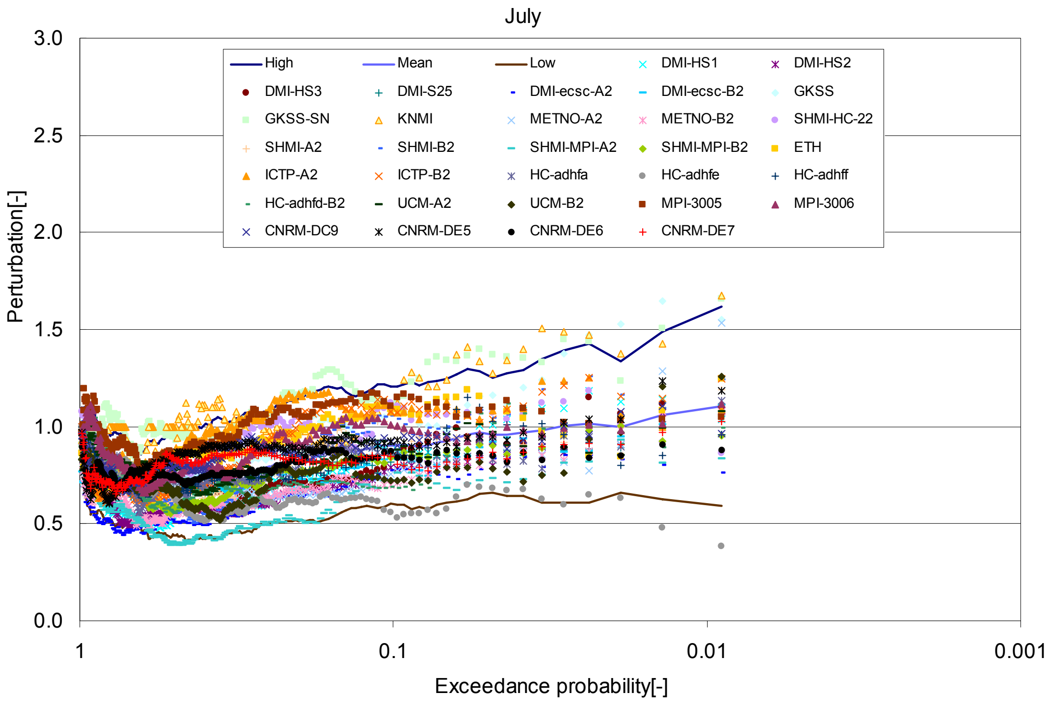


Figure 13: Perturbation on the number of wet days. High, mean and low scenarios are calculated based on 95% confidence limits of a normal distribution (normal high, normal mean, and normal low). Selected high, mean and low models are also shown.

In addition to the wet day frequency perturbation, the perturbation on the intensity is necessary. The method selected was based on the principles of the quantile-perturbation method. The perturbations are calculated based on a frequency analysis by comparing ranked daily extremes in the control period to ranked daily extremes in the scenario period. The n(=28) perturbations are then statistically assessed based on the normal distribution to derive the high, mean and low intensity perturbations. This is done for any given exceedance probability (or recurrence interval) after which patterns can be traced through the limits to produce curves representing the high, mean and low scenario changes. These curves can then be used to interpolate the intermediate recurrence intervals and to smoothen the intensity perturbation versus recurrence interval. This is particularly important when transferring the perturbation to an observed series. The exceedance probability is calculated relative to the wet days within the series.

Figure 14 shows the wet day rainfall quantile-perturbation plot for the PRUDENCE RCMs. The months selected represent the typical perturbation variability during summer (July) and winter (January). During the winter months, the daily rainfall perturbations are fairly invariable with exceedance probability for most of the models. However, during summer, the perturbations are dependent on the exceedance probability with the higher extremes having higher perturbations. During winter, the extremes are expected to increase uniformly while the summer high extremes will be more intense.



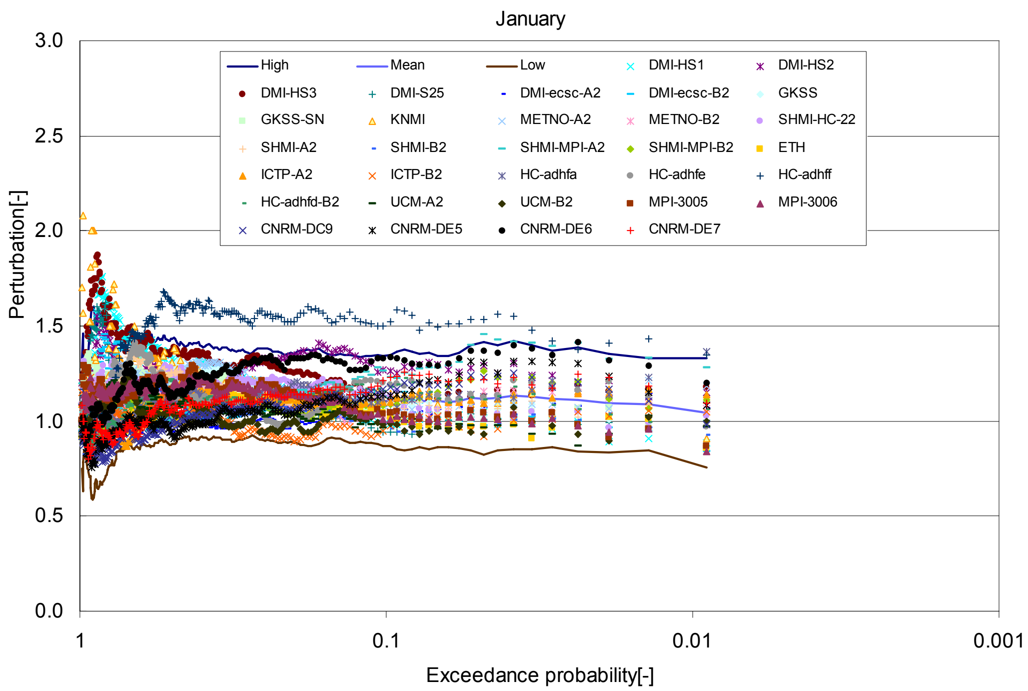
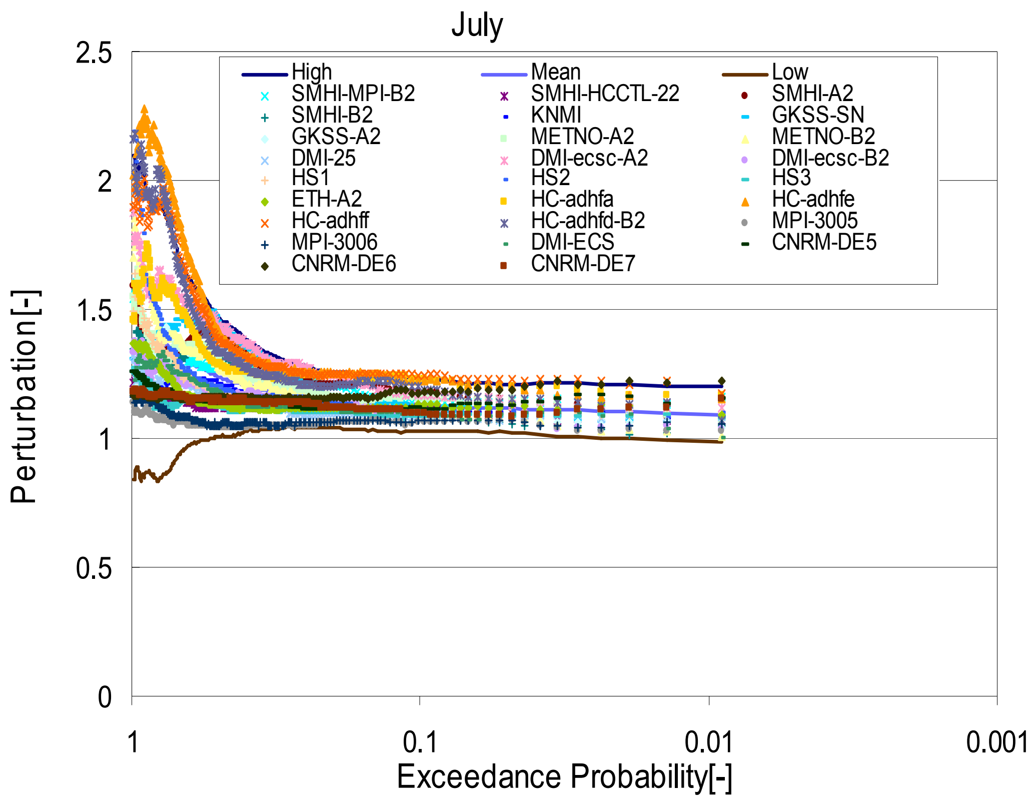


Figure 14: Typical wet day rainfall quantile-perturbation projections for summer (July) and winter (January). The high, mean and low scenarios are based on the normal distribution (95% confidence limits) and represent the range of the perturbations.

For ETo, the perturbations in winter are fairly constant with exceedance probability implying that the extremes in winter increase uniformly (Figure 15). Summer, however, shows unstable perturbations for the high frequency values. These perturbations are likely unrealistic as the models have been found to have excessive drying within the soil-water models of the RCMs. Thus, there is little confidence in the extremely high perturbations for the high frequency values. Indeed these anomalous values affect the high, mean, and low scenario perturbation curves. The Hadley centre models form the majority of the models with sharp bends in the perturbation factors (HC-adhfe, HC-adhff, and HC-adhfd-B2). Compared to summer, the winter perturbations were more stable considering the range of the recurrence intervals.



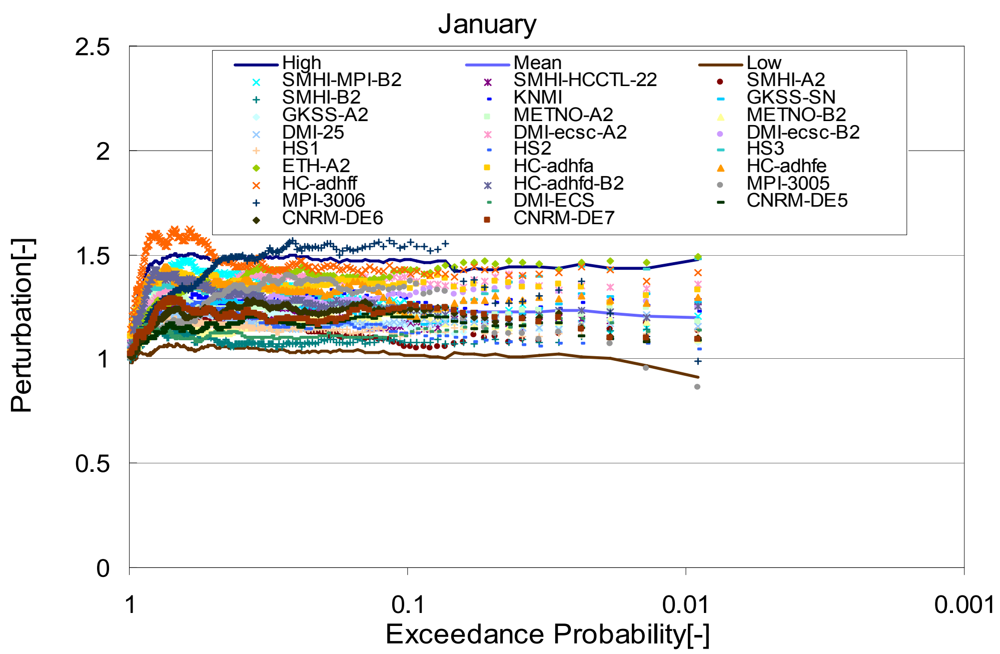


Figure 15: Typical daily ETo quantile-perturbation projections for summer (July) and winter (January). The high, mean and low are based on the normal distribution (95% confidence limits) and represent the range of the perturbations.

Time series perturbations

To obtain changes to the input series of hydrological models, based on the wet day intensity and frequency scenarios, time series perturbation procedure has been developed. For rainfall series, it is basically a two step process (Figure 16). First, the number of wet days to be added or removed is determined for the high, mean and low wet day frequency perturbations. The wet day correction is applied through a stochastic procedure. When adding wet days, the wet days are randomly selected from the set of empirical wet days of the observed series and added to dry days. When removing the wet days, the wet days are also randomly selected but are equated to zero. Second, the intensity perturbations are applied to the wet days in the series. Three final series are obtained representing the perturbed series for the high, mean and low climate change scenarios. For ETo, the first step is omitted given that for the ETo series the day to day variability is minimal compared to the rain series.

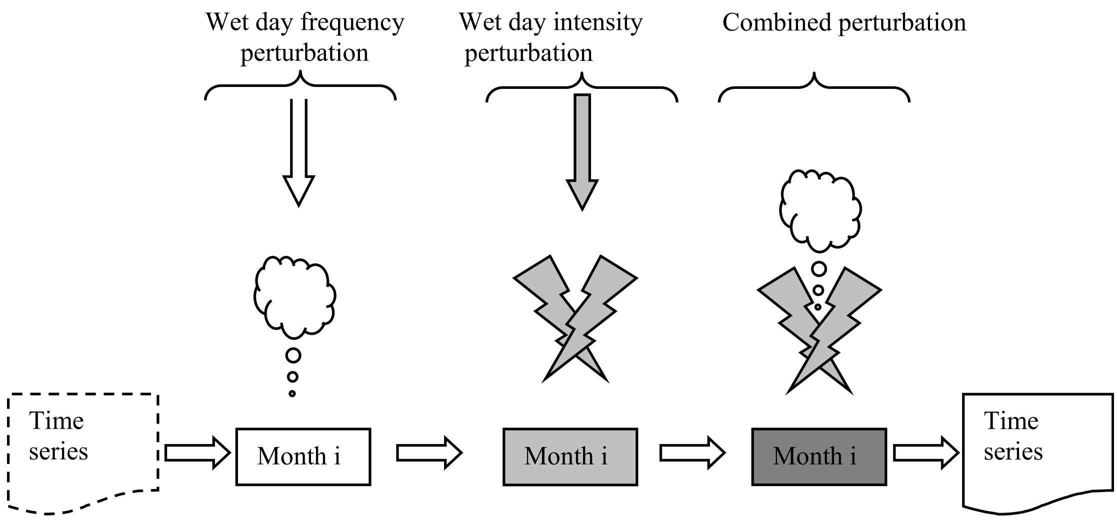


Figure 16: Rainfall time series perturbation.

The perturbations for rainfall and ETo have to be done concurrently to preserve the internal physics of the climate system. For each month three rainfall and ETo series were produced for the high, mean, and low scenarios. However, it is not clear whether a high rainfall perturbation (implicit for a high flood impact) should be combined with a high ETo perturbation. In other words, an investigation into the possible correlations between the two variables is necessary. Regression analysis was performed to identify the relationships between rainfall and ETo. The aim of this analysis was to infer what combinations of rainfall and ETo perturbations are physically meaningful, i.e., consistent with the RCM projections. To elaborate further, it was important to investigate the seasonal relationships of the perturbations. For instance, whether a model with high rainfall perturbations in winter also projects high perturbations in ETo and what projections for rainfall and ETo this model gives for other seasons. To deduce these relationships, the perturbations of the same models were traced across all the seasons. The relationships were then be used to define the high, mean and low hydrological impact scenarios. The high impact scenario is explained by high rainfall perturbations (mainly during winter) while the low impact scenario is associated with the low rainfall perturbations.

The quantile perturbation method was performed on the daily seasonal values and average perturbations were then estimated (return period > 0.1 year) for both rainfall and ETo. Since each model has data for rainfall and ETo, a perturbation correlation analysis was possible. Figure 17 shows the ETo-rainfall perturbations for the four climatological seasons. The possible combinations could be identified by observing the behaviour of the same models across all the seasons. By classifying models as high, mean and low based on the winter rainfall perturbations, the perturbations of the same models in spring, summer, and autumn suggest the potential combinations of ETo and rainfall. The high rainfall perturbations in winter appeared to be followed by low rainfall perturbations in summer. Summer perturbations for the same winter high models appeared to predominantly be located in the lower half of the rainfall perturbations. The ETo perturbations appeared to be high for both the winter and summer. Similarly, the mean and low scenarios were derived. It is apparent that for the transitional seasons (spring and autumn), relationships are difficult to ascertain from the correlations alone meaning that several trials are investigated to infer the combinations. For the main seasons, it was clearer albeit not obvious. Table VII illustrates the combinations that were found to realistically represent the range of RCM impact perturbations. For the high impact scenario, the rainfall series can be compiled by selecting the high rainfall (highest perturbations) for winter months, low rainfall (lowest perturbations) for the summer months, and mean rainfall (mean perturbations) for the spring and autumn months. Using a similar approach, the ETo high series is perturbed. The two series are then input in a hydrological model to simulate the high impact scenario. The same procedure is followed to derive rainfall and ETo series for the mean and low impact scenarios.

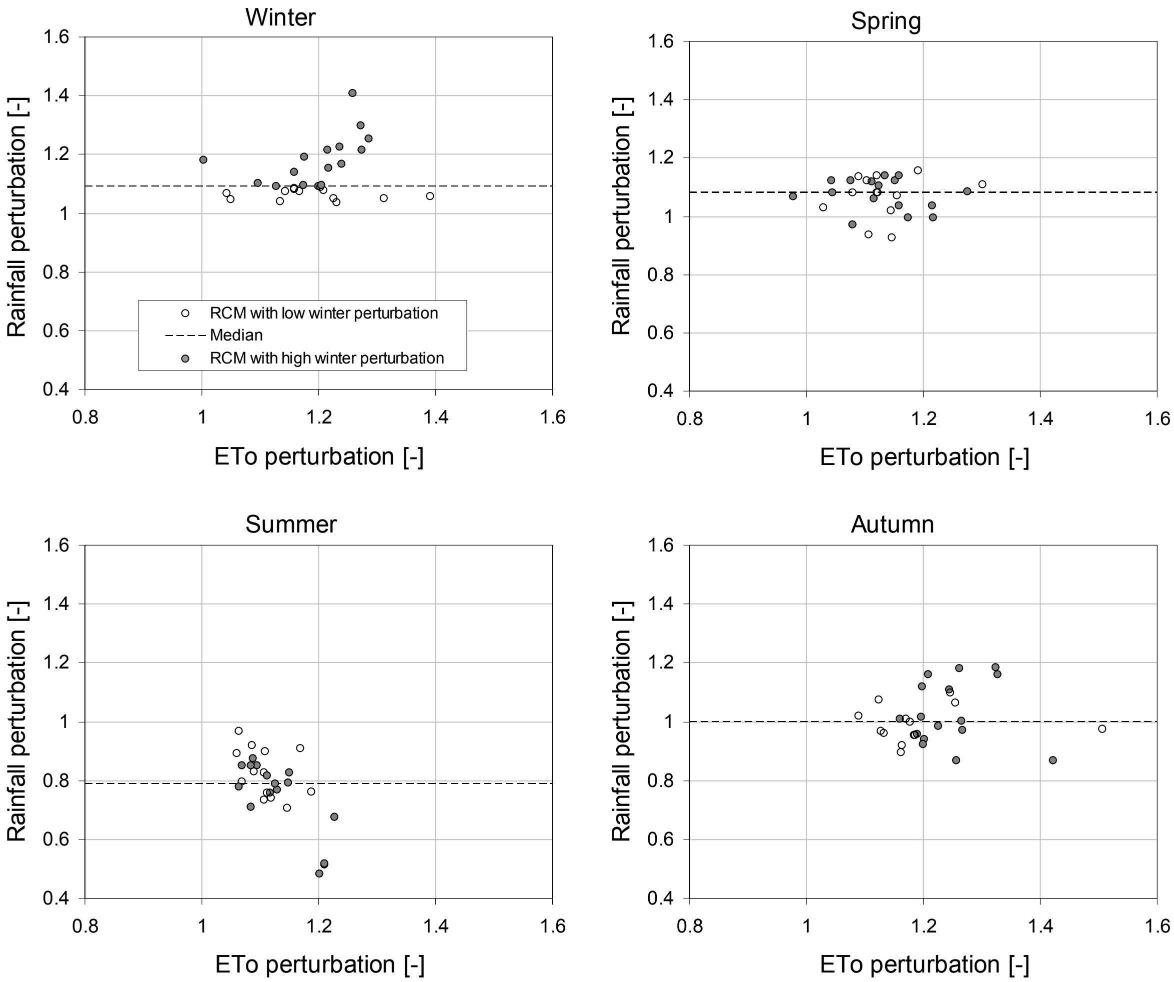


Figure 17: Seasonal tracking of rainfall and ETo perturbations (climatological seasons) to determine the potential ETo and rainfall combinations. Models that project high winter perturbations are tracked to determine how they respond across the other seasons.

Table VII: Seasonal correlations and scenario definition (climatological seasons).

Season	ETo	Rainfall	Scenario
Winter	High	High	High
Spring	Mean	Mean	
Summer	High	Low	
Autumn	Mean	Mean	
Winter	Mean	Mean	Mean
Spring	Mean	Mean	
Summer	Mean	Mean	
Autumn	Mean	Mean	
Winter	Low	Low	Low
Spring	Low	Mean	
Summer	Low	Low	
Autumn	Low	Mean	

The three climate change scenarios are defined as high, mean and low based on the expected hydrological high flow impacts. The definition is thus not dependent on the projected rainfalls alone. Rather it is based on the combined effect of the rainfall and

ETo; in other words, the variables are combined to generate an impact which can then be classified as high, mean and low.

The high scenario projects a future with wet winters and dry summers while the low scenario projects a future with dry winters and dry summers. Thus, it is expected that the risk associated with flooding is higher in the high scenario than the low scenario which is critical for low flows. In essence, the high, mean and low scenarios may be referred to as wet, mild and dry scenarios respectively. It is notable that the mean scenario represents mean conditions and is not the best future guess. We will consider all the three scenarios to account for the overall uncertainty. Figure 18 illustrates the relevance and interpretation of the scenarios.

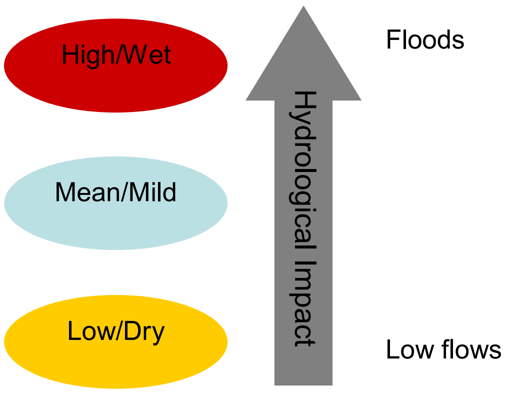


Figure 18: Relevance and interpretation of the CCI-HYDR scenarios.

Scenario scaling factors

As explained above, the PRUDENCE project mainly provides regional data for the SRES A2 and B2 scenarios. By definition, the A2 scenario is considered a medium-high scenario while the B2 scenario is taken as a medium-low scenario. These scenarios account for a limited range of the projections. Other scenarios are required to estimate the expected range of impacts for all the scenarios including the high scenarios (A1) and the low scenarios (B1). Due to various constraints, only a few scenarios from regional climate models exist to date but there are many available scenarios from global circulation models, which can provide a basis for estimating regional factors. By applying scaling factors, impacts for emission scenarios not available at regional scale could be estimated. For this project, the scaling approach involved a comparison of both the GCM and RCM estimates. The scaling factor was derived by comparing the range of perturbations of the RCMs to the range of perturbations of the GCMs (including additional scenarios).

From the IPCC AR4 database (Table III), rainfall series for the A1B, A2 and B1 scenarios were extracted. The monthly data from the database were analysed to estimate the seasonal perturbations for all the scenarios. The seasonal scale factors were preferred because at a seasonal scale it was expected that for the same scenario the projected changes for RCM based scenarios would fairly match those of the GCM based scenarios. Scaling requires a comparison of the GCM and RCM outputs. The scaling factor is estimated by comparing the range of perturbations of the RCMs to the range of perturbations of GCMs. The scaling is initially performed for rainfall and the ETo scaling is approximated from the correlation with rainfall. The correlation of rainfall and ETo perturbations are somewhat linear during the half-year winter and summer seasons. The scaling factors are derived based on the premise that the differences in the ranges are attributed to the emission scenarios A2, A1B, and B1, and the new GCM boundaries. One could argue that the A2 scenario for the GCMs has a minor contribution to the overall differences with the RCM range due the similarity in the emission scenario. Indeed based on only the A2 scenarios the RCM and GCM ranges are somewhat similar (Figure 19). Such an observation increases the confidence in the GCM data. Due to the adopted methodology for impact analysis which requires an estimate of the high, mean, and low scenarios, 3 scaling factors were derived (Table VIII).

The scenario scaling factors are applied to the time series at a seasonal scale; all the months of summer and winter are to be multiplied by the corresponding factor. Scaling factors were higher during the summer season with winter showing low changes (< 10%). The inclusion of more scenarios (A1B and B1) in the GCM predictions creates a significant difference in summer.

Table VIII: Seasonal scaling factors to account for extra scenarios A1B, B1 and GCM uncertainties.

Variable	Season	High	Mean	Low
	Winter	1.04	1.02	1.02
Rainfall	Summer	1.18	1.13	1.16
	Winter	1.17	1.10	1.08
ETo	Summer	0.83	0.87	0.84

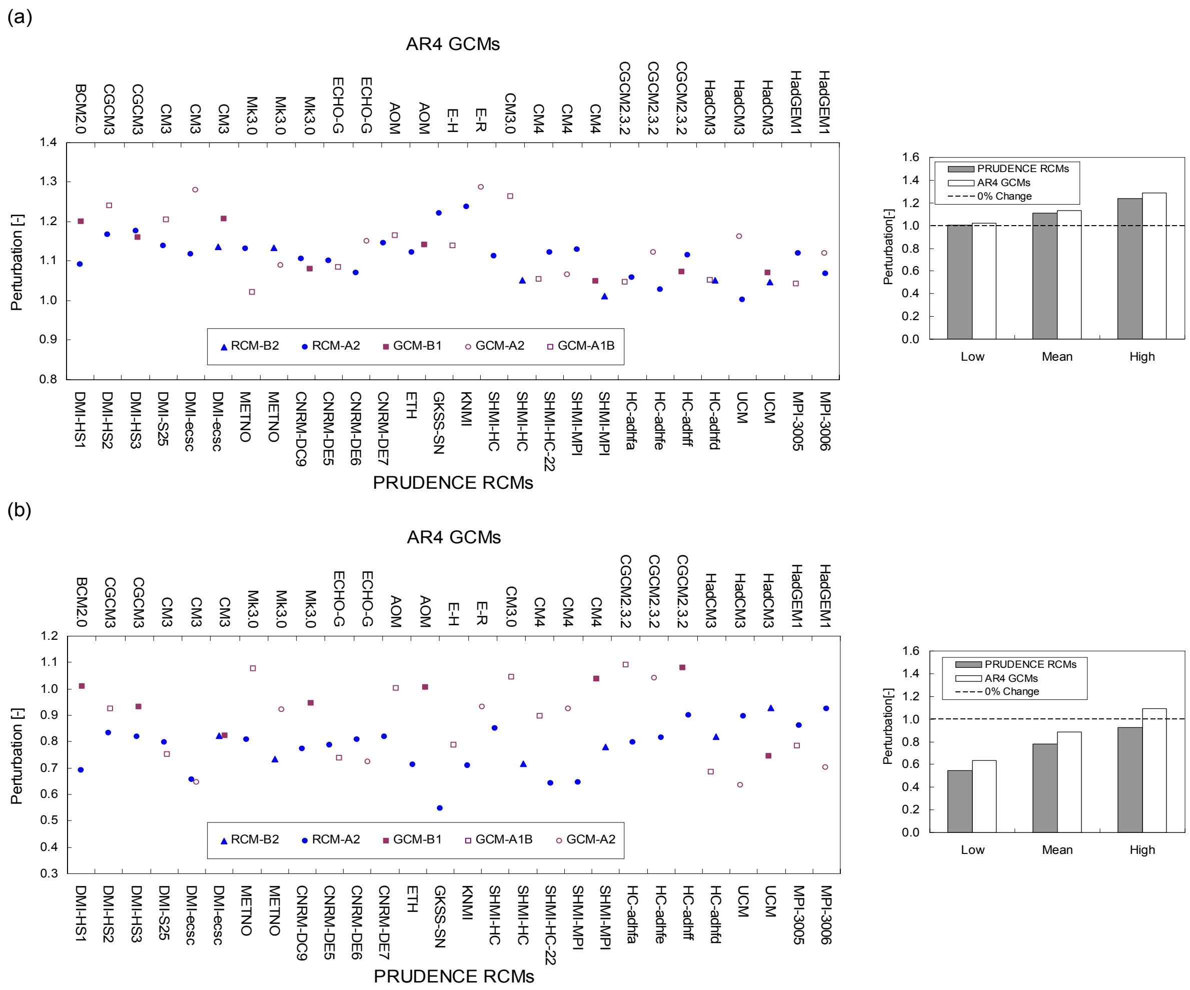


Figure 19: Perturbations (a–winter,b–summer) for seasonal rainfall. PRUDENCE RCMs and AR4 GCMs are shown on the left and the perturbation ranges are shown on the right. The scaling factors are estimated by comparing the RCM and the GCM ranges.

CCI-HYDR Perturbation Tool

Originally, the plan was to incorporate the scaling factors to the rainfall and ETo input series only for the hydrological models considered in the case-studies of this CCI-HYDR project. However, because several parallel impact studies have been started up by end users of this project (see also Section 3), the project partners considered it extremely useful to develop a software algorithm that can be applied by all hydrological modelers that use the CCI-HYDR climate change scenarios for their impact studies. A perturbation algorithm consequently was developed so that impact analysts in Belgium can more easily assess the hydrological impacts of climate change. The algorithm imparts a perturbation to observed series to generate future time series. The observed time series are perturbed on the basis of the high, mean and low climate change scenarios.

The algorithm developed and implemented in the perturbation tool perturbs or changes the input series of rainfall (mm) and ETo (mm), following the time series perturbation approach outlined above. The algorithm uses time series at hourly or daily time steps.

These are time scales relevant for river subbasins. The scenarios were developed mainly for catchments up to 1000 km^2. The time series perturbation procedure was primarily developed from the PRUDENCE regional climate models which mainly dealt with a 30 year control period of 1961-1990 and a 30 year scenario period of 2071-2100. Interpolation is made for other periods to account for potential differences between the period covered by the input series and the standard 1961-1990 control period. The use of a 30 year period would be ideal given that it covers exactly the length of the climate model control and scenarios periods. Also, a 30 year period corresponds to an average climate "oscillation'' cycle (see section 2.1, or see Ntegeka and Willems, 2008). Perturbed series can also be conducted for shorter or longer periods, but the rainfall-runoff modeller has to keep in mind that the results may be biased from the long-term averaged climate. Due to the oscillations, the impact will be overestimated if the input series period covers an oscillation peak and underestimated when it covers an oscillation low.

The output series is the perturbed input series for a given time horizon in the future. Target years of 2020, 2030, 2040, 2050, 2060, 2070, 2080, 2090, and 2100 can be selected. Each target year is in the centre of a 30 year block e.g., 2050 represents changes from 2036-2065. Thus, no predictions are made for a particular year or day in the future. It is important to emphasize that the future changes are most reliable if the observed data input is 30 years and covering the period 1961-1990. Since the modelled future scenario period was 2071-2100, the changes during the target years within the block, i.e., 2070, 2080 and 2090, would also be more reliable. For other target years, the interpolation and extrapolation of the changes leads to less certain future perturbations.

In the original version of the CCI-HYDR Perturbation Tool, only scenarios for rainfall and ETo were involved. The tool in the mean time has been extended to include scenarios for temperature and wind speed, developed by the project "Klimaatscenario's voor Vlaanderen" for INBO (Instituut voor Natuur- en Bosonderzoek) (Demarée et al., 2008; Baguis et al., 2008; see the full references to these reports in Section 3).

2.3 Hydrological impact investigations along Belgian rivers

The impact of the climate change scenarios, developed in Phase 1 of the project, on flood and low flow risk along rivers has been quantified. This has been done making use of hydrological or combined hydrological – hydraulic models.

The impact modeling has been done at two scales: the larger scale of the entire basin, and the subbasin scale. Study regions are the Meuse and the Scheldt river basins. For the larger scale applications, less detailed coarse-scale models have been applied, while more detailed fine-scale models have been used at the subbasin scale. For the large scale applications, use was made of the SCHEME model of the RMI, which has been designed before for the purpose of climate change impact modelling for both the Meuse basin (Roulin et al., 2001) and the Scheldt basin (Roulin and Arboleda, 2002) during a previous BELSPO (SSTC) – Global Change project.

Also for the smaller subbasin scale applications, the SCHEME model was used (for comparing the results with the larger scale application in a consistent way), and complemented by more fine-scale models of the type currently used by the responsible water authorities and used for decision support within the current water management activities. Given the hydrological and hydrodynamical modeling experience previously built up by K.U.Leuven, and the link with the projects ADAPT and SUDEM-CLI, the subbasins of Dender and Grote Nete & Grote Laak were selected as pilot cases for the local scale hydrological impact study. For these subbasins, the hydrological impact analysis was done with coupled hydrological-hydrodynamic models. Next to these pilot cases, the local hydrological impact investigation has been extended to a total of 67 subbasins in the Scheldt river basin, in cooperation with the Flanders Hydraulics authority (member of the CCI-HYDR Follow-up Committee. For the latter extended analysis, the local models developed by the Flanders Hydraulics authority have been applied.

For each of these cases, the rainfall and evapotranspiration input series of the hydrological models have been modified (perturbed) according to the climate change scenarios developed in Phase 1 of the project (see section 2.2; thus making use of the CCI-HYDR Perturbation Tool). After perturbation of these series, the hydrological model simulations have been performed again (long-term simulation), the long-term time series of rainfall runoff model results processed statistically (extreme value analysis at the different aggregation levels), the QDF relationships recalculated, and also the hydraulic model simulated again.

Hydrological models

All hydrological simulations performed by the RMI for the needs of the project make use of the SCHEME hydrological model. This is the distributed version of the IRMB conceptual model (Bultot and Dupriez, 1976) and is designed to simulate a variety of basins and hydrological conditions in the river Scheldt and Meuse Basins in Belgium and upstream in France (Roulin et al, 2001, 2002); it is also used in mid-range streamflow forecasts (Roulin and Vannitsem 2005). The horizontal resolution of the model is 7 km x 7 km and 9 different land covers are taken into account in the calculations. There is a snow accumulation and melting module. The actual evapotranspiration is calculated on the base of the water intercepted by the vegetation and the water content of two soil layers, as well as the potential evapotranspiration according to the Penman formula. Surface water is simulated with a unit hydrograph and the underground water is represented with two reservoirs. The streamflow produced on each grid cell is routed to the outlet with a 1D submodel taking into account the river network.

The input meteorological variables used by the SCHEME hydrological model have to be organized in a special vector format and stored in binary files, which are machine-specific. The tools to create and manipulate such files have been developed in the RMI. The set of binary files used as input in the hydrological model for a certain period of time is organized by date. In this way, for each day of the given period, we have one file containing the values of all the necessary meteorological variables for each grid cell of the model over each (sub)basin. This time-ordered series of binary files embodying spatial meteorological information is the database needed in order to perform hydrological simulations using the SCHEME model. In practice, we have two sets of binary files to store data extending to the same period of time, one for the precipitation and another one for the rest of meteorological variables. These variables are: (1) cloud covering, (2) temperature, (3) wind speed, (4) humidity, (5) radiation, (6) water vapor pressure. For the needs of the project, we had to update the database for the river Meuse basin. In this process, we used data from Belgian and French stations covering the basin. The interpolated fields have been calculated using the Thiessen polygon method for precipitation and using weights depending on the inverse of the square of the distance from the stations for the other meteorological variables.

The studied catchments are presented in Figure 20 and their characteristics in Table IX. It is worth mentioning here that the model does not take explicitly management actions into account.

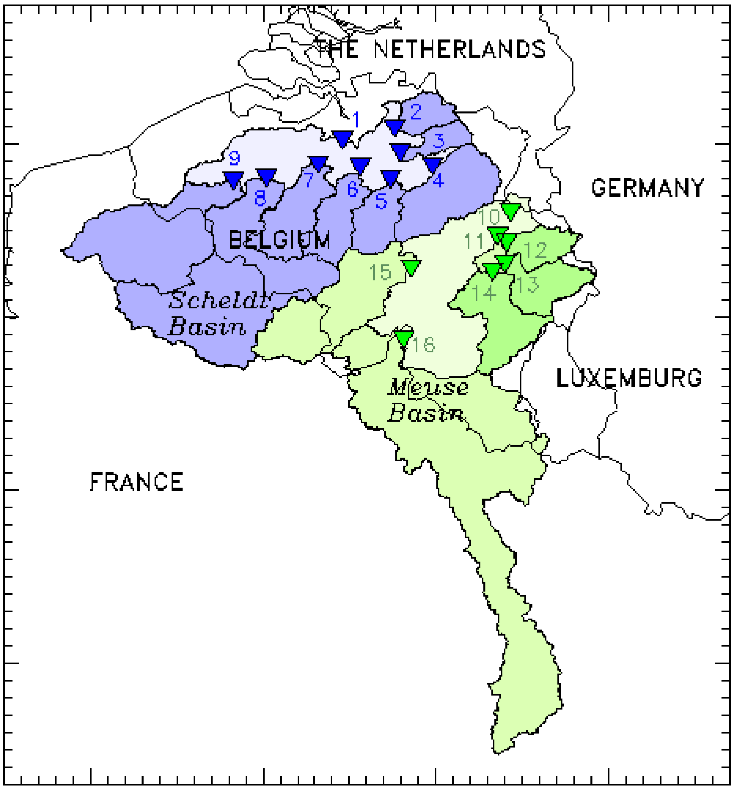


Figure 20: Map of studied catchments.

Table IX: Subbasin area and actual land use (percentage of deciduous forest, coniferous forest, grassland, crops and urban areas).

	Watershed	Outlet	Area (km^2)	Dec.	Con.	Grass	Crops	Urban
Scheldt Basin								
1	Scheldt	Antwerp	18801	10.1	2.0	29.4	51.8	6.2
2	Kleine Nete	Grobbendonk	590	10.3	17.3	40.8	24.4	5.8
3	Grote Nete	Hulshout	468	12.8	14.2	47.9	16.8	7.0
4	Demer	Diest	1908	14.4	3.6	29.2	46.4	5.7
5	Dijle	Wilsele	896	14.9	4.2	24.5	48.7	7.4
6	Zenne	Eppegem	1096	11.1	0.9	34.6	41.8	11.5
7	Dender	Confluence	1389	9.5	0.4	35.4	49.4	5.3
8	Bovenschelde	Asper	5810	9.2	0.2	24.0	61.8	4.4
9	Leie	St Baafs	3506	6.6	0.1	20.3	66.2	6.6
Meuse Basin								
10	Meuse	Visé	20588	29.1	10.8	33.2	24.4	2.2
11	Ourthe	Angleur	3627	22.5	24.7	38.8	11.3	2.5
12	Vesdre	Confluence	708	20.6	25.7	40.7	7.6	5.1
13	Amblève	Martinrive	1068	19.3	31.2	42.7	5.1	1.7
14	Ourthe	Tabreux	1616	22.1	22.4	35.8	15.2	1.5
15	Sambre	Namur	1964	18.9	1.3	39.8	35.2	4.4
16	Meuse	Chooz	10120	35.7	8.1	31.7	23.5	0.9

For the local scale hydrological impact investigations along the basin of Grote Nete – Grote Laak, three different hydrological models have been implemented: two lumped conceptual rainfall-runoff models (NAM and VHM), and a detailed physically based and spatially distributed hydrological model (MIKE-SHE: DHI, 2008). The MIKE-SHE model considers the hydrological processes (kinematic wave equation for overland flow, Richard’s equation for the unsaturated zone and 3 dimensional finite differences method applied to Darcy’s law) at a 500m grid size (Figure 21).

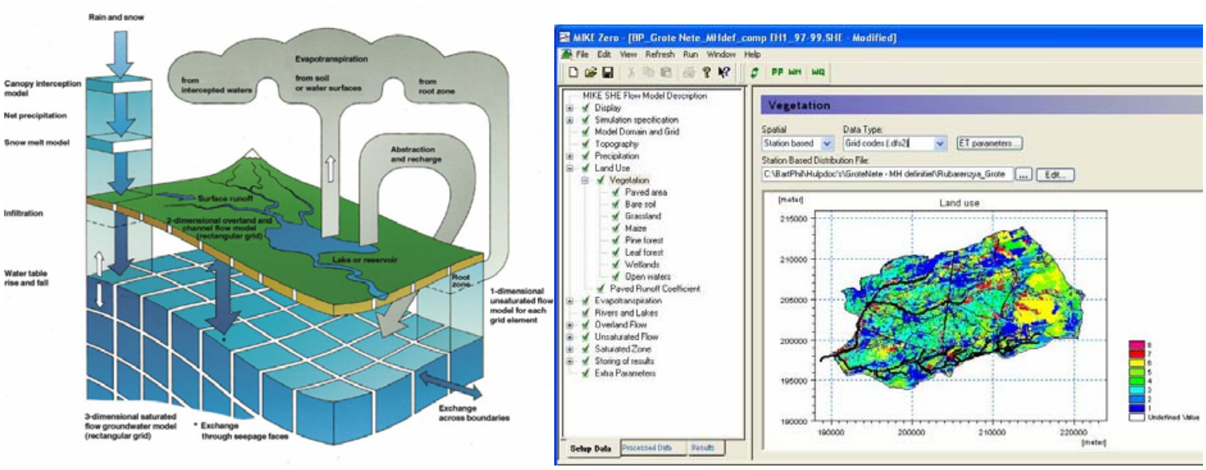


Figure 21: Spatially distributed and detailed physically-based hydrological model set up for the Grote Nete – Grote Laak river basin.

Model calibration and validation has been done applying split-sample test to the available hourly river flow series (Figure 22) and groundwater well piezometric levels (Figure 23 and Figure 24).

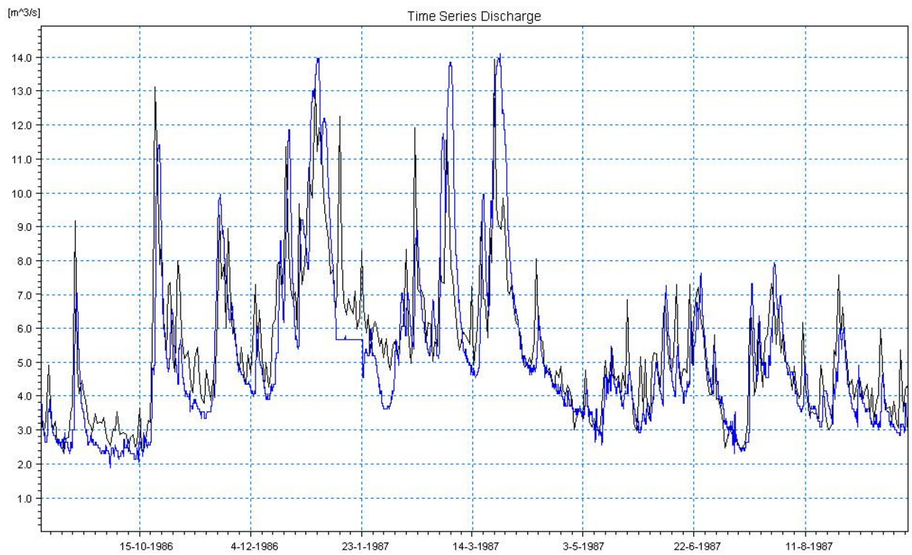


Figure 22: Validation of the hourly river flow series downstream the Grote Nete basin (at Varendonk / Geel-Zammel; observed series in blue; MIKE-SHE model simulation results in black; only 1 year shown).

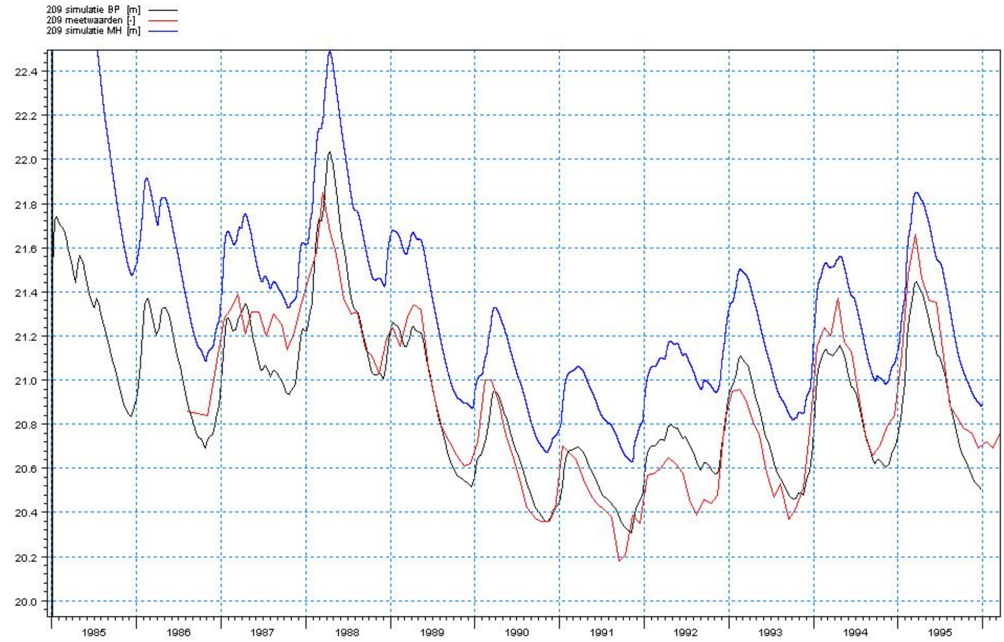


Figure 23: Validation of the groundwater levels at piezometer nr. 209 (observed series in red; MIKE-SHE model simulation results before calibration in blue, after calibration in black).

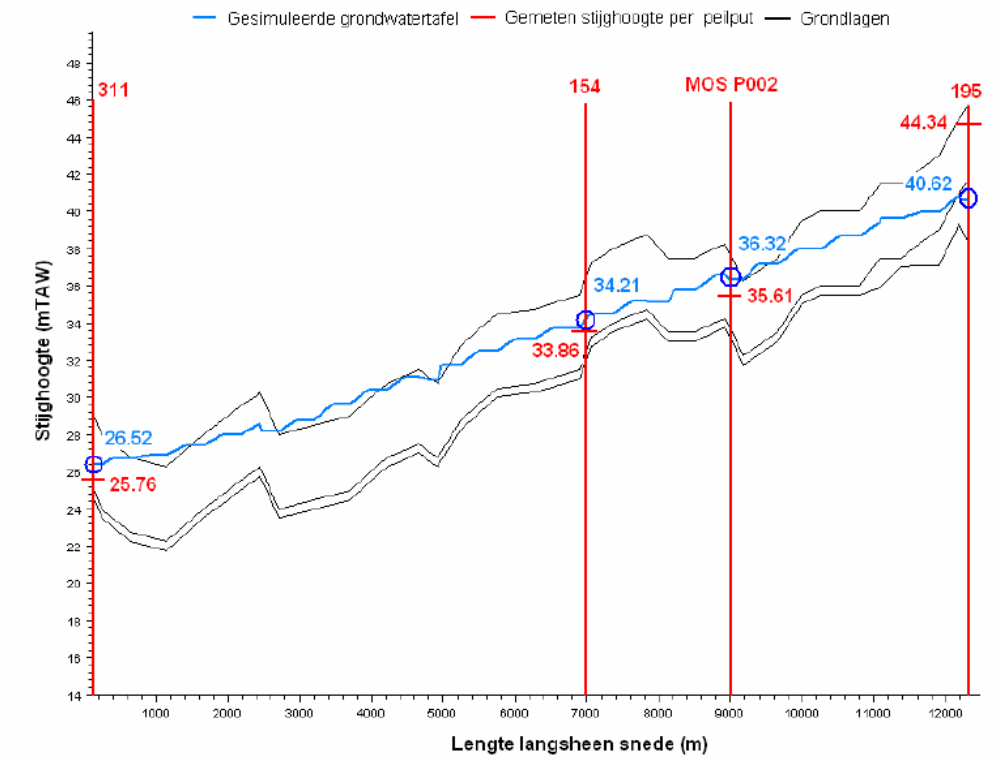


Figure 24: Validation of the groundwater levels along a transect crossing the river basin (observed values in red; MIKE-SHE model simulation results after calibration in blue).

In all local scale cases, catchment rainfall-runoff results have been simulated as input in detailed river hydrodynamic models (full hydrodynamic models implemented in MIKE11 (DHI, 2008) considering river cross-sections approx. each 50m and most bridges, weirs, culverts and hydraulic regulation structures). The river floodplains have been modeled using a quasi-2D approach (Willems at al., 2002) based on a 4m (Dender) and 10m (Grote Nete and Grote Laak) digital elevation model.

Analysis of the impact of non-meteorological trends

Apart from the trends in the rainfall and the evapotranspiration, other factors can contribute to the trends or changes in the river discharges. In particular, land use changes can have big impact in the hydrological balance of a region. We have tested the SCHEME model sensitivity in such changes by varying sufficiently the land occupation in order to include some important cases. This would help to acquire an estimation of the changes in the hydrological regime of the rivers of Belgium under specific land use change scenarios.

We have considered two categories of land use change: (1) expansion of existing urban areas from 0% up to 25% of the basin area with proportional decrease of the other land occupations, and (2) occupation at 100% of the available land by conifers only or grassland only. For each case, we calculate the mean streamflow and the exceedance frequencies of certain thresholds defining low or high flows. The thresholds used here are the 0.05 and the 0.95 percentiles of the control streamflow series. Based on these, we can obtain the average number of days per month with low or high flow. The results are presented graphically for a selection of outlets. These are Antwerp (Scheldt) and Diest (Demer) for the Scheldt basin, and Visé (Meuse) and Tabreux (Ourthe) for the Meuse basin. For the rest of the outlets studied, we provide a synopsis in tables (Table X, XI, XII).

As far as the mean streamflow is concerned, we observe everywhere an increase as the urban areas are expanded, due to decreased ETo. In particular, inside the 0-25% limits of urbanization considered here, the SCHEME model response is linear. For almost all the catchments, the streamflow increase is close to 16 mm/year per 5% of urban area increase. The same rate was found in Bultot et al. (1990) for the small catchment of the Houille in Southern Belgium. In the experiments with the natural covers (100 % conifers and 100% grassland), the qualitative features of the model output depend on the basin. In the river Scheldt basin, the mean streamflow appears decreased with respect to the control situation when only conifers or only grassland are present; in the Meuse river basin, in almost all cases the grassland experiment leads to increased streamflow while the conifers experiment leads to decreased streamflow.

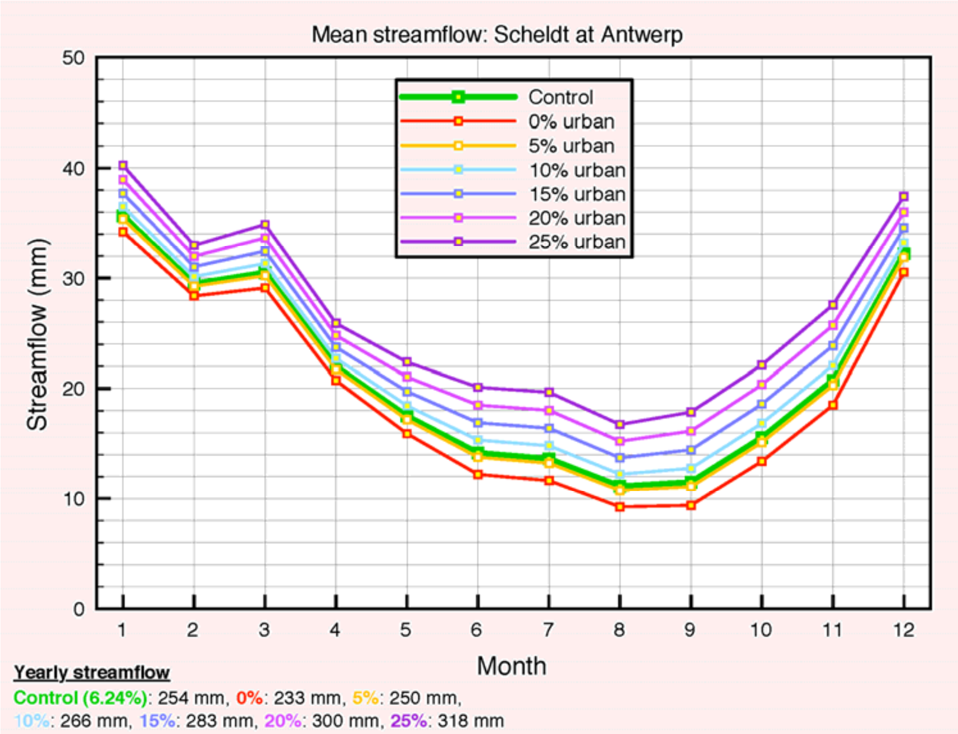
The low flow frequencies (0.05 percentile) can have a very large variation in the 0-25% interval of urban expansion of the sensitivity test conducted, and this is related to a non-linear response of the SCHEME model in this variable. This is true for the two basins considered here. In all cases this frequency decreases as the urban zones area in the basin increases. When only natural cover in the basin is considered, we find low flow frequencies higher than in the control case (especially high in the conifers case and in the Scheldt basin), due to increased ETo.

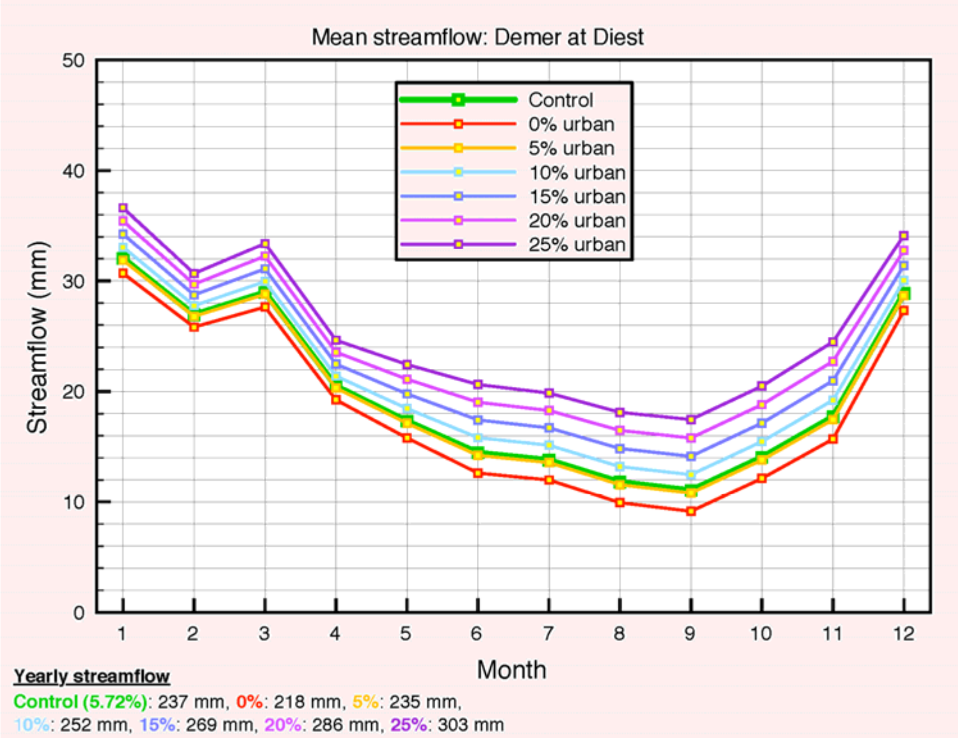
A different behavior of the SCHEME model is observed in the high flow frequency (0.95 percentile). Indeed, while this frequency exhibits a relatively high sensitivity to urban area changes in several outlets of the Scheldt basin, it is quite stable in the outlets of the Meuse basin. This is clearly represented graphically in Figure 27 for selected outlets and in a synoptic way for all outlets in Table XII. Also, when only natural cover is present, the results again differ qualitatively between the two basins. In the Scheldt basin, 100% conifers or grassland implies in almost all outlets a decrease in the frequency of high flow days, while in the Meuse basin we can have increase (100% grassland) or decrease (100% conifers).

Investigating the relative differences between the hydrological profiles of catchments over Belgium was part of the more general analysis for the River Scheldt and Meuse Basins in this phase of the project.

Table X: Yearly streamflow (in mm) for land use change sensitivity simulations.

		Control	Urban expansion						100% nature	
			0 %	**5 %**	**10 %**	**15 %**	**20 %**	**25%**	**100% conifers**	**100% grass-land**
Scheldt	Scheldt at Antwerp	254	233	250	266	283	300	318	204	234
	Scheldt at Asper	243	229	245	260	276	292	308	196	227
	Demer at Diest	237	218	235	252	269	286	303	196	222
	Dijle at Wilsele	271	245	262	280	298	316	334	213	249
	Kleine Nete at Grobbendonk	294	274	291	308	325	342	359	255	282
	Leie at St Baafs	238	217	233	249	265	283	300	182	211
	Zenne at Eppegem	289	246	265	283	302	321	339	219	249
Meuse	Meuse at Chooz	481	478	492	508	526	546	568	442	488
	Ourthe at Angleur	512	505	519	534	549	565	582	472	525
	Ourthe at Tabreux	479	475	489	503	517	532	546	445	494
	Sambre at Namur	388	377	389	402	414	426	441	335	381
	Meuse at Visé	456	450	464	478	493	511	530	414	461


Mean streamflow: Scheldt at Antwerp
Control
0% urban
5% urban
10% urban
15% urban
20% urban
25% urban
Streamflow (mm)
Month
Yearly streamflow
Control (6.24%): 254 mm, 0%: 233 mm, 5%: 250 mm,
10%: 266 mm, 15%: 283 mm, 20%: 300 mm, 25%: 318 mm


Mean streamflow: Demer at Diest
Control
0% urban
5% urban
10% urban
15% urban
20% urban
25% urban
Streamflow (mm)
Month
Yearly streamflow
Control (5.72%): 237 mm, 0%: 218 mm, 5%: 235 mm,
10%: 252 mm, 15%: 269 mm, 20%: 286 mm, 25%: 303 mm

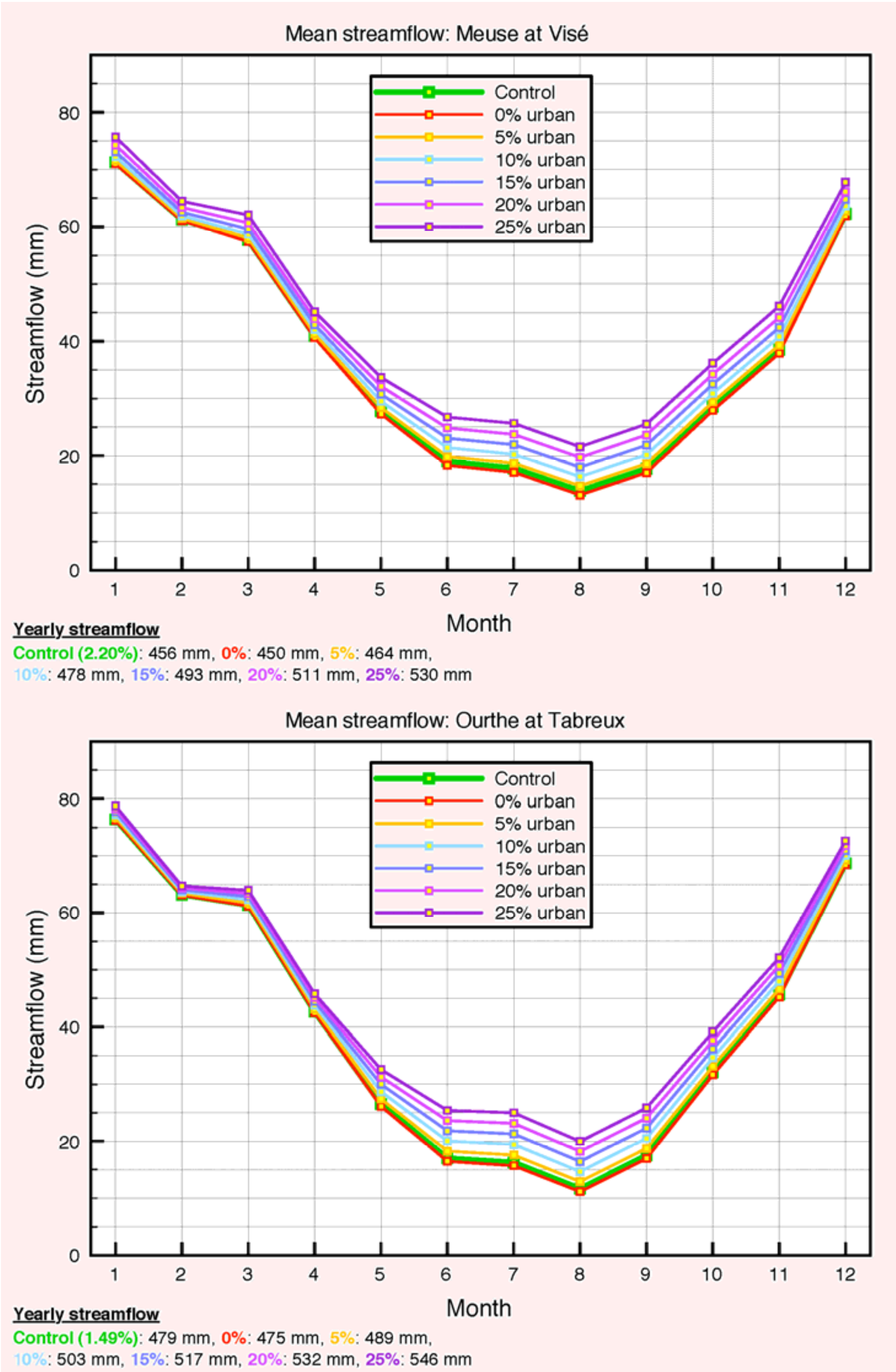
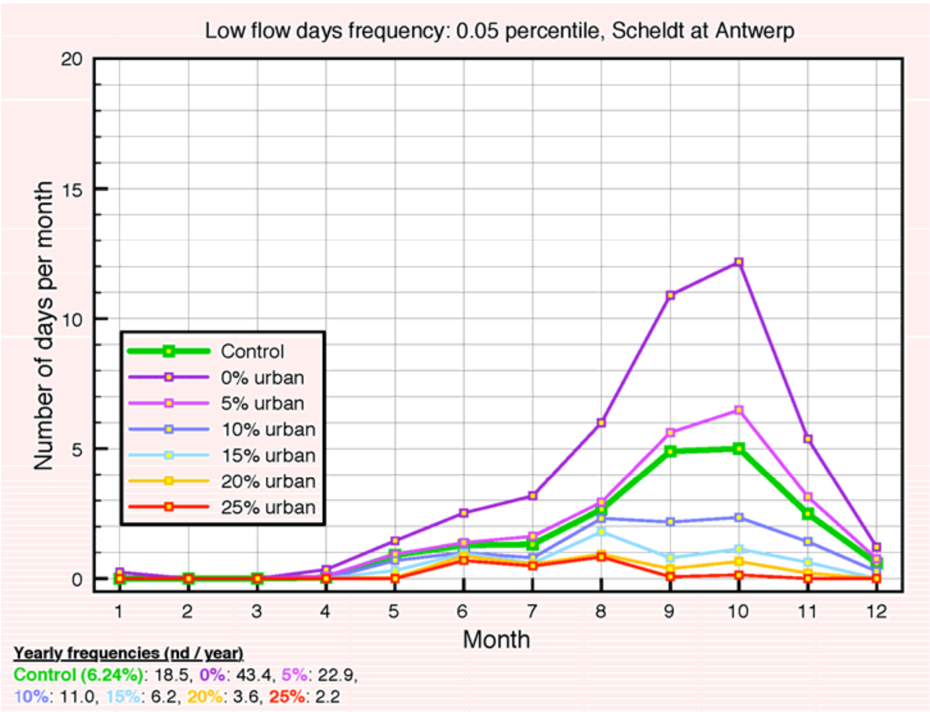
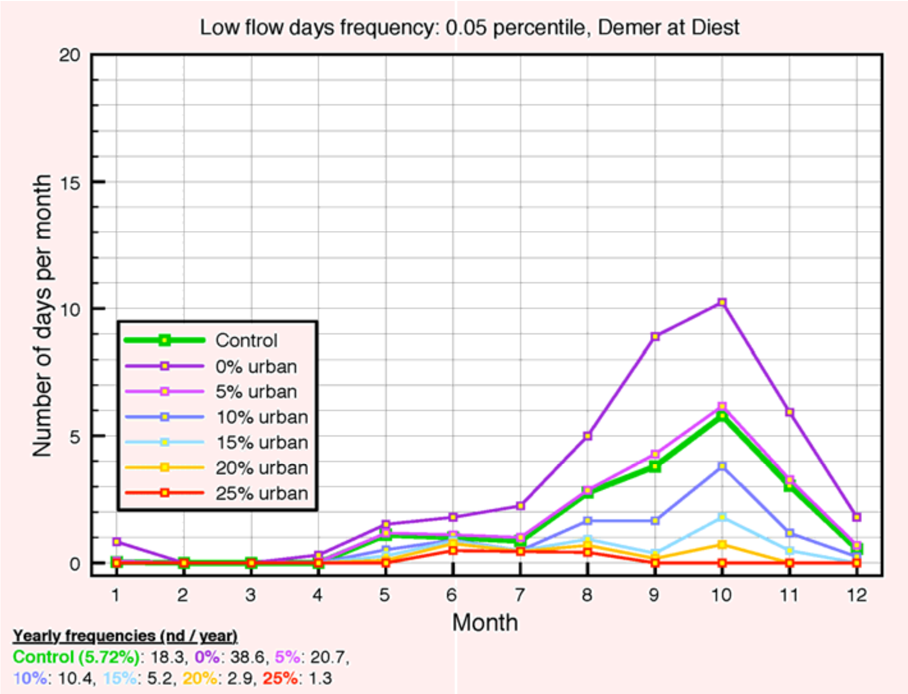


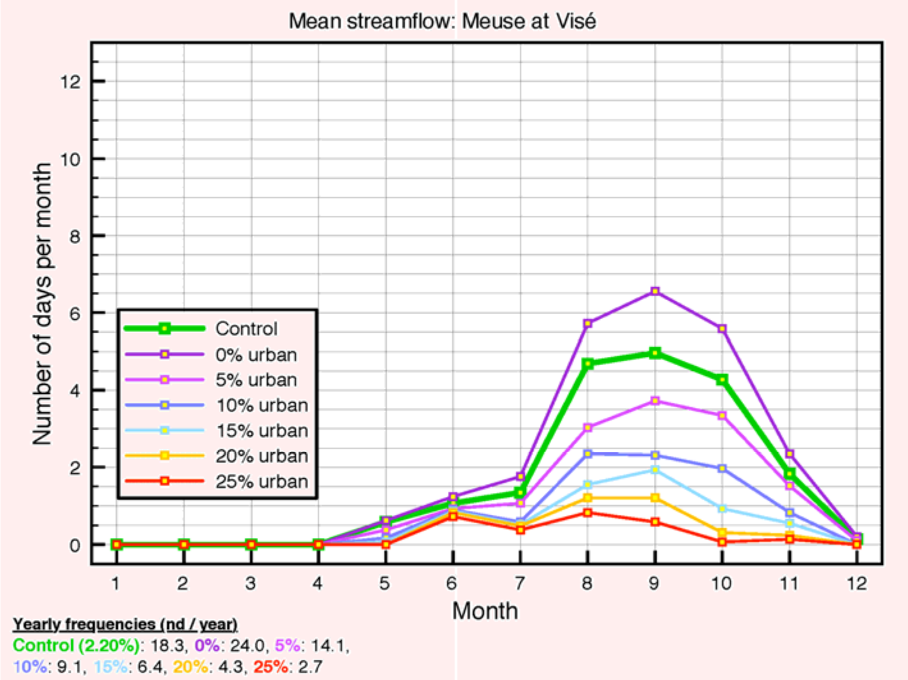
Figure 25: Sensitivity of mean streamflow under land-use change for selected outlets in the Scheldt and Meuse basins.

Table XI: Yearly frequencies (number of days/year) of low flow days for land-use change sensitivity simulations.

		Control	Urban expansion						100% nature	
			0 %	**5 %**	**10 %**	**15 %**	**20 %**	**25%**	**100% conifers**	**100% grass-land**
Scheldt	Scheldt at Antwerp	18.5	43.4	22.9	11.0	6.2	3.6	2.2	59.8	38.6
	Scheldt at Asper	18.4	39.1	17.4	7.8	4.3	2.2	1.0	53.8	32.9
	Demer at Diest	18.3	38.6	20.7	10.4	5.2	2.9	1.3	53.9	34.2
	Dijle at Wilsele	18.4	28.9	20.8	17.4	15.1	13.4	12.0	68.1	26.8
	Kleine Nete at Grobbendonk	18.3	37.0	20.6	11.3	6.5	4.4	3.7	47.0	30.8
	Leie at St Baafs	18.5	50.6	24.1	11.2	4.5	1.5	0.8	67.5	46.6
	Zenne at Eppegem	18.4	56.3	34.7	21.8	13.8	8.5	5.4	88.3	51.5
Meuse	Meuse at Chooz	18.5	21.0	12.4	7.6	4.7	2.7	1.6	32.7	17.4
	Ourthe at Angleur	18.4	26.9	15.9	11.9	9.4	7.0	4.9	39.6	20.8
	Ourthe at Tabreux	18.3	22.9	12.8	8.3	4.8	2.4	1.1	35.4	18.9
	Sambre at Namur	18.4	26.7	18.2	12.5	9.2	6.9	4.7	44.4	22.9
	Meuse at Visé	18.3	24.0	14.1	9.1	6.4	4.3	2.7	38.6	19.9




Low flow days frequency: 0.05 percentile, Demer at Diest
Number of days per month
Month
Control
0% urban
5% urban
10% urban
15% urban
20% urban
25% urban
Yearly frequencies (nd / year)
Control (5.72%): 18.3, 0%: 38.6, 5%: 20.7,
10%: 10.4, 15%: 5.2, 20%: 2.9, 25%: 1.3


Mean streamflow: Meuse at Visé
Number of days per month
Month
Control
0% urban
5% urban
10% urban
15% urban
20% urban
25% urban
Yearly frequencies (nd / year)
Control (2.20%): 18.3, 0%: 24.0, 5%: 14.1,
10%: 9.1, 15%: 6.4, 20%: 4.3, 25%: 2.7

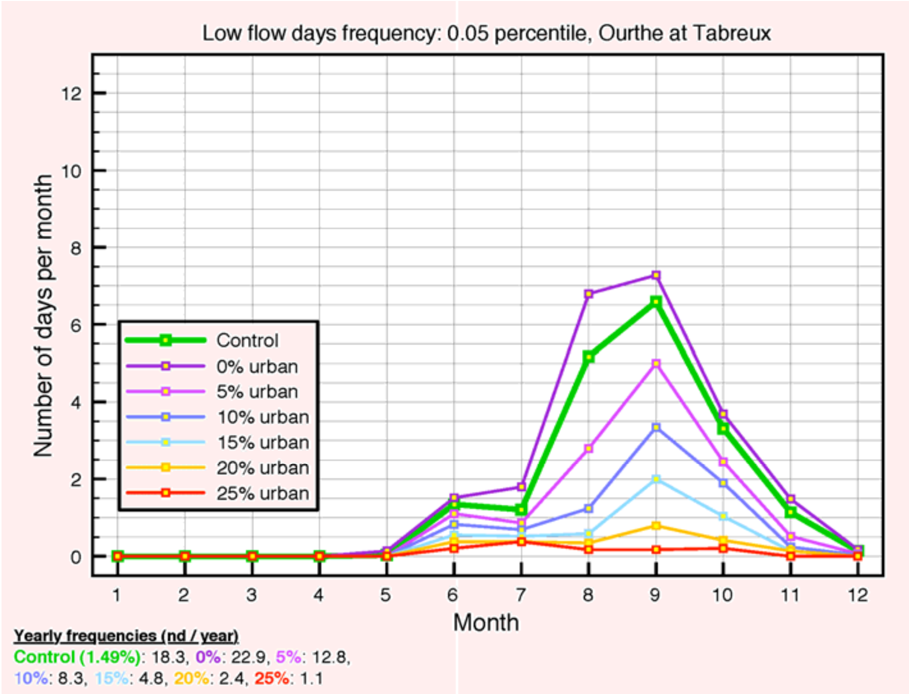
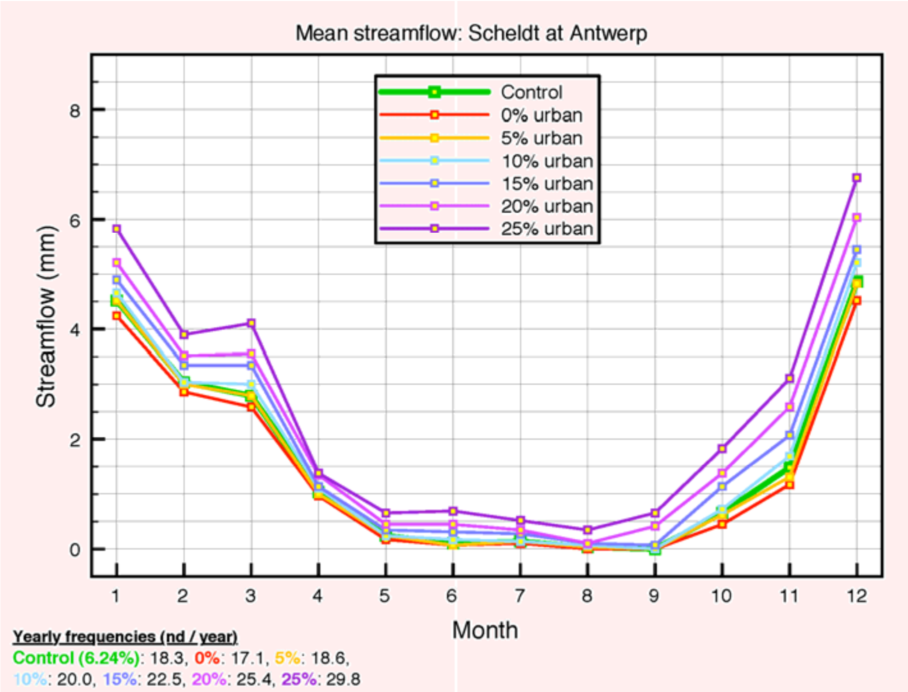
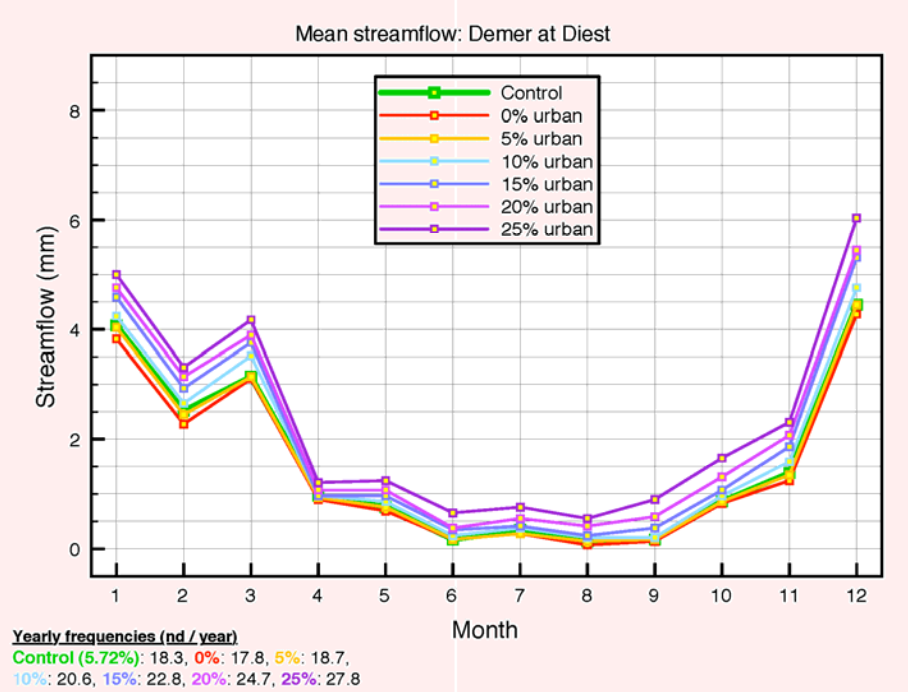


Figure 26: Sensitivity of low flow days frequency under land-use change for selected outlets in the Scheldt and Meuse basins.

Table XII: Yearly frequencies (number of days/year) of high flow days for land-use change sensitivity simulations.

		Control	Urban expansion						100% nature	
			0 %	**5 %**	**10 %**	**15 %**	**20 %**	**25%**	**100% conifers**	**100% grass-land**
Scheldt	Scheldt at Antwerp	18.3	17.1	18.6	20.0	22.5	25.4	29.8	12.4	16.6
	Scheldt at Asper	18.3	18.6	19.0	21.0	23.1	25.9	29.7	12.7	17.6
	Demer at Diest	18.3	17.8	18.7	20.6	22.8	24.7	27.8	14.1	17.9
	Dijle at Wilsele	18.3	13.2	16.4	22.1	28.9	36.0	44.0	9.8	13.5
	Kleine Nete at Grobbendonk	18.3	18.3	18.7	19.4	20.3	22.6	24.8	15.4	19.0
	Leie at St Baafs	18.3	17.3	18.4	20.4	23.6	28.2	34.1	11.7	16.0
	Zenne at Eppegem	18.3	13.6	15.0	17.7	21.3	25.4	29.9	10.7	13.8
Meuse	Meuse at Chooz	18.3	18.9	19.1	19.3	20.1	21.3	22.3	16.5	19.1
	Ourthe at Angleur	18.3	19.0	19.0	18.8	19.3	19.7	20.2	17.6	20.0
	Ourthe at Tabreux	18.3	18.9	19.0	19.1	19.1	19.2	19.9	17.3	20.1
	Sambre at Namur	18.3	18.9	18.8	19.2	19.4	20.0	21.2	14.0	18.9
	Meuse at Visé	18.3	18.9	19.1	18.9	19.3	20.1	21.7	15.9	19.5


Mean streamflow: Scheldt at Antwerp
Control
0% urban
5% urban
10% urban
15% urban
20% urban
25% urban
Streamflow (mm)
0
2
4
6
8
1
2
3
4
5
6
7
8
9
10
11
12
Month
Yearly frequencies (nd / year)
Control (6.24%): 18.3, 0%: 17.1, 5%: 18.6,
10%: 20.0, 15%: 22.5, 20%: 25.4, 25%: 29.8


Mean streamflow: Demer at Diest
Control
0% urban
5% urban
10% urban
15% urban
20% urban
25% urban
Streamflow (mm)
0
2
4
6
8
1
2
3
4
5
6
7
8
9
10
11
12
Month
Yearly frequencies (nd / year)
Control (5.72%): 18.3, 0%: 17.8, 5%: 18.7,
10%: 20.6, 15%: 22.8, 20%: 24.7, 25%: 27.8

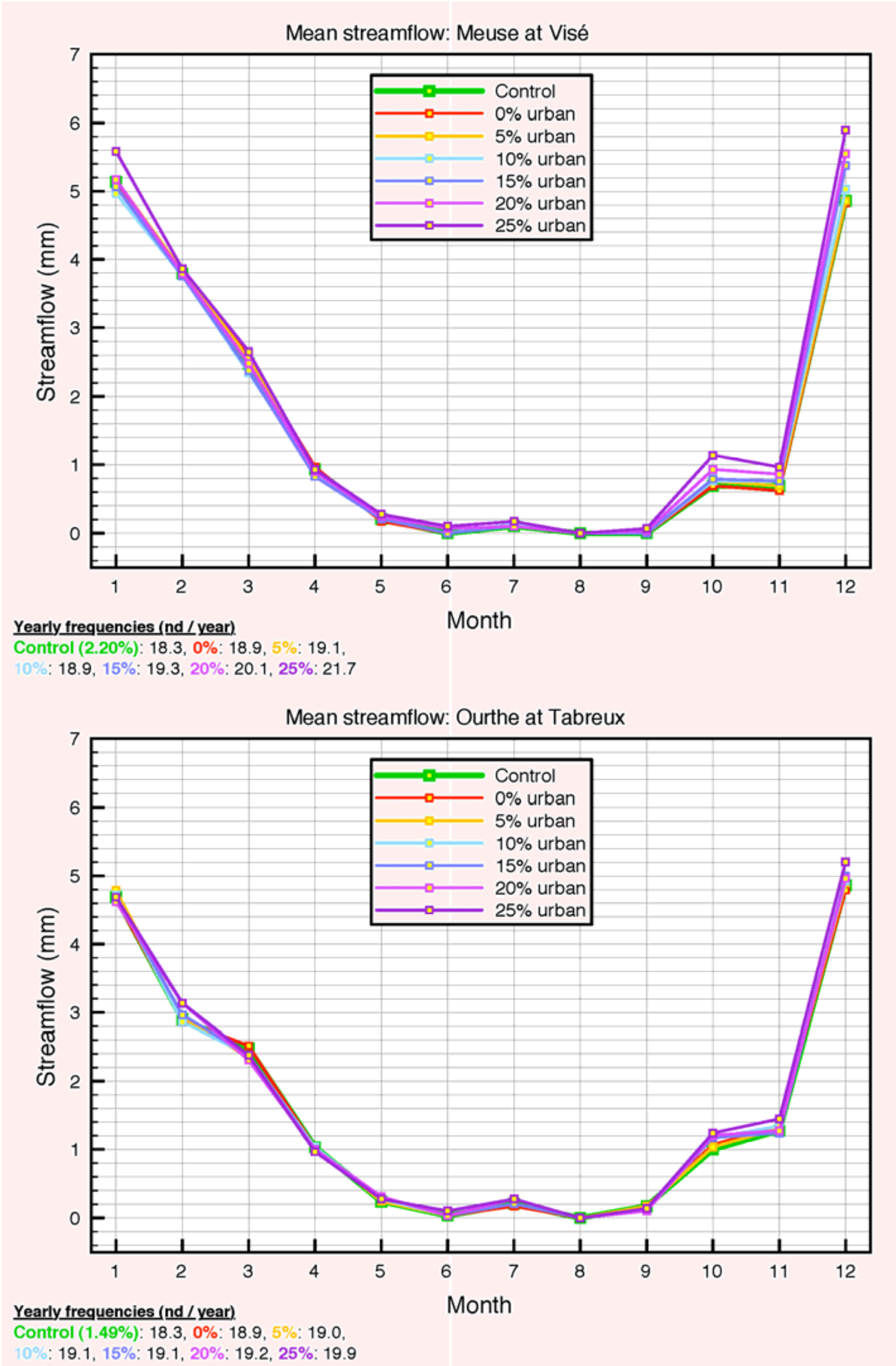


Figure 27: Sensitivity of high flow days frequency under land-use change for selected outlets in the Scheldt and Meuse basins.

At the local scale of the basin of Grote Nete – Grote Laak, impacts of non-meteorological trends have been studied by means of the MIKE-SHE model. Increases from 0% to 6% in the urban area were simulated in that model. This range encompasses the value discussed in Vazquez et al. (2004), which is based on both the comparison of different land use maps and data from the Belgian National Institute for Statistics (NIS): average increase in the paved area with 0.4% per year during the last 15 to 20 years. This value was implemented in the MIKE SHE model by increasing the urban-paved area fraction up to 7.7 % of the total catchment area, representing a 15 years period.

For generating the land cover (LC) trends, the fraction of urban-paved (i.e. completely impermeable) area was varied. The LC input in the MIKE-SHE model was based on the LC map of the Flemish Region and Brussels, developed by DWTC-VLM-OC-KULeuven in 1995. This map has a grid resolution of 20m and was re-sampled from the DWTC-1995 original resolution to the model grid resolution. The urban-unpaved 20m pixels were taken into account for defining the map at the model grid resolution, depicting the likelihood of the grid cells to become urban-paved. The likelihood measures were defined on the basis of the frequency of 20m urban-unpaved pixels falling into every model grid cell. In this way, an urban-unpaved model grid cell having a higher frequency of 20m unpaved-urban pixels was treated as having a higher likelihood of becoming urban-paved. Figure 28 depicts the likelihood distribution and the resulting relationship between the percentage of urban-paved areas and the predicted overland flow volumes. The figure depicts that the predicted overland flow volumes increase with a linear tendency in relation to the percentage of change in urban-paved area. This percentage of change in urban-paved area is expressed with respect to the catchment area. In the second plot of Figure 28, an urban-paved change of about 7.7% represents, in average terms, a 15-years trend in LC. It is found that the annual overland flow volumes linearly increase with the paved area change. This is consistent with the linear increase of the annual total runoff volumes found on the basis of the SCHEME model results.

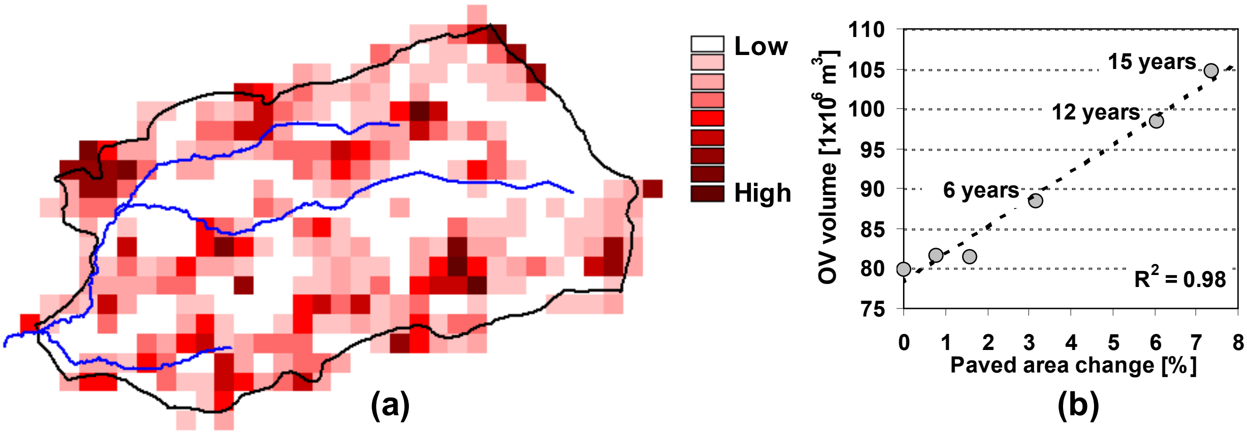


Figure 28: (a) Likelihood of an unpaved MIKE-SHE grid cell for becoming paved; and (b) variation of the predicted overland flow in relation to the changes in urban-paved (impermeable) area in the Grote Nete – Grote Laak basin.

Simulation of climate change scenarios

Based on the perturbations to the rainfall and ETo series, the impact of the climate change scenarios on the hydrological responses of the river subbasins considered in the case-studies were investigated. The hydrological simulation results were processed and compared to the original results (representing current conditions) in terms of hydrological extremes. For the local scale hydrological impact investigations, the following steps have been followed:

- Long-term simulation of the hydrological models for the current climate and for the high, mean and low climate change scenarios. This leads to hourly runoff series since 1986.
- Extraction of high runoff peaks from these long-term runoff series through a Peak Over Threshold (POT) method and for different time scales ranging from 1 hour to 15 days (method described in Willems, 2008); idem for low flow extremes.
- Analysis of the change in high and low runoff extremes in function of the time scale and the return period (mean recurrence interval between two extremes).
- Similar analysis of the overland flow and actual evapotranspiration volumes.

Example of the change in hourly runoff peaks in function of the return period is shown in Figure 29 for one of the subbasins of the Dender basin. The original distribution (control period) shows a shift up or down depending on the applied scenario. This shift is small for short return periods and grows for longer return periods. The increases/decreases in the hourly peaks are calculated for every climate scenario as a percentage of variation of runoff peaks (difference between the new resulted runoff peaks after applying climate scenarios and the actual runoff peaks). For the mean scenario, climate change would not introduce big variation where, on average for return periods higher than 0.1 years, the runoff peaks would have 10% of change. For the low and high scenarios, the sub-basin responds severely with respectively -5% and +35% change thus decreasing and increasing flood risks. Overland flow volumes show similar behaviour as the runoff peaks. As for the evapotranspiration, differences are seen up to 15% increase, resulting from regional warming.

For low flows (Figure 30), results indicate considerable decrease in runoff minima for the three climate scenarios. This is due to decrease of summer rainfall together with an increase of evapotranspiration. Similar conclusions are obtained for all investigated subbasins by the local scale hydrological models of K.U.Leuven in the Dender and Grote Nete – Grote Laak basins, the local scale hydrological models of the Flanders Hydraulics authority in the Scheldt basin, and the larger scale hydrological SCHEME model of RMI for the Meuse and Scheldt basins. Figure 31 summarizes the percentage change in hourly runoff peaks and low flows (on average for return periods higher than 0.1 years) for all subbasins investigated with the NAM models of the Flanders Hydraulics authority. The results show that, while for the mean scenario, the runoff peaks experience slight decrease reaching a maximum of -14% comparing to the current runoff peaks condition, the decrease is very large for the low scenario to the level of -70%. For the high scenario, climate change acts positively where we expect an increase in runoff peaks to the order of ~35% depending on the sub-catchment. Uncertainties on these impacts are very high. Depending on the ratio between the increase in rainfall versus the increase in ETo, and the ratio between the increase in winter rainfall versus the decrease in summer rainfall, the hydrological impact results (i.e. flood risk) might turn over from a positive trend into a negative trend. Low flows decrease dramatically for the entire Flanders area for all climate scenarios (-88%) indicating that future increase in low flow problems might be in more concern than the increase in flood problems.

Spatial hydrological response heterogeneities are seen within the Flanders area with respect to climate change scenarios forcing. These hydrological response heterogeneities have been investigated by means of statistical correlations between the high scenario runoff peaks and three local physico-morphological constraints (soil type, land use and topographical slope). The correlation results show that the signature of the local characteristics does not provide efficient explanation to the spatial hydrological heterogeneity. No strong correlations have been found, although some tendencies can be detected explained by soil type and topographical slope.

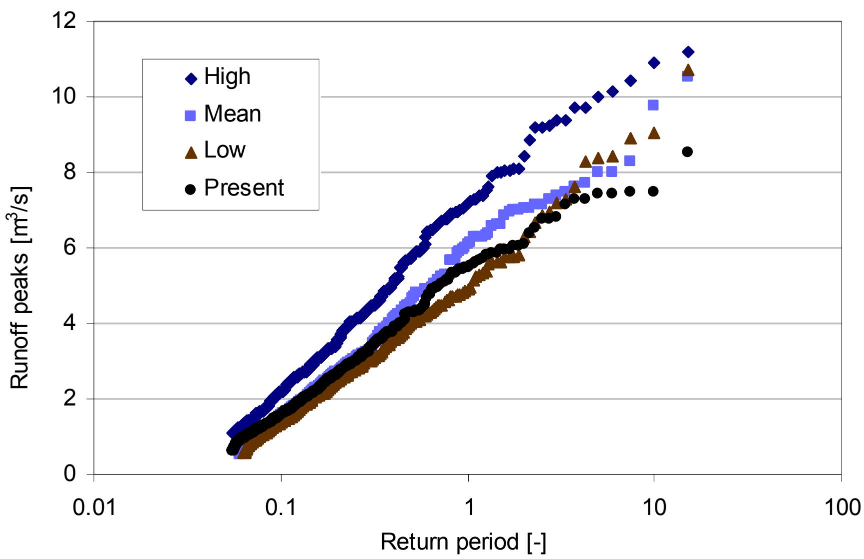


Figure 29. Hourly flow peaks versus return period for the low, mean and high CCI-HYDR climate scenarios for subbasin "431" of the Dender basin.

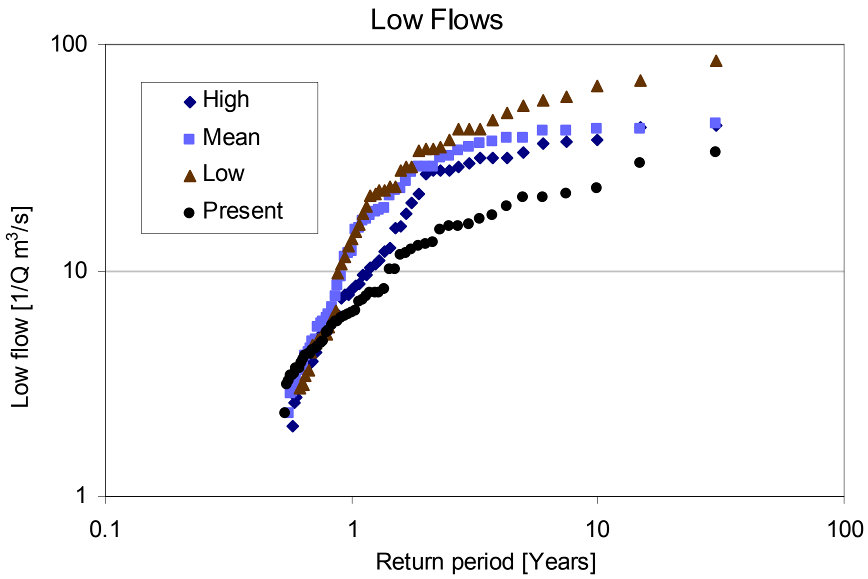


Figure 30. Hourly low flows versus return period for the low, mean and high CCI-HYDR climate scenarios for subbasin "431" of the Dender basin.

These impacts on the runoff discharges were also transferred to changes in flood maps. This was done after construction of high flow-duration-frequency (QDF) relationships and synthetic rainfall-runoff hydrographs (composite hydrographs) for given return periods. These hydrographs were simulated in the calibrated river hydrodynamic model MIKE11 (DHI, 2008) to create flood maps following the methodology of Willems et al (2002). Flood maps are produced for return periods in the range from 1 to 500 years, and represent regions that become inundated with given mean recurrence intervals. These flood maps are frequently used in support of flood management.

Example of results is shown in Figure 32 for the impact on the flood map along the Dender for a return period of 100 years. These results also have been implemented by the colleagues of the ADAPT project. Upon request of the ADAPT team, additional results have been produced such as the maximum flow velocities along the flood plains, the maximum velocities of the rising water, the season and month of the flood and the flood duration. These additional variables are indeed of relevance for the socio-economical and ecological impact analysis of the changes in river floods. In cooperation with the ADAPT team, K.U.Leuven also worked on a conceptual hydraulic model of the upstream Dender reach between Deux-Acren and Ninove. This conceptual model was useful for incorporation in a decision support system regarding climate change adaptation (see project ADAPT).

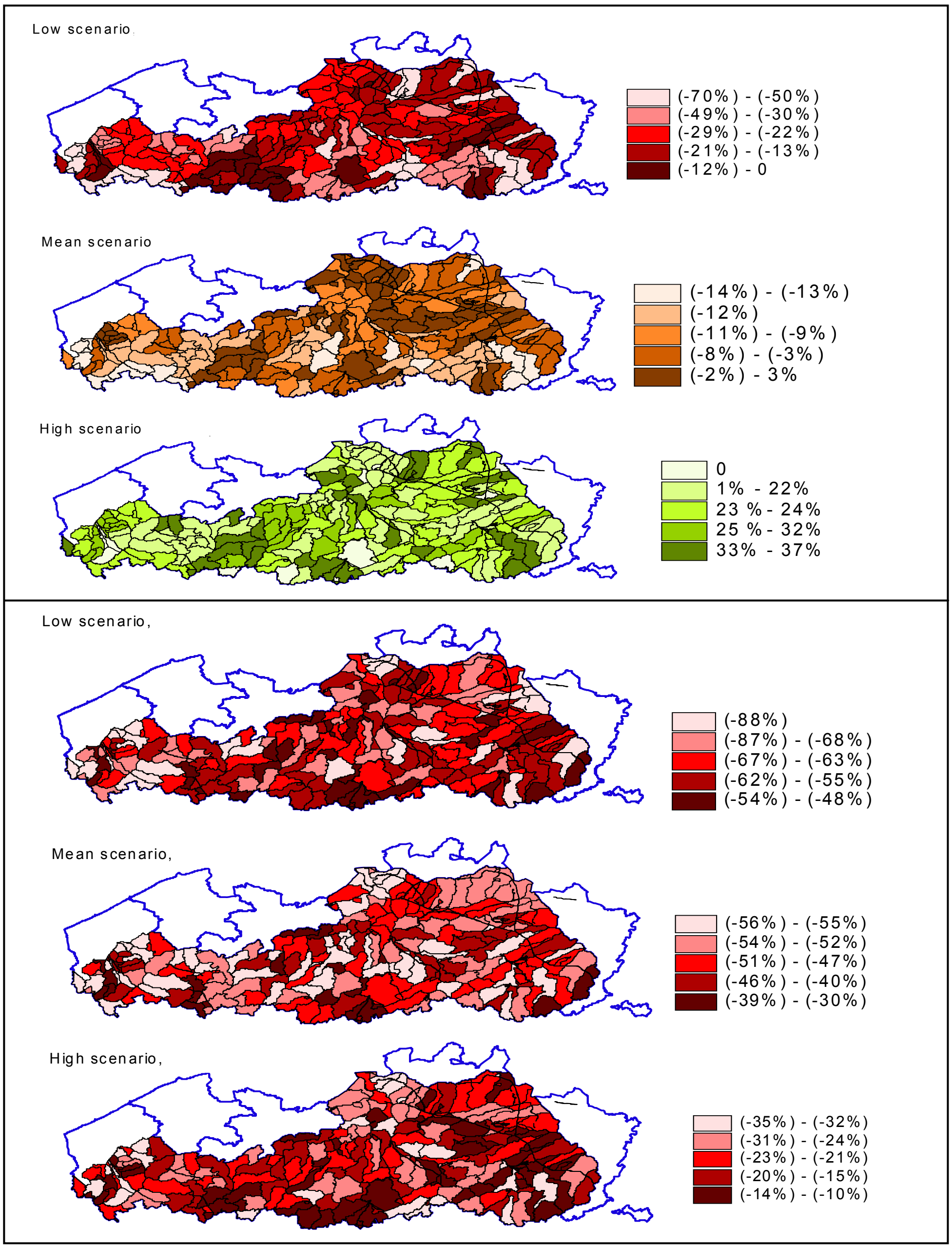


Figure 31. Percentage of variation (for the future climate 2071-2100 compared to the control period 1961-1990) of hourly runoff peaks (top panel) and low flows (down panel) for the low, mean and high CCI-HYDR climate scenarios and based on the hydrological models of the Flanders Hydraulics authority.

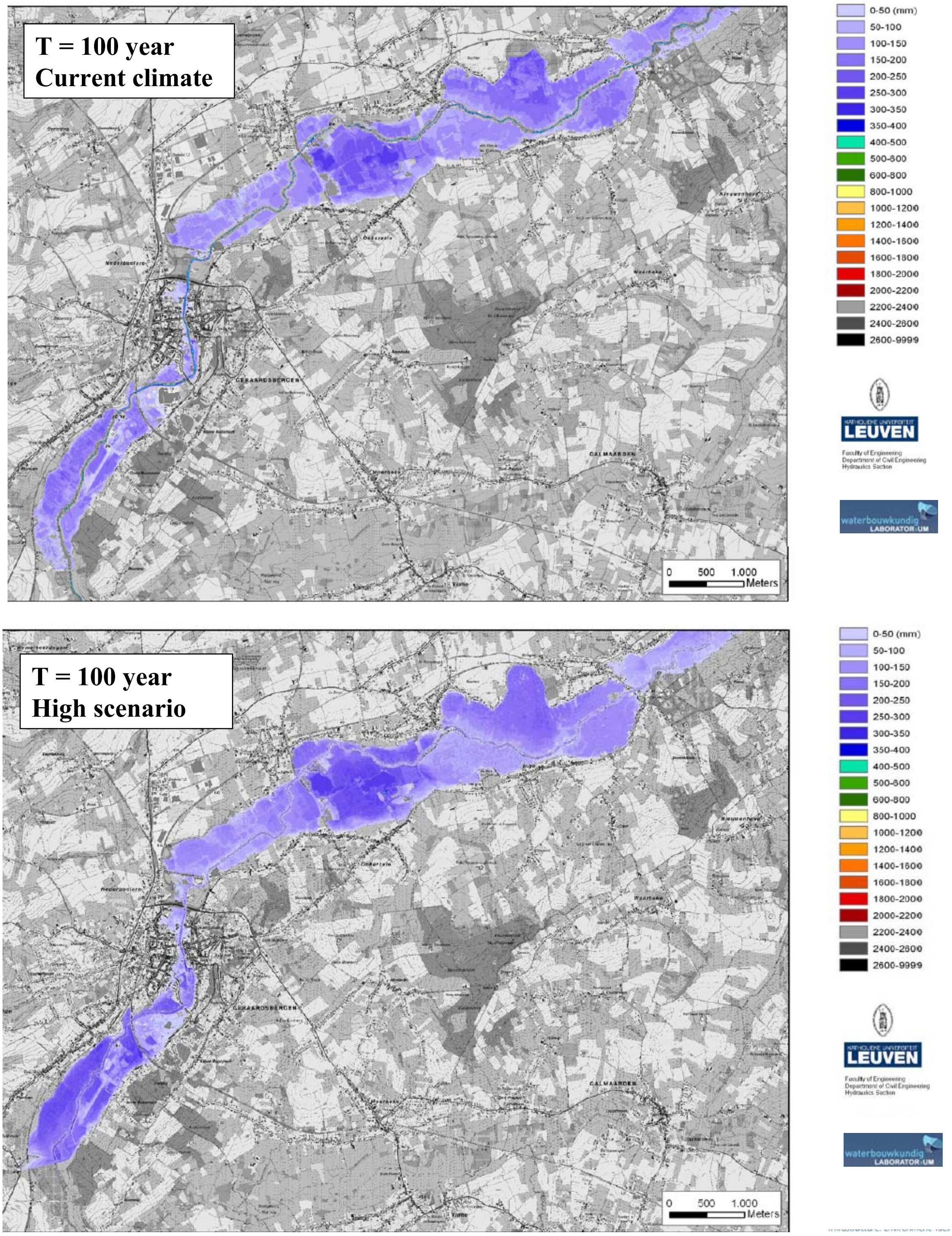


Figure 32: Flood maps for the region around Geraardsbergen along the Dender and a return period of 100 years, for the current climate and the high CCI-HYDR climate change scenario.

The impacts of climate change have also been studied using the SCHEME model. In that model, first reference streamflow time series at each outlet of interest were obtained under control conditions; then, the control values of the PET, precipitation and temperature were perturbed using all the possible perturbations calculated from the PRUDENCE database (31 based on the SRES A2 scenario and 10 based on the B2 scenario) and scenario simulations conducted. This produced an ensemble of 41 members for the streamflow output under climate change conditions, at each outlet of the river basins considered. The streamflow statistics presented hereafter are based on this ensemble. All the available SRES scenarios (A2 and B2) are taken into account in the statistics calculations.

In Figure 33, the mean monthly streamflow (in mm) is presented for the selected outlets. This representation includes the results of the control simulations and the maximum, mean and minimum of the ensemble of the 41 streamflow curves coming from the climate change hydrological simulations. These three levels are determined by calculating for each month the maximum, mean and minimum value of the ensemble. So the corresponding curves are not actual simulations, as the control one is, but they define the limits between which the values of all the simulations are situated.

In each case a decrease of the mean streamflow is projected with respect to the reference simulation, with some occasional increase in the end of winter or the beginning of spring. It is worth mentioning that in all cases considered here during summer and beginning of autumn, even the maximum of all runs lies below the control level. This again is an indication that future summers may be significantly drier than todays and that this should be investigated further.

The mean yearly streamflow (in mm) for the control and scenario simulations, as well as the difference (as percentage) between mean scenario and control simulations, are given in Table XIII. The low and high flow frequency results for the selected outlets in the Scheldt and Meuse basins are presented in Figure 34 and Figure 35.

In Figure 34, an interesting phenomenon is observed. Even the minimum values of the projected yearly number of low flow days under climate change, are much larger than the corresponding control values. The deviation of the mean value of the scenario runs from the control value (Table XIV) reflects this very large projected increase in the number of low flow days. This also agrees with the results presented previously on the mean streamflow decrease near the end of the current century, although the decrease is very strong in the low end of the distribution (0.05 percentile here).

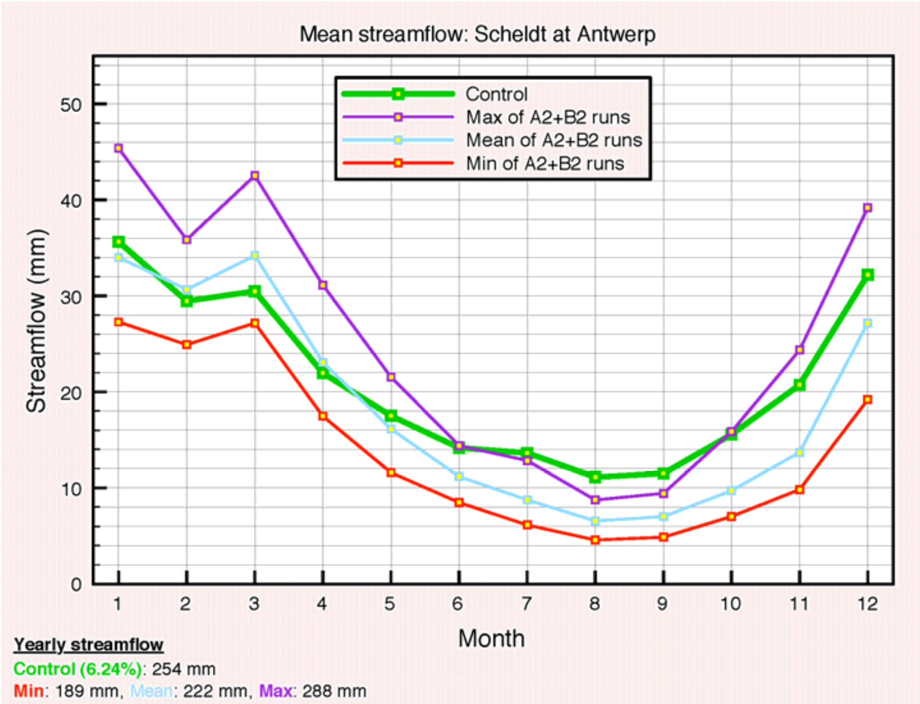
Such changes were not observed in the case of the high flow frequency. Indeed, as can be seen in Figure 35, the monthly number of high flow days is nearly zero from the end of spring until the beginning of autumn in any case of simulation, scenario or control. During autumn and most part of winter, the mean of the scenario values lies below the control value, while from the end of winter until mid of spring it exceeds the control value. The results for the yearly number of high flow days (Table XV, mean value of scenario runs) are mixed: there are positive and negative changes as well depending on the location, but of magnitude much lower than in the case of low flow days.

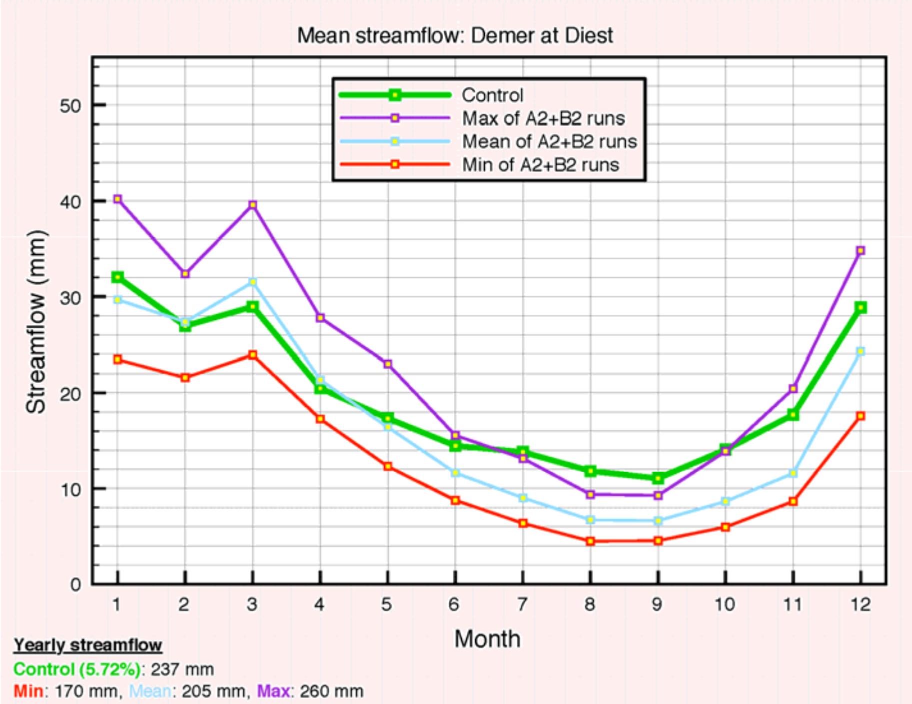
The temporary (end of winter – mid of spring) increase of high flow days may be related to the increase of precipitation in winter due to climate change (Table V); on the other hand, the very large increase in the number of low flow days, which reaches the highest values in the beginning of autumn, seems to be related to the high PET and temperature increase and to the strong precipitation decrease in summer (Table IV, Table VI and Table V respectively). The combination of three factors during summer would explain the much stronger change in the low end (0.05 percentile) compared to what we observe in the high end (0.95 percentile, dominated by the wet period of the year – end of autumn beginning of spring).

Qualitatively, these results are compatible with the results of previous sensitivity analysis of SCHEME model impacts to IPCC climate changes scenarios (Roulin et al., 2001, 2002). However, the range of projected changes is very different between the two studies. For instance, the change in the number of low flow days ranged from +2 to +13 for the Scheldt at Antwerp depending on the 6 IPCC scenarios for the horizon 2070–2099. In the present study, the changes found with the 41 scenarios based on the PRUDENCE database range from +8 to +75 for the same period. For the change in the number of high flow days, the range was from –2 to +3 in the past study; it is now updated as from –7 to +13. Similar differences are observed in the case of other basins and catchments.

Table XIII: Yearly streamflow (in mm) for control and climate change scenario simulations; change (%) between mean scenario and control.

		Control	Scenario			Change (%)
			Minimum	Mean	Maximum	
Scheldt	Scheldt at Antwerp	254	189	222	288	-12.6
	Scheldt at Asper	243	178	211	276	-13.1
	Demer at Diest	237	170	205	260	-13.5
	Dendre	258	194	225	292	-12.8
	Dijle at Wilsele	271	179	218	290	-19.6
	Grote Nete at Hulshout	283	222	254	314	-10.2
	Kleine Nete at Grobbendonk	294	230	265	327	-9.9
	Leie at St Baafs	238	176	215	285	-9.7
	Zenne at Eppegem	289	213	248	310	-14.2
Meuse	Ambleve at Martinrive	575	411	496	625	-13.7
	Meuse at Chooz	481	387	460	572	-4.4
	Ourthe at Angleur	512	379	447	512	-12.7
	Ourthe at Tabreux	479	362	433	560	-9.6
	Sambre at Namur	388	294	341	427	-12.1
	Vesdre	536	357	441	567	-17.7
	Meuse at Visé	456	359	420	531	-7.9


Mean streamflow: Scheldt at Antwerp
Control
Max of A2+B2 runs
Mean of A2+B2 runs
Min of A2+B2 runs
Streamflow (mm)
Month
Yearly streamflow
Control (6.24%): 254 mm
Min: 189 mm, Mean: 222 mm, Max: 288 mm


Mean streamflow: Demer at Diest
Control
Max of A2+B2 runs
Mean of A2+B2 runs
Min of A2+B2 runs
Streamflow (mm)
Month
Yearly streamflow
Control (5.72%): 237 mm
Min: 170 mm, Mean: 205 mm, Max: 260 mm

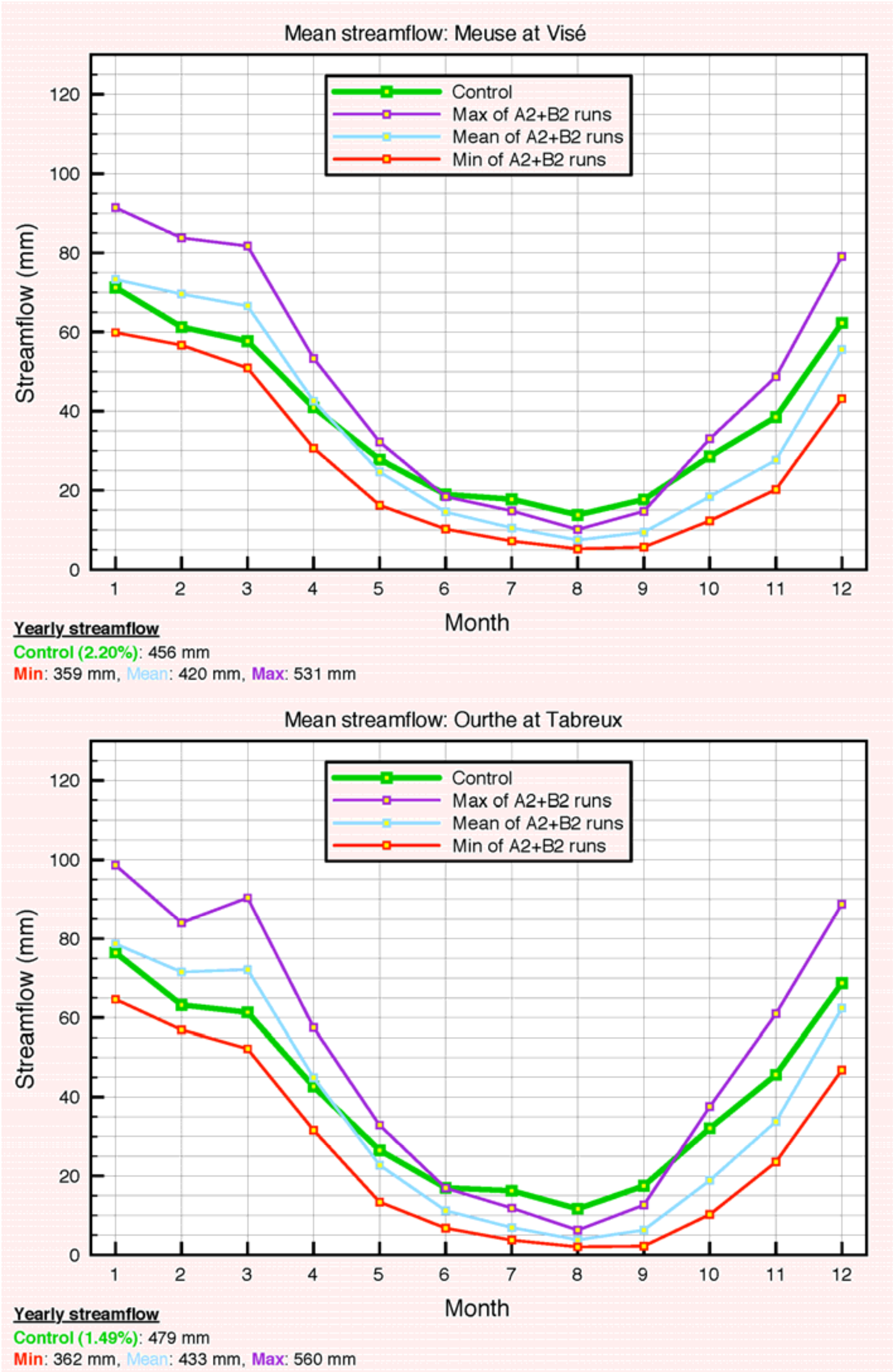
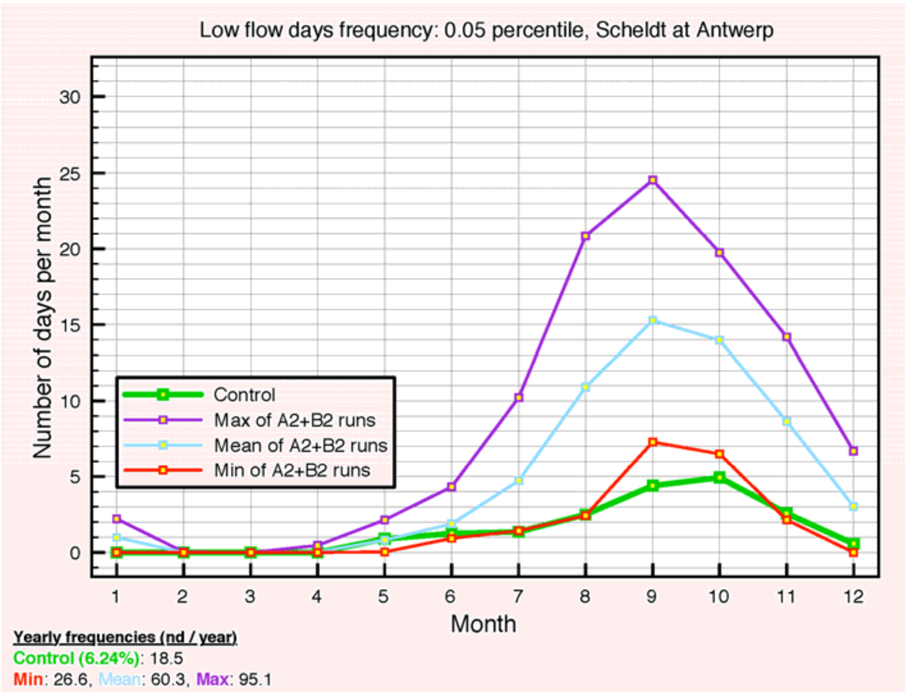
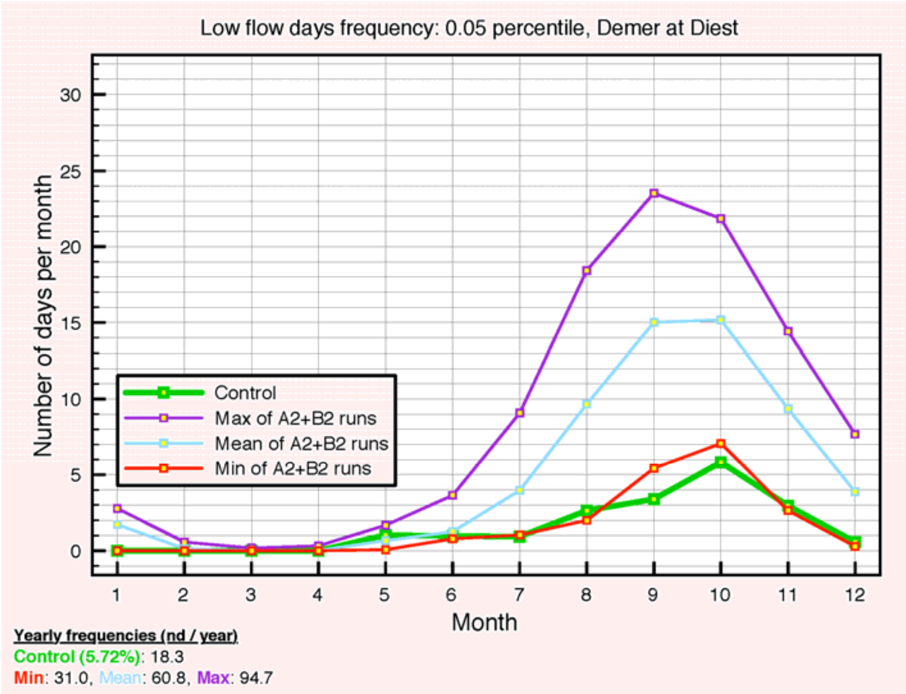


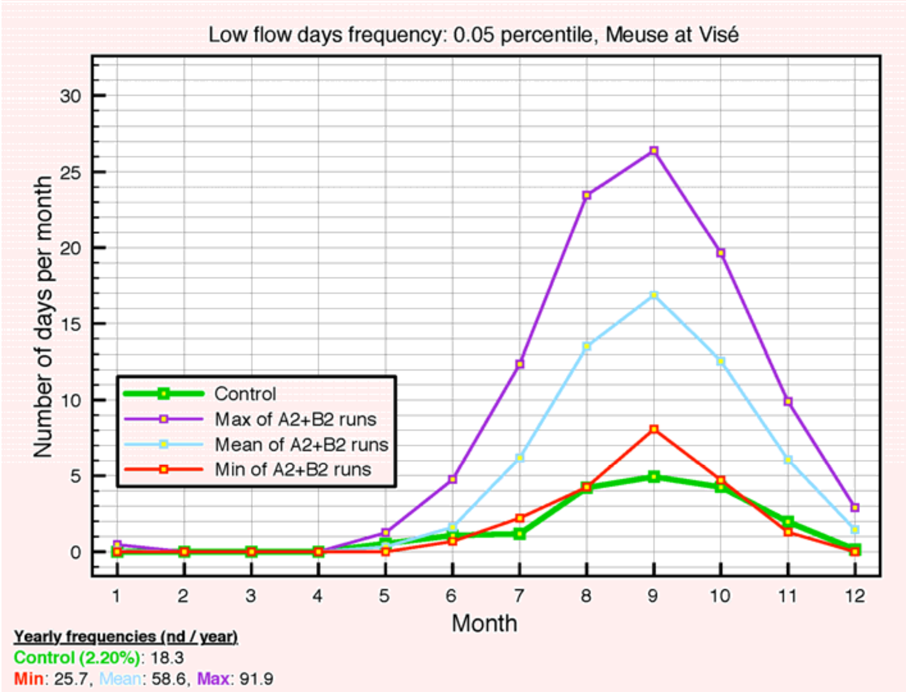
Figure 33: Mean streamflow under climate change for selected outlets in the Scheldt and Meuse basins.

Table XIV: Yearly frequencies (number of days/year) of low flow days for control and climate change scenario simulations; change (%) between mean scenario and control.

		Control	Scenario			Change (%)
			Minimum	Mean	Maximum	
Scheldt	Scheldt at Antwerp	18.5	26.6	60.3	95.1	225.9
	Scheldt at Asper	18.4	24.9	54.5	90.2	196.2
	Demer at Diest	18.3	31.0	60.8	94.7	232.2
	Dendre	18.6	29.8	60.3	89.4	224.2
	Dijle at Wilsele	18.4	19.5	93.8	156.5	409.8
	Grote Nete at Hulshout	18.3	28.1	55.6	84.1	203.8
	Kleine Nete at Grobbendonk	18.3	24.5	53.2	81.3	190.7
	Leie at St Baafs	18.5	15.8	42.8	73.6	131.4
	Zenne at Eppegem	18.4	28.1	73.1	113.8	297.3
Meuse	Ambleve at Martinrive	18.4	43.0	88.0	130.8	378.3
	Meuse at Chooz	18.5	20.9	48.4	77.5	161.6
	Ourthe at Angleur	18.4	39.6	74.9	112.4	307.1
	Ourthe at Tabreux	18.3	35.2	71.2	105.4	289.1
	Sambre at Namur	18.4	29.8	56.7	86.0	208.2
	Vesdre	18.6	30.4	58.7	92.4	215.6
	Meuse at Visé	18.3	25.7	58.6	91.9	220.2




Low flow days frequency: 0.05 percentile, Demer at Diest
Number of days per month
Month
Control
Max of A2+B2 runs
Mean of A2+B2 runs
Min of A2+B2 runs
Yearly frequencies (nd / year)
Control (5.72%): 18.3
Min: 31.0, Mean: 60.8, Max: 94.7


Low flow days frequency: 0.05 percentile, Meuse at Visé
Number of days per month
Month
Control
Max of A2+B2 runs
Mean of A2+B2 runs
Min of A2+B2 runs
Yearly frequencies (nd / year)
Control (2.20%): 18.3
Min: 25.7, Mean: 58.6, Max: 91.9

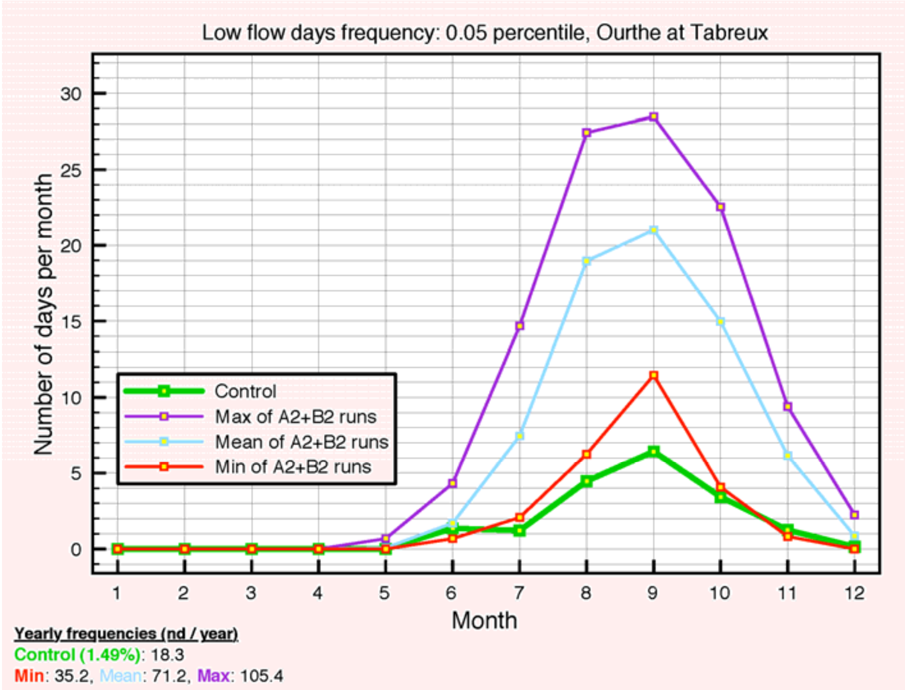
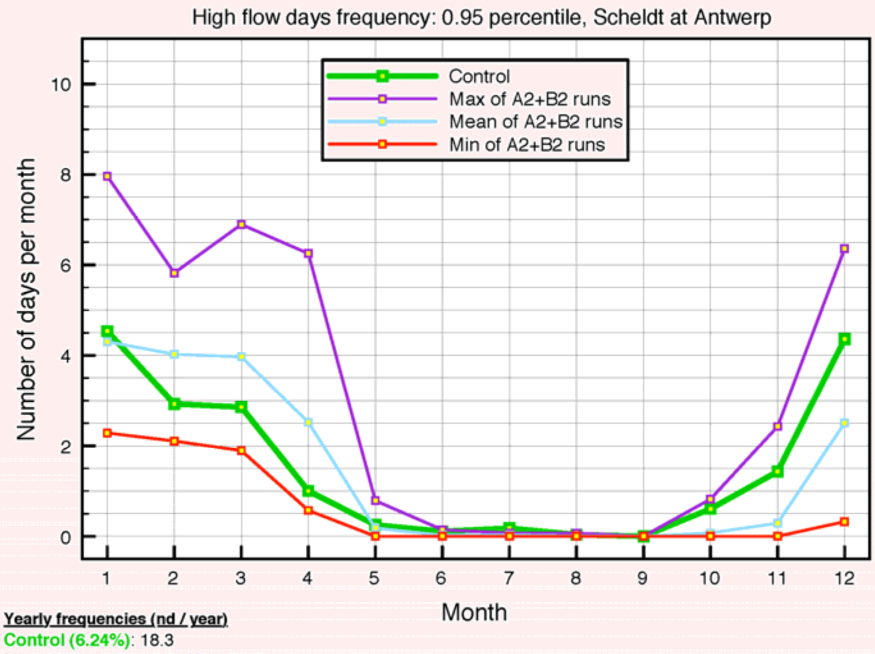


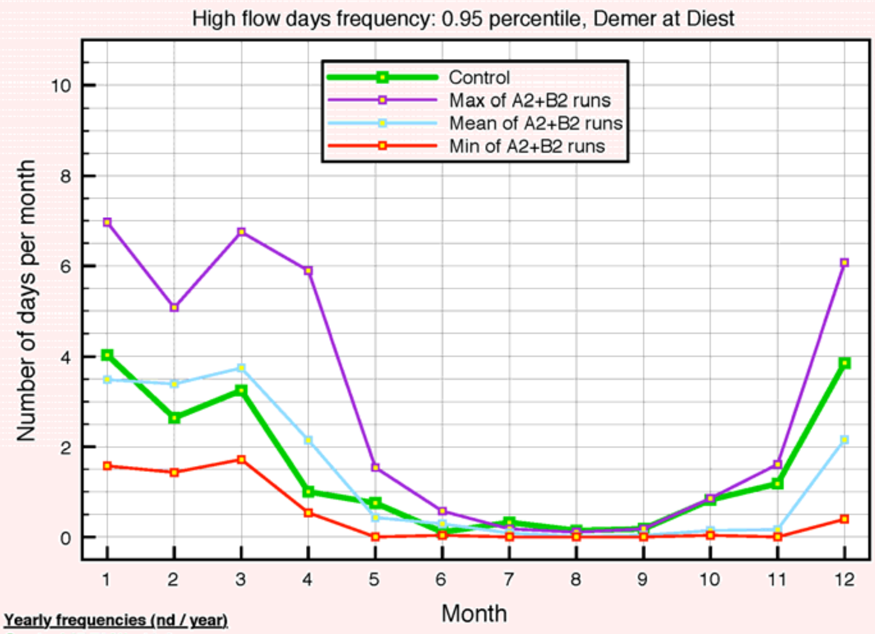
Figure 34: Low flow days frequency under climate change for selected outlets in the Scheldt and Meuse basins.

Table XV: Yearly frequencies (number of days/year) of high flow days for control and climate change scenario simulations; change (%) between mean scenario and control.

		Control	Scenario			Change (%)
			Minimum	Mean	Maximum	
Scheldt	Scheldt at Antwerp	18.3	11.1	17.9	31.1	-2.2
	Scheldt at Asper	18.3	11.1	18.0	32.3	-1.6
	Demer at Diest	18.3	9.2	16.1	29.1	-12.0
	Dendre	18.3	11.4	16.8	29.2	-8.2
	Dijle at Wilsele	18.3	9.5	16.0	30.6	-12.6
	Grote Nete at Hulshout	18.3	11.1	16.2	26.8	-11.5
	Kleine Nete at Grobbendonk	18.3	12.0	17.0	26.6	-7.1
	Leie at St Baafs	18.3	12.6	20.1	38.0	9.8
	Zenne at Eppegem	18.3	10.8	16.9	29.1	-7.7
Meuse	Ambleve at Martinrive	18.4	12.8	18.3	26.1	-0.5
	Meuse at Chooz	18.3	14.4	22.0	33.4	20.2
	Ourthe at Angleur	18.3	12.0	18.4	28.1	0.5
	Ourthe at Tabreux	18.3	12.6	19.5	32.4	6.6
	Sambre at Namur	18.3	10.3	16.7	29.3	-8.7
	Vesdre	18.6	9.8	15.8	24.6	-15.0
	Meuse at Visé	18.3	13.2	19.7	31.1	7.7



Yearly frequencies (nd / year)
Control (6.24%): 18.3
Min: 11.1, Mean: 17.9, Max: 31.3



Yearly frequencies (nd / year)
Control (5.72%): 18.3
Min: 9.2, Mean: 16.1, Max: 29.1

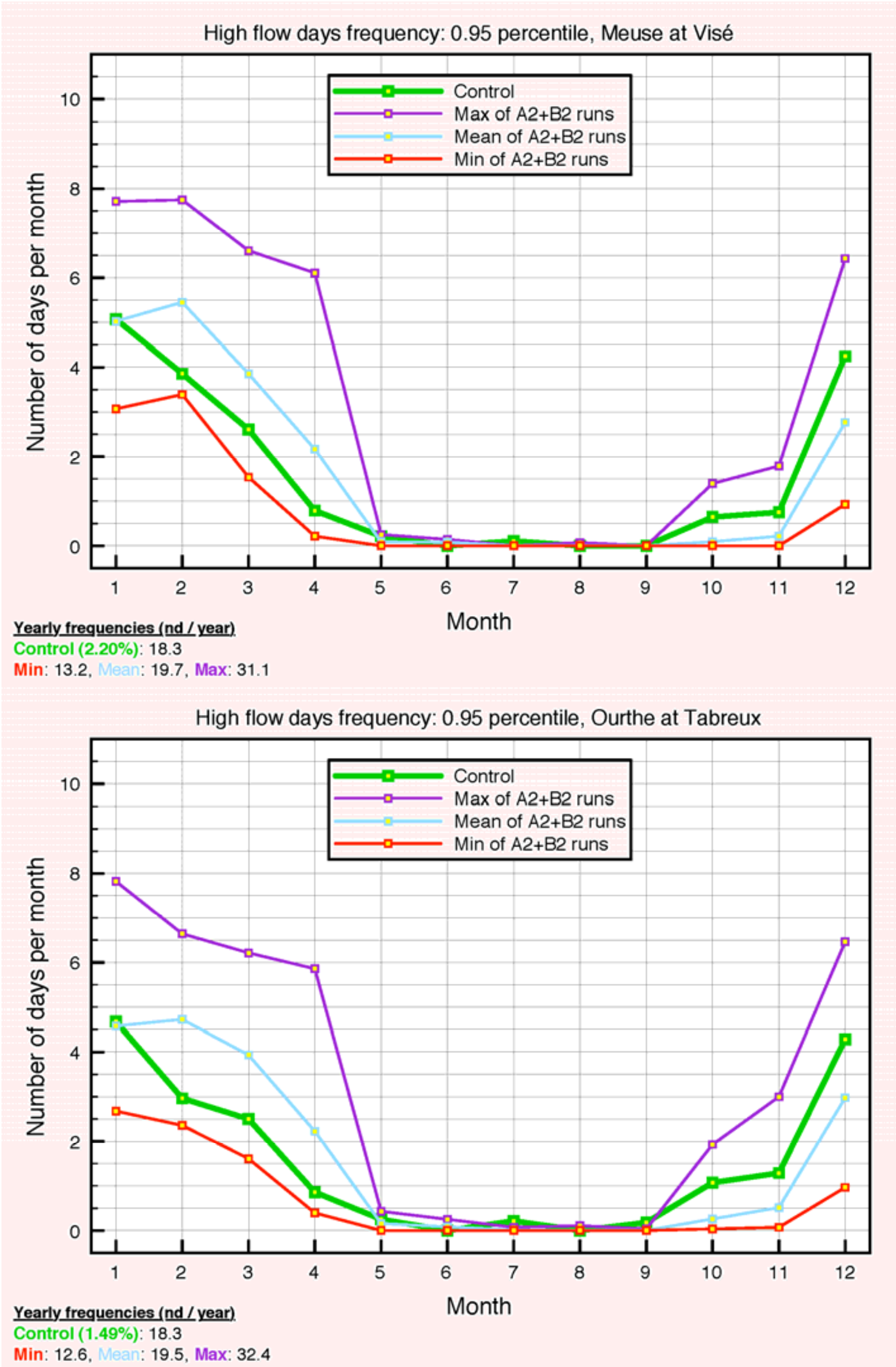


Figure 35: High flow days frequency under climate change for selected outlets in the Scheldt and Meuse basins.

As a response to a request of the ADAPT project, the upper range of the streamflow distribution from the SCHEME model simulations was investigated based on the annual extreme values. In particular, a Gamma distribution was fitted to the sample of these extremes and the streamflow with a return period of 100 years was calculated. The distribution used has the following form:

$$f(x,\alpha,\beta) = \frac{1}{\beta^{\alpha}\Gamma(\alpha)} x^{\alpha-1} e^{-x/\beta}$$

where $x \geq 0, \alpha > 0, \beta > 0$. The fitting method adopted here is the one described in Sneyers (1990).

The methodology can be summarized as follows. The annual maximum values were obtained for a selection of two outlets (Ourthe at Angleur and Ourthe at Tabreux) and for each SCHEME simulation based on the control conditions and the mean scenario for PET, precipitation and temperature. To each one of these samples of maximum values a Gamma distribution was fitted and the streamflow value with a return period of 100 years (P99) calculated using the parameters of the distribution. In order to calculate the confidence intervals (5% and 10%) around each such value, a non-parametric bootstrap method was used by applying random re-sampling with replacement on the sample of the maximum values. A total of 10000 bootstrap iterations was used for this experiment. The results are summarized in Table XVI and Table XVII.

Table XVI: P99 values and confidence intervals for the Ourthe at Angleur.

	P99	10%	5%
Control	18.91	[13.87, 23.50]	[13.60, 23.77]
Scenario	19.73	[13.75, 25.35]	[13.43, 25.67]

Table XVII: P99 values and confidence intervals for the Ourthe at Tabreux.

	P99	10%	5%
Control	15.22	[10.87, 18.84]	[10.65, 19.06]
Scenario	15.84	[10.64, 20.06]	[10.38, 20.32]

An extended extreme value analysis taking into account the scenario variability (41 members) has been conducted as well.

2.4 Hydrological impact investigations along urban drainage systems

For the impact on the flood risk along urban drainage systems, a similar approach was followed in comparison with the method described above for rivers, but with rainfall changes statistically downscaled to 10 minutes. Design storms, which are typically used for the design of urban drainage systems, are directly derived from the IDF-relationships for rainfall. It has been found (for the range of time scales relevant for urban drainage systems) that the rainfall intensities with a return period of 1.5 months for the current climate conditions, after the CCI-HYDR high climate scenario will correspond to a return period of 1 month. A return period of 2 years will decrease to 1 year. For higher return periods, the results are less uniform; for time scales less than 1 hour a return period of 100 years will decrease to 10 years and a return period of 50 years will

decrease to 10 years. Systems that are designed for a 2 years return period of flooding thus would flood twice that frequent based on the CCI-HYDR high climate scenario.
In collaboration with the Flemish Environment Agency (member of the CCI-HYDR Follow-up Committee), the guidelines for the design of urban drainage systems are currently under revision based on these results. Next to the design of urban drainage systems, also the design of local source control measures (storage facilities, rainwater tanks, infiltration reservoirs, etc) has been investigated. It has been found that larger storage capacities need to be built (15% to 35% increase for the CCI-HYDR high climate scenario) if one wants to limit the overflow frequency of the facility to the same level. Correspondingly, storage facilities with an overflow return period of 2 years would (after the CCI-HYDR high climate scenario) overflow approx. twice per year; facilities with an overflow return period of 5 years would (for the same scenario) overflow approx. once per 1 - 1.5 years. Table XVIII gives an overview of the % increases in storage required for given overflow return periods and throughflow discharges.

Table XVIII. Percentage increase in storage required depending on the throughflow discharge of the storage facility and the return period of overflow of the facility (for systems with 10 minutes response times and for the CCI-HYDR high climate scenario).

Constant throughflow discharge [l/(s.ha)]:	Return period of overflow [years]:					
	0.5	1	2	5	10	20
50	+51%	+37%	+28%	+34%	+44%	+43%
40	+38%	+35%	+23%	+31%	+38%	+39%
30	+25%	+28%	+23%	+33%	+36%	+34%
25	+24%	+27%	+23%	+31%	+40%	+31%
20	+22%	+25%	+26%	+29%	+39%	+29%
15	+24%	+26%	+24%	+23%	+28%	+20%
10	+20%	+26%	+26%	+29%	+25%	+22%
5	+16%	+17%	+21%	+24%	+27%	+24%
2	+21%	+25%	+28%	+27%	+33%	+18%
1	+22%	+30%	+39%			

The latter results indicate that there is a need for more and larger local stormwater storage. In case this storage is built by means of infiltration ponds, the stormwater stored in the ponds will enhance the groundwater infiltration and consequently will help to solve the enhanced low flow problems expected for river catchments.

2.5 Wider ecological and socio-economic impacts

The wider implications of the hydrological impacts to the environment and society are being studied by the parallel research project ADAPT, for the Dender and Ourthe basins. One of the environmental aspects that is not be considered in the ADAPT project is the impact on the water quality. This aspect is taken up in the cluster project SUDEM-CLI, also considering the case-study of Grote Nete – Grote Laak. The reader is referred to the reports of the ADAPT and SUDEM-CLI projects for these impact results.

3 POLICY SUPPORT

The CCI-HYDR climate change scenarios developed in the project were almost immediately applied by several **national water and environmental authorities**:

- Flanders Hydraulics Research (Waterbouwkundig Laboratorium): for investigating impacts on high and low flows (along navigable rivers in Flanders, including the upstream subbasins);
- Flemish Environment Agency (VMM): for investigating impacts on floods along non-navigable rivers 1st category and for updating the urban drainage design guidelines;
- INBO (Institute for Nature and Forest Research): for investigating impacts on nature, after extension of CCI-HYDR scenarios to other variables (temperature, wind speed, ...) and comparison with KNMI'06 scenarios.

This shows that there was a great need for the results obtained within the scope of the CCI-HYDR project. The three authorities mentioned are all (water management and environment related) policy implementers, which means that the results of the CCI-HYDR project almost immediately supported policy implementation and related sustainable development of the region. This is far beyond all original expectations.

Hereafter, a summary is given on the policy implementation activities by the three authorities mentioned.

In cooperation with K.U.Leuven, coordinator of the CCI-HYDR project, ***Flanders Hydraulics Research*** (Flemish Government of Belgium, Dept. for Mobility and Public Works) applied the CCI-HYDR climate change scenarios and CCI-HYDR Perturbation Tool to all subbasins of the Scheldt river basin district for which rainfall-runoff models have been developed during previous studies by the authority. Currently, the project is extended to the Meuse basin. For all these subbasins, hydrological impacts of climate change are being investigated for ***high flows, low flows***, cumulative runoff volumes, overland volumes, actual evapotranspiration volumes, etc. Also the impact on flood risks (incl. spatial flood probability, damage and risk maps) is being quantified. These calculations aim to provide policy support towards adaptation measures to limit the current and future flood and low flow risks in the region under changing climate conditions. The following reports have been produced and uploaded to the CCI-HYDR website:

- Boukhris O.F., Willems P., Vanneuville W., Van Eerdenbrugh K., 2008. "Climate change impact on hydrological extremes in Flanders: Regional differences", Final report Flanders Government of Belgium, Flanders Hydraulics authority, Antwerp, Belgium, April 2008, 91 p.

- Boukhris O.F., Willems P., Vanneuville W., Van Eerdenbrugh K., 2008. "Climate change impact on hydrological extremes in Flanders: Regional differences; Subreport literature review Meuse basin", Final report Flanders Government of Belgium, Flanders Hydraulics authority, Antwerp, Belgium, April 2008, 27 p.
- Vansteenkiste T., Holvoet K., Willems P., Vanneuville W., Deckers P., Mostaert F., 2009. "Impact of climate change on high and low runoff flows and water availability: case study of the Leie and Bovenschelde river basins (in Dutch)", Report Flanders Government of Belgium, Flanders Hydraulics Research, Antwerp, Belgium, November 2009, 43 p., Projectno. 706/13a.
- Vansteenkiste T., Holvoet K., Willems P., Vanneuville W., Deckers P., Mostaert F., 2009. "Impact of climate change on high and low runoff flows and water availability: case study of the Meuse basin (in Dutch)", Report Flanders Government of Belgium, Flanders Hydraulics Research, Antwerp, Belgium, November 2009, 14 p., Projectno. 706/13a.
- Vansteenkiste T., Holvoet K., Willems P., Vanneuville W., Mostaert F., 2009. "Impact of climate change on high and low runoff flows and water availability: Literature review hydrological modeling of low flow scenarios (in Dutch)", Report Flanders Government of Belgium, Flanders Hydraulics Research, Antwerp, Belgium, December 2009, Projectno. 706/13a.

In a research project for the regional ***Institute for Nature and Forest Research*** (INBO), carried out by the CCI-HYDR project partners together with the Dutch Royal Meteorological Institute (KNMI), the CCI-HYDR climate change scenarios have been extended for temperature and wind speed. These extended scenarios are currently been applied for ***environmental impact*** investigations (MIRA Environmental Report 2009 of the Flemish Environment Agency). The impact investigations are supported by colleagues from the Free University of Brussels (impact analysis on groundwater), VITO (impact analysis on air quality), U.Antwerp (ecological impact analysis). The following reports summarize the extended CCI-HYDR climate change scenarios; they also were uploaded on the CCI-HYDR website:

- Demarée G., Baguis P., Deckmyn A., Debontridder L., Pinnock S., Roulin E., Willems P., Ntegeka V., Kattenberg A., Bakker A., Lenderink G., Bessembinder J., 2008. "Climate scenarios for Flanders (in Dutch)", Report Institute for Nature and Forest Research INBO, by the Royal Mteorological Institute of Belgium, the Dutch Roral Meteorological Institute (KNMI) and K.U.Leuven – Hydraulics Division, December 2008.

- Baguis P., Ntegeka V., Willems P., Roulin E., 2009. "Extension of CCI-HYDR climate change scenarios for INBO", Instituut voor Natuur- en Bosonderzoek (INBO) & Belgian Science Policy – SSD Research Programme, Technical report by K.U.Leuven – Hydraulics Section & Royal Meteorological Institute of Belgium, January 2009, 31p.

The INBO has won the Innovation Price "Spitsprijs Innovatie" 2009 of the Flemish Government, for their methodology developed (including the application of the extended CCI-HYDR climate change scenarios).

The ***Flemisch Environment Agency*** (VMM) recently started several activities regarding water and climate change impacts:

- A review report is being produced (Annex to the MIRA-S Environmental Report 2009) on the ***impact of climate change on water management***. P.Willems (CCI-HYDR coordinator) is first author of this report.
- The CCI-HYDR climate change scenarios and Perturbation Tool are being applied to investigate the impact on ***flood probabilities and risks*** along the non-navigeable rivers of 1st category (EU Flood Directive implementation). These calculations are being conducted by consultancy agency IMDC.
- Rainfall and related **urban drainage design statistics** have been updated based on the CCI-HYDR scenarios. P.Willems (CCI-HYDR coordinator) coordinated this research. The updated design values are considered in the on-going revision of the regional guidelines for the ***design of urban drainage systems***, and related storage and infiltration infrastructure, by the Coordination Commission Integrated Water Management (CIW).

Next to their direct policy development and implementation support, the above-mentioned "end user projects" also were considered interesting because of the intensive interactions between the regional authorities (end users) and the CCI-HYDR project team. The application of the CCI-HYDR results was almost immediately tested in practice, and feedback provided to the CCI-HYDR team. A number of times along the course of the project, the CCI-HYDR climate change scenarios and Perturbation Tool were updated based on this feedback.

Next to the regional water and environmental authorities, the CCI-HYDR team was invited to communicate their results to/at the:

- **Commission of Social Affairs of the Belgian Parliament (Senate)**: presentation "Impact of climate change on hydrological extremes along Belgian rivers (in Dutch)", Brussels, 14 Febr. 2007
- **Working group on low flows of the Royal Academy of Sciences** (KAOW): note "Impact of climate change on regional inland low flow extremes (in Dutch)", P.Willems, 28 Aug. 2008, 5 p.
- **EU Interreg IVB NWE project FloodResilienCity**, presentation CCI-HYDR project and results, Leuven, 25 March 2009
- **ARGUS/VLEVA Symposium in preparation of the 'Belgian chairmanship of the EU'** on the topic of 'Is our climate changing?? (in Dutch)': presentation P.Willems "Impact of climate change on water management in Belgium", Brussels, 26 Oct. 2009
- Seminar series **Belgian National Committee for Geodesy and Geography**: seminar by P.Willems on "Climate change impacts on hydrological extremes along rivers and urban drainage systems in Belgium", Leuven, 29 April 2010
- Workshop of **Flemish Government of Belgium, Dept. Environment, Nature and Energy** on 'Adaptation and climate change: living with a future (in Dutch)': presentation P.Willems on "Climate change in Belgium", Brussels, 28 June 2010
- Workshop on local water management of the **Flemish Union of Cities and Communities (Vlaamse Vereniging van Steden en Gemeenten VVGS)**: session chair on "climate change" and presentation P.Willems on "climate change and urban drainage", Expo Antwerpen, 26 Sept. 2010
- **4th Belgian Geography Days**: presentations Willems P. & Vansteenkiste T. on "Climate change impacts on hydrological extremes (floods, low flows) along rivers in the Scheldt and Meuse basins in Belgium", Leuven, 22-23 Oct. 2010
- Fall meeting of the **Dutch Hydrological Union (Nederlandse Hydrologische Vereniging NHV)**: presentation P.Willems "Impact of climate change on hydrological extremes in Flanders", Leuven, 25 Nov. 2010

Also the **general public** has been informed by means of the following communications in newspapers and periodicals:

- Interview on flood risk evolutions and causes for periodical Knack, article "Rainfall becomes more extreme (in Dutch)", 13 Sept. 2006, 28-34
- Newspaper article "Belgium has to be prepared for water shortage", De Standaard, 8 Febr. 2007

- Newspaper article "Water will become limited in Belgium (in Dutch)", Het Nieuwsblad, 8 Febr. 2007
- Newspaper article "Climate change will increase droughts more than floods (in Dutch)", Het Volk, 8 Febr. 2007
- Newspaper article "Our rivers dry out in summer (in Dutch)", De Standaard, 25 Aug. 2008
- Belga press message "National rivers dry out in summer (in Dutch)", 25 Aug. 2008
- Newspaper K.U.Leuven "Rivers and climate change", front article 27 Aug. 2008
- Interview journal "Land+water" on "Research investigated regional effects of climate change on water management (in Dutch)", Sept. 2008
- Newspaper article "Increased drought risks might affect nature along Scheldt (in Dutch)", De Standaard 15 Oct. 2008, reference to CCI-HYDR presentation at Antwerp "Water & Climate change congress"
- 30 min radio interview on "Climate change and water (in Dutch)", Radio Centraal, 27 Dec. 2008
- Radio and TV news interview "More rain and also more droughts (in Dutch)", Radio 1 evening news, TV1 evening news, 19 Oct. 2009
- Newspaper article "Put parks and playing gardens under water (in Dutch)", De Standaard, 19 Oct. 2009
- Newspaper article "More heavy showers (in Dutch)", Het Laatste Nieuws, 19 Oct. 2009
- Periodical article "From rain to drought", Eos, Febr. 2010, no.2, 30-33

- Newspaper article "Take climate change into account in water management (in Dutch)", De Morgen, 16 Nov. 2010
- Newspaper article "New rain means more floods (in Dutch)", De Morgen, 17 Nov. 2010
- Periodical article "We know already now that our sewer systems will not be able to cope with the effects of climate change", Knack, 24 Nov. 2010, 102-105
- Newspaper article "Extreme weather proves importance of climate deal (in Dutch)", De Morgen, 6 Dec. 2010

4 DISSEMINATION AND VALORISATION

Dissemination and valorization activities are hereafter classified in reports and documents, project workshops, presentation at external workshops and conferences, press communications, and other activities, etc.

Flyers, reports and documents

Several types of documents have been prepared. These range from summaries for the general public and policy makers to detailed technical reports. All these reports are publicly available on the project website:
http://www.kuleuven.be/hydr/CCI-HYDR.htm (see "Reports")

The following detailed **technical reports** have been produced:

- Baguis P., Boukhris O., Ntegeka V., Roulin E., Willems P., Demarée G., 2008. "Climate change impact on hydrological extremes along rivers and urban drainage systems. ***I. Literature review***", Belgian Science Policy – SSD Research Programme, Technical report CCI-HYDR project by K.U.Leuven – Hydraulics Section & Royal Meteorological Institute of Belgium, May 2008, 57 p.
- Ntegeka V., Baguis P., Boukhris O., Willems P., Roulin E., 2008. "… ***II. Study of rainfall and ETo climate change scenarios***", May 2008, 112 p.
- Ntegeka V., Willems P., 2008. "…***III. Statistical analysis of historical rainfall, ETo and river flow series trends and cycles***", May 2008, 37 p.
- Willems P., Baguis P., Ntegeka V., Roulin E., 2010. "…***IV. Hydrological impact analysis***", making reference to:
- Baguis P., Roulin E., Willems P., Ntegeka V., 2010. "Climate change and hydrological extremes in Belgian catchments", Hydrol. Earth Syst. Sci. Discuss., 7, 5033-5078, doi:10.5194/hessd-7-5033-2010
- Ntegeka V., PhD manuscript "Assessment of the observed and future climate variability and change in hydroclimatic and hydrological extremes", K.U.Leuven – Faculty of Engineering, promoters: P.Willems, J.Berlamont, 142 p.

To enable these climate change scenarios to be applied in the hydrological modelling and/or water engineering practice, a Perturbation Tool has been developed. The **CCI-HYDR Perturbation Tool** can be used to perturb historical rainfall and ETo series, which are input series to the hydrological models. For the rainfall series, the perturbation involves both changes in the frequency of rain storms and changes in the rainfall intensity. The changes are being made in a variable way, depending on season and month, on return period or storm frequency and on time scale. The series to be perturbed can be daily or hourly and can have any length (typical lengths vary from a few years to 100 years). The perturbations can be made for time horizons till 2100 (e.g. for 2020, 2030, ..., 2100). Final results are perturbed series of rainfall and ETo for the high, mean, and low CCI-HYDR climate change scenarios.

The CCI-HYDR Perturbation Tool tool takes the form of a Microsoft Excel workbook (with algorithms implemented in VBA code). The following manual has been prepared explaining the background of the tool and how to use the tool (by hydrological modelers):

- Ntegeka V., Willems P., 2009. "***CCI-HYDR Perturbation Tool: a climate change tool for generating perturbed time series for the Belgian climate***", Belgian Science Policy – SSD Research Programme, Manual version January 2009, K.U.Leuven – Hydraulics Section & Royal Meteorological Institute of Belgium, 7 p.

Next to this report, which summarizes the results of the entire project, a separate summary report has been prepared after Phase 1 of the project. The latter summarizes the literature review (technical report I) and the development of the climate scenarios for climate change impact investigations in Belgium (technical reports II and III):

- Ntegeka V., Willems P., Baguis P., Roulin E., 2008. "Climate change impact on hydrological extremes along rivers and urban drainage systems. ***Summary report Phase 1: Literature review and development of climate change scenarios***", Belgian Science Policy – SSD Research Programme, CCI-HYDR project by K.U.Leuven – Hydraulics Section & Royal Meteorological Institute of Belgium, April 2008, 64 p.

Through the project website, all these reports are made available in digital format to all interested parties. The project team also prepared a **folder** / **flyer** in which the CCI-HYDR climate change scenarios for Belgium and the CCI-HYDR perturbation tool are being announced. The flyer includes a reply card that can be filled and send to receive a hard copy of the summary report and/or the more detailed technical reports.

Project workshops

Five project workshops (Follow-up Committee meetings) have been organized, jointly with the project ADAPT. The minutes of these workshops can be found in Annex 2. The aim of these workshops was to collect feedback from the members of the Follow-up Committee (the end users of the climate change scenarios and impact results produced) prior to the written reporting and dissemination of the results to a wider audience.

Presentations at other meetings

The results of the CCI-HYDR project were presented during many occasions (conferences, workshops, meetings of projects in which the results of this CCI-HYDR project are being applied, ...).

International conferences and workshops:

- Congrès "Variations climatiques et hydrologie" de la Société Hydrotechnique de France / 29e Journées de l'hydraulique, Lyon, 27-28 March 2007: poster presentation P.Baguis
- Postacademic course TUDelft on "Climate change: Flooding and urban drainage", Delft, 18 - 19 March 2008: lectures P.Willems on 'Changes in rainfall climate' and 'Translation of rainfall changes to changes in urban drainage design values'
- EGU General Assembly 2008, Vienna, 13-18 April 2008: poster presentation P.Baguis 'Assessment of RCM climate change scenarios for hydrological impact studies in Belgium'
- International Conference on "Water Resource systems management under extreme conditions", 4-5 June 2008, Moscow, Russia: presentation O.Boukhris on 'Rainfall and evapotranspiration climate change scenarios for impact analysis on hydrological extremes in Belgium'
- International Conference on 'Water & Urban Development Paradigms', Leuven, 15-17 September 2008 : presentation O.Boukhris on 'The impact of climate change on the hydrology in highly urbanized Belgian areas'
- FloodRisk 2008 Conference, 30 Sept. – 2 Oct. 2008, Oxford, UK : presentation O.Boukhris 'Climate change impact on hydrological extremes along rivers in Belgium'
- Conférence Eau et changement climatique / Congres Water en klimaatverandering, Universiteit Antwerpen, 14 - 15 Oct. 2008, presentation P.Willems on 'Impact of climate change on hydrological and hydraulic extremes in the Scheldt and Seine river basins and along the coasts of Northern France and Belgium'
- EGU General Assembly 2009, Vienna, 19-24 April 2009: presentation V.Ntegeka on 'Detecting temporal extreme clusters in long-term precipitation records'
- EGU General Assembly 2009, Vienna, 19-24 April 2009: poster presentation P.Baguis 'Sensitivity of hydrological extremes in climate and land use changes in Belgium'
- 8th International Workshop on Precipitation in Urban Areas - Rainfall in the urban context: forecasting, risk and climate change, St.Moritz, December 2009: presentation P.Willems on 'Climate change impact assessment on urban rainfall extremes and urban drainage: methodologies and difficulties'

- EGU General Assembly 2010, Vienna, 2-7 May 2010: presentation P.Willems on 'Statistical downscaling of rainfall and small-scale hydrological impact investigations of climate change'
- EGU General Assembly 2010, Vienna, 2-7 May 2010: presentation P.Willems on 'Climate change impacts on hydrological extremes (floods, low flows) along catchments in the Scheldt river basin'
- EGU General Assembly 2010, Vienna, 2-7 May 2010: poster presentation 'Multidecadal oscillations in rainfall extremes'
- EGU General Assembly 2010, Vienna, 2-7 May 2010: poster presentation 'Assessing the relative impact of urban expansion and climate change on high flows in a small catchment in Flanders (Belgium)'
- IPC10 International Precipitation Conference, Coimbra, Portugal, 23-25 June 2010: presentation V.Ntegeka on 'Multidecadal clustering of rainfall extremes over northwestern Europe during the past century'
- International Conference "Adaptation to the changing climate: time to intensify efforts", Brussels, 23-24 November 2010: poster presentation on 'Flanders Environment Outlook 2030: Climate change and impacts on water systems till 2100'
- International Conference "Adaptation to the changing climate: time to intensify efforts", Brussels, 23-24 November 2010: poster presentation on 'Hydrological impact analysis of climate change and urban expansion: a base for adaptation strategies (cases in Flanders, Belgium)'
- International Conference "Adaptation to the changing climate: time to intensify efforts", Brussels, 23-24 November 2010: poster presentation on 'Adaptation to climatic change of urban drainage in Europe'

National workshops:

- Workshop Coordination Commission Integrated Water Management (CIW), 12 Oct. 2006
- International Scheldt Commission, Sept. 2006
- Workshop Flanders Hydraulics authority, Antwerp, Jan. 2008
- Seminar students bio-engineering U.Gent, 4 March 2008
- ARGUS/VLEVA Symposium in preparation of the 'Belgian chairmanship of the EU' on the topic of 'Is our climate changing??', Brussels, 26 Oct. 2009
- SUDEM-CLI cluster project workshop, Antwerp, 29 Jan. 2009
- External Launch Leuven Research Center Sustainable Earth, 19 June 2009
- SUDEM-CLI cluster project workshop, Heist-op-den-Berg, 20 Nov. 2009
- Seminar Belgian National Committee for Geodesy and Geography, Leuven, 29

April 2010

- Workshop of Flemish Government of Belgium, Dept. Environment, Nature and Energy on 'Adaptation and climate change: living with a future (in Dutch)', Brussels, 28 June 2010
- Workshop on local water management of the Flemish Union of Cities and Communities (Vlaamse Vereniging van Steden en Gemeenten VVGS), Expo Antwerpen, 26 Sept. 2010
- 4th Belgian Geography Days, Leuven, 22-23 Oct. 2010
- Fall meeting of the Dutch Hydrological Union (Nederlandse Hydrologische Vereniging NHV), Leuven, 25 Nov. 2010

New international collaborations

Thanks to the CCI-HYDR research project and the innovative research expertise built up, new international cooperations were established:

- In preparation of the Conférence Eau et changement climatique / Congres Water en klimaatverandering at Antwerp on Oct. 2008: visit to the research group of A.Ducharne, Université Paris VI : comparison impact results of climate change between Belgium and Norther France (Scheldt, Somme and Seine)
- 6 months research stay (Febr.-July 2009) of P.Willems at the Laboratoire des Sciences du Climat et de l'Environnement (UMR CEA-CNRS), Gif-sur-Yvette, France: research cooperation on statistical downscaling of rainfall extremes
- Collaboration with the Dutch Royal Meteorological Institute (KNMI) initiated by the INBO project
- Collaboration with Deltares, The Netherlands (member of the CCI-HYDR Follow-up Committee): comparison of the climate change impact results on the Meuse river applying the CCI-HYDR versus KNMI'06 climate change scenarios (project for Flanders Hydraulics authority); contribution to the new book by M. de Wit on the river Meuse (rainfall trend analysis Uccle).
- IWA/IAHR International Working Group on Urban Rainfall (IGUR) of the International Water Association (IWA) and the International Organization of Hydraulic Engineering and Research (IAHR): P.Willems coordinates the preparation of a review paper on the topic of 'Climate change impact assessment on urban rainfall extremes and urban drainage: methodologies and difficulties',
- VLIR-ICP PhD Scholarship obtained on the topic of 'Climate change impact on the hydrology of Lake Victoria' in cooperation with Makarere University Uganda: see also the abstract and poster by Ogiramoi P.N., Ntegeka V., Willems P. (2009), 'GCM based perturbation analysis over Katonga and Ruizi Catchments in

Lake Victoria basin', International Symposium 'Developing Countries facing Global Warming: a Post-Kyoto Assessment', Brussels, 12 - 13 June 2009

- K.U.Leuven SBA Scholarship obtained on the topic of 'Climate change impact on the Andes hydrology of the Paute basin in Ecuador' in cooperation with the University of Cuenca Ecuador (PhD Diego Mora)
- K.U.Leuven DBOF Scholarship obtained on the topic of 'Low flow analysis and related drought conditions in selected catchments of the Nile basin under climate change' (linked to the FRIEND/Nile project of UNESCO-IHP) (PhD Meron Teferi Taye)
- Partner in new ERASMUS Curriculum Development Project "The Lived Experience of Climate Change : interdisciplinary e-module development and virtual mobility" (LECH-e), EC DG EAC/31/08 Lifelong Learning Programme, Coordinator: Dr. Gordon Wilson, Environment, Development and International Studies at the Open University, UK, 2009-2012
- Partner in new EU FP7 project on "Innovative technologies for safer European coasts in a changing climate" (Theseus), Coordinator: Prof. Barbara Zanuttigh, University of Bologna, 2010-2013
- Erasmus Mundus – Ánimo, ¡Chévere! Scholarship obtained on the topic of 'Hydro-climatic variability and climate change effect on hydrologic response of Tropical Andean Mountains in Southern Ecuador-Northern Peru' (PhD Luis Pineda Ordoñez)
- Reviewer of the IPCC Special Report on Extreme events and disasters (SREX), 2010

New national collaborations

- Cooperations established with the ADAPT team: common Follow-up Committee meetings, joint research for the Dender basin case study, MSc thesis at K.U.Leuven (promoter P.Willems) linked to the ADAPT project: simulation of adaptation measures in the Dender hydrodynamic model
- Joint contributions to the MIRA-S Environmental Report 2009 (scientific report theme Climate change and water) with R. De Sutter (ADAPT)
- New collaborations with Prof. J-P. Van Ypersele and Dr. Ph.Marbaix (members of the CCI-HYDR and ADAPT Follow-up Committee) in the BelSPO cluster project SUDEM-CLI on "Impact of climate change on river hydrology and ecology: A case study for interdisciplinary policy oriented research"
- New collaborations with the Dutch Royal Meteorological Institute (KNMI): research project on climate change scenarios for the Institute for Nature and Forest Research (INBO)

- As a follow-up of the CCI-HYDR and ADAPT Follow-up Committee meetings, research cooperation has been initiated with Prof. D. Raes on "assessing the consequences of climate change on crop development and the soil water balance" (FWO PhD scholarship obtained for Eline Vanuytrecht): poster Vanuytrecht E., Geerts S., Willems P., Raes D. (2009), 'AquaCrop (FAO crop water productivity model) as a tool to assess the consequences of climate change on crop development and the soil water balance', International Symposium 'Developing Countries facing Global Warming: a Post-Kyoto Assessment', Royal Academy for overseas sciences and United Nations, Brussels, 12 - 13 June 2009, 82-83; and presentation Vanuytrecht E., Geerts S., Willems P., Raes D. (2009), 'Effects of elevated atmospheric CO2 concentrations on crop development and soil water balance. A review and implementation in the water productivity model AquaCrop', In: Smagghe, G., Boeckx, P., Bossier, P., Steurbaut, W., Van Damme, E.J.M., Verhoest, N. (Pub.). Communications of Agricultural and Applied Biological Sciences 74(4), p 83-88. Ghent University & Proceedings of the PhD symposium on Applied Biological Sciences; 15th PhD Symposium on Applied Biological Sciences, Leuven, Belgium, November 2009.
- New research collaboration on impact of climate change on groundwater with Prof. O. Batelaan: CCI-HYDR climate scenarios are used in the PhD research by Jef Dams: submitted paper Dams, J., Salvadore, E., Van Daele, T., Ntegeka, V., Willems, P., Batelaan, O. (2010), 'Spatio-temporal impact of climate change on the groundwater system', Geophysical Research Letters
- New research collaboration on comparing land use trends impacts versus climate change impacts with Prof. A. Van Rompaey: CCI-HYDR climate scenarios are used in the PhD research by Lien Poelmans on "Modelling urban expansion and its hydrological impacts": paper in revision Poelmans, L., Van Rompaey, A., Ntegeka, V., Willems, P. (2010), 'The relative impact of climate change and urban expansion on river flows: a case study in central Belgium', Hydrological Processes
- FWO project accepted in cooperation with Prof. N. Verhoest of U.Gent on "Stochastic rainfall generation accounting for climate changes"
- Review for SCK/CEN van rapport NIROND-TR 2009-07 "Long-term climate change and consequences on near field, geosphere and biosphere parameters - project near surface disposal of category A waste at Dessel"
- Collaborations on climate change impact investigations with several water and environmental authorities (see Section 3)

5 PUBLICATIONS

International peer-reviewed journal publications

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- Baguis P., Roulin E., Willems P., Ntegeka V., 2010. “Climate change and hydrological extremes in Belgian catchments”, Hydrol. Earth Syst. Sci. Discuss., 7, 5033-5078, doi:10.5194/hessd-7-5033-2010
- Ntegeka V., Willems P., Roulin E., Baguis P. (in revision), ‘Developing tailored climate change scenarios for hydrological impact assessments’, Journal of Hydrology, [in revision]

International conference proceedings publications

- Boukhris O., Willems P. (2008), ‘Climate change impact on hydrological extremes along rivers in Belgium’, FloodRisk 2008 Conference, 30 Sept. – 2 Oct. 2008, Oxford, UK In: Flood Risk Management: Research and Practice (Eds. Samuels et al.), Taylor & Francis Group, London, 1083-1091 (ISBN 978-0-415-48507-4)
- Boukhris O., Willems P., Vanneuville W. (2008), ‘The impact of climate change on the hydrology in highly urbanized Belgian areas’, International Conference on ‘Water & Urban Development Paradigms’, Leuven, 15-17 September 2008; Proceedings “Water and urban development paradigms: Towards an integration of engineering, design and management approaches” (Eds. J.Feyen, K.Shannon, M.Neville), CRC Press, Taylor & Francis Group, 271-276
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- Willems P., Deckers P., De Maeyer Ph., De Sutter R., Vanneuville W., Brouwers J., Peeters B. (2010), 'Environmental Outlook towards 2030 for the Flanders region of Belgium: possible climate changes and their consequences for the water systems', International Conference 'Deltas in Times of Climate Change', 29 September 29 – 1 October 2010, Rotterdam, The Netherlands
- Coninx I., Willems P., De Smet L., De Sutter R. (2010), 'Reducing tangible and intangible flood risks in a climate change context: a micro level decision support tool', International Conference 'Deltas in Times of Climate Change', 29 September 29 – 1 October 2010, Rotterdam, The Netherlands

National peer-reviewed journal publications

- Willems P., Ntegeka V., Berlamont J. (2007), 'Analyse van trends en meerjarige schommelingen in de neerslagextremen op basis van de meer dan 100 jaar 10 minuten neerslag te Ukkel', Rioleringswetenschap, jaargang 7, nr. 26, juni 2007, 45-53
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